ABTG
Research Report

Assessment of Water Vapor Control Methods for Modern Insulated Light-Frame Wall Assemblies

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of the American Chemistry Council

Report Written By:

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This research report is based on practical scientific research (literature review, testing, analysis, etc.). This research report complies with the following sections of the building code:

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Finally, this report is considered an "open file" research report. It will be revisited periodically as substantive additional or new information becomes available which adds to or improves the content of this report. Such information from interested parties is welcomed and should be directed to the principle investigator for this work:

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About this Research Report:

Applied Building Technology Group (ABTG) is committed to using sound science and generally accepted engineering practice to develop research supporting the reliable design and installation of foam sheathing. ABTG's work with respect to foam sheathing is provided through a grant by the the Foam Sheathing Committee (FSC) of the American Chemistry Council. Foam sheathing research reports, code compliance documents, educational programs, and best practices can be found at www.continuousinsulation.org.

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Introduction

This research report embodies a comprehensive assessment of the state-of-the-art of water vapor control for modern, code-compliant, light-frame wall assemblies. The primary goal of this effort is to evaluate and reconcile, to the greatest extent possible, existing building science knowledge and practices. An important secondary goal is to support the development of practical and comprehensive water vapor control requirements or recommendations that may be used as a basis to reach various audiences and serve multiple purposes, including building industry education and building code development. Thus, this report is aimed at rational answers to confidently respond to common building industry questions such as: *"How much exterior insulation is required, if any, to provide acceptable performance and minimize moisture accumulation risk in a building envelop assembly with consideration of cavity insulation amount and the water vapor permeance of the interior and exterior material layers?"*

The knowledge base on the topic of water vapor control is vast. While generally agreeing at the level of fundamental building science principles, it can differ substantially in assumptions, analysis methodology, degree of completeness, treatment of material properties and boundary conditions, stringency of performance limit states or criteria, and judgments regarding acceptable or preferred solutions. These uncertainties contribute to confusion in the building design and construction market place regarding appropriate methods or best practices for water vapor control, particularly in view of implementing improved energy code requirements for the insulation of building envelopes. A comprehensive review and evaluation of the state-of-the-art is needed to better understand and resolve these real or perceived uncertainties while also identifying gaps where continual improvements can be pursued with further research.

Moisture control in building envelope assemblies is an integrated design and construction challenge. Integrated design recognizes inter-relationships between variations in climate (outdoor moisture load), methods used to control indoor environment (indoor moisture load), and various materials and methods for constructing building envelopes to serve as an interface between the indoor and outdoor environments. Furthermore, building envelope assemblies can be complex systems and may include multiple permutations of materials and components, each serving one or more functions to varying degrees such as thermal control (e.g., insulation), water vapor control (e.g., vapor retarders), rain water control (e.g., water-resistive barriers, flashing and cladding), air-leakage control (e.g., air barriers), and other structural or non-structural functions. Within the building envelope, these functions often overlap and unavoidably interact from a bulk water and water vapor management perspective. Clearly, the science of integrated design and moisture control is complex. Yet, communication of appropriate solutions to the building industry requires practical simplifications that minimize complexity and confusion while still providing robust answers for reliable outcomes in practice.

This research report strives to address the above challenge by attempting to untangle a vast web of information defining the current state-of-the-art in order to help move it forward and put it more fully and confidently into practice. To achieve this goal, an extensive background section covers fundamental principles and a host of topics relevant to understanding the state-of-the-art of water vapor control. A review of current U.S. and Canadian building code requirements is included. Next, the technical basis of current U.S. and Canadian building code requirements is presented and followed by an evaluation of those requirements by way of comparison to a multitude of data from various studies including actual building monitoring, test hut studies, and hygrothermal modeling efforts. Based on the findings, various improvements to current practices are evaluated and presented. Next, the report is summarized and then conclusions and recommendations are offered for consideration.

Finally, Appendix A compiles the relevant information and findings from this research report to create a comprehensive water vapor control framework in the form of a single table of requirements or recommendations. The framework is intended to represent state-of-the-art guidance for the integrated design and construction of wall assemblies that are resilient to the effects of water vapor (e.g., limiting condensation and mold and ensuring adequate drying potential). In addition, Appendix B addresses the important coordinating link between water vapor control and wall insulation requirements found in modern energy codes.

Background

Water Vapor Control Concepts

Five key factors for successfully integrated solutions to moisture control are: (1) rainwater control, (2) air-leakage control, (3) indoor relative humidity control, (4) construction moisture control, and (5) water vapor control. While all of these factors are important and receive their due attention in this research report, the primary focus herein is in regard to appropriate building envelope strategies for water vapor control, including the specification and location of materials in an assembly relative to their vapor retarder properties and thermal properties. Appropriate water vapor control practices are intended to function in coordination with equally appropriate practices for the other moisture control factors mentioned above.

Commonly recognized design principles for water vapor control can be summarized in two simple concepts that must be kept in reasonable balance to prevent moisture accumulation and damage:

1. Seek to minimize the risk of the assembly getting wet, and
2. Provide a means for an assembly to adequately dry.

At a minimum, the following key material or assembly properties must be considered to achieve a reasonable balance in pursuing the above two goals to avoid unacceptable moisture accumulation and consequences:

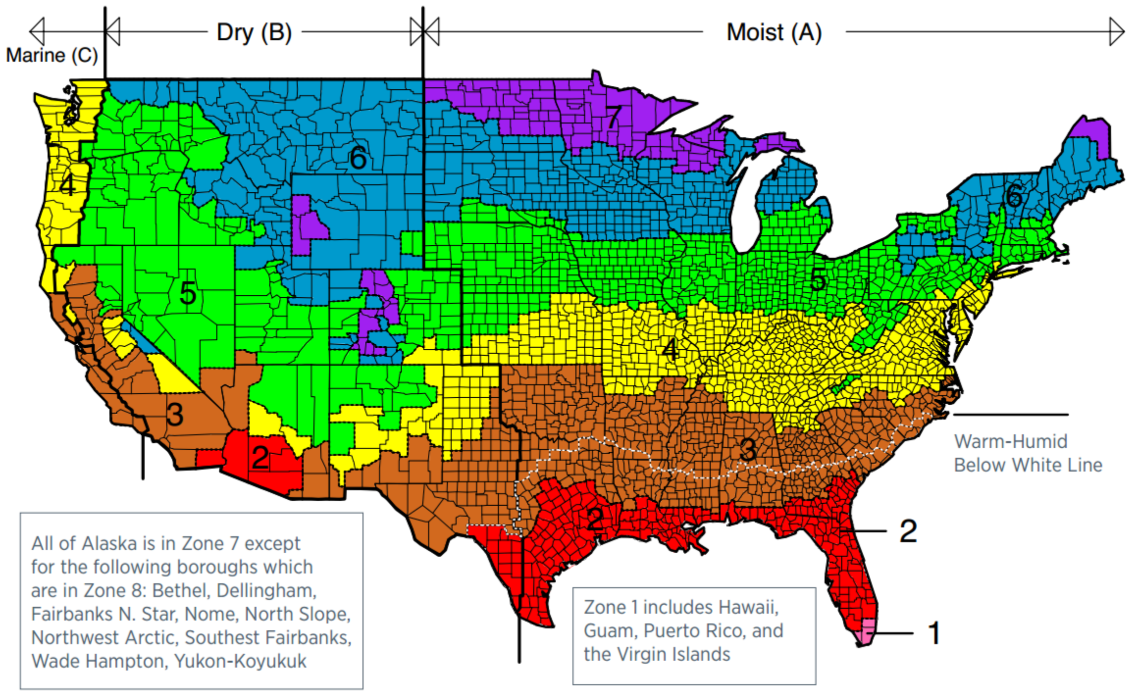
- Water vapor permeance of the interior layers (e.g., vapor retarder, paint, etc.)
- Water vapor permeance of the exterior layers (e.g., sheathing, water-resistive barrier, etc.)
- Cavity insulation R-value and vapor permeance (e.g., vapor-permeable vs. non-permeable cavity insulation options)
- Exterior R-value (e.g., R-value of sheathing, continuous insulation, and siding)

Furthermore, the appropriate balance of the above material properties within an envelope assembly is governed by the outdoor climate (Figure 1) and the indoor environment. For example, high indoor relative humidity levels cause significant outward vapor drives during the coldest months of the winter. Persistently high outdoor humidity levels in warm, humid climates or solar-driven moisture from reservoir claddings (e.g., stone or brick) cause significant inward water vapor drives during the spring and summer. While these factors vary by climate, high indoor relative humidity levels can overwhelm any climate-specific water vapor control strategy for a building envelope; thus, indoor relative humidity control (e.g., ventilation in the winter or dehumidification in the spring/summer) is important for all envelope assembly types and is a crucial determinant of performance as found in a number of case studies and experience (Tsongas, 2009; NAHB-RC, 2004; HIRL, 2014; *ASTM*, 2009a; Glass and TenWolde, 2007).

Two representative and accepted means of design commonly used to execute the above principles and properly balance design parameters to achieve acceptable moisture control performance of envelope assemblies include (*ASTM*, 2009a, *ASTM*, 2009b; BSI, 2002; Straube, 2011):

1. *Permeance Controlled Approach* – Envelope assemblies designed to dry to the exterior in cold climates with a relatively high degree of water vapor resistance on the interior side to prevent excessive moisture accumulation (the reverse applies in warm/humid climates), or
2. *Temperature Controlled Approach* – Envelope assemblies designed to dry to the interior with a sufficient exterior insulation R-value (relative to cavity insulation R-value) to keep the interior of the assembly warm (i.e., low risk of condensation) in the winter. This approach can be appropriately balanced to work in all climates.

Each of these approaches actually uses a combination of means to control moisture in that both methods depend to some degree on temperature control and permeance of materials, but the emphasis differs in each approach; hence the different names given to these two design approaches. These approaches are illustrated in Figure 2.



All of Alaska is in Zone 7 except for the following boroughs which are in Zone 8: Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southest Fairbanks, Wade Hampton, Yukon-Koyukuk

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

TABLE R301.3(2)
INTERNATIONAL CLIMATE ZONE DEFINITIONS

ZONE NUMBER	THERMAL CRITERIA	
	IP Units	SI Units
1	9000 < CDD50°F	5000 < CDD10°C
2	6300 < CDD50°F ≤ 9000	3500 < CDD10°C ≤ 5000
3A and 3B	4500 < CDD50°F ≤ 6300 AND HDD65°F ≤ 5400	2500 < CDD10°C ≤ 3500 AND HDD18°C ≤ 3000
4A and 4B	CDD50°F ≤ 4500 AND HDD65°F ≤ 5400	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000
3C	HDD65°F ≤ 3600	HDD18°C ≤ 2000
4C	3600 < HDD65°F ≤ 5400	2000 < HDD18°C ≤ 3000
5	5400 < HDD65°F ≤ 7200	3000 < HDD18°C ≤ 4000
6	7200 < HDD65°F ≤ 9000	4000 < HDD18°C ≤ 5000
7	9000 < HDD65°F ≤ 12600	5000 < HDD18°C ≤ 7000
8	12600 < HDD65°F	7000 < HDD18°C

Source: *2018 IECC*, International Code Council, Inc.

Figure 1: U.S. Climate Zone Map, Heating Degree Days (HDD65°F), & International Climate Zone Definitions

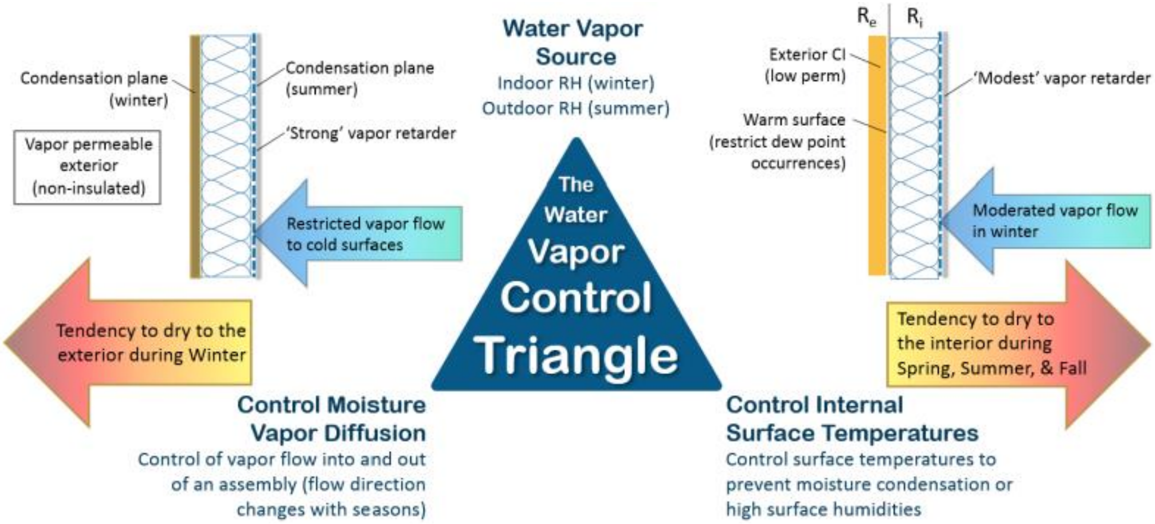


Figure 2: Illustration of the "Water vapor Control Triangle"& Two Accepted Moisture Control Design Approaches for Cold Climates

For a given cavity insulation amount, the “permeance controlled approach” can be made less risky in cold climates with decreased vapor permeance (increased vapor resistance) of the interior layers and increased vapor permeance of the exterior layers. Conversely, with increased cavity insulation amounts (conservatively assumed to be vapor permeable insulation in this report unless otherwise noted) and decreased vapor permeance of exterior layers, walls designed following this approach reach a margin or limit of acceptable performance in cold climates. Therefore, to ensure adequate performance of such walls, it is important to specify minimum exterior permeance levels (relative to the interior vapor resistance and cavity insulation amount provided). The reverse applies in warm/humid climates. For example, greater vapor resistance (lower permeance) is desired on the outside with less vapor resistance on the inside (higher permeance). In mixed climates, moderation is generally the appropriate balance when using the “permeance controlled approach” (e.g., avoid very low perm materials on either side of the assembly). The variation in permeance ratio for materials located on the outer and inner sides of assemblies under various climate conditions is addressed later in this report.

Similarly, for walls that are designed following the “temperature controlled approach” in cold climates, moisture accumulation risk is reduced with increasing exterior insulation amount (relative to cavity insulation amount and the interior vapor resistance provided). In warm/humid climates, the amount of exterior insulation is not as important as the need to maintain a vapor open condition on the interior side (same for the “permeance controlled approach”). A key relationship is defined by the insulation ratio of the assembly, that is, the ratio of exterior insulation R-value, R_e, to cavity insulation R-value, R_i, located to the interior of the exterior insulation (see Figure 2). The insulation ratio, R_e/R_i, governs the surface temperature of the wintertime condensation plane on the inside face of the exterior sheathing. For the purpose of this report and as a conservative simplification, the exterior insulation (R_e) is assumed to have low water vapor permeance. The variation in insulation ratio with variation in climate and the permeance of interior vapor retarder is reflected in requirements found in the Canadian and U.S. building codes, as will be addressed later in this research report.

It is well known that indoor relative humidity, air leakage control, rain water leakage control, and initial construction moisture control are important considerations to avoid overwhelming water vapor control strategies (e.g., HUD 2006; NAHB/RC 2004; HIRL 2014; *ASTM* Manual 18, *ASTM E241*, NAHB 1987; Glass and TenWolde 2007, etc.). Therefore, both water vapor control design approaches discussed above are predicated on good rain-water control, air-leakage control (e.g., air-barrier effectiveness), and indoor relative humidity control (e.g., adequate building ventilation). While walls with sufficient exterior insulation are known to be less prone to consequences of moist indoor air exfiltration (Straube, 2011; Saber, 2014), control of rain water leakage, air-leakage (exfiltration) and indoor relative humidity are very important design considerations for all walls with modern insulation requirements, such as found in newer model energy codes like the 2018 International Energy Conservation Code (ICC, 2018c).

Finally, all walls on light-frame buildings necessarily require a code-compliant water-restive barrier (WRB) and flashing installation to prevent rain water penetration that can easily overwhelm any wall assembly and cause eventual durability failures and other moisture control problems. This is particularly important in severe moist climates with high wind-driven rain hazard (see Figure 3). Fortunately, much of the U.S. is not in a severe wind-driven rain climate, except the Atlantic and Gulf seaboards and the Pacific Northwest. Regardless, water vapor control strategies are not intended to act as a “bilge pump” to offset defective rain water control whether by poor design, poor WRB and flashing installation, or poor maintenance. Instead, it is commonly understood that water vapor control strategies should provide a reasonable level of tolerance for non-diffusion sources of moisture (e.g., incidental moist air leakage and/or rain water leakage). This design objective is often understood to mean “drying potential”. What constitutes adequate drying potential is still a vague concept and a matter of debate among researchers and design professionals. Based on literature reviewed herein, this research report addresses the issue of drying potential by (1) seeking appropriate limits of use and emphasizing alternatives to the current code-compliant applications of “double vapor barrier” wall assemblies (e.g., avoiding potential and uncertain moisture accumulation risk associated with low water vapor permeance materials on both sides of a wall in climate conditions or applications where risks are relatively high) and (2) recommending minimum vapor permeance levels to promote drying to the interior or exterior as appropriate for the two representative design approaches discussed above. In modern wall assemblies, relying on air-leakage as a method for providing drying potential is not viewed as reliable or advisable.

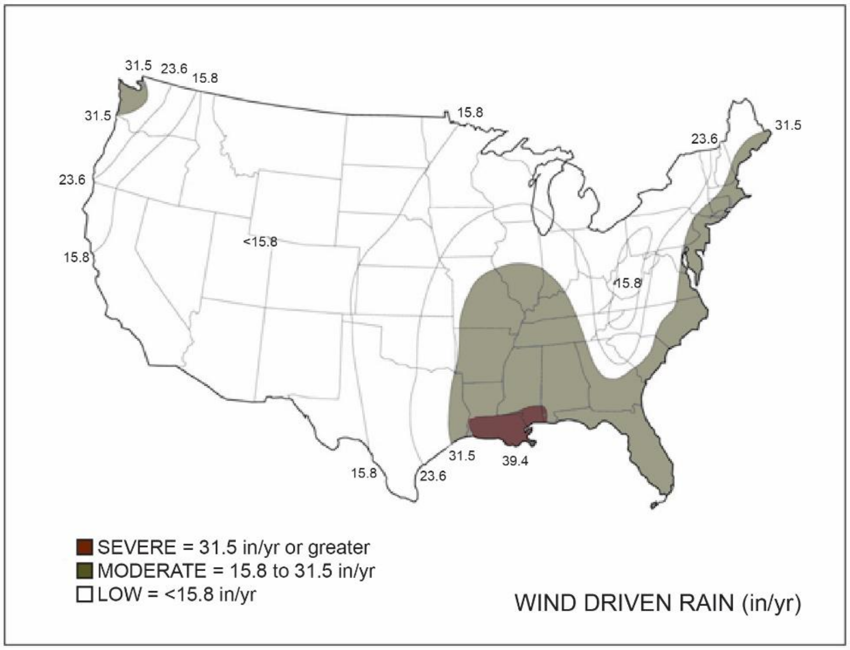


Figure 3: Wind-Drive Rain Climatology for the United States
(Source: Underwood, University of Georgia, 1999)

Vapor Retarder Types and Classes

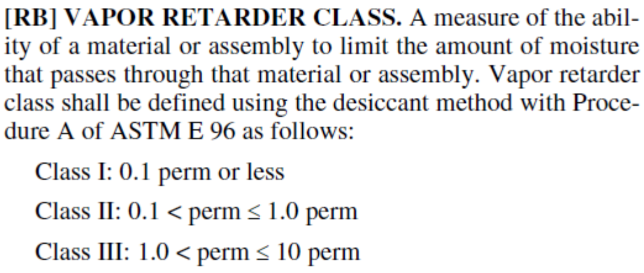
The water vapor permeance property of building material layers on an envelope assembly affects the ability of water vapor to move into and out of the assembly by diffusion. Thus, the location and permeance of such material layers affect the moisture performance of an envelope assembly, including its potential for wetting and drying by vapor diffusion.

Vapor retarders are used for the purpose of controlling water vapor flows through (into and out of) building envelope assemblies. The ability of a material to allow passage of water vapor under specified conditions is known as its water vapor permeance. Permeance is measured by a standard test method such as *ASTM E96* and the result is often reported in units called “perms” (*ASTM*, 2016). A material that has a high perm rating allows water vapor to easily pass through it by diffusion. Conversely, a material that has a low perm rating allows comparatively little water vapor to pass through; it is a “water vapor barrier”. Those with a moderate vapor permeance are generally labeled as “water vapor retarders”.

Also, water vapor permeance as described above should not be confused with a related measure called water vapor permeability. Water vapor permeability is reported in units called “perm-in” which is the permeance for a one-inch thickness of a homogenous material. Water vapor permeability must be adjusted for the actual material thickness used and, for some materials (particularly composites), an adjustment based on actual thickness alone may not account for the effect of various layers in the composite or other non-homogeneities that may occur across the thickness of some materials. Thus, this report uses water vapor permeance as it relates to the behavior of the whole product at its actual thickness and with all layers included if the product is a composite (e.g., sheathing with a facer).

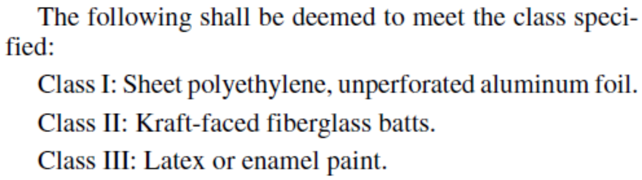
All material layers – not just those designated as vapor retarders – have vapor retarding properties and should be coordinated with the overall water vapor control strategy for building envelope assemblies (e.g., refer to Section X2.3 of *ASTM*, 2011). But, the common use of the term “vapor retarder” is referring to a single material layer with a designated function of controlling water vapor movement by diffusion. It is sometimes more specifically called an interior vapor retarder in reference to its location on an envelope assembly (e.g., “warm-in-winter” side of the assembly in heating dominated climates). The designated vapor control layer also may be located on the exterior side in any climate with proper design, and it is the preferable location in warm/humid climates.

In the U.S., vapor retarders are generically classified and defined in the *International Residential Code* (*IRC*) as follows (ICC, 2018a):



> **[RB] VAPOR RETARDER CLASS.** A measure of the ability of a material or assembly to limit the amount of moisture that passes through that material or assembly. Vapor retarder class shall be defined using the desiccant method with Procedure A of ASTM E 96 as follows:
>
> Class I: 0.1 perm or less
>
> Class II: 0.1 < perm ≤ 1.0 perm
>
> Class III: 1.0 < perm ≤ 10 perm

Examples of vapor retarders in each class include (ICC, 2018a)[1]:



> The following shall be deemed to meet the class specified:
>
> Class I: Sheet polyethylene, unperforated aluminum foil.
>
> Class II: Kraft-faced fiberglass batts.
>
> Class III: Latex or enamel paint.

Materials that are not intended to serve as a vapor retarder are often "vapor permeable" (ICC, 2018b):

> **[RB] VAPOR PERMEABLE.** The property of having a moisture vapor permeance rating of 5 perms (2.9 x 10-10 kg/ Pa · s · m2) or greater, where tested in accordance with the desiccant method using Procedure A of *ASTM E96*. A vapor permeable material permits the passage of moisture vapor.

That these vapor retarder classes and definitions are somewhat arbitrary is reflected in an apparent conflict between a Class III vapor retarder and the definition of vapor permeable. In this case, a material with a vapor permeance between 5 perms and 10 perms could be considered as both a vapor retarder material and also a vapor permeable material. Also, a Class II vapor retarder that is near 0.1 perm will perform very differently than one that is 1 perm. Similarly, broadly classified vapor permeable materials are not always equally preferable on that basis alone; a 5 perm material may be preferred over a 50 perm material depending on the circumstances of use. Conversely, a Class I vapor retarder that is 0.09 perm will perform little different than a Class II vapor retarder that is 0.11 perm. Generally, a Class I vapor retarder (0.1 perm or less) is also considered to be a vapor barrier. Clearly, these terms are all relative and must be associated with actual performance objectives for their use in a given assembly based on properties of the actual materials used and an analysis of the assembly under the intended or expected conditions of use. But, such classes and definitions are useful for the purpose of enabling and communicating the use of generic prescriptive requirements for vapor retarders in building codes and standards.

Also, *ASTM E96* defines vapor permeance using two methods: Procedure A (dry cup) at a mean ambient relative humidity of 25% and Procedure B (wet cup) at a mean ambient relative humidity of 75%. As described above, building codes generally only require materials to be classified in relationship to Procedure A and manufacturers frequently just report vapor permeance data based on Procedure A. While some materials have a stable vapor permeance that does not change with Procedure A or B, others are more dynamic in response to different levels of ambient relative humidity. Thus, for some materials and in some applications, Procedure B (wet cup) may be more reflective of a performance conditions in actual end use. This is perhaps best summarized in Section 8.3 of ISO 10456 (ISO, 2007):

> *"At low ambient relative humidities water vapour is transported through porous materials predominantly by vapour diffusion. As the relative humidity rises the pores start to fill with liquid water and liquid flow becomes*

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[1] The use of paint as a Class III vapor retarder should be done with reasonable caution. For example, it may be important to verify the vapor retarder properties for the intended application. Depending on the number and thickness of coats and other factors, the actual permeance may result in greater than 10 perm (too vapor permeable to be considered a Class III vapor retarder and a potential problem in colder climates) or less than 1 perm (which would mainly be a concern in hot/humid climates). For these reasons, many prefer to use Class II vapor retarders, particularly those that have "smart" vapor retarder properties, like Kraft paper facing, when vapor-permeable cavity insulation materials are used.

> *an increasingly important transport mechanism. The apparent vapour resistance therefore falls with increasing relative humidity [or vapor permeance rises with increasing relative humidity]. This effect is summarised by the dry cup values which apply when the mean relative humidity across a material is less than 70% and the wet cup values that apply when the mean relative humidity is greater than or equal to 70%. For heated buildings the dry cup values are generally applicable to materials on the inside of an insulation layer and wet cup values to those on the outside of an insulation layer."*

Many traditional materials such as Kraft paper, asphalt felt paper, wood-based sheathing, and other similar materials or products exhibit variable or adaptable vapor permeance behavior in response to changing ambient relative humidity conditions affecting the material's equilibrium moisture content. New additions to the family of materials with adaptable vapor permeance attempt to mimic this characteristic and they are commonly known as "smart" vapor retarders. Vapor retarders and other materials with adaptable vapor permeance can be used to enhance water vapor control in wall assemblies by taking advantage of the ability to change vapor permeance with change in ambient relative humidity. These types of vapor retarders are discussed in more detail later under the topic of "drying potential".

Hygrothermal Analysis

Hygrothermal analysis methods have been available in various forms for a long time. They provide a means to evaluate new designs, question the limits of use of traditional vapor retarder prescriptive requirements, consider the implications of unique conditions, or help troubleshoot the potential cause of moisture problems in existing building envelope assemblies. Hygrothermal analysis methods can be used to explore the appropriate use of materials and methods that are alternatives to those that are more familiar or traditional. More recently, the specific mention of "accepted engineering practice for hygrothermal analysis" is included in the 2018 *International Building Code* (*IBC*), Section 1404.3.2, as a means to justify use of alternative solutions (ICC, 2018b). This specific allowance is consistent with the concept of alternative means and methods of design as addressed in Section 104.11 of the *IBC* and *IRC*.

Acceptable practices for hygrothermal analysis are varied in nature. There are many ways to arrive at a reasonable answer. Some may be better than others depending on the circumstances. The remainder of this topical discussion attempts to put some boundaries on what may be considered as accepted practice for hygrothermal analysis.

