Designation: C 755 – 03

Standard Practice for
Selection of Water Vapor Retarders for Thermal Insulation[1]

This standard is issued under the fixed designation C 755; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice outlines factors to be considered, describes design principles and procedures for water vapor retarder selection, and defines water vapor transmission values appropriate for established criteria. It is intended for the guidance of design engineers in preparing vapor retarder application specifications for control of water vapor flow through thermal insulation. It covers commercial and residential building construction and industrial applications in the service temperature range from −40 to +150°F (−40 to +66°C). Emphasis is placed on the control of moisture penetration by choice of the most suitable components of the system.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

C 168 Terminology Relating to Thermal Insulation
C 647 Guide to Properties and Test Methods of Mastics and Coating Finishes for Thermal Insulation
C 921 Specifications for Jackets for Thermal Insulation
C 1136 Specification for Flexible, Low Permeance Vapor Retarders for Thermal Insulation
E 96 Test Methods for Water Vapor Transmission of Materials

3. Terminology

3.1 For definitions of terms used in this practice, refer to Terminology C 168.

4. Significance and Use

4.1 Experience has shown that uncontrolled water entry into thermal insulation is the most serious factor causing impaired performance. Water entry into an insulation system may be through diffusion of water vapor, air leakage carrying water vapor, and leakage of surface water. Application specifications for insulation systems that operate below ambient dew-point temperatures should include an adequate vapor retarder system. This may be separate and distinct from the insulation system or may be an integral part of it. For selection of adequate retarder systems to control vapor diffusion, it is necessary to establish acceptable practices and standards.

4.2 *Vapor Retarder Function*—Water entry into an insulation system may be through diffusion of water vapor, air leakage carrying water vapor, and leakage of surface water. The primary function of a vapor retarder is to control movement of diffusing water vapor into or through a permeable insulation system. The vapor retarder system alone is seldom intended to prevent either entry of surface water or air leakage, but it may be considered as a second line of defense.

4.3 *Vapor Retarder Performance*—Design choice of retarders will be affected by thickness of retarder materials, substrate to which applied, the number of joints, available length and width of sheet materials, useful life of the system, and inspection procedures. Each of these factors will have an effect on the retarder system performance and each must be considered and evaluated by the designer.

4.3.1 Although this practice properly places major emphasis on selecting the best vapor retarders, it must be recognized that faulty installation techniques can impair vapor retarder performance. The effectiveness of installation or application techniques in obtaining design water vapor transmission (WVT) performance must be considered in the selection of retarder materials.

4.3.2 As an example of the evaluation required, it may be impractical to specify a lower "as installed" value, because difficulties of field application often will preclude "as installed" attainment of the inherent WVT values of the vapor retarder materials used. The designer could approach this requirement by selecting a membrane retarder material that has a lower permeance manufactured in 5-ft (1.5-m) width or a sheet material 20 ft (6.1 m) wide having a higher permeance. These alternatives may be approximately equivalent on an installed basis since the wider material has fewer seams and joints.

4.3.3 For another example, when selecting mastic or coating retarder materials, the choice of a product having a permeance value somewhat higher than the lowest obtainable might be

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[1] This practice is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.33 on Insulation Finishes and Moisture.

Current edition approved Nov. 1, 2003. Published December 2003. Originally approved in 1973. Last previous edition approved in 2002 as C 755 – 02.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

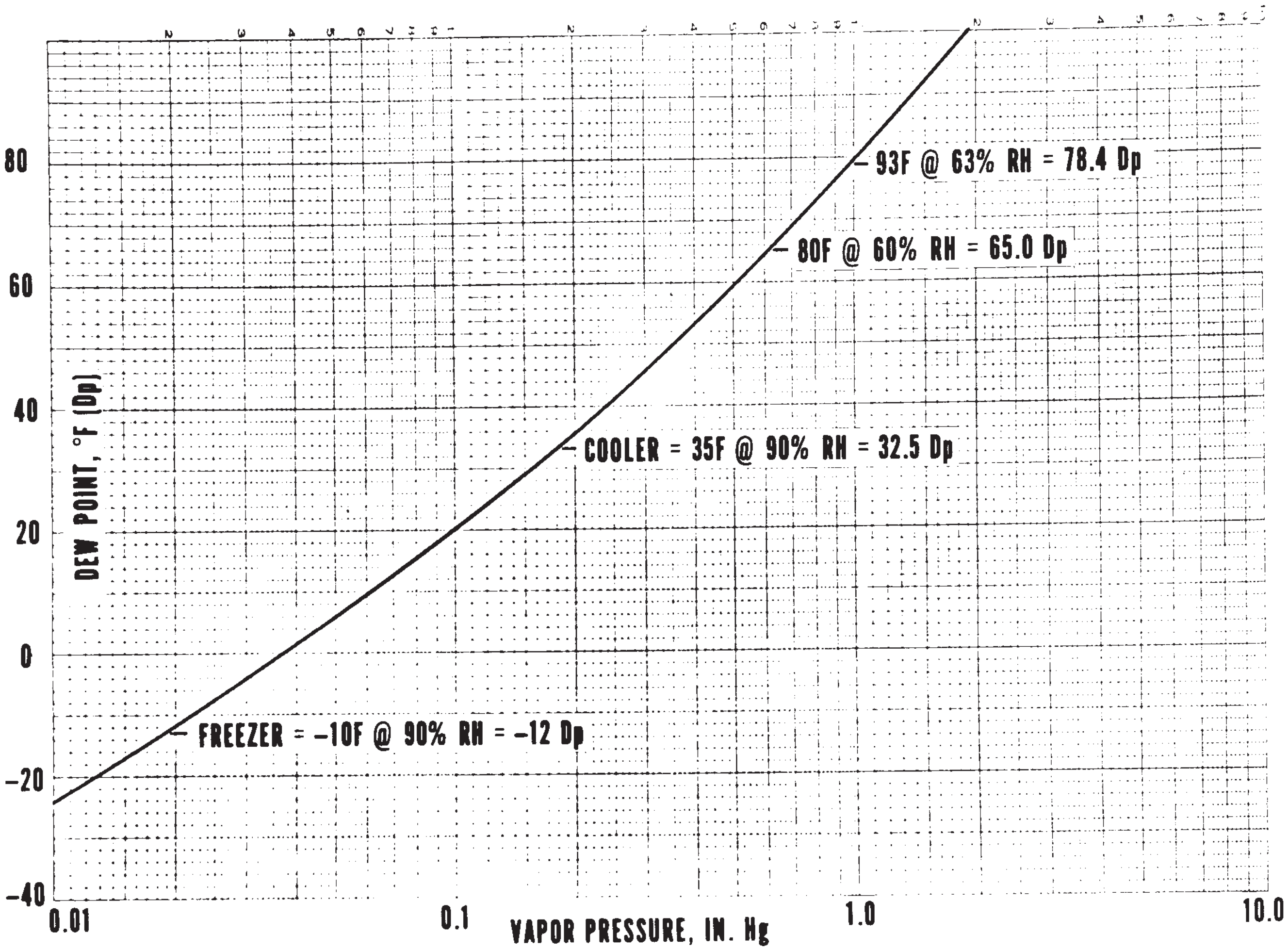

FIG. 1 Dew Point (Dp) Relation to Water Vapor Pressure

justified on the basis of its easier application techniques, thus ensuring "as installed" system attainment of the specified permeance. The permeance of the substrate and its effects on the application of the retarder material must also be considered in this case.

