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METHODS OF MOISTURE CONTROL AND THEIR APPLICATION TO BUILDING CONSTRUCTION

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TABLE OF CONTENTS

Page

PART I—General

Acknowledgment v
Introduction 1
Analysis of problems 2
Theory of vapor transmission through materials 5

PART II—Equipment and Instruments

Test apparatus 15
- Cold room 15
- Cooling equipment 15
- Air conditioning equipment 15
- Control equipment 20

Instruments 21
- Moisture control methods 21
- Wet and dry bulb temperature apparatus 21
- Special humidity controller 21
- Dew-point temperature apparatus 22

Test units 23
- Wall construction 23
- Attic construction 23
- Vapor barrier test apparatus 25

PART III—Test Results

Vapor barriers 29
- Test procedure 29
- Barriers tested in combination with walls 29
- Barriers tested by special test apparatus 34
- Practical application of barriers 36

Rate of condensation with variable temperatures 36
Rate of condensation with variable relative humidity 38
Water vapor within a wall 39
- Wood absorption blocks 40
- Dew-point temperature measurements 41

Vapor transmittance coefficients 43
- Coefficients by two different test methods 43
- Vapor transmittance coefficients for mineral wool insulation and plaster 45
- Vapor transmittance coefficients for paint 47
- Vapor transmittance coefficients for plaster and plaster base materials 48

Wet plaster and vapor barrier 49
Ventilation and condensation within a structure 50
- Ventilation of walls by diffusion 51
- Ventilation of walls by convection currents 51
- Ventilation of attic spaces 51

Conclusions 56

TABLES

Table		Page
I.	Condensation on inner surface of sheathing for different types of membrane vapor barriers placed between metal lath and studs	30
II.	Condensation on inner surface of sheathing for test walls with different types of finishes on interior surfaces of plaster	31
	Addenda for Table III	32
III.	Vapor transmission for different materials by special test method	32
IV.	Relative vapor transmission for different surface coatings by special test method	34
	Addenda for Table IV	35
V.	Calculated temperatures and vapor pressures through insulated wall for different outside air temperatures—other conditions remaining constant	38
VI.	Dry bulb and dew-point temperatures by test at various vertical planes in an uninsulated and an insulated wall	42
VII.	Vapor transmittance coefficients for ¾-inch plaster on metal lath and 3⅝ inches of mineral wool	44
VIII.	Vapor transmittance coefficients for mineral wool pad 2⅛ inches thick and for ¾ inch of plaster applied to metal lath	46
IX.	Vapor transmittance coefficients for different types of vehicles and paints	47
X.	Vapor transmittance values for plaster in combination with plaster base material	48
XI.	Air temperatures and humidity conditions for wet plaster tests	49
XII.	Attic ventilation	53

ILLUSTRATIONS

Figure		Page
1.	Wall built of nonhygroscopic, homogeneous material permeable to water vapor	9
2.	Wall built of nonhygroscopic, homogeneous material permeable to water vapor	9
3.	Wall built of hygroscopic, homogeneous material impermeable to water vapor	9
4.	Wall built of nonhygroscopic, homogeneous material permeable to water vapor	11
5.	Wall built of nonhygroscopic, homogeneous material permeable to water vapor	11
6.	Frame wall without insulation showing normal temperature and vapor pressure gradient through wall	12
7.	Frame wall with insulation showing normal temperature and vapor pressure gradients as established through wall	13

Figure | Page

8. View of cold room showing test houses in place ... 16
9. Sectional view through cold room and cooling unit ... 16
10. Interior view of cooling unit while under construction ... 17
11. View of cooling unit while under construction ... 17
12. View of completed cooling unit and one end of control room ... 18
13. Ammonia compressor, control room, and defrosting fan for cooling equipment ... 18
14. Air conditioning unit for test houses ... 19
15. Sectional view of air conditioning unit with distribution ducts to test houses in cold room ... 19
16. Control and thermocouple panel for test equipment ... 20
17. Sectional view of test houses showing details of construction ... 24
18. Type of wall construction used to facilitate inspection ... 24
19. Test house used for wet plaster test and also subsequent tests on wall ventilation ... 25
20. Construction details of attic for attic ventilation tests ... 26
21. View of set-up for ventilated and unventilated attics ... 26
22. Line drawing showing details of construction for special vapor barrier test apparatus ... 27
23. View of apparatus for making tests on vapor barriers ... 27
24. Per cent moisture absorbed by wood absorption blocks placed at various planes in walls ... 40
25. Dry bulb and dew-point temperatures in the interior sections of an uninsulated wall ... 41
26. Dry bulb and dew-point temperatures in the interior sections of an insulated wall ... 41

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Methods of Moisture Control and Their Application to Building Construction

PART I—GENERAL

INTRODUCTION

Experience in low temperature storage rooms and in many industrial buildings where high indoor relative humidities prevail (such as creameries and laundries) has demonstrated that certain precautionary measures are necessary with respect to moisture control. Specifically, it has been found that in such cases insulation is necessary to prevent surface condensation. It has also been found in building construction of the types mentioned that moisture barriers must be properly employed to protect the insulation and other constituent portions of the construction against undesirable effects of excessive moisture.

In recent years it has become common practice to increase indoor humidities in residences for purposes of better health, greater comfort, and protection of buildings and furnishings. Thus, the control of moisture in residential construction has become quite as important as the control of moisture in industrial construction, and accordingly this problem has had the consideration of architects and residential builders. While the principles of proper moisture control which have been established in certain industrial fields obviously apply in residential construction, the conditions in residences vary sufficiently from those which prevail in industry to justify specific investigations to develop the most practical means of adjusting residential building practice and operating methods to the new conditions which prevail.

In the early part of 1937 the National Mineral Wool Association in co-operation with the University of Minnesota started a comprehensive research program, the objects of which were: first, to determine the extent of condensation within modern buildings and with different methods of operation; second, to measure the effectiveness of different types of construction; and third, to find the limiting conditions under which various types of building designs may be used without excessive condensation and still retain the benefits of air conditioning and good building construction.

It was decided to approach the problem in a practical way and to make tests, the results of which would apply to full-scale building construction under temperature and humidity conditions to be expected in severe climates. To accomplish this, a large-size test room was constructed and provided with cooling equipment of sufficient capacity to maintain inside air temperature at 25° F. below zero. Small-size test houses were constructed and placed within this room, with provision for maintaining the air temperatures and humidities within these houses at any desired level. The walls of the test houses were so constructed that they could be taken apart and examined from time to time throughout a test period to determine the physical conditions of their interiors, and to make comparisons between various types of structures. The details of the test apparatus will be described later in this bulletin.

In addition to the results presented in this bulletin three papers have been published as follows:

"Condensation within Walls," by F. B. Rowley, A. B. Algren, and C. E. Lund. *Journal of the American Society of Heating and Ventilating Engineers,* 10:49-60. January, 1938.

"Condensation of Moisture and Its Relation to Building Construction and Operation," by F. B. Rowley, A. B. Algren, and C. E. Lund. *Journal of the American Society of Heating and Ventilating Engineers,* 11:41-49. January, 1939.

"A Theory Covering the Transfer of Vapor through Materials," by Frank B. Rowley. *Journal of the American Society of Heating and Ventilating Engineers,* 11:452-65. July, 1939.

The next step in the program is to construct a large-scale test house within the cold room and to apply to full-scale building construction those principles which have been proven satisfactory in the smaller test houses.

ANALYSIS OF PROBLEMS

In practical ventilating problems all air contains moisture in the form of water vapor, and we speak of it as saturated or partly saturated, depending upon whether the maximum, or only a part of the maximum amount of moisture, is present. The amount of vapor which may be contained in a given volume of air increases as its temperature is increased. Consequently, if air which is partly saturated is cooled, the percentage of saturation will be increased until it reaches 100 per cent, after which further cooling will condense out some of the vapor. The properties of the water vapor are not changed by the presence of the air. The maximum amount of vapor that can be contained in a given space at a given temperature, the pressure exerted by the vapor, the dew-point temperature, etc., are all the same, regardless of whether or not air is present. Water vapor exerts a pressure which depends upon its temperature and percentage of saturation. Water at 80° F. temperature will boil at a pressure of 1.03 inches of mercury, and this is the vapor pressure of saturated vapor at 80° F. If the vapor at 80° F. is only 50 per cent saturated, then the vapor pressure is likewise 50 per cent that of saturation, or .516 inch of mercury. The saturation temperature corresponding to .516 inch of mercury is 59.8° F. Therefore, if a vapor which is 50 per cent saturated at 80° F. is cooled to 59.8° F., it will become saturated and further cooling will cause condensation. When air is mixed with the vapor, the pressure exerted by the air is added to that exerted by the vapor, but the vapor pressure is the one that must be considered in connection with the properties of the vapor or its action in connection with the condensation problem in a building.

Condensation may take place on the interior surfaces of the windows or walls of a building if the temperatures of these surfaces are below the dew-point temperature of the vapor within the building. For most types of building construction now in use sufficient data are available for calculating the minimum inside surface temperatures which may be expected for given outside and inside air temperatures. These surface temperatures, together with data available on the properties of water vapor, give a basis for determining the temperature and humidity conditions which are likely to cause surface condensation. The vapor within a building is not confined to contact with the interior surfaces of the glass and walls. It penetrates into the interior parts of the walls and will pass through some types of materials very readily. As the vapor passes outwards through the walls of a house located in a cold climate it will come in contact with colder materials, and a condition may be set up in which the dew-point temperature of the vapor in a given part of the wall is above the temperature of the material in contact with this vapor. Under these conditions condensation may take place, and free moisture or frost may be formed in the wall, depending upon the temperature.

The conditions which cause condensation within a wall are no different from those which cause condensation on the surfaces of the wall. In both cases the temperature of the material is below the dew-point temperature of the vapor in contact with it. For most types of construction it is possible to calculate the temperatures which may be expected throughout the wall with the same degree of accuracy as for the interior surface temperatures. There is, however, at present no method by which the vapor density within the wall may be calculated with any degree of certainty, even tho the vapor conditions on both sides of the wall are known. The laws governing the transmission of vapor through materials, and the vapor transmitting properties of the various materials and combinations of materials used in building construction have not as yet been investigated.

The motive force which causes vapor flow is usually considered to be the difference in vapor pressure along the path of flow, and the rate of vapor flow through any part of the wall is considered to be directly proportional to the drop in vapor pressure, and inversely proportional to the vapor resistance of the material along the path of flow. Thus, high vapor pressures within a building as compared with those on the outside will give a high potential rate of vapor flow. In general there will be a vapor pressure gradient through the wall from the high vapor pressure to the low vapor pressure side. The vapor density at various sections of the wall will depend upon vapor resistance throughout the walls. Thus, if the interior section has a high resistance, and the exterior section a low resistance, to the passage of vapor, there will be a tendency toward a low vapor density within the wall; whereas if reverse conditions are true there will be a tendency for high vapor densities within the wall. For any given condition of temperatures and vapor pressures on the two sides of a wall, the vapor pressure and temperature gradient through the wall will be governed by the type of material selected and its arrangement in the wall. If the vapor pressures within all sections of the wall are below the saturated vapor pressures which correspond to the temperatures for the given sections there can be no condensation within the wall. There is, however, no relation between the heat-transmitting and vapor-transmitting properties of materials.

During recent years several changes have taken place which emphasize the importance of proper moisture control in residential construction. Part of these changes come under the heading of air conditioning, and part under the heading of better building construction. The essential change under air conditioning is that of maintaining higher relative humidities which are so often advocated for buildings located in cold climates. Those changes which may be classified under better building construction are the prevention of air leakage by the addition of weather strips and tighter building construction, the prevention of vapor passage through the exterior surface of the wall by better building papers, and the addition of insulation to the exterior walls of the building.

For several years past the low relative humidities found in the average residence and public building located in cold climates have been a subject for much discussion, and a great deal has been said about the possible effect of these low relative humidities upon health, furniture, and the interior finishings of buildings. As a result of these discussions, together with the development of the science of air conditioning and air conditioning appliances, many devices have been installed in homes and public buildings for the express purpose of increasing the relative humidities carried in cold weather. Many of these devices have been installed without control, and have often been of a type which operate to excess in the coldest weather. Excessive humidities thus are supplied to buildings equipped with these humidifiers during the period when there is the greatest possibility of condensation trouble.

The loss of heat caused by the leakage of air through the exterior walls of buildings is another factor which has received a great deal of attention in recent years. Weather strips have been developed and added to doors and windows, and there has been a tendency toward tighter building construction. The reduction of air filtration through the exterior walls of a building due to better construction has resulted in higher inside relative humidities due to the build-up of moisture from normal living processes.

The widespread use of insulation in recent years has probably been one of the most influential factors for better building construction in cold climates. The addition of insulation to a wall retards the flow of heat through the wall, changes the temperature gradient, and reduces the possibility of condensation on the warm side of the wall.

There is no logical argument against the use of moderate humidities for better conditions of comfort and health, nor against the addition of weather strips and other means of reducing the air leakage between the inside and outside of the building. Much less could any argument be applied against the addition of insulation in cold climates as a factor in saving heat. Each of these are essential elements for a well-constructed building and a comfortable place in which to live. Under certain conditions each may be a factor in the condensation problem, but the elimination of any one would not be a logical solution. The condensation problem requires investigation on a practical and scientific basis—a practical basis to the extent of finding what may be expected from present practice in building construction and operation with practical methods of eliminating trouble, and a scientific basis to the extent of investigating the laws which govern the transmission of vapor through materials, and of determining the vapor-transmission properties of various materials and combinations of materials which are practical for building construction.

THEORY OF VAPOR TRANSMISSION THROUGH MATERIALS

The theory relating to the transfer of vapor through materials has not been fully developed, altho it has often been assumed that the laws governing vapor transmission are similar in form to those governing the flow of heat through the walls of buildings, and that coefficients of vapor transmittance may be developed for materials, or combinations of materials, which may be applied in the same manner as the coefficients of heat transmission are applied. According to this theory the difference in vapor pressures between the two parts of a structure is the motive force which causes the flow of vapor, and the amount of vapor transmitted is directly proportional to the difference in vapor pressure, and inversely proportional to the vapor resistance of the material between the two parts of a wall. The overall vapor resistance of a built-up wall section is then equal to the sum of the vapor resistances of its component parts. A vapor transmittance coefficient would be defined as the quantity of vapor transmitted per unit of time per unit cross-sectional area per unit difference in vapor pressure along the path of transmittance, and there would be coefficients for surfaces, air spaces, homogeneous materials, and combinations of materials. This theory appears to satisfy many of the practical conditions, but there are specific differences between heat and vapor, and the methods by which they may be transmitted, which make it doubtful that it could be applied in all cases.

Heat is a form of energy having no physical properties, and unless it is changed from sensible to latent, or vice versa, it will be transferred through a wall without change of state. Vapor is a substance with physical properties, and in the course of its transfer through a structure may change its state several times. Heat may be transmitted by radiation, conduction, and convection. Vapor may be transmitted by molecular diffusion and convection, and the condensed vapor may be transmitted by capillarity or other means.

The method by which water vapor travels from one point to another depends partly upon the material through which it travels and partly upon the temperature along its path. In so far as its transfer through building construction is concerned, the materials through which it travels may be classified as air and solids. The conditions of air which seem to be of greatest importance are temperature, pressure, and air movement. The properties of the solids which seem to have the greatest significance are permeability to gases and power to absorb water vapor from the air. These two properties of solid materials, together with temperature, largely determine the state of the moisture as it travels through them.

If the temperature of air is above the dew-point temperature of vapor the vapor may be transmitted through the air by turbulence and by molecular diffusion. The transfer of vapor by convection currents is similar to the transfer of heat by convection currents. The resistance of the flow of vapor through air by molecular diffusion is a function of density and temperature of the air through which it passes. For a given temperature and density of air vapor mixture the rate of vapor travel by molecular diffusion between two points may be considered as inversely proportional to the distance between the points. Thus under ordinary conditions it may be substantially correct to assume that the laws governing the rate of vapor travel through air by either convection currents or molecular diffusion are similar in form to those governing the flow of heat through air by conduction and convection.

When vapor passes through a solid material there are at least three types of materials which seem to be of importance: first, those materials which are permeable to air or gas and which will not absorb water vapor; second, those materials which are impermeable to gas but which will absorb water vapor; and third, those materials which are permeable to gas and which will also absorb water vapor. Temperature is also an important factor.

If a nonhygroscopic, homogeneous material is permeable to water vapor and its temperature at all parts is above the dew-point temperature of the vapor in contact with those parts there will be no condensation. If the temperatures and static pressures on the two sides of the material are balanced, any vapor transmittance should be by molecular action, and the rate should be directly proportional to the vapor pressure drop along the path. If there is a temperature gradient along the path of vapor flow and the material is of a porous nature, then the rate of vapor travel may be increased by convection currents. This additional rate of transfer due to convection currents will lower the vapor pressure in the material, which would normally have been established by the vapor pressure conditions on the two sides of the material. The temperature gradient through a wall establishes the maximum vapor pressures which can be carried at any point without condensation. If there are no convection currents possible, then condensation may occur at any point in the wall where the normal vapor pressure line as established by diffusion alone, crosses the maximum vapor pressure line. If, however, there is a temperature gradient through the wall and the porosity of the material is such that convection currents are possible, the rate of vapor passage through the material will be increased and the actual vapor pressure within the material may be far below that indicated by the normal vapor pressure line due to molecular diffusion alone. Under these conditions condensation will not occur in the porous material. This point is well illustrated in the average frame wall with fill insulation between the studs. The increased rate of vapor flow through the insulation due to convection currents reduces the actual vapor pressure line through that part of the wall below the line which would normally be established by molecular diffusion, and condensation does not occur in the loose material, but may under certain conditions occur on the surface of the sheathing, lining the cold side of the material. This fact is discussed later and has been proved by tests as well as by practical installations.