First, the following references may be considered representative of accepted engineering practice in the United States:

- ASHRAE Standard 160, 2009 Edition, Criteria for Moisture-Control Design Analysis in Buildings, American Society of Heating, Refrigeration, and Air-conditioning Engineers, Atlanta, GA.
- *ASTM C755-10*, Standard Practice for Selection of Water Vapor Retarder for Thermal Insulation, *ASTM* International, West Conshohocken, PA.
- 2013 ASHRAE Handbook of Fundamentals (HOF), Chapter 26 – Heat, Air, and Moisture Control in Building Assemblies, American Society of Heating, Refrigeration, and Air-conditioning Engineers, Atlanta, GA.
- TenWolde and Bomberg (2009). Chapter 10 – Design Tools, *ASTM* Manual 18 – 2nd Edition, Moisture Control in Buildings: The Key Factor in Mold Prevention, *ASTM* International, West Conshohocken, PA.
- Ten Wolde (2001). Chapter 7 – Manual Analysis Methods, *ASTM* Manual 40, *ASTM* International, West Conshohocken, PA.
- *ASTM* (2009). E241-09, Standard Guide for Limiting Water-Induced Damage to Buildings, *ASTM* International, West Conshohocken, PA.
- Lstiburek (2011). Understanding Vapor Barriers, Building Science Digest 106, www.buildingscience.com
- Straube (2012). High Performance Enclosures: Design Guide for Institutional, Commercial and Industrial Buildings in Cold Climates, Section 3.4 Vapor Diffusion Control, Building Science Press, www.buildingscience.com

Other international standards and design practice references include:

- BS EN 15026:2007 - Hygrothermal performance of building components and building elements — Assessment of moisture transfer by numerical simulation.
- BS 5250:2002, Code of Practice for Control of Condensation in Buildings (British Standard)
- ABCB (2011). Information Handbook, Condensation in Buildings. Australian Building Codes Board and Australian Institute of Architects. Canberra ACT 2601
- ISO 13788:2012. Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods, 2nd edition

- DIN 4108-3, Thermal protection and energy economy in buildings – Part 3: Protection against moisture subject to climate conditions – Requirements and directions for design and construction[2]

As documented in much of the scientific literature reviewed in the development of this research report, water vapor control is not an exact science. The inexactness and complexity of moisture control in building assemblies is due to the many variables and associated uncertainties that affect performance and the ability to accurately predict performance. The design variables include: (1) exterior climate conditions (temperature, relative humidity, solar radiation exposure, wind and rainfall frequency), (2) interior environmental conditions (particularly indoor relative humidity), (3) location and properties of vapor retarders and other building materials within an envelope assembly (particularly water vapor permeance and thermal resistance properties and their variation under conditions of use), (4) air leakage control (continuous air-barrier), (5) weather resistance (continuity of water-resistive barrier and flashing), (6) moisture storage capacity and moisture-durability tolerance of materials comprising an envelope assembly, (7) building ventilation and pressurization characteristics, and (8) initial or "built-in" moisture content of materials as a result of construction conditions, scheduling, and sequencing.

ASTM E241 (*ASTM*, 2009a) and various other literature sources (see References) recognize that many factors can contribute to or help prevent moisture problems; and some are more or less important than others. NAHB (1987, p15) states that *"Under cold weather conditions, moisture is usually controlled by a combination of measures: regulation of indoor humidity, use of vapor retarders, reduction of air leakage from conditioned spaces, ventilation of attics and crawlspaces."* Five key factors repeatedly mentioned in the reviewed literature are: (1) rainwater control, (2) air-leakage control, (3) indoor relative humidity control, (4) construction moisture control, and (5) water vapor control through the specification and location materials in an assembly relative to their vapor retarder properties and thermal properties. In case studies of many homes in various climate zones, the importance of these factors have been well evidenced in practice (NAHB-RC, 2004; Tsongas, 2009; HIRL, 2014; Glass and TenWolde, 2007).

The above discussion speaks to the importance of a "systems approach" to moisture control when considering or analyzing appropriate water vapor control strategies (BSC, 2005). These or similar conditions of use also should apply to and are implicit to current water vapor control practices in US model building codes, even though they may not be explicitly stated within the code.

Water vapor control performance objectives and evaluation criteria that may be considered in design include (based on ASHRAE 160, BS 5205, etc.):

1) Minimizing Risk of Mold Growth (see discussion that follows):
   a) limit the duration of time (e.g., < 30 days) over which surface relative humidity of an organic material layer is 80% or greater when the surface temperature is between 41°F and 104°F, or,
   b) limit peak wood sheathing moisture content to less than 20%
2) Minimizing Condensation Risk – limit the duration of time that the interior surface temperature of exterior sheathing is equal to or less than the dew point temperature of indoor conditioned space air.
3) Minimizing Long-Term Moisture Accumulation Risk - Any interstitial condensation that occurs within the structure in the winter evaporates during the next summer (and vice versa); e.g., the annual moisture balance is neutral or showing a drying trend over the long term.
4) Minimizing Potential for Material Degradation – If interstitial condensation occurs over the winter and evaporates in the summer, the risk of degradation of the materials present should be considered in terms of the maximum accumulated condensation or maximum tolerable moisture content of the material.

The application of the above criteria and the degree to which judgment may be required also depends on the method of analysis used as well as uncertainties or limitations in its execution. In some cases, criteria are assessed in a relative sense by comparing results of a proposed assembly to that of one or more assemblies considered to represent successful practice by experience.

Of the above criteria, the most stringent relates to prevention of mold growth. The two criteria to evaluate potential risk of mold growth are not necessarily equivalent, but both are used in practice. Other means of assessing mold growth potential, including different limits for tolerable wood sheathing moisture contents, are mentioned in the literature with recognition of the need for continued research to better refine these criteria. For example, a mold risk rating ("mold index")

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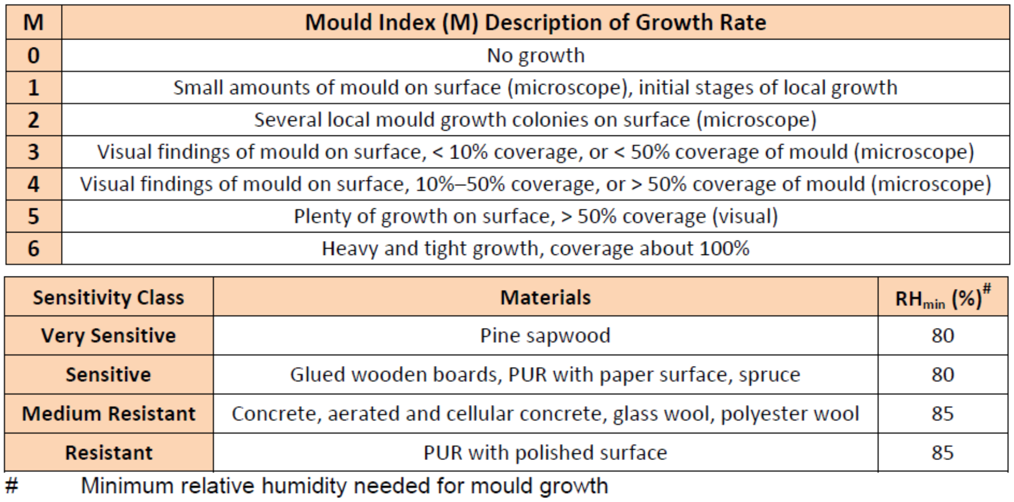
[2] It should be noted that the DIN 4108-3 standard includes an annual moisture surcharge intended to account for the effect of incidental moist air-leakage or bulk water intrusion and, therefore, provides a drying potential "safety factor" when evaluating annual moisture balance using monthly average climate data for an annual cycle with the Kieper or Glaser-type hygrothermal analysis methods (Kunzel, Zirkelbach, and Shafaczek 2011). It is also considered most appropriate for analysis of light-frame assemblies with low moisture storage or buffering capability in comparison to mass building construction, such as concrete or masonry (Kunzel, 2000).

methodology has been proposed by Ojanen et al. (2010) and, at the time of this writing, is expected to eventually replace the above mold "pass/fail" criteria presently in the ASHRAE 160 standard. This newer mold index approach is shown in Figure 4. While this newer method provides an improved way of characterizing levels of mold risk, it does not necessarily answer the question of an appropriate or "tolerable" level of risk. This question must ultimately be answered with judgment and careful calibration to successful experience together with the application of any specific hygrothermal modeling method or tool, including significant assumptions and inputs being employed for a given analysis. The Ojanen et al. (2010) mold index approach has been used by Saber (2014) in a recent re-evaluation of moisture control provisions in the National Building Code of Canada. In addition, Lstiburek, Ueno, and Musunuru (2015) have similarly employed this newer mold index approach in hygrothermal modeling with comparisons to observed performance of some actual envelope assemblies. These and other studies, together with available performance data, are evaluated and discussed in greater detail later in this research report.



M	Mould Index (M) Description of Growth Rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Sensitivity Class	Materials	RH$_{min}$ (%)$^{\#}$
Very Sensitive	Pine sapwood	80
Sensitive	Glued wooden boards, PUR with paper surface, spruce	80
Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85
Resistant	PUR with polished surface	85

\# Minimum relative humidity needed for mould growth

Figure 4. Mold index methodology in accordance with Ojanen et al. (2010) as reported in Tables 5 and 6 of Saber (2014).

While a tolerable wood sheathing moisture content may be closely related to mold risk, it warrants a separate consideration in regard to material durability (see item #4 in the design objectives list above). High moisture levels may occur in the winter with cold sheathing temperatures that prevent mold growth and dry before temperatures conducive to mold occur regularly (i.e., Spring season). If mold were the only basis for concern, then other consequences such as material degradation and long-term durability may go overlooked or under-emphasized. For example, data from HIRL (2013) and Dow (2014) and several other studies evaluated later in this research report provide evidence that high moisture contents (>20%) are being experienced in oriented strand board (OSB) sheathing as a result of winter water vapor drives in code compliant walls in Climate Zones 4 and 5 (with vapor-permeable cavity insulation only and use of a Class III or Class II interior vapor retarder, respectively). In the HIRL (2014) test hut study, OSB samples were removed from the test hut walls and those samples exposed to significant vapor drives in use (with a Class III interior vapor retarder in CZ 4) experienced degraded structural properties (e.g., 19% reduction in bending strength).

ASTM E241 (*ASTM*, 2009) recognizes three methods of evaluating water vapor control: (1) conceptual, (2) mathematical using transient simulation computer models, and (3) mathematical using steady-state or static conditions suitable to manual or spreadsheet calculation. While the second method can provide a more sophisticated and comprehensive framework for hygrothermal analysis (e.g., ASHRAE Standard 160 and BS EN 15026), the third method is still commonly employed as an accepted practice (e.g., *ASTM C755*, BS EN ISO 13778, DIN 4108-3, ASHRAE *Handbook of Fundamentals*, etc.). For example, as discussed in detail later in this research report, a simple steady-state dew point analysis approach has been employed to help develop and justify certain provisions for water vapor control in the *IBC* and *IRC*; although, its particular use was heavily informed by test hut studies, transient simulation modeling, and experience (Lstiburek, 2013). Conversely, a transient simulation computer modeling approach was used to justify and confirm similar provisions in the *National Building Code* of Canada (NBC) (NBC, 2015; Saber 2014).

NBC Commentary Section A-5.5.1.2.(1) recognizes that:

> *"Steady state heat transfer and vapour diffusion calculations may be used to determine acceptable permeance levels for the vapour barrier and to identify appropriate positions for the vapour barrier within the building assembly."*

In a study reviewing hygrothermal analysis methods and issues (Brown, 2012), the following observation is made regarding European practice:

> *"By far the most popular method of assessing the hygrothermal behaviour of walls is the Glaser methodology which is presented in BS EN ISO 13788:2002."*

Thus, while transient computer modeling methods provide many benefits and are gaining popularity, the older Glaser methodology and newer Kieper methodology (*ASTM*, 2009b) are still widely recognized and used as design tools. But, limitations are commonly recognized. For example, according to BS EN ISO 13778 (ISO, 2012):

> "*The method used assumes built-in water has dried out and does not take account of a number of important physical phenomena including:*
>
> > *- the dependence of thermal conductivity on moisture content;*
> > *- the release and absorption of latent heat;*
> > *- the variation of material properties with moisture content;*
> > *- capillary suction and liquid moisture transfer within materials;*
> > *- air movement through cracks or within air spaces;*
> > *- the hygroscopic moisture capacity of materials.*
>
> *Consequently the method is applicable only to structures where these effects are negligible (BSI 2002)… Neglecting moisture transfer in the liquid phase normally results in an overestimate of the risk of interstitial condensation (BSI 2002)."*

BS EN 15026:2007 makes the following statement in regard to the use of transient numeric computer models:

> "*The application of such models has become widely used in building practice in recent years, resulting in a significant improvement in the accuracy and reproducibility of hygrothermal simulation (BSI 2007)."*

According to Brown (2012):

> *"Software conforming to this standard [BS EN 15026] is not easy to use and good results can only be obtained by using accurate input data for climate and all material properties. Clearly, a good understanding of physics in relation to buildings and the implications of making one input choice over another is required. These factors make it clear why BS 15026 [transient modeling] has not been widely adopted by the building industry."*

Similarly, in a recent DOE Building America expert meeting on dynamic hygrothermal modeling concerns, participants recognized increased use of dynamic models such as "WUFI" and the common experience of unreliable or unrealistic predictions by typical practitioners (Ueno and Lstiburek, 2014). Participants identified the need for more user education, better material properties, better understanding of boundary conditions (e.g., indoor relative humidity), and improved definition of failure criteria (e.g., tolerable wood moisture content and mold criteria). Consequently, they called for more field experience and monitoring research.

Clearly, the state-of-the-art of hygrothermal modeling is itself transient and moisture analysis is still as much an art as it is a science with design methods and tools informing designer judgment and experience in view of many uncertainties. This realization presents difficulties in meeting one of the goals of this research report: to reconcile different findings in the literature in relation to moisture control practices. To help overcome this difficulty, however, data from various sources is compiled and compared to a baseline of accepted practice as defined by current accepted practices in the U.S. and Canada. Special emphasis is given to "real world" data (e.g. test hut studies and actual building monitoring) when this data is adequately defined and characterized to permit meaningful analysis and comparison. However, simulated data is also considered together with the "real world" data.

Cold-Climate Design Considerations

Based on BS 5205:2002 (Section 7.1.3) and *ASTM E241* (Section 5.5), one or more of the following design actions are required to minimize interstitial condensation in heating dominated (cold) climates:

a) Obtain low vapor pressures by ventilation, and /or reduced moisture input to the building (e.g., control indoor relative humidity to acceptably low levels),
b) Use materials of high vapor resistance near to the warmer side of the construction (e.g. interior vapor retarders) and, consequently, use material of low vapor resistance near the colder side of the construction (e.g., exterior side),
c) Use materials of low thermal resistance near to the warmer side of the construction and materials of high thermal resistance near to the colder side of the construction (e.g., keep internal condensation surfaces warm).

Design action ‘a’ in the above list speaks to the importance of indoor relative humidity control as a part of any water vapor control strategy for a building envelope assembly. Design actions ‘b’ and ‘c’ are two methods or approaches to achieve water vapor control, one emphasizing control of water vapor flow (e.g., “permeance controlled approach”) and the other emphasizing control of internal surface temperatures to minimize condensation potential (e.g., “temperature controlled approach”). Consequently, a typical application of design action ‘b’ relies more heavily on vapor diffusion drying to the exterior while design action ‘c’ relies more heavily on drying to the interior and is important when materials on the exterior of the wall have a low water vapor permeance (high water vapor resistance). In theory, there is a continuum of acceptable solutions that may employ the principles represented by design actions ‘b’ and ‘c’ to varying degrees. In each case, the goal is to adequately control and balance the seasonally changing wetting and drying processes associated with water vapor diffusion.

Where design action ‘b’ is used, it relies on restricting water vapor entry from the interior and promotes vapor removal or drying through the exterior side of the assembly. In such cases, BS 5205 recommends that designers should aim to specify materials of decreasing vapor resistance from inside to out. As an approximation, it suggests that materials on the warm side of any insulation should have a total vapor resistance of at least five times the sum of the vapor resistances on the cold side of the insulation. Provided some reasonable minimum limit on exterior permeance is considered, this approach ensures that cavity insulated walls have adequate drying potential in at least one direction, in this case through the exterior side of the wall. The “HUD Code” for manufactured housing in the U.S. implements this concept in the following manner in Section 3280.54 (CFR, 2004):

> *“The [exterior] covering and/or sheathing shall have a combined permeance of not less than 5.0 perms. In the absence of test data, combined permeance may be computed using the formula:*
>
> $P_{Total} = 1/[(1/P_1) + (1/P_2)]$
>
> *Where P_1 and P_2 are the permeance values of the exterior covering and sheathing in perms.*

Similarly *ASTM E1677* (*ASTM*, 2011) makes the following recommendations:

> *“X2.3 …..All materials in a wall assembly must be considered in evaluating condensation, not just one material. It is the relationship of the total permeance of all the wall materials, the position of those materials in the opaque wall, and the temperature at those positions that influences condensation potential.”*

It goes on to mention that calculation methods (e.g., Glaser or Kieper methods) and computer modeling of moisture transport is available to account for the vapor permeance of all material layers. Finally, it states that:

> *“X2.3.1.2 A less accurate method is to compare just the permeance of materials on either side of the insulation cavity. Generally, a ratio of at least 5:1, outside to inside, for heating dominated climates is recommended so that moisture vapor has the possibility to escape the wall. Some very cold geographic areas may require a higher ratio that is, 20:1 and other climates, such as hot and humid, may require the ratio to be reversed.”*

ASTM E1677 continues by addressing means of mitigating condensation that include elements of methods ‘b’ and ‘c’ described previously.

Wall designs following design action ‘b’ tend to be more susceptible to inward vapor drives that may occur during non-winter seasons due to solar-driven inward moisture movement when “reservoir” claddings are present (Straube, 2011; BSC, 2014). The topic of solar-driven inward moisture movement is addressed later.

Where design action ‘c’ is used, it relies on the use of exterior continuous insulation to warm the internal components or surfaces of the wall to minimize the potential for interstitial condensation and moisture accumulation. This approach requires an appropriate ratio of exterior insulation to interior (cavity) insulation. This practice is combined with the use of moderate interior vapor retarders to control vapor flow into the assembly during the winter while maintaining drying ability to the interior during other times of the year when vapor flows reverse direction toward the interior. This approach is especially important in colder climates when low perm material layers are included on the exterior side of an assembly.

Design action ‘c’ is consistent with the “self-drying” or inward drying principle widely and successfully applied to low-slope roofs with “above deck” insulation and low-perm roof membranes as described in Straube (2011). Furthermore, when low perm exterior continuous insulation is used, it can mitigate the risk of significant moisture accumulation events due to extreme inward vapor drives that may occur from solar heating of wetted “reservoir” cladding materials (Straube, 2011); also refer to later discussion on this topic. For similar reasons in moderately cold and wet climates (e.g., Climate Zone Marine 4C in the Northwest US), use of a low perm insulating sheathing as exterior continuous insulation has been found to perform very well in controlling moisture in comparison to other design options (Smegal and Straube, 2010, p.15). Straube (2011) also acknowledges that use of exterior insulation as described in design action ‘c’, when used in appropriate amounts, tends to mitigate implications associated with undesirable warm, moist indoor air leakage into wall assemblies during the winter because the internal wall surfaces are warmer and less likely to experience condensation. This also finds agreement with results reported by Saber (2014). Alternatively, walls with or without exterior insulation that rely more heavily on a permeance control (design action ‘b’) can be improved by including an effective air-barrier on the interior side of the assembly, in combination with or integral to the interior vapor retarder.

The approach described above as design action ‘c’ is often executed with the use of foam plastic insulating sheathing (FPIS) placed on the exterior as continuous insulation. With a proper ratio of exterior insulation to cavity insulation, this approach can accommodate foam plastic insulating sheathing materials covering a broad range of permeance values which vary according to the foam plastic material type, thickness, and facer characteristics, when present. The successful use of this practice with a variety of FPIS materials is well established. According to Tsongas (2009), there are no known cases where use of foam plastic insulating sheathing (exterior continuous insulation) in accordance with design action ‘c’ has been the cause of moisture problems. According to Straube et al. (2011, p22), insulating sheathing has been applied to the outside of wood-framed residential structures for more than 30 years and provides a superior means of addressing thermal bridging and moisture control concerns in comparison to vapor-permeable cavity insulation only approaches that attempt to meet high R-value criteria.

Clearly, design actions ‘b’ and ‘c’ represent two accepted design approaches to control water vapor in building envelope assemblies. However, there are other approaches. For example, a “vapor open” design is sometimes considered but is not without its own limitations (Lstiburek, 2011). Another approach, which is perhaps an ideal application of design action ‘c’ (e.g., “temperature controlled approach”) relies exclusively on exterior insulation serving as the thermal, vapor, and air control layer. This assembly is robust in all climates and is appropriately described as the “perfect wall” (Lstiburek, 2008).

Warm Climate Design Considerations

In warm, humid climates, materials closer to the interior should be more vapor permeable than those toward the exterior of an assembly because the dominant vapor flow is from the outside in (the opposite of that discussed above for cold climates) (ABCB, 2011). This practice limits moisture vapor entry from the exterior climate and provides drying toward the interior to reduce the likelihood of interstitial condensation on the cool interior side of an assembly during summer air-conditioning operation. This recommendation is essentially the hot-humid climate counterpart to design action ‘b’ discussed above for cold climates and, likewise, is a traditional approach with a history of successful performance. However, moisture problems have occurred when low-perm interior finishes have been applied (e.g., vinyl wall paper) creating a vapor retarder on the wrong side of the assembly (Figure 5). Problems are exacerbated when interior set-point temperatures for air-conditioning are abnormally low (refer to *ASTM E241*).

According to SBRA (2000), the HUD code for manufactured housing requires a minimum combined permeance of 3 perms for interior layers in hot-humid climates (Climate Zones 1 and 2 and part of 3). Research and testing has shown that many typical interior finishes and materials meet this 3 perm or greater requirement with the exception of surfaces finished with vinyl wall coverings (SBRA, 2000).

Figure 5: Mold Behind Vinyl Wall Paper
– Vapor Retarder on the Wrong Side in Warm/Humid Climate
(Source: https://www.epa.gov/mold/brief-guide-mold-moisture-and-your-home)

Indoor Relative Humidity

NAHB (1987) correctly recognizes and characterizes the importance of controlling indoor relative humidity:

> *"The first step to preventing moisture damage is to maintain reasonable indoor relative humidity of between 30 and 40%."*

While maintaining a reasonably low indoor relative humidity is important for building moisture durability, this goal must be balanced with human comfort and potential health considerations. Thus, various sources recommend that indoor relative humidity levels not be maintained less than 25% to 30% nor greater than about 60%, which represent the lower and upper bounds generally recognized as acceptable for human comfort and health for most of the population (BSC 2005). As illustrated in Figure 6, lower relative humidity levels are commonly advised (and expected) during the winter to help protect the building envelope from excessive water vapor exposure (high vapor pressure differentials and/or moist air exfiltration) whereas higher indoor relative humidity levels can be tolerated in the summer. The indoor relative humidity target in the coldest winter months should also decrease with severity of climate (e.g., 40% - Climate Zone 4; 35% - Climate Zone 5; 30% - Climate Zone 6; 25% - Climate Zones 7/8) unless special design accommodations are made (Lstiburek, 2009). Several sources agree in general that persistent relative humidity levels greater than 40% in the winter or 60% in the summer are problematic (*ASTM*, 2009a; *ASTM*, 2009b; NAHB-RC, 2004; etc.).

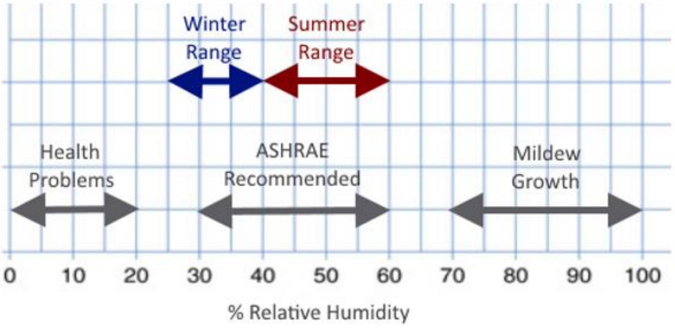
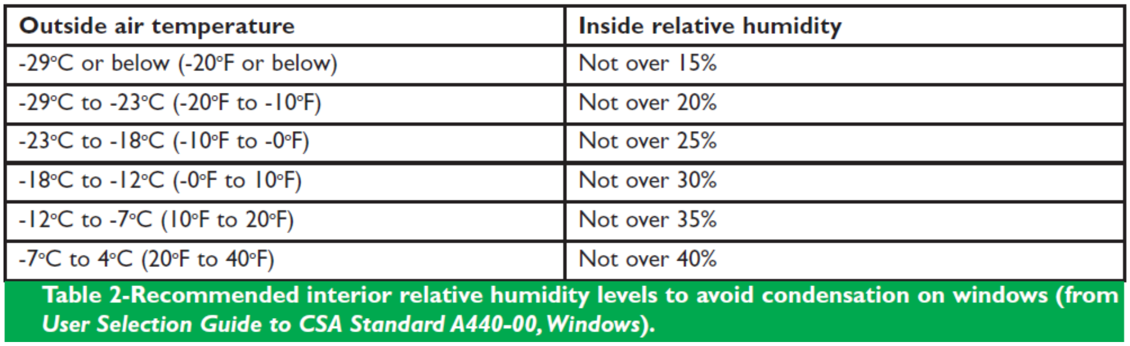


Figure 6. Target range of indoor relative humidity for comfort ("ASHRAE-Recommended") and building envelope water vapor control ("Winter/Summer Ranges")

In accordance with (Kerr, 2005): *"As a rule, interior moisture, measured as relative humidity, should not exceed 25 per cent to 35 per cent during the heating season to prevent condensation on windows. CSA Standard A440.1-00,"User Selection Guide to CSA Standard A440-00, Windows" recommends the humidity levels shown in Table 2 to minimize* *condensation on windows."* As shown in Figure 7, the presence of condensation on windows is a reasonable visual means for building occupants or operators to be alerted to the potential need to control (reduce) indoor relative humidity levels to ensure adequate performance of the building envelope. However, lowering indoor relative humidity below 25% to prevent condensation on windows may not be advisable from an occupant health and comfort perspective (Figure 6). In such a case, specification of windows with improved thermal performance (lower U-factor and lower condensation potential) may provide an optimal solution.



Outside air temperature	Inside relative humidity
-29°C or below (-20°F or below)	Not over 15%
-29°C to -23°C (-20°F to -10°F)	Not over 20%
-23°C to -18°C (-10°F to -0°F)	Not over 25%
-18°C to -12°C (-0°F to 10°F)	Not over 30%
-12°C to -7°C (10°F to 20°F)	Not over 35%
-7°C to 4°C (20°F to 40°F)	Not over 40%

Table 2-Recommended interior relative humidity levels to avoid condensation on windows (from *User Selection Guide to CSA Standard A440-00, Windows*).

Figure 7. Indoor relative humidity levels to control window condensation.
Source: Kerr (2004)

Currently, there are no indoor relative humidity limitations stated explicitly in the *IBC* and *IRC*. A limitation on indoor relative humidity, however, is included in the NBC. Where 'high' indoor relative humidity levels are expected or intended, the NBC requires envelope assemblies to be designed. While the meaning of 'high' indoor relative humidity is vague, it does draw attention to the concern.

To complicate matters, not all enclosure designs have the same level of sensitivity to indoor relative humidity. For example, the use of a Class III interior vapor retarder (e.g., latex paint) can result in a greater sensitivity to indoor relative humidity levels in the winter (CMHC 2009; HIRL, 2013; Glass, 2013) unless matched appropriately with a "temperature controlled" approach to envelope design (e.g., appropriate use of exterior insulation) or the permeance of exterior materials is high. For this and other reasons, it is important to ensure that enclosure design is coordinated with the building's design and operation in regard to control of indoor moisture or relative humidity.

In cold climates, proper ventilation system design is a very effective means of controlling wintertime indoor relative humidity levels. When balanced properly, ventilation systems can help avoid high indoor air pressures and even help offset the effect of higher pressures in the upper stories of a building due to stack effect. Thus, the flow rate of moist indoor air exfiltration into and through a building envelope assembly can be reduced, lowering the potential for moisture accumulation inside the assembly. However, care must be taken to ensure adequate supply air for any combustion equipment as a part of safe ventilation system design. In addition to the applicable building or mechanical code, there are several resources for ventilation system design (e.g., ASHRAE Standards 62.1 and 62.2). In warm, humid climates, dehumidification is the common method employed to control excessive indoor relative humidity. Proper sizing, operation, and maintenance of air-conditioning equipment also is important to maximize its capability to remove moisture (condensate) from the air as it is chilled. HVAC system design is beyond the scope of this research report, but it is paramount to the control of indoor relative humidity levels.