5. Factors to Be Considered in Choosing Water Vapor Retarders

5.1 *Water Vapor Pressure Difference* is the difference in the pressure exerted on each side of an insulation system or insulated structure that is due to the temperature and moisture content of the air on each side of the insulated system or structure. This pressure difference determines the direction and magnitude of the driving force for the diffusion of the water vapor through the insulated system or structure. In general, for a given permeable structure, the greater the water vapor pressure difference, the greater the rate of diffusion. Water vapor pressure differences for specific conditions can be calculated by numerical methods or from psychrometric tables showing thermodynamic properties of water at saturation.

5.1.1 Fig. 1 shows the variation of dew-point temperature with water vapor pressure.

5.1.2 Fig. 2 illustrates the magnitude of water vapor pressure differences for four ambient air conditions and cold-side operating temperatures between +40 and −40°F (+4.4 and −40°C).

5.1.3 At a stated temperature the water vapor pressure is proportional to relative humidity but at a stated relative humidity the vapor pressure is not proportional to temperature.

5.1.4 Outdoor design conditions vary greatly depending upon geographic location and season and can have a substantial impact on system design requirements. It is therefore necessary to calculate the actual conditions rather than rely on estimates. As an example, consider the cold-storage application shown in Table 1. The water vapor pressure difference for the facility located in Biloxi, MS is 0.96 in. Hg as compared to a 0.001 in. Hg pressure difference if the facility was located in International Falls, MN. In the United States the design dew point temperature seldom exceeds 75°F (24°C) **(16)**.[3]

5.1.5 The expected vapor pressure difference is a very important factor that must be based on realistic design data (not estimated) to determine vapor retarder requirements.

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[3] The boldface numbers in parentheses refer to the list of references at the end of this practice.

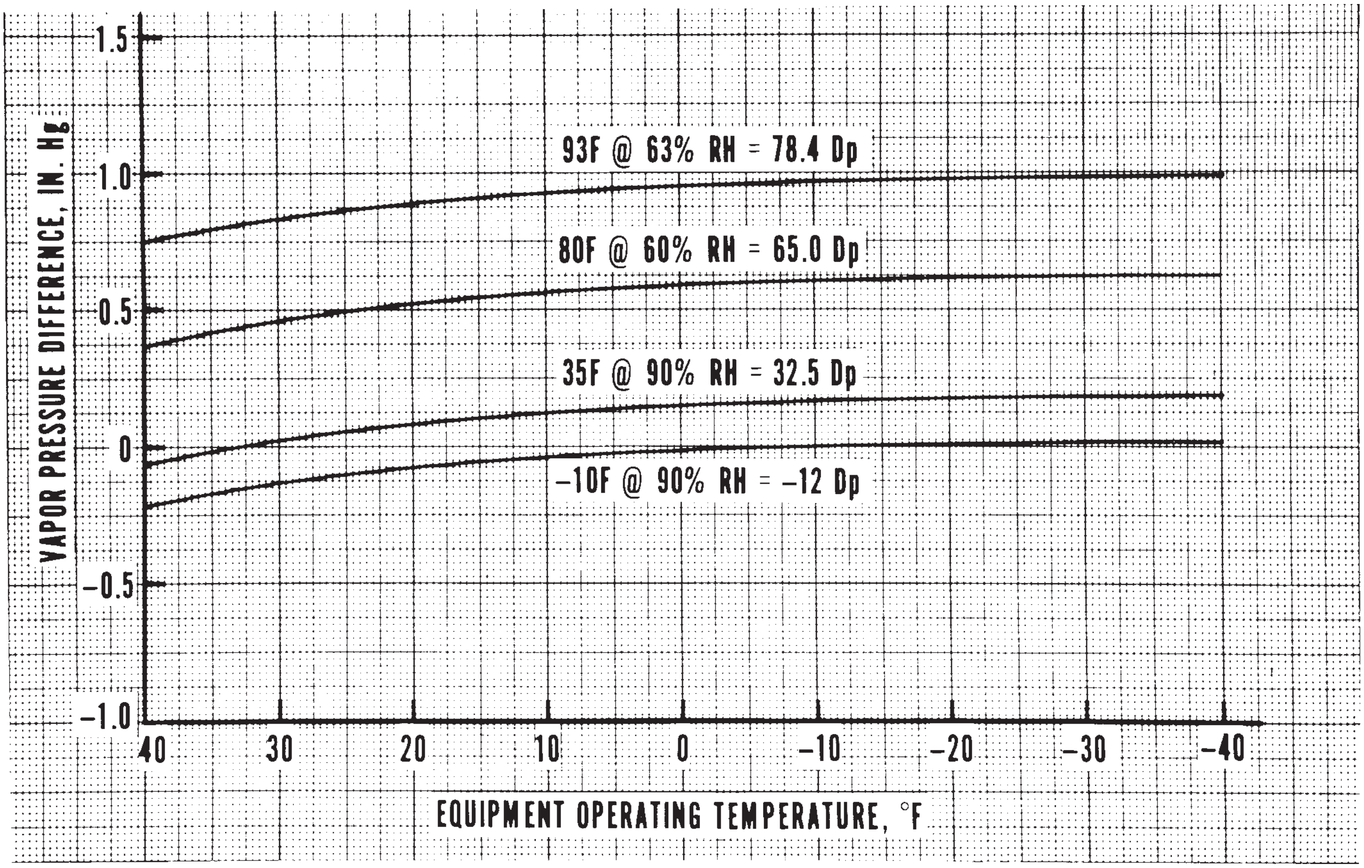

FIG. 2 Magnitude of Water Vapor Pressure Difference for Selected Conditions (Derived from Fig. 1)

TABLE 1 Cold Storage Example

Location	Biloxi, MS	International Falls, MN
Season	Summer	Winter
Outside Design Conditions		
Temperature , °F (°C)	93 (34)	-35 (-37)
Relative Humidity, %	63	67
Dew Point Temperature, °F (°C)	78.4 (26)	-42 (-41)
Water Vapor Pressure in. Hg	.9795	.003
Inside Design Conditions		
Temperature, °F (°C)	-10	-10
Relative Humidity, %	90	90
Water Vapor Pressure in. Hg	.02	.02
System Design Conditions		
Water Vapor Pressure Difference in. Hg	0.9795	0.001
Direction of Diffusion	From outside	From inside

5.2 *Service Conditions*—The direction and magnitude of water vapor flow are established by the range of ambient atmospheric and design service conditions. These conditions normally will cause vapor flow to be variable in magnitude, and either unidirectional or reversible.

