ABTG

Research Report

Assessment of Moisture Control & Insulation Requirements in Vermont's Final Draft *2015 Residential Building Energy Standard* (*RBES*) and *Handbook*

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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:

The final draft of the *2015 Vermont Residential Building Energy Standards* (*RBES*) includes newly added moisture vapor control provisions in Section R402.2.15 (see Appendix A) that specifically question the performance of 6" wall construction (e.g., R20 cavity insulation) with R-5 continuous insulation. It is unclear why this condition is singled out. Concerns regarding moisture control performance can affect walls of any thickness, with or without the added protection of exterior continuous insulation. Therefore, one purpose of this Research Report is to present data to evaluate and substantiate an appropriate application of continuous insulation in the *Vermont RBES*, particularly an R20+5 assembly (e.g., R20 cavity insulation plus R-5 continuous insulation on the exterior). The data and engineering principles used herein are broadly applicable and also may be used to establish appropriate prescriptive guidelines and limitations for a wider variety of wall assemblies and materials.

The approach taken in this Research Report relies on an extensive review and analysis of recognized scientific literature, including relevant building code provisions in the U.S. and Canada. The goal is to provide a rational answer to the following question: “How much exterior insulation is required, if any, to prevent unacceptable 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 intent in posing and answering this question is to provide a more complete, consistent, and equitable basis for considering prescriptive moisture control provisions in the *RBES*.

The findings and analysis in this Research Report are intended to support the inclusion of supplemental guidance information for the Vermont Residential Building Energy Standard (RBES) Handbook. This report may also serve as a basis for future improvements or enhancements to the RBES provisions.

Background:

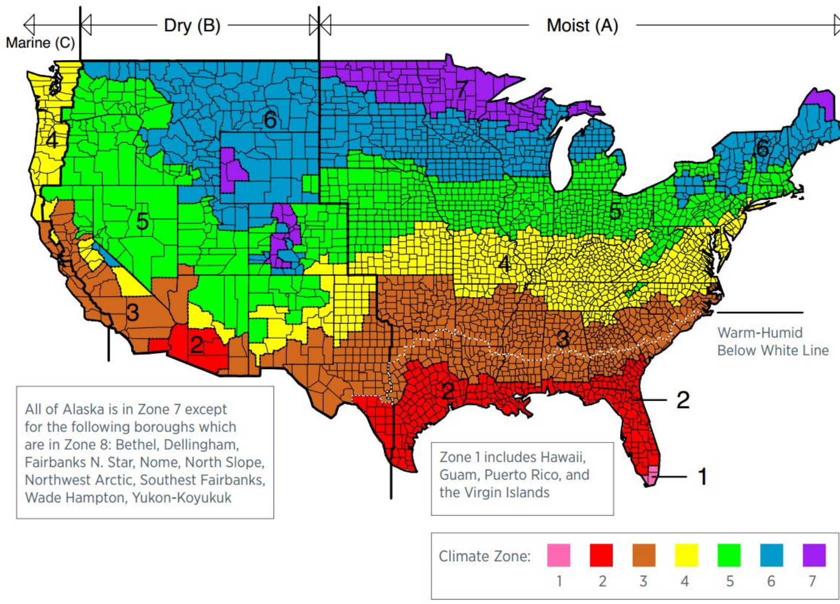
Commonly recognized principles behind the moisture vapor control approaches for cold climates, like Vermont, can be summarized in two simple concepts:

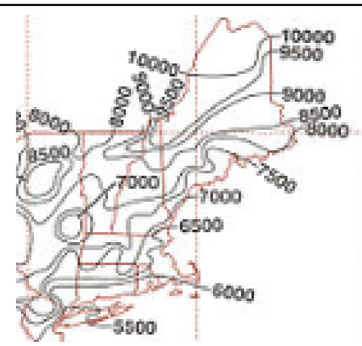
1. Maintain the envelope assembly's ability to adequately dry in at least one direction by not installing low-perm vapor retarder materials (e.g., vapor barrier) on both sides of an assembly.
2. Depending on climate zone and insulation strategy, seek to optimize the assembly's ability to dry and limit the potential for wetting.