Drying Potential

According to Straube (2011), the permeance of the exterior portions is only slightly less influential than the interior portions of an envelope assembly. This observation finds its practical application with the understanding that envelope assemblies should have the capability to dry at an adequate rate in at least one direction (BSC 2005). The drying capability of an assembly is associated with ability to tolerate incidental rain water intrusion, moist air leakage, or extreme events (e.g., colder than normal winters or wetter than normal years). Thus, drying potential is like a "safety factor" for design of water vapor control and its purpose is similar to the use of a safety factor for structural design purposes (e.g., manage uncertainties and reduce risk). Of course, this risk is also influenced heavily by the degree to which the climate presents a hazard (e.g., wind-driven rain and overall dryness or moistness which varies regionally). There are several ways to implement this design concept and it necessarily involves coordinating the permeance of materials on both sides of an assembly together with consideration of climate.

One simple way to provide for improved drying potential is to avoid the use of "double vapor barrier" assemblies. The most common example of a double vapor barrier assembly is one with an interior polyethylene vapor barrier (i.e., Class I interior vapor retarder) and a low-perm exterior sheathing layer, membrane material, or combination of materials (i.e., effectively a Class I vapor retarder material or "vapor barrier"). Thus, one could follow a simple rule-of-thumb such as: *"Don't place Class I vapor retarder materials on both sides of an assembly."* However, it is generally understood that, under specific conditions of use, such a simple approach could restrict applications in conditions where experience has establish a longstanding basis for successful and acceptable practice. For example, Section X2.3.2.1 of *ASTM E1677* (*ASTM*, 2011) recognizes that:

> *"In a moderate to cold climate, the opaque wall must either be permeable to water vapor, or when the permeance of materials on the exterior is less than 1 perm it may be beneficial to insulate on the outside. When the exterior is permeable, moisture vapor from the opaque wall can escape to the outdoors without accumulating in the wall. When the exterior is insulated, the temperature of the opaque wall is increased to minimize wall moisture accumulation (see 5.1.4 for the water vapor permeance performance requirement).*
>
> *Note X2.2 – Designers should evaluate the amount of insulation necessary to keep condensation from forming in the wall assembly when the AB [air barrier] is rated as a vapor retarder less than 1 perm and exterior applied."*

A more sophisticated method of evaluating drying potential involves modeling the effect of incidental water intrusion events or moist air leakage conditions using transient hygrothermal modeling programs. Static analysis methods (e.g., Kieper analysis) coupled with monthly average indoor and outdoor boundary conditions can also be used to evaluate drying potential for an annual cycle (refer to DIN 4108-3 and Kunzel, et al., 2011). However, these methods of analysis do not necessarily resolve the question of an appropriate level of drying potential in relation to an appropriate assumption regarding non-diffusion moisture sources (e.g., incidental rain water intrusion or moist air leakage). As with any practical criteria for design, it must agree with what has worked acceptably in the past and this too is difficult to quantify with precision.

One way of enhancing drying potential is through the use of "smart vapor retarders". One of the most common examples is a Kraft-paper facer typically adhered to the interior side of fiberglass batt cavity insulation. According to the 2013 ASHRAE *Handbook of Fundamentals*, Kraft paper has the following dynamic water vapor permeance properties:

ASTM E96 (dry cup):	0.3 perms (tested at a 25% average relative humidity)
ASTM E96 (wet cup):	1.8 perms (tested at a 75% average relative humidity)

Such a dynamic vapor retarder material when used on the interior side of a wall tends to beneficially restrict outward moisture vapor diffusion into and through a wall assembly during winter heating conditions and, conversely, promotes increased inward drying to the interior during other seasons of the year by increasing in vapor permeance as water vapor diffusion shifts to an inward direction (Gatland et al., 2007). However, dynamic vapor retarders are not currently recognized in U.S. model codes for this benefit.

For the purposes of this Research Report, a "smart" or dynamic vapor retarder (also known as an adaptable vapor retarder) is defined as follows:

> **ADAPTABLE VAPOR RETARDER:** A material that is classified as a Class I or II vapor retarder by Procedure A (dry cup method) of *ASTM E96* and also as a Class III vapor retarder or vapor permeable material when tested in accordance with Procedure B (wet cup method) of *ASTM E96.*

In addition to Kraft paper, various proprietary vapor retarders also are available to provide this characteristic to promote increased drying potential and better control moisture accumulation in wall assemblies. This interior vapor retarder characteristic is especially useful for envelope assemblies that are designed using a "temperature controlled" approach (e.g., drying to the interior) when a low perm exterior insulation product is used.

Dynamic vapor permeance also is very important for some materials used on the exterior side of a wall in cold climates. For example, wood structural panels behave as a Class II vapor retarder material when subject to low relative humidity, but become a Class III vapor retarder when exposed to higher relative humidity. Thus, such a sheathing material may be classified as "vapor permeable" (i.e., 5 perm or greater) based on the *ASTM E96* wet cup method, although this is not necessarily the case for all types of wood based sheathing materials and may vary substantially within a given sheathing type. This attribute is important to cold-climate envelope assemblies that are designed based on the vapor permeance approach (e.g., drying to the exterior). However, use of highly vapor permeable materials on the exterior under conditions where reservoir claddings are used can result in substantial moisture movement into the assembly under solar-driven conditions (refer to later discussion). Also, dynamic vapor permeance does not necessarily compensate for such materials that may become damaged by experiencing high levels of moisture, even though they may dry quickly when conditions change to allow drying to occur.

Finally, it is important to recognize that "double vapor barrier" assemblies are permitted in current U.S. and Canadian building codes and have been permitted and constructed successfully for many decades when combined with sufficient exterior insulation to reduce the potential for condensation. For example, code-compliant double vapor barrier assemblies are included in the Canadian Wood Council's "Wall Thermal Design Calculator" (CWC, 2013). For one such assembly type including a polyethylene interior vapor barrier with exterior foil-faced polyisocyanurate foam sheathing (refer to http://cwc.ca/wall_thermal_design/f6-s16-i19-o1p-v-2/, 4/19/2015), the following notation is made on the assembly assessment provided: *"While sheathings with extremely low permeance might raise questions of trapped vapour within the assembly, thousands of such walls exist and seem to perform relatively well."* Extenuating circumstances, however, are mentioned that may help explain this successful experience with a double vapor barrier assembly. For example, good air-leakage control and water vapor diffusion control may be typically provided by a polyethylene interior vapor barrier when properly installed and sealed at penetrations to also serve as an air barrier. It is also recognized that the exterior foam insulating sheathing reduces the risk of interstitial condensation by warming the assembly when used with an appropriate R-value for the assembly and climate. However, the CWC calculator cautions that care must be taken to achieve good rain-water leakage control due to the low drying potential. This concern implies that the double vapor barrier approach may tend to perform more reliably in relatively dry climates or protected conditions not subject to severe wind-drive rain exposure (e.g., see Figure 3).

Clearly, there appear to be conditions where double vapor barrier assemblies are considered to be an accepted practice and have performed adequately. However, evidence also exists of conditions where double vapor barrier assemblies have performed poorly. For example, rapid deterioration of wood framed walls with barrier EIFS cladding occurred in rainy, humid climates with poorly installed or absent flashing and sealing details and no secondary water-resistive barrier for drainage. The rate of decay appeared to be especially rapid with the presence of an interior vapor barrier (Crandell and Smart, 2004). However, the major cause of failures was poor rain water management. When present, the double vapor barrier condition served to accelerate the damage that would have otherwise occurred at a slower rate. Consequently, rain water management concerns have been addressed more stringently in modern building codes. Regardless, the practice of building assemblies that are "double vapor barriers" is generally understood to be somewhat more risky than providing a nominal amount of drying potential in at least one direction through or out of an envelope assembly. Consequently, appropriate limitations for use of a double vapor barrier condition is a topic where additional research is warranted to better understand appropriate applicability limits to this currently permitted and accepted U.S. and Canadian practice.

Moisture Storage and Initial Construction Moisture

Another factor affecting the ability of a wall assembly to tolerate or "buffer" conditions when moisture accumulation is occurring is known as moisture storage capacity. The capacity of an assembly to store moisture depends on the nature of the materials used in the assembly. For example, wood materials constantly take up and release moisture during the course of the year as the equilibrium moisture conditions change seasonally. Provided the moisture content does not exceed a tolerable level, this can provide a useful buffering effect where moisture is accumulated and stored at one time of the year and expelled at another. However, even if controlled to tolerable levels to prevent rot or mold, such moisture content cycling can create serviceability problems or potential long term weakening of materials (Lstiburek and Carmody, 1991; HIRL, 2013).

Interestingly, the impact of differences in moisture storage capacity of assemblies is not addressed in the prescriptive water vapor retarder requirements of current US and Canadian model building codes. For example, there is no distinction between the moisture storage capacity of steel framing and wood framing. However, the moisture storage capacities are very different and likely should have some modest effect on water vapor control requirements. Thermal bridging differences may also magnify the potential for localized condensation or high surface relative humidity levels (e.g., this effect is often seen as "ghosting" on the interior surface of exterior walls that do not use an exterior insulation approach in cold climates). The presence or absence of wood sheathing, selection of an organic cavity insulation material, or other material serving as a moisture sink will also affect moisture storage capacity.

Wood materials and some cavity insulation materials, such as such as wet-blown cellulose, can also significantly load a wall with initial construction moisture if walls using these materials are closed-in prior to adequate drying. Even dry applied cavity insulations can be exposed to and store large amounts of initial moisture if installed prior to water-tight enclosure of the exterior shell of the building as may occur with poor construction sequencing (see Figure 8).

Figure 8. Initial Construction Moisture (Intruded Rain Water) Being Expelled from Fiberglass Batt Cavity Insulation Due to Poor Construction Sequencing (e.g., cavity insulation installed prior to dry-in of the exterior wall with, at a minimum, a complete installation of the exterior water resistive barrier and flashing).

Thus, under certain avoidable conditions of use, the ability of a material to store large amounts of water may not be an advantage. This concern with initial construction moisture is addressed in *ASTM E1677*, Section X2.3.2.1(2) as follows:

> *"When vapor retarders are used on both sides of the opaque wall, precautions should be used to ensure that building materials within the wall cavity have a moisture content below 19%".*

The above statement is based on Lstiburek and Carmody (1991, pp80-81) and is applicable to a variety of wall assemblies and exterior sheathing materials:

> *"Should the wall assembly be built wet due to wet framing materials or wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it may not dry. Accordingly, dry framing materials (wood at a moisture content of 19 percent by weight or lower) and dry applied insulations are recommended. Alternatively, wall assemblies must be allowed to dry prior to enclosure."*

It should be noted, however, that the spray-applied cellulose industry's installation instructions recommends that the insulation may be enclosed when it is "sufficiently dry, having a moisture content of 25% or less." (CIMA Technical Bulletin #3, http://www.cellulose.org/userdocs/CIMA-TechnicalBulletin03.pdf , accessed 8/16/2018). This criteria still represents a significant initial moisture load that, depending on wall assembly conditions and time of enclosure, may result in a long duration of wetting and moisture movement into and through other materials in the assembly, causing potential moisture problems. Thus, lower moisture content levels should be considered in practice.

A study by Salonvaara, Pazera, and Karagiozis (2010), reports that "built in moisture in spray-applied cellulose fiber insulation (CFI) can significantly affect the hygrothermal performance of residential wood frame walls." Further, "…the minimum recommended time by the industry to accommodate drying…is typically inadequate." And, "…this built-in moisture can lead to performance related problems in walls." It finds that the time of year and weather conditions can delay drying, particularly north-facing walls in cold weather. The study investigated typical walls with OSB (noted as a relatively "low permeance" sheathing in the report) and a membrane WRB on the exterior. The walls had no siding to replicate construction at the time insulation may be applied to cavities. Even under this more favorable condition for drying of the cavity (and with no interior finish or vapor retarder applied) and in a mild Georgia winter climate, it took about 2-1/2 months for the relative humidity at the interior surface of the OSB to begin to drop below 100% and moisture concentrated toward and into the OSB as the wall attempted to dry in an outward direction during the winter. Consequently the moisture content of the OSB was high (>20 percent) for an extended period of time – a condition that is known to decrease the structural property of OSB (HIRL, 2013). The study findings suggest that it may take as much as a week or more for wet-applied cellulose insulation to dry sufficiently before wall enclosure. Even so, the exterior sheathing is cycled through a significant moisture uptake episode. This condition is worsened if walls are enclosed too early.

Because most walls will have at least interior paint finish (generally a Class III vapor retarder) and exteriors are often less than 10 perm (particularly when the net permeance of multiple exterior layers is considered) causing them act as a vapor retarders, it is prudent to control moisture levels of the enclosed materials. Even if a wall assembly has greater than 10 perm on one side (and a vapor retarder material only on one side of the wall), stored or accumulated moisture can be driven toward the vapor retarder depending on the time of the year of enclosure, thus delaying drying and causing the moisture to accumulate in materials toward the inside or outside of the construction. Simply put, there are few cases or conditions where high initial moisture levels could be tolerated without consequences.

Solar-Driven Inward Moisture Movement

When reservoir cladding materials store moisture, usually from a rain event, and then are exposed to solar radiation (sunshine), significant inward vapor drives can occur (BSC/DOE, 2014). Reservoir claddings include claddings made of hygroscopic materials such as wood, fiber cement, stucco, concrete and masonry. Solar-driven inward vapor drives can greatly exceed the magnitude of outward vapor drives that occur during cold climate conditions (Straube, 2011). Observations and concerns with manifestations of this problem are noted in several sources as reported by Wilkinson, et al. (2007) and also Glass and TenWolde (2007). Thus, with highly vapor permeable layers located on the outside of walls behind unventilated reservoir claddings, the potential for episodes of significant moisture accumulation or condensation may occur, causing undetected damage, particularly in air-conditioned buildings with low-perm vapor retarders on the interior side.

A study sponsored by ASHRAE investigated conditions associated with solar-driven inward vapor drives that may lead to durability problems (Derome, 2010). The study included laboratory testing, field monitoring, and modeling. It was found that inward vapor flows may occur year round, but are most prevalent in the summer time. The presence of a low-perm interior vapor retarder (i.e., polyethylene sheet) or a low-perm interior finish (i.e., vinyl wall covering) resulted in high local vapor pressure near the interior gypsum board and increasing moisture content. The main design guidelines derived from the work are quoted as follows:

1) Predominantly cold climates have lower occurrence of inwards vapor flow
2) Predominantly warm climates have a high potential of inwards vapor flow. Thus, their building envelope design should aim at short-circuiting the moisture source, i.e., applying capillary break, ventilation, or low absorption. Furthermore, their interior finish should be vapor open.
3) Mixed climates may require special evaluation. Such evaluation could be performed, for example, by running hygrothermal simulations with and without solar radiation and assessing the impact in terms of moisture content of the interior finish.

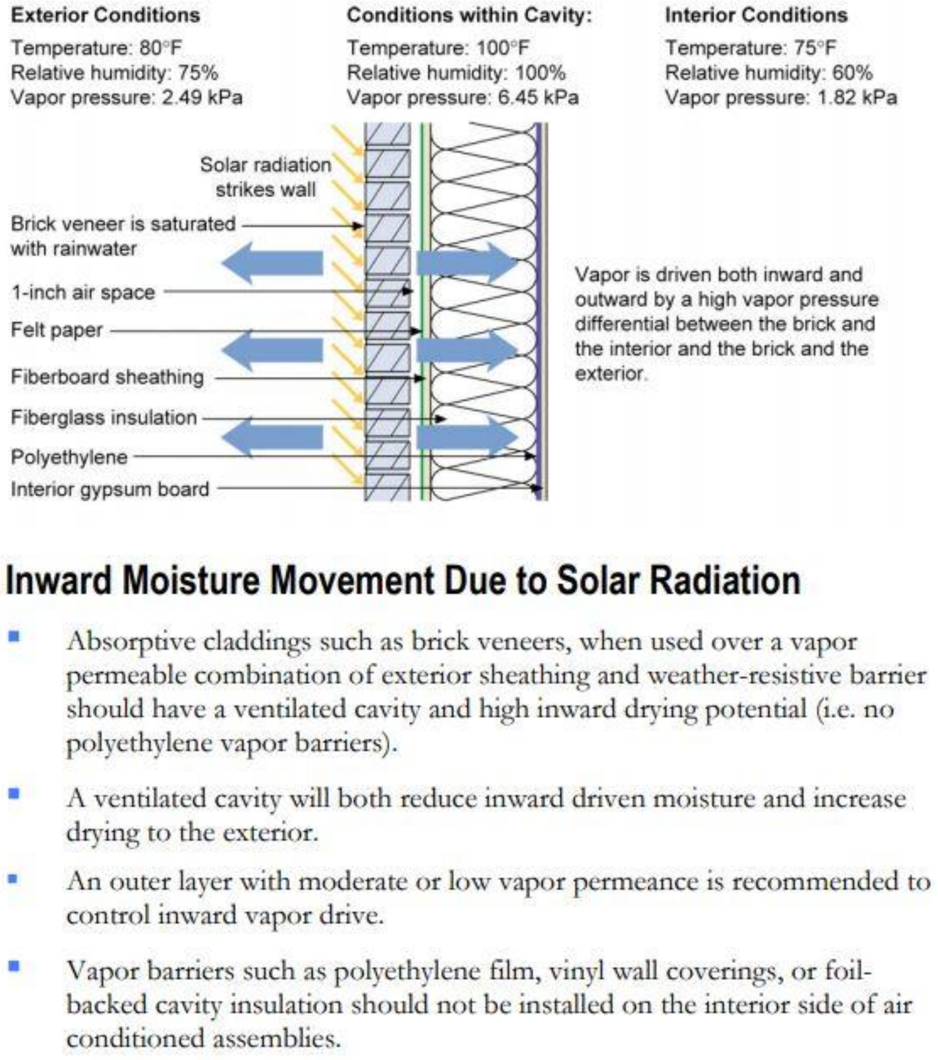
Wilkinson et al. (2007) and BSC (2005) present several ways to reduce or mitigate the solar-driven inward moisture movement problem: (1) avoid the use of a Class I interior vapor retarder (e.g., polyethylene vapor retarder/barrier), (2) back ventilate the reservoir cladding or use a non-reservoir cladding with a low or reduced water absorption, and/or (3) avoid the use a vapor permeable exterior sheathing or membrane (which may require use of exterior insulation in cold climates to also control water vapor under winter conditions with outward vapor drives). The solar-driven inward moisture movement problem and solutions are illustrated in Figure 9. While the problem is notable, explicit solutions are not addressed in current U.S. and Canadian model codes. Instead, codes may currently rely on traditional prescriptive solutions, such as two layers of Grade D paper behind Portland cement stucco (a practice that has proven unsuccessful in particularly moist climates).

Using transient hygrothermal modeling, Lepage and Lstiburek (2013) investigated the moisture durability of walls with vapor permeable insulating sheathing, such as mineral fiber board. A variety of reservoir cladding materials were considered, including brick, stucco, wood, and cement board. The results indicated high OSB sheathing moisture contents (> 25% MC) for cases where the permeance of the water-resistive barrier exceeded approximately 10 perms. The results trended similarly over a range of climate zones (1-7) and tended to be significantly worse for assemblies with a Class I or II interior vapor retarder. The results and recommendation of the study are summarized as follows:

> *“The results of these simulations suggest that the addition of at least 1 in. of exterior insulation significantly helps improve the moisture durability of the wall assembly. However, highly vapor permeable WRBs should be avoided when used with reservoir claddings and mineral fiber insulation (MFI) on the exterior. Consequently, WRBs below 10 perms and at least 1 in. of exterior insulation are recommended when used in combination with reservoir claddings in nearly every climate zone. Certain climate zones, such as 6 to 8, require additional exterior insulation. In summation, vapor-impermeable WRBs may be utilized only when at least 1 in. of exterior insulation is used in climate zones 1 through 5. A minimum of 2 in. (greater than R7.5) of exterior insulation should be used in climate zones 6 and 7. Climate zone 8 was not modeled in these simulations.”* (p.33)

> *“The team found that WRBs with vapor permeances above 10 perms increase the MC of the structural sheathing. The use of vapor-control layers within the wall, such as Kraft or polyethylene sheet on the interior, increase the risk for moisture damage within the wall by effectively trapping moisture within the wall. Consequently, BSC recommends using latex paint to inhibit outward flowing moisture in combination with exterior insulation to reduce any moisture damage potential.”* (p37)

It should be emphasized that the above recommendations to limit the vapor permeance of the WRB are based on use in combination with a high perm exterior insulation material (e.g., MFI has a permeance of 110 perms) and a reservoir cladding material. Lower perm exterior insulation materials will tend to block solar-driven inward water vapor drives, but require consideration of an appropriate exterior insulation amount to protect against outward vapor drives in colder climates, depending on the interior vapor retarder class used.



Inward Moisture Movement Due to Solar Radiation

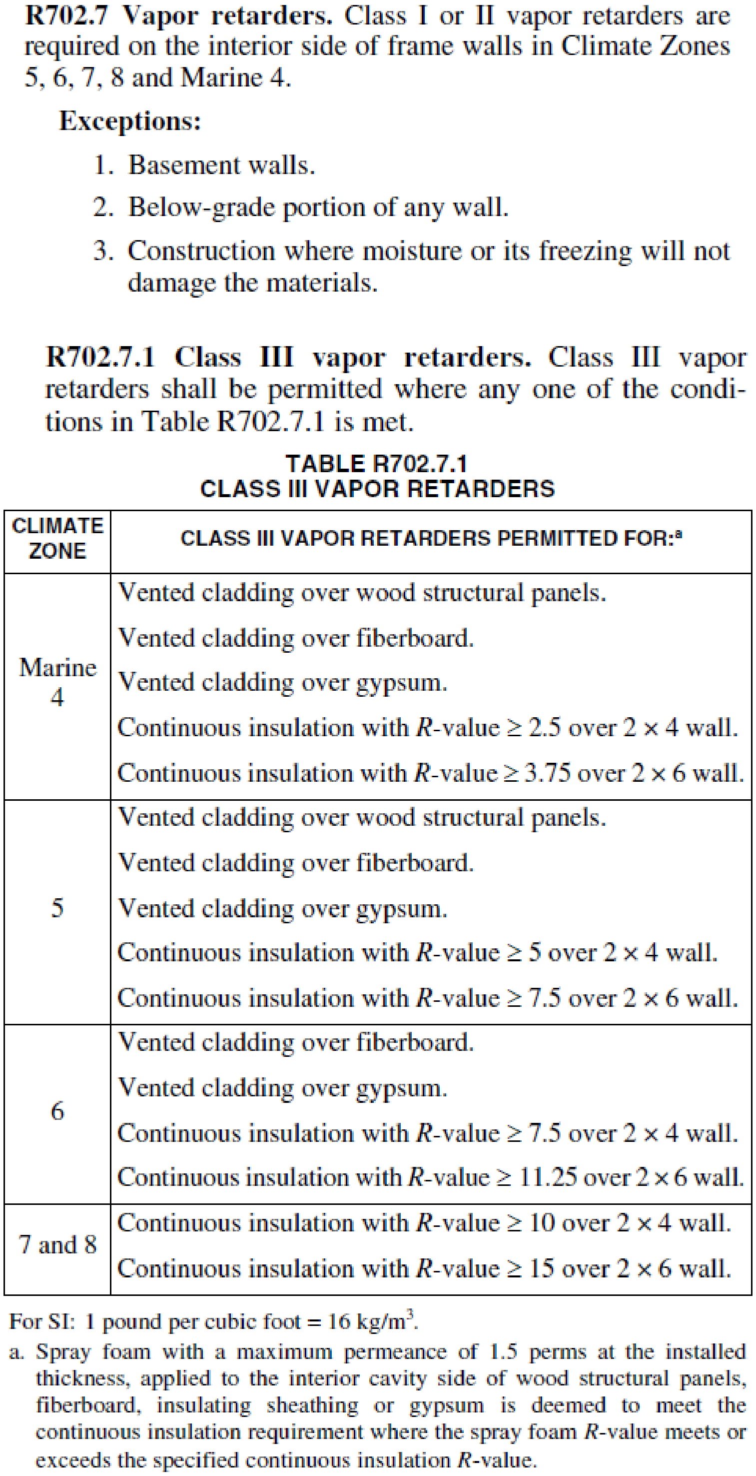
- Absorptive claddings such as brick veneers, when used over a vapor permeable combination of exterior sheathing and weather-resistive barrier should have a ventilated cavity and high inward drying potential (i.e. no polyethylene vapor barriers).
- A ventilated cavity will both reduce inward driven moisture and increase drying to the exterior.
- An outer layer with moderate or low vapor permeance is recommended to control inward vapor drive.
- Vapor barriers such as polyethylene film, vinyl wall coverings, or foil-backed cavity insulation should not be installed on the interior side of air conditioned assemblies.

Figure 9: Illustration of solar-driven inward water vapor movement and recommend practices.
Source: BSC/DOE (2014)

Building Code Requirements

U.S. Practice

As shown in Figure 10, model building codes in the U.S., such as the *IRC*, require the use of a Class I or II interior vapor retarder on above-grade walls in colder climate zones, but also permit the conditional use of a Class III interior vapor retarder (ICC, 2018a):



R702.7 Vapor retarders. Class I or II vapor retarders are required on the interior side of frame walls in Climate Zones 5, 6, 7, 8 and Marine 4.

Exceptions:

1. Basement walls.
2. Below-grade portion of any wall.
3. Construction where moisture or its freezing will not damage the materials.

R702.7.1 Class III vapor retarders. Class III vapor retarders shall be permitted where any one of the conditions in Table R702.7.1 is met.

TABLE R702.7.1
CLASS III VAPOR RETARDERS

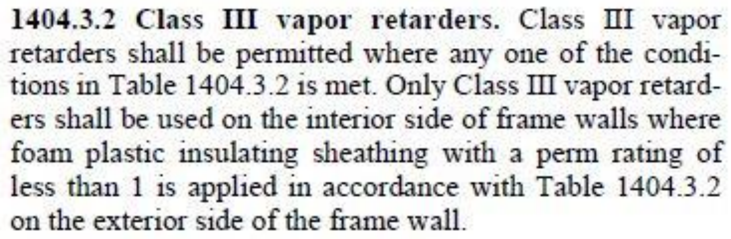
CLIMATE ZONE	CLASS III VAPOR RETARDERS PERMITTED FOR:[a]
Marine 4	Vented cladding over wood structural panels. Vented cladding over fiberboard. Vented cladding over gypsum. Continuous insulation with *R*-value ≥ 2.5 over 2 × 4 wall. Continuous insulation with *R*-value ≥ 3.75 over 2 × 6 wall.
5	Vented cladding over wood structural panels. Vented cladding over fiberboard. Vented cladding over gypsum. Continuous insulation with *R*-value ≥ 5 over 2 × 4 wall. Continuous insulation with *R*-value ≥ 7.5 over 2 × 6 wall.
6	Vented cladding over fiberboard. Vented cladding over gypsum. Continuous insulation with *R*-value ≥ 7.5 over 2 × 4 wall. Continuous insulation with *R*-value ≥ 11.25 over 2 × 6 wall.
7 and 8	Continuous insulation with *R*-value ≥ 10 over 2 × 4 wall. Continuous insulation with *R*-value ≥ 15 over 2 × 6 wall.

For SI: 1 pound per cubic foot = 16 kg/m^3.

a. Spray foam with a maximum permeance of 1.5 perms at the installed thickness, applied to the interior cavity side of wood structural panels, fiberboard, insulating sheathing or gypsum is deemed to meet the continuous insulation requirement where the spray foam *R*-value meets or exceeds the specified continuous insulation *R*-value.