If a material which is impermeable to water vapor is hygroscopic it will absorb water vapor and establish a moisture equilibrium when in contact with air vapor mixtures. The percentage of moisture absorbed by the material will depend somewhat on the temperature, but largely upon the relative humidity of the air with which it is in contact. The transmission of moisture through materials of this character will be by capillarity or some similar process and will not depend upon vapor pressure difference. Under certain conditions it appears that vapor may be absorbed from a mixture of low vapor pressures, transmitted through the material, and delivered to a mixture of high vapor pressures. If the temperature of either surface of the material is below the dew-point temperature of the vapor in contact with it, some of the vapor will be condensed. Free moisture or water may disturb the normal moisture equilibrium which would have been established by the water vapor in contact with the material and thus change the rate, and perhaps direction, of moisture flow through the material.

If a material is hygroscopic and permeable to water vapor, it may transmit water vapor and free moisture, the net result depending upon several factors. For instance, a condition might be set up in which vapor would be transmitted in one direction due to vapor pressure differences and the permeability of the material, and moisture would be transmitted in the opposite direction due to the hygroscopic properties of the material and the relative percentages of vapor saturation on the two sides of the material. The rate of vapor transmission due to the hygroscopic properties of a material is very low and the net result for any practical wall would be in the direction of the vapor pressure drop. The above principles are illustrated in Figures 1, 2, and 3.

In order to illustrate the above theory the walls of Figures 1 to 5, inclusive, are assumed to be constructed of materials having ideal properties for the theory under consideration. The wall of Figure 1 is built of a homogeneous, nonhygroscopic material which is permeable to water vapor. The material will transmit the vapor by diffusion but is not sufficiently porous to transmit the vapor by convection. The air in contact with the left-hand surface of the wall is at 70° F. and 40 per cent relative humidity, and that in contact with the right-hand side is at 0° F. and 40 per cent relative humidity. The temperature gradient line through the wall is plotted to the temperature scale shown at the left, and the vapor pressure lines are plotted to the vapor pressure scale shown at the right. In each instance a reasonable drop in temperature and vapor pressure is indicated between the surface of the material and vapor in contact with this surface.

Under the conditions given, the line *A-B,* plotted to the temperature scale, represents the temperature gradient through the wall. The curved line *C-D,* plotted to the vapor pressure scale, represents the maximum vapor pressure that it would be possible to carry at any point within the wall without condensation. In other words, any point on this curve gives the vapor pressure at saturation for the temperature of the material in the wall at that point. The straight line *E-F* is the normal vapor pressure gradient established in the wall due to the vapor pressures on each side of the wall. In this case the line *E-F* does not cross the curved line *C-D,* indicating that the temperatures at all points in the wall are above the dew-point temperature of vapor at corresponding points. Vapor should thus pass through the wall from *E* to *F* without condensing within the wall.

The wall shown in Figure 2 is identical in every respect to that shown in Figure 1, and the conditions as to surrounding temperatures and vapor pressures are the same with the exception that the relative humidity of the air in contact with the left-hand surface of the wall has been raised from 40 to 60 per cent, thus increasing the pressure of the vapor in contact with this surface. In this case the vapor pressure line *E-F* which would be established through the wall due to vapor pressure conditions in contact with the two surfaces, will be much steeper than that for Figure 1, and as shown will cross the limiting vapor pressure line *C-D* at some point *X* within the wall. This means that the temperature of the material at *X* will be below the normal dew-point temperature of the vapor at this point and condensation might be expected. Since the temperature of the material in the wall at points immediately beyond *X* is such that the maximum vapor pressures are below those which would normally be established, the rate of vapor travel will be accelerated and new vapor pressure gradients will be estab-

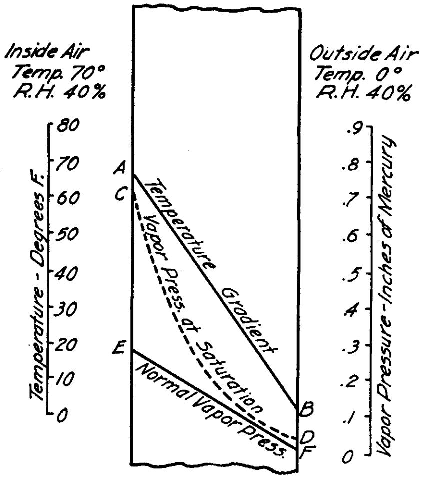

FIGURE 1. WALL BUILT OF NON-HYGROSCOPIC, HOMOGENEOUS MATERIAL PERMEABLE TO WATER VAPOR

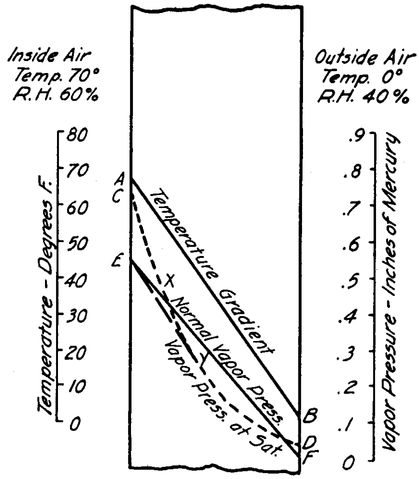

FIGURE 2. WALL BUILT OF NON-HYGROSCOPIC, HOMOGENEOUS MATERIAL PERMEABLE TO WATER VAPOR

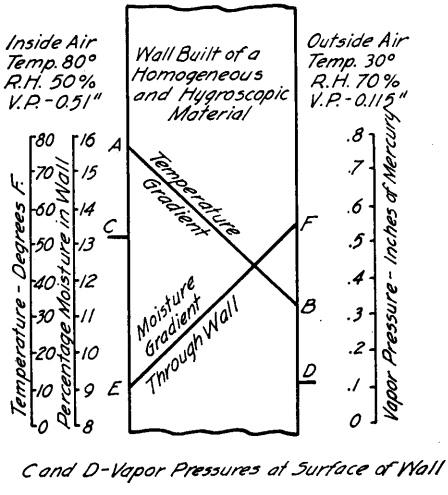

FIGURE 3. WALL BUILT OF HYGROSCOPIC, HOMOGENEOUS MATERIAL IMPERMEABLE TO WATER VAPOR

lished through the wall. If the straight line *E-Y* is drawn tangent to the curve *C-D* at *Y,* it seems probable that *E-Y* would represent the vapor pressure gradient established in the wall up to the point *Y.* From this point on, the maximum vapor pressure gradient for each successive point would be established by a tangent to the curved line *C-D,* and when the slope of this tangent is less than the slope of the line *E-F,* the rate of vapor travel would be less than the normal rate. The rate at which moisture enters the wall would thus be increased and the rate at which it leaves would be decreased from the normal, and there would be an accumulation of moisture within the wall from the point *Y* to the outer surface. Since in this case the interior temperatures of the wall might be below 32° F., frost or ice would be formed.

The wall of Figure 3 is assumed to be built of a homogeneous, hygroscopic material which is impermeable to water vapor. The air on the left-hand side is at 80° F. and 50 per cent relative humidity, and that on the right-hand side is at 30° F. and 70 per cent relative humidity. The normal temperature gradient through the wall is shown by the straight line *A-B,* plotted to the temperature scale at the left. The pressure of the water vapor in contact with the two surfaces is shown by the two short heavy lines *C, D,* and plotted to the vapor pressure scale on the right. This represents the vapor pressure difference on the two sides of the wall, but, since the material is impermeable to vapor, the vapor cannot pass through as such and therefore there is no connecting vapor pressure line between *C* and *D.* Materials of this nature absorb water directly from the vapor with which they are in contact. The percentage of water which they will absorb does not depend upon the absolute vapor pressure, but does depend on the per cent of saturation or, in this case, the relative humidity of the air.

While wood is not an impermeable material, it is hygroscopic and its hygroscopic properties may be used to illustrate this principle. From data published by the United States Forest Products Laboratory, the moisture equilibrium content of wood in contact with 80° F. and 50 per cent relative humidity air would be approximately 9 per cent by weight and, when in contact with air at 30° F. and 70 per cent relative humidity, it would be slightly over 13 per cent by weight. Thus the line *E-F* shows the probable moisture gradient through the wall which would be established by the air conditions shown. From this it is evident that the moisture travel through this wall would be from right to left, or from the side in contact with low vapor pressure air to that in contact with high vapor pressure air. This is contrary to the usual assumption that moisture travels through a wall in direct proportion to the vapor pressure drop between the two sides of the wall. It should be remembered, however, that in this case the vapor does not pass through the wall, but is condensed and absorbed by one surface of the wall, transferred through as absorbed moisture, and evaporated from the other surface. The direction of vapor travel is determined by the moisture equilibrium conditions for the two sides of the material and not by the absolute vapor pressure differences. As previously pointed out the rate of moisture travel by this process would be very low, and while wood has been taken as a hygroscopic material to illustrate the principle, it should be remembered that when wood is used in a wall the sheets are not continuous and vapor will normally travel through the openings by diffusion or convection at a much more rapid rate than it could travel by the hygroscopic action of the wood. Furthermore, wood is not entirely impermeable to water vapor.

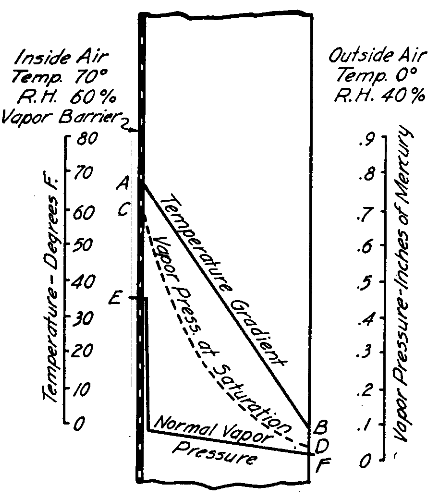

FIGURE 4. WALL BUILT OF NON-HYGROSCOPIC, HOMOGENEOUS MATERIAL PERMEABLE TO WATER VAPOR

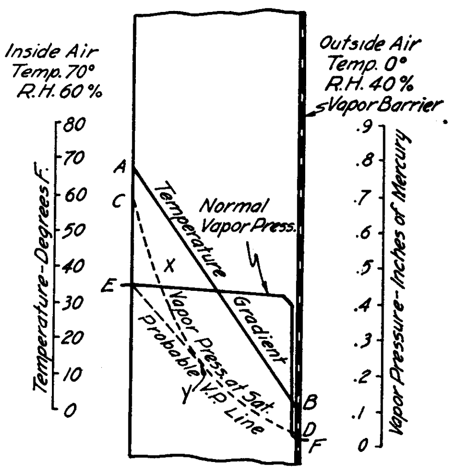

FIGURE 5. WALL BUILT OF NON-HYGROSCOPIC, HOMOGENEOUS MATERIAL PERMEABLE TO WATER VAPOR

In most practical cases where the vapor pressures are different on the two sides of a building wall, a vapor pressure gradient will be established through the wall, and the vapor will travel in the direction of vapor pressure drop. The slope of the vapor pressure line for different sections of a wall will depend upon the resistance to vapor passage at various parts of the wall, and to the temperature of the material. Figures 4 and 5 represent two walls which are built of nonhygroscopic, homogeneous materials which are permeable to water vapor but not sufficiently porous to allow convection currents to be set up within the wall. Both are subjected to air on the warm side at 70° F. and 60 per cent relative humidity, and air on the cold side at 0° F. and 40 per cent relative humidity. The inside or warm surface of the wall shown in Figure 4 is lined with a material which has a high resistance to vapor penetration, and for the wall shown in Figure 5 this vapor-resisting material has been improperly applied to the outer or cold surface of the wall. The normal vapor pressure gradient which would be established by the vapor pressures on the two sides of the walls is shown by the solid lines *E-F*. Since

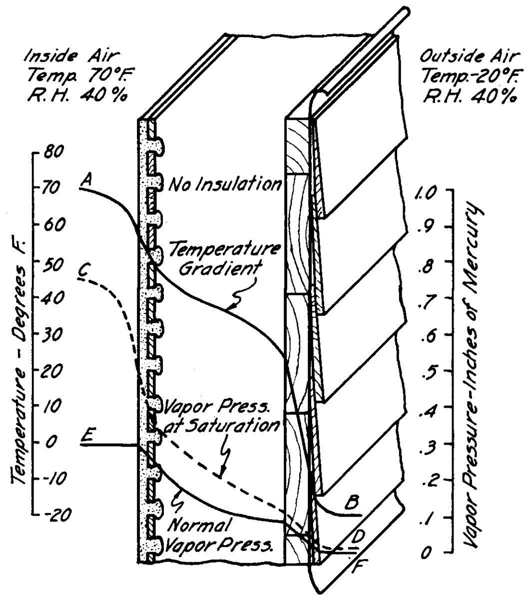

FIGURE 6. FRAME WALL WITHOUT INSULATION SHOWING NORMAL TEMPERATURE AND VAPOR PRESSURE GRADIENT THROUGH WALL

the wall of Figure 4 has a high vapor resistance on its warm surface the vapor pressure within the wall is comparatively low, but in the wall of Figure 5 with the vapor resistance on the cold surface the vapor pressure within the wall is high. If the temperatures throughout both walls were at all points above the dew-point temperatures of the vapor at these points in the wall there would be no condensation. For the temperature conditions shown, however, the high vapor pressures within the wall of Figure 5 are above the maximum allowable vapor pressures throughout the greater part of the wall, and moisture will be formed. In the wall of Figure 4 the vapor pressures are below the condensation point throughout the wall and no vapor will condense. From the discussion of the condition shown in Figure 2 it is evident that the solid line *E-F* of Figure 5 does not represent the true vapor pressure gradient established in the wall. The actual line cannot be above the curved line *C-D*.

Figures 6 and 7 represent two typical frame walls which are identical with the exception that fill insulation has been added to Wall No. 7. In both cases the air on the warm side is at 70° F. and 40 per cent relative humidity, and that on the cold side is at —20° F. with 40 per cent relative humidity. The temperature gradient through each wall is shown by the line *A-B,* and the maximum vapor pressure cor-

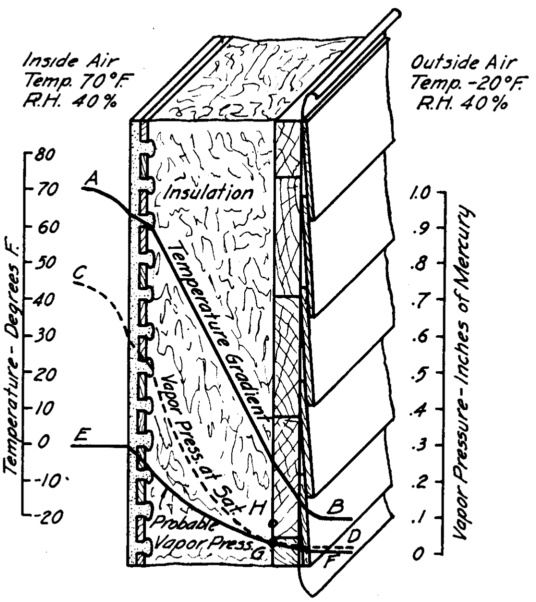

FIGURE 7. FRAME WALL WITH INSULATION SHOWING NORMAL TEMPERATURE AND VAPOR PRESSURE GRADIENTS AS ESTABLISHED THROUGH WALL

responding to the temperature at any point in the wall is shown by the line of dashes *C-D.* The probable vapor pressure gradient for each wall as established by the vapor pressure conditions on the two sides of the wall is shown by the line *E-F.* These lines are shown as curved lines through the central section of the wall as it is probable that the vapor is carried through this section partly by convection.

The addition of insulation to Wall No. 7 reduced the heat loss through this wall to approximately one third of that for Wall No. 6. This caused a reduction in the temperature of the inner surface of the sheathing from approximately 26° F. for Wall No. 6 to —6° F. for Wall No. 7, thus reducing the maximum vapor pressure that can be carried at the inner sheathing surface without condensation. In Wall No. 6 the normal vapor pressure line as established by the conditions on the two sides of the wall does not cross the maximum vapor pressure line as established by the temperature gradient through the wall, and under these conditions condensation will not occur on the warm surface of the sheathing, but may occur between the sheathing and siding. In the Wall of Figure 7 the point *H* on the inner surface of the sheathing represents the normal vapor pressure which would be required at this surface to give a uniform rate of vapor flow throughout the wall. The point *G* which is below *H* represents the maximum vapor pressure which can be carried at the sheathing line without condensation. The point *G* is established by the temperature of the sheathing and will be the governing point in determining the rate of vapor flow to and from the sheathing under the given air conditions. In order to have a uniform continuous rate of vapor flow through the wall the vapor pressure drop from inside air to sheathing line should be no greater than that between *E* and *H*, and the drop from sheathing line to outside air should be at least equal to that from *H* to *F*. Since the point *G* is below *H*, the vapor pressure drop, and therefore the vapor transmission from inside air to sheathing line, has been increased above the normal and that from sheathing line to outside air has been decreased below normal. Obviously there will be an accumulation of moisture at the sheathing line and the accumulation will continue until a correct relation is established between the vapor pressure drop for the inner and outer sections of the wall. There are several possible methods for making this adjustment. First, if the air temperatures and type of construction are to remain the same, the relative humidity of the inside air may be reduced until the rate of vapor travel through the inner section is no greater than the possible rate through the outer section under the temperature conditions. Second, if the vapor pressures of the two sides of the walls and the type of construction are to remain the same, conditions may be improved by raising the air temperatures on the warm side of the wall. Third, if the temperatures and humidities are to remain the same, vapor resistance may be added to the warm section of the wall, or some type of ventilation may be applied to the cold section. The effectiveness of the various methods will be discussed in Part III of this bulletin.

