NATIONAL BUREAU OF STANDARDS REPORT

5223

SUMMARY REPORT - VAPOR BARRIER INVESTIGATION

Thule and Sondrestrom Air Force Bases, Greenland

by

F. J. Powell, National Bureau of Standards
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(Alfred Hopkins & Associates)
R. J. Persson, Metcalf & Eddy

Report to
U. S. Army Engineer District
Eastern Ocean
New York 11, New York

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Thule and Sondrestrom Air Force Bases, Greenland

I. INTRODUCTION

A. Purpose

At the request of the Office of the District Engineer, U. S. Army Engineer District, Eastern Ocean, an investigation and inspection of various buildings located at two Air Force Bases, Sondrestrom (BW-8) and Thule, Greenland, was completed to study the cause of frost, ice, and water accumulation in the interior construction of walls, floors, and ceilings of several buildings. This report covers the observations, discussion, results of laboratory tests, and conclusions of the investigating team. Individual reports containing recommendations for remedial action to correct failures in the buildings observed, or other existing buildings showing similar failures, will be submitted by the four offices involved. It is also proposed that this study be utilized as an aid to the development of data for future design of Arctic construction.

B. Personnel

Personnel charged with carrying out the investigation were as follows:

F. J. Powell - National Bureau of Standards
W. O. McClune - Eastern Ocean District, C. E.
B. J. Small - La Pierre, Litchfield & Partners
(Alfred Hopkins & Associates)
R. J. Persson - Metcalf & Eddy

C. Itinerary

1. Departed McGuire Air Force Base, 29 April 1956, at 1600.

2. Sondrestrom (BW-8), five days.

3. Thule, three days.

4. Returned McGuire Air Force Base, 9 May 1956, at 1630.

II. FINDINGS

A. General

Permanent prefabricated buildings were examined, such as airmen's and officers' quarters, hangars, mess halls, and communications buildings. Evidence of ice and water accumulation was found or reported observed in the cavities of most buildings examined. The extent of the accumulations of moisture observed varied from traces to completely soaked or frozen insulation. Water dripping or running into occupied spaces was observed in several instances.

Several buildings of each of the two main types of construction described below, were inspected. Conferences and interviews were held with field engineering personnel to discuss the past performance and failures of the buildings and corrective investigations undertaken to date. Several samples of representative vapor barriers and building sections were selected for transmission to the National Bureau of Standards for water vapor permeance and thermal conductivity tests.

Weather data for the first four months of 1956 was procured from base weather stations for use in studying the problem.

B. Description of Buildings

General descriptions of the two main types of prefabricated buildings observed, designated as Nos. 1 and 2, are as follows:

1. No. 1 (See Figure 1).

This is an aluminum clad structure consisting of an assembly of prefabricated insulated panels of various sizes composed of 1/4-inch interior grade plywood faced with 0.015-inch 2S or 3S half-hard mill finish aluminum, cold bonded adhesively to the plywood on the exterior and interior faces, the cavity being filled completely with 3 1/2-inch thick glass fiber batt insulation. The panels contain for their framework 3/4 x 3 1/2-inch vertical plywood stiles and 3/4-inch thick overlays at the top and bottom for proper integration with the structural frame. Where panels abut, solid wood splines, 13/32 x 1 27/32 inches are provided. In addition to being bolted to the structural frame, within each panel at the top and bottom a 3/4-inch pipe runs continuously around the structure. Joints are filled in the field with a specially prepared low temperature resistant caulking compound.

These panels are employed for exterior walls, and flat and pitched roofs, as well as building liners, as in the case of hangars. Floor panels are constructed of aluminum clad plywood which has been previously secured to the floor joists. The floor joist spaces are filled in the field with insulation of the glass fiber batt type and subsequently floored over with an asphaltic vapor barrier, 1 x 4-inch wood sleepers, 5/8-inch interior grade plywood, and finished with various materials such as felt backed vinyl and vinyl-coated glass fiber floor tiles. There are several panel types such as those incorporating windows, doors, previously prepared penetrations for admission of piping, corner members, filler pieces, eave members, joint covers, etc. On most buildings, a vinyl coating approximately 0.040 inches thick has been sprayed on the exteriors of roofs or of roofs and walls. In other instances, roof panel joints are covered on the exterior with an asphaltic type mastic reinforced with burlap. In some instances, some joints are covered on the interior with one-inch wide lead tape. This is applied to both wall and roof panels.

2. No. 2 (See Figure 2).

This is a precast steel-reinforced concrete structure consisting of an assembly of prefabricated concrete panels placed on a prefabricated steel-reinforced concrete structural frame. The buildings are of one or two stories, with first floor constructions of two basic types; (a) with floor raised above grade and (b) slab on grade. Type (a) consists of prefabricated concrete panels covered with a minimum of two inches of cellular glass insulation which was in turn protected by a concrete finish slab over which floor tile was applied. Type (b) consists of a concrete base slab on grade covered with insulation, concrete finish slab, and floor tile. External wall cladding of the building consists of prefabricated waffle-like steel-reinforced concrete panels on a four-foot four-inch module. The inner wythe of the walls, separated from the external cladding by a two-inch air space, consists of a four-inch thick preformed steel-reinforced insulating panel on a two-foot module. This panel has 1/2-inch fine aggregate concrete skins covering a three-inch rigid core of a mixture of wood chips and portland cement. The interior concrete face was finished with a cement-water wash and a varying number of coats of rubber base or lead-in-oil paint. Weep holes to the outside are provided from the bottom of the two-inch air space. Joints in the exterior cladding were packed with rammed mortar or gunnited. The joints of the inner wythe of insulating panels are ram-mortared or gunnited except for the top joint which is caulked. Window frames are inserted with back-up pieces intended to seal the two-inch cavity from the room, and are caulked inside and outside to

prevent infiltration of air. In two-story buildings, the second floor consists of prefabricated reinforced concrete panels on reinforced beam supports with a two-inch concrete floor finish covered with floor tile. The ceilings are not painted or finished. The flat roof consists of reinforced concrete panels over which a vapor barrier and three inches of thermal insulation are placed. A five-ply built-up roof is applied on the top surface of the insulation, and a mixture of asphalt and gravel three inches thick is placed over the roll roofing to complete the weather side.

C. Observations

1. Thule Air Force Base, Buildings Type No. 1.

a. Barracks 1-20.

This building was unoccupied and was being subjected to tests to determine the quantity of moisture penetrating the insulation. This was done by measuring the gain in weight of the insulation and the weight of water consumed by the humidifier at building conditions of 70 F and 40 percent relative humidity. Measurements were being made on the windward, center, lee, and wash room portions of the building.

Visual observations were also being recorded. The exterior roof joints of this building had been sealed with a low temperature asphaltic compound.

The interior surfaces of the building were dry. Caulking in the interior joints appeared continuous and the metal surfaces were unbroken. Some joints could have been assembled with more caulking while others had too much. Most triple-pane windows had condensation on the interior surface of the outer pane. Most test areas of insulation were dry to the touch. Upon opening the test area in the flat ceiling of the wash room, some water dripped from around the sealed edge; the insulation itself appeared dry. A sling psychrometer measurement of the relative humidity in the wash room was 50 percent at the time.

Numerous panels in the roof and sidewalls were deformed or buckled, and considerable delamination was observed between the outer aluminum skin and its adjacent plywood.

b. VIP Barracks 1-112.

This building had been re-roofed. The top surface of each of the horizontal aluminum skin panels was cut out,

exposing the insulation and an inclined roof of 2 x 6 rafters, plywood sheathing and roll roofing fastened with nailing strips was erected in cap fashion on the building. The between-roofs space, or plenum, varied in height from about 1 1/2 feet at one long edge to three feet at the other, and was closed at the edges with plywood. The plenum was divided into two equal parts by a partition at mid-length of the building.

The plenum at the windward (east) end of the building was ventilated by three-inch diameter ports, on approximately eight-inch centers, high in the longitudinal plywood sides of the plenum; designed to exclude blown snow. The plenum on the west or lee end of the building was not ventilated. This building was occupied and tests were being conducted to determine the rate of moisture gain by the insulation and to the plenum.

The interior of the building was dry and there were no recent reports of dripping from ceilings. Traces of condensation were visible on the triple-pane glass windows. Interior caulked joints were tight and appeared in good condition. In the unvented roof plenum, the plywood sheathing appeared wet and the top surface of the exposed insulation contained frozen beads of water. The day was sunny and the undersurface of the plywood sheathing was above 32 F. The exposed insulation looked and felt soaked with water down to the room side aluminum-faced plywood, which was wet. In the vented end of the plenum, signs of moisture on the plywood sheathing were not visible, but the insulation was wet down to the inner or room side face.

A second visit was made to this building on a windy colder day as compared with the still sunny day of the first visit. The unventilated end of the attic had frost patterns on the underside of the sheathing and on protruding nails. The insulation was wet to the touch for about one inch in depth from the top side and appeared damp at the lower levels. The ventilated end of the building did not exhibit any frost patterns on the sheathing but had traces on protruding nails and the insulation felt damp throughout but not wet.

No reliable observation could be made as to the degree of ventilation occurring through the ports in the east plenum, equipped as they were with filters to exclude driven snow.

c. Airmen's Mess Hall, 43-1.

This building was similar in construction to others visited except for its larger volume and a peaked instead of a flat roof. Several insert-type specimens of the roof insulation were being observed for moisture gain.