5.2.1 Unidirectional flow exists where the water vapor pressure is constantly higher on one side of the system. With buildings operated for cold storage or frozen food storage, the summer outdoor air conditions will usually determine vapor retarder requirements, with retarder placement on the outdoor (warmer) side of the insulation. In heating only buildings for human occupancy, the winter outdoor air conditions would require retarder placement on the indoor (warmer) side of the insulation. In cooling only buildings for human occupancy (that is, tropic and subtropic locations), the summer outside air conditions would require retarder placement on the outdoor (warmer) side.

5.2.2 Reversible flow can occur where the vapor pressure may be higher on either side of the system, changing usually because of seasonal variations. The inside temperature and vapor pressure of a refrigerated structure may be below the outside temperature and vapor pressure at times, and above the outside temperature and vapor pressure at other times. Cooler rooms with operating temperatures in the range from 35 to 45°F (2 to 7°C) at 90 % relative humidity and located in northern latitudes will experience an outward vapor flow in winter and an inward flow in summer. This reversing vapor flow requires special design consideration.

5.3 *Properties of Insulating Materials with Respect to Moisture*—Insulating materials permeable to water vapor will allow moisture to diffuse through at a rate defined by its permeance and exposure. The rate of movement is inversely proportional to the vapor flow resistance in the vapor path. Insulation having low permeance and vapor-tight joints may act as a vapor retarder.

5.3.1 If condensation of water occurs within the insulation its thermal properties can be significantly affected where wetted. Liquid water resulting from condensation has a thermal conductivity some fifteen times greater than that of a typical low-temperature insulation. Ice conductivity is nearly four times that of water. Condensation reduces the thermal effectiveness of the insulation in the zone where it occurs, but if the zone is thin and perpendicular to the heat flow path, the reduction is not extreme. Water or ice in insulation joints that are parallel to the heat flow path provide higher conductance paths with consequent increased heat flow. Generally, hygroscopic moisture in insulation can be disregarded.

5.3.2 Thermal insulation materials range in permeability from essentially 0 perm-in. to greater than 100 perm-in. Because insulation is supplied in pieces of various size and thickness, vapor diffusion through joints must be considered in the permeance of the materials as applied. The effect of temperature changes on dimensions and other physical characteristics of all materials of the assembly must be considered as it relates to vapor flow into the joints and into the insulation.

5.4 *Properties of Boundary or Finish Materials at the Cold Side of Insulation*—When a vapor pressure gradient exists the lower vapor pressure value usually will be on the lower temperature side of the system, but not always. (There are few exceptions, but these must be considered as special cases.) The finish on the cold side of the insulation-enclosing refrigerated spaces should have high permeance relative to that of the warm side construction, so that water vapor penetrating the system can flow through the insulation system without condensing. This moisture should be free to move to the refrigerating surfaces where it is removed as condensate. When the cold side permeance is zero, as with insulated cold piping, water vapor that enters the insulation system usually will condense within the assembly and remain as an accumulation of water, frost, or ice.

5.5 *Effect of Air Leakage*—Water vapor can be transported readily as a component of air movement into and out of an air-permeable insulation system. This fact must be taken into account in the design and construction of any system in which moisture control is a requirement. The quantity of water vapor that can be transported by air leakage through cracks or air-permeable construction can easily be several times greater than that which occurs by vapor diffusion alone.

5.5.1 Air movement occurs as a result of air pressure differences. In insulated structures these may be due to wind action, buoyancy forces due to temperature difference between interconnected spaces, volume changes due to fluctuations in temperature and barometric pressure, and the operation of mechanical air supply or exhaust systems. Air leakage occurs through openings or through air-permeable construction across which the air pressure differences occur. Water vapor in air flowing from a warm humidified region to a colder zone in an insulation system will condense in the same way as water vapor moving only by diffusion.

5.5.2 If there is no opportunity for dilution with air at lower vapor pressure along the flow path, there will be no vapor pressure gradient. Condensation may occur when the air stream passes through a region in the insulation system where the temperature is equal to or lower than the dew point of the warm region of origin. The airflow may be from a warm region on one side of the system through to a cold region on the other side, or it may consist of recirculation between interconnected air spaces at different temperatures forming only a part of the system. Sufficient airflow rate could virtually eliminate the temperature gradient through the insulation.

5.5.3 When air flows from a cold region of low vapor pressure through the system to the warm side there will be a drying effect along the flow path; the accompanying lowering of temperatures along the flow path, if significant, may be undesirable.

5.5.4 In any insulation system where there is a possibility of condensation due to air leakage, the designer should attempt to ensure that there is a continuous unbroken air barrier on the warm side of the insulation. Often this can be provided by the vapor retarder system, but sometimes it can best be provided by a separate element. Particular attention should be given to providing airtightness at discontinuities in the system, such as at intersections of walls, roofs and floors, at the boundaries of structural elements forming part of an enclosure, and around window and service openings. The insulation system should be designed so that it is practical to obtain a continuous air barrier under the conditions that will prevail on the job site, keeping in mind the problem of ensuring good workmanship.

5.5.5 Recirculation of air between spaces on the cold side of the insulation and a region of low vapor pressure (usually on the cold side of the insulation system) can be utilized advantageously to maintain continuity of vapor flow, whether due to diffusion or air leakage, and thus to avoid condensation. This will often be the only practical approach to the control of condensation and maintenance of dry conditions within the system. In thus venting the insulation system, whether by natural or mechanical means, care must be taken to avoid adverse thermal effects.

5.6 *Other Factors*—Other physical properties of retarder material, insulations, and structures that are not within the scope of this practice may affect choice of barrier. These include such properties as combustibility, compatibility of system components, damage resistance, and surface roughness.

6. Fundamental Design Principles of Vapor Control

6.1 *Moisture Blocking Design*—The moisture blocking principle is applied in a design wherein the passage of water vapor into the insulation is eliminated or minimized to an insignificant level. In such a design, unless a totally impermeable vapor retarding system can be provided, condensation will occur in the system eventually, probably limiting service life. It is applicable in cases of predominantly or exclusively unidirectional vapor flow. The design must incorporate the following:

6.1.1 A vapor retarder with suitably low permeance.

6.1.2 A joint and seam sealing system which maintains vapor retarding system integrity.

6.1.3 Accommodation for future damage repair, joint and seam resealing, and reclosing after maintenance.

6.2 *Flow-Through Design*—The flow-through principle is limited to essentially unidirectional vapor flow in installations where any water vapor that diffuses into the insulation system is permitted to pass through without significant accumulation. This concept is acceptable only:

6.2.1 Where vapor can escape beyond the cold side of the system, or

6.2.2 Where vapor cannot so escape it may continuously be purged out, or

6.2.3 Where provision is made to collect it as condensation and to remove it periodically.

6.3 *Moisture-Storage Design*:

6.3.1 Thus far the discussion has dealt with methods of avoiding any condensation. In many cases, however, some condensation can be tolerated, the amount depending on the water-holding capacity or water tolerance of a particular construction under particular conditions of use. The moisture-storage principle permits accumulation of water vapor in the insulation system but at a rate designed to prevent harmful effects. This concept is acceptable when:

6.3.1.1 Unidirectional vapor flow occurs, but during severe seasonal conditions, accumulations build up, which, in less severe (compensating seasonal) conditions are adequately expelled to the low vapor-pressure side.