PART II—EQUIPMENT AND INSTRUMENTS

TEST APPARATUS

Cold room.—The large cold room in which test houses were built is 30 feet square, 25 feet high, interior dimensions. The photograph (Fig. 8) shows an interior view with six small test houses in place, and the drawing (Fig. 9) shows a vertical cross-sectional view with cooling coils and fan in basement below. The exterior walls, floor, and ceiling are constructed with 6-inch studs spaced 16 inches on center with the space between filled with mineral wool. The interior surfaces of the walls and ceiling are constructed with ½-inch insulating board without additional finish. The exterior finish consists of a vapor-proof paper thoroly sealed over the studs, cemented at the joints, and covered with ½-inch insulating board. The floor joists are sealed on top and bottom with vapor-proof paper and the space between is filled with mineral wool. The object of this construction was to prevent the leakage of any outside air into the insulation and to allow some ventilation between the insulation and the cold interior air. Two doors are provided in one wall, one of them 6 feet by 7 feet 6 inches, used to move large pieces of equipment into and out of the room, and the other a small service door, 3 feet 6 inches by 7 feet. The floor is provided with 9 openings, each 10 inches square, through which air ducts can be passed from the basement below to supply conditioned air to the test units.

Cooling equipment.—The large test room is cooled by circulating the air through direct expansion ammonia cooling coils. There are two coils, each 10 rows deep, 18 inches wide, and 34.5 inches high. Each coil is provided with face and by-pass dampers. The coils are placed in separate parallel compartments and provided with shut-off doors on each side so that either coil may be operated independently of the other. Figure 10 shows a side view, and Figure 11 a top view of the partially completed cooling unit assembly, taken during the course of construction.

Figure 12 shows in the foreground the complete assembly of cooling coils with air ducts leading to test room. Air is circulated through the cooling coils by a 6,000 c.f.m. fan located on the discharge side of the unit as shown in Figures 9 and 10. The cooled air is carried to the top of the large test room and distributed through outlets in a horizontal duct at ceiling, from whence it circulates through the room and is then taken by a horizontal return duct, placed at the ceiling of the opposite side from the supply duct, and carried back to the cooling unit. The direct expansion cooling coils are supplied with ammonia from a 25-ton ammonia machine shown in the left foreground of Figure 13.

Air conditioning equipment.—Conditioned air is supplied to each of the test units in the large cold room through openings provided in the floor directly under the test unit from an air conditioning plant located

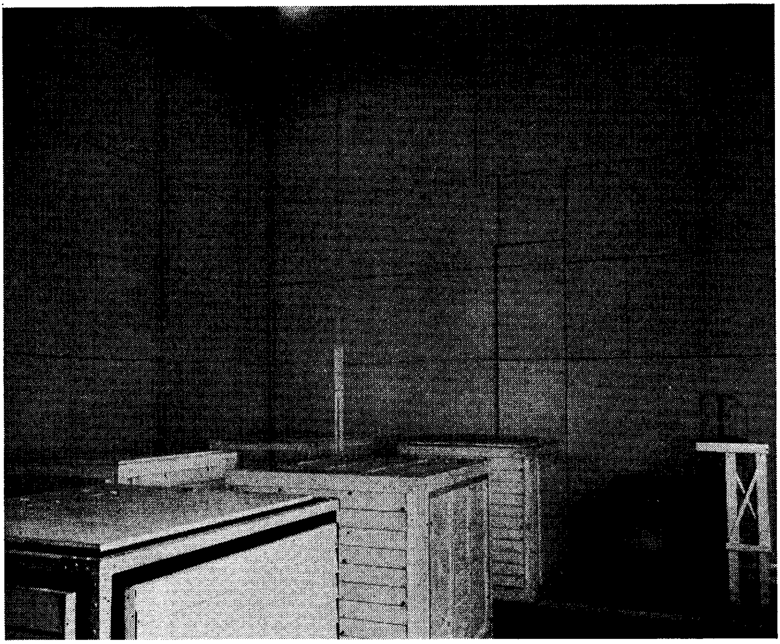

FIGURE 8. VIEW OF COLD ROOM SHOWING TEST HOUSES IN PLACE

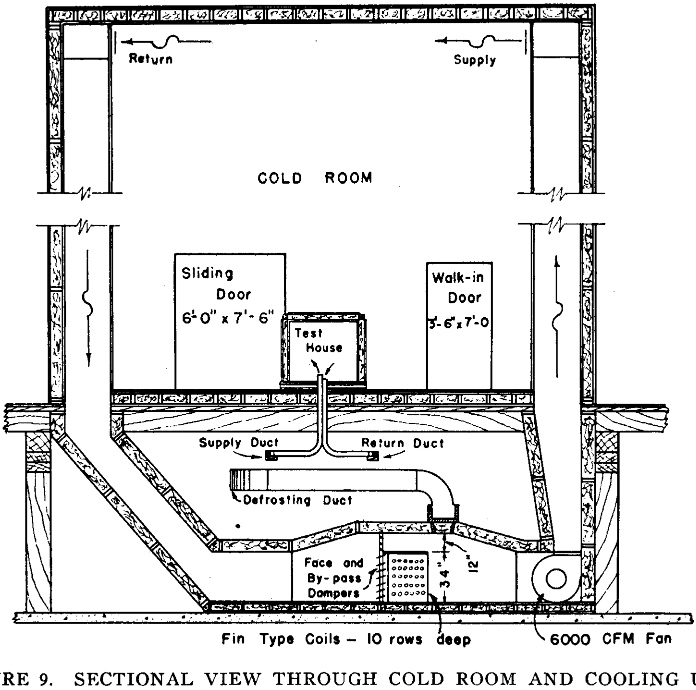

FIGURE 9. SECTIONAL VIEW THROUGH COLD ROOM AND COOLING UNIT

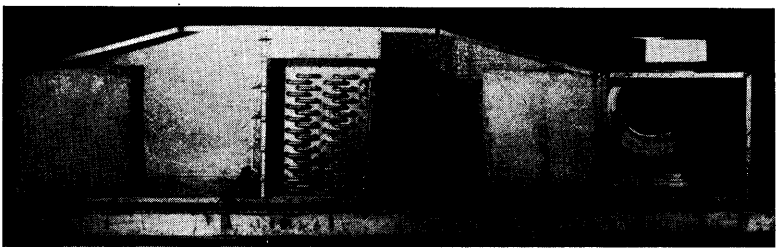

FIGURE 10. INTERIOR VIEW OF COOLING UNIT WHILE UNDER CONSTRUCTION

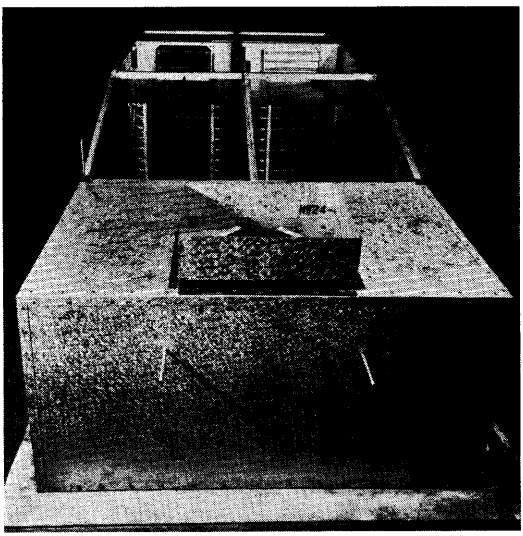

FIGURE 11. VIEW OF COOLING UNIT WHILE UNDER CONSTRUCTION

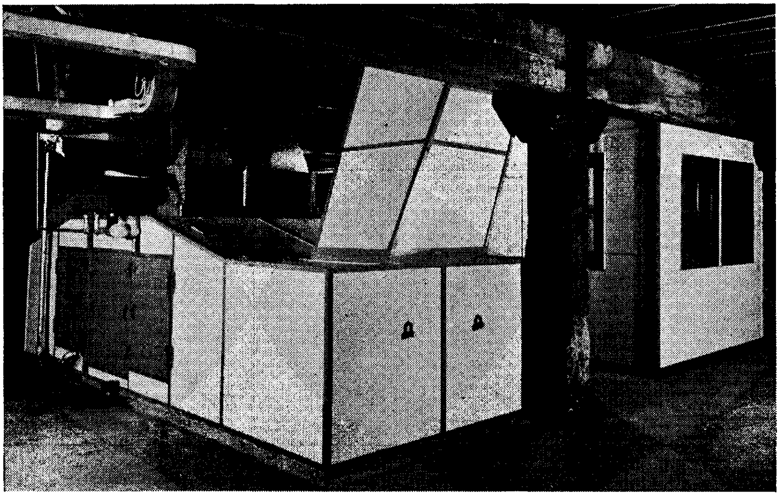

FIGURE 12. VIEW OF COMPLETED COOLING UNIT AND ONE END OF CONTROL ROOM

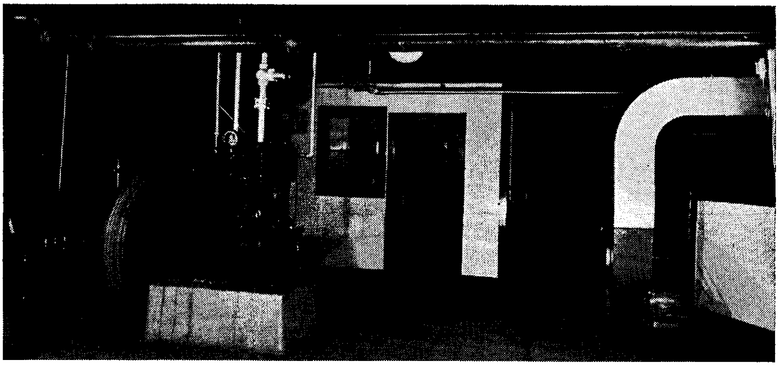

FIGURE 13. AMMONIA COMPRESSOR, CONTROL ROOM, AND DEFROSTING FAN FOR COOLING EQUIPMENT

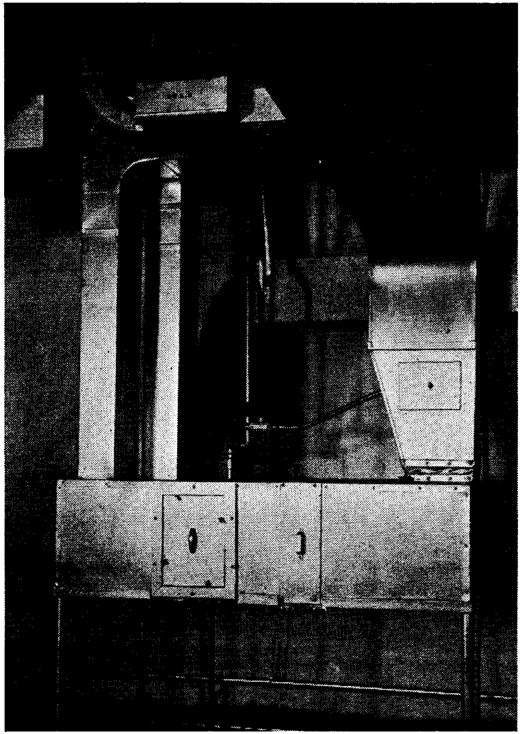

FIGURE 14. AIR CONDITIONING UNIT FOR TEST HOUSES

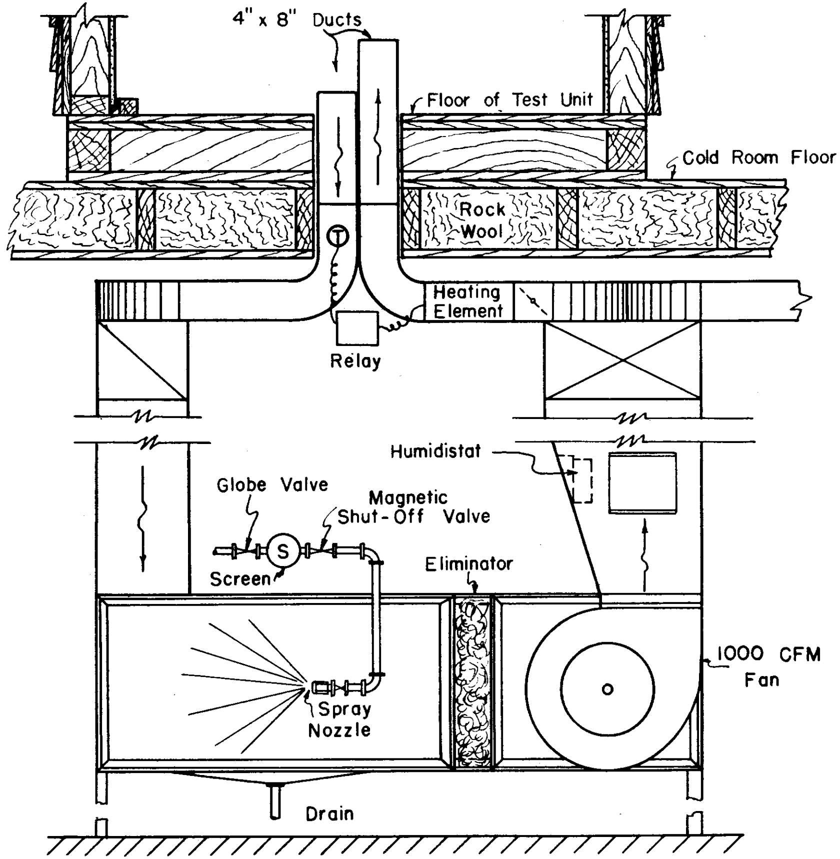

FIGURE 15. SECTIONAL VIEW OF AIR CONDITIONING UNIT WITH DISTRIBUTION DUCTS TO TEST HOUSES IN COLD ROOM

in the basement, and shown in the photograph of Figure 14 and drawing of Figure 15. The air conditioning plant controls the humidity and distributes the air to the test houses from whence it is collected and returned to the air conditioner. The temperature of the air is controlled independently for each test house by electric heating elements which are placed in the supply duct for the particular unit, and controlled by a thermostat placed in the corresponding return air duct. Electrical heaters are arranged so that a part of the load may be carried by a constant supply and a part by a thermostatically controlled supply.

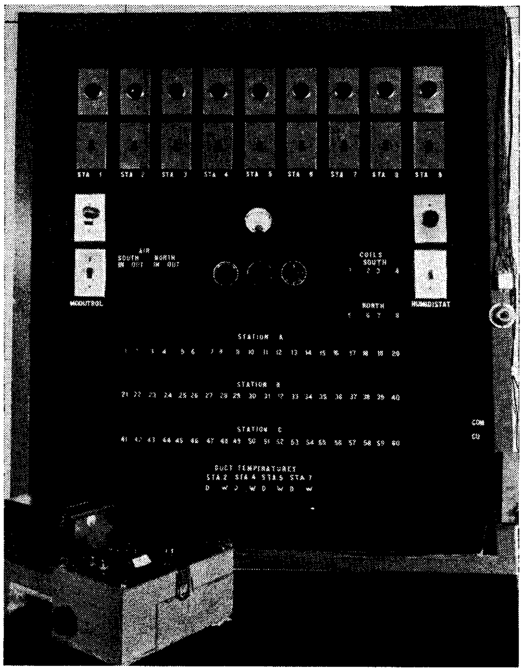

FIGURE 16. CONTROL AND THERMOCOUPLE PANEL FOR TEST EQUIPMENT

Control equipment.—The air temperature in the cold room is regulated partially by the operation of the ammonia compressor, but finally by face and by-pass dampers at the entrance to the cooling coils, which are controlled by a thermostat in the return air duct. The humidity for the test houses is controlled by a humidistat which is placed in the air discharge line from the air conditioning unit and which controls the water supply to a spray nozzle. The temperature of the air to the test units is controlled as previously described. All the control instruments are operated from a control panel shown in Figure 16 and located in the control room shown at the right in Figure 12. At the top of the control panel there are nine switches with pilot lights for the heating elements for the nine test stations located in the cold room. At the right central section is shown a switch and pilot light for the humidity control of the air conditioning unit, and at the central and left section of the panel are shown the controls for the motor which operate the face and by-pass dampers for the control of the air temperature in the cold room. On the lower part of the board there are switches for sixty thermocouples which are wired directly to corresponding panels on the inside walls of the large cold room. Thus the thermocouples may be connected directly from the test houses to the panels within the cold room without the necessity of running wires from the cold room to the control board for each set-up.

INSTRUMENTS

Moisture control methods.—In practically all of the tests the air has been supplied to the test houses at a given temperature and humidity, and it has been important throughout the research program to accurately measure and control the amount of water vapor in the air. In some cases it has been necessary to measure not only the moisture content of the inside air, but also that of the air within the walls of the test houses. In general the wet and dry bulb temperature method has been used as a standard of measuring the moisture content of the air, but due to the nature of the problem, the dew-point temperature method was better adapted for measuring the moisture conditions within the walls of the building. In all cases the humidity controls have been operated by some form of humidistat sensitive to the relative humidity of the air. In some instances it was necessary to build special test apparatus to get the desired measurements.

Wet and dry bulb temperature apparatus.—The wet and dry bulb apparatus used consisted of two thermocouples each mounted in a glass tube with the beaded end extending through into a solid brass tip of the same diameter as the glass tube. The brass tip of the wet bulb thermometer served to give a good thermal contact between the thermocouple and wicking material. Water was fed to the wick of the wet bulb thermometer from a constant level water reservoir, which in turn was kept filled by an inverted water bottle. In operation the wet and dry bulb part of the apparatus was placed inside an air duct with an air velocity of at least 800 feet per minute over the thermal elements. For accurate wet bulb readings it was found desirable either to wash or renew the wick every forty-eight hours.