The condition of this building was similar to that of the barracks previously inspected. A joint high in the peaked roof was dripping water one drop at a time. Personnel in the building reported that this was the first sign of water so far this season.

d. Readiness Hangar, 3B-1.

This large building has a peaked roof that had been re-roofed. The top of each insulated panel was cut out, exposing the insulation. A cap-roof consisting of 2 x 6-inch nominal rafters covered with plywood sheathing was laid over the sloping roof. Roll roofing had not yet been installed; the joints in the plywood sheathing were covered with wood nailing strips. A crack vent was left at each eave, and several roof ventilators were mounted at the ridge to provide ventilation through the space immediately above the insulation. Insulated panels were being observed for moisture ingress by utilizing test sections containing an adsorbent, and, in other cases, plain test sections of insulation.

The interior of this building was not inspected. Observations made through removable areas of the cap-roof showed the insulation to be dry in appearance and to the touch throughout its thickness. A definite current of air between the rafters was perceptible, indicating an appreciable ventilating effect. The relative humidity at the peak inside the building was measured with a sling psychrometer. It was less than five percent at a dry bulb temperature of 99 F. The condition of the insulation was better in this roof than in any other building roof examined. Presumably, this building was modified with a cap-roof because of previous difficulty with wet roof insulation.

e. Other Barracks, Similar to 1-20.

The exterior of the roofs and some interior rooms of occupied barracks similar to and in the near vicinity of Building 1-20 were examined. The aluminum on the roof was noticeably delaminated from the plywood on many panels. Walking on the roof produced further delaminations. Crunching noises were heard when a man shifted his weight to the center of a

panel, and this was presumed to be due to ice within the insulation. This effect was noticeable on about 50 percent of the panels examined. Mastic covering the exterior joints was soft and appeared in good condition. Dripping was reported in a room in one of these barracks. The particular panel affected was dished downward toward the room approximately two inches from the normal ceiling level. The joints at the edge of this panel appeared to be typical, and similar to other joints in the building. By pressing upward on the sagged portion of the panel, one could hear a soggy sloshing sound originating within the panel. A small hole was cut with a knife through the aluminum skin and plywood at the center of the panel. Some droplets of water ran out and wet insulation was present. After this, the hole and joints of this panel were patched with a pressure-sensitive adhesive lead tape.

f. Communications Center, N-32.

This group of buildings is located on a mountain peak in the vicinity of the air base. Buildings at this site are exposed to high winds and weather of greater severity than buildings on the air base. The roof joints of these buildings were heavily covered with low temperature mastic. Most buildings had flat roofs. Some delamination of aluminum from the outside plywood was noticeable, and considerable buckling and deformation accompanied the delamination. Within the buildings, several spots were observed where dripping was occurring at joints, particularly at the low end of connecting corridors. In one instance, light was visible through a wall joint, but in most cases, joints and aluminum cladding appeared tightly constructed.

2. Sondrestrom Air Force Base (BW-8), Building Type No. 2.

a. Airmen's Dormitory - Building 320.

A portion of the north wall of this two-story building built on grade was damaged by a truck, affording an opportunity for inspection of the interior of the wall. The painted indoor concrete surface appeared pitted. Joints appeared tight and continuous except for the joint at the ceiling under the fascia board. This joint in some cases was cracked and appeared open. The smooth reinforced dense concrete exterior cladding appeared well sealed against the weather. Recent reports on this and other buildings of this type state that during thaws water drained from the wall cavity toward the interior causing a condition of water on the first floor. This occurred during a period of foehn winds which caused a sudden rise in outdoor air temperature from much below

freezing to above freezing (as much as 50 deg. F in eight hours). Weep holes from the cavity to the outside were plugged with ice, and sudden melting of ice within the cavities of the walls caused water to drain onto the first floor of the building, since insufficient thawing time elapsed to allow weep holes to melt open. Manual opening of the weep holes dissipated relatively large quantities of accumulated water, and sounds of what was presumed to be falling ice in the wall cavity were audible.

b. Bachelor Officers Quarters, Building 321.

The construction of this building was identical with the airmen's dormitory except that it was constructed with an open crawl space beneath. Frozen puddles of water were still visible on the ground where water in the cavities was relieved by opening weep holes and by drilling upward into the cavity from the crawl space. The condition of the building in general was comparable with that of the airmen's dormitory. Field reports indicate that this building also had a serious drainage of water onto the floor from the wall cavity.

3. Sondrestrom Air Force Base (BW-8), Building Type No. 1.

a. Global Communications Center.

This center is located on a mountain top in the vicinity of the air base. The larger main building was constructed with a peaked roof. The exterior of the building had been sprayed with a vinyl plastic. The building as a whole appeared in excellent condition as regards tightness and caulking of interior joints. Operating personnel report no trouble from leaks or drips. Several sections of the exterior vinyl coating on the roof were peeled and had been blown off.

D. Laboratory Tests and Inspection

Representative panels or components of Building Types Nos. 1 and 2 were inspected and water-vapor permeance and thermal conductivity tests were completed in the laboratories of the National Bureau of Standards.

1. Panel Inspection, Building Type No. 1.

Several representative pieces of aluminum-plywood skin typical of those in service were requested and subsequent to the inspection trip were forwarded from salvage to the National Bureau of Standards for water-vapor permeance tests. The results of these tests show that the permeance of the samples, not including joints, was zero.

Two full-size panels from buildings in service were requested for detailed inspection. Photographs of these panels are labeled Figures 3, 4, and 5. The location in buildings from which these panels were removed is unknown at this time, but it is believed the smaller panel was taken from a wall section and the larger panel from the corner of a roof. Figures 3, 4, and 5 show the panels as viewed from the exterior side with the insulation removed. These panels were examined approximately 1.5 months after removal from the buildings.

The smaller panel (Figures 3 and 4) was 16 inches wide and approximately eight feet high, and is probably of 1951 construction. This panel was generally in poor condition; most nailed joints were loose and the interior of the panels was wet and water-marked. The exterior skin was in good bond with the 1/4-inch plywood except near the edges (see Figure 3) where the aluminum is wrapped around the edge to form part of the joint. Nails holding this wrapped edge in place were loose and rusty and the thin strip of plywood down the eight-foot length was warped and delaminated to the extent that the three plies could be peeled with the fingers. The plywood immediately under the exterior skin (left side of Figure 4) was damp and wet to the touch; some delamination was visible on the inner ply next to the insulation, especially near knot holes. The 3/4-inch plywood overlay at the bottom of the panel was water-marked and contained surface cracks. This piece was probably exposed to exterior weather conditions. One 3/4-inch plywood stile was sound, but the other near the male portion of the tongue and goove joint was delaminated two plies deep in two places (center of Figures 3 and 4). The thickness of this stile ranged from its original value of 3/4 inch to a maximum swelled dimension of 1 1/2 inches, and the stile was wet completely through its thickness and 3 5/8-inch width. The sound stile showed moisture marking for 1 1/2 inches of its width as measured from the exterior side. The insulation was moist to the touch for depths of 1/2 inch to two inches in 3 1/2 inches, as measured from the exterior side. Several samples of the glass fiber insulation were weighed, oven-dried, and re-weighed, and the results showed overall moisture contents from 10 to 14.5 percent above dry weight at this time. The dry density was 3.1 pounds per cubic foot. Normally, insulation of this type could have one or two percent hygroscopic moisture above dry weight. The greatest concentration of moisture occurred near the bottom of the panel. The warm side plywood was not delaminated, and the bond between aluminum and plywood was tight and continuous. This plywood was damp near the stiles, presumably from moisture migrating from the stiles.

The larger panel (Figure 5) was 18 inches wide (insulated space), approximately eight feet high, and was probably of recent construction. This panel, generally, was in good condition. Considerable moisture-staining and wet areas were noted on the interior plywood. A small amount of delamination occurred on this sheet. Moisture concentrated near the central 3/4-inch plywood divider (Figure 5) and at the edges of the panel. The wood members of the remainder of the panel were sound. The insulation was damp on the indoor surface and did not appear so moist as in the smaller panel. Both interior and exterior aluminum skins were well bonded to their respective sheets of plywood except for the wet areas near the center of the interior sheet; at this point, the aluminum was separated from its backing sheet of plywood.

2. Water-Vapor Permeance Tests.

Water-vapor permeance measurements were conducted on several samples of materials from Building Types 1 and 2. The dry-cup method of testing was used, conforming to the requirements of ASTM E96-53T, "Measuring Water Vapor Transmission of Materials in Sheet Form," Procedure E. The edges of each specimen were sealed with microcrystalline wax over a metal cup approximately four inches in diameter, providing an exposed area of approximately 11.5 square inches. The cup contained eight mesh anhydrous calcium chloride as a desiccant and the atmosphere above the specimen was controlled at 100 ±2 F and 82 ±2 percent relative humidity. Weighings were taken periodically and the steady rate of weight gain indicated the rate of water-vapor transfer, or permeance, of the specimen.

RESULTS

Building Type No. 1 - Four specimens of the aluminum skin, cut from salvage panels removed from roofs, were measured and all results showed a permeance of zero.