6.3.1.2 Reverse-flow conditions regularly occur on a seasonal cycle and can occur on a diurnal cycle. Possible design solutions include:

(a) Prevention of reverse flow by flushing the usually colder side with low dew point air. This procedure requires a supply of conditioned air and means for its adequate distribution in passages.

(b) Limitation of the magnitude of one reversed flow cycle to a level of accumulation that can be absorbed safely by system materials without insulation deficiency or damage. System design must enable the substantial removal of the vapor accumulation during the opposite cycle.

(c) Use of an insulation system of such low permeability that an accumulation of vapor during periods of flow reversal is of little importance. Such a design must ensure that the expulsion of the accumulation during the opposite cycle is adequate.

(d) Supplementation of design (*c*) by the use of selected vapor retarders at the boundaries of the insulation.

6.3.2 The moisture storage design practice is in widespread use throughout industry. However, a thorough understanding of a given system is necessary. The effect of moisture accumulation on thermal conductivity, frost action on wet materials, dimensional changes produced by changes in moisture content, and many other factors must be considered before this solution is adopted. References **8, 14, 15,** and **16** contain information on results taken from in-use systems and studies on moisture accumulation in insulation products and systems under varied environmental conditions. A realistic design approach normally assumes there will be some moisture accumulation but desirably within controllable limits to do the job intended.

7. Vapor Retarder Materials

7.1 Vapor retarder materials should be water resistant, puncture resistant, abrasion resistant, tear resistant, fire resistant, noncorrosive, rot and mildew resistant, and of strong tensile strength, in addition to having low permeance.

7.2 *Types*:

7.2.1 *Membrane retarders* are non-structural laminated sheets, plastic films, or metal foils of low permeance. See Specifications C 1136 or C 921 for required physical properties. The vapor retarders may be applied with adhesives or mechanical fasteners. All joints, penetrations, holes and cuts, or any other discontinuities in the vapor retarder must be sealed to maintain system integrity. Proper sealants, methods, and workmanship must be employed to insure overall design vapor resistance of the installed system.

7.2.2 *Mastic and Coating Retarders*:

7.2.2.1 Mastic and coating retarders are field-applied semi-liquid compositions of low permeance after curing. They are intended for application by spraying, brushing, or troweling. The specified thickness must be applied, in one or more continuous coats, and suitable membrane reinforcement may also be required. The system must resist cracking caused by substrate movement. Good workmanship during application is essential to attain design vapor diffusion resistance. See Guide C 647 for properties of mastics and coatings.

7.2.2.2 The permeance of mastics and coatings varies with varying dry thickness, and data showing this relationship for specific products are available from manufacturers. Comparison of permeance values for various mastics and coatings should not be based on wet thickness, but rather on dry thickness (after curing and evaporation of all volatile ingredients).

7.2.3 Structural retarders may be formed from rigid or semirigid materials of low permeability, which form a part of the structure. They include some insulation materials, as well as prefabricated composite units comprising insulation and finish, and metal curtain walls. They require careful sealing of joints and seams.

7.2.4 Caulks and mastics are the typical sealants used in conjunction with vapor retarder materials. Pressure sensitive tapes are also employed as a sealing method. Consideration must be given in the selection of the product most appropriate to the specific application, including installation, ambient, and system operating conditions. Manufacturers' recommendations for proper application must be followed.

7.3 *Test Method and Values*:

7.3.1 Test Methods E 96 is acceptable for determining water vapor transmission of materials.

7.3.1.1 This test method provides isothermal conditions for testing materials by the cup method. In the "dry cup" method, Procedure A (desiccant method), relative humidity inside is approximately 0 % and approximately 50 % on the outside. In the "wet cup" method or water method, the relative humidity inside is approximately 100 % and usually 50 % on the outside. When evaluating WVT data it is preferable to use data obtained by the procedure in which the test conditions approximate the service conditions.

7.3.1.2 This test method does not permit measurement of WVT values under all conditions of temperature and moisture found in service. It does provide values that permit the selection of suitable barrier materials.

7.4 *Recommended Vapor Retarder Practices*—Three design principles of vapor control have been presented: blocking, flow-through and moisture storage. All three systems are used in general practice.

7.4.1 The moisture blocking principle eliminates or minimizes the passage of water vapor into the insulation, utilizing a virtually impermeable vapor retarding system. It is generally used in unidirectional vapor flow.

7.4.2 The intent of the flow-through principle is to eliminate condensation within the insulation system to continuously periodically purge condensation from the insulation system; therefore, this system is used with insulation materials with higher permeability to prevent accumulation of moisture.

7.4.3 The moisture-storage principle allows some accumulation of moisture within the insulation system. This principle is used with lower permeability insulation systems because the rate of accumulation is small.

7.4.4 The rate and quantity of moisture accumulation in insulation used in a given end-use application is a function of the permeability of the insulation and the operating conditions of the application as well as being a function of the vapor retarder materials. Therefore, the vapor retarder requirements necessary to control moisture and ensure successful operation can deviate from indicated theory. A case in point is the practice of using higher permeance vapor retarder systems with lower permeability insulations, whereas the flow-through theory would indicate the opposite. This is where the moisture-storage theory comes into practice. From a practical standpoint, a lower permeability insulation collects and stores less water in case of moisture entry, and, therefore, a higher permeance vapor retarder is tolerable.

7.4.5 Table 2 outlines the general recommended vapor retarder practices presently advocated in various field applications by specifiers and manufacturers. In this table, the recommended permeance for vapor retarder systems is listed for two types of insulations: those with permeabilities of 0.3 to 4.0 perm-in. and those greater than 4.0 perm-in. For insulations having permeabilities of less than 0.3 perm in. where the joints and seams have a permeance equal to or less than that of the insulation, no separately applied vapor retarder is normally recommended except under severe service conditions.