Special humidity controller.—The humidity control apparatus devised for the test consisted of a hygroscopic tape about 10 inches long suspended at each end and deflected at the center with a spring tension. The amount of deflection at the center was controlled by the length of the tape, which in turn was controlled by the initial setting of the instrument and the relative humidity of the air. The deflection of the center section of the tape, which varied with the humidity in the air, operated a make-and-break mechanism which controlled the circuit to a relay through a vacuum tube.

Dew-point temperature apparatus.—Measuring the dew-point temperatures within the test walls proved to be a difficult problem. The wet and dry bulb method was considered, but it was impractical to get circulation of the air over the wet bulb thermometer without seriously disturbing the air within the test wall and thus making the readings of doubtful value. The dew-point temperature method was considered next, and the first apparatus built was one in which a small stream of air from the test wall was conducted over a polished mirror, the temperature of which was controlled by a stream of carbon-dioxide gas. The temperature of the mirror was reduced until condensation appeared, and this temperature was taken as the dew-point temperature of the air. While this method proved fairly sensitive it still disturbed the air within the test walls and left some doubt as to the accuracy of the readings.

The instrument as finally developed consisted of a glass tube about ¼-inch internal diameter, covered on the exterior surface for a distance of approximately 4 inches with a silver and copper plate. A band of the plating was completely removed around the central section of the tube for a length of about ⅛ inch. The ends of the copper-plated section thus separated were connected through a vacuum tube circuit to a milliammeter, and a copper constantan thermocouple was soldered to one section of the copper-plated tube. In using this instrument the tube was anchored in the wall at the point where the dew-point temperature was to be measured, and its temperature was controlled by passing carbon-dioxide gas through the tube. As the temperature of the tube was gradually reduced the dew-point temperature of the surrounding vapor was reached and moisture was condensed on the exposed surface of the glass. The moisture deposit reduced the electrical resistance across the gap between the two sections of metal plating and the deflection of the ammeter was appreciably increased.

When the tube is washed in distilled water before the test, dew-point temperatures may be obtained which will check within less than 1° F. as compared with wet and dry bulb temperature readings, providing the temperature of the tube is above 32° F. If the temperature of the tube is below 32° F., the conditions may be improved by dipping the tube into a 5 per cent salt solution and letting the salt precipitate and dry on the bare section of the tube. The thin salt coating thus formed does not materially affect the electrical resistance across the gap, but it does prevent the formation of frost at low temperatures. Since there is practically no movement of the air around the tube when it is placed in a wall, it is necessary to cool it very gradually in order not to pass through the dew-point temperature during the cooling process.

TEST UNITS

Wall construction.—The test units were all of wood frame construction, and the walls were built in sections so that they could be taken apart and inspected during a test without disturbing the continuity of the test. During the first tests 4-foot cubical test units were used. Later these were increased to 8 feet in height. Figures 17 and 18 show typical wall construction for all test units. Figure 17 is a sectional view of one of the smaller test units. The main frame is built of 3½ x 3½-inch wood framing members. The top and each wall section is built with 2 x 4 studs spaced 16 inches on the centers with metal lath and plaster on the inside surface and 8-inch pine shiplap, building paper, and 6-inch redwood siding on the outside surface. Figure 18 shows the type of wall construction used. The sheathing, building paper, and lap siding are applied to nailing strips which fit snugly into grooves made in the outside surface of the studs. The assembled outside wall section is applied with screws and may be removed without disturbing any other part of the test set-up. Small removable panels are provided in the sheathing and may be removed for the purpose of determining the accumulation of moisture or frost in the sheathing during a test period. In some of the test panels removable aluminum sheets were applied to the surface of the sheathing between the stud sections. The plaster was applied to the metal lath in three coats: scratch, brown, and finish coats, making a total thickness of approximately ¾ of an inch. Various types of vapor proof paper were placed under the metal lath and different surface finishes were used on the plaster, as described in the test results. Figure 19 shows the assembled view of an 8-foot high test house. The details of wall construction are the same as those shown in Figures 17 and 18, with the exception that the removable sheathing panels shown in Figure 18 include sections of the siding as well as the sheathing.

Attic construction.—In the preliminary investigation covering the ventilation of attics three of the small-sized test units were rebuilt to provide attic spaces over the ceilings. The roof construction, as shown in Figure 20, was built with removable units similar to the outside sections of the walls for the small test houses. In some instances aluminum condensation panels were provided for the space on the under side of the roof boards between the rafters. The ceilings dividing the attic spaces from the rooms below were constructed with metal lath and plaster applied to 2 x 4 joists spaced 16 inches on center. In most cases 3⅝ inches of mineral wool was applied between the ceiling joists with no vapor barrier underneath. This provided attic spaces which were typical, without vapor barriers.

Three types of attics were used: the first, completely enclosed, without ventilation; the second, provided with an adjustable opening in each gable, as shown in Figure 20; and the third provided with mechanical

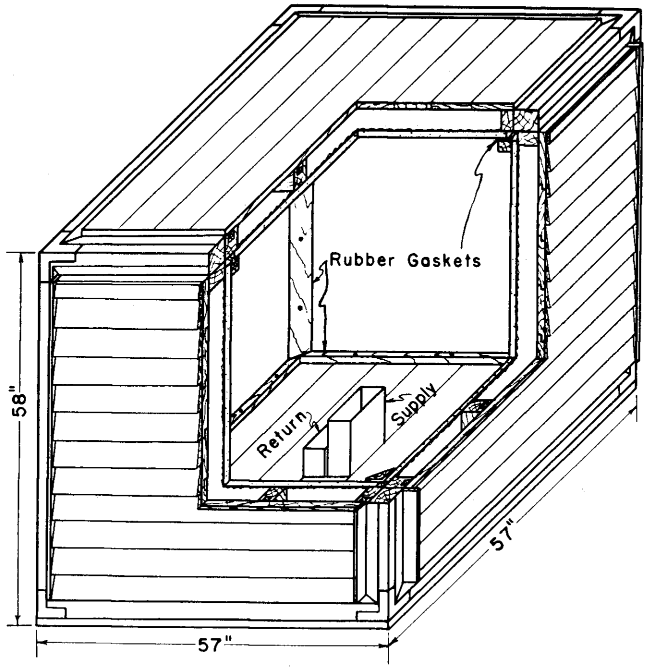

FIGURE 17. SECTIONAL VIEW OF TEST HOUSES SHOWING DETAILS OF CONSTRUCTION

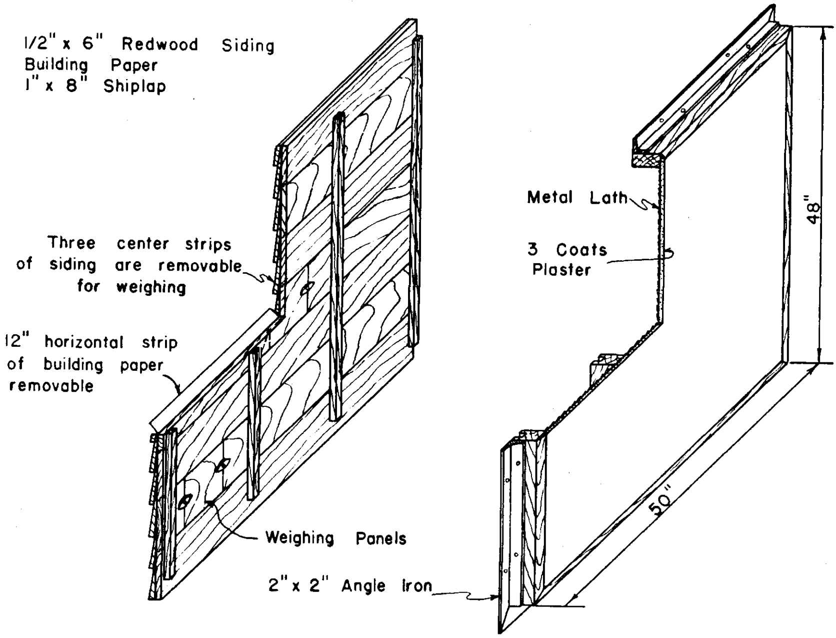

FIGURE 18. TYPE OF WALL CONSTRUCTION USED TO FACILITATE INSPECTION

ventilation by which the amount of air supplied to the attic could be measured. An observation opening was provided in one of the gables of each test house for inspection of the interior surfaces during a test period.

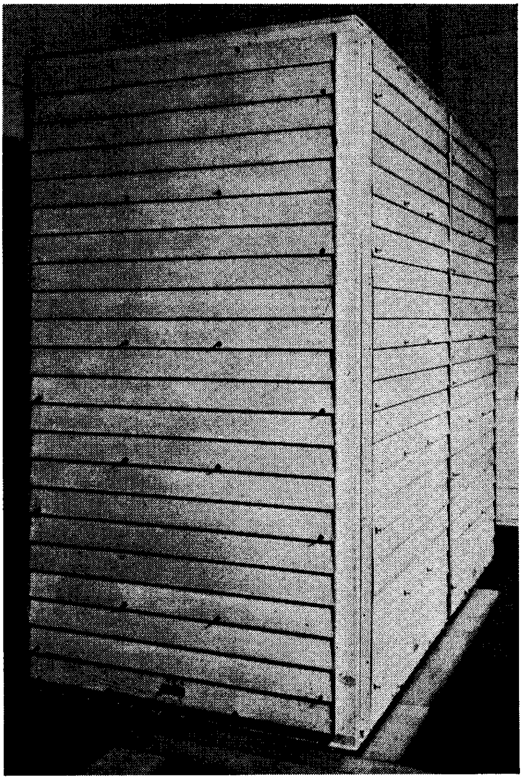

FIGURE 19. TEST HOUSE USED FOR WET PLASTER TEST AND ALSO SUBSEQUENT TESTS ON WALL VENTILATION

Figure 21 shows the three types of test attics assembled in the cold room, together with the pump and meter used to furnish the air to the mechanically ventilated attic.

Vapor barrier test apparatus.—Two different test methods were devised for evaluating vapor barriers. In the first, the barriers were built into the walls of a test house, and in the second, the vapor-resisting properties of the barriers were compared by the use of a special test apparatus. The general method of constructing the walls for the first method of test is shown in Figure 18. The barriers were applied either under the metal lath or on the surface of the plaster, depending upon the type of barrier used. Small removable sheathing panels were pro-

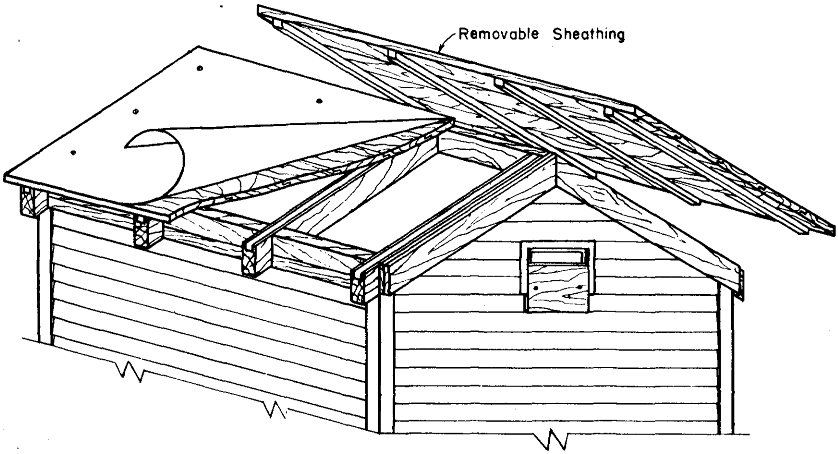

FIGURE 20. CONSTRUCTION DETAILS OF ATTIC FOR ATTIC VENTILATION TESTS

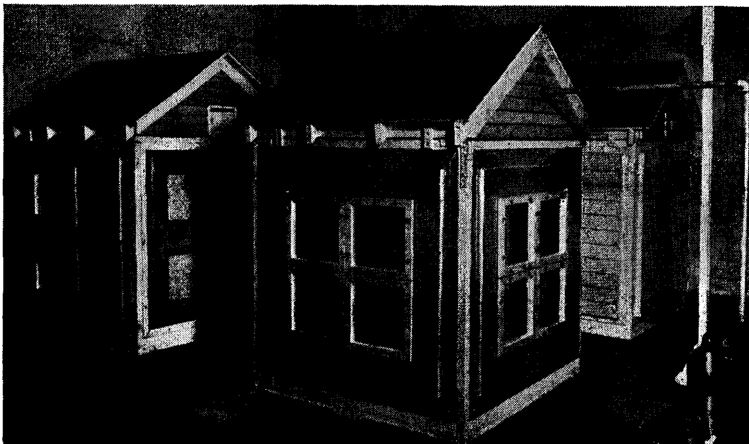

FIGURE 21. VIEW OF SET-UP FOR VENTILATED AND UNVENTILATED ATTICS

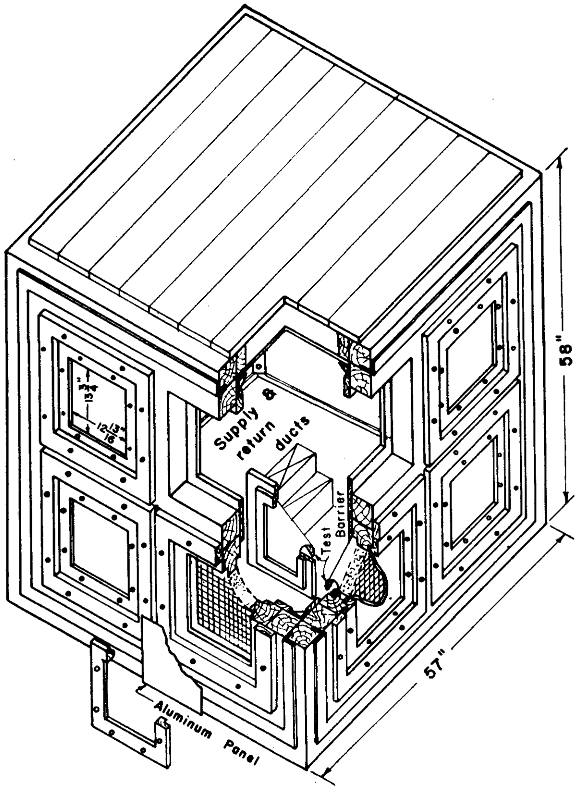

FIGURE 22. LINE DRAWING SHOWING DETAILS OF CONSTRUCTION FOR SPECIAL VAPOR BARRIER TEST APPARATUS

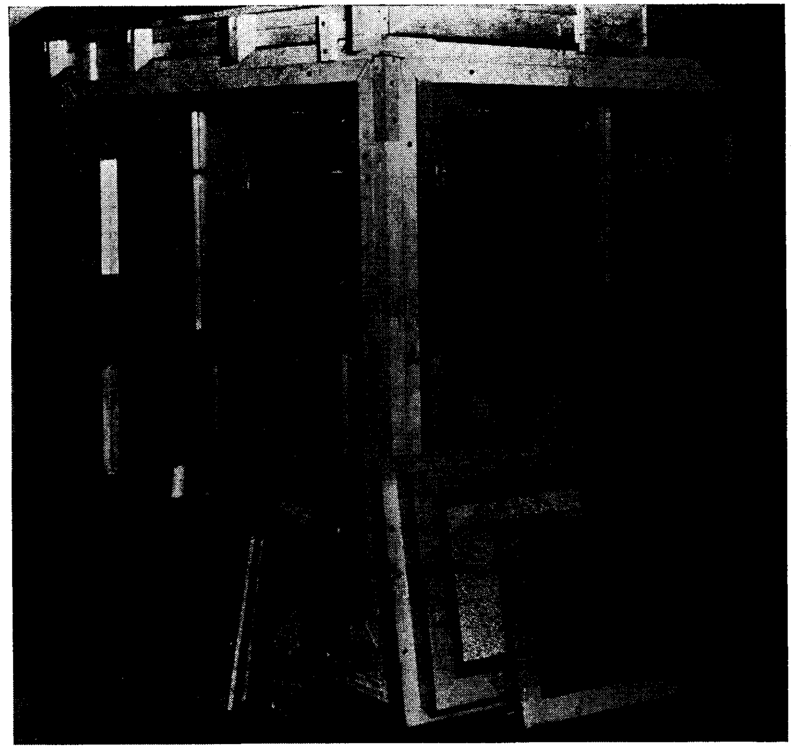

FIGURE 23. VIEW OF APPARATUS FOR MAKING TESTS ON VAPOR BARRIERS

vided, as shown, for the purpose of measuring the accumulation of frost on the surface of, or moisture within, the sheathing. In addition to the removable sheathing panels, sheets of aluminum were applied to some of the test walls to completely cover the surface of the sheathing between a given stud space. The aluminum panels were removed and weighed at various periods during the test, and the rate of frost accumulation on the surface was used as a measure of the vapor transmitted through the barrier for the given test conditions. In using this test method it was necessary to maintain outside air temperatures low enough to keep the interior surface of the sheathing below 32° F. The aluminum panel prevented some of the natural ventilation of the wall to the exterior, and in some cases the accumulation of frost on the aluminum panel was slightly greater than that on the removable sheathing panel for the same type of construction. In many tests, however, these differences were negligible.

For the second test method, the four walls of a small test house were each divided into four parts and special test panels were constructed to fit each of these divisions. The construction of one of these units is shown in the drawing of Figure 22 and the photograph of Figure 23. Each of the special test panels was made up of a mineral wool insulating pad 2⅛ inches thick held in place by a coarse-mesh wire screen on each side of the pad. The insulating pads were carefully made up to get uniform density and thickness of material for all of the panels. The pads were lined on the warm side with a barrier to be tested and on the cold side with a light weight sheet of aluminum. A clearance of approximately 3/16 inch was allowed on each side of the insulation. The vapor barrier and aluminum panel were both sealed into the test frame to prevent leakage of water vapor, and the assembled test panel was sealed into an opening provided in a wall of the test house.