Building Type No. 2 - Specimens from the inner wythe of the building included the painted interior concrete skin, wood-chip and cement insulation, and exterior unpainted skin all removed from Building No. 320 at Sondrestrom. Specimens of the outer cladding of the building were not measured because a suitable specimen could not be cut from between the steel reinforcing. Additional specimens of inner-wythe concrete skins, procured from stock material, were also measured. The inner-wythe concrete specimens were manufactured with two different surface finishes. One side of each panel had a steel-troweled finish and the other a wood form cast finish. The reported coatings of the painted specimen were as follows: one coat of cement

water wash for pore sealing, two coats of latex-base paint and two coats of lead-in-oil paint. The permeance results of specimens measured are shown in Table 1.

Further dry-cup permeance tests were conducted on the above specimens after various coatings were applied.

Coatings were selected on the basis of the following: (a) alkali-resistant to prevent rapid failure, (b) low permeance based on past specification tests of selected coatings, and (c) readily available and reproducible under a Federal Specification. The original specimens of cast surfaced concrete, from stock materials Nos. 7 and 8, were not suitable for retest because the calcium chloride in the permeance cup went into solution at the conclusion of the last tests, saturating these specimens. Four additional specimens, cut from the same stock as specimens 7 and 8, were used for applying coatings. These specimens were assigned the numbers 7a, 8a, 10, and 11. All coatings were brush applied and water-vapor permeance results are shown in Table 2. Measurements were not made after the first or primer coat of the first finish coat because the coverage or hiding power of these coats was not satisfactory when applied to porous surfaces. The estimated spreading rates applied per coat are 400-500 ft^2/gal. for primers and 300-400 ft^2/gal. for finish coats. A permeance result for specimen No. 11 was not obtained because of a leak that developed in the test cell.

3. Thermal Conductivity Tests.

The thermal conductivity of the wood-chip and cement insulating core of the inner wythe of Building Type No. 2 was measured in an eight-inch guarded hot-plate apparatus conforming with the requirements of Federal Specification LLL-F-321b and of ASTM C177-45. The specimen was air dried to constant weight in an oven at 215 F immediately prior to the conductivity measurement. The conductivity of the specimen was about 0.67 Btu/hr ft^2(deg. F/in.) at 64 F mean temperature. The density was 29.3 lb/ft^3 after drying, which caused a loss in weight of about 13 percent of the dry weight.

Measurements of the concrete skins of the inner wythe, and of the concrete of the outer cladding, were not made because of the difficulty of procuring suitable samples of large enough size. On the basis of past measurements of many concretes of various densities and aggregate sizes, it is believed that the thermal conductivity of the concrete used in these buildings may be estimated with sufficient accuracy.

The thermal conductivity of these concretes was estimated as about 6.2 Btu-in./hr ft^2 deg. F, assuming an average density of 125 pounds per cubic foot.

E. Discussion of Principles, Observations, and Laboratory Results

1. Introduction.

In this section, a discussion is given of the several ways in which the observed moisture could have entered the various building constructions and, where possible, quantitative estimates are made of rates of moisture ingress by the several possible mechanisms. This information is used to assist in reaching conclusions as to the most probable cause or causes of the moisture accumulations observed, and thus to point to the preventive or curative measures of most importance.

The moisture observed in the various constructions could have been the result of one or more of the following:

a. Materials wet or moisture laden when erected.

b. Inleakage of water or snow through exterior joints or openings.

c. Vapor permeance through inside finish.

d. Vapor diffusion through still air in unsealed interior joints.

e. Flow of moist indoor air into constructions through leaks in interior finish.

f. The probable extent of moisture egress from the interior of the wall construction to the outdoors, as a result of the vapor permeance of the exterior finish, or of ventilation with outdoor air, or of water drainage during thaws.

The considerations involved in estimating vapor permeance and condensation in constructions are given in National Bureau of Standards Report BMS-63, "Moisture Condensation in Building Walls," attached hereto as an Appendix.

The entry of moisture into a construction by its conveyance in a flow of relatively moisture-laden air into its interior from the indoor space may be considerable, depending on the rate of inflow of air, its moisture content, and the effective dewpoint maintained in the interior of the construction by the existing temperature conditions. As an illustration, if

leaks at the top and bottom of a panel construction allowed a flow of one cfm of indoor air at 70 F and 30 percent relative humidity (moisture content = 2.5 grain/cu ft) through the panel interior, and the temperature of the inside surface of the outer panel face were 0 F (moisture content of air at 0 F dew-point = 0.4 grain/cu ft), the rate of accumulation of moisture in the cavity would be 126 grains/hr or 0.43 lb/day. The problem of estimating moisture ingress due to air inleakage is therefore chiefly one of estimating the rate of air inleakage.

2. Sondrestrom Air Force Base (BW-8), Building Type No. 2.

Observations concerning Building Type No. 2 are discussed in relation to the factors (a through f) listed in the introductory paragraphs.

a. Materials Initially Wet.

Observations were made on the walls of the concrete buildings only, since the roofs and floors have not exhibited any visible moisture damage. The materials from a broken wall that was examined appeared dry to the touch.

If a wall of this kind were erected in a wet condition, the moisture in its inner wythe would tend to migrate to the outer wythe as a result of the indoor-outdoor temperature difference in winter.

Only a rough estimate can be made of the possible moisture content of this construction as erected. A sample of the wood-chip concrete insulation had a moisture content of 13 percent of its oven-dry weight, when it was measured at the National Bureau of Standards after shipment from BW-8. Assuming a possible initial moisture content of 25 percent for this component, which weighed approximately 147 pounds per 2 x 10-foot panel, and of 10 percent for the 1/2-inch concrete faces of the inner wythe, which weighed approximately 200 pounds per panel, the moisture available for migration would be less than 57 pounds per panel. This amount of water is equivalent to a layer of ice 0.6-inch thick on the inner surface of the outer wythe.

It may be added that in the first winter of exposure of an initially-wet wall, its excess moisture would probably be removed from the inner wythe by migration, and drained away through the weepholes during thaws. Thereafter, normal hygroscopic moisture in the inner wythe would be equivalent to a much smaller ice-layer thickness in successive winters.

b. Exterior Leaks.

The exterior joints of wall panels appeared tight and, based upon observation, it appears that little if any moisture could have entered the joints from the exterior. The whole surface of the outer cladding appeared well able to resist the elements.

c. Vapor Permeance Through Inside of Finish of Wall.

The method of manufacture of these prefabricated interior wythes yields one concrete skin with a form or cast finish and the other with a steel-troweled finish. Since these panels are reversible end-wise in construction, it is possible to have either a cast or a steel-troweled surface facing the interior.

Data on the vapor permeance of various samples of materials from typical walls are given in Table 1, and of the materials with various paint coatings in Table 2. The permeance of unpainted concrete skins of the insulating wythe was approximately three perms when they had been steel-troweled, and about 20 perms when they had a cast surface. It is evident that since these panels are reversible face-for-face, the steel-troweled surface should be on the indoor side to reduce vapor permeance into the insulation. The data for the various painted specimens show that the overall permeance of the wythe can be reduced to less than one perm by suitable paint coatings.

An estimate of the possible amount of moisture over a winter, using a permeance of one perm for the wythe based on measurements of the materials for Building No. 320 given in Table 1, shows the total amount of water vapor transferred to be equivalent to a layer of ice 0.028-inch thick on the inner surface of the outer wythe.

d. Vapor Diffusion Through Unsealed Interior Joints.

The inside vertical wall joints that were visually inspected appeared tight. However, the existence of vertical wall joint cracks in various buildings has been reported but the extent of joint cracking is not known. The joints between the floor and wall were hidden by floor tile and wood molding and possible cracks were not readily visible. The joint between the wall and the spandrel beam at the ceiling in some cases revealed gaps about 1/16-inch in width.

If such a gap were continuous from the interior of the room to the wall cavity, water vapor could diffuse through

it and be carried by convection to the inner surface of the outer wythe where it could condense.

An estimate of the amount of moisture that could accumulate over a winter by diffusion through a 1/16-inch gap, two feet long, indicates the equivalent of a layer of ice 0.0004-inch thick, if this moisture were distributed over the area of one 2 x 10-foot prefabricated panel.

e. Flow of Moist Indoor Air Into Construction Through Leaks in Interior Finish.

If a passage for air flow between the room and the interior space of the wall existed at both top and bottom, stack action would cause a circulation of room air through the wall interior, carrying moisture with it. Joint cracks were observed at the ceiling-wall junction; the leakage of water into the room at the floor during foehn winds indicates a passage also at the bottom of the wall. Thus, air circulation between the room and the wall interior seems possible in at least some panels. An additional contributing factor to air circulation between the room and the wall cavity are the cracks around the periphery of the window casing. (It should be noted that one gap into a panel could also allow room air to enter its interior if exterior wind caused a pressure differential from the room to the wall interior, i.e., on the lee side of the building.)

A quantitative estimate of the amount of moisture transferred by circulation of moist air through openings 1/32 inch wide and two feet long at the top and bottom of the inner wythe show an accumulated amount over a winter equivalent to a layer of ice 1.33 inches in thickness distributed uniformly over the area between the top and bottom cracks and deposited on the inner face of the outer cladding. Cracks at both the top and bottom probably are not continuous or may not exist for every prefabricated panel and their frequency around the periphery is unknown for comparative purposes. If the rate of vapor flow accomplished by convection under the above assumed conditions were expressed in terms of equivalent vapor permeance for a wall area between the top and bottom cracks, the value calculated is 48 perms. Thus, moist air inleakage appears to be potentially a much more important method of moisture entry than vapor permeance through the panel itself.