7.4.6 These are general recommendations which should be used in conjunction with the design principles of this practice.

8. Problem Analysis and Vapor Retarder Selection

8.1 *Building Construction*:

8.1.1 Once the vapor pressures on the two sides of the building envelope are known and selection and arrangement of the building materials have been made, the vapor flow calculation is carried out in a manner similar to that used for heat flow. The relation:

Vapor flow (f) $\propto$ (vapor pressure difference/vapor flow resistance)

is similar to that for heat flow. There is, however, one important difference owing to the ability of the vapor to condense. The initial calculation is based on the premise that there is a continuity of flow and that all the vapor entering the envelope on the high vapor pressure side will emerge on the low vapor pressure side. If, on its passage through the building envelope, the vapor is cooled to below the dew point, condensation will occur and the basis of the calculation is upset. Even so, once the plane of condensation has been established the method can be applied to calculate the flow of vapor to it and away from it. The difference between the two gives the accumulation of water within the envelope. The example in X1.1 illustrates the process of calculating the vapor pressure gradient and the manner in which it may be used to avoid condensation problems (**(6)**). These vapor flow calculations can be considered reasonably accurate when the primary mechanism for moisture migration is vapor diffusion and when coefficients are available that define the rate of vapor flow for the material under the conditions of use. When, however, the material is capable of holding substantial quantities of absorbed water, the diffusion approach may be inadequate or even inappropriate, depending on the situation. Nevertheless, these calculations provide the best available basis for improved judgment on condensation control.

8.2 *General Practices for Buildings*—Buildings for human occupancy can be considered subject to cyclic conditions as far as the building insulation is concerned. For non-air-conditioned buildings the winter warm and cold side conditions result in significantly greater vapor pressure differentials than for summer conditions and in an outward direction. Therefore, it is general practice to place the vapor retarder on the side of the insulation facing the interior of the building, with the retarder permeance determined by the winter conditions and building construction. For air conditioned buildings vapor pressure differentials in summer may cause vapor flow in an inward direction. However, in normal wood frame construction, the vapor retarder should still be located on the side of the insulation facing the interior of the building to control vapor flow under the more severe conditions.

8.2.1 In the case of impermeable insulation materials a separate vapor retarder system is not needed on either side

TABLE 2 Recommended Maximum Permeance of Water Vapor Retarders for Blocking Design[A]

Insulation Application	Insulation Permeability Less than 4.0 perm-in.[B]	Insulation Permeability, 4.0 or greater perm-in.[B]
	Vapor Retarder Permeance, perms[A]	Vapor Retarder Permeance, perms1
Wall (residential)	1.0	1.0
Underslab (residential and commercial)	1.0	0.4
Roof deck	1.0	0.4[C]
Pipe and vessels (33 to Ambient (1°C to Ambient))	0.05	0.05
Pipe and vessels (−40 to 32°F (−40 to 0°C))	0.02	0.02
Ducts (39°F and below (4°C and below))	1.0	0.03[C]
Ducts (40°F to Ambient (4°C to Ambient))	0.02	0.02
Metal buildings	1.0	1.0[C]
Cold storage	0.1	0.1

[A] Water vapor permeance of the vapor retarder system in perms when tested in accordance with Test Methods E 96.

[B] Water vapor permeability of the insulation material when tested in accordance with Test Methods E 96, Desiccant Method at 73.4°F (23°C) at 50 % RH.

[C] Subject to climatic and service conditions.

provided that insulation joints (if any) are made impermeable by suitable sealing methods.

8.2.2 In most residential construction where separate vapor retarder systems are used provision must be made for moisture that does pass through the retarder into the insulation to continue on to the outside air. This requires some effective method of venting moist air to the outside.

8.3 *Cold Storage Construction*:

8.3.1 For a cold storage warehouse held continuously below 0°F (−18°C) the flow-through design may be utilized to supplement an effective vapor retarder. Calculation example 1 is outlined in X1.2 **(14)**.

8.3.2 For vapor transfer through a cold-room wall the calculation example 2 is outlined in X1.3.

8.3.3 *General Practices for Cold-Storage Construction*—Cold-storage facilities require detailed consideration of all components of the building and insulation installation, as influenced by the outdoor and inside operating conditions, for proper vapor retarder design. Freezers generally operate at 0°F (−18°C) and below. It is a rare case in the United States where winter conditions outside of a freezer will result in reversal of vapor pressure difference. This reverse difference will generally be small and of short enough duration that for design purposes normal vapor flow is considered to be essentially unidirectional.

8.3.3.1 Coolers generally operate in the range from 35 to 45°F (2 to 7°C) and approximately 90 % relative humidity. In the more southerly latitudes the year-round outdoor conditions allow design on the basis of essentially steady unidirectional vapor flow. However, in more northerly latitudes long periods of low winter outdoor temperature with a corresponding appreciable reversal in the direction of vapor flow from summer conditions, require special consideration of insulation system materials and their permeances. In combination with other vapor resistances in the overall building and insulation construction, this flow reversal will affect vapor retarder design for control of vapor flow and minimization of condensation within the insulation.

8.3.3.2 The avoidance of low cold side permeance should be given special attention in cold storage freezers. Concern with cleanliness or cleanability of interior finishes requires the use of plaster, tile, or other materials that have medium to high permeance. It is desirable that insulations used with such finishes should have permeance lower than that of the finish so that the finish does not form a vapor dam. If such finishes must be used with high permeance insulations, a highly effective vapor retarder/air barrier is required on the warm side. Alternatively, consideration should be given to providing space between the insulation and the interior finish for venting to the interior space, or purging with a low dew-point air supply. This practice requires expert advice.

8.4 *Industrial Low-Temperature Construction*—Industrial installations (pipes and vessels) are usually steady-state (unidirectional vapor flow) and can range downward in temperature considerably below 0°F (−18°C). The metal of piping and vessels is an absolute barrier on the cold side of the insulation and poses a significant problem, particularly for steady-state (or continuous temperature) operation. With the metal as an absolute barrier there will be no place for the migrating moisture to go, and it will therefore be trapped.

8.4.1 With permeable insulation and less than a perfect vapor retarder, the eventual result is that a significant percentage of the void space within the insulation will contain water, both water and ice, or ice alone, depending on whether the operating temperature is above 32°F (0°C) or how far it may be below 32°F.

8.4.2 The rate at which water or ice, or both, accumulate depends upon the permeance of the retarder system and the specific nature of insulation material as applied. The expected life and operating cost of the low-temperature equipment should determine the economic justification for a given insulation application.

8.4.3 However, the exact mechanisms of vapor flow, condensation, and ice formation within insulation under the condition of an absolute cold side barrier are still to be determined.

8.4.4 Obviously, vapor retarder selection must start with the lowest obtainable permeance. The system of insulation with vapor retarder must be substantial enough to resist rugged industrial environments. Careful retarder application is always of first importance, particularly with insulation materials of relatively high permeance. With insulations of very low permeance it is important that all joints be staggered and sealed with low permeance sealants in the joints. For very low service temperatures, or where long service life is required, it may be justified to use multiple water vapor retarders, inert gas (nitrogen) purging coupled with permeable insulation, or a vapor-impermeable metal barrier system.

8.4.5 Low-temperature operation in some processes may require periodic purging at elevated temperature, in which case the insulation and vapor retarder combination must be adequate for the low-temperature operation, while withstanding the pressure increase during the purging operation.