PART III—TEST RESULTS

VAPOR BARRIERS

Test procedure.—From the nature of the vapor condensation problem in buildings it is evident that one of the best solutions in so far as construction of the building is concerned is to use a type of construction which will prevent vapor from penetrating the warm side of the wall. Certain types of building materials are known to have a high resistance, and others a low resistance, to the passage of vapor. There is, however, no standard method of evaluating the vapor-resisting properties of building materials, and in most cases very little information is available as to the relative merits of these materials when applied to the walls of a building. All materials have some resistance to the passage of vapor, but in this bulletin the term vapor barrier has been applied to those materials which have a relatively high resistance to the passage of vapor. In studying the vapor-resisting properties of materials, two different test methods were used. In the first method, the materials were used in the construction of a full scale wall and in the second, they were placed in a special test panel. In all cases where the barriers were applied to a standard test wall, the wall was built of 2 x 4 studs spaced 16 inches on centers, finished on the inside with metal lath and plaster and on the outside with 8-inch Ponderosa pine shiplap sheathing, asphalt-saturated building paper, and 6-inch redwood siding covered with three coats of white lead paint. The finished plaster was approximately ¾ inch thick and applied in three coats: a scratch coat, a brown coat, and a finish coat. The scratch and brown coats were made by mixing one part of Gypsum plaster with two parts of plaster sand, and the finish coat was a thin coat of white lime plaster.

Two types of barriers were investigated by both test methods; first, those barriers which were built in the form of a self-supporting membrane, and second, those barriers such as paints which were used as a surface coating. When the membrane barriers were tested in combination with the complete wall they were applied in a continuous sheet underneath the metal lath. When they were tested with the special test apparatus they were applied as a continuous sheet over the warm surface of the special test panel. When the surface coating type of barrier was tested by either method it was applied as a surface finish over the plaster. In the standard wall it was applied over the interior surface of the wall, and in the special test apparatus it was applied over the warm surface of specially prepared plaster samples. The plaster samples were all built after the same specifications for both types of tests.

Barriers tested in combination with walls.—The results from tests for several types of membrane barriers placed underneath the metal lath of the test walls are shown in Table I, and the results for several

TABLE I

CONDENSATION ON INNER SURFACE OF SHEATHING FOR DIFFERENT TYPES OF MEMBRANE VAPOR BARRIERS PLACED BETWEEN METAL LATH AND STUDS

Vapor Barriers		Outside Air Temperature, Degrees Fahrenheit	Inside Surface Temperature of Sheathing, Degrees Fahrenheit	Condensation on Sheathing, Grams* per Square Foot per 24 Hours		
				Test number	Test results	Average of tests
None		—19.5	—0.3	4	2.16	
		—19.5	—1.5	4	2.26	
		—19.3	1.3	8	2.02	2.15
None		9.9	23.0	7	1.02	
		10.1	22.8	20	1.55	
		9.9	22.5	7	1.65	1.41
Asphalt impregnated and surface coated glossy sheathing paper. Weight of paper tested, 51.9 pounds per roll of 500 square feet	Edges lapped not sealed	—19.5	—4.1	4	0.09	
		—19.5	—2.0	8	0.05	0.07
		9.9	20.5	7	0.00	0.00
	Edges lapped and sealed	—19.5	—3.5	4	0.02	0.02
		9.9	19.7	7	0.00	0.00
30-30-30 duplex. 2 sheets 30 lb. kraft paper cemented together with layer of asphalt, equal in weight to one layer of paper. Weight of paper tested, 16.1 pounds per roll of 500 square feet	Edges lapped not sealed	—19.5	—3.2	4	0.31	
		—19.3	0.7	8	0.20	0.25
		9.9	20.9	7	0.00	0.00
	Edges lapped and sealed	—19.5	—3.0	4	0.19	0.19
		9.9	20.7	7	0.00	0.00
Rag felt paper saturated with asphalt. Weight of paper 73.0 pounds per roll of 500 square feet	Edges lapped not sealed	—19.5	—2.2	4	0.52	0.52
		9.9	21.3	7	0.18	0.18
Duplex crepe paper. Weight of paper tested, 40.7 pounds per 500 square feet	Edges lapped and sealed	—19.5	—1.8	4	0.09	0.09
		9.9	21.6	7	0.00	0.00

NOTE: Inside air conditions 70° F., 40 per cent relative humidity. All walls constructed with 2 x 4 studs spaced 16 inches on centers; metal lath and plaster on interior surface; 8-inch Ponderosa pine shiplap, building paper, and 6-inch redwood siding on outside; 3⅝ inches of mineral wood between studs; vapor barriers as specified.

* 1 gram=.0022 pound.

types of barriers in the form of surface coatings placed on the inner surface of the plaster for the test walls are shown in Table II. The general description of the membrane barriers is given in Table I, and the specifications for the surface coatings are given as an addenda for Table II. The results for these tests are given as the rate of moisture condensation on the warm side of the sheathing in grams per square foot per twenty-four hours. From these results it is evident that the vapor passes rather freely through the untreated plaster of the ordinary

TABLE II

CONDENSATION ON INNER SURFACE OF SHEATHING FOR TEST WALLS WITH DIFFERENT TYPES OF FINISHES ON INTERIOR SURFACES OF PLASTER

Finishes on Inside Surface of Plaster	No. of Tests	Outside Air Temperature, Degrees Fahrenheit	Inside Surface Temperature of Sheathing, Degrees Fahrenheit	Condensation on Sheathing, Grams* per Square Foot per 24 Hours
Unfinished	3 3	—19.5 +10.0	—0.2 22.8	2.15 1.40
2 coats seal coat paint[b]	1 1	—19.5 +10.0	0.8 23.6	0.20 0.00
2 coats white flat paint[a]	1 1	—19.5 +10.0	—1.5 20.6	0.24 0.00
2 coats aluminum paint[c]	1 1	—19.5 +10.0	0.5 23.6	0.25 0.00
1 coat asphalt applied hot	1 1	—19.5 +10.0	1.1 23.3	0.13 0.00
1 coat seal coat paint[b] 2 coats white flat paint[a]	1 1	—19.5 +10.0	1.8 22.5	0.23 0.00
1 coat seal coat paint 2 coats aluminum paint	1 1	—19.5 +10.0	3.9 24.3	0.16 0.00
1 coat glue size[d] with plain wall paper	1 1	—19.5 +10.0	—0.9 22.2	2.11 1.11
1 coat glue size with dull surface-treated canvas wall covering	1 1	—19.5 +10.0	0.4 22.3	0.64 0.10
1 coat glue size with glossy surface-treated canvas wall covering	1 1	—19.5 +10.0	0.7 21.7	0.47 0.01
1 coat glue size[d] with duplex crepe paper	1 1	—19.5 +10.0	—0.2 21.8	0.32 0.00

NOTE.—Inside air conditions 70° F. and 40 per cent relative humidity. All walls constructed with 2 x 4 studs spaced 16 inches on centers; metal lath and plaster on interior surface; 8-inch Ponderosa pine shiplap, building paper, and 6-inch redwood siding on outside; 3⅝ inches of mineral wool between studs; surface finish as specified.

* 1 gram=.0022 pound.

See Addenda for Table II on page 32.

ADDENDA FOR TABLE II

[a]White flat interior paint specifications:	
Pigment	62.3 per cent
Vehicle	37.7 per cent
Pigment composition	
Titanium calcium pigment	78.0 per cent
Calcium carbonate	22.0 per cent
Composition of titanium calcium pigment	
Titanium oxide	30.0 per cent
Calcium sulphate	70.0 per cent
Vehicle composition	
Vegetable oil and resin	34.3 per cent
Volatile thinner and drier	65.7 per cent
[b]Seal coat specifications for priming coat on plaster surfaces:	
Pigment	40.0 per cent
Vehicle	60.0 per cent
Pigment composition	
Titanium calcium pigment	100.0 per cent
Composition of titanium calcium pigment	
Titanium oxide	30.0 per cent
Calcium sulphate	70.0 per cent
Vehicle composition	
Resins	16.7 per cent
Vegetable oil	28.8 per cent
Drier and thinner	54.5 per cent
[c]Aluminum paint specifications:	
Aluminum paste	1.75 lb.
Vehicle	7.40 lb. or 1 gal.
Composition of paste	
Pure aluminum powder	65.0 per cent
Volatile liquid	35.0 per cent
Vehicle	
Water-resisting spar varnish	
[d]Glue size specifications:	
A cold water size containing animal glue	
Mixture: 11 pints of water to 1 pound of size	
NOTE.—Outside white lead paint specifications	
Pigment by weight	70.0 per cent
Vehicle by weight	30.0 per cent
Composition of pigment	
A pure white lead paste	
Composition of vehicle	
Linseed oil	90.0 per cent
Drier	10.0 per cent

wall, but that there are many membrane barriers, and also surface coatings, which are effective in preventing the passage of vapor through to the inner section of the wall.

TABLE III

VAPOR TRANSMISSION FOR DIFFERENT MATERIALS BY SPECIAL TEST METHOD

Inside Air, 70° F. and 40 Per Cent Relative Humidity. Outside Air, —10° F.

Lab. No.	Type of Material	No. Tests	Condensation, Grams* per Square Foot per 24 Hours		
			Maximum	Minimum	Average
......	Insulating pad only	17	13.4	10.7	12.2
	Asphalt impregnated and surface coated glossy sheathing paper				
1	51.9 pounds per 500 square feet	8	0.22	0.04	0.14
21	69.0 pounds per 500 square feet	4	0.30	0.08	0.15
22	31.0 pounds per 500 square feet	3	0.21	.011	0.15
57	48.6 pounds per 500 square feet	2	0.14	0.12	0.13
58	34.0 pounds per 500 square feet	1	....	....	0.12
64	47.5 pounds per 500 square feet	1	....	......	0.25
65	35.2 pounds per 500 square feet	2	0.18	0.14	0.16

* 1 gram=.0022 pound.

TABLE III—*Continued*

Lab. No.	Type of Material	No. Tests	Condensation, Grams* per Square Foot per 24 Hours		
			Maximum	Minimum	Average
	Duplex paper 30-30-30				
2	16.1 pounds per 500 square feet	4	0.34	0.11	0.22
17	17.2 pounds per 500 square feet	6	0.42	0.14	0.22
18	16.5 pounds per 500 square feet	6	0.50	0.17	0.38
	Duplex paper 30-60-30				
16	21.9 pounds per 500 square feet	6	0.40	0.14	0.22
	Duplex paper				
12	40.7 pounds per 500 square feet	7	0.30	0.02	0.13
52	29.6 pounds per 500 square feet	3	0.17	0.14	0.15
53	19.5 pounds per 500 square feet	2	0.24	0.19	0.22
67	20.7 pounds per 500 square feet	2	0.19	0.17	0.18
60	20.3 pounds per 500 square feet (1 side metal coated)	2	0.07	0.08	0.08
62	25.8 pounds per 500 square feet (both sides metal coated)	2	0.11	0.03	0.07
	Duplex paper reinforced				
8	29.6 pounds per 500 square feet	5	0.28	0.06	0.19
51	29.6 pounds per 500 square feet	2	0.26	0.19	0.22
9	32.0 pounds per 500 square feet	6	0.32	0.09	0.17
13	63.0 pounds per 500 square feet (1 side metal coated)	3	0.13	0.04	0.08
	Insulation back-up paper				
4	15.3 pounds per 500 square feet	6	0.46	0.11	0.29
24	Approximately 15.0 lbs. per 500 sq. ft.	2	0.35	0.16	0.25
25	Approximately 15.0 lbs. per 500 sq. ft.	3	0.27	0.13	0.19
20	Approximately 15.0 lbs. per 500 sq. ft.	2	0.32	0.24	0.28
26	Approximately 15.0 lbs. per 500 sq. ft.	2	0.33	0.27	0.30
68	13.9 pounds per 500 square feet	1	....	....	0.23
69	15.6 pounds per 500 square feet	1	....	....	0.23
23	14.3 pounds per 500 square feet (1 side metal coated)	4	0.23	0.06	0.12
59	49.5 pounds per 500 square feet (1 side metal coated)	1	....	....	0.06
19	Paraffin-coated kraft paper, 13.2 pounds per 500 square feet	3	0.32	0.27	0.29
3	Asphalt saturated rag felt building paper, 73.0 pounds per 500 sq. ft.	6	2.39	1.04	1.70
63	Red rosin paper, 24.8 pounds per 500 square feet	1	....	....	9.36
56	50-pound brown kraft paper	1	....	....	9.44
......	40-pound black kraft paper, 6.94 pounds per 500 square feet	4	10.83	9.66	10.22
......	40-pound black kraft paper, 1 side coated with asphalt, 24.9 pounds per 500 square feet	4	0.29	0.18	0.22
	½-inch plaster on wood lath, ¾-inch grounds	1	....	....	2.21
	½-inch plaster on metal lath, ½-inch grounds	1	....	....	4.19
	¾-inch plaster on metal lath, ¾-inch grounds	20	4.46	3.44	3.79
	1-inch plaster on metal lath, 1-inch grounds	1	....	....	3.24
	13/16-inch clear pine	1	....	....	0.43

* 1 gram=.0022 pound.

Barriers tested by special test apparatus.—Both the membrane and surface coating types of barriers were tested by the special test apparatus as previously described. The test results for the membrane barriers are given in Table III and those for the surface coating barriers are given in Table IV. The general description of the membrane barriers is included in Table III, and that for the surface coatings is given in the Addenda for Table IV.

In all tests the results are in grams of moisture condensed per square foot per 24 hours on the aluminum panel which was used to line the cold side of the test panel.

As will be noted, the relative values for two barriers tested by two different methods are the same. However, the absolute test values for a barrier tested by the two different methods may not be the same. The reason for this difference in test values for the same barrier tested by two different methods is that the net vapor pressure drop across the test material is different in the two methods, even tho the air conditions are the same for both sides of the test specimen. When a vapor barrier is

TABLE IV

RELATIVE VAPOR TRANSMISSION FOR DIFFERENT SURFACE COATINGS BY SPECIAL TEST METHOD

All Surface Finish Applied with Brush on Surface of ¾ Inch of Plaster. Inside Air, 70°F., 40 Per Cent Relative Humidity. Outside Air, —10° F.

Surface Coating No.	General Description	Condensation—Grams* per Square Foot per 24 Hours	
		Two coats	Three coats
None	¾-inch plaster on metal lath (3.79 grams)	....	....
V-1	Linseed rosin varnish	0.82	0.45
P-1	White flat interior paint	0.83	0.62
V-2	Rosin Perrilla oil	0.45	0.33
P-2	White flat interior paint	0.58	0.44
V-5	Varnish	0.63	0.44
P-5	White seal coat paint	0.63	0.41
V-6	Phenol formaldehyde varnish	0.55	0.41
P-6	High grade aluminum paint	0.61	0.34
V-7	Varnish (glycerol phthalate)	0.77	0.54
P-7	White enamel	0.49	0.39
V-8	Bronzing liquid	1.16	0.84
P-8	Aluminum bronze	1.04	0.45
V-10	90 per cent linseed oil and 10 per cent drier and thinner	0.93	0.92
P-10	A linseed oil paint used on both interior and exterior surfaces	1.05	0.50
V-13	50 per cent linseed-tung oil and 50 per cent mineral spirits	1.19	0.97
P-13	Semi-gloss interior white paint	0.80	0.60

* 1 gram=.0022 pound.

See Addenda for Table IV on page 35.

ADDENDA FOR TABLE IV

DESCRIPTION OF PAINTS AND VEHICLES

No. from Table IV	Vehicle	Per Cent	No. from Table IV	Paint	Per Cent
V-1	Linseed rosin varnish		P-1	White flat interior paint	
	Linseed oil	60.4		Pigment	65.0
	Rosin	3.6		Vehicle (V-1)	35.0
	Mineral spirits	35.0		Pigment composition:	
	Drier	1.0		Lithopone	75.0
				Titanium dioxide	10.0
				Magnesium silicate	15.0
V-2	Rosin Perrilla oil		P-2	White flat interior paint	
	Perrilla oil	33.0		Pigment	58.0
	Rosin	12.0		Vehicle (V-2)	42.0
	Mineral spirits	54.0		Pigment composition:	
	Drier	1.0		Titanium calcium dioxide	66.6
				Zinc oxide	8.4
				Magnesium silicate	25.0
V-5	Varnish		P-5	White seal coat paint	
	Rosin	16.7		Pigment	40.0
	Chinawood oil	28.8		Vehicle (V-5)	60.0
	Mineral spirits	53.5		Pigment composition:	
	Drier	1.0		Titanium oxide	30.0
				Calcium sulphate	70.0
V-6	Varnish (phenol formaldehyde)		P-6	Aluminum paint	
	Pure phenol resin	11.0		Pigment (aluminum paste)	1.75 (lbs.)
	Chinawood oil	44.0		Vehicle (V-6) 1 gal. or	7.40 (lbs.)
	Mineral spirits	44.0		Pigment composition:	
	Drier	1.0		Pure aluminum powder	65.0
				Volatile liquid	35.0
V-7	Varnish (glycerol phthalate)		P-7	White enamel	
	Solids	49.5		Pigment	51.2
	Mineral spirits	49.5		Vehicle (V-7)	48.8
	Drier	1.0		Pigment composition:	
				Titanium dioxide	84.5
				Calcium sulphate	15.5
V-8	Bronzing liquid		P-8	Aluminum bronze	
	Rosin	30.0		Aluminum powder mixed with bronzing liquid.	
	Mineral spirits	70.0		Vehicle (V-8)	
V-10	Linseed oil	90.0	P-10	A linseed oil paint used on both interior and exterior surfaces	
	Drier and thinner	10.0		Pigment	66.7
				Vehicle (V-10)	33.3
				Pigment composition:	
				Titanium barium	44.4
				White lead	25.6
				Zinc oxide	30.0
V-13	Linseed—tung oil	50.0	P-13	Semi-gloss interior white paint	
	Linseed oil 85.0			Pigment	49.0
	Tung oil 15.0			Vehicle (V-13)	51.0
	Mineral spirits	50.0		Pigment composition:	
				Magnesium silicate	4.8
				High strength lithopone	85.4
				Titanium dioxide	9.8

added to the wall section on the warm side of the insulation under the plaster, the resistance of the plaster is added to the resistance of the barrier, whereas when this same barrier is added to the special test apparatus no plaster is used. The insulating material also has some resistance, and in the case of the wall it is somewhat thicker than in the case of the special test apparatus. In the test wall there is some natural venting of the vapor through the sheathing to the outside, whereas in the special test apparatus the outside section is thoroly sealed, thus preventing any escape of vapor. The net results of these differences is a lower rate of vapor transmittance for a barrier tested as a part of a wall than for the same barrier tested by the special test apparatus. This difference will be decreased as the vapor resistance of the barrier is increased. In a later section of this bulletin the test results have been reduced to standard transmittance coefficients which show a rather close correlation of the results obtained by the two different test methods.