A summary of the amounts of moisture estimated as possibly accumulating as a layer of ice on the inner surface of the cladding per winter is given below.

Cause		Equivalent thickness of ice, inches
a)	Initial moisture	0.6
b)	Exterior leaks	---
c)	Vapor permeation	0.028
d)	Vapor diffusion	0.0004
e)	Convection	1.33
	Total	1.96

f. Egress of Moisture From the Cavity to the Outdoors by Vapor Permeation Through Exterior Cladding, Ventilation with Outdoor Air, or Water Drainage Through Weepholes.

The vapor permeance of the two-inch concrete exterior cladding was not measured. Data on concrete permeance are very limited, especially for conditions of below-freezing temperatures. Assuming the permeability of the cladding concrete to be about the same as that of the cast inner wythe skins (10.4 perm-inches), the permeance of the cladding is taken as 5.2 perms. On this basis, vapor permeation to outdoors per winter would be equivalent to an ice layer of 0.014 inch. This is negligible compared to the total accumulation of 1.96 inches of ice within the wall cavity per winter as given above.

If the cavity were to be ventilated with outdoor air to remove this moisture, it is estimated that the necessary ventilation to remove it, with outdoor air at -10 F and 55 percent relative humidity, would be on the order of 17.7 cfm per story for each two linear feet of wall.

On the basis that the maximum winter accumulation of ice on the outer cladding is 1.96 inches thick, sudden thawing due to a foehn wind would call for a water run-off through the cavity weepholes for each interior panel of 22 gallons of water (89 percent of the cavity volume). This volume of water could readily escape from open weepholes, especially since thawing would not be rapid, but if weepholes were not open from the start of the thaw, there would be danger of soaking the inner wythe with the melt water until drainage occurred, leading to a condition somewhat similar to that considered under the heading of initial moisture in the construction.

3. Thule Air Force Base, Building Type No. 1.

Observations concerning Building Type No. 1 are discussed in relation to factors (a) through (f) listed in the introductory paragraphs of this section.

a. Materials Initially Wet.

Field observations and previously reported observations at Thule indicate that water does not drip into the interior from every roof panel. Observed badly-wetted areas were more or less localized and not always at the lowest point on the roof in any particular buildings, and some roofs of some buildings did not drip at all. This distribution suggests that the panels that are wet might have been erected containing considerable moisture while the others did not. Admission of moisture could conceivably have occurred during manufacture, storage, transportation, and erection of some of the panels. One field observation, on one flat roof and based on the sound of ice crunching in roof panels when walked upon, indicated that about 50 percent of these roof panels contained some moisture. Other reported observations of several buildings and of cored samples removed from selected sections of the roof panels of buildings indicate that some buildings did not exhibit any visible moisture, while others showed as high as 80 percent of the panels examined contained moisture in varying amounts. Of the ten buildings examined, only two showed high percentages of the incidence of moisture.

If prefabricated panels of this type were erected in a wet condition, the moisture would tend to migrate to the outer face as a result of the indoor-outdoor temperature difference in winter. The metal exterior skin constitutes a good vapor barrier and if the exterior joints were vapor tight, the initial moisture would remain trapped in the panel.

Only a rough estimate can be made of a possible moisture content of a panel as erected. For moisture contents of 50 percent of the dry weight of the insulation and plywood, the total amount of water in a two-foot by eight-foot panel would be equivalent to a layer of ice 0.35-inch thick, distributed uniformly over the inner surface of the outdoor face.

b. Exterior Leaks.

A possible source of moisture trapped in roof and communicating wall panels could originate from rain or melting snow entering the exterior joints of the roof panels immediately after erection and prior to the application of mastics or other joint coverings. Lack of caulking during construction, contraction of the exterior portion of the panel joints, and movement or settling of the building are reasonable possibilities. Flat roofs allow puddling of water and one could expect more moisture problems on this type than on pitched roofs. Water entering pitched roofs could run on panel

interior surfaces from panel to panel from the ridge to the eaves if it did not drain through unsealed interior joints at the ends of the panels.

An estimate of the amount of leakage per panel cannot be made with any accuracy. Use of weather precipitation data would be misleading because of run-off from one panel entering another, puddling in low spots, varying amounts of caulking, degree of joint opening, and the various ages and histories of the buildings.

c. Vapor Permeation Through Inside Finish of Walls and Roofs.

Laboratory tests on aluminum skins taken from salvage panels indicate zero perms; hence, these specimens were not capable of passing water vapor. If the interior aluminum skins were penetrated or marred, a path for the transfer of water vapor would exist. Field observations indicate that very few large penetrations are present.

d. Vapor Diffusion Through Unsealed Interior Joints.

Most of the joints examined visually appeared tight and continuous. In some cases caulking was sparse and in others excessive. For most of the buildings observed, the exterior joints were treated with a continuous thick mastic which provided a seal impermeable to water vapor.

An estimate of the amount of moisture that could accumulate in a 2 x 8-foot panel during a winter by diffusion through a 1/32-inch gap in half the peripheral joint length indicates the equivalent of a layer of ice 0.0016-inch thick, if this moisture were distributed uniformly over the outdoor face.

e. Flow of Moist Indoor Air Into Panels Through Leaks in Interior Finsih.

If caulking of the interior joints of the walls or ceilings were faulty, paths for the circulation of the relatively moist room air into the joint space between panels would be possible. Presumably, the vapor conveyed in the air would condense in the colder parts of the joint spaces, whence it might soak through or run through cracks into the panel space itself. In some cases, the room air might circulate even through the panel space, and condense on the cold surface of the outer skins. In any case, such moisture in cold weather would tend to migrate to and collect on the inner surface of the outer skin.

Only a rough estimate can be made of the possible moisture transfer by convection. The most reliable information concerning the total rate of moisture ingress with this type of joint would be a laboratory test on roof, wall, and floor panels. Laboratory observations of some panels removed from the walls and ceiling of a building indicated more rapid deterioration of the wood had occurred in the wall panel as compared to the ceiling panel examined. An estimate for the joint in the walls of a two-foot by eight-foot wall panel with openings through the joints at the top and bottom, and with an estimated air path in the joint space of 0.00125 sq ft in area, shows the total amount of water transferred as vapor over a winter would be equivalent to a layer of ice 0.24 inch thick distributed uniformly over the area of the inner face of the outdoor surface, assuming that the moisture accumulation in the joint space as ice or frost did not prevent continued air circulation. However, for the low outdoor temperatures generally prevalent, it seems probable that the deposited moisture would choke the joint space and inhibit the continued flow of air. It is judged that the ingress of moisture due to convection in ceiling and floor panels would be less than for wall panels.

A summary of the amounts of moisture estimated as possibly accumulating on the inner surface of the outer face as a layer of ice is given below.

Cause	Equivalent thickness of ice, inches
a) Initial moisture	0.35
b) Exterior leaks	Fortuitous
c) Vapor permeation	0
d) Vapor diffusion	0.0016
e) Convection	0.24
Total	0.59

f. Egress of moisture from the interior of the cavity to outdoors by permeation through exterior finish, ventilation of the cavity with outdoor air, or water drainage.

The zero permeance of the exterior surface and the resistance of the heavy mastic covering the exterior joints effectively prevents moisture transfer to the outdoors. For buildings without mastic over the joints, some moisture transfer out of the joints probably takes place but is quickly canceled by the leakage of rain or melting snow.

Venting the cavity with outdoor air cannot be readily accomplished without structural changes and venting ports that would exclude blown snow. The rates of ventilation necessary to dry out the present construction and keep it dry without seriously affecting the heat transfer rate are difficult to predict, especially for roof panels.

4. Remedial Considerations and Drying.

a. Sondrestrom Air Force Base (BW-8), Building Type No. 2.

The moisture accumulated in the wall cavity as ice will probably drain through exterior weepholes during the summer. If further accumulation does not occur, a second winter season would have the effect of self-drying the inner wythe. Preventing the ingress of moisture to the cavity from indoors through leaking inside joints is imperative if the effects of rapid thawing during an above-freezing temperature foehn wind are to be avoided.

b. Thule Air Force Base, Building Type No. 1.

If the structural soundness of these buildings is to be maintained, the wet insulation and wooden portions of the panels should be dried or replaced. In view of the heavy mastic over the exterior joints, a practicable and economic way to expel moisture from these panels appears to be an approach from the interior of the structure. Some possible methods considered include: (1) cutting holes in the interior surface of roof and wall panels for water drainage and resealing with tape or a self tapping plug, (2) circulation of dry air in the panel cavity, and (3) removal of one or both surfaces. The first method does not dry out the interior of the panel and the second method would probably take too much time. It appears that a solution involves removing either the indoor or outdoor surface and replacing or drying existing wet insulation.

5. Curative Measures.

Curative measures taken should provide for better protection against leakage of indoor air into the construction through the joints. All gaps and cracks should be filled to prevent convection of indoor air to the building cavities. For walls and roofs, ventilation or an exterior covering arrangement that would allow escape of water vapor to the outdoors and at the same time provide protection from the elements would provide additional protection against the effects of condensation.

For future construction, the use of dry materials and installation in a manner to prevent wetting should be rigidly controlled. The design of Building Type No. 1 and the walls of Building Type No. 2 should be changed to accommodate provisions to prevent moisture accumulation in future construction.