At a minimum, the following key material or assembly properties must be considered and balanced to prevent unacceptable moisture accumulation and consequences:

- Water vapor permeance of the interior layers (e.g., interior 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 (assumed vapor permeable as a worst-case for this Research Report, although use of closed-cell spray foam is addressed)
- Exterior R-value (e.g., R-value of sheathing, continuous insulation, and siding)

Furthermore, the appropriate balance of the above material properties is governed by the outdoor climate and the indoor environment, particularly indoor relative humidity levels during the coldest months of the winter. For this Research Report, only Climate Zone 6 is considered because of its relevance to the *Vermont RBES* (see Figure 1). However, the principles apply similarly in other cold climate zones. Also, high indoor relative humidity levels can overwhelm any moisture vapor control strategy; thus, it is important for all wall assembly types and is a crucial determinant of performance as found in a number of case studies and experience.[1,2,3,4]





Source: NOAA Annual Heating Degree Days (1961-1990 Normals)

[1] Tsongas, G. (2009). Chapter 13 – Case Studies of Moisture Problems, ASTM Manual 18, 2nd Edition, Moisture Control in Buildings, ASTM International, West Conshohocken, PA.
[2] NAHB-RC (2004). Mold & Moisture Intrusion Case Study Report, prepared for the National Center for Housing and the Environment by the NAHB Research Center, Inc. Upper Marlboro, MD.
[3] HIRL (2014). Moisture Performance of Walls in Energy Efficient Homes, Home Innovation Research Labs, Upper Marlboro, MD
[4] ASTM (2009). E 241-09, Standard Guide for Limiting Water Induced Damage to Buildings (Section 8.3.3), ASTM International West Conshohocken, PA.

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: *2015 IECC*, International Code Council, Inc.

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

Two accepted means of design to execute the above principles and properly balance design parameters to achieve acceptable moisture control performance include[5,6,7]:

1. *Permeance Controlled Assembly* – Walls designed to dry to the exterior with a relatively high degree of moisture vapor resistance on the interior side to prevent excessive moisture accumulation, or
2. *Temperature Controlled Assembly* – Walls designed to dry to the interior with a high degree of exterior insulation R-value (relative to cavity insulation R-value) to keep the interior of the assembly warm (i.e., low risk of condensation).

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.

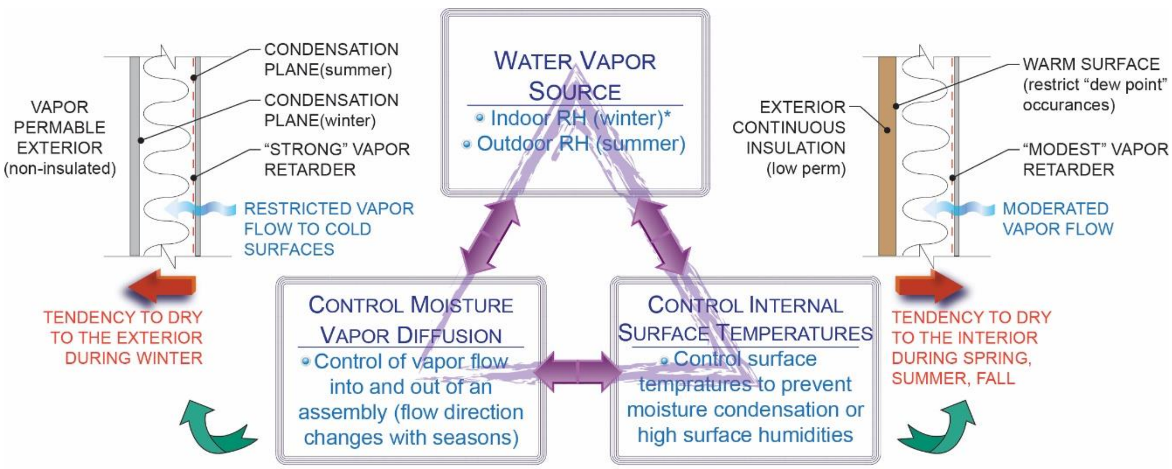


Figure 2: Illustration of the "Moisture Vapor Control Triangle" & Two Accepted Moisture Control Design Approaches (Source: Newport Partners, LLC)

The first approach becomes less risky with decreased vapor permeance (increased vapor resistance) of the interior layers, increased vapor permeance of the exterior layers, and decreased cavity insulation amounts. Conversely, with increased cavity insulation amounts (conservatively assumed to be vapor permeable insulation in this Research Report) and decreased vapor permeance of exterior layers, walls designed following approach #1 reach a margin or limit of acceptable performance. 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).