Practical application of barriers.—The application of a vapor barrier is an important factor in its performance. The results given in Table I were obtained from barriers applied lengthwise of the studs with joints made over one of the studs. As indicated in the table some of the joints were lapped and not sealed and others were lapped and sealed. From the test results it appears that for practical purposes a joint well lapped on the studs is sufficient without the addition of an asphalt seal. To be most effective, however, a barrier must be applied to cover all of the surface and the joints at corners, around fixtures, etc., must be carefully made.

There are many types of membranes which make good vapor barriers but usually they are specially treated for this purpose. Some of the good barriers are sheets of metal surfaced paper, and continuous sheets of asphalt or paraffin. In the case of asphalt or paraffin, or any similar materials, the coating is usually supported by a sheet of paper, and the coating must be continuous without cracks or breaks. An asphalt saturated building paper does not make a good barrier as the asphalt is not in a continuous sheet. If, however, this paper is finished on the surface with a smooth continuous coat of asphalt, or if the asphalt is placed between two layers of kraft paper in such a manner as to have a continuous unbroken layer of asphalt it should be effective. The results given in Table III indicate the types of paper which are usually successful.

RATE OF CONDENSATION WITH VARIABLE TEMPERATURES

In obtaining the results for the various materials of Tables I and II the air conditions were maintained constant on each side of the test walls throughout the test period. In practical applications the outside air temperatures do not remain constant throughout long periods; the average daily variation in air temperature is approximately 15 degrees, and the maximum variation in any normal low temperature period will be much greater than this. In addition to the variation in air temperatures, the radiant heat from the sun may have a marked effect on the temperatures of the walls that are exposed to the sun. The question arises as to whether or not the condensation conditions in a wall subjected to variable outside air temperatures will be the same as when the wall is subjected to a uniform outside air temperature which is equal to the average of the variable temperatures. In order to make a comparison between the condensation rates which might be expected for the two different conditions, consider any ordinary frame wall with 3⅝ inches of insulation between the studs. Assume that this wall is to be subjected to two different test conditions, in both of which the air on the warm side of the wall is to be maintained uniformly at 70° F. and 40 per cent relative humidity. In the first test, the air on the cold side is to be maintained continuously at 0° F. and 50 per cent relative humidity, and in the second test, it is to be maintained at +20° F. and 50 per cent relative humidity for the first half of the test period, and at −20° F. and 50 per cent relative humidity for the second half of the test period, thus giving an average outside temperature of 0° F. with approximately 50 per cent relative humidity for the second test.

The accumulation of moisture on the sheathing of the test wall will be equal to the amount of vapor transmitted through the inner section to the sheathing minus that transmitted from the surface of the sheathing to the outside cold air. If we assume that the rate of vapor transfer through any part of the wall is equal to a vapor transmittance coefficient multiplied by the difference in vapor pressure over that part of the wall, there will be two important vapor transmittance coefficients to be considered: first, that from the warm air to the inner surface of the sheathing, which will be designated as V_1; and second, that from the inner surface of the sheathing to the cold outside air, which will be designated as V_2. The maximum vapor pressures for the different parts of the wall can readily be calculated from the air conditions on both sides of the wall and the temperatures within the wall. From the vapor pressures and the assumed coefficients the relative rates of moisture accumulation may be calculated for the two different test conditions.

The figures in Table V give the vapor pressures and the calculated rates in terms of V_1 and V_2 at which moisture would be expected to accumulate under the two different test conditions. Equation 1 gives the results for a uniform outside air temperature, and Equation 4 the results for a variable outside air temperature which is equivalent to the uniform temperature of Equation 1. By a comparison of the coefficients for V_1 and V_2 in these two equations it will be noted that the coefficient for V_1 is greater, and that for V_2 is less in Equation 1 than the corresponding coefficients in Equation 4.

From the above it follows that the rate of condensation must be greater for a constant temperature condition of Equation 1 than for a variable temperature condition of Equation 4. This point is demonstrated in the test data of Table XII and is important in interpreting the test results, since in practice there is not only a considerable amount of variation in the air temperatures, but also, in most instances, there is an

TABLE V

CALCULATED TEMPERATURES AND VAPOR PRESSURES THROUGH INSULATED WALL FOR DIFFERENT OUTSIDE AIR TEMPERATURES—OTHER CONDITIONS REMAINING CONSTANT

Inside Air		Outside Air		Inside Surface Temperature of Sheathing	Vapor Pressure		
Temperature, degrees Fahrenheit	Per cent relative humidity	Temperature, degrees Fahrenheit	Per cent relative humidity		Inside air	Sheathing	Outside air
70	40	0	50	11.9	0.2955	0.0693	0.0189
70	40	—20	50	—4.75	0.2955	0.0321	0.0063
70	40	20	50	28.5	0.2955	0.1535	0.0514

Equation 1. $(0.2955 - 0.0693)V_1 - (0.0693 - 0.0189)V_2 =$ rate of condensation for zero degrees $0.2262\ V_1 - 0.0504\ V_2 = R_1$.
Equation 2. $(0.2955 - 0.0321)V_1 - (0.0321 - 0.0063)V_2 =$ rate of condensation for $-20°$ F. $0.2634\ V_1 - 0.0258\ V_2 = R_2$.
Equation 3. $(0.2955 - 0.1535)V_1 - (0.1535 - 0.0514)V_2 =$ rate of condensation for 20° F. $0.1420\ V_1 - 0.1021\ V_2 = R_2$.
Equation 4. Average of Equation 2 and Equation 3, $0.2027\ V_1 - 0.0639\ V_2 =$ rate of condensation for average of two conditions, +20 and −20° F.

effect of the sunshine on the surface of the wall, which will raise the sheathing temperature and thus reduce the rate of moisture accumulation for a practical application.

The conclusions reached in this theoretical calculation have been borne out by tests in which all other conditions have remained the same excepting outside air temperatures.

RATE OF CONDENSATION WITH VARIABLE RELATIVE HUMIDITY

When moisture accumulates within a wall the rate of accumulation is equal to the difference between the rates of moisture travel through the inner and outer sections of the wall. If these rates are proportional to vapor pressure differences multiplied by vapor transmittance coefficients, which are fixed by the materials used, then the rate of accumulation will be affected directly by any change in operating conditions which alter the vapor pressure differences across any part of the wall. In most cases where condensation occurs, the vapor pressure at the point of condensation is governed by the temperature, and will remain constant regardless of the vapor pressure carried on the warm side of the wall. The vapor pressure carried on the warm side of the wall is directly proportional to the relative humidity of the air for any given temperature. Thus, if the relative humidity of inside air at 70° F. is reduced from 40 to 20 per cent the vapor pressure head will be reduced by 50 per cent, and since the vapor pressure at the point of moisture accumulation has not been changed, the rate of vapor travel through the inner section of the wall will be reduced by 50 per cent. Likewise, since the vapor pressure at the point of accumulation has not been changed, the rate of vapor travel through the outer section of the wall has not been changed, and therefore the reduction in the rate of moisture accumulation, due to changing the relative humidity, will be more than 50 per cent. This theory is demonstrated by the test results of Table VII.

In case all of the vapor is stopped at the condensation line and none passes through to the outer section of the wall, the rate of frost accumulation should be directly proportional to the relative humidity of the inside air. Under the section, "Vapor Transmittance Coefficients" in the tests reported in Table VIII, fifteen plaster samples were all constructed after the same specifications and tested in the special apparatus. In the first series of tests the relative humidity of the inside air was maintained at 40 per cent, and in the second series, at 60 per cent. The average rate of vapor travel through the fifteen samples was 4.09 grams (.009 pound) for the first series of tests and 6.24 grams (.0137 pound) per square foot per 24 hours for the second. The vapor pressure drop across the samples was increased by 50 per cent in the second series as compared to the first, and the rate of vapor transmission was increased by 52.5 per cent. In the special test apparatus all vapor was stopped at the barrier. Thus the amount of frost accumulated was equal to the amount of vapor passing the test specimen. Many other test results have indicated the same direct relation between rate of vapor travel through a material and the relative humidity on the warm side when all other conditions were equal. It is thus evident that the relative humidity of the air within a building is one of the most important operating factors to be considered in the control of condensation troubles.

WATER VAPOR WITHIN A WALL

The action of water vapor within a wall depends upon its density and the type and temperature of the materials with which it is in contact. If the surface temperature of a material is below the dew-point temperature of the vapor, surface condensation will take place, and if condensation occurs when the temperature is above 32 degrees, water will penetrate certain materials. If the surface temperature is above the dew-point temperature of the vapor, the vapor will penetrate permeable, non-hygroscopic materials without change in state, or it may be condensed and absorbed by hygroscopic materials as previously described. In the first part of this investigation condensation panels were used in the cold sections of the wall, and the rate of frost accumulation on these panels was used as a measure of the vapor conditions within the wall. This method gives valuable information as to the performance of a wall under extreme temperature and humidity conditions, but does not show the conditions in those parts of a wall where the temperatures are above the dew-point temperatures of the vapor. In order to get more complete information as to the vapor conditions throughout the walls two other test methods were used. In one the relative humidities or vapor densities were measured by making use of the hygroscopic properties of wood, and in the other a special dew-point temperature apparatus as described under the section, "Instruments" in this bulletin was used.

In each case the walls were constructed with 2 x 4 studs spaced 16 inches on centers. The studs were covered on the outside with standard 8-inch Ponderosa pine shiplap sheathing, building paper, and 6-inch redwood lap siding; and on the inside surface with metal lath and three coats of plaster. Some of the walls were insulated with full thickness mineral wool batts as indicated.

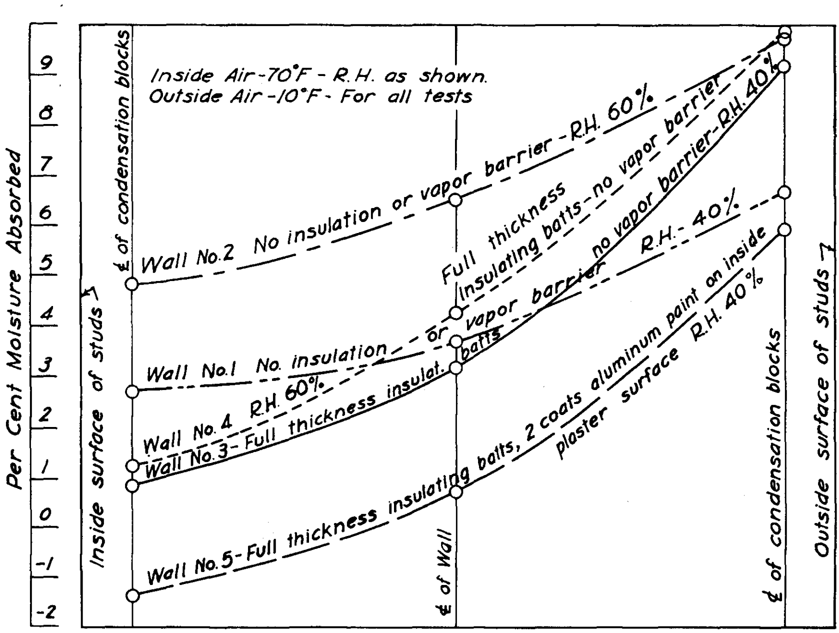

FIGURE 24. PER CENT MOISTURE ABSORBED BY WOOD ABSORPTION BLOCKS PLACED AT VARIOUS PLANES IN WALLS

Wood absorption blocks.—Since wood is a hygroscopic material, it will absorb water vapor from the air even tho its temperature is above the dew-point temperature of the vapor, and the weight of moisture absorbed will be proportional to the relative humidity of the air in contact with the wood. In making use of this principle, removable wood panels were built into the sheathing and soft wood blocks 2 x 3 x ¼ inches were placed in various sections throughout the test walls. These panels and blocks were weighed at various intervals during a test and the gain in weight was used as an indication of the relative humidities of the air in various sections of the wall. The vapor absorption blocks were placed in the stud sections of the walls with their largest surfaces in planes parallel to the surfaces of the test wall. They were placed in planes near the plaster at the central section of the wall and near the sheathing. The test results are shown in the curves of Figure 24. From these curves it will be noted that the rate of moisture gain in the block increases from the warm to the cold side of the wall. As the relative humidity of the air in contact with the warm surface of the wall is increased the rate of moisture gain is increased for the blocks in all sections of the wall.

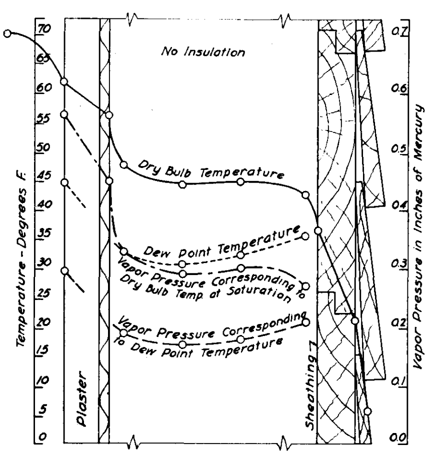

FIGURE 25. DRY BULB AND DEW-POINT TEMPERATURES IN THE INTERIOR SECTIONS OF AN UNINSULATED WALL

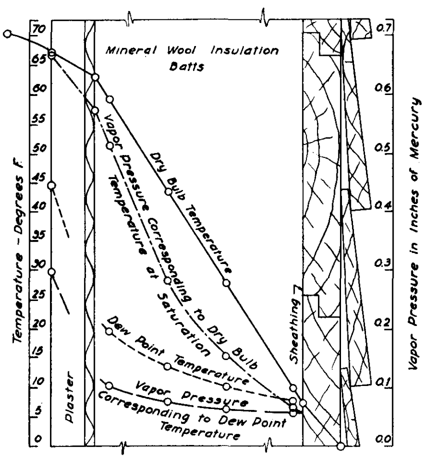

FIGURE 26. DRY BULB AND DEW-POINT TEMPERATURES IN THE INTERIOR SECTIONS OF AN INSULATED WALL

With inside air at 40 per cent relative humidity the rate of moisture gain for blocks from the warm to the cold side of the wall is greater for the insulated than for the uninsulated walls, but with air at 60 per cent relative humidity the rate in moisture gain for the absorption blocks is substantially the same for both walls. The percentage moisture gain for the sheathing panels varied through a wide range for different types of construction, but for the 4-foot high walls the gains were consistently higher for those panels taken from the upper than for those taken from the lower part of the wall.

Dew-point temperature measurements.—In making dew-point temperature measurements four dew-point temperature thermometers were placed each in an uninsulated and an insulated wall as follows: 1/4 inch, 1 1/4 inches, 2 1/4 inches, and 3 1/4 inches from inside surface of the plaster. The dry bulb and dew-point temperatures were measured at these positions in the walls after equilibrium conditions had been established with air on the inside of 70° F. and 40 per cent relative humidity, and on the outside of −10° F. The results of these tests are shown in Table VI and in Figures 25 and 26 for the uninsulated and insulated walls, respectively. The dew-point temperatures as shown in Figure 25 for the uninsulated wall are slightly lower at the central section of the wall than they are near either the plaster or the sheathing. This condition would not be expected and is somewhat difficult to explain. However, in all of the tests of uninsulated walls convection currents have been apparent, and in all cases where vapor conditions have been studied vapor appears to increase from bottom to top along the plaster line, and to decrease from top to bottom along the sheathing line. In other words, there are upward currents along the plaster which pick up the vapor and carry it to the top of the wall from whence it passes over and downward along the sheathing. These convection currents disturb the equilibrium conditions within the wall and may explain the unexpected results obtained. In the insulated wall, Figure 26, the vapor pressures corresponding to the measured dew-point temperatures are well below the maximum allowable vapor pressures corresponding to the dry bulb temperatures throughout the insulated section. The two vapor pressure lines meet

TABLE VI

DRY BULB AND DEW-POINT TEMPERATURES BY TEST AT VARIOUS VERTICAL PLANES IN AN UNINSULATED AND AN INSULATED WALL

	Position in Wall Space				
	¼ inch from plaster	1¼ inches from plaster	2¼ inches from plaster	¼ inch from sheathing	Surface of sheathing
No Insulation in Wall					
Dry bulb temperature	47.6	44.1	45.0	42.7	36.3
Maximum vapor pressure for dry bulb temperature	.3314	.2902	.3003	.2751	.2145
Dew-point temperature as measured	33.2	31.2	33.0	35.6	....
Vapor pressure from dew-dew-point temperature	.1895	.1738	.1879	.2086	....
Relative humidity per cent in wall	57.18	59.88	62.57	75.82	....
Mineral Wool Insulation, Full Thickness of Wall					
Dry bulb temperature	59.6	43.6	28.3	10.8	5.7
Maximum vapor pressure for dry bulb temperature	.5131	.2848	.1521	.0655	....
Dew-point temperature as measured	19.6	13.8	10.1	7.8	....
Vapor pressure from dew-point temperature	.1027	.0762	.0632	.0563	....
Relative humidity per cent in wall	20.01	26.75	41.55	85.95	....

at the inner surface of the sheathing, indicating that condensation should take place along this line rather than at some place within the insulation. This agrees with the test data taken with condensation panels and explains why condensation does not take place in the interior of a porous insulation. Referring to the figures in Table VI, the relative humidities of the vapor in contact with the dew-point temperature thermometers near the plaster and sheathing for the two walls are as follows:

	Relative Humidity Per Cent	
	Next to Plaster	Next to Sheathing
Uninsulated wall	57.2	75.8
Insulated wall	20.0	85.9

These results agree with those obtained with the adsorption blocks as shown in Figure 24 for Walls Nos. 1 and 3.