III. GENERAL CONCLUSIONS

A. Thule

1. The factors contributing to the accumulation of moisture in the interior construction of these buildings are believed to be residual moisture at the time of erection, leakage from the exterior after construction, and condensation of water vapor originating in the interior of the building.

2. Quantitative estimates indicate that residual moisture and exterior leakage before sealing over joints probably provided the largest portion of the moisture presently in the panels.

3. It is difficult if not impossible to determine quantitatively the proportionate part of the total accumulation contributed by each of the above factors. Quantitative estimates indicate the possibility of each factor, it taken separately, being capable of contributing enough moisture to produce a wetting or dripping from joints.

4. Any transfer and subsequent condensation of water vapor from the interior occurred through the joints rather than the panel faces.

5. Deleterious effects of moisture in panel cavities and joints include (a) water and caulking falling from ceilings to the interior space, (b) disintegration of bonding materials and glues causing delamination of plywood and separation of aluminum skins resulting in the loss of structural soundness, and (c) increased heating fuel consumption resulting from greater heat loss caused by wet materials.

B. Sondrestrom

1. The factors contributing to the accumulation of moisture in the wall cavities are believed to be residual moisture at the time of construction and condensation of water vapor transferred from the interior of the structure to the wall cavity.

2. Quantitative estimates of each of the above factors indicate that water-vapor transfer was probably the largest contributing factor. This transfer was probably accomplished by (a) convection of air and water vapor from the interior through openings at the floor and ceiling levels, (b) diffusion of moisture from the interior through holes or cracks to the wall cavity, and (c) permeation of water vapor through the surface of the wall itself. The last two are estimated as small compared to the amount possible by convection alone.

3. Laboratory measurements of the water vapor permeance of the inner wythe skins indicated that the permeance of the skin with a steel-troweled surface is about one-seventh of that with a cast surface, and therefore the panels should be erected with the steel-troweled surface facing the interior of the building.

4. Damaging effects from excessive moisture include (a) leakage of water from the bottom of the wall cavity to the first floor caused by melting of ice or frost in the wall cavity at a time when weepholes are frozen closed, (b) increased fuel consumption for heating due to lower thermal resistance of the wall because of wet materials, and (c) possible structural and material damage from freezing and thawing.

Table 1

WATER-VAPOR PERMEANCE RESULTS FOR INNER-WYTHE MATERIALS

NBS Spec. No.	Material	Specimen Surface	Thickness of Specimen, Inches	Permeance Grains/ hr ft^2 (in. Hg)	Permeability Grains-inch/ hr ft^2 (in. Hg)	Perms for Design Thickness*
		Specimens from Stock				
5	Concrete Skin	Steel-Troweled, Unpainted	0.61	3.1	1.9	3.8
6	"	"	0.63	2.9	1.8	3.6
						avg. 3.7
7	"	Cast Side Unpainted	0.36	24.9	9.0	18.0
8	"	"	0.70	16.7	11.7	23.4
						avg. 20.7
		Specimens from Building No. 320				
3	Interior Skin	Painted on Cast Side	0.29	2.3	0.67	1.34
4	"	"	0.32	2.0	0.64	1.28
4a	"	"	0.35	1.7	0.60	1.19
						avg. 1.27
9	Wood-Chip Cement Core	Specimen Sanded	0.63	27.8	17.4	5.8
1	Exterior Skin	Steel-Troweled, Unpainted	0.59	3.5	2.1	4.2
2	"	"	0.55	3.1	1.7	3.4
						avg. 3.8

*For inner wythe skins 1/2", for wood chip-cement, 3".

Table 2

WATER-VAPOR PERMEANCE RESULTS FOR INNER-WYTHE MATERIALS

NBS Spec.	Coatings Applied*	Permeance grains/ hr ft^2 (in. Hg)	Permeability grains-inch/ hr ft^2 (in. Hg)	Perms for Design Thickness
	Specimens from Stock, Steel-Troweled Finish			
1	No cement wash; 1 coat primer; 2 coats enamel	0.52	0.31	0.62
2	Cement wash; 1 coat primer; 2 coats enamel	0.43	0.24	0.48
5	No cement wash; 2 coats latex base paint	1.10	0.67	1.34
6	Cement wash; 2 coats latex base paint	1.17	0.74	1.48
	Specimens from Stock, Cast Finish#			
7a	Cement wash; 1 coat primer; 1 coat enamel undercoat; 2 coats enamel	0.18	0.12	0.24
8a	Cement wash; 1 coat primer; 2 coats enamel	0.57	0.34	0.68
10	Cement wash; 1 coat primer; 2 coats latex base	0.80	0.49	0.98
11	Cement wash; 2 coats latex base	--	--	--
	Painted Specimens from Building No. 320			
3	Two coats enamel	0.58	0.17	0.34
4	Two coats flat oil paint	0.84	0.27	0.54
4a	Two coats latex base	1.28	0.45	0.90

Table 2 (Continued)

*Coatings applied to specimens of Table 1 (numbers and thicknesses correspond in Table 2) as follows:

Cement Wash - 2 parts cement plus 1 part water by weight
Primer, alkalai resistant - Sherwin Williams No. 61 used
Enamel, gloss interior - Federal Specification No. TT-E-506c.
Undercoat, enamel - Fereral Specification No. TT-E-543
Oil paint, interior flat - Federal Specification No. TT-P-51d.
Latex base, interior flat - Federal Specification No. TT-P-29

#Thicknesses of these four specimens were: 7a, 0.64"; 8a, 0.60"; 10, 0.61"; 11, 0.53".