5 ASTM (2009). E 241-09, Standard Guide for Limiting Water Induced Damage to Buildings (Section 5.5), ASTM International West Conshohocken, PA.
6 BSI (2002). BS5250:2002, Code of Practice for control of condensation in buildings. British Standard.
7 Straube, J. (2011). The Influence of Low-Permeance Vapor Barriers on Roof and Wall Performance, Research Report 1101, Buildings VII, www.buildingscience.com

Similarly, for walls that are designed following approach #2, moisture accumulation risk is reduced with increasing exterior insulation amount (relative to cavity insulation amount and the interior vapor resistance provided) and vice-versa. 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. 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 Research Report and for reasons of simplification, the exterior insulation (R_e) is conservatively assumed to have low water vapor permeance. The variation in insulation ratio with variation in the permeance of interior vapor retarder is reflected in requirements found in the Canadian and U.S. building codes, as will be addressed in the next section of this Research Report.

In addition, both wall assembly design approaches benefit from good 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[8], control of air-leakage (exfiltration) and indoor relative humidity is an important design consideration for all walls. Unfortunately, indoor relative humidity is usually an undefined parameter in relation to establishing appropriate limits of use for prescriptive moisture vapor control strategies in current codes.

Finally, all walls necessarily require a code-compliant water-restive barrier (WRB) 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, Vermont is not in a severe wind-driven rain climate (e.g., such as the Atlantic and Gulf seaboards and the Pacific Northwest). Regardless, moisture vapor control strategies are not intended to act as a "bilge pump" to offset defective rain water control whether by poor design or poor WRB installation. Instead, it is commonly understood that moisture vapor control strategies should provide a reasonable level of tolerance for non-diffusion sources of moisture (e.g., incidental air leakage and/or moisture 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; therefore, this report addresses the issue from a practical perspective by (1) avoiding the obvious concern of a "double vapor barrier" wall assembly (e.g., Class I vapor retarder materials on both sides of a wall) and (2) recommending minimum vapor permeance levels to promote drying to the interior or exterior as dictated by the two design approaches to control moisture vapor presented earlier.

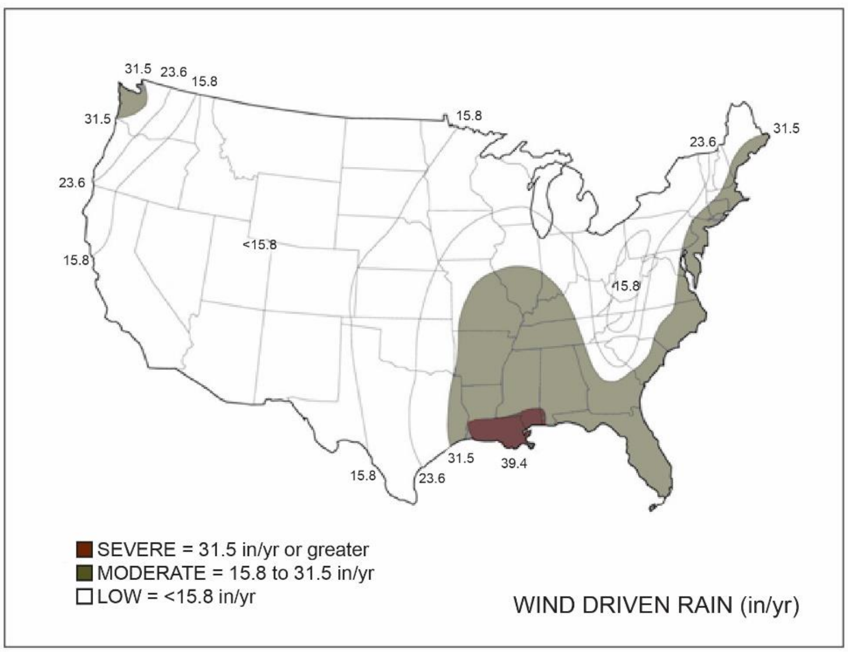


Figure 3: Wind-Drive Rain Climatology for the United States
(Source: Underwood, University of Georgia, 1999)