VAPOR TRANSMITTANCE COEFFICIENTS

In discussing the theory covering the transmission of vapor through materials it was assumed that for permeable, nonhygroscopic materials the rate of vapor transmission would be directly proportional to the drop in vapor pressure across the material, and that the amount of vapor transmitted would be governed by a factor designated as the vapor transmittance coefficient for the material or combination of materials. The transmittance coefficient may be defined as the amount of vapor transmitted in grams per 24 hours per square foot of area per unit of vapor pressure drop, the unit of vapor pressure drop being taken as inches of mercury. In order to check the correctness of this assumption, vapor transmittance coefficients have been calculated for the combination of ¾ inch of plaster, metal lath, and 3⅝ inches of insulation, from test data obtained on complete wall sections. The same transmittance coefficients have also been calculated from test results obtained by the special test apparatus for insulation and combinations of metal lath and ¾ inch of plaster.

Coefficients by two different test methods.—The calculated transmittance coefficients from test data obtained on full-sized walls for the combination of ¾ inch of gypsum plaster on the inside surface, 8-inch pine shiplap sheathing, building paper, and 6-inch redwood lap siding on the outside surface, with 3⅝ inches of mineral wool between the studs are shown in Table VII. The tests were all made with inside air temperatures of approximately 70° F., and with outside air temperatures varying from +15° F. to —11.4° F., as indicated. For each inside and outside air temperature combination, the relative humidity of the inside air was held at 20 and 40 per cent for a complete test period. The test results in the table are arranged in pairs. The only difference between the test conditions for the two tests of each pair is in the inside relative humidity used. The amount of frost deposited upon the sheathing as

TABLE VII

VAPOR TRANSMITTANCE COEFFICIENTS FOR ¾ INCH OF PLASTER ON METAL LATH AND 3⅝ INCHES OF MINERAL WOOL

Calculated from Test Results

Test and Period No.	Outside Air Temp., Degrees Fahrenheit	Inside Air Conditions		Vapor Pressure, Inches Mercury			Condensation on Sheathing, Grams per Square Foot per 24 Hours	V_1*
		Degrees Fahrenheit	Per cent relative humidity	Inside air	Inside surface of sheathing	Outside air		
20-1	15.0	70.2	40.7	0.3003	0.1392	0.0565	1.53	....
20-7	15.1	70.1	20.8	0.1543	0.1392	0.0568	—0.29	12.46
20-2	10.1	69.9	40.6	0.2992	0.1175	0.0442	1.55	....
20-6	10.0	70.1	20.6	0.1521	0.1175	0.0440	—0.44	13.50
20-3	5.0	70.3	40.7	0.3037	0.0980	0.0342	1.93	....
20-5	5.0	70.1	20.6	0.1521	0.0980	0.0342	0.40	10.10
20-2	—11.4	70.4	40.0	0.3016	0.0566	0.0144	2.66	....
20-13	—11.4	70.0	20.0	0.1480	0.0561	0.0144	0.97	11.05
7-4	9.9	70.0	41.0	0.3029	0.1159	0.0438	1.65	....
20-6	10.0	70.1	20.6	0.1521	0.1175	0.0440	—0.44	13.82

* V_1 = Calculated vapor transmittance coefficient from inside air to inside surface of sheathing in grams of vapor per square foot per 24 hours per inch of mercury pressure difference.

recorded for a test is equal to the amount of vapor which passed from the inside air to the sheathing, minus that which passed from the sheathing to the outside air. The amount which passed through the inner section of the wall is equal to the vapor transmittance coefficient V_1, multiplied by the vapor pressure drop in inches of mercury from the inside air to the sheathing, and the amount that passed through the outer section is equal to the vapor transmittance coefficient for the outer section V_2, multiplied by the vapor pressure drop from the surface of the sheathing to the outside air. The temperature gradients through the walls were maintained constant for all tests, and since there was always condensation on the inner surface of the sheathing the vapor pressure at this point remained constant. Thus, when the inside relative humidity was changed from 20 to 40 per cent the vapor pressure drop across the inner section of the wall was increased accordingly, but since the vapor pressure at the sheathing line and in the outside air was not changed, there was no change in vapor pressure drop across the outside section of the wall with a change of inside relative humidity. Since the amount of condensation on the sheathing is known, the results for any pair of tests provide a means for calculating the transmittance coefficient V_1, for the inner section of the wall, as illustrated by the following calculations made from the results of the first pair of tests.

(1) $(.3003 - .1392)\ V_1 - (.1392 - .0565)\ V_2 = 1.53$ grams
(2) $(.1611)\ V_1 - (.1827)\ V_2 = 1.53$ grams
(3) $(.1543 - .1392)\ V_1 - (.1392 - .0568)\ V_2 = -.29$ gram
(4) $(.0151)\ V_1 - (.0824)\ V_2 = -.29$ gram

By subtracting (4) from (2), $V_1 = 12.46$ grams

When the remaining pairs of equations are solved in the same manner the results for V_1 vary from 10.10 to 13.82, with an average of 12.19.

From Table VIII the average transmittance coefficient for mineral wool pads 2⅛ inches thick is 47.33, and that for ¾ inch of plaster on metal lath is 23.2. From these test results the calculated transmittance coefficient for ¾ inch of plaster on metal lath and 3⅝ inches of mineral wool is 12.66, which corresponds very closely with the test results on the full scale wall construction.

Vapor transmittance coefficients for mineral wool insulation and plaster.—Sixteen test samples were prepared by applying three coats of plaster: scratch, brown, and finish coats, to metal lath surfaces, giving a total thickness of plaster of approximately ¾ inch. These samples were tested in the special test apparatus in combination with the 2⅛ inches thick insulation pads. Test values were also obtained for the insulation pads without the plaster samples. Two sets of test conditions were used. In the first, the air on the warm side of the panels was maintained at 70° F. and 40 per cent relative humidity, and in the second, it was maintained at 70° F. and 60 per cent relative humidity. In all cases the air on the cold side of the panel was maintained at −10° F.

TABLE VIII

VAPOR TRANSMITTANCE COEFFICIENTS FOR MINERAL WOOL PAD 2⅛ INCHES THICK AND FOR ¾ INCH OF PLASTER APPLIED TO METAL LATH

Test Results by Special Test Apparatus

Panel No.	Test Condition A			Test Condition B				Test Condition C			
	Condensation, grams per square foot per 24 hours	Vapor transmittance, V_1	Vapor resistance, $1/V_1$	Condensation, grams per square foot, per 24 hours	Vapor transmittance, V_2	Vapor resistance, $1/V_2$	Net plaster transmittance	Condensation, grams per square foot, per 24 hours	Vapor transmittance, V_3	Vapor resistance, $1/V_3$	Net plaster transmittance
1	12.8	50.2	0.0199	4.02	15.5	0.0645	22.4	6.17	15.2	0.0658	21.8
2	12.1	47.4	0.0211	4.19	16.2	0.0621	24.4	6.47	15.9	0.0629	23.9
3	11.7	45.9	0.0218	3.81	14.7	0.0681	21.6	5.85	14.4	0.0694	21.0
4	11.8	46.2	0.0216	4.21	16.2	0.0617	24.9	6.47	15.9	0.0629	24.2
5	11.6	45.4	0.0220	4.24	16.3	0.0614	25.4	6.45	15.9	0.0629	24.4
6	12.9	50.2	0.0199	3.90	15.1	0.0662	21.6	6.00	14.8	0.0676	21.0
8	11.9	46.6	0.0214	4.00	15.4	0.0649	23.0	6.14	15.1	0.0662	22.3
9	12.6	49.3	0.0203	4.23	16.3	0.0614	24.3	6.53	16.1	0.0621	23.9
10	11.8	46.2	0.0216	4.39	16.9	0.0592	26.6	6.82	16.8	0.0595	26.4
11	11.4	44.6	0.0224	4.46	17.2	0.0581	28.0	6.74	16.6	0.0602	26.4
12	10.7	41.9	0.0239	3.99	15.4	0.0649	24.4	6.18	15.2	0.0658	23.9
13	12.8	50.2	0.0199	3.98	15.4	0.0649	22.2	6.08	14.9	0.0671	21.2
14	12.3	48.2	0.0207	3.81	14.7	0.0681	21.1	5.78	14.2	0.0704	20.1
15	12.6	49.4	0.0202	4.24	16.3	0.0613	24.4	6.13	15.1	0.0662	21.7
16	12.5	49.2	0.0204	3.83	14.8	0.0676	21.2	5.78	14.2	0.0704	20.0
Average	12.08	47.33	0.0211	4.09	15.8	0.0636	23.7	6.24	15.4	0.0649	22.8

Condition A—Insulation only. Inside air 70° F. and 40 per cent relative humidity, outside air —10° F. Temperature, condensation panel, 1.3° F. Vapor pressure drop across insulation, 0.2552 inch of mercury.

Condition B—Insulation and ¾-inch plaster. Inside air 70° F. and 40 per cent relative humidity, outside air —10° F. Temperature, condensation panel, —0.6° F. Vapor pressure drop across insulation and plaster, 0.2589 inch of mercury. Test period, 144 hours.

Condition C—Same as B, except inside air at 70° F. and 60 per cent relative humidity. Vapor pressure drop across insulation and plaster, 0.4066 inch of mercury. Test period, 71 hours.

The test conditions, together with the results of the tests, are shown in Table VIII. The average rate of condensation for 40 per cent and 60 per cent relative humidities are 4.09 and 6.24 grams, respectively, giving transmittance coefficients for the combination of plaster and metal lath of 23.7 and 22.8 for the respective relative humidities. In making calculations for the vapor transmittance coefficient the vapor pressures on the cold side of the test sample were taken as those corresponding to the temperatures of the condensation panels in each case.

Vapor transmittance coefficients for paint.—Several plaster panels were built up for the special test apparatus and tested first without any surface finish, and then pairs of samples were selected, one of which was coated with a certain type of vehicle, and the other, with the vehicle mixed with pigment. Tests were made for two and three coats of each material. The rate of condensation for the different samples, together with a complete description of the vehicles and pigments used, is given in Table IV. The vapor transmittance coefficients for the insulation, the plain plaster on metal lath, and the different surface coatings are given in Table IX.

TABLE IX

VAPOR TRANSMITTANCE COEFFICIENTS FOR DIFFERENT TYPES OF VEHICLES AND PAINTS[a]

Test Results by Special Test Apparatus

Paint or Vehicle No.[b]	2⅛ Inches of Insulation Only	¾ Inch of Plaster on Metal Lath	Two Coats of Paints or Vehicles	Three Coats of Paints or Vehicles
V-1	50.2	22.4	3.98	2.44
P-1	47.4	24.4	4.00	2.81
V-2	45.9	21.6	1.96	1.39
P-2	46.2	24.9	2.60	1.90
V-5	45.4	25.4	2.86	1.89
P-5	50.2	21.6	2.90	1.76
V-6	46.6	23.0	2.46	1.76
P-6	49.3	24.3	2.75	1.42
V-7	46.2	26.6	3.61	2.38
P-7	44.6	28.0	2.12	1.66
V-8	46.6	27.2	6.02	4.00
P-8	49.0	21.2	5.51	2.46
V-10	48.2	21.1	4.75	3.67
P-10	49.4	24.4	5.39	1.79
V-13	41.9	24.4	6.53	4.97
P-13	50.2	22.2	3.86	2.73

[a] Test panels built with ¾-inch plaster and metal lath.
[b] Description for vehicles and paints given in Addenda for Table IV.

From the results of Table IX it can be said that in most cases the greater part of the resistance to the transmittance of vapor through a surface coating is in the vehicle rather than in the pigment. Most types of paint give a rather low transmittance coefficient when compared with ¾ inch of plaster on metal lath.

Vapor transmittance coefficients for plaster and plaster base materials.—The transmittance coefficients for several types of plaster base with plaster applied, as obtained by the special test apparatus, are given in Table X. In calculating these transmittance coefficients from test data the average transmittance coefficient for the insulating material used in each test specimen was taken as 47.3 from Table VIII. This is not strictly accurate for all materials as there was a small variation in the insulating pads used for the different test specimens.

TABLE X

VAPOR TRANSMITTANCE VALUES FOR PLASTER IN COMBINATION WITH PLASTER BASE MATERIAL

Test Results by Special Test Apparatus

Description of Material	Transmittance Value, V	Vapor Resistance, 1/V
½-inch plaster on metal lath	25.0	.040
¾-inch plaster on metal lath	21.1	.0464
1-inch plaster on metal lath	17.3	.0577
½-inch plaster on wood lath	10.56	.0945
½-inch plaster on ⅜-inch Gypsum board, one piece	17.6	.0567
½-inch plaster on ⅜-inch Gypsum board joined at center	17.8	.056
½-inch plaster applied to ½-inch fiber board without treatment	25.6	.039
½-inch plaster applied to ½-inch wood fiber board joined along centers, no surface treatment	25.4	.0393

If the vapor transmittance coefficients for the ½-, ¾-, and 1-inch plaster samples are plotted against thickness they will be found to lie in a straight line, indicating that the vapor resistance of plaster is substantially proportional to its thickness, or in other words that the resistance to the passage of vapor is substantially all within the plaster and not on the surface.

In considering these values for transmittance coefficients it must be remembered that they were all determined in substantially the same range of temperatures, and that some variations might be expected for different temperature ranges. There are also variations in samples constructed after the same specifications. In the case of the surface finishes given in Tables IV and IX the specifications were obtained from the manufacturers of the various paints and were not checked by chemical analysis. There is much research work yet to be done in the field of vapor transmittance coefficients.

WET PLASTER AND VAPOR BARRIER

When an effective vapor barrier is placed on a wall underneath plaster, all of the water from the wet plaster must eventually pass out through the room surface of the plaster, whereas without a barrier a part of this water will pass to the interior section of the wall. The question arises as to whether or not the barrier may affect the drying-out period, and thus the quality of the plaster. In order to answer this question a test house 4 feet wide, 8 feet long, and 8 feet high was constructed as shown in Figure 19. The walls were built in sections 4 feet wide, 8 feet high, with 2 x 4 studs spaced 16 inches on centers. Metal lath was placed on the interior surface of the studs, and 8-inch Ponderosa pine shiplap sheathing, building paper, and 6-inch redwood lap siding were used for the exterior finish. The sheathing, building paper, and lap siding were built in one unit so that they could be removed for inspection during the test without disturbing other parts of the wall. Aluminum panels were placed between each stud section next to the sheathing for the purpose of collecting and weighing the frost which might accumulate due to the passage of moisture through the wall. All but one of the walls were insulated with 3⅝ inches of mineral wool applied between the studs. A part of the walls were constructed without vapor barriers, and a part of them were constructed with vapor barriers placed in continuous sheets underneath the metal lath. The barriers were of different types and of various efficiencies.

The ventilation of a building during the drying-out period for the plaster is extremely important and is too often overlooked by the builder. In order to supply a reasonable amount of ventilation for this test, an air duct was provided through which cold air could be admitted to the interior of the test house. The amount of cold air supplied during the test was regulated to correspond with two air changes an hour for the average house. This was considered the minimum that should be supplied to adequately dry the plaster.

TABLE XI

AIR TEMPERATURES AND HUMIDITY CONDITIONS FOR WET PLASTER TESTS

Plaster	No. of Hours	Cold Room, Degrees Fahrenheit	Test House			
			Dry bulb temperature, degrees Fahrenheit	Per cent relative humidity		
				Maximum	Minimum	Average
Scratch coat[a]	66	—15.2	69.9	73.0	57.0	63.6
Brown coat[b]	96	—15.4	70.1	78.0	59.0	62.7
Finish coat[c]	171	—14.3	70.0	75.0	34.0	58.0

[a] Scratch coat—sand passing No. 10 sieve, 500 pounds; fiber plaster, 204 pounds; and water, 106 pounds.

[b] Brown coat—sand passing No. 10 sieve, 880 pounds; fiber plaster, 353 pounds; and water, 185 pounds.

[c] Finish coat—hydrated lime and unfibered plaster in the ratio of approximately 3 parts of lime to 1 part of plaster mixed with water to give proper workability.

NOTE.—The mixtures for the scratch and brown coats consisted of 2½ parts of sand by weight, 1 part of plaster, and 6 gallons of water per sack of plaster.