Figure 10: Vapor Retarder Requirements (2018 *IRC*)

The *IRC* regulates permeance of vapor retarders used on the inside of a wall assembly, but does not regulate the permeance of exterior layers of a wall assembly. Thus, it also permits the construction of double vapor barrier assemblies (e.g., Class I interior vapor retarder with low-perm exterior layers with or without the presence of any amount of exterior insulation). While the provisions in the *IBC* are similar, a recent change to the *IBC* requires use of a Class III interior vapor retarder to ensure inward drying potential when exterior foam plastic insulating sheathing has a permeance of less than 1 perm (ICC, 2018a):



1404.3.2 Class III vapor retarders. Class III vapor retarders shall be permitted where any one of the conditions in Table 1404.3.2 is met. Only Class III vapor retarders shall be used on the interior side of frame walls where foam plastic insulating sheathing with a perm rating of less than 1 is applied in accordance with Table 1404.3.2 on the exterior side of the frame wall.

The *IBC* requirement shown above may be considered as an initial attempt to address a minimum level of drying potential for wall assemblies that have low-perm materials on the exterior side of the assembly. But, this new requirement only applies to walls with exterior foam plastic insulating sheathing. It may be considered to be of greater concern with low perm non-insulating exterior sheathings or coverings, but the code remains silent on this matter. Also, it may be considered overly restrictive in its application to insulating sheathings because it does not recognize the benefits of using an adaptable interior vapor retarder (such as a Class II vapor retarder Kraft paper which performs like a Class III vapor retarder under seasonal conditions when inward drying is afforded).

The consideration of permeance limits to ensure adequate drying potential should apply to all assemblies. For example, wall assemblies that do not have adequate exterior insulation in cold climates are prone to increased condensation wetting in the winter. Unfortunately, for walls that do not use exterior continuous insulation, the *IBC* continues to permit the construction of "double vapor barrier" assemblies. The *IRC* continues to allow it for all wall assemblies (with or without exterior insulation) in any Climate Zone. For example, the *IRC* provisions in Figure 10 do not "require" a Class I interior vapor retarder in Climate Zones 1-3, but it also is not prohibited. This has the potential additional consequence of being interpreted to allow a vapor barrier on the wrong side of the assembly (inside) in a warm, humid climate – something that is known to be problematic and was certainly not intended. The *IBC* has corrected this interpretative concern by explicitly prohibiting the use of Class I interior vapor retarders in the warmer climate zones.

The use of a double vapor barrier assembly can also be found elsewhere in the U.S. practice for vapor retarders. For example, a code reference standard for construction of permanent wood foundation walls recommends use of a double vapor barrier assembly for below-grade wood-frame walls, known as "permanent wood foundations" (AWC, 2007; refer to Section 4.2). However, various other sources for design of vapor control for below-grade walls strongly recommend that such walls be designed to dry to the interior as this is the primary direction of water vapor drives in below-grade walls of all material types.

The provisions for use of Class III vapor retarders (Figure 10, Table R702.7.1) address two methods of managing outward water vapor flows during the winter while also promoting enhanced drying to the interior with the use of a Class III interior vapor retarder instead of a Class I or II interior vapor retarder. The first set of options listed for each Climate Zone represent a "permeance controlled approach" using cavity insulation only, specified non-insulating exterior sheathing materials, and ventilated cladding. The added ventilation is needed to help manage the greater wintertime outward vapor flows that come with use of a Class III interior vapor retarder in a permeance controlled design approach. Also, the variation in allowed exterior sheathing material type implies permeance limits (minimum permeance) for non-insulated exterior sheathing materials and layers. It also implies that these limits change (increasing exterior permeance) with increasing (colder) Climate Zone to achieve an acceptable performance. However, it does not provide an upper limit on the vapor-permeable cavity insulation amount which may affect the temperature of the sheathing and, thus, the rate at which condensation occurs on or moisture accumulates within the exterior sheathing layer during the winter.

The second set of options listed for each Climate Zone (Figure 10, Table R702.7.1) represents a limited application of the "temperature controlled approach" for 2x4 and 2x6 walls. Another variation of this temperature controlled approach (limited to use with Class I or II interior vapor retarders) is presented in the next section and is based on the Canadian National Building Code (NBC). In Figure 10 (Table R702.7.1), the increasing amount of exterior continuous insulation (e.g., foam plastic insulating sheathing) with increasing Climate Zone is based on the need for an increasing insulation ratio (R_e/R_i) to keep the temperature of the condensation plane (inside surface of the exterior sheathing) above the dew-point temperature of the heated indoor air under wintertime conditions.

Table 1 below presents the insulation ratios that serve as the basis for the exterior continuous insulation amounts for use with Class III interior vapor retarders in the *IBC* and *IRC* (see Figure 10, Table R702.7.1). Various substantiating technical references are listed below Table 1. These ratios are based on the conservative assumption of a low-perm exterior insulating sheathing material as an assumption implicit to the use of a simplified dew-point analysis methodology described later. While a wide selection of vapor permeance properties are possible with available foam plastic insulating sheathing products, many have a low permeance depending on foam type, foam density, facer type and/or thickness. The low-perm insulating sheathing assumption has the benefit of simplifying prescriptive construction requirements because it does not then require that the permeance of other layers on the exterior of the wall be checked and controlled to ensure some specified level of overall permeance for the exterior side of the assembly.

TABLE 1
Minimum Insulation Ratio (R_e/R_i)
for Use with a Class III Interior Vapor Retarder

CLIMATE ZONE	Maximum Heating Degree Days (HDD65°F)	Minimum R_e/R_i Ratio
Marine 4	5,400	0.2
5	7,200	0.35
6	9,000	0.5
7	12,600	0.7

Table Sources & References:

- 2009/2012/2015/2018 *International Building Code* (*IBC*) and *International Residential Code* (*IRC*)
- Lstiburek (2011). Understanding Vapor Barriers, *Building Science Digest* 106, www.buildingscience.com
- Lstiburek (2004). Vapor Barriers and Wall Design, Research Report – 0410, www.buildingscience.com
- Karagiozis, Lstiburek, and Desjarlais (2007). Scientific Analysis of Vapor Retarder Recommendations for Wall Systems Constructed in North America, ASHRAE, Buildings X
- Straube (2012). High Performance Enclosures: Design Guide for Institutional, Commercial and Industrial Buildings in Cold Climates, Section 3.4 Vapor Diffusion Control, Building Science Press, www.buildingscience.com

The following provides an example application of the above insulation ratios for Climate Zone 6 to demonstrate the basis of the R13+7.5 and R20+11.25 wall assemblies in the *IBC and IRC* when a Class III interior vapor retarder is used (see Figure 10):

Example #1 (2x4 wall with Class III interior vapor retarder)
Cavity insulation = R-15 maximum
Insulation Ratio = 0.5
Minimum required amount of exterior continuous insulation = 0.5 * (R-15) = R-7.5ci
Acceptable Solution = R15+7.5ci (R-6.5ci is required if R-13 cavity insulation is used)

Example #2 (2x6 wall with Class III interior vapor retarder)
Cavity insulation = R-22.5 maximum
Insulation Ratio = 0.5
Minimum required amount of exterior continuous insulation = 0.5 * (R-22.5) = R-11.25ci
Acceptable Solution = R22.5+11.25ci (R-10ci is required if R-20 cavity insulation is used)

Canadian Practice

First, the terminology used in the NBC varies from that in the *IRC* and *IBC*. For example, the *IRC* and *IBC* reference three classes of vapor retarders based on ranges of vapor permeance. And, vapor retarders that have the greatest vapor resistance (e.g., Class I < 0.1 perm) are commonly understood to be vapor barriers. However, the NBC uses the term “vapour barrier” in a much broader sense (NBC 2015):

> “*Vapour barrier* means the elements installed to control the diffusion of water vapour.” (Part 9, Section 1.4.1.2)

Second, the NBC only recognizes the use of Class I and II vapor retarders (i.e., vapour barriers are considered to have a permeance of 1 perm or less). The use of Class III interior vapor retarders is not specifically addressed or prescribed. However, the NBC is similar to the *IRC* and *IBC* in that it also allows the construction of double vapor barrier walls (e.g., Class I vapor retarder materials on both sides of the assembly). But, the NBC always requires a sufficient quantity of exterior insulation to minimize the risk of interstitial condensation when an exterior sheathing or sheet material is less than 1 perm.

The NBC provides two compliance paths for control of water vapor diffusion. One path for compliance is found in Part 5, Section 5.5 – Vapor Diffusion. It provides performance requirements that must be implemented by design. In Section 5.5.1.1, it states that a vapour barrier and the properties and locations of other materials in the assembly should be designed and specified to *“minimize the accumulation of condensation in the building component or assembly.”* The objective is further explained in Section 5.5.1.2 as follows (NBC, 2015):

1) reduce moisture transfer by diffusion, to surfaces within the assembly that would be cold enough to cause condensation at the design temperature and humidity conditions, to a rate that will not allow sufficient accumulation of moisture to cause deterioration or otherwise adversely affect any of
    a. the health or safety of building users,
    b. the intended use of the building, or
    c. the operation of building services.

The use of the term “minimize” is further explained in the commentary for the NBC as follows (NBC, 2015):

> *“The word “minimize” is used in Sentence 5.5.1.1.(1) because not all moisture accumulation in an assembly need be of concern. Incidental condensation is normal but should be sufficiently rare and in sufficiently limited quantities, and should dry rapidly enough, to avoid material deterioration and the growth of mould or fungi.”(Section A-5.5.1.1)*

Section A-5.5.1.2(1) of the 2015 NBC commentary also provides guidance on an acceptable practice for hygrothermal analysis to demonstrate compliance with Section 5.5:

> *“Steady state heat transfer and vapour diffusion calculations may be used to determine acceptable permeance levels for the vapour barrier and to identify appropriate positions for the vapour barrier within the building assembly.”*

The other path to compliance is prescriptive and it is found in NBC Part 9 for Residential Buildings. Part 9 buildings are generally less than 3 stories and of small to moderate size. Part 9 provisions are also used for other major occupancies including business and mercantile. NBC Section 9.25.4, Vapour Barriers, includes the following requirements:

- A *vapour barrier* is required on the interior side (warm-in-winter) of insulated assemblies. [All Canadian climate zones are considered cold climate zones.]
- *Vapour barriers* shall have a permeance not exceeding 60 ng/(Pa•s•m^2) (~ 1 perm) measured in accordance with *ASTM E96* (dry cup). [The requirement for a minimum 60 ng/Pa•s•m^2 vapour barrier is based on the assumption that the building assembly is subjected to conditions that are considered normal for typical residential occupancies, and business and personal services occupancies.]
- Where the intended use of the interior space will result in high moisture generation, the assembly is required to be designed in accordance with Part 5 [e.g., swimming pools, greenhouses, laundromats, and any continuous operation of hot tubs and saunas].

- Where foamed plastic insulation functions as the *vapour barrier*, it shall be sufficiently thick so as to meet the first requirement above. [This addresses the use of foam plastic insulation on the interior side of envelope assemblies in Canada’s cold climates].

The properties and position of other materials in the building envelope are addressed in NBC Section 9.25.5. Specifically, sheet and panel-type materials that have a low air-permeance (less than 0.1 L/s-m^2 at 75 Pa) and which have a water vapor permeance of less 60 ng/(Pa•s•m^2) (~1 perm) when measured in accordance with *ASTM E96/E96M* (dry cup) are required to be used in assemblies complying with special requirements in Section 9.25.5.2 for low vapor permeance materials. Wood-based sheathing materials of 12.5 mm (1/2 inch) thick or less are exempted which is presumed to be based on the adaptive vapor permeance properties of common wood sheathing materials (e.g., vapor permeance increases with ambient relative humidity and equilibrium moisture content). A new exemption has been added to the 2015 edition of the NBC based on an extensive hygrothermal analysis project (Saber, 2014):

> *“Where a material has a water vapour permeance of 30 ng/(Pa-s-m^2)* [~0.5 perm] *or greater and has a thermal resistance of at least 0.7 m^{2}K/W (R4) and the building is in a location with an HDD*[18^{o}C] *of less than 6000* [10,800 HDD 65^{o}F]*, the assembly need not comply with Sentence (1).”*

For walls with low-perm (< 1 perm) exterior materials that are not exempted as discussed above, the following requirements from Section 9.25.5.2 apply (NBC, 2015):

1) Sheet and panel-type materials described in Article 9.25.5.1. shall be installed
    a. on the warm face of the assembly (see also Article 9.25.4.2.),
    b. at a location where the ratio between the total thermal resistance of all materials outboard of its innermost impermeable surface and the total thermal resistance of all materials inboard of that surface is not less than that required by Table 9.25.5.2., or
    c. outboard of an air space that is vented to the outdoors.
2) For walls, the air space described in Clause (1)(c) shall comply with Clause 9.27.2.2.(1)(a).

The above requirements provide three options for the location of low-perm sheet and panel-type materials. On the warm face of the assembly, these low-perm (< 1 perm) materials serve essentially the same function as a *vapour barrier* in accordance with NBC Part 9 discussed previously. However, when these materials are located within or on the outside surface of the assembly, the insulation ratio must comply with NBC Table 9.25.5.2 (Figure 11). The final permissible location of low-perm materials is to the outboard side of a well-ventilated airspace (e.g., vented cladding).

Heating Degree Days (HDD18C)	Minimum Ratio of Total Thermal Resistance Outboard of Material’s Inner Surface to Total Thermal Resistance Inboard of Material’s Inner Surface
Up to 4999	0.20
5000 to 5999	0.30
6000 to 6999	0.35
7000 to 7999	0.4
8000 to 8999	0.5
9000 to 9999	0.55
10,000 to 10999	0.6
11000 to 11999	0.65
12000 or higher	0.75

Note: 1 HDD(18^{o}C) = 1.8 HHD(65^{o}F)

Figure 11: Canadian Insulation Ratios (Based on 2015 NBC Table 9.25.5.2)

Figure Source and References:

- 1995/2000/2005/2010/2015 *National Building Code* of Canada, Part 9, Section 9.25.4 Vapour Barriers and 9.25.5 Properties and Position of Materials in the Building Envelope
- Kumaran and Haysom (2000). Low-Permeance Materials in Building Envelopes, Construction Technology Update No. 41, National Research Council of Canada (revised March 2002)
- Kumaran and Haysom (2001). Avoiding Condensation with low-permeance materials, NRCC-44704, National Research Council Canada, Institute for Research in Construction.
- Chown and Mukhopadhyaya (2005). *NBC* 9.25.1.2: The on-going development of building code requirements to address low air and vapour permeance materials, NRCC-47656, National Research Council Canada, Institute for Research in Construction.
- Brown, Roppel, and Lawton (2007). Developing a Design Protocol for Low Air and Vapour Permeance Insulating Sheathing in Cold Climates, Buildings X, ASHRAE.
- Saber, H.H. (2014). Report on Properties and Position of Materials in the Building Envelope for Housing and Small Buildings, National Research Council, Canada

NBC 2015 Commentary Section A-9.25.5.2 explains that:

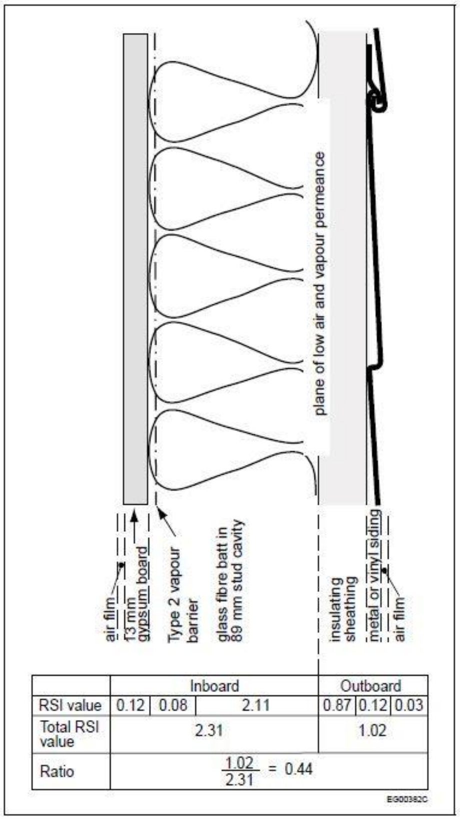
> *"It has been demonstrated through modeling, under these conditions that assemblies constructed according to the requirements of 9.25.5.2 do not lead to moisture accumulation levels that may lead to deterioration…"*.

It further stipulates that:

> *"…during colder periods, indoor RH higher than 35% will cause significant condensation on windows. When this occurs, occupants are likely to increase the ventilation to remove excess moisture…Where higher relative humidities are maintained for extended periods in these colder climates, the ratios listed in the Table may not provide adequate protection…In these cases, Table 9.25.5.2 cannot be used and the position of materials must be determined according to Part 5 …It should be noted that Part 9 building envelopes in regions with colder winters have historically performed acceptably when the interior RH does not exceed 35% over most of the heating season. With tighter building envelopes, it is possible to raise interior RH levels above 35%. There is no information, however, on how Part 9 building envelopes will perform when exposed to these higher indoor RH levels for extended periods during the heating season over many years. Operation of the ventilation system, as intended to remove indoor pollutants, will maintain the lower RH level as necessary."*

It is also important to recognize that the NBC contains comprehensive air-leakage control provisions that help ensure adequate performance of wall assemblies using any of the above methods for water vapor control. Thus, the above insulation ratios and vapor retarder requirements in the NBC are predicated on good air-leakage control practices. While the U.S. model building codes (*IRC* and *IBC*) do not include air-barrier provisions, such provisions are included in the U.S. model energy codes and standards (e.g., IECC and ASHRAE 90.1).

An example application of NBC Table 9.25.5.2 (Figure 11) is shown below in Figure 12:



	Inboard			Outboard		
RSI value	0.12	0.08	2.11	0.87	0.12	0.03
Total RSI value	2.31			1.02		
Ratio	$\frac{1.02}{2.31} = 0.44$					

Figure 12. Calculation of Insulation Ratio (2015 NBC Commentary, Figure A9.25.5.2)

The insulation ratio values in Figure 11 are for climates defined by metric Heating Degree Days (e.g., HDD18ºC). These values must be converted to imperial units (e.g., HDD65ºF) for use with Climate Zones as defined in the U.S. (see Figure 1). The conversion factor is 1 HDD18ºC = 1.8 HDD65ºF. The conversion to US Climate Zones (based on HDD65ºF), however, must consider some differences in how climate zones are discretized in the U.S. and Canada. For example, Climate Zone 6 in the U.S. corresponds with a maximum limit of 9,000 ºF-days. When converted to SI units, 9,000/1.8 = 5,000 ºC-days, this would appear to require an insulation ratio of 0.3 from the table in Figure 11, but this value actually applies for only the margin between Climate Zone 6 and Climate Zone 7. Because essentially all of Climate Zone 6 has an HDD65ºF of less than 9,000 ºF-days (5,000ºC-days) an insulation ratio of 0.2 for the maximum 4,999 ºC-days in Figure 11 is applicable to Climate Zone 6. This will be an important consideration when later converting the Canadian practice for use with U.S. defined climate zones.

The following provides an example application of the above insulation ratios in accordance with Figure 11 when a Class I or II (e.g., 1 perm or less) interior vapor retarder is used in Climate Zone 6 and the exterior sheathing is less than 1 perm[3]:

Example #1 (2x4 wall with Class I or II interior vapor retarder)
Cavity insulation = R-15 maximum
Insulation Ratio = 0.2
Minimum required amount of exterior continuous insulation = 0.2 * (R-15) = R-3ci
Acceptable Solution = R15+3ci

Example #2 (2x6 wall with Class I or II interior vapor retarder)
Cavity insulation = R-22.5
Insulation Ratio = 0.2
Minimum required amount of exterior continuous insulation = 0.2 * (R-22.5) = R-4.5ci
Acceptable Solution = R22.5+5ci (rounded up from calculated R-4.5ci)

Finally, the commentary for NBC Section 9.25.5.2 recognizes that foam plastic insulating sheathing *"may serve as the vapour barrier if it can be shown that the temperature of the interior surface of the sheathing will not fall below that at*

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[3] These examples make the simplifying assumption that the insulation ratio is adequately represented merely as a ratio of insulating sheathing (exterior) and cavity (interior) insulation components. This approach is similar to that used in the U.S. Practice discussed earlier.

which saturation will occur." This allowance recognizes the "perfect wall" application of the "temperature controlled approach" to water vapor control. As mentioned, the foam plastic insulating sheathing provides a multi-functional protection of moisture sensitive structural components inside the wall (Lstiburek, 2008).

Derivation of Insulation Ratios

This section investigates the derivation of insulation ratios used in U.S. and Canadian building code provisions for water vapor control as presented in the previous section of this research report.

U.S. Practice

The analysis approach applied to develop the *IRC* and *IBC* insulation ratios for use with Class III interior vapor retarders is very different than that used to justify the Canadian practice for insulation ratios intended to be used with Class I or II interior vapor retarders (e.g., 1 perm or less). A simple steady-state dew point analysis serves as the analysis framework for the current U.S. practice, although its particular use was informed by field studies, modeling, and experience (Lstiburek, 2004; Lstiburek, 2013). This same methodology has been employed for the purpose of making insulation ratio recommendations for light frame cold formed steel construction (Burnette and Bombino, 2009). The methodology provides a condensation analysis of the assembly by determining the temperature of the condensation plane (assumed to be the interior side of the exterior continuous insulation) and checking it against the dew point temperature of the indoor air (assuming a worst-case condition of the condensation plane being directly exposed to moist indoor air).

The design approach assumes that the primary source of water vapor is transported into the wall by air leakage, not vapor diffusion. It further assumes that this air-leakage does not significantly change the temperature conditions within the assembly. This assumption is equivalent to assuming there is no vapor diffusion resistance between the indoor environment and the condensation plane within an assembly. The interior vapor retarder is considered to be completely by-passed. Thus, the result of the check is unaffected by the vapor permeance of the interior vapor retarder as would occur in a typical static or transient hygrothermal analysis. Consequently, the general methodology may be considered by some to represent a "cautious assumption" that will restrain the design of many assemblies (Roppel and Lawton, 2014). But, interior relative humidity values that appropriately decrease with severity of the cold climate were used for a calibrating effect to bring the result in in line with experience and findings from a more extensive transient hygrothermal modeling effort. The methodology is explained in the previously listed references for the US practice (see Table 1), but is most thoroughly described by Lstiburek (2004; 2011).

The following equations, based on a linear relationship between thermal resistance and temperature, explain and replicate the derivation of minimum required insulation ratios using the above-described dew point analysis approach[4]:

$$T_{cp} = T_o + R_e/R_{tot} \times (T_i - T_o) \geq T_{dp} \qquad \text{(Eq. 1)}$$

Solving for the insulation ratio R_e/R_{tot} and substituting $T_{cp} = T_{dp}$,

$$R_e/R_{tot} = (T_{dp} - T_o)/(T_i - T_o) = T_{cr} \qquad \text{(Eq. 2)}$$

To convert to an R_e/R_i insulation ratio, substitute $R_{tot} = R_e + R_i$ and solve Eq. 2,

$$R_e/R_i = T_r / [1 - T_{cr}] \quad \text{or} \quad = R_e/R_{tot} / [1-R_e/R_{tot}] \qquad \text{(Eq. 3)}$$

where,

R_e = exterior continuous insulation component nominal R-value (to the outside of the condensation plane)
R_i = vapor permeable cavity insulation component nominal R-value (to the inside of the condensation plane)
$R_{tot} = R_e + R_i$ (not equivalent to actual or effective R-value or 1/U of the assembly)
T_{cp} = temperature of the condensation plane or inner surface of the exterior continuous insulation (R_e)
T_i = indoor set-point temperature for heating (70 F is used as a default assumption)
T_o = outdoor average temperature for three coldest winter months, Dec-Feb (see Table 2 for default values)
T_{cr} = temperature ratio defined as $(T_{dp} - T_o)/(T_i - T_o)$

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[4] It is important to be sure the insulation ratio being referenced in any given document is properly distinguished as R_e/R_i or R_e/R_{tot}. Both forms are commonly used. While R_e/R_i ratio approaches infinity as the R_i value approaches zero (e.g., exterior insulation only), the R_e/R_{tot} ratio more sensibly ranges from 0 to 1 for cavity insulation only and exterior insulation only extremes, respectively. However, insulation ratios used in the Canadian practice are based on R_e/R_i and that is the format adopted in this research report, unless otherwise noted.

T_{dp} = dew point temperature of indoor air (see Table 2 for default values) based on maximum relative humidity of indoor air at T_i = 70 F (or other indoor set point temperature if used). T_{dp} also may be approximated for a given T_i and RH using the following equation:

$$T_{dp} = T_i - (14.55 + 0.114 * T_i)(1 - RH/100) - [(2.5 + 0.007 * T_i)(1 - RH/100)]^3 - (15.9 - 0.117 * T_i)(1 - RH/100)^{14}$$

Note: Various other empirical equations have been postulated with varying degrees of precision and accuracy in determining the dew point temperature from dry-bulb temperature and relative humidity of air for various temperature ranges. This equation is just one example.

TABLE 2
Simplified Dew Point Analysis Parameters (Winter Conditions)
Used to Determine Insulation Ratios for *IRC* Table R702.7.1 and *IBC* Table 1405.3.1

Climate Zone	Indoor Air Relative Humidity at 70F	Dew point Temperature of Indoor Air at 70F	Average Outdoor Temperature (Dec-Feb)[1]
4 Marine	40%	45F	39F
5	30%	37F	24F
6	25%	32F	10F
7	20%	28F	-7F

Source: Table 1 in BSD 106 (Lstiburek, 2011)

1. The design outdoor temperature values are not reported in Lstiburek (2011), but are reverse engineered by use of Equation 3, the stated indoor air relative humidity at 70F, and the insulation ratios reported in Table 1 for each climate zone. Thus, these represent the static outdoor design temperatures associated with the insulation ratios for the US practice (e.g., *IRC* and *IBC*).

The indoor relative humidity values reported in Table 2 are an index for the purposes of the static dew point analysis method used. These parameters are consistent with the derivation of insulation ratios in the *IRC* and *IBC* (US Practice) as reported in Figure 10 and Table 1. They also are simplified from an earlier methodology as described in Lstiburek (2004) where the indoor relative humidity value was varied depending on the exterior sheathing permeance using a similar methodology although a bit more complicated in its logic of application. For example, guidance in RR-0410 (Lstiburek, 2004) requires a higher indoor relative humidity to be used for low permeance exterior sheathings (e.g., 35% RH in CZ 5, 30% RH in CZ 6, and 25% in CZ 7 for exterior sheathing that is “vapor impermeable”, e.g., <0.1 perm). This RH variation was noted by the author as a compensating “trick” in applying the simple dew point analysis to bring the result into agreement with experience and transient hygrothermal modeling results. These parameters represent an index for wintertime vapor pressure differential ranging from about 350 Pa (Climate Zone 4) to about 600 Pa (Climate Zone 7).

Lstiburek (2011) notes that the dew point analysis parameters shown in Table 2 are “*not the actual service conditions for typical residential occupancy – but the design conditions for the simple steady state design procedure being used*”. Therefore, the relative humidity values in Table 2 are not intended to represent actual targets for control of indoor relative humidity or an explicit limitation on the use of the vapor retarder requirements. Lstiburek (2011) does mention some limitations of use in general terms, such as *“enclosures are ventilated meeting ASHRAE Standard 62.2 or 62.1.”* This qualifier was generally applied to all vapor control strategies, including those with and without continuous insulation. It also implies that ventilation is important to provide at least some unspecified level of control for indoor relative humidity.

It is also notable that design conditions for Climate Zone 8 were not addressed in BSD 106 (Lstiburek, 2011) or other related sources reviewed. But, the insulation ratio for Climate Zone 7 was evidently extended to application in Climate Zone 8 when provisions for use of Class III vapor retarders were first adopted by the *IBC* and *IRC* in the 2006 editions. In addition, it appears that a direct correlation of the outdoor design temperature to the maximum heating degree day limits of the climate zones was not established. However, the design method was demonstrated for specific cities within various Climate Zones (Lstiburek, 2004) and not necessarily at the extreme northern boundaries of the climate zones.