[8] Straube, J. (2011). The Influence of Low-Permeance Vapor Barriers on Roof and Wall Performance, Research Report 1101, Buildings VII, www.buildingscience.com

Findings and Analysis:

In current U.S. model codes (e.g., Table R702.3 of the *2015 IRC*) and also the draft final *RBES* (Section 402.7), minimum exterior continuous insulation (ci) amounts are prescribed only for the condition where there is a low moisture vapor diffusion resistance on the interior side of the cavity (i.e., Class III, latex paint vapor retarder). This practice has been recognized in the *IRC* and *IBC* since the 2006 editions (roughly 9 years). But, it represents only one particular application of the second accepted means of design mentioned in the previous section (i.e., a "temperature controlled" or drying to the interior design approach). Another variation of this approach is found in the *2010 Canadian National Building Code* (*NBC*) and it has been recognized in the *NBC* since the 1995 edition (roughly 20 years). Both of these variations address the performance-based goal of a wall assembly with adequate moisture control, and both are supported by North American building codes, experience, analysis, and research.

In this section, the U.S. practice as found in the *IBC*, *IRC* and *RBES* is presented first followed by the Canadian practice based on the *NBC*. Example applications also are included to represent the determination of acceptable wall assemblies with continuous exterior insulation in accordance with the U.S. and Canadian practices. The examples are focused on Vermont's climate zone and represent potential prescriptive or performance solutions for the *REBS*.

- **Insulation Ratios for Use with Class III Interior Vapor Retarder (U.S. Practice)**

The prescribed exterior insulation amounts for use with Class III interior vapor retarders in the *IRC* and *RBES* address only two cavity insulation conditions for 2x4 (R13) and 2x6 (R20) walls. However, these requirements are actually based on a simple insulation ratio (exterior R / cavity R) to control the temperature of the inner surface of the exterior sheathing such that it is above the indoor air's dew point temperature. The insulation ratios are shown in Table 1 and are supported by the References listed below the table. These insulation ratios are applicable to wall constructions with a Class III interior vapor retarder.

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 *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 serving as the basis of the R13+7.5 and R20+11.25 wall assemblies in the *IBC*, *IRC* and *RBES* when a Class III interior vapor retarder is used:

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)

- **Insulation Ratios for Use with Class I or II Interior Vapor Retarder (Canadian Practice)**

The insulation ratios in the *2010 NBC* Table 9.25.5.2 are summarized in Table 2. Section 9.25.5 of the *2010 NBC* requires the use of insulation ratios in Table 2 where a sheet or panel type material is placed on the exterior side of an assembly, and the material has a water vapor permeance of 60 ng/(Pa-s-m^2) [~1 perm] or less. They are also based on an interior vapor retarder of 1 perm (e.g., Class II), although the NBC permits their use with an interior vapor retarder of 1 perm or less (e.g., Class I or II).

TABLE 2
Canadian Insulation Ratios
[based on Table 9.25.5.2 of the *2010 NBC*]

Heating Degree Days (HDD18ºC)	Minimum Ratio of Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface (R_e/R_i)
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

1 HDD(18ºC) = 1.8 HHD(65ºF)

Table Sources and References:

- 1995/2000/2005/2010 *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

The values in the table above 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). For Vermont, the applicable Climate Zone is 6, which corresponds to a maximum HDD65ºF of 9,000 ºF-days. The conversion factor is 1 HDD18ºC = 1.8 HDD65ºF. Thus, 9,000 ºF-days = 9,000/1.8 = 5,000 ºC-days. From Table 2, this would appear to require an insulation ratio of 0.3, but this value actually applies for only the margin between Climate Zone 6 and Climate Zone 7 and is a consequence of how climate zones are discretized differently in Canada vs. the U.S. Because essentially all of Climate Zone 6 has 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 Table 2 is applicable to Vermont.