After the test house was constructed, and before any plaster was applied, the inside and outside air temperatures were brought to +70° F. and −15° F., respectively, and maintained for a sufficient length of time to establish equilibrium temperatures throughout the structure. After equilibrium conditions were established the plaster was applied in three coats, consisting of a scratch coat, a brown coat, and a finish coat, each coat being allowed to dry for the time indicated before application of the succeeding coat. The record of test data, together with specifications for the plaster as applied, is given in Table XI.

The conclusions drawn from the test results are:

1. A good vapor barrier placed underneath the plaster is effective in preventing the moisture from the wet plaster from passing to the interior section of the wall.

2. The relative humidity within the test house was very high during the test, and in those cases where no vapor barrier was used there was a large amount of frost accumulation on the sheathing of the walls, indicating that a rather long drying-out period would be required to bring the walls back to normal dry conditions.

3. When effective vapor barriers were used, the vapor from the wet plaster condensed on the vapor barrier on the surface next to the plaster, and free moisture was found on this surface during the drying-out period. As the plaster dried out this moisture re-evaporated and disappeared, passing through the plaster to the room air.

4. The plaster was inspected during the test and after the test was completed, by an experienced plaster contractor. No difference could be detected in the qualities of the plaster which was applied without a vapor barrier and that applied with a vapor barrier underneath the plaster. No difference could be detected between the hardness of different samples of plaster during the drying-out period, nor between the strength of samples removed after the test was finished.

5. A vapor barrier reduces the amount of moisture which may accumulate within a newly plastered wall without apparently affecting the drying-out period of the plaster or the final quality of the plaster.

6. In order to properly dry out the plaster, a house should be well ventilated. A rate equal to two volumetric changes per hour gave satisfactory results in these tests and is a minimum to be recommended.

VENTILATION AND CONDENSATION WITHIN A STRUCTURE

Vapor passes through the various parts of the wall from points of high vapor pressure to points of low vapor pressure. It will pass through certain materials by the process of diffusion, and if the materials are sufficiently porous and open, it will be carried through by convection currents. The rate of passage by diffusion depends upon the vapor pressure difference along the path of travel and the vapor resistance of the materials through which the vapor passes. The rate of passage by convection depends upon the convection currents which may be established due to temperature differences, construction of materials, etc. When vapor accumulates within any section of the wall, in the form of moisture or frost, it indicates that vapor is traveling to that section at a greater rate than it is traveling from it. This suggests the possibility that the condition may be remedied by increasing the rate of vapor flow from the point of accumulation. For a given set of air temperatures and humidities the rate of vapor flow through the exterior section of a wall may be increased; first, by reducing the vapor resistance of the materials in the outer section of the wall, and second, by providing conditions which will set up induced convection currents for the circulation of the vapor through the outer section of the wall, thereby increasing its rate of transfer. These methods of increasing the rate of vapor flow through the exterior section of a structure are often spoken of as ventilation, and are applied in practice to walls and attics of a building.

Ventilation of walls by diffusion.—Effective ventilation by diffusion requires that the vapor pass from the wall in the shortest possible direction, which is usually in a path normal to the surface of the wall. When it reaches the surface, it must be immediately released in order to maintain the vapor pressure gradient through the material. Venting by the process of diffusion cannot be effectively accomplished if the venting process requires the vapor to travel through a distance which is materially greater than that from the source of the vapor to the natural plane of condensation in the wall. When vent holes are provided at the top and bottom of a wall, or at points which will require the vapor to travel by diffusion through long distances of the materials, the vapor will travel through the shorter distance to the outside surface of the sheathing where it will condense rather than pass to the vent openings.

If conditions are such as to cause condensation within a wall, it is often possible to prevent it by providing an outer surface finish through which the vapor may pass by diffusion, but for severe conditions the effectiveness of ventilation is usually limited by the low drop in vapor pressure which it is possible to obtain across the outer section of the wall as compared to the drop in vapor pressure across the inner section of the wall. This is particularly true for a wall which is so constructed that condensation occurs relatively close to the cold side.

Ventilation of walls by convection currents.—The ventilation of a wall or structure by convection currents may be effectively accomplished if the structure is such that convection currents can be set up between the space to be ventilated and some other space of lower vapor pressure. Convection currents imply that there is free circulation of the vapor, and in practice this requires free circulation of air through the space to be ventilated. If a wall is to be ventilated by the circulation of cold outside air through the wall there will naturally be some heat loss. However, it is often possible to admit sufficient air to carry the vapors out of a space without serious loss of heat.

Ventilation of attic spaces.—An open attic space above an insulated ceiling presents a suitable problem for ventilation by convection currents. If insulation is used in the ceiling of the upper floor and the attic space above is unheated, the under side of the roof boards and the inner surfaces of attic walls may become very cold and provide surfaces for the condensation of vapor and the accumulation of frost. The most effective way of preventing condensation is to place a vapor barrier on the warm side of the insulation and thus prevent the vapor from entering the attic space. In case a vapor barrier is not practical, or as a precaution against any moisture which may pass the vapor barrier, it is often possible and practical to ventilate the attic space to the exterior and to carry the vapor away by convection currents. The question then arises as to the type of ventilation system to use, the minimum amount of air required, and the loss of heat which may be expected due to the ventilation.

In a preliminary investigation of attic ventilation problems three of the small-sized test houses were provided with attics. The ceilings below the attics were constructed with 2 x 4 joists, metal lath, and plaster, and 3⅝ inches of mineral wool between the joists. No vapor barriers were used. The roof surfaces were constructed with 8-inch pine shiplap sheathing covered with roofing paper. The first attic was completely enclosed without ventilation, the second was provided with adjustable vent openings in each gable for natural ventilation, and the third was provided with mechanical ventilation by which the amount of air supplied to the attic could be accurately measured. The roof boards, with the roofing material attached, were built as a unit so that the entire roof section could be removed during a test for inspection of interior conditions. Small condensation panels were placed on the under side of the roof sections to provide means for collecting and weighing the frost which might accumulate during a test period. Observation openings were provided in the gables of each test house for inspection of the interior during the test procedure. Figure 20 shows a line drawing of one of the attics in which openings were provided for natural ventilation through the gables, and Figure 21 shows three test attics as assembled in the cold room, together with pump and meter used to furnish air to the mechanically ventilated attic.

The results for several tests on the different types of attics are shown in Table XII. In each case the condensation rates are the averages for several days of testing. The test results are arranged in six different groups in order to show more clearly the effect of varying such factors as outside air temperatures, relative humidity of inside air, openings in gables for natural ventilation, and cubic feet of air per hour for mechanical ventilation. A few test results have been repeated in the table in order to complete each group of tests.

The first group of four tests represents a series in which all conditions were maintained constant excepting outside air temperatures, which were varied from +15° F. to −10° F. for different tests. In this series no condensation was shown in any of the attic spaces until the outside temperature dropped to +5° F. With inside air at 40 per cent relative humidity there was a small amount of condensation in the attic without ventilation, but not in the other two attics with ventilation, as indicated.

TABLE XII

ATTIC VENTILATION

Outside Air Temperature, Degrees Fahrenheit	Inside Air Conditions		No Ventilation		Natural Ventilation			Mechanical Ventilation		
	Degrees Fahrenheit	Per cent relative humidity	Attic air temperature, degrees Fahrenheit	Condensation[a]	Opening, square inch[b]	Attic air temperature, degrees Fahrenheit	Condensation[a]	Air supplied, cubic feet[c]	Attic air temperature, degrees Fahrenheit	Condensation[a]
+15	70	40	26.9	0.0	0.125	24.2	0.0	1.5	24.3	0.0
+10	70	40	22.6	0.0	0.125	19.9	0.0	1.5	19.7	0.0
+ 5	70	40	17.3	1.16	0.125	13.9	0.0	1.5	14.4	0.0
—10	70	40	3.9	2.38	0.125	0.2	0.53	1.5	1.6	0.72
+ 5	70	40	17.3	1.16	0.125	13.9	0.0	1.5	14.4	0.0
+ 5	70	30	17.6	0.78	0.125	14.6	0.0	1.5	15.0	0.0
+ 5	70	20	16.9	0.0	0.125	14.1	0.0	1.5	14.4	0.0
—10	70	40	3.9	3.15	0.125	0.2	0.53	1.5	1.6	0.72
—10	70	20	2.8	2.28	0.125	— 1.4	0.0	1.5	— 0.5	0.0
—10	70	40	3.9	3.15	0.125	0.2	0.53	1.5	1.6	0.72
—10	70	40	4.6	3.15	0.250	— 0.4	0.0	3.0	1.8	0.0
0	70	20	11.8	1.76	0.125	7.8	0.0	1.5	9.6	0.0
—15 to +15	70	20	....	0.0	0.063	....	0.0	1.0	....	0.0
+ 5	70	30	17.6	0.78	0.125	14.6	0.0	1.5	15.0	0.0
—15 to +15	70	30	....	0.18	0.063	....	Trace	1.0	....	0.0

[a] Condensation in grams per square foot of ceiling area per 24 hours (1 gram=.0022 pound).
[b] Opening in square inches in each gable per square foot of ceiling area.
[c] Outside air supplied to attic space in cubic feet per hour per square foot of ceiling area.

At −10° F. there was condensation in all attics, altho not a serious amount for either the naturally or mechanically ventilated attics.

In the second group of three tests the outside air was maintained at +5° F. and the relative humidity of the inside air was maintained at 40, 30, and 20 per cent for the three tests, as indicated. At 40 per cent, and even at 30 per cent, there was some condensation in the attic without ventilation, but at 20 per cent this had entirely disappeared. There was no condensation in any of the tests for the naturally or mechanically ventilated attics.

In the third group of two tests the outside air was maintained at −10° F., and the inside relative humidity was maintained at 40 per cent for the first test, and 20 per cent for the second test. In both cases there was condensation in the unventilated attics. At 40 per cent relative humidity there was condensation in both the naturally and mechanically ventilated attics, but none at 20 per cent relative humidity.

In the fourth group of two tests the outside temperature was maintained at −10° F. and the inside relative humidity at 40 per cent for both tests. The openings in the attic gables for the naturally ventilated attic were changed from .125 to .25 inch per square foot of ceiling area, and the air supply to the mechanically ventilated attic was increased from 1.5 to 3.0 cubic feet per hour per square foot of ceiling area for the second test. The increased amount of ventilation for both the naturally and mechanically ventilated attics eliminated the condensation.

In the fifth group of two tests the outside air for the first test was maintained uniform throughout the test at 0° F., and for the second test it was varied from −15° F. to +15° F., giving an average of 0° F. for the test. In the results for this series it is interesting to note that for the unventilated attic there was condensation in the uniform test, whereas there was no condensation for the variable temperature test, even tho the average outside air temperature was equal to that of the uniform test. There was no condensation in either case for the naturally or mechanically ventilated attics; however, in the second test with variable temperatures the amount of ventilation was reduced for both.

In the sixth group of two tests the outside air was maintained at +5° F. for the first test and varied from −15° F. to +15° F., giving an average of 0° F. for the second test. In both cases the inside relative humidity was maintained at 30 per cent. It is interesting to note in this case that for the attic without ventilation there was more condensation for the test at uniform temperature of 5° F. than for the test with a variable outside temperature with an average equal to 0° F. The results for the tests of groups five and six verify the fact, as shown by calculation, that the rate of condensation should be less for variable outside air temperatures than for constant outside temperatures.

Data have been obtained on small-sized attics under still air conditions to show that they may be given sufficient ventilation to eliminate most condensation troubles without seriously adding to the heat loss, particularly when the insulation is applied at the ceiling line of the upper floor, giving a natural cold attic space. There are two approximate methods by which this may be calculated from the data of Table XII. First, it may be assumed that since the ceilings of all the attics have the same amount of insulation the heat loss for the different types of ventilation will be proportional to the temperature drop between the air in the rooms below and that of the attic space for a given attic. Calculations on this basis for the tests of groups two and three in which the outside temperatures were maintained constant at +5° F. and −10° F. for each group respectively, show that for the +5° F. outside temperature the attic with natural ventilation loses 5.5 per cent, and that with mechanical ventilation 4.7 per cent, more heat than the attic with no ventilation. At −10° F. outside air temperature, the attic with natural ventilation loses 5 per cent, and that with mechanical ventilation 3 per cent, more heat than the attic without ventilation. In all tests used in these calculations the attic with natural ventilation had an opening in each gable of .125 square inch per square foot of ceiling area, and that with mechanical ventilation was supplied with 1.5 cubic feet of air per hour per square foot of ceiling area.

The second approximate method of calculating heat loss may be applied to the mechanically ventilated attic. It may be assumed that the loss is equal to the amount of heat required to heat the air for ventilation from outside temperature to attic temperature, and this heat may be added to the total heat loss through the ceiling of the unventilated attic, or it may be taken as a percentage of that lost through the unventilated attic, to show the increase due to mechanical ventilation. If the overall conductivity coefficient of the insulated ceiling is taken as .075, then the percentage of the heat loss through the ceiling for the unventilated attic required to heat the outside air from +5° F. to the attic air temperature for the mechanically ventilated attic is 4.7 per cent of the heat loss through the unventilated attic ceiling with outside air at +5° F. A similar calculation for the third group of tests at −10° F. outside air temperature shows an increase of 4.3 per cent in heat loss for the mechanically ventilated attic.

From the above calculations it appears that ventilating the attic through natural ventilation with an opening of .125 square inch of area in each gable per square foot of ceiling area, or by ventilating with mechanical ventilation by supplying 1.5 cubic feet of air to the attic per hour per square foot of ceiling area, gives an average additional heat loss through the ceiling of 5 per cent over that for the unventilated attic. A 5 per cent additional heat loss through a ceiling having a coefficient of .075 would make the combined heat loss equivalent to that through a ceiling having a coefficient of .079. It can thus be seen that the loss of heat caused by the required ventilation is insignificant.

CONCLUSIONS

When vapor comes in contact with a material whose temperature is below the dew-point temperature of the vapor, condensation is apt to take place and the physical laws governing that condensation are the same, regardless of whether it takes place on the exposed surface of the wall or within the interior section of the wall. The logical method of preventing condensation is to establish conditions which will keep the temperatures of the material with which the vapor comes in contact above the dew-point temperature of the vapor. In order to determine how best to accomplish this in residential construction, severe test conditions have been imposed on certain types of construction and the test data obtained have been used as a basis for the following conclusions.

It is recognized that inside air of 70° F. and 40 per cent relative humidity with outside air of −10° F. cannot be carried without serious window condensation even tho storm windows are used. It is also recognized that long periods of continuous low outside air temperatures as used in the test room are more severe than equal periods of variable outside temperatures which would be encountered in practice, and furthermore that the effect of normal sunshine would reduce the magnitude of the results obtained. Test data obtained have, however, established certain definite principles which, if followed in the construction and operation of buildings, will eliminate condensation problems.

The problems in residential buildings may be divided into three groups: first, those in which moisture condenses on the room surface of the walls; second, those in which moisture condenses on some interior part of the walls; and third, those which are encountered in cold attics and similar places. There are usually several factors entering into each of these problems and a solution may lie either in a change in building construction or in some modification of operating conditions.

Wall surface condensation problems can usually be solved by adding sufficient insulation to raise the room surface temperatures above the dew-point temperature of the inside air. If conditions are too severe to be met by the addition of insulation, then it is necessary to consider methods of reducing the dew-point temperature of the inside air. If the outside walls of a residence are well insulated, condensation will occur on the room surface of the windows (even with storm windows) before any trouble would be experienced with wall surfaces.

Condensation within the interior parts of a wall may be prevented by using a type of construction which will prevent the vapor from entering the warm side of the wall. Conditions may often be improved by using a type of construction which will allow the vapor to pass freely through the outer section of the wall. There are several materials now on the market made either in the form of a membrane or as an integral part of the plaster base, or as a surface finish for the plaster, which have a high resistance to the passage of vapor and may be used on the warm side of the wall to effectively stop vapor from entering the wall. There are other materials such as good building papers which are weatherproof but not vapor proof, and which are well adapted for use on the cold side of the wall. It is possible and practical to construct a wall that will prevent the passage of vapor under any reasonable humidity conditions that may be imposed on its warm surface.

The use of a good vapor barrier underneath the plaster does not affect the drying-out process of the plaster. Regardless of whether or not a vapor barrier is used it is essential that a building be thoroly ventilated during the drying-out period of the plaster. Many condensation problems are due to lack of ventilation during this period of construction.

The investigations thus far made in regard to attic ventilation have been made with small-scale construction. It is evident from data taken that sufficient ventilation may often be used in cold attics to eliminate condensation difficulties without materially adding to the heat loss from the buildings. For effective ventilation the openings to the outside must be arranged to give reasonable circulation of outside air to all parts of the attic.

Operating conditions within a building are a vital factor in most condensation problems, and when condensation occurs in a residence after the plaster has been thoroly dried out one of the most common causes is that of high relative humidities carried within the building. For a given type of construction the maximum allowable inside relative humidities must be reduced as the outside temperature drops. Unfortunately some of the present-day humidifying equipment is so operated that the relative humidity is increased rather than decreased during cold periods.

If condensation occurs within a frame wall with fill insulation between the studs it usually takes place on the inner surface of the sheathing rather than in the insulation. This is apparently due to the rapid transfer of vapor through the porous insulation and can be explained by the fact that the rate of vapor transfer is increased by the normal convection currents which are set up by the natural temperature gradients through the wall.

The theory covering the transfer of vapor through materials has not been completely developed or proven, but from the results obtained in this research it is evident that it follows rather definite laws and that with suitable vapor transmission coefficients for various materials the moisture conditions to be expected with a given type of construction and with given vapor and temperature conditions may be calculated. It is not necessary, however, to wait for the full development of the theory before making practical application of the principles involved and obtaining satisfactory operating conditions.