Canadian Practice

The derivation of the insulation ratios reported in Figure 11 relied on a transient hygrothermal modeling approach as reported by Kumaran and Haysom (2000), Kumaran and Haysom (2001), Chown and Mukhopadhyaya (2005), Saber (2014). Based on the NBC 2010, Commentary Section A-9.25.5.2, and the above reports, the analysis parameters are summarized as follows:

- building includes a mechanical ventilation system (between 0.3 to 0.5 air changes per hour)
- a 1 perm (60 ng/Pa-s-m^2) interior vapor retarder
- low perm exterior insulation (as low as 0.017 perm for foil-faced polyisocyanurate board)
- an air barrier (modeled air leakage rates varied in magnitude and in the simulated leakage flow pathway; the leakage rates were based on a prior air-tightness survey of Canadian homes; air leakage rates ranged from 0.024 to 0.1 L/s-m^2 through the wall assembly representing up to the maximum diffuse air leakage limit of 0.1 L/s-m^2 at 75 Pa in the code for defined low-perm materials)[5]
- total occupant moisture generation of 7.5 to 11.5 L/day
- water vapor pressure difference across envelope does not increase above 750 Pa (associated with a maximum wintertime indoor relative humidity of 35%)
- No rainwater intrusion

Figure 13 illustrates the effect of indoor relative humidity on the insulation ratios based on Canadian practice as reported by Brown et al. (2007). The insulation ratios for ~35% indoor relative humidity (red line) are based on the NBC Table 9.25.5.2. The insulation ratios for 50% and 60% indoor relative humidity are as modeled by Brown et al. (2007) with other parameters consistent with the derivation of the NBC provisions as mentioned above. The values in Table 3 are derived from Figure 11. A chart similar to Figure 11 is used later in this Research Report to compare various sources of actual performance data with the U.S. and Canadian insulation ratio requirements (see Figure 14).

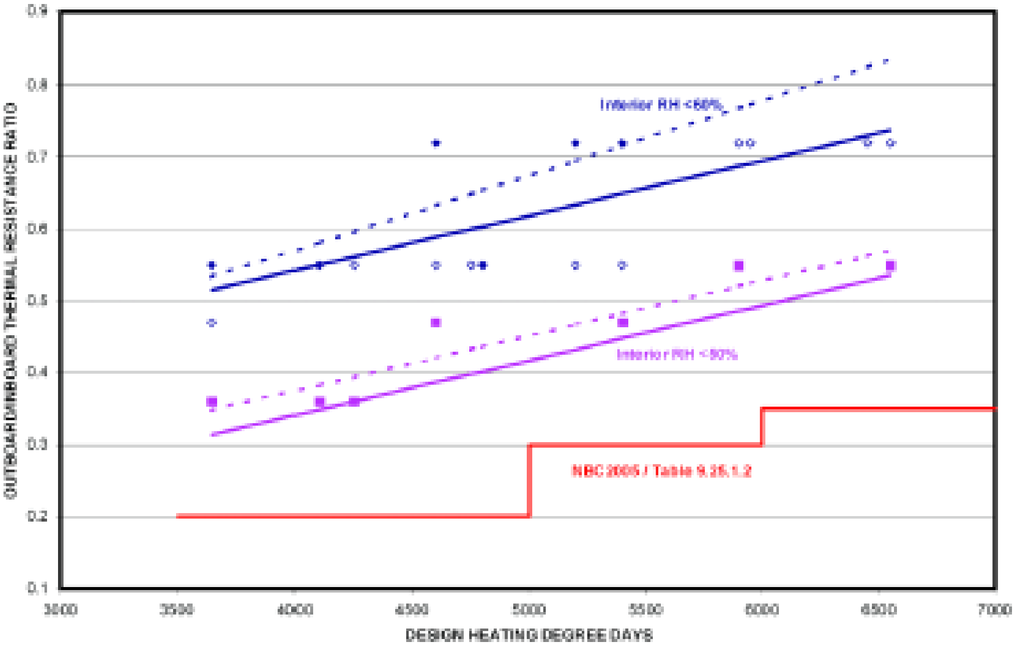

Figure 13: Graphic showing a trend of minimally acceptable insulation ratios at 50% and 60% indoor relative humidity levels in comparison to insulation ratios in NBC 2005 Table 9.25.1.2 for ~35% indoor relative humidity.
Source: Brown et al. (2007)

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[5] The variation in leakage rate was based on determination of an average normalized air leakage area of 1.44 cm^2/m^2 (0.02 in^2/ft^2) from housing air-tightness survey data in Canada. For a typical house size with a typical distribution of air leakage flow through envelope assemblies, the range of 0.024 to 0.1 L/s-m^2 for air leakage through wall assemblies corresponds to an air-change per hour at 50 Pa (ACH50) of about 2 to 8 ACH50 for the whole house. In terms of natural air-change rate for the home, this roughly corresponds to 0.1 to 0.4 ACH (natural).

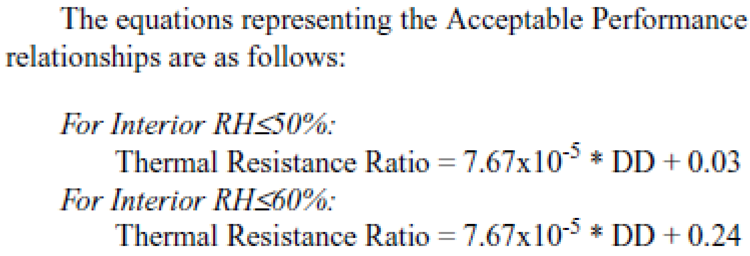
TABLE 3
Evaluation of Effect of Indoor Relative Humidity on Canadian/NBCC Insulation Ratios
[based on 1 perm interior vapor retarder]

US CLIMATE ZONE	Heating Degree Days		Minimum R_e/R_i Ratio		
	HDD65°F	HDD18°C	~35% indoor RH[1] (NBC Table 9.25.5.2)	50% indoor RH Brown et al. (2007)	60% Indoor RH Brown et al. (2007)
4 (mixed)	5,400	3,000	0.2	0.26	0.47
5 (cold)	7,200	4,000	0.2	0.34	0.55
6 (cold)	9,000	5,000	0.2	0.41	0.62
7 (very cold)	12,600	7,000	0.35	0.57	0.78
8 (sub-arctic)	16,200	9,000	0.5	-	-
	19,800	11,000	0.60	-	-
	>21,600	>12,000	0.75	-	-

1 HDD(18°C) = 1.8 HDD(65°F)

1. The ratios shown for the "~35% indoor RH" condition are derived from Figures 11 and 13 based on the minimum ratios permitted for a given range of HDD values. Therefore, these represent a linear trend rather than a step function as shown in Figures and 13.

The linear trends shown for acceptable performance in Figure 13 and used to derive values in Table 3 above are reported by Brown et al. (2007) for the 50% RH and 60% RH conditions as follows:



The equations representing the Acceptable Performance relationships are as follows:

For Interior RH≤50%:

$$\text{Thermal Resistance Ratio} = 7.67\text{x}10^{-5} * \text{DD} + 0.03$$

For Interior RH≤60%:

$$\text{Thermal Resistance Ratio} = 7.67\text{x}10^{-5} * \text{DD} + 0.24$$

Where DD is heating degree days, 18°C basis.

A recent and extensive hygrothermal analysis of the NBC water vapor control provisions provides further confirmation of the above data and the NBC provisions discussed in the previous section (Saber, 2014). The study investigated light-frame wood wall assemblies with varying levels of cavity insulation only with OSB exterior sheathing and several walls with varying R-value and vapor permeance of exterior continuous insulation. In all cases, a 1 perm interior vapor retarder was used (the maximum permeance permitted in Canada for materials considered to be a "vapour barrier"). In addition, moist indoor air exfiltration rates through the assembly were based on worst-case wind orientation conditions and walls located on the third story (e.g., wind + stack effect). Climates were selected to represent wet and dry cold conditions for heating degree days ranging from about 3000 HDD18°C (5400 HDD65°F) to 5120 HDD18°C (9216 HDD65°F). All walls were modeled with 2x6 wood framing. A comparative analysis of mold potential, based on the mold index of Ojanen et al. (2010), served as the primary metric for evaluating relative performance of the evaluated assemblies.[6]

In general, the study by Saber (2014) supports the following observations:

1. The modeled walls with the addition of exterior insulation ranging from R-4 to R-6 and permeance ranging from 0.03 perm to 30 perms always performed better (e.g., lower mold potential) than a comparable baseline wall with cavity insulation only (R-19 and R-24) and OSB sheathing on the exterior.
2. The walls with exterior foam plastic insulating sheathing tended to perform increasingly better (e.g., lower mold index) with increasing exterior insulation vapor permeance or increasing exterior insulation R-value, although the effect of differences in the material's vapor permeance was generally insignificant or slight in an overall sense (e.g., effected little change in mold potential).
3. The study confirmed that the mold potential of walls with or without continuous insulation increased slightly (generally about 5%) with increasing cavity insulation amount (i.e., R-19 vs. R-24) due to the consequence of a colder OSB sheathing surface temperature resulting in greater moisture accumulation. For walls with continuous

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[6] The mold criteria used in Saber (2014) is based on Ojanen, et al. (2010); see the Background section of this report for an explanation of the mold index values (Figure 4).

insulation, this effect was realized only for the case where the exterior insulation amount was held constant (e.g., not increased proportionately with the increase in cavity insulation as required by insulation ratios in the building code).

4. For a hypothetical non-adaptive vapor permeance sheathing material with the same R-value as 7/16" OSB (R-0.62), mold potential decreased with increasing water vapor permeance.
5. Moisture storage effects were found to have a moderate effect on performance; the absence of wood sheathing requires an increased insulation ratio (more exterior insulation) to compensate for the decrease in moisture storage capacity and maintain equivalent performance. The significance of differences in moisture storage on required insulation ratios is addressed later in this report and references relevant data from Saber (2014).
6. The performance of the modeled assemblies depended heavily on the "combined effect" of three main environmental/climate parameters: Heating Degree Days (HDD), Moisture Index (MI), and wind speed.

It should be noted that the mold index used in the Saber (2014) study to judge and compare the performance of the many wall assemblies evaluated was presented in various ways. First, various points of the wall were considered and, at particularly sensitive regions of the walls, the mold index with or without exterior insulation experienced maximal values for periods of time that exceeded a value or 4 (6 being the most severe). A value of 4 indicates potential for significant visual mold coverage at the specific locations. Averaged values were also considered, including spatially and temporally averaged values which dramatically lowered the magnitude of the mold index in an overall sense, but tended to obscure the performance in a detailed sense. A spatial average of maximum values was also considered. Interpreting these averaged values requires judgment as to their meaning in regard to an acceptable performance baseline. Thus, the study tended to use the averaged mold index in a relative (comparative) manner.

The use of the mold index does provide a reasonably consistent performance-based approach to consider a consistent performance benchmark for the wall assemblies evaluated. For example, the cavity insulation only wall with OSB sheathing had a spatially averaged maximum mold index of 3 whereas the walls with added continuous insulation amounts of R-4 through R-6 had values of approximately 2 for the Edmonton climate (HDD65F = 9,216) which is slightly greater than Climate Zone 6 in the U.S. (refer to Figure 40 in Saber (2014)). To achieve a mold index of 2 or less (below the limit of visual mold growth), the required amount of exterior insulation for an R-24 cavity insulation amount and a 1 perm interior vapor retarder would be R-5 which results in an insulation ratio, Re/Ri, of 5/24 = 0.21. For the wall assembly with cavity insulation only and exterior OSB sheathing, interior vapor retarder of somewhat less 1 perm (e.g., a Class I or polyethylene vapor barrier) is needed to achieve a consistent mold index of 2 or less.

When viewed from the perspective of using the mold index to establish a consistent performance baseline (rather than choosing the cavity only wall as a benchmark for acceptable performance irrespective of its mold index), the findings lend support to the insulation ratios in the NBC (see Table 3) and tend to question the veracity of the wood sheathing exception in the NBC provisions when a maximal 1 perm interior vapor retarder is used (which applies in all climate zones) as presented in the previous section of this report addressing the codified Canadian practice. Because the cavity only insulation wall was used as an accepted baseline (with a mold index of approximately 4 which is associated with the potential for extensive visible mold growth), using a mold index of 2 as a safe criteria (just below the onset of visible mold growth) would align with the current insulation ratio requirements in the NBC, but require reconsideration of the newly approved exception for use of R4 exterior insulation for climates up to 10,800 HDD65F and also the existing exception for walls with wood structural panel sheathing (particularly OSB) exempting the need to use an insulation ratio. Furthermore, the generic representation of performance of an R-0.62 non-adaptive (static vapor permeance) exterior sheathing material in Figure 42 of Saber (2014) shows that a minimum exterior vapor permeance of even up to 5 perms (with a 1 perm interior vapor retarder) still results in a maximum average mold index of greater than 3 for non-insulating exterior sheathing materials (e.g., no exterior insulation). This suggests that the longstanding use of the 1 perm trigger for application of insulation ratios in the NBC should be significantly increased (Brown, et al., 2007) or the NBC insulation ratios be used unless an interior vapor retarder of somewhat less than 1 perm is required (e.g., a polyethylene vapor barrier) for assemblies without exterior insulation.

Performance Data Evaluation

General

Figure 14 presents the insulation ratio requirements from Table 1 (US practice) and Figure 11 (Canadian practice) reported earlier covering the full gambit of interior vapor retarder conditions ranging from Class I through Class III. Also, various data points from hygrothermal modeling, test hut, and field studies are included in Figure 14 representing observations of successful and poor moisture performance in relation to the codified US and Canadian practices. These data points provide a means to assess the current US and Canadian practices and to evaluate those practices in light of current empirical knowledge.

At face value, the graph of insulation ratios in Figure 14 draws attention to an inconsistency in the in the relative trend of insulation ratio requirements between the two cases for Class I/II interior vapor retarder (Canadian practice – the red line) and for Class III interior vapor retarder (US practice – the blue line). In particular, the insulation ratios coincide in the coldest range of heating degree days despite the difference in interior vapor resistance. Instead, the insulation ratios for use with a Class III interior vapor retarder should always trend above that required for use with a Class I or II interior vapor retarder. Even with some reasonable amount of air-leakage considered, a wall with a Class III interior vapor retarder will tend to have a higher rate of vapor diffusion from the interior to the condensation plane and this should always necessitate a somewhat greater insulation ratio in all Climate Zones. This inconsistency may be explained in part by differences in analysis method and also differences in assumptions as presented in the previous section. But, for reasons mentioned earlier in this report, the Climate Zone 8 insulation ratio for use with Class III interior vapor retarders appears to be an artifact of the code development process in the U.S. whereby the solution for Climate Zone 7 was inadvertently extended to include Climate Zone 8.

Canadian Insulation Ratios

Some of the data points in Figure 14 lend support the insulation ratios as reported by Brown et al. (2007) and, thus, those in the 2015 NBC as well. For example, two data points from a test hut study by HIRL (2013) using a 55% indoor relative humidity tend to agree with the insulation ratios determined by Brown et al. (2007) and, thus, confirm the analysis approach used for the minimum insulation ratios in 2015 NBC Table 9.25.5.2 as reported in Figure 11 for use with a Class I or II interior vapor retarder (maximum 1 perm).

Similarly, a case study data point based on condensation problems reported by GBA (2013a) for a condition with inadequate insulation ratio tends to support the adequacy of a minimum 0.2 insulation ratio required by NBC Table 9.25.5.2. A data point from Smegal and Grin (2013) also provide confirmation at a 50% indoor relative humidity condition as does a similar data point from CMHC (2009) at a 50% indoor relative humidity with a Class II interior vapor retarder paint. The same CMHC study included an identical wall with a Class III (latex paint) interior vapor retarder which experienced moisture problems and which testifies to the importance of the interior vapor retarder (or much higher insulation ratios) when interior relative humidity conditions are high. While these data points generally fall within Climate Zones 4 and 5 (up to 7,200 HDD65ºF or 4,000 HDD18ºC), they provide a basis for having some confidence in the Canadian practice and also the additional modeling by Brown et al. (2007) for a range of indoor relative humidity conditions. These findings complement the apparent absence of evidence suggesting any problem with the Canadian practice since the time the provisions were first implemented in the 1995 NBC.

Conversely, a test hut study by Craven and Garber-Slaght (2012) in Fairbanks, AK (~ 13,560 HDD65ºF) may be misinterpreted to imply that the Canadian insulation ratios are non-conservative even for an insulation ratio as great as 1.4 and even with a Class I (4 mil polyethylene) interior vapor retarder. However, in this test hut study, a wintertime indoor relative humidity of 40% was used together with an intentionally leaky air-barrier installation which are considered very conservative test conditions for the Fairbanks environment (where indoor relative humidity levels should generally be maintained well below 40% during the coldest months of the winter, if for no other reason than to prevent excessive condensation on windows and doors). As additional evidence that the test condition is overly conservative, even the traditional wall assembly without exterior insulation and only R-11 fiberglass batt cavity insulation with a Class I (poly) vapor retarder exhibited a similar degree of mold growth on the wood-based OSB sheathing. For both of these walls, mold growth was initiated only within the vicinity of the intentional air-leakage point (an electric box penetration). If localized visible interstitial mold growth is to be prevented in walls with substantial indoor air leakage (exfiltration) and high indoor relative humidity, then it appears that the most viable approach may require substantially greater amounts of exterior continuous insulation than currently required in the Canadian practice and also in the US practice. Therefore, this study may be better understood as providing additional evidence of the importance of providing adequate indoor relative humidity control and air leakage control in coordination with reasonable vapor control practices for very cold climates. The many other data sources and modeling studies included in Figure 14, together with the several modeling studies confirming the Canadian insulation ratios in the 2010 NBC (as discussed in the previous section), give no indication of any real or significant concern regarding their effectiveness in practice (with the possible exception of the recent changes to the 2015 NBC as considered in the previous section of this research report).

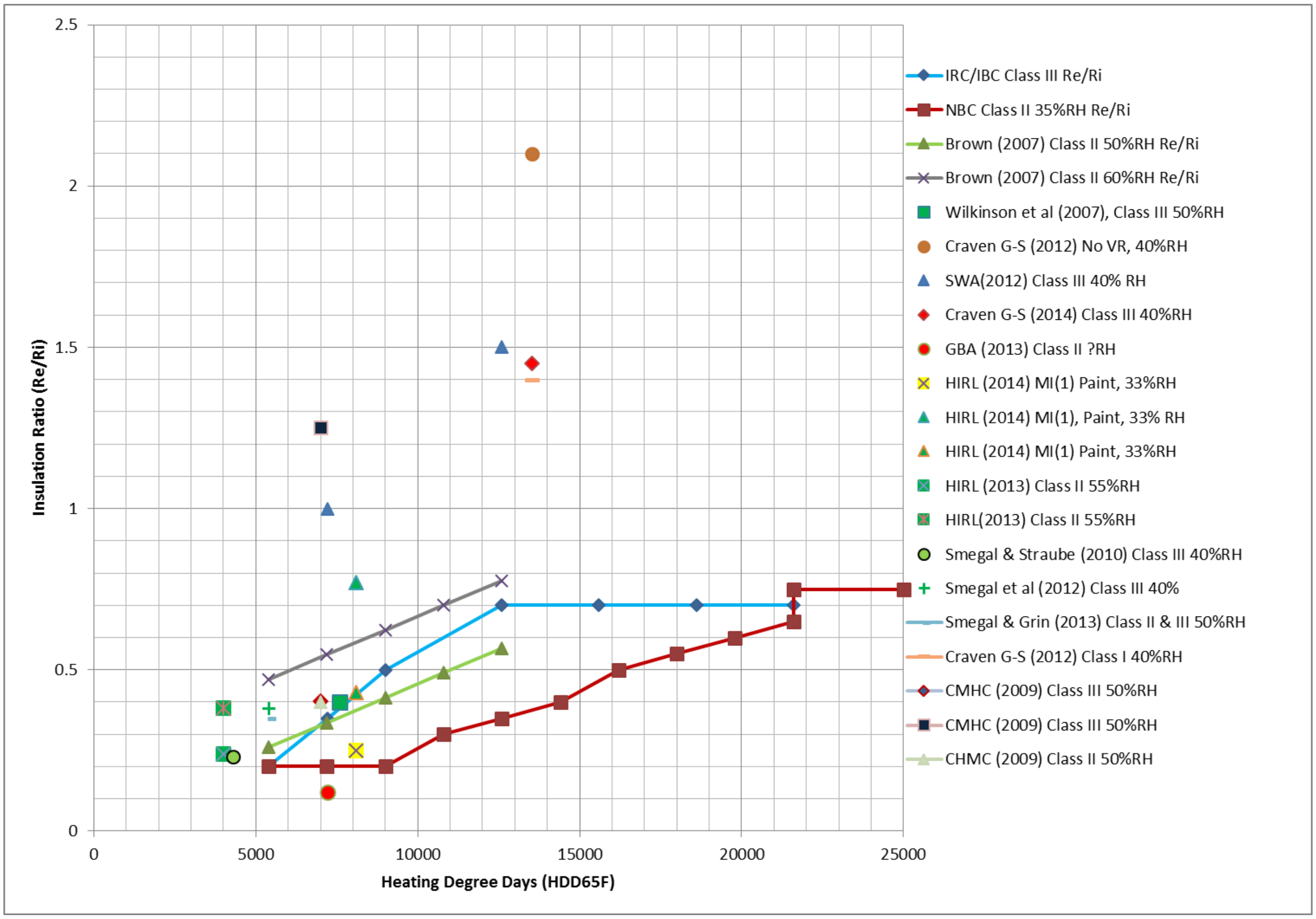

Figure 14: *IRC*/*IBC* and NBC Wall Insulation Ratio Requirements Compared to Data Points from Various Modeling, Test Hut, Case Studies, and Field Monitoring Studies Reported in the Literature

U.S. Insulation Ratios

Several modeling, test hut, and field studies spanning Climate Zones 4 through 6 provide confirmation of acceptable performance of wall assemblies using the insulation ratios reported in Table 1 which serve as the basis of exterior continuous insulation requirements in the *IBC* and *IRC* for use with Class III interior vapor retarder. These data also are shown in Figure 14.

For example, a test hut data point from Wilkinson et al (2007) shows that a wall assembly nearly exactly coinciding with the *IRC*/*IBC* Class III insulation ratios demonstrated acceptable performance with a high indoor relative humidity of 50%. However, this is balanced by another data point for 50% indoor relative humidity from a test hut study with Class III vapor retarder and a similar Re/Ri of 0.4 which experienced moisture problems; an insulation ratio of 1.25 was suggested as necessary under the condition of Climate Zone 5 and high indoor relative humidity (CMHC, 2009). Both of these data points represent conditions well above the intended indoor relative humidity values for the *IBC*/*IRC* insulation ratios and may be considered as very stringent tests that demonstrate the significance of indoor relative humidity control.

Also, a successful performance is shown for a data point reported by HIRL (2014) representing a field monitoring study site in Climate Zone 6 with an indoor relative humidity of 33%. Likewise, two data points reported from test hut studies by Smegal et al (2010) and Smegal and Grin (2013) agree reasonably well with the minimum insulation ratios required by the *IRC* and *IBC* (see Table 1) as shown in Figure 14.

Finally, a field study data point from HIRL (2014) with an insulation ratio less than required by the *IBC*/*IRC* but with 33% indoor relative humidity demonstrated marginal performance in Climate Zone 6, suggesting together with other data discussed above, that a code compliant insulation ratio would have performed adequately. Thus, the acceptability of minimum insulation ratios in the US Practice is reasonably well confirmed for Climate Zones 4 through 6. Consequently, the simple dew point analysis approach and design conditions as described previously (see Equation 3 and Table 2) appear to provide a suitable basis for solutions in Climate Zones 4 through 6.

Conversely, three studies may be misinterpreted as indicating that the insulation ratio values reported in Table 1 for Climate Zones 6-8 are grossly inadequate (SWA, 2012; Craven and Garber-Slaght, 2012; Craven and Garber-Slaght, 2014). For 40% indoor RH during the winter, SWA (2012) found from hygrothermal modeling that walls with insulation ratios of 1.0 (Climate Zone 6) and 1.5 (Climate Zone 7) are required to prevent the potential for moisture problems. For Climate Zone 8 (e.g., Fairbanks, AK at ~13,560 HDD65ºF), Graven and Garber-Slaght (2014) found through a test hut study that an insulation ratio (Re/Ri) of greater than 1.4 is necessary to avoid moisture problems when a Class III interior vapor retarder is used with indoor relative humidity of up to 40% for an extended period during the winter. Without any interior vapor retarder (unpainted gypsum wall board), Craven and Garber-Slaght (2012) found in a prior test hut study that the insulation ratio must be at least 2.0 to prevent the initiation of mold growth. Both of these studies included pressurization of the test hut to induce indoor air exfiltration and the 2012 study included an intentional air-leakage pathway. The 40% indoor relative humidity level used in these studies, however, is conservative in comparison to recommendations from multiple sources for indoor relative humidity control in very cold and sub-arctic climates. Therefore, these studies do not appear to provide a realistic basis for suggesting changes to the insulation ratios in Climate Zones 6-8.

While the SWA (2012) modeling study indicates that insulation ratios for Climate Zone 6 may also be non-conservative, other studies covering Climate Zones 4 through 6 using test hut studies and field monitoring indicate that the insulation ratios in Climate Zone 6 are adequate. Because the same modeling assumptions in SWA (2012) were used for Climate Zones 6 and 7 and the result is very similar to a data point from Craven Garber-Slaght (2014) in Climate Zone 7, this observation tends to suggest that the SWA (2012) and Craven and Garber-Slaght (2012;2014) studies do indeed represent conservative test hut or modeling conditions. These studies are best understood in the context of the more robust data sources confirming the current *IBC* and *IRC* insulation ratios in Climate Zones 4-6 which do exhibit a trend suggesting a possible need to revisit the insulation ratio in Climate Zone 7 (see Figure 14), but not nearly to the extent suggested in the above two studies. The need to make adjustment in Climate Zone 8 is more obvious for reasons stated earlier. As mentioned, such adjustments would cause the US practice to trend more consistently above the insulation ratios represented by the Canadian Practice as should be expected given the differences in interior vapor retarder requirements.

In Alaska, a statewide minimum insulation ratio requirement of 2.0 is applied as an amendment to the 2012 IECC (AHFC, 2012). This insulation ratio requirement has been in practice at least since the 1990s (Musick, et al., 1998). But, it may be interpreted to only apply to a vapor control layer (vapor retarder) installed within the insulation layers with no vapor retarder on the interior side of the assembly (refer to https://www.ahfc.us/pros/builders/building-energy-efficiency-standard/, 8/16/2018). This assumption differs from the approach of always using a Class III interior vapor retarder in the *IRC*/*IBC* practice. Furthermore, it appears that if a Class I or II interior vapor retarder is applied on the warm side of an assembly, then there is no minimum limit to the insulation ratio in the Alaskan practice as also is the case in the current *IRC* provisions (US practice). Regardless of these distinctions and despite the basis for the 2.0 insulation ratio not being found in the reviewed literature, this value does align with the data point from Craven and Garber-Slaght (2012) for the “No VR, 40% RH” condition shown in Figure 14. Thus, for reasons stated earlier in reviewing available test data, it appears that the insulation ratio of 2.0 is intended to be a conservative solution for the case of high indoor relative humidity, a leaky air-barrier, and no interior vapor retarder. This understanding is found to be consistent with an analysis later in this research report to develop requirements for walls that rely substantially on exterior insulation only with no interior vapor retarder (i.e., the “perfect wall”).

Based on the above review of multiple lines of evidence, the *IRC* and *IBC* insulation ratios for use with Class III interior vapor retarders appear adequate for Climate Zones 4-6. However, there is clear indication for the need to change the insulation ratio for Climate Zone 8 while any modest change to the insulation ratio for Climate Zone 7 must be determined by an analysis that agrees with and appropriately extends the successful performance observed in Climate Zones 4-6 to Climate Zones 7 and 8.

Walls without Exterior Continuous Insulation

By their very nature, light-frame walls without exterior continuous insulation have a very low insulation ratio and, therefore, are not intended to perform in accordance with a “temperature controlled” (insulation ratio) design approach as discussed in the Background section and evaluated in the previous sections of this report. Instead, they function on the basis of a “permeance controlled” design approach whereby water vapor control on the interior side of the wall assembly becomes more important in cold climates. Also, maintaining a suitably high vapor permeance on the exterior side of the wall becomes significantly more important, yet the properties of many materials used on the exterior of walls (such as OSB sheathing or other structural sheathing products) are not manufactured to control vapor permeance as a design property and building codes do not require it (i.e., the U.S. codes ignore the issue and the Canadian code specifically exempts it). Thus, moisture control design and actual performance reliability may result in unpredictable or varied outcomes in end use, even when following the code, accepted practice, or commonly assumed properties. This section evaluates this potential concern in terms of observed performance from available data for actual assemblies in end use as was done in the previous sections for walls with exterior continuous insulation.