The following provides an example application of the above insulation ratios in accordance with the *NBC* when a Class I or II interior vapor retarder is used and the exterior sheathing is less than 1 perm:

<u>Example #1 (2x4 wall with Class I or II interior vapor retarder)</u>
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

<u>Example #2 (2x6 wall with Class I or II interior vapor retarder)</u>
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)

The above examples show only a couple of representative solutions that are possible. Table 3A combines all of the above information into a simple set of prescriptive requirements consistent with the *NBC* (for insulation ratios with Class I and II vapor retarders) and *IRC* (for insulation ratios with Class III vapor retarders). The simple solutions in Table 3A are derived from a more comprehensive analysis of pre-calculated prescriptive solutions appropriate for Vermont's climate range as shown in Table 3B. Insulation ratios are interpolated from Table 1 and Table 2 to match the HDD divisions represented in Table 3B. The values in Table 3A for the Class I and II vapor retarder condition do not include the values based on a 0.3 insulation ratio for reasons stated previously.

TABLE 3A (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)	
Maximum Cavity Insulation R-value		Maximum Cavity Insulation R-value	
2x4 walls	2x6 walls	2x4 walls	2x6 walls
R-3ci	R-5ci	R-7.5ci	R-11.25ci

TABLE 3B (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	0.3	R-3.9ci	R-4.5ci	R-5.7ci	R-6.9ci	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. Combinations of cavity-applied spray foam and exterior continuous insulation also shall be permitted to satisfy the minimum continuous insulation R-value for the purposes of this table only.

- **Interior Vapor Retarder Selection and Exterior Permeance Limits for Moisture Control and Acceptable Drying Potential (Applies to All Walls)**

An important issue not explicitly addressed in the above *IRC*, *IBC*, *NBC*, and current *RBES* 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. Thus, there are permeance limits for walls with and without exterior continuous insulation that are as important to consider as the insulation ratios. For walls without adequate exterior insulation, permeance limits for the interior and exterior of the wall are especially important and must be appropriately balanced. But, all walls must be capable of providing adequate drying in either the inward or outward direction to prevent progressive (year-by-year) moisture accumulation that may result from uncertain moisture sources other than by diffusion (e.g., incidental moist indoor air exfiltration and rain water intrusion).

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 avoids "double vapor barrier" assemblies by applying analysis recommendations from a German Standard DIN 4108[9,10], which uses the Keiper

[9] 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.

hygrothermal analysis method[11,12] to determine relative, equivalent limits for walls with and without continuous insulation meeting the insulation ratios described previously. The analysis applies a moisture surcharge of 250 $g/m^2/yr$ (0.05 $gal/ft^2/yr$) to the condensation plane within a wall assembly (over and above any moisture accumulation or drying amount due to diffusion alone) and the wall is required to dry out this excess moisture 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. Furthermore, for the applications with a Class I interior vapor retarder in Table 4, the drying potential required by the above criteria is exceeded by the requirement of a minimum net 1 perm on the exterior side of the wall.

TABLE 4
Minimum Net Water Vapor Permeance (WVP) of Material Layers on the Exterior Side of Vapor-Permeable Cavity Insulation in Climate Zone 6[1]

Interior Vapor Retarder Class	Walls without Exterior Continuous Insulation[2]	Walls with Exterior Continuous Insulation Meeting Table 3
I	1 perm	1 perm
II	5 perm	No minimum perm
III	Class III not permitted[3]	No minimum perm

1. Where there are multiple exterior material layers, 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, vented siding = 30 perm, then P_{Total} = 1/[1/2 + 1/5 + 1/30] = 1/0.73 = 1.4 perm. Thus, a Class I vapor retarder is required for this example wall. Permeance values for exterior material layers shall be permitted to be determined in accordance with the wet cup method (Method B) of ASTM E 96.
2. Walls with exterior continuous insulation of any R-value are permitted without complying with Table 3 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 in accordance with Section 402.7 of the final draft RBES and Table R702.7.1 of the 2015 IRC. It is recommended that any other exterior layers, such as the water-resistive barrier, be at least as vapor permeable as fiberboard and gypsum sheathing (e.g., >15 perm)

Because materials on the exterior side of a wall are subject to high relative humidity conditions in the winter caused by cold 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*. However, allowing the use of a dry-cup WVP value will result in a conservative solution for 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 4 to these types of materials should be based on their vapor permeance as measured by the wet-cup method (Method B) of *ASTM E96*.