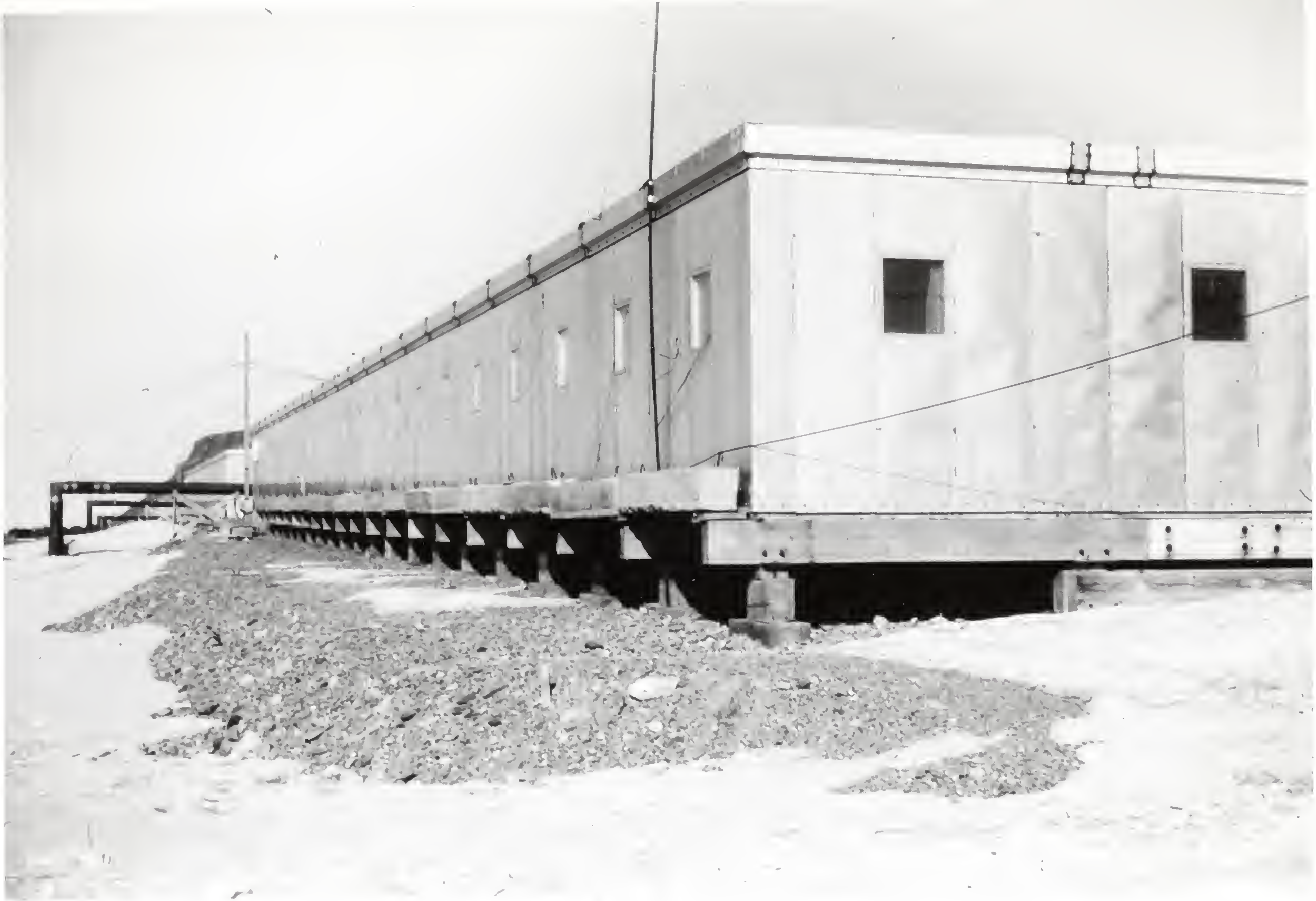

Figure 1

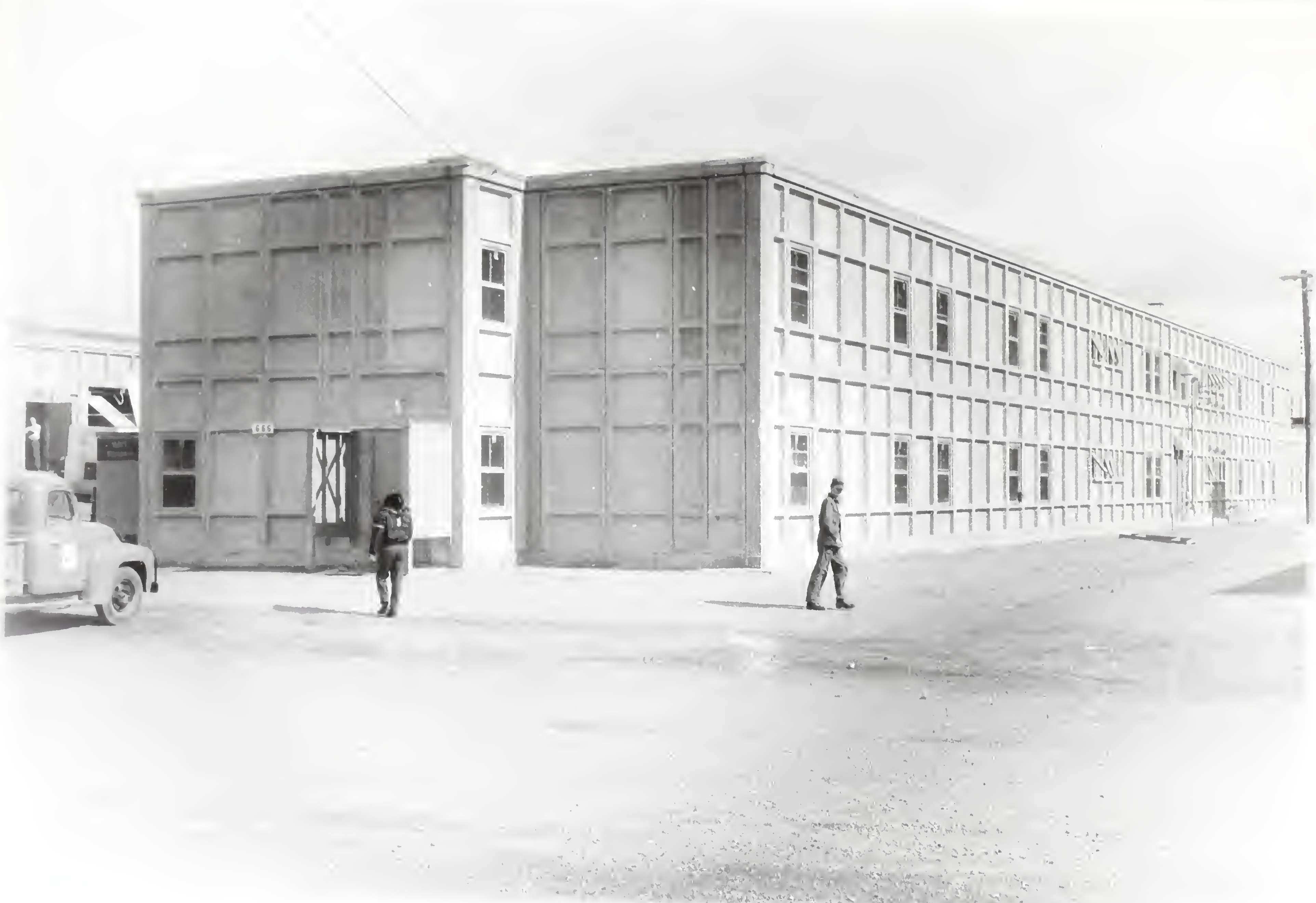

Figure 2

Figure 3

Figure 5

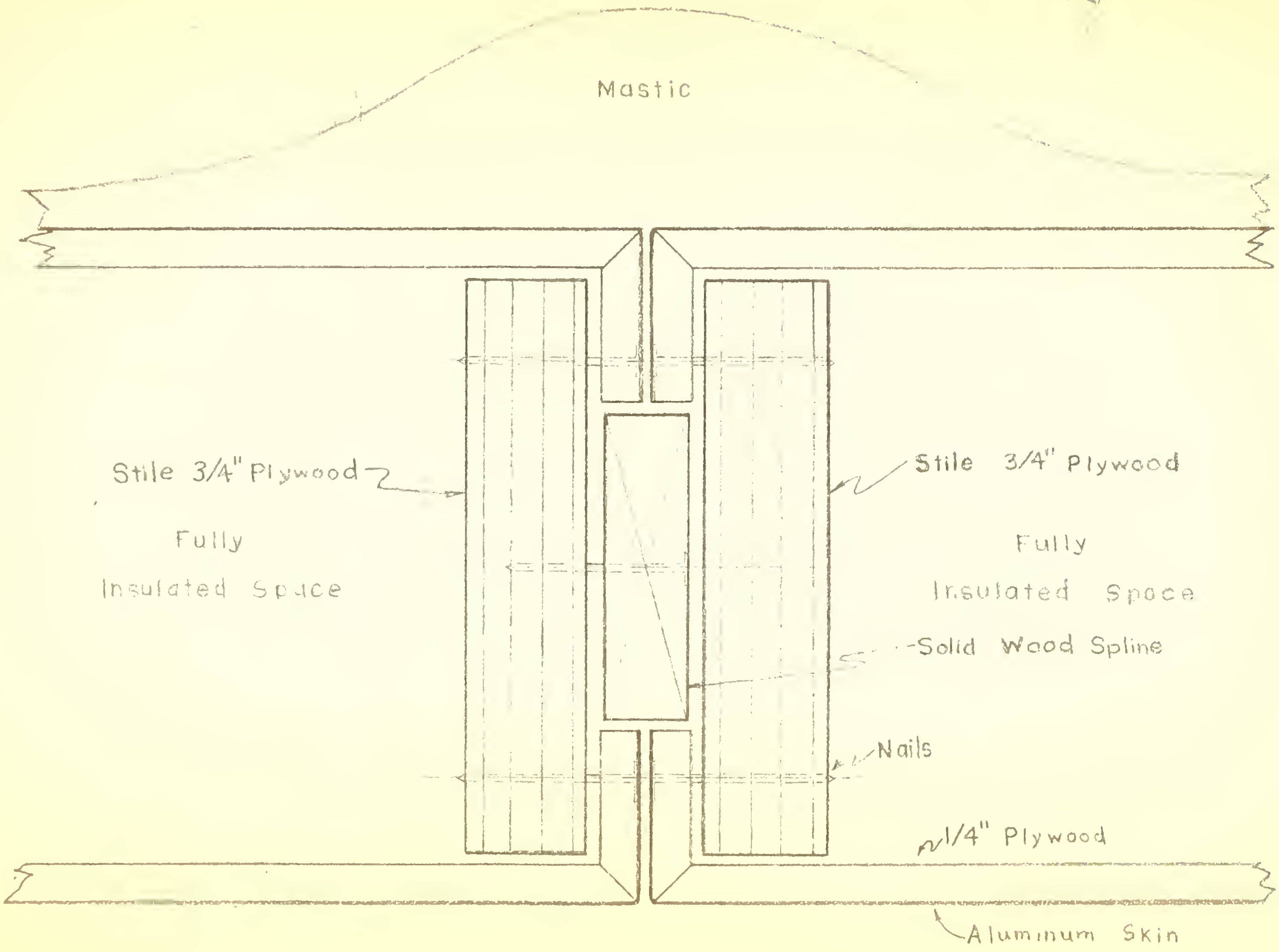

Figure 6

Panel Joint, Building Type No. 1, Exploded View

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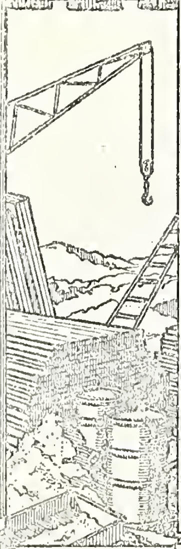
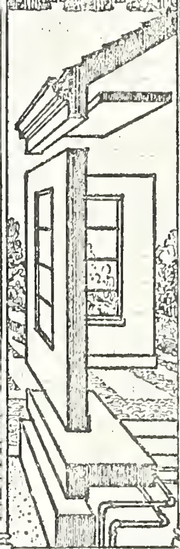




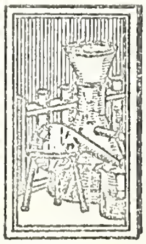
BUILDING MATERIALS AND STRUCTURES

REPORT BMS63

Moisture Condensation in Building Walls

by

HAROLD W. WOOLLEY



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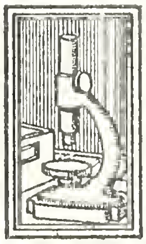

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[For list of BMS publications and directions for purchasing, see cover page III]

UNITED STATES DEPARTMENT OF COMMERCE · Harry L. Hopkins, Secretary

NATIONAL BUREAU OF STANDARDS · Lyman J. Briggs, Director

BUILDING MATERIALS *and* STRUCTURES

REPORT BMS63

Moisture Condensation in Building Walls

by

HAROLD W. WOOLLEY

ISSUED DECEMBER 14, 1940

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

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Foreword

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

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

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

Lyman J. Briggs, *Director.*

Moisture Condensation in Building Walls

BY HAROLD W. WOOLLEY

CONTENTS

ABSTRACT

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

I. INTRODUCTION

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

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

II. GENERAL PRINCIPLES INVOLVED IN CONDENSATION

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

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

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

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

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

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

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

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

[a] 7,000 grains equals 1 pound.