A test hut study (HIRL, 2013) investigated the performance of wood frame wall assemblies with vapor-permeable cavity insulation and OSB sheathing using a Class III (latex paint) interior vapor retarder and vented exterior sheathing built in accordance with the *IRC*. The study was conducted in Climate Zone 4 over the course of two winter cycles. While the winter conditions were mild (outdoor temperatures generally above average), the test hut indoor relative humidity was run at a conservative 55% level, consistent with the ASHRAE 160 standard (which was recognized as a conservative criteria in the study). The water vapor permeance of the OSB sheathing was measured and found to be 1.4 perm (wet cup) on average – well below typical expectation of about 3.8 perms on average. In addition, the interior latex paint was found to have a permeance of 34 perm (dry cup) – well above expectation and the 10 perm maximum limit anticipated by the *IRC* provisions. These two findings tend to confirm a concern with the “reliability” of the permeance controlled design approach due to uncertainties in the control of material properties (even when typical assumptions may be made as a matter of design or code compliance). Consequently, the properties of these two key interior and exterior layers on the assembly erred in the direction of creating a more severe moisture load condition on the OSB sheathing during the winter (but with the benefit of increased drying to the interior in the summer).

As a result of the above conditions in the HIRL (2013) study, the OSB sheathing was exposed to high humidity levels and condensation and it sustained moisture contents of 23% to 25% over most of the winter season and into early spring. OSB samples were removed from two wall configurations and bending strength tests were conducted.[7] The OSB walls which used a Class II (Kraft paper) interior vapor retarder had experienced moisture contents of less than 20 percent and were used as a baseline for bending strength. In comparison, the OSB from the wall with a Class III vapor retarder which had experienced the higher moisture contents for two winter cycles, exhibited a 19 percent average decrease in bending strength. To the extent such damage may be occurring in actual buildings (perhaps randomly, or at a slower rate, or not at all in some cases), the consequences may be hidden for quite some time because of the redundancy of light-frame structural systems and concealment of the sheathing by exterior and interior finishes. Clearly, control of the OSB sheathing moisture content is not just a mold growth concern; it is also a structural and material durability concern.

Walls in the HIRL (2013) study with exterior insulation with a Class II interior vapor retarder (Kraft paper facing on fiberglass batts) performed without observed moisture problems and maintained OSB moisture contents below 15 percent (and similar to or slightly better than the walls without exterior insulation and also with a Class II Kraft paper interior vapor retarder). This finding speaks to the value of using a Class II Kraft paper interior vapor retarder in Climate Zone 4 on walls without or without exterior continuous insulation. Finally, this study signals a potential need to re-evaluate the Class III vapor retarder provisions for application on walls without exterior continuous insulation in adequate amount, particularly the reliability of latex paint permeance values and uncertainty in OSB water vapor permeance which are critical material properties for assemblies without exterior continuous insulation.

In another study, double stud walls with 12 inches of open cell spray foam (ocSPF) or 12 inches of dense-pack cellulose insulation, both using a Class III (latex paint) interior vapor retarder and exterior OSB sheathing, were monitored for three winters in an actual home. As reported by Lstiburek, Ueno, and Musunuru (2015), instrumentation in the cellulose insulated wall indicated extended winter periods with high moisture content in the OSB sheathing and high relative humidity at the sheathing interior surface, as well as possible condensation. The instrumentation indicated less severe conditions in the ocSPF insulated wall, but not without risk. The problems were reported to be worst when the house experienced a 30-50% indoor relative humidity during the second of the three monitored winters due to occupancy and

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[7] According to Chapter 14 of the USDA-FPL *Wood Handbook*, changes to bending strength to wood based products due to environmental factors is a reasonable proxy for other structural property changes as well. These other properties associated with bending strength may include shear strength and fastener edge-tear-out resistance which relate to wall bracing capacity.

late-winter operation of the ventilation system. The other two winters registered indoor relative humidity in the range of 10-20% (first winter) and 20-30% (third winter). Walls were disassembled and the sheathing, framing, and insulation conditions were observed to be "surprisingly intact." While it was reported that "no signs of moisture damage or mold were visible", it was also reported that slight grain raise of the OSB on the cellulose wall was observed. Grain raise is indicative of the OSB sheathing's exposure to high moisture levels. However, no testing was reported to have definitively determine if the OSB structural properties had been affected. Based on the HIRL (2013) study, it appears likely that some structural property degradation occurred based on the visual observation of "grain raise" in the one case and the instrument data showing high moisture levels during one or more of the three winters for both vapor permeable cavity insulation only conditions.

Lstiburek, Ueno, and Musunura (2015) used the above described walls as a basis for WUFI hygrothermal modeling calibration and verification (in addition to other assembly data similarly used for the same benchmarking purpose). For example, they modeled these walls using the ASHRAE Standard 160 mold criteria and concluded that the criteria "are providing false positives in terms of wall failures" based on the visual inspection of the above-described walls after three years of exposure. They also applied the alternative mold growth model and index of Viitanen and Ojanen (refer to Background section and reference to Ojanen et al. (2010)). With this approach, the OSB sheathing on the ocSPF insulated wall remained below a mold growth index of 2 (no visible mold growth) whereas OSB sheathing on the cellulose insulated wall remained marginally below a mold growth index of 3 (visual mold growth <10% of surface area). Based on this comparison and others in the report, it was concluded that the Viitanen and Ojanen mold growth index provides a better correlation to observed performance when the WUFI model, including consideration of rain water wetting and air-flow, is properly "tuned" (for which recommendations were made in the report). However, as mentioned previously, mold growth is not necessarily the only or the most significant limit state of concern in some circumstances. Exposure to high moisture levels is also a limit state of concern in terms of long term durability of OSB sheathing and other similar moisture-sensitive exterior wall sheathings. For example, the investigated walls (particularly the cellulose insulated wall) experienced repeated high moisture levels in the OSB for the duration of each winter and a similar level of moisture exposure was shown in the HIRL (2013) study to have a significant impact on the structural property of the OSB sheathing which cannot be readily discerned by visual inspection.

While it is apparent from the Lstiburek, Ueno, and Musunuru (2015) modeling study that the more conservative and limited ASHRAE Standard 160 mold growth criteria is not a suitable predictor of varying degrees of mold risk, it may have served as a substitute in protecting against structural durability concerns with long term moisture cycling in walls with high moisture levels occurring in the winter, even though drying out at other times of the year. Thus, it may be concluded that an appropriate moisture content limit also is needed as well as an appropriate limit state for the mold index for which a mold index of 3 as determined for the cellulose insulated wall may be considered non-conservative based on the observed results and instrumented data.

From a practical perspective related to the goals of this research report, the observed performance of the cellulose insulated walls with repeated episodes or cycles of high wintertime OSB moisture levels indicates that the OSB sheathing may not be adequately protected by the use of a Class III (latex paint) interior vapor retarder in Climate Zone 5. Consequently, Ueno (2015) recommended consideration of a Class II vapor retarder for such walls insulated with cellulose. The OSB sheathing on the ocSPF wall, however, received some protection against water vapor due to the ~2 perm value of the 12-inch-thick ocSPF in addition to the interior latex paint as well as its lower air-permeability in relation to cellulose. Thus, the use of a Class II vapor retarder for this condition (even though high moisture levels were experienced when the ventilation system failed to operate for a large portion of the winter season) was considered a judgment call. In both cases, use of a Class I interior vapor retarder in Climate Zone 5A was not recommended for reasons of its impact on the ability of the wall assemblies to dry to the interior. Also, the findings from early results of this monitoring study and several other similar studies on the performance of double stud wall assemblies are reported by GBA (2013b) and all seem to indicate similar findings in relation to exterior sheathing moisture content concerns for double stud walls.

In another actual occupied home study in Climate Zone 5, twelve homes were instrumented and monitored, including 6 identical homes with R20 Kraft-faced fiberglass batt cavity insulation with OSB exterior sheathing and with no exterior insulation (Dow, 2014). The walls included house wrap with a relatively high water vapor permeance (i.e., Tyvek) as an exterior air-barrier. The indoor relative humidity during the coldest month of the year varied from 25% to 35%, mainly attributed to occupant behavior differences. For these homes with conventional 2x6 wall construction, the OSB sheathing reached 23% moisture content on average during the coldest months of the winter (similar to the HIRL (2013) study above, but under more representative environmental conditions). Several of the homes experienced up to 30% moisture content in the OSB sheathing, well above a commonly accepted limit of 20% moisture content. These findings suggest that a Class II (Kraft paper) interior vapor retarder may not be sufficient to adequately protect the OSB sheathing against typical water vapor pressure differentials during the winter in Climate Zone 5 when exterior insulation is not used. This finding also agrees with the findings reported previously from Saber (2014) where similar modeled walls were found to have a relatively high risk potential for visible mold growth in comparison to walls with a minimally code-compliant amount of exterior foam plastic insulating sheathing (per NBC insulation ratios discussed previously).

It should be noted, however, that the Dow (2014) data is for a colder than average winter (e.g., 7,558 HDD65F in 2013-2014 which is approximately a 40-year return period winter for Midland, Michigan). But, the heating degree days recorded only slightly exceeded the maximum limit (northern boundary) of 7,200 HDD65F for Climate Zone 5. A previous report on data from the same homes for a more typical winter (i.e., 6,559 HDD65F which is slightly warmer than the average 6,808 HDD65F for Midland, MI) shows that the moisture content of the OSB reached a peak of 23% and the winter average was under 20% (Parsons and Lieburn, 2013). This speaks to the potential importance of considering extreme winter conditions for hygrothermal evaluations in contrast to the typical or mean conditions representative of climate zones as defined by heating degree days for energy code purposes. It also speaks to the sensitivity of a given wall assembly design to the variation of winter conditions within a given climate zone, in this case a wall with a Class II interior vapor retarder and R20 Kraft-faced fiberglass batt insulation with a 7/16” OSB exterior sheathing in Climate Zone 5. For example, in an average winter the performance may be marginally acceptable, but in an extreme winter the performance may be clearly unacceptable. Similarly, performance of a given wall assembly in the more northern extreme of a climate zone will be much different than at the more southern extreme of a climate zone. Thus, it is important to associate and interpret data points (such as those shown previously in Figure 14 and others discussed in this section) with the specific conditions of each study, including the actual winter outdoor conditions and the indoor relative humidity experienced.

Yet, still other data points also tend to agree with the above observations regarding vapor retarder applications with OSB sheathings and vapor-permeable cavity insulations in a variety of cold climates for walls without exterior insulation. For example, the test hut study by Craven and Garber-Slaght (2010) in Fairbanks, AK (Climate Zone 8) found mold growth on the OSB sheathing for a wall with only R11 cavity insulation with a Class I (4 mil poly) interior vapor retarder. An air-leakage pathway through the assembly was included in the study. The test hut was generally maintained at 40% relative humidity (a conservative condition) during two winters which experienced slightly warmer winters than average (i.e., average is 13,933 HDD65F and the two winters 2009-2010 and 2010-2011 were 13,082 and 13,601 HDD65F, respectively). In contrast, a field monitoring study of an actual occupied home by HIRL (2014) in Climate Zone 5A (a less severe climate) using a wall assembly with R23 air-permeable cavity insulation and OSB sheathing with a Class I (4 mil poly) interior vapor retarder performed without recorded moisture problems (OSB moisture contents of less than 15%) in two homes which experienced winter time indoor relative humidity of 28% and 40%.

The above several studies collectively indicate value in considering the use of a Class I interior vapor retarder with assemblies having vapor-permeable cavity insulation and OSB exterior sheathing in Climate Zones 6-7 and possibly also Climate Zone 5 with some reservation in recognition of the interior drying potential trade-off and also possible concern with solar-driven inward vapor drives with use of reservoir claddings. Similarly, these several studies collectively indicate value in considering use of a Class II (Kraft paper) interior vapor retarder for walls with OSB exterior sheathing and vapor-permeable cavity insulation in Climate Zone 4 and marginally also in Climate Zone 5, recognizing that a Class I interior vapor retarder may better control wintertime moisture accumulation in the exterior sheathing.

Improvements & Additional Solutions

U.S. Insulation Ratios (Climate Zones 7 & 8)

In the previous section of this research report, current practices in the U.S. and Canada were evaluated in comparison to various data sources representing actual and predicted performance under various conditions. While the findings tend to support the current practice in the U.S. and Canada, one area for potential improvement relates to insulation ratios in Climate Zones 7 and 8 for use with Class III interior vapor retarders (i.e., the U.S. practice). Therefore, this section is devoted to refining the analysis method used to derive the insulation ratios for the U.S. practice as a means to then recommend improvements. A similarly compelling need to consider improvements to insulation ratios used with Class I or II (≤ 1 perm) vapor retarders (i.e., the Canadian practice) was not identified.

First, a more robust correlation of outdoor design temperature with heating degree days is needed for the dew point analysis so that the outdoor design temperature condition (see Table 2) can be associated with the maximum heating degree day limits of the Climate Zones associated with the insulation ratios used in the code. The result of this exercise is shown in Figure 15 with findings and recommended outdoor average design temperatures reported in Table 4. As before, these design temperatures are intended for use with the simplified dew point analysis used as the basis to determine minimum insulation ratios for use with a Class III interior vapor retarder in the *IRC* and *IBC*.

The climate data in Table 4 also is useful for other static hygrothermal analysis methods such as the Glaser method or Kieper method (*ASTM*, 2009). Furthermore, this data can be extended to the development of an annual cycle of monthly average outdoor temperatures for use with the Kieper method in a semi-transient manner (e.g., refer to DIN 4108-3 standard and Kunzel et al., 2011). This application of the Kieper method is used later in this research report for the purpose of evaluating various potential enhancements to current vapor retarder practices.

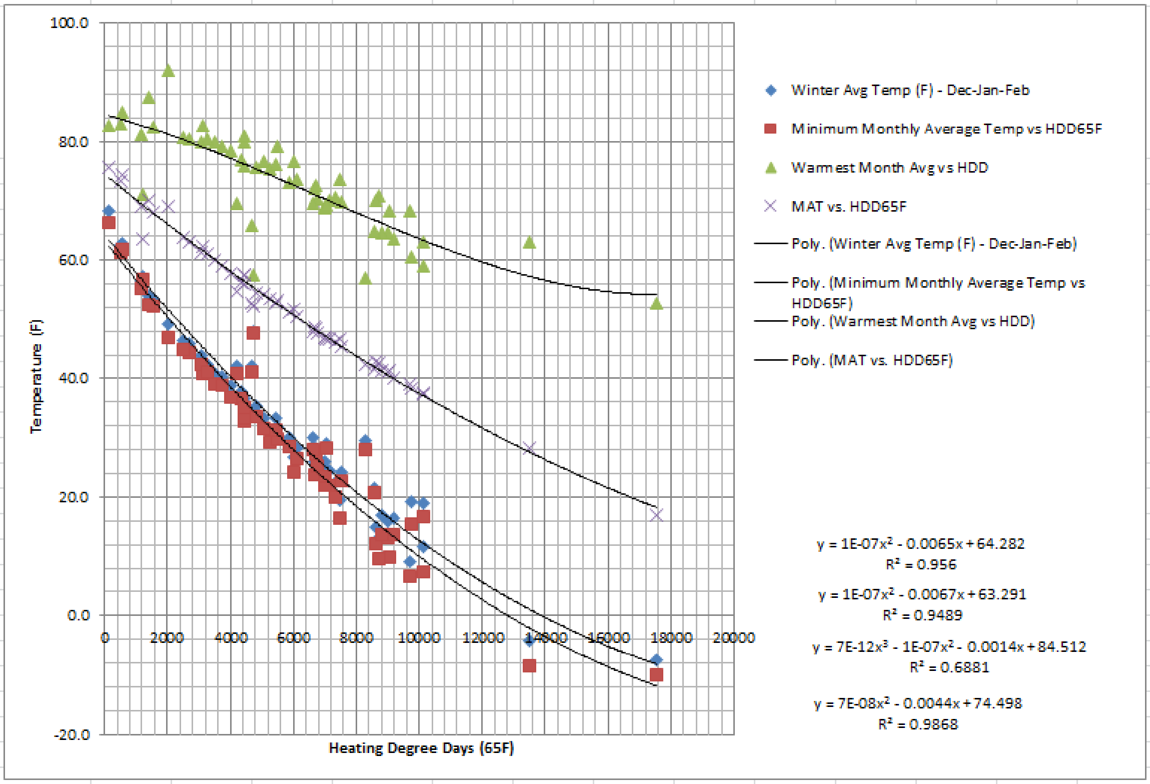


Figure 15: Analysis of climate data from ASHRAE Handbook of Fundamentals (2013) to determine relationship between heating degree day (65F basis) and three design parameters of interest: (1) coldest monthly average temperature and winter (Dec-Feb) average temperature, (2) warmest month average temperature, and (3) mean annual temperature (MAT).

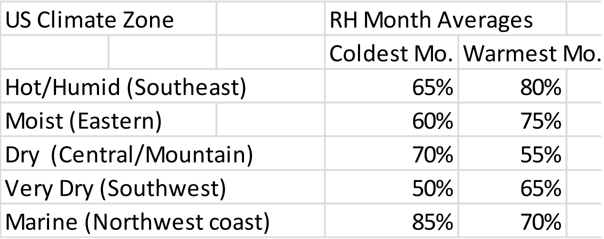
TABLE 4
Average Outdoor Design Temperatures vs. HDD65F and Climate Zone
(based on analysis in Figure 13)

US Climate Zone	Max HDD65F	Avgerage Outdoor Temperature (°F)			
		Dec_Feb	CoMoAvg	WaMoAvg	M.A.T.
	0	64.3	63.3	84.5	74.5
	1800	53.1	51.7	81.6	66.8
3	3600	42.7	41.0	78.1	59.6
4C	5400	39.3	38.5	63.4	49.9
4	5400	33.3	31.2	74.2	52.8
5	7200	24.8	22.3	70.1	46.4
6	9000	17.1	14.3	66.1	40.6
7	12600	4.6	1.1	59.2	30.2
8a	16200	-4.3	-8.5	55.3	21.6
8b	>16200	Design using local data			

1. Values for Climate Zone 4C are based on separate analysis of climate data for a representative sample (n=16) of weather stations located in Climate Zone 4C and represent a “worst-case” bias for design purposes (e.g., coldest and warmest average temperature values).
2. As a point of reference, the annual extreme low (winter) temperature is generally about 30°F below the coldest month average temperature (‘CoMoAvg’) or 15°F below for Climate Zone 4C.

3. Climate Zone 8 is broken into two sub-zones due to the large range of conditions represented.

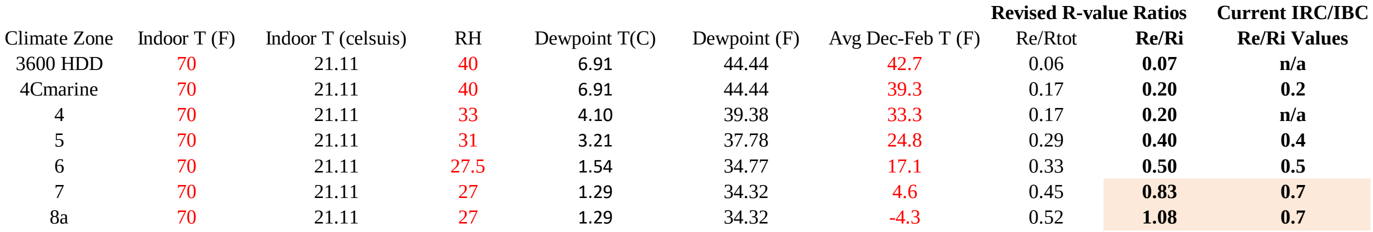
In a similar fashion, climate data from ASHRAE *Handbook of Fundamentals* (2013) were reviewed to roughly typify monthly average outdoor relative humidity for different climate classifications as shown in Figure 16 below. However, these values are not applicable to the simple dewpoint analysis which only evaluates the temperature of the condensation plane relative to the dewpoint temperature of the indoor air. This data is applicable for use with the Glaser or Kieper static analysis methods and can be used to construct a representative sinusoidal annual trend for monthly average outdoor relative humidity.



US Climate Zone	RH Month Averages	
	Coldest Mo.	Warmest Mo.
Hot/Humid (Southeast)	65%	80%
Moist (Eastern)	60%	75%
Dry (Central/Mountain)	70%	55%
Very Dry (Southwest)	50%	65%
Marine (Northwest coast)	85%	70%

Figure 16: Outdoor relative humidity characterization for coldest and warmest months in U.S. Climate Zone categories (see Figure 1)

Using the above "Dec_Feb" (coldest three month) average outdoor design temperatures for each climate zone (at the maximum HDD65ºF value defining each climate zone), the insulation ratios for Climate Zones 7 and 8 are revised as follows (Figure 17) using the same dew point analysis approach (see Eq. 1 through 3 reported earlier) supporting the current *IRC* and *IBC* insulation ratios for use with Class III interior vapor retarders.



							Revised R-value Ratios		**Current IRC/IBC**
Climate Zone	Indoor T (F)	Indoor T (celsuis)	RH	Dewpoint T(C)	Dewpoint (F)	Avg Dec-Feb T (F)	Re/Rtot	**Re/Ri**	**Re/Ri Values**
3600 HDD	70	21.11	40	6.91	44.44	42.7	0.06	**0.07**	**n/a**
4Cmarine	70	21.11	40	6.91	44.44	39.3	0.17	**0.20**	**0.2**
4	70	21.11	33	4.10	39.38	33.3	0.17	**0.20**	**n/a**
5	70	21.11	31	3.21	37.78	24.8	0.29	**0.40**	**0.4**
6	70	21.11	27.5	1.54	34.77	17.1	0.33	**0.50**	**0.5**
7	70	21.11	27	1.29	34.32	4.6	0.45	**0.83**	**0.7**
8a	70	21.11	27	1.29	34.32	-4.3	0.52	**1.08**	**0.7**

Figure 17: Refined design conditions (indoor RH and Dec-Feb average outdoor temperature) and static dew point analysis of insulation ratios for use with Class III interior vapor retarders per *IRC* and *IBC*

The revised analysis shown in Figure 17 results in no change to the insulation ratios in Climate Zones 4-6 which agrees with findings from various studies evaluated in the previous section of this research report. And, by extension of the analysis agreement with actual data and experience in Climate Zones 4-6, the result is a modest increase to insulation ratios in Climate Zones 7-8. This finding is consistent with findings and recommendations reported previously.

To achieve this revision, an improved correlation of the average Dec-Feb design temperature was used (Figure 15 and Table 4). Also, the indoor relative humidity index values were re-calibrated such that in all cases, except Climate Zone 4, the indoor relative humidity used for the purpose of the simplified dew point analysis is increased slightly (e.g., made more conservative) as shown by comparing RH values in Figure 17 to Table 2. These RH values also align more consistently with a modeled trend between outdoor temperature and indoor relative humidity as shown in Figure 18 (Saber, 2014), which also shows it to be less conservative than the approach used in ASHRAE Standard 160 (also shown in Figure 18). Also, the application in Climate Zone 8 is limited to 16,200 HDD65F given the large range of conditions in Climate Zone 8.

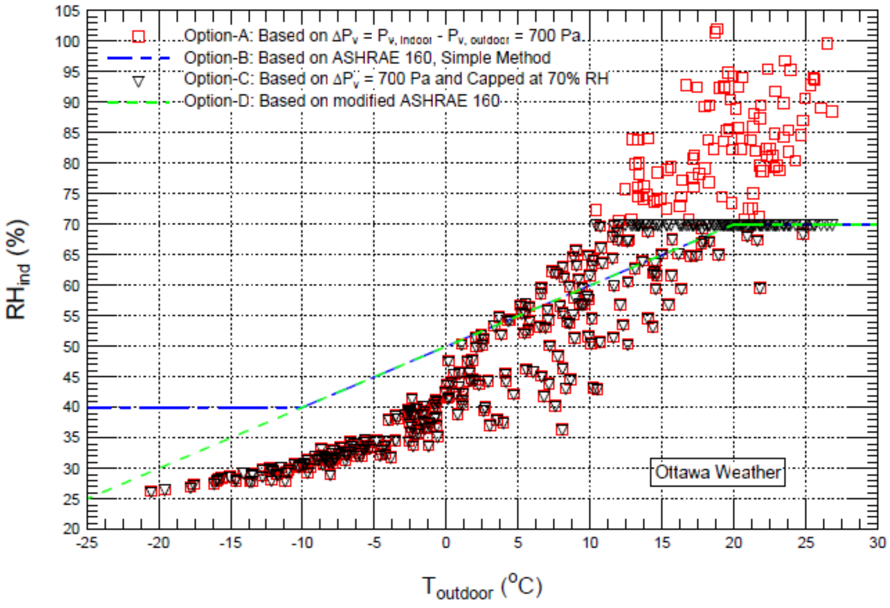


Figure 18: Various representations of expected indoor relative humidity for hygrothermal modeling purposes (Option C used in Saber (2014))

In summary, the results of this refined analysis align with current US practice (Climate Zones 4-6) and provide a moderate improvement for Climate Zone 7 while making a necessary correction to Climate Zone 8 which was not previously differentiated from Climate Zone 7 in the *IRC* code development process. For the northern boundary of Climate Zone 7, an insulation ratio of 0.8 (minimum) is recommended and for the northern boundary of Climate Zone 8a (up to 16,200 HDD65F) an insulation ratio of 1.1 (minimum) is recommended.

Exterior Continuous Insulation Only with No Interior Vapor Retarder

In the “exterior continuous insulation only” approach, there is limited or no cavity insulation and no interior vapor retarder. This wall assembly approach is a rather simple and robust extension of the insulation ratio concept. It also is ideally suited to a simple dew point analysis approach as used in the previous section. Furthermore, it is essentially identical to the common application of “above deck” insulation on compact, low-slope membrane roof systems.

In this approach, the exterior continuous insulation (R_e) must be specified to perform the thermal and water vapor control functions on its own (or a separate vapor control layer added to the immediate interior side of the continuous insulation). Depending on the application, the continuous insulation may also be used as the water control layer (e.g., water-resistive barrier) or in combination with a separate layer for this purpose (also located to the immediate interior side of the continuous insulation if it is a vapor retarder).

This approach has many advantages and has been called the “perfect wall” for good reason from a building science perspective (Lstiburek, 2008). First, the exterior continuous insulation can be sized to suppress the occurrence of condensation or other moisture related problems (e.g., mold growth from high surface relative humidity) within or on the building assembly. It does this simply by keeping the wall warm, above the dew point temperature of the indoor air in a cold climate. This attribute is similar to the role that exterior continuous insulation provides in combination with cavity insulation when an appropriate insulation ratio is coordinated with the class of interior vapor retarder used. However, without substantial cavity insulation, it is even easier for the exterior continuous insulation to perform its purpose as an exterior water vapor control layer because its interior surface is not “cooled” by the presence of substantial cavity insulation. Second, with most of the thermal resistance of a wall assembly located external to the framing and structure, the structural and interior finish materials are better protected from the elements. For example, thermal and moisture cycling and the magnitude of such cycling is better controlled or dampened. This attribute provides durability and serviceability benefits.

Figure 19 provides recommended minimum continuous insulation amounts using the same dew point analysis approach as described in the previous section for the *IBC*/*IRC* insulation ratios (see Figure 17). In this case, a more stringent interior relative humidity is used (5% greater RH) than used in the previous analysis, which is consistent with recommendations by Lstiburek (2011) for determining continuous insulation amounts for unvented roof systems in the *IRC* and *IBC*. In addition, the outdoor temperature condition in this analysis is changed to a far more stringent annual extreme low temperature value. These very conservative assumptions are used for the purpose of demonstrating and ensuring the robustness of the exterior insulation only approach. Finally, an allowance for up to R-5 insulation value to the interior side of the exterior insulation is provided to address framing cavity air-spaces, interior finishes, and an interior air-film.