8.4.6 On the other hand, where the operation reverses with the season, such as chilled water for summer air conditioning and hot water for winter heating, the vapor-retarder requirements may be less stringent (as vapor flow can reverse with temperature reversal) if operating costs and equipment are adequate.

9. Keywords

9.1 design; materials; selection; thermal insulation; vapor retarders; water vapor retarders

APPENDIX

(Nonmandatory Information)

X1. PROBLEM ANALYSIS

X1.1 Building Construction

X1.1.1 *Calculation Example*—A heated building consisting of 4-in. (101-mm) reinforced concrete with an inside finish of ¾-in. (19.05-mm) plaster over 1 in. (25 mm) of foamed plastic insulation that separates an internal environment of 73°F (23°C) and 35 % relative humidity from an outside environment of 0°F (−18°C) and 80 % relative humidity. Table X1.1 lists the appropriate design data. The actual vapor pressures are, respectively, $0.818 \times 0.35 = 0.286$ in. Hg (968 Pa) and $0.038 \times 0.8 = 0.030$ in. Hg (102 Pa) and the total pressure difference is 0.256 in. Hg (865 Pa). This pressure difference must be apportioned among the various components of the envelope in proportion to their resistance to vapor flow. These calculations are tabulated in Table X1.1 and the resulting vapor pressure gradient for continuity of flow is plotted in Fig. X1.1*a* as curve p_c. Up to this point the method is the same as that for the arithmetical determination of temperature gradient of Fig. X1.1*b*. The permeability of foamed plastic insulations varies between 0.75 and 5.0 perm-in. depending on the type.

X1.1.1.1 To discover whether condensation will take place, the temperature gradient must be determined so that the corresponding saturation vapor pressure curve can be obtained. This is tabulated in Table X1.1 and the saturation vapor pressure curve plotted in Fig. X1.1*a* as curve p_s. The values for the temperature gradient have been rounded to the nearest degree, although no greater accuracy than two decimal places has been retained in the example for clarity. Note that a uniform drop in temperature through a material gives a cured saturation vapor pressure line. It may be seen that the p_s curve is above the p_c curve on the warm side of the wall, crosses to below it in the foamed plastic, and finally rises above the p_c curve near the cold face of the concrete. As the maximum amount of water that can exist as vapor is set by the temperature; which also establishes the saturation vapor pressure, the actual vapor pressure curve can never be above the saturation vapor pressure curve. Thus, when the p_c curve lies above the p_s curve, condensation will take place and a discontinuity of flow will exist.

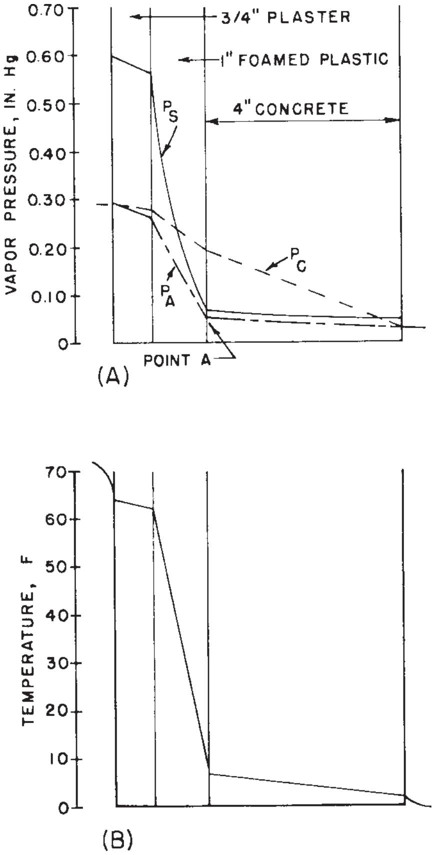

FIG. X1.1 Vapor Pressure and Temperature Gradients of Building Wall (6)

X1.1.1.2 Under equilibrium conditions condensation does not take place at the point where the two curves cross; it can usually be assumed to occur at the next interface. The actual vapor pressure gradient between the inside and Point A (Fig. X1.1*a*) and between Point A and the outside can now be determined by calculation, using the saturation vapor pressure

TABLE X1.1 Tabulated Vapor and Temperature Calculations Used in X1.1.2 (6)

		Air Film		Plaster		Insulation		Concrete		Air Film		Total
Thickness, *n*		...		¾		1		4				
Permeance, *M*		...		15		...		...		...		
Permeability,µ		...		...		1.6		3.2		...		
Vapor resistance, $1/M \cdot n/\mu$		0		0.7		0.62		1.25		0		1.94
Vapor pressure drop for continuity		0		0.009		0.082		0.165		0		0.256
Vapor pressure for continuity, p_c	0.286		0.286		0.277		0.195		0.030		0.030	
Thermal conductance, *C*		1.46		6.66		...		...		6.00		
Thermal conductivity, *k*		...		...		0.25		12.0		...		
Thermal resistance, $1/C \cdot n/k$		0.68		0.15		4.00		0.33		0.17		5.33
Temperature drop		9		2		55		5		2		73
Temperature	73		64		62		7		2		0	
Saturation vapor pressure, p_s	0.818		0.601		0.560		0.054		0.042		0.038	
Actual vapor pressure, p_a	0.286		0.286		0.264		0.054		0.030		0.030	

of 0.054 in. Hg (183 Pa) at Point A. This calculation is tabulated in Table X1.1 and plotted in Fig. X1.1*a* as curve p_a.

The vapor flow-to-Point A is

$$(0.286 - 0.054)/(0.07 + 0.62) = 0.34 \text{ grain/h·ft}^2,$$

and that from Point A

$$(0.054 - 0.030)/1.25 = 0.02 \text{ grain/h·ft}^2,$$

giving a condensation rate of

$$0.34 - 0.02 = 0.32 \text{ grain/h·ft}^2$$

X1.1.2 *Vapor Retarder Selection*—To avoid condensation the designer must arrange so that the saturation vapor pressure curve always lies above the vapor pressure curve for continuity of flow. In broad terms this can be achieved by adjusting the vapor flow resistances, which will change the p_c curve; by adjusting the thermal resistances, which will change the p_s curve; or by a combination of the two.

X1.1.2.1 The initial reaction is to change the vapor flow resistances by adding a vapor retarder on the warm side. In Example 1 the total resistance required to prevent condensation can be calculated by dividing the vapor pressure drop from the warm side to Point A (Fig. X1.1*a*) by the rate of flow from Point A to the outside, giving 11.6 units of resistance. The plaster and the insulation provide 0.69 units of resistance, leaving 10.9 units to be provided by the vapor retarder. Thus, the vapor retarder should not have a permeance greater than 1/10.9 = 0.09 perm. Adding such a vapor retarder between the plaster and the insulation will produce the vapor pressure curve shown in Fig. X1.2*a* as p_c. It will not materially alter the temperature gradient or the p_s curve.