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

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

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

Water has several effects on building materials. As is very well known, some materials, such as wood, expand with increasing moisture content. If conditions of greatly varying humidity occur in different parts of the cross section of a single framing member there will be some tendency for the wood to warp. High humidity favors decay of wood. Some other materials are adversely affected by continued

exposure to liquid water. Water promotes corrosion of metals, and even some mineral insulating materials show permanent change in the course of time when in contact with water. The insulating value of materials in general is greatly decreased by the presence of free water. Droplets of water tend to bridge gaps between separate solid portions of ordinary insulating materials and increase the transfer of heat. The distillation of moisture from place to place in the wall can also increase heat transfer since heat must be added to evaporate the moisture and then is released again in the colder region where the moisture may happen to condense. Normally this effect will be important mainly when the temperature indoors is increasing.

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

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

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

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

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

Material	Thickness	Permeability to moisture (*P*)	Vapor resistance (1/*P*)
TEESDALE [11]			
	Inches	*Grains* / *sq ft hr (lb/sq in.)*	*sq ft hr (lb/sq in.)* / *Grains*
Foil-surfaced reflective insulation, double-faced		0.172 to 0.263	5.82 to 3.8
Roll roofing—smooth, 40 to 65 lb/roll 108 sq ft		.263 to .348	3.8 to 2.87
Asphalt impregnated and surface-coated sheathing paper, glossy, 50 lb and 35 lb/500 sq ft		.433 to 1.57 .348 to 4.19	2.31 to 0.637 2.87 to .239
Duplex or laminated papers, 30-30-30		2.80 to 5.24	0.357 to .191
Duplex or laminated papers, 30-60-30		1.05 to 1.75	.952 to .572
Duplex papers, reinforced		1.396 to 4.19	.716 to .239
Duplex paper, coated with metal oxides		1.05 to 2.63	.952 to .381
Insulation backup paper, treated		1.75 to 6.97	.572 to .144
Gypsum lath with Al-foil backing		0.173 to 0.785	5.78 to 1.27
Plaster, wood lath		22.4	0.0446
Plaster, 3 coats of lead and oil		7.5 to 7.84	0.133 to .127
Plaster, 3 coats of flat wall paint		8.72	.115
Plaster, 2 coats of Al paint		2.35	.425
Plaster, fiberboard or gypsum lath		40.2 to 41.9	.0249 to .0239
Slater's felt		10.5 to 52.4	.0952 to .0191
Plywood, ¼-in., Douglas fir, soy bean glue, plain		8.72 to 13.1	.115 to .0764
Plywood, 2 coats of asphalt paint		0.87	1.15
Plywood, 2 coats of Al paint		2.63	0.38
Plywood, ½ in., 5-ply Douglas fir		5.43 to 5.59	.184 to .179
Plywood, ¼ in., 3-ply Douglas fir, artificial resin glue		8.72 to 13.1	.115 to .0761
Plywood, ½ in., 5-ply Douglas fir, artificial resin glue		5.59 to 6.85	.179 to .146
Insulating lath and sheathing, board type		52.3 to 69.8	.0191 to .0143
Insulating sheathing, surface-coated		6.17 to 8.88	
Compressed fiber board, $^3/_{16}$ in		10.3	.097
Insulating cork blocks, 1 in		12.6	.0794
Blanket insulation between coated papers, ½ and 1 in		3.90 to 4.07	.256 to .246
Mineral wool, unprotected, 4 in		59.2	.0169
FOREST PRODUCTS LABORATORY			
Kraft paper		112.	0.00893
Plastered wall, no paint, plasterboard lath		41.7	.024
Plastered wall, no paint, wood lath		22.2	.045
Slater's felt, best type		10.1	.099
Duplex paper		2.78	.36
Plastered wall, 2 coats of Al paint, wood lath		2.43	.411
Asphalt-coated paper, 35 lb/500 sq ft roll		2.08	.481
Asphalt-coated paper, 50 lb/500 sq ft roll		1.04	.962
Metal-coated paper		0.174	5.75
INTERNATIONAL CRITICAL TABLES			
Still air, 3⅝ in		70.9	0.0141
Still air, 1 in		257	.00389
WRAY [3]			
1 coat of Al paint on wood, Bakelite resin varnish		1.22	0.82
1 coat of Al paint on wood, glycerol phthalate varnish		1.22	.82
2 coats of ordinary paint, linseed oil		3.48	.287
1 coat of Al paint on wood, ester gum varnish		2.26	.445

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

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

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

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

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

[1] Strictly, the space contains the moisture.

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

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

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

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

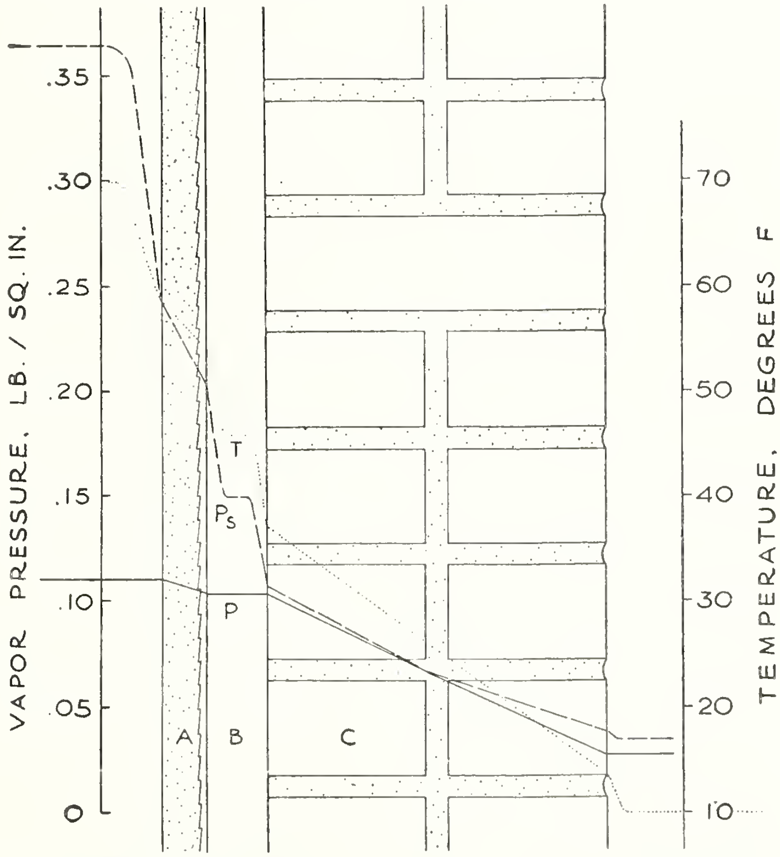

FIGURE 1.—*Nature of the temperature, corresponding saturation vapor pressure, and actual vapor pressure distributions in an uninsulated brick wall.*

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

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

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

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

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

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

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

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

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

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

TABLE 3.—*Thermal resistance of various materials*

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

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

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

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

The same procedure may be continued in regard to temperature. The temperature in-

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

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

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

	Vapor resistance	*Thermal resistance*
Air to surface of plaster	0. 001	0. 61
Lath and plaster	. 045	. 23
Insulation (1⅝-in. mineral wool)	. 014	6. 01
Brick	. 9	1. 24
Surface to air	0	0. 17

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

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

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

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

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

TABLE 1.—*Illustrative calculations concerning vapor barriers*

Wall type	Thermal resistance [a]		Thermal-resistance fraction (to chosen point: Cold side of insulation, or hollow space, if present	Vapor resistance [b]		Vapor-resistance fraction (to chosen point)	Necessary increase in inner vapor resistance [b] to prevent condensation at the chosen point		
	Inner part	Total		Inner part	Total		30° F, 80% outside; 70° F, 40% inside	10° F, 80% outside; 70° F, 30% inside	10° F, 80%, outside; 70° F, 20%, inside
Frame wall:									
Uninsulated	1.92	3.85	0.50	0.06	0.460	0.13	0	0	0
3⅝ in. of insulation	14.41	16.34	.88	.06	.460	.13	.47	1.28	2.21
1 in. of insulation in middle of space	6.53	8.46	.77	.06	.460	.13	.14	0.48	0.83
2 in. of insulation in middle of space	10.23	12.16	.84	.06	.460	.13	.32	.90	1.54
Frame and stucco:									
Uninsulated	1.92	3.09	.62	.06	.305	.197	0	0	0.06
3⅝ in. of insulation	14.41	15.58	.93	.06	.305	.197	.43	1.24	2.30
1 in. of insulation	6.53	7.70	.85	.06	.305	.197	.19	0.58	1.01
2 in. of insulation	10.23	11.40	.90	.06	.305	.197	.32	.92	1.65
Brick veneer:									
Uninsulated	1.92	3.87	.50	.06	.71	.0845	0	0	0
3⅝ in. of insulation	14.41	16.36	.88	.06	.71	.0845	.80	2.11	3.67
1 in. of insulation	6.53	8.48	.77	.06	.71	.0845	.27	0.82	1.38
2 in. of insulation	10.23	12.18	.84	.06	.71	.0845	.56	1.49	2.54
Brick, solid 8 in., furred, metal lath, and plaster:									
Uninsulated	1.75	3.16	.554	.06	.96	.0625	0	0	0.05
1⅝ in. of insulation	6.85	8.26	.83	.06	.96	.0625	.73	1.92	3.21