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.[13,14,15] Such recommendations are aimed at walls intended to dry to the exterior and provide sufficient control of condensation during a period of the year when the interior surface temperature of exterior non-insulated sheathing is below the dew-point temperature.

- **Combined Energy Code and Moisture Control Solutions**

The above findings and analysis have addressed minimum insulation and moisture 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 *Vermont RBES*. This section addresses assemblies with R-values that meet both of these performance requirements for the two wall U-factors representing two prescriptive options or packages in the *RBES* (Table 402.1.2). The analysis follows the same parallel path heat transfer calculation method as applied in the development of the *2015 IECC* residential prescriptive R-values.

[10] Kunzel, H.M, Zirkelbach, D., Shafaczek, B. (2011). Modelling Effect of Air-Leakage in Hygrothermal Envelope Simulation, www.brikbase.org (4/7/2014)
[11] ASTM (2009). Moisture Control in Buildings: The Key to Mold Prevention, 2nd Edition, Manual 18, ASTM International, West Conshohocken, PA.
[12] TenWolde, A. (2001). Chapter 7 – Manual Analysis Methods, ASTM Manual 40, ASTM International, West Conshohocken, PA.
[13] CFR (2004). Manufactured Home Construction Standards, United States Code of Federal Regulations, 24 CFR Chapter XX, Part 3280.54.
[14] BSI (2002). BS5250:2002, Code of Practice for control of condensation in buildings. British Standard.
[15] Vinha, J. (2008). Analysis method to determine sufficient water vapour retarder for timber-framed walls. Department of Civil Engineering, Tampere University of Technology, Best 1 Conference, June 10-12, 2008, Minneapolis, MN.

The wood-frame wall U-factors associated with the two prescriptive packages in *RBES* Table 402.1.2 are as follows:

- R13+10ci (U-0.045)
- R25 (U-0.054)

Other R-value assemblies with equivalence to R25 (U=0.054) include: R-13+5.9, R-11+7, and R-15+5. All of these provide useful solutions for 2x4 walls that are not currently included in Package #2 in the *RBES* Table 402.1.2. Of these, the wall assembly that most efficiently meets the U-factor requirement and aforementioned moisture control requirements is the R-15+5 wall assembly. It provides an insulation ratio of 5/15 = 0.33, which more than satisfies the required insulation ratio for Vermont for use with a Class I or II interior vapor retarder (see Table 3A and Table 3B).
It should be noted that the R13+10 wall assembly is conservative in that its insulation ratio of 10/13 = 0.77 exceeds the worst-case insulation ratios for use with a Class I, II, or III interior vapor retarder in Vermont. Thus, it is suitable for any location in Vermont and with any interior vapor retarder (provided the exterior permeance requirements of Table 4 are satisfied when a Class I interior vapor retarder is used). It also has a U-factor of 0.044 (slightly more conservative than the required U=0.045).

Finally, an R-20+5 R-value assembly meets the wall U-factor of 0.045 for Package #1 (equal to R13+10), and it has an insulation ratio of 5/20 = 0.25. According to Table 3A and Table 3B, this assembly also is suitable for use with a Class I or II interior vapor retarder in Vermont. According to Table 3B and Table 2, if this assembly were used in Climate Zone 7 (> 9000 HDD65ºF or 5,000 to 5,999 HDD18ºC), it would not meet the required 0.3 insulation ratio. However, this does not mean that the assembly cannot be used, even in conditions that exceed Climate Zone 6 in Vermont. For example, if the R-5 continuous insulation has a perm rating of 1 perm or more when a Class I interior vapor retarder is used according to Table 4 (footnote 2), then the insulation ratio is no longer relevant and the R20+5 assembly can be used on that basis. In such case, the wall relies on a combination of temperature control and permeance control to maintain balanced wetting and drying potential, as discussed in the Background section.