X1.1.2.2 The installation of such a vapor retarder, which would have to be of 4-mil (0.10 mm) polyethylene or better, raises various practical problems. This leads one to consider the alternative method of changing the p_c curve: reduction of the vapor flow resistance between Point A (Fig. X1.1*a*) and the outside. The maximum resistance tolerable is given by the quotient of the pressure drop to the outside and the rate of flow from the inside to Point A, that is, 0.024/0.34 = 0.071 unit of resistance, giving a required permeance of at least 14 perms. This can only be achieved by replacing the concrete with a structural member of the required permeability.

X1.1.2.3 The second general method of attacking the problem is to raise the p_s curve by raising the temperature on the warm side of the concrete. In this instance the concrete provides an adequate retarder. Removing insulation from the warm side of the wall will have this effect, but with this particular design condensation will still take place (Fig. X1.2*b*). In any case, the reduction in insulation will increase the heat loss through the wall and reduce the inside surface temperature, neither of which may be acceptable.

X1.1.2.4 Alternatively, additional insulation can be added on the outside, but the same effect can be achieved by simply reversing the relative positions of the concrete and the insulation. This results in a most satisfactory wall design (Fig. X1.2*c*), but requires an exterior weathering surface to protect the insulation. Such a surface should either have a high permeance or be designed as an open rain screen. Although for the sake of clarity the effects of adjusting the vapor resistance and the thermal resistance of the wall have been discussed separately, in practice it is usual to adjust both to obtain the most satisfactory overall solution.

X1.1.2.5 This example shows that although a component of the wall may be selected initially to fulfill a primary function such as structural strength or thermal resistance, it may also have an effect on the vapor and thermal properties of the wall. In particular, the vapor resistance of the insulation can have a significant effect on the proper location of the insulation in the wall.

X1.2 Cold Storage Construction (14)

X1.2.1 Assume a monthly average weather condition of 80°F (27°C) and 50 % relative humidity which represents 59.8°F (15.4°C) dew point and 0.517 in. Hg (1.75 kPa) vapor pressure. With a single-wall insulation material at an appropriate thickness for an operating temperature of −30°F (−34°C) the designer can determine the limiting vapor pressure gradient p_s (saturation curve) for the design (Fig. X1.3).

X1.2.2 Vapor pressure is plotted against the temperature range from 80 to −30°F (27 to −34°C) coincident with the total wall insulation thickness (representing the temperature gradient and dew-point limit through the north or coolest wall).

X1.2.3 The minimum slope of the limiting vapor pressure gradient is at or near the cold side, indicating the critical zone for vapor flow. In this coolest zone within the insulation, assume 100 % relative humidity, and let: S_2 = slope of limiting pressure gradient, in. Hg/in., and M_2 = permeability of the cold side insulation, perm-in. Then M_2S_2 = design cold side vapor flow, grains/h·ft^2.

X1.2.4 If a single-wall insulation material is used, and there is no other obstruction or condensation in the vapor path, the

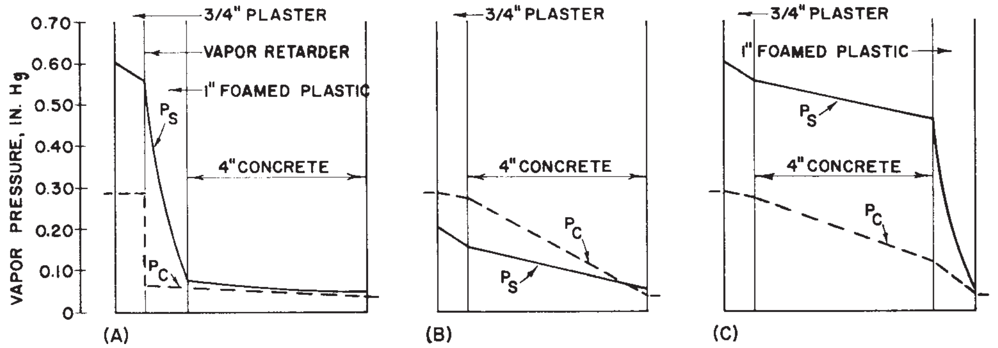

FIG. X1.2 Vapor Pressure Gradients of Modified Building Wall (6)

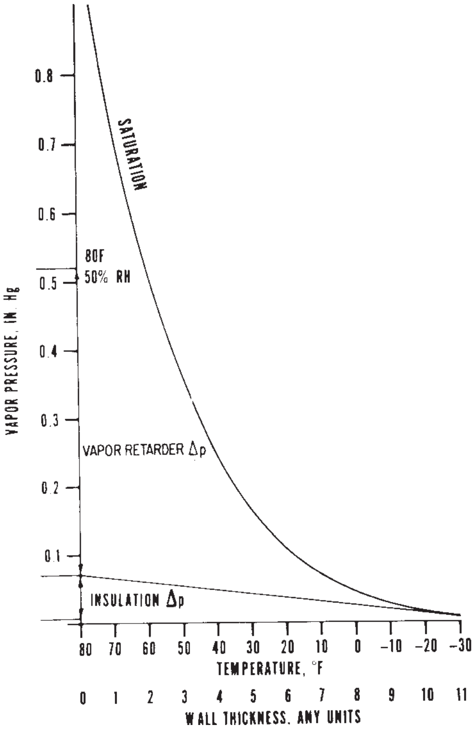

FIG. X1.3 Limiting Vapor Pressure Gradient Plot (14)

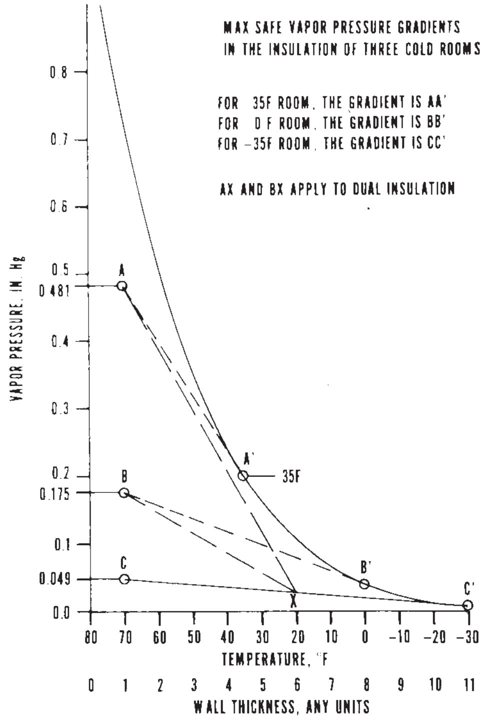

FIG. X1.4 Saturation Vapor Pressure vs. Temperature (14)

normal vapor pressure gradient through the total insulation thickness is substantially linear. It can be constructed as a straight line tangent to (but not crossing) the saturation curve at −30°F (−34°C), and its slope is S_2, as in the coldest inch of insulation.