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

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

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

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

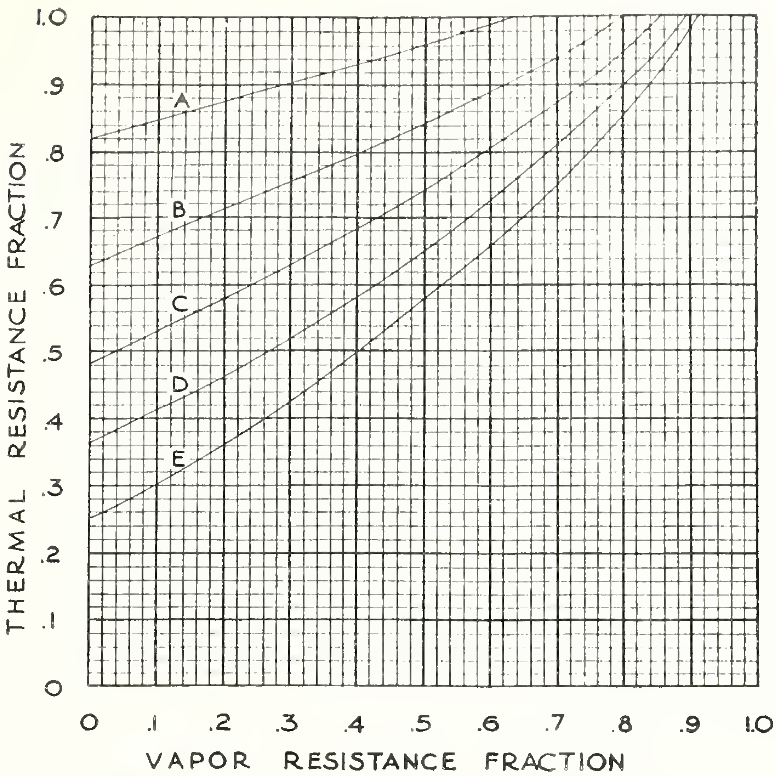

Figure 2.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

(Fraction of thermal resistance on warm side of the point and fraction of vapor resistance on warm side of the point in question.)
Curves *A*, 30%; *B*, 40%; *C*, 50%; *D*, 60%; and *E*, 70% indoor relative humidity.
Conditions: *30° F outdoors;* 70° F indoors; and 80-percent relative humidity outdoors.

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

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

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

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

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

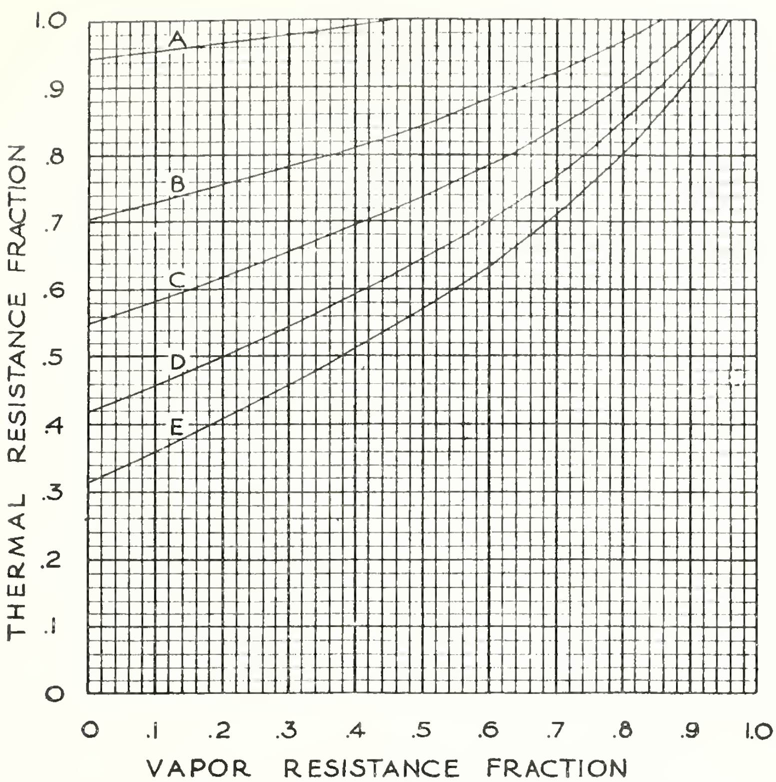

FIGURE 3.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

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

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

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

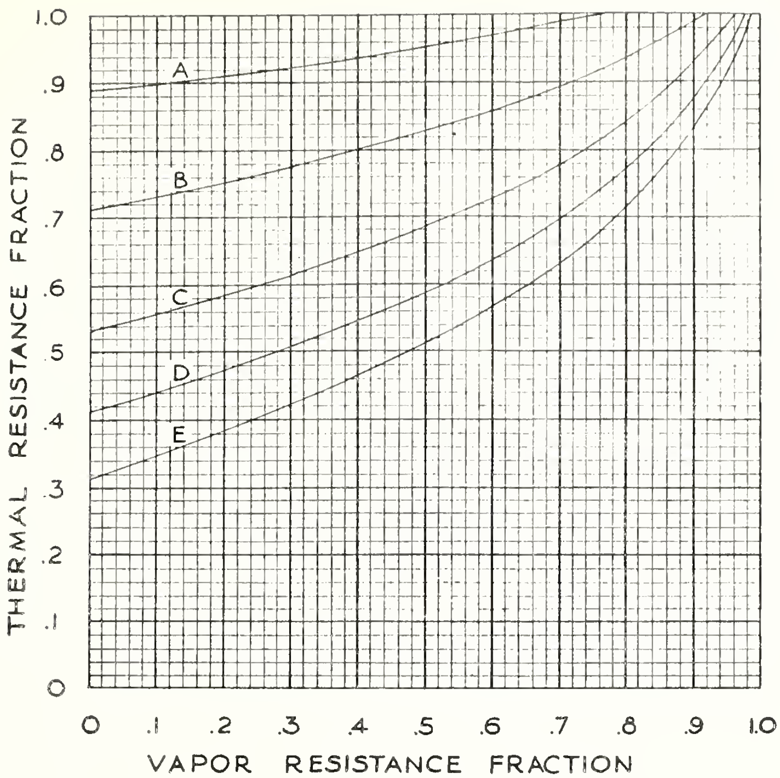

FIGURE 4.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

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

Curves *A*, 5%; *B*, 10%; *C*, 20%; *D*, 30%; and *E*, 40% indoor relative humidity.
Conditions: −10° *F outdoors*; 70° F indoors; and 80-percent relative humidity outdoors.

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

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

III. MEANS OF PREVENTING CONDENSATION

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

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

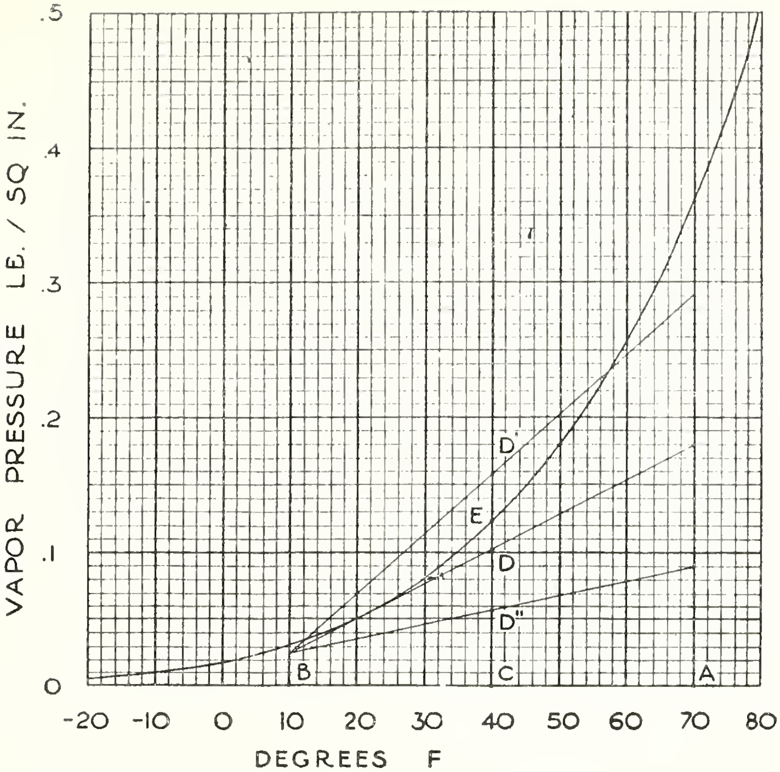

FIGURE 5.—*Method of predicting vapor pressure conditions in a wall composed of a single slab of permeable material.* 80-percent outside humidity (at *B*); *D'*, line for 80-percent humidity inside (at *A*); *D*, line for 50-percent humidity inside (at *A*); *D''*, line for 25-percent humidity inside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

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

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

These will be considered in order.

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

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

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

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

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

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

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

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

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

IV. CONCLUSIONS

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

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