The results in Figure 19 show that the required R-value of the continuous insulation only approach (with no interior vapor retarder) is far less than that required to comply with modern energy code requirements for wall assembly insulation amounts. For example, the 2018 IECC (ICC, 2018c) provides an R-value assembly prescription of R13+10ci or R20+5ci in Climate Zones 7 and 8 which equates to an assembly U-factor of approximately 0.045 Btu/hr-°F-ft^2 using the parallel path calculation method in the ASHRAE *Handbook of Fundamentals* (ASHRAE, 2013). This same U-factor applied to a light frame wall assembly with exterior continuous insulation only, would require a continuous insulation R-value of approximately R-18ci, well above that shown in Figure 19 below for Climate Zones 7 and 8. Thus, simply meeting modern energy code requirements with an exterior continuous insulation only assembly will generally provide more than adequate water vapor control. Also, the exterior insulation material used should be specified as a vapor retarder (e.g., not vapor permeable) to prevent excessive vapor flows through the assembly unless the vapor flows are otherwise managed, (e.g., use of vented cladding, back-priming of wood-based claddings, use of a separate vapor control layer immediately to the interior side of the foam sheathing, etc.). It is also worth noting that this analysis recommends an insulation ratio of approximately 2.0 or greater for Alaska, which is consistent with its current state building and energy code requirements (refer to previous discussion) for the case where there is no separate interior vapor retarder provided.

R-value to interior of CI = 5

							Proposed R-value Ratios		**Minimum R-value of CI Only to Prevent Condensation**
Climate Zone	Indoor T (F)	Indoor T (celsuis)	RH	Dewpoint T(C)	Dewpoint (F)	Annual Extreme Low Temp (F)	Re/Rtot	**Re/Ri**	**R-value CI**
3600 HDD	70	21.11	45	8.69	47.65	11	0.62	**1.64**	**8.2**
4C marine	70	21.11	45	8.69	47.65	23.5	0.52	**1.08**	**5.4**
4	70	21.11	38	6.15	43.07	1.2	0.61	**1.55**	**7.8**
5	70	21.11	36	5.36	41.64	-7.7	0.64	**1.74**	**8.7**
6	70	21.11	32.5	3.88	38.99	-15.7	0.64	**1.76**	**8.8**
7	70	21.11	32	3.66	38.59	-28.9	0.68	**2.15**	**10.7**
8a	70	21.11	32	3.66	38.59	-38.5	0.71	**2.45**	**12.3**

Figure 19: Dew Point Analysis Results for Continuous Insulation Only Wall Assemblies with No Interior Vapor Retarder

Figure Note: *For other values of "R-value interior of CI" (Ri) multiply by the appropriate Re/Ri ratio to determine the minimum required R-value of the exterior continuous insulation. For example, R-13 x 2.15 = R-28 ci.*

An alternate method of analysis makes use of a Kieper analysis approach (*ASTM*, 2009b) with analysis of monthly average conditions for a complete annual cycle assuming a sinusoidal variation in monthly average temperatures between the coldest winter month average temperature and warmest summer month average temperature (see Table 4). Monthly average indoor relative humidity levels also were assumed to vary sinusoidally from the maximum winter indoor relative humidity (shown in Table 5) to a maximum summer indoor relative humidity of 60%. This approach allows for a month-by-month assessment of a mold potential index (based on surface relative humidity and temperature), condensation potential index (based on number of months showing occurrence of condensation), and drying potential (e.g., ability to demonstrate an annual drying trend with the introduction of incidental moisture from moist air-exfiltration and/or rain water intrusion). For the purpose of this analysis and again to demonstrate the robustness of the exterior insulation only approach (with no interior vapor retarder), all of these indices were set at the most stringent level for a condensation plane assumed to occur at the inside surface of the exterior sheathing:

- no mold growth conditions during any month (e.g., no occurrences of an 80% surface relative humidity or greater in combination with a surface temperature of 41°F or greater)[8],
- no condensation occurrences (100% surface relative humidity) during any month, and
- drying potential greater than 1 for a complete annual cycle (e.g., more drying by diffusion than diffusion wetting including an annual incidental moisture surcharge of 0.05 gal/ft^2 (250g/m^2) as required in the DIN 4108-3 standard).

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[8] This conservative and imprecise mold criteria was applied in this case to demonstrate the robustness of the exterior insulation only wall approach. This should not be taken as an endorsement of this criteria for other applications; refer to discussion in the Background section of this report regarding mold criteria.

The vapor permeance of the exterior continuous insulation is assumed to be 0.05 perm, representative of a lower bound value for continuous insulation materials. The vapor permeance for the interior layer(s) was evaluated from a range of 1 to 1,000 perms to represent the absence of a vapor retarder as intended (i.e., 1000 perms) or the inclusion of an interior paint finish (minimum 1 perm).

Results of this alternative analysis approach are shown in Table 5 for a range of indoor relative humidity values. The solutions are provided for variations in wintertime indoor relative humidity so that an appropriate amount of continuous insulation can be determined based on the intended use and occupancy (interior moisture generation) and ventilation efficacy of a given building. This also provides a simple representation of the importance of relative humidity on the design of insulated assemblies, even those that are fairly robust like the exterior insulation only approach. It also demonstrates that the above dew-point analysis (Figure 19) is generally more conservative than the Kieper analysis for similar indoor relative humidity values.

TABLE 5
Minimum R-value for Walls with Exterior Continuous Insulation Only and No Interior Vapor Retarder[a,b]

Climate Zone (CZ) Figure 1	Maximum Winter Indoor Relative Humidity (70°F indoor set-point dry-bulb temperature)		
	Low (RH ≤ 30%)	Typical (RH ~ 40%)	High (RH = 50%)
3	R-2.0ci (0.4)	R-2.0ci (0.4)	R-5.0ci (1.0)
4C	R-2.0ci (0.4)	R-2.5ci (0.5)	R-6.0ci (1.2)
4	R-2.0ci (0.4)	R-4.5ci (0.9)	R-8.5ci (1.7)
5	R-3.5ci (0.7)	R-6.5ci (1.3)	R-11.5ci (2.3)
6	R-5.0ci (1.0)	R-8.5ci (1.7)	R-14.5ci (2.9)
7	R-7.0ci (1.4)	R-11.5ci (2.3)	R-19ci (3.8)
8a	R-9.0ci (1.8)	R-14.0ci (2.8)	R-22.0ci (4.4)

(a) Values in parentheses are the insulation ratio, Re/Ri.
(b) Insulation value of all materials to the interior of the exterior continuous insulation, including interior air-film, finishes and cavity air-spaces, shall not exceed R-5. Alternatively, the interior insulation R-value, Ri, shall be multiplied by the appropriate insulation ratio, Re/Ri, to determine the minimum required R-value for the exterior continuous insulation.

Exterior Permeance Limits

An important issue not explicitly addressed in the *IRC*, *IBC*[9], and *NBC* requirements for vapor retarders and insulation ratios is the matter of maintaining adequate drying potential, which may occur predominantly in an inward or outward direction. Consequently, there is a need for explicit permeance limits for walls with and without exterior continuous insulation. These limits are as important to consider as the insulation ratios discussed previously. For walls without adequate exterior insulation, permeance limits for the interior and exterior side of a wall are especially important and must be appropriately balanced for the climate with regard to wetting and drying episodes that occur seasonally. For walls with adequate exterior insulation to control moisture accumulation, the permeance of the exterior is less important except in the case where a vapor barrier (Class I vapor retarder such as polyethylene) is used on the interior side of the assembly potentially resulting in a double vapor barrier assembly as discussed earlier in this report. All of these considerations, if treated risk-consistently, depend on the climate (temperature, relative humidity, wind-driven rain hazard, etc.) and indoor relative humidity and temperature control.

Because the issue of minimum adequate drying potential is not explicitly addressed in U.S. or Canadian model codes and remains a matter of debate among designers and researchers, this research report generally recommends avoidance of "double vapor barrier" assemblies and applies a hygrothermal analysis recommendation similar to that found in a German Standard DIN 4108-3 (Kuzel, et al., 2011) with use of the Kieper hygrothermal analysis method (*ASTM*, 2009b;

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[9] The 2018 *IBC* includes a conservative provision in Section 1404.3.2 to control drying potential in foam sheathed walls only. Similar requirements have not been equivalently applied to other types of wall assemblies.

TenWolde, 2001). This method is capable of accounting for inward and outward vapor diffusion depending on vapor drives occurring at a given time (month) of the year. A moisture surcharge of 250 $g/m^2/yr$ (0.05 $gal/ft^2/yr$) is applied to the condensation plane within a wall assembly and the wall is required to dry out this additional (non-diffusion generated) moisture in either direction from the condensation plane and show a net annual drying trend. The moisture surcharge may be likened to a "safety factor" to address the uncertainties associated with the analysis method, input parameters, actual end-use conditions, and incidental moist air exfiltration or water intrusion. The static analysis (Kieper method) is performed on a month-by-month basis for a complete annual cycle as described in the previous section, making use of monthly averaged climate data corresponding to each Climate Zone as also described previously (see Table 4 and Figure 16).

While this analysis method accounts for the major indoor and outdoor boundary conditions, it does not account for solar radiation effects which can improve drying potential (mainly affecting south-facing walls only) and it also does not account for varying material properties as a function of temperature, ambient relative humidity, or other factors such as moisture storage and redistribution. Consequently, the analysis results shown in Table 6 are approximations. However, as important to any analysis or modeling effort, it has produced results that are reasonably consistent with multiple sources of actual performance data and experience as evaluated earlier in this report, including general agreement with accepted practices represented in existing building codes and standards. In summary, this analysis and the results presented in Table 6 should be viewed as a rational and approximate framework subject to improvement through additional experience and research including modeling and comparisons to well-documented field data as expanded beyond and including the data addressed earlier in this report.

TABLE 6
Minimum Net Water Vapor Permeance (WVP) of Material Layers on the Exterior Side of Vapor-Permeable Cavity Insulation[1,2,3]

Climate Zone	Walls with Cavity Insulation Only (Max. R-28 Vapor Permeable Cavity Insulation)			Walls with Exterior Continuous Insulation Complying with Minimum Re/Ri Ratios		
	Interior Vapor Retarder Class			Interior Vapor Retarder Class		
	I	II	III	I	II	III
1	NP (*IBC* 2015)	NP (*IBC* 2015)	No minimum WVP	NP (*IBC* 2015)	NP (*IBC* 2015)	No minimum WVP
2						
3		No minimum WVP			No minimum WVP	
4		0.5 perm	3 perm			
5	0.5 perm[4]	3 perm	5 perm	See Note 4		
6	1 perm	5 perm	15 perm			
7	1 perm	10 perm	NP (*IBC*/*IRC* 2015)			
8a (≤16,200 HDD65F)	1.5 perm	NP				

1. Table requirements apply only to normal indoor relative humidity conditions in ventilated buildings (e.g., RH not exceeding 60% during summer cooling season or 40% (CZ 4), 35% (CZ 5), or 30% (CZ 6-8) during the winter heating season). If high indoor moisture generation is expected, a hygrothermal analysis should be conducted and an alternative solution designed.
2. Where there are multiple exterior material layers, excluding vented cladding, determine the net WVP as follows : $P_{Total} = 1/[(1/P_1) + (1/P_2)+\cdots]$. For example, if structural sheathing = 2 perm, WRB = 5 perm, then P_{Total} = 1/[1/2 + 1/5] = 1/0.7 = 1.4 perm. Thus, a Class I vapor retarder is required for this example wall without exterior insulating sheathing of an adequate amount when used in Climate Zones 5-7.
3. Permeance values for exterior material layers shall be permitted to be determined in accordance with the wet cup method (Method B) of *ASTM E96*.
4. Accepted practice in the U.S. (*IBC* and *IRC*) has permitted and many state or local building codes in cold climates zones may require the use of a Class I interior vapor retarder without consideration of a minimum permeance limit for exterior layers, with or without the presence of exterior continuous insulation. However, accepted practice in Canada (NBC) specifically allows the use of an interior vapor barrier (Class 1 vapor retarder) when the exterior sheathing permeance is less than 1 perm provided exterior insulation is used meeting a minimum R-value that complies with minimum required insulation ratios as shown. In locations where a Class I interior vapor retarders is permitted and used and where exposure to exterior moisture sources is significant (e.g., severe wind-driven rain amounts per Figure 3), exterior material layers, including exterior insulation and excluding vented cladding, are recommended to have a net vapor permeance (see note 2) of 1 perm or greater. Alternatively, a Class II or Class III interior vapor retarder may be used to provide improved inward drying potential with low-perm exterior layers.

Because materials on the exterior side of a wall are subject to high surface relative humidity conditions and moisture accumulation in the winter caused by cold surface temperatures and exterior vapor drives, the vapor permeance of exterior materials should be permitted to be based on the wet-cup method (Method B) of *ASTM E96*. Using a dry-cup WVP value with Table 6 will result in overly restrictive interior vapor retarder selection for use with exterior materials that have dynamic or adaptable hygroscopic behavior (e.g., vapor permeance increases with increasing moisture content). Examples of exterior material layers that typically exhibit this type of dynamic WVP behavior include OSB, plywood, and asphalt-impregnated felt paper. Thus, the application of Table 6 to these types of materials is intended to be based on their vapor permeance as measured by the wet-cup method (Procedure B) of *ASTM E96*. This approach also will serve to promote the selection of a higher permeance interior vapor retarder which has benefits in regard to improving drying potential and avoiding uncertain risks with inward vapor drives during the summer cooling season when reservoir claddings are used without back ventilation.

The net exterior permeance values determined for the case without exterior continuous insulation also happen to agree reasonably well with common recommendations and practices, such as a 5:1 (exterior:interior) permeance ratio (CFR, 2004; BSI, 2002; Vinha, 2008; *ASTM*, 2011). As appropriate, this ratio also varies rationally with climate zone in Table 6. Such recommendations are aimed at walls intended to dry to the exterior to achieve acceptable moisture control performance in the absence of exterior insulation of an adequate amount to control condensation or moisture accumulation due to vapor diffusion.

Finally, the above requirements for the control of water vapor permeance levels on the exterior side of a wall assembly provide a rational and conceptually simple means to control water vapor diffusion wetting and drying for durable, energy efficient construction. However, they necessitate greater knowledge of the water vapor permeance properties of materials that generally have not been carefully considered and widely reported in the past. Thus, material manufacturers will need to be prepared to provide such WVP values for their materials. Consequently, designers, builders, and inspectors will need to have access to these values. While generic material properties may be found in various material standards and guides such as the ASHRAE *Handbook of Fundamentals*, these generic values may not accurately represent specific products or any given lot of a given type of material that is not manufactured to attain a specified permeance value and tolerance.

Insulation Ratios for Limited Moisture Storage Capacity

A solution to the concern discussed previously with the lower moisture storage capacity of light-frame cold-formed steel wall assemblies has been investigated by Burnett and Bombino (2001). They employed a static dew point analysis approach similar to that used to substantiate the use of Class III vapor retarders in U.S. model codes. However, the authors used a shorter duration 60-day (2 month) lowest average outdoor temperature instead of a 3-month (Dec-Feb) average temperature. Using a slightly more conservative coldest month average temperature, insulation ratios are derived as shown in Figure 20 below following a dew point analysis procedure and using parameters otherwise identical to Figure 17.

							Proposed R-value Ratios	
Climate Zone	Indoor T (F)	Indoor T (celsuis)	RH	Dewpoint T(C)	Dewpoint (F)	oldest Mo. Avg T (F	Re/Rtot	**Re/Ri**
3600 HDD	70	21.11	40	6.91	44.44	41	0.12	**0.13**
4C marine	70	21.11	40	6.91	44.44	38.5	0.19	**0.23**
4	70	21.11	33	4.10	39.38	31.2	0.21	**0.27**
5	70	21.11	31	3.21	37.78	22.3	0.32	**0.48**
6	70	21.11	27.5	1.54	34.77	14.3	0.37	**0.58**
7	70	21.11	27	1.29	34.32	1.1	0.48	**0.93**
8a	70	21.11	27	1.29	34.32	-8.5	0.55	**1.20**

Figure 20: Analysis of insulation ratio for cold-formed steel framing assemblies.

The above results indicate about a 0.1 additive increase in the magnitude of insulation ratio in comparison to Figure 14. Thus, the insulation values in Figure 17 (and also currently represented in the *IBC/IRC*) may be appropriate for use with steel frame wall assemblies with a simple additive increase of 0.1 (e.g., if a 0.5 insulation ratio is required for wood-framed walls, then a 0.6 insulation ratio should be required for steel framed walls).

Given that the approach above (a modification of that used by Burnett and Bombino (2001)) only indirectly accounts for moisture storage effects, this topic should be the subject of further research and is ideally suited to a comparative hygrothermal analysis effort using a transient model that includes moisture storage modeling capabilities. However, the recommendation above is consistent with the effect of the presence or absence of wood sheathing in wall assemblies studied by Saber (2014) and the change in insulation ratio required to offset the effect on modeled mold index (e.g., compare Figures 40 and 42 in Saber (2014)).

Summary

All of the reviewed literature, analyses, findings and recommendations in this research report either confirm, improve (modify), or add new requirements that address "gaps" in current practice. In cases where modifications or new requirements are recommended, they are considered to be equivalent to or exceed current requirements in modern building codes (e.g., *IRC*, *IBC*, and NBC). A summary compilation of existing code requirements and recommendations from this research report are provided in Appendix A in the form of a comprehensive framework of requirements for water vapor control in typical low-rise, light-frame buildings.

It is important to recognize that the scope of this research report is focused on water vapor control in coordination with other related design considerations such as rain water management through the use of water-resistive barriers and flashing, air-leakage control through the use of continuous air-barriers, and indoor relative humidity control through the use of ventilation (winter) and/or dehumidification (summer). The water vapor control provisions and recommendations in this research report also affect appropriate insulation strategies and amounts. Where insulation strategies are addressed herein, they do not necessarily result in assemblies that meet modern energy code requirements. However, they can be used to ensure that assemblies that are compliant with the energy code are also compliant with water vapor control intentions of the building code. Supplemental information is provided in Appendix B for this purpose.

Conclusions and Recommendations

The following conclusions and recommendations are offered as a result of the findings of this research report:

1. Insulation ratios for use with Class III interior vapor retarders as defined in the current US Practice appear to be well-justified by comparative results of several studies in Climate Zones 4-6. However, findings reported herein suggest a need to reconsider insulation ratios in Climate Zones 7 and 8 as applied in Appendix A, Table A1.
2. Similarly, the Canadian practice for insulation ratios for use with Class I or II interior vapor retarders appears to be well-justified by various studies and data evaluated herein. However, caution is recommended when using a Class I interior vapor retarder with low-perm materials on the exterior side of the wall assembly (e.g., “double vapor barrier”) as indicated in Appendix A, Table A1 (Note ‘f’). Additional research should be conducted to better ascertain limits to conditions under which the use of a “double vapor barrier” assembly (such as currently allowed with reported success in the US and Canadian practice) are not susceptible to moisture accumulations and damage from water sources and transport mechanisms other than vapor diffusion.
3. Vapor control in wall assemblies without continuous insulation and with only air- or vapor-permeable cavity insulation must rely predominantly on coordination and balancing of the vapor permeance of the interior vapor retarder with the vapor permeance of the exterior materials to ensure adequate or intended performance. The preferable approach in cold climates has been to minimize water vapor entry from the interior (e.g., use of interior vapor retarders) rather than attempting a “flow through” or “vapor open” assembly with little vapor control and potential limitations not yet adequately defined. Recommended permeance limits for exterior materials based on the interior vapor retarder class are applied in Appendix A, Tables A1 and A2. These recommendations are based on the findings and analyses reported herein, including multiple data sources representing field, test hut, and modeling studies. These studies show significant risk of winter time high moisture content occurrences and potential strength degradation of OSB sheathing when its use is not consistent with the minimum exterior vapor permeance levels (based on *ASTM E96* wet cup measurement) as indicated in Table A1.
4. One of the more robust methods of wall construction is known as the “perfect wall” whereby exterior insulation serves the dual role of a thermal and moisture control layer and does not require a separate interior vapor retarder. Results of the analysis reported herein are applied in Appendix A (Table A1), representing an initial effort to quantify water vapor control requirements to support broader implementation of this beneficial wall design strategy.
5. Use of cold-formed steel framing and different sheathing materials and cavity insulation materials can alter the moisture storage capacity of an assembly and, hence, affect the optimization of a water vapor control strategy (e.g., permeance and R-value of materials and/or their locations in an assembly). While this effect may not be large, this is an area where additional research is warranted to better quantify the magnitude of effect on water vapor control strategies.
6. Additional research on the frequency and extent of solar-driven inward moisture movement problems in buildings where Class I interior vapor retarders (e.g., polyethylene) are permitted for use or are commonly used should be conducted to ascertain the need for provisions to more precisely identify and mitigate the problem, particularly in mixed, humid climates (Derome, 2010). Foam sheathing materials offer one means of mitigating this problem. Recommendations are made in Appendix A (footnote to Table A1) for avoidance of moisture problems associated with inward vapor drives when highly permeable exterior insulations are used with reservoir claddings (Lepage and Lstiburek, 2013).
7. More field monitoring studies of actual buildings is still considered important to help quantify experience, calibrate analysis models, establish appropriate design criteria, and support efficient and robust prescriptive solutions for water vapor control that help build market confidence, support good decisions, and provide a baseline for future innovation. The data obtained should consider the framework established in Table A1 of Appendix A and be compared to the initial compilation of existing data as presented in and with Figure 14. Realistic field data of actual buildings built to code minimum requirements in Climate Zones 7 and 8 would be particularly useful.
8. The design and actual performance reliability (or uncertainty) of a “permeance controlled” assembly in view of the findings of several studies addressed in this report (see “Walls without Exterior Insulation” section) needs to be better understood. Of particular interest is the impact of uncertainty in the permeance of key materials (e.g., exterior structural sheathing, interior paint used as a vapor retarder, etc.) that are not typically manufactured to specified permeance tolerance limits or design value targets, but which can have a significant influence on the performance outcome of a given assembly.

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Appendix A – Water Vapor Control Framework

Because water vapor control is technically complex with many variables affecting the performance outcome, it also is challenging to communicate in both simple and accurate terms for implementation by construction industry audiences with a suitable collection of prescriptive solutions or options. While adept building designers can typically tolerate and even benefit from a more complex treatment of design principles and data, others in the construction industry are better served by simple, easy-to-implement prescriptive solutions. They just want to be told what to do and know that it will work. They may become confused with too much information or too many options. Yet, they also recognize options are important and this requires some level of detail to ensure the options are used properly and with a reasonable expectation for equivalent performance outcomes. For alternative solutions, accepted engineering practices for hygrothermal modeling should be relied upon and are encouraged.

As prefaced with the above context, this appendix represents an effort toward integrating and implementing all of the key information and findings included in this research report in the context of a reasonably comprehensive framework of prescriptive requirements and options for water vapor control (see Table A1). The reader is referred to the main body of this research report for more detailed information supporting this framework and the specific requirements or recommendations represented. Also, example applications of Table A1 are provided in Appendix B. Tables A2 and A3 represent alternate versions of Table A1 for application in Climate Zone 6. Similarly, Tables A4 and A5 address Climate Zone 7 (which is particularly useful given that Climate Zone 7 spans a greater range of heating degree days than the lower Climate Zones). These alternate tables demonstrate how derivative solutions based on Table A1 may be "repackaged" for individual climate zones, including rounding off of values or inclusion of more options, for improved ease of use or design efficiency (ABTG, 2015).

The provisions of Table A1 are tailored to provide, to the greatest extent possible, sufficient information to ensure reasonably equivalent and consistent performance across various options for constructing common light-frame wall assemblies. The solutions are categorized into two basic water vapor control wall types or design approaches:

- ***Method A ("Cavity Insulation Walls"):*** A wall with vapor-permeable cavity insulation only (maximum R28) which commonly relies on an interior vapor retarder and drying to the exterior for moisture performance in cold climates. The wall commonly includes a non-insulative (<R-2) exterior sheathing material. Thus, the key design parameter (next to the climate zone and interior vapor retarder class) is the minimum tolerable water vapor permeance of materials or layers comprising the exterior side of the wall such that drying potential sufficiently exceeds wetting potential to minimize risk of unacceptable moisture accumulation events or trends.

- ***Method B ("Continuous Insulation Walls"):*** A wall with vapor permeable cavity insulation and exterior continuous insulation (assumed to have a low vapor permeance) that relies on a combination of a modest interior vapor retarder, internal temperature control provided by the exterior insulation, and drying to the interior for moisture control performance. Therefore, the determination of total exterior permeance is not required as in Method A (with the exception of Note 'f' in Table A1). The key design parameters (next to climate zone and interior vapor retarder class) are cavity insulation amount and the amount of exterior continuous insulation (i.e., the insulation ratio).

Finally, in many parts of Table A1, existing requirements in the U.S. (e.g., *IBC* and *IRC*) and Canada (e.g., NBC) are replicated without change. Where modifications are made in Table A1, they are based on findings and recommendations in this research report. In some cases new requirements are provided where none currently exist (e.g., exterior permeance requirements, new continuous insulation only approach with no vapor retarder, etc.). In other cases, existing requirements are enhanced (e.g., improved insulation ratios in Climate Zones 7 and 8 for use with Class III interior vapor retarders).

NOTE: The vapor retarder and insulation requirements in Table A1 are not intended to address minimum energy code compliance. The energy code may require greater or lesser insulation than required by Table A1. Table A1 is intended to serve as a means of confirming that walls satisfying the energy code also meet the building code's water vapor control intent. Refer to examples in Appendix B.