X1.2.5 This linear gradient defines the allowable vapor pressure, P_w, on the warm side of the insulation, and it is so limited by the vapor retarder at the design weather conditions, or

$$P_w = P_c + LS_2$$

where:

P_c = the vapor pressure on the cold side, and

L = the total thickness of insulation. The pressure drop across the vapor retarder is $(P_1 - P_w)$.

X1.2.6 Since the vapor flow is limited by the retarder to M_2S_2 (the same as the cold side flow), the retarder permeance must be:

$$M = M_2S_2/(P_1 - P_w)$$

X1.3 Vapor Transfer Through a Cold-Room Wall

X1.3.1 For simplicity, a wall that is a single slab of insulation with no covering on either side will be considered first. If its thermal conductivity and vapor permeability are everywhere constant, the gradients of temperature and vapor pressure are both linear. Such conditions are the basis of Fig. X1.4 for three cold room walls. The linear relation of temperature and thickness is indicated by their parallel scales, and the thickness unit may be an inch or any other.

X1.3.2 The vapor pressure gradient *AA′* is a linear function of thickness. It ends at 35°F (2°C), the cold-room temperature, and 100 % relative humidity, the highest possible room condition. Being tangent to the saturation curve, it is the steepest straight line that can be drawn without crossing the curve, which would indicate condensation. On the warm side of the wall at 70°F (21°C), the gradient touches 0.481 in. Hg (1.6290 kPa), the highest safe surface vapor pressure, corresponding to 65 % relative humidity. At this exterior condition, no vapor retarder is required and neither thickness nor permeability of the insulation are factors in the matter of condensation, although they determine the rate of vapor inflow and affect the latent heat load. It may be noted that a lower temperature, 60°F (16°C) on the exterior of the same or any homogeneous wall would allow only 0.401 in. Hg (1.358 kPa) or 77 % relative humidity.

X1.3.3 Likewise, the maximum vapor pressure gradient for a room at 0°F (−18°C) is *BB′*, and the vapor pressure on the exterior surface at 70°F (21°C) may not exceed 0.175 in. Hg (0.59 kPa), or 24 % relative humidity. If the exposure is 65 % relative humidity, a vapor retarder must reduce the pressure from *A* to *B*. *Flow balance* requires that the vapor flow in a series system, with no condensation, be everywhere the same, or

$$\Delta P_1M_1 = P_2M_2 \qquad \text{(X1.1)}$$

where:

M = permeance, and

ΔP = vapor pressure difference, and Subscripts 1 and 2 apply to the retarder insulation.

In this example, the maximum retarder permeance

$$M_1 = \Delta P_2M_2/\Delta P_1 = 0.45\ M_2 \qquad \text{(X1.2)}$$

X1.3.4 Thus, the required retarder permeance is proportional to the insulation permeance, or to its permeability for a given thickness. In this example, utilizing the flow-through principle, which allows no accumulation of water in the insulation system, for 7 in. (178 mm) of 1 perm-in. insulation, the retarder permeance must be not greater than:

$$0.45/7 = 0.064 \text{ perm} \tag{X1.3}$$

For a room at −30°F (−34°C) the maximum gradient is *CC′* and a similar calculation determines the retarder limit as 0.0097 perm if a 10-in. (254-mm) thickness of 1 perm-in. insulation is used. With no retarder on this wall, the vapor pressure gradient would be *AA′B′C′*, starting as a straight line and curving along the path *A′B′C′* within the colder two-thirds of the insulation thickness, where most of the entering vapor would condense.

X1.3.5 This analysis assumes a constant exterior vapor pressure, which is unlikely, especially when the exterior is exposed to weather. Although temporary condensation resulting from a peak of vapor pressure will ultimately be dissipated in better weather, it is recommended that the design vapor pressure be the maximum monthly average, if known. If estimated, it should include a safety margin (**(16)**).

X1.3.6 In buildings where the vapor flow is predominately from the inside-out, special consideration should be given to the roof and walls which are faced with vapor impermeable materials. Roofing is usually a good vapor retarder and if it forms the cold side of the construction moisture will condense under it and cause problems. Provisions should be made to prevent the moisture from entering the roof construction and there should be venting provided directly under the roofing.

X1.4 Nonlinear Gradients

X1.4.1 The straight-line vapor pressure gradients shown in Fig. X1.4 require uniform thermal conductivity and uniform vapor permeability throughout the insulation. However, on the cold side of the wall, the dry conductivity may be as much as 10 % lower, and the permeability of certain materials may range up to 50 % higher than on the warm side. Each of these factors tends to improve the safety from condensation, as follows:

X1.4.2 With lower conductivity of the insulation slab on its cold side, the temperature gradient will be slightly arched, and the saturation pressure curve, plotted against thickness, will have less curvature than shown in Fig. X1.4.

X1.4.3 Higher vapor permeability on the cold side, corresponding to the high relative humidity in that region, causes a curved pressure gradient that sags in the middle, reducing the relative humidity along the vapor path and widening the gap of safety under the saturation pressure curve. Furthermore, the cold side change increases the permeance of the slab, and as indicated in Eq X1.1, a proportional increase of retarder permeance is allowable. However, these departures from the basic analysis of Fig. X1.4 are rarely large enough to be exploited in design. They help to offset defects in assembly, but do not justify them.

X1.5 Dual Insulation in a Cold Room Wall

X1.5.1 Condensation can be avoided by using two insulations, one of low permeability on the warm side and another of higher permeability on the cold side of a wall without lining. This method may be essential at very low temperatures, where the insulation must be thick and the retarder requirement stringent, as indicated by the vapor pressure gradient *ACC′* in Fig. X1.4.

X1.5.2 Another gradient, such as *AXC′* is also safe and requires no vapor retarder. Two insulations, each 5 in. (127 mm) thick, with the same thermal conductivity, are chosen. If their permeability values are “*w*” perm-inch on the warm side, and “*c*” perm-inch on the cold side, their ratio may be calculated by Eq X1.1 as follows:

$$(0.481 - 0.028)\, w/5 = (0.028 - 0.007)\, c/5, \tag{X1.4}$$

or

$$c/w = 22 \tag{X1.5}$$

X1.5.3 Thus, if the warm side insulation has a permeability of 1 perm-in., the cold side permeability should be 22 perm-in., or more. A good assembly of the warm side insulation is essential. If insulation joints are imperfect or air infiltration is possible, a retarder is needed. With a retarder added, the vapor pressure gradient has three segments, such as *ABXC′* for which the ratio $c/w = 7.0$, and the required retarder permeance is 0.096*w*. With 5 in. (127 mm) of 1 perm-in. insulation on the warm side, and 5 in. of 7 perm-in. insulation on the cold side, the vapor retarder permeance must be 0.096 perm, or less. (This permits ten times the required retarder permeance calculated in X1.3.)

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