TABLE A1
Framework of Requirements for Water Vapor Control[a]

<table>
<tr><td>Design Logic Flow
(Applies equally to all methods)</td><td rowspan="4">Climate Zone – Figure 1</td><td colspan="3">Method A: Permeance Control with Predominant Drying to Exterior (e.g., Cavity Insulation Walls) SEE FIGURE A1</td><td colspan="7">Method B: Temperature Control with Predominant Drying to Interior (e.g., Continuous Insulation Walls) SEE FIGURE A2</td></tr>
<tr><td rowspan="2">(1) Interior Vapor Permeance ➔</td><td colspan="3">Interior Vapor Retarder Class</td><td colspan="7">Interior Vapor Retarder Class</td></tr>
<tr><td>I (perm≤0.1)</td><td>II (0.1<perm≤1)</td><td>III (1<perm≤10)</td><td colspan="2">I (perm≤0.1)</td><td colspan="2">II (0.1<perm≤1)</td><td colspan="2">III (1<perm≤10)</td><td>None</td></tr>
<tr><td rowspan="9">(2) Exterior Vapor Permeance ➔</td><td colspan="3">Minimum Total Exterior Permeance[c,d]</td><td colspan="7">Minimum Total Exterior Permeance[d]</td></tr>
<tr><td>1</td><td rowspan="4">NP (<i>IBC</i> 2015)</td><td rowspan="2">NP (<i>IBC</i> 2015)</td><td>No minimum</td><td colspan="2" rowspan="4">NP (<i>IBC</i> 2015)</td><td colspan="2" rowspan="2">NP (<i>IBC</i> 2015)</td><td colspan="2" rowspan="8">No Minimum</td><td rowspan="8">No Minimum</td></tr>
<tr><td>2</td><td>No minimum</td></tr>
<tr><td>3</td><td>No minimum</td><td>No minimum</td><td colspan="2" rowspan="6">No Minimum (NOTE: <i>IBC</i> 2015 requires Class III VR if FPIS < 1 perm)</td></tr>
<tr><td>4</td><td>0.5 perm</td><td>3 perm[e]</td></tr>
<tr><td>5</td><td>0.5 perm[f]</td><td>3 perm</td><td>5 perm[e]</td><td colspan="2" rowspan="4">See Note ‘f’ (NOTE: <i>IBC</i> 2015 requires Class III VR if FPIS < 1 perm)</td></tr>
<tr><td>6</td><td>1 perm</td><td>5 perm</td><td>15 perm[e]</td></tr>
<tr><td>7</td><td>1 perm</td><td>10 perm</td><td rowspan="2">NP (<i>IBC/IRC</i> 2015)</td></tr>
<tr><td>8[b]</td><td>1.5 perm</td><td>NP</td></tr>
<tr><td rowspan="2">(3) Cavity Insulation Conditions ➔</td><td rowspan="3">Climate Zone – Figure 1</td><td colspan="3">Maximum Cavity Insulation R-value[g]</td><td colspan="7">Maximum Cavity Insulation R-value[g] (Ri)</td></tr>
<tr><td colspan="3">R28 (up to 2x8 construction)</td><td>2x4 (R-13)</td><td>2x6 (R-20)</td><td>2x4 (R-13)</td><td>2x6 (R-20)</td><td>2x4 (R-13)</td><td>2x6 (R-20)</td><td>Not required (max R-5)</td></tr>
<tr><td rowspan="14">(4) Continuous Insulation Requirements ➔</td><td colspan="3">Minimum R-value for Continuous Insulation</td><td colspan="7">Minimum R-value for Continuous Insulation (Re)[h,i]</td></tr>
<tr><td>1</td><td rowspan="5">NP (<i>IBC</i> 2015)</td><td rowspan="2">NP (<i>IBC</i> 2015)</td><td rowspan="5"></td><td colspan="2" rowspan="5">NP (<i>IBC</i> 2015)</td><td colspan="2" rowspan="2">NP (<i>IBC</i> 2015)</td><td colspan="2">R-2ci</td><td>R-2ci</td></tr>
<tr><td>2</td><td colspan="2">R-2ci</td><td>R-2ci</td></tr>
<tr><td>3</td><td rowspan="3"></td><td colspan="2">R-2ci</td><td colspan="2">R-2ci</td><td>R-2ci</td></tr>
<tr><td rowspan="2">4</td><td colspan="2" rowspan="2">R-2ci</td><td>R-2.5ci</td><td>R-3.8ci</td><td rowspan="2">R-4.5c (Re/Ri=0.9)</td></tr>
<tr><td colspan="2">Re/Ri=0.2</td></tr>
<tr><td rowspan="2">5</td><td colspan="3" rowspan="4">Re=0ci, No continuous insulation required
(<i>Exception:</i> <i>Continuous insulation of any amount permitted where minimum total exterior permeance values are met)</i></td><td>R-2.6ci</td><td>R-4.0ci</td><td>R-2.6ci</td><td>R-4.0ci</td><td>R-4.6ci</td><td>R-7.0ci</td><td rowspan="2">R-6.5ci (Re/Ri=1.3)</td></tr>
<tr><td colspan="2">Re/Ri=0.2</td><td colspan="2">Re/Ri=0.2</td><td colspan="2">Re/Ri=0.35</td></tr>
<tr><td rowspan="2">6</td><td>R-2.6ci</td><td>R-4.0ci</td><td>R-2.6ci</td><td>R-4.0ci</td><td>R-6.5ci</td><td>R-10ci</td><td rowspan="2">R-8.5ci (Re/Ri=1.7)</td></tr>
<tr><td colspan="2">Re/Ri=0.2</td><td colspan="2">Re/Ri=0.2</td><td colspan="2">Re/Ri=0.5</td></tr>
<tr><td rowspan="2">7</td><td colspan="2" rowspan="2"></td><td rowspan="4">NP</td><td>R-4.6ci</td><td>R-7.0ci</td><td>R-4.6ci</td><td>R-7.0ci</td><td>R-10ci</td><td>R-16ci</td><td rowspan="2">R-12ci (Re/Ri=2.3)</td></tr>
<tr><td colspan="2">Re/Ri=0.35</td><td colspan="2">Re/Ri=0.35</td><td colspan="2">Re/Ri=0.8</td></tr>
<tr><td rowspan="2">8[b]</td><td rowspan="2"></td><td rowspan="2">NP</td><td>R-6.5ci</td><td>R-10ci</td><td>R-6.5ci</td><td>R-10ci</td><td>R-14ci</td><td>R-22ci</td><td rowspan="2">R-14ci (Re/Ri=2.8)</td></tr>
<tr><td colspan="2">Re/Ri=0.5</td><td colspan="2">Re/Ri=0.5</td><td colspan="2">Re/Ri=1.1</td></tr>
</table>

LEVEL OF DIFFICULTY: ------------- COMPLEX[1] ---------→--------- MODERATE[2] ---------→--------SIMPLE & ROBUST[3]----

1. Complex = requires verifying net permeance of all exterior material layers to consistently ensure adequate performance.
2. Moderate = may require verification of net permeance of all exterior material layers (only when a Class I interior vapor retarder is used – see Note ‘f’); otherwise, only need to verify exterior and interior insulation R-values as commonly done.
3. Simple/Robust = only need to verify insulation R-values; easily modified for increased moisture control and thermal performance by increasing exterior insulation amount required.

TABLE A1 NOTES:

NP = not permitted

a. The water vapor control requirements of this table are based on the following conditions:
   i. The table requirements are based on the maximum heating degree day limit of the associated Climate Zones (see Figure 1). Interpolation of exterior water vapor permeance limits for Method A or continuous insulation amounts (insulation ratios) for Method B shall be permitted based on a site-specific heating degree day value.
   ii. The building indoor relative humidity is controlled to level not exceeding 60% during summer cooling season and not exceeding the following values (by Climate Zone) during the winter heating season: 45% (3), 40% (4), 35% (5), and 30% (6-8).
   iii. A code-compliant water-resistive barrier system (including flashing) and a continuous air barrier system is provided.
   iv. Exterior roof coverings and wall coverings and components are completed to provide a weather-resistant (“dried-in”) status for the building enclosure prior to installation of cavity insulation materials.
   v. Wall framing and insulation materials shall be reasonably dry (e.g., <19% moisture content, mass basis) prior to installation of an interior vapor retarder (where required) and interior finishes.

b. Where heating degree days (65°F basis) exceeds 16,200 °F-days, a design shall be required.

c. Perm values for exterior materials (sheathing, wrap, cladding, etc.) shall be based on the wet cup or dry cup method of *ASTM E96*. The total permeance of all exterior material layers shall meet or exceed the perm value shown in the table for Method A based on the interior vapor retarder class used, except as further limited by Note ‘d’. Total exterior permeance, excluding vented cladding, should be determined using the following equation where there are multiple exterior material layers: $P_{Total} = (1/[(1/P_1) + (1/P_2)+\cdots]$ where P_x is the water vapor permeance value for each exterior layer considered. Refer to Appendix B, Example 3.

d. Where an unvented reservoir cladding is used (e.g., brick, stone, stucco, wood, etc.), the material layer(s), namely the water-resistive barrier layer and/or exterior continuous insulation layer, located between the reservoir cladding and moisture-sensitive wall framing (such as wood-based or gypsum sheathing) shall have a net water vapor permeance (see Note ‘c’) not exceeding 10 perm to prevent excessive inward water vapor movement. Alternatively, the reservoir cladding shall be separated from underlying materials by a ventilated air space.

e. **Exception:** Walls with fiberboard sheathing, gypsum sheathing, and wood structural panels are permitted with vented cladding in Climate Zones 4 and 5 (plywood sheathing instead of OSB is recommended in Climate Zone 5). In climate Zone 6, only fiberboard and gypsum sheathing are permitted with vented cladding. Other exterior layers, such as the water-resistive barrier, should be at least as vapor permeable as fiberboard and gypsum sheathing (e.g., >15 perm). This exception is not applicable to wood structural panel sheathing products that have water vapor permeance (per *ASTM E96* wet cup method) less than the minimum values specified in Table A1 for use with Class III interior vapor retarders.

f. Accepted practice in the U.S. (*IBC* and *IRC*) has permitted and many state or local building codes in cold climates zones may require the use of a Class I interior vapor retarder without consideration of a minimum permeance limit for exterior layers, with or without the presence of exterior continuous insulation. However, accepted practice in Canada (NBC) specifically allows the use of an interior vapor barrier (Class 1 vapor retarder) when the exterior sheathing permeance is less than 1 perm provided exterior insulation is used meeting a minimum R-value that complies with minimum required insulation ratios as shown. In locations where a Class I interior vapor retarders is permitted and used and where exposure to exterior moisture sources is significant (e.g., severe wind-driven rain amounts per Figure 3), exterior insulation in combination with other exterior material layers, excluding vented cladding, are recommended to have a net vapor permeance (see note ‘b’) of 1 perm or greater. Alternatively, a Class II or Class III interior vapor retarder may be used to provide improved inward drying potential with low-perm exterior layers.

g. Where cavity insulation is compressed in the cavity, the compressed R-value shall be used. For Method A in Table A1, the maximum cavity insulation R-value limitation of R-28 applies only to vapor permeable (>5 perm) cavity insulation materials at their installed thickness.

h. Re/Ri = insulation ratio where Re = exterior continuous insulation (ci) component R-value; Ri = interior cavity insulation component R-value adjusted for compression as appropriate. Examples are shown for combinations of cavity insulation (Ri, first value) plus continuous insulation (Re, second value) that satisfy the required minimum insulation ratio. Other solutions of cavity insulation and continuous insulation, including continuous insulation only, with equal or greater insulation ratio shall be permitted. These solutions address minimum requirements for water vapor control only; energy code compliance shall be separately verified in accordance with the locally applicable energy code.

i. As permitted in *2015 IRC* Table R702.3, spray foam with a maximum permeance of 1.5 perms at the installed thickness, applied to the interior cavity side of wood structural panels, fiberboard, insulating sheathing or gypsum is deemed to meet the continuous insulation requirement for the purposes of this table only where the spray foam *R*-value meets or exceeds the specified continuous insulation *R*-value.

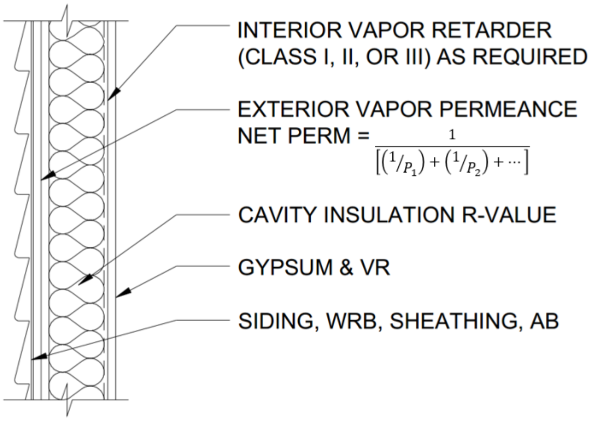
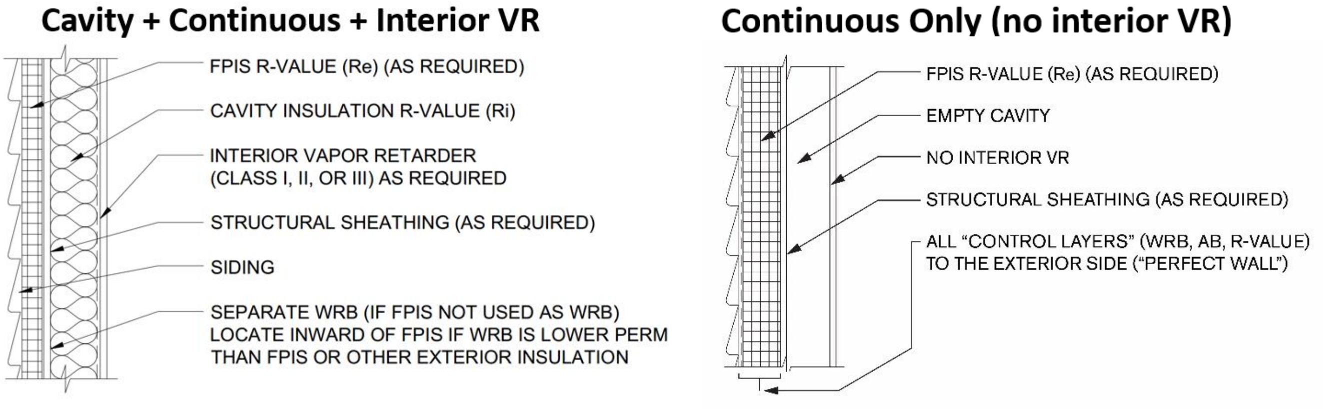


Figure A1. Typical “Method A” Wall Assembly with Cavity Insulation Only



(a) Cavity Insulation + Continuous Insulation + Interior VR

(b) Exterior Insulation Only (no interior VR)

Note: Arrangement of control layers is material and climate specific.

Figure A2. Typical “Method B” Wall Assemblies

EXAMPLE ALTERNATE FRAMEWORK FOR CLIMATE ZONE 6:

TABLE A2
Minimum Net Water Vapor Permeance (WVP) of Material Layers on the Exterior Side of Vapor-Permeable Cavity Insulation in Climate Zone 6

Interior Vapor Retarder Class	Walls with Cavity Insulation Only[1,2]	Walls with Exterior Continuous Insulation Meeting Table A3
I	1 perm	See Note '4'
II	5 perm	No minimum perm
III	15 perm[3]	No minimum perm

1. Permeance values for exterior material layers shall be permitted to be determined in accordance with the wet cup method (Method B) of *ASTM E96*. Where there are multiple exterior material layers, determine the net WVP, excluding vented cladding, as follows : $P_{Total} = 1/[(1/P_1) + (1/P_2)+\cdots]$ *where* P_x *is the water vapor permeance value for each exterior layer considered.*
2. Walls with exterior continuous insulation of any R-value are permitted without complying with Table A5 provided the net total permeance on the exterior side of the wall meets or exceeds the listed values.
3. **Exception:** Walls with fiberboard sheathing and gypsum sheathing are permitted with vented cladding. Other exterior layers, such as the water-resistive barrier, should be at least as vapor permeable as fiberboard and gypsum sheathing (e.g., >15 perm).
4. Where a Class I interior vapor retarders is used and where exposure to exterior moisture sources is significant (e.g., severe wind-driven rain amounts per Figure 3), the net water vapor permeance (see Note 1) of the exterior insulation in combination with other exterior material layers, excluding vented cladding, shall be 1 perm or greater. Alternatively, a Class II or Class III interior vapor retarder may be used to provide improved inward drying potential with low-perm exterior layers.

TABLE A3 (Simple)
Minimum Exterior Continuous Insulation R-value for Moisture Control in Climate Zone 6[1]

Class I or II Interior Vapor Retarder (polyethylene sheet, Kraft paper)		Class III Interior Vapor Retarder (latex or enamel paint)	
Wall Type		Wall Type	
2x4 walls	2x6 walls	2x4 walls	2x6 walls
R-3ci	R-5ci	R-7.5ci	R-12ci

TABLE A3 (Comprehensive)
Minimum Exterior Continuous Insulation R-value for Moisture Control in Climate Zone 6[1]

Heating Degree Days (Climate Zone 6)		Class I or II Interior Vapor Retarder (1 perm or less)					Class III Interior Vapor Retarder (1<perm≤10)				
		Min. R_e/R_i Ratio	Maximum Cavity Insulation R-value				Min. R_e/R_i Ratio	Maximum Cavity Insulation R-value			
			2x4 walls		2x6 walls			2x4 walls		2x6 walls	
HDD65°F	HDD18°C		R-13	R-15	R-19	R-23		R-13	R-15	R-19	R-23
7,000	3,889	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.33	R-4.3ci	R-5ci	R-6.3ci	R-7.6ci
7,500	4,167	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.38	R-4.9ci	R-5.7ci	R-7.2ci	R-8.7ci
8,000	4,444	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.42	R-5.5ci	R-6.3ci	R-8ci	R-9.7ci
8,500	4,722	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.46	R-6ci	R-6.9ci	R-8.7ci	R-11ci
9,000	5,000	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.5	R-6.5ci	R-7.5ci	R-9.5ci	R-12ci

1. As permitted in *2015 IRC* Table R702.3, spray foam with a maximum permeance of 1.5 perms at the installed thickness, applied to the interior cavity side of wood structural panels, fiberboard, insulating sheathing or gypsum is deemed to meet the continuous insulation requirement for the purposes of this table only where the spray foam *R*-value meets or exceeds the specified continuous insulation *R*-value.

EXAMPLE ALTERNATE FRAMEWORK FOR CLIMATE ZONE 7:

TABLE A4
Minimum Net Water Vapor Permeance (WVP) of Material Layers on the Exterior Side of Vapor-Permeable Cavity Insulation in Climate Zone 7

Interior Vapor Retarder Class	Walls with Cavity Insulation Only[1,2]	Walls with Exterior Continuous Insulation Meeting Table A5
I	1 perm	See Note '3'
II	10 perm	No minimum perm
III	Not Permitted	No minimum perm

1. Permeance values for exterior material layers shall be permitted to be determined in accordance with the wet cup method (Method B) of *ASTM E96*. Where there are multiple exterior material layers, determine the net WVP, excluding vented cladding, as follows : $P_{Total} = 1/[(1/P_1) + (1/P_2)+\cdots]$ *where* P_x *is the water vapor permeance value for each exterior layer considered.*
2. Walls with exterior continuous insulation of any R-value are permitted without complying with Table A5 provided the net total permeance on the exterior side of the wall meets or exceeds the listed values.
3. Where a Class I interior vapor retarders is used and where exposure to exterior moisture sources is significant (e.g., severe wind-driven rain amounts per Figure 3), the net water vapor permeance (see Note 1) of the exterior insulation in combination with other exterior material layers, excluding vented cladding, shall be 1 perm or greater. Alternatively, a Class II or Class III interior vapor retarder may be used to provide improved inward drying potential with low-perm exterior layers.

TABLE A5 (Simple)
Minimum Exterior Continuous Insulation R-value for Moisture Control in Climate Zone 7[1]

Class I or II Interior Vapor Retarder (polyethylene sheet, Kraft paper)		Class III Interior Vapor Retarder (latex or enamel paint)	
Wall Type		Wall Type	
2x4 walls	2x6 walls	2x4 walls	2x6 walls
R-5ci	R-7ci	R-12ci	R-18ci

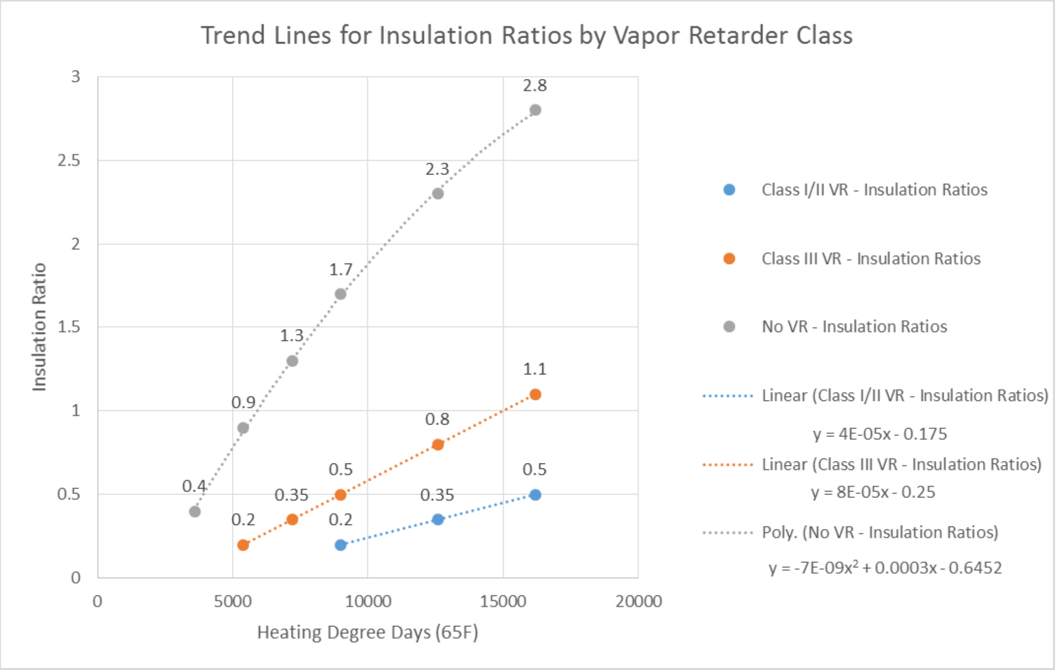
TABLE A5 (Comprehensive)
Minimum Exterior Continuous Insulation R-value for Moisture Control in Climate Zone 7[1]

Heating Degree Days (Climate Zone 7)		Class I or II Interior Vapor Retarder (1 perm or less)					Class III Interior Vapor Retarder (1<perm≤10)				
		Min. R_e/R_i Ratio	Maximum Cavity Insulation R-value				Min. R_e/R_i Ratio	Maximum Cavity Insulation R-value			
			2x4 walls		2x6 walls			2x4 walls		2x6 walls	
HDD65°F	HDD18°C		R-13	R-15	R-19	R-23		R-13	R-15	R-19	R-23
9,000	5,000	0.2	R-2.6ci	R-3ci	R-3.8ci	R-4.6ci	0.5	R-6.5ci	R-7.5ci	R-9.5ci	R-12ci
9,900	5,500	0.25	R-3.3ci	R-3.8ci	R-4.8ci	R-5.8ci	0.6	R-7.8ci	R-9.0ci	R-12ci	R-14ci
10,800	6000	0.3	R-3.9ci	R-4.5ci	R-5.7ci	R-6.9ci	0.7	R-9.1ci	R-11ci	R-13ci	R-16ci
12,600	7,000	0.35	R-4.6ci	R-5.3ci	R-6.7ci	R-8.1ci	0.8	R-11ci	R-12ci	R-15ci	R-18ci

1. As permitted in *2015 IRC* Table R702.3, spray foam with a maximum permeance of 1.5 perms at the installed thickness, applied to the interior cavity side of wood structural panels, fiberboard, insulating sheathing or gypsum is deemed to meet the continuous insulation requirement for the purposes of this table only where the spray foam *R*-value meets or exceeds the specified continuous insulation *R*-value.

INSULATION RATIO CHART AND REGRESSION EQUATIONS FOR TABLE A1 “METHOD B” WALLS

Table A1 and various other tables in this Appendix with insulation ratios may be represented in chart form as shown below.



Based on the above chart, regression equations to determine the insulation ratio from a site-specific heating degree day value are as follows:

Class I/II Vapor Retarder: Ratio = 0.000042(HDD65F) - 0.18 (but not less than 0.2 in CZ 4, n/a in CZ 1-3)		
Class III Vapor Retarder: Ratio = 0.0000833(HDD65F) - 0.25 (Climate Zone 4-8, n/a in CZ 1-3)		
No Vapor Retarder: Ratio = -6.6E-09 (HDD65F)^2 + 0.00032 (HDD65F) - 0.67 (Climate Zones 3-8, n/a in CZ 1 and 2)		

Appendix B – Energy Code Compliance Supplement

This Research Report has addressed insulation and water vapor permeance requirements for moisture control purposes only. The solutions for moisture control, however, may be above or below thermal performance levels (U-factors or R-values) required for compliance with the locally applicable energy code which may be based on a model energy code, such as the *International Energy Conservation Code* (ICC, 2018c). This section addresses the verification of assemblies for compliance with requirements for water vapor control and thermal performance. The important link between water vapor retarder and energy code requirements has been emphasized in the IECC (ICC, 2018c):

> **R402.1.1 Vapor retarder.** Wall assemblies in the *building thermal envelope* shall comply with the vapor retarder requirements of Section R702.7 of the *International Residential Code* or Section 1404.3 of the *International Building Code,* as applicable.

In the examples that follow, applications of water vapor control provisions are based on Appendix A. Required insulation component R-values used in the examples are based on common prescriptive solutions included in the IECC.

Example 1: Using insulation ratios to check energy code solutions and alternative wall insulation strategies for adequate moisture durability

Given: Assume the energy code requires R20+5ci (2x6 wall with R20 cavity insulation and R5 continuous insulation). This is a "Method B" wall in accordance with Table A1 of Appendix A.

Find: What is the maximum (coldest) permissible climate zone for this wall when using a Class I, II or Class III interior vapor retarder?

Solution: First, determine the insulation ratio, $R_e/R_i = 5/20 = 0.25$. In accordance with Table A1 or A3 (Appendix A), the maximum/coldest climate zone is 6 with a Class I or II interior vapor retarder and Climate Zone 4 with a Class III interior vapor retarder (actually moderately into the lower portion of Climate Zone 5 by interpolation in Table A1). Alternatively, a more precise use of insulation ratios as shown in Table A5 (Comprehensive) indicates that an R20+5ci wall with a Class I or II vapor retarder works within Climate Zone 7 for up to 9,900 heating degree days (HDD65F). While this example assembly may be permitted as a prescriptive solution in the energy code, the insulation ratio should be checked as demonstrated in this example as moisture control considerations may "override" the energy code. Consequently, the insulation locations and amounts may need to be adjusted to achieve moisture control while also still complying with the required energy code thermal performance in a given climate zone. For example, changing to a R13+R10ci insulation strategy using a 2x4 wall which is thermally equivalent will increase the insulation ratio to 10/13 = 0.77, providing much improved water vapor control or the ability to tolerate higher indoor RH conditions and/or much colder climate zones.

Example 2: Getting More Creative with Insulation Ratios

Given: Consider a wall assembly comprised of R15 high density batt insulation in a 2x4 wall, the use of exterior continuous insulation, and R2 insulating (foam backed) vinyl siding. This is a "Method B" wall assembly in accordance with Table A1 of Appendix A.

Find: What would be the required R-value (and thickness) of the exterior continuous insulation to use this assembly in Climate Zone 6 with a Class III interior vapor retarder (e.g., latex paint on drywall)?

Solution: In accordance with Table A1 a *minimum* R_e/R_i ratio of 0.5 is required (which more precisely applies to the extreme northern boundary of Climate Zone 6). Thus, the exterior continuous insulation amount must be at least R15 x 0.5 = R7.5ci. Because the insulating siding provides at least R2 of this exterior continuous insulation, the insulated sheathing only needs to make up the difference of 7.5R – R2 = R5.5.

Thus, the following insulated sheathing options are possible:

- 1.5 inches of EPS foam sheathing (~R6),
- 1" of XPS (R5) plus an insulated vinyl siding of R2.5 instead of R2, or
- 1" of foil-faced polyisocyanurate foam sheathing(~R6)

While the above wall meets the moisture control objective, energy code compliance must also be checked. In this case, a U-factor for the assembly should be determined following procedures in the energy code and the ASHRAE *Handbook of Fundamentals* or an approved method. For example, if the R15+7.5ci objective is exactly satisified with a combination of insulating sheathing and insulating siding as discussed above (e.g., R5.5 sheathing and R2 siding), the calculated U-factor of the wood-frame wall assembly is approximately 0.049 with an effective R-value of 20.4.

Example 3: Verify compliance of a conventional 2x6 (cavity insulation only) wall assembly in Climate Zone 5 with exterior permeance requirements for water vapor control

Given: Assume the energy code requires minimum R-20 cavity insulation and the product used is vapor permeable (e.g., fiberglass, cellulose, etc.). This is a "Method A" wall assembly in accordance with Table A1 of Appendix A. Also assume that 7/16" OSB sheathing is used (typical wet cup vapor permeance ~ 3.8 perm – verify with manufacturer) together with a 10 perm building wrap (verify with manufacturer) and a vented cladding (e.g., anchored brick veneer, vinyl siding, furred lap siding, etc.).

Find: What Class of interior vapor retarder is permitted for use with this assembly in Climate Zone 5?

Solution: First, determine the net vapor permeance of the exterior material layers (excluding the vented cladding) in accordance with Note 'c' of Table A1. Thus, net permeance = 1 / [(1/3.8) + (1/10)] = 1 / 0.36 = 2.75 perm. This is just under the minimum 3 perm required by Table A1 for use with a Class II (e.g., Kraft paper) vapor retarder. Thus, a Class I vapor retarder is required. However, there are alternatives. For example, one could use a sheathing product with a minimum permeance of 4.3 perm (e.g., ½" plywood sheathing, fiberboard, etc) which would result in a net vapor permeance of 3.0 perms or greater, allowing use of a Class II vapor retarder. Alternatively, the OSB sheathing can be used (assuming it has a wet cup vapor permeance of 3.8 perm or greater) with a building wrap or other water resistive barrier having a permeance of at least 15 perms. Thus, the net permeance = 1 / [(1/3.8) + (1/15)] = 1 / 0.33 = 3.03 perm which would also allow use of a Class II interior vapor retarder instead of a Class I. Using a non-vented cladding material of low water vapor permeance will require similar adjustments (or conversion to a vented cladding using furring) to achieve a similarly suitable design.