Conclusions and Recommendations:

Where exterior insulation is used, Canadian and U.S. building codes taken together provide technical substantiation and guidance to ensure adequate moisture performance for wall assemblies appropriate to Vermont. The findings of this Research Report support the following recommendations for the *RBES* and also the *REBS Handbook*:

Recommendation #1. Revise or delete *RBES* Section R402.2.15 per one of the following options:

Option A: Delete two sentences in *RBES* Section R402.2.15 as follows:

> **R402.2.15 Wood framed walls.** Efforts must be made to protect insulated cavities from airborne water vapor and condensation. Air sealing the interior face of the assembly, controlled mechanical ventilation (targeting 30% relative humidity), exterior continuous insulation and proper consideration of the vapor permeance of materials are all design elements that can contribute to this protection. ~~Adequate protection from condensation within a standard 6" assembly is likely with R-11.25 or higher exterior insulating sheathing; R-5 exterior insulating sheathing likely does not prevent condensation within a standard 6" assembly and may increase its likelihood.~~ Consultation with design professionals on these details is strongly encouraged.
>
> **REASON:** These two sentences are not complete and not entirely accurate. First, the R-11.25 requirement is necessary only when a Class III interior vapor retarder is used per the IRC and the substantiating data included in this Research Report. This is already adequately and more completely addressed in Section R402.7 of the RBES. Second, the only case where R-5 insulating sheathing is not code compliant is when it is used with a Class III interior vapor retarder. But, this section does not make that qualification. Current practice and code requirements in the US and Canada provide adequate justification that R-5 exterior insulation works in Climate Zone 6 with a Class I (polyethylene) or Class II (Kraft paper) interior vapor retarder, particularly with the inclusion of controlled ventilation (targeting 30% relative humidity) which is important to walls with and without exterior insulating sheathing.

Option B: Revise Section R402.2.15 as follows:

> **R402.2.15 Wood framed walls.** Efforts must be made to protect insulated cavities from airborne water vapor and condensation. Air sealing the interior face of the assembly, controlled mechanical ventilation (targeting 30% relative humidity), exterior continuous insulation and proper consideration of the vapor permeance of materials are all design elements that can contribute to this protection. Adequate protection from condensation ~~within a standard 6" assembly is likely with R-11.25 or higher exterior insulating sheathing~~ when a Class III interior vapor retarder is used shall be in accordance with Section R402.7; ~~R-5 exterior insulating sheathing likely does not prevent condensation within a standard 6" assembly and may increase its likelihood.~~ Consultation with design professionals on these details is strongly encouraged.
>
> **REASON:** These revisions bring the RBES Section 402.2.15 into agreement with the vapor control provision in the IRC and Section R402.7 of the RBES. Insulating sheathing amounts less than R11.25 are achievable for 6" assemblies, including R-5 exterior insulating sheathing, while creating performance consistent with assemblies without exterior insulating sheathing for which the code gives no limitations on permeance values for exterior materials.

Option C: Delete Section R402.2.15 in its entirety as follows:

> ~~**R402.2.15 Wood framed walls.** Efforts must be made to protect insulated cavities from airborne water vapor and condensation. Air sealing the interior face of the assembly, controlled mechanical ventilation (targeting 30% relative humidity), exterior continuous insulation and proper consideration of the vapor permeance of materials are all design elements that can contribute to this protection. Adequate protection from condensation within a standard 6" assembly is likely with R-11.25 or higher exterior insulating sheathing; R-5 exterior insulating sheathing likely does not prevent condensation within a standard 6" assembly and may increase its likelihood. Consultation with design professionals on these details is strongly encouraged.~~
>
> **REASON:** These provisions are written in commentary or guidance language and are not enforceable. They also are not complete and contain problems as mentioned in the reasons given for Options A and B above. The better place to address non-enforceable guidance information may be in the RBES Handbook (see Recommendation #2 below) to ensure adequate moisture control considerations are addressed more completely for all wall types, including those with foam sheathing.

Recommendation #2: Revise *RBES* Handbook (Review Draft) as follows:

Refer to separately submitted comments to the Handbook summarizing the principles and findings included in this Research Report and specifically, the guidance included in Tables 3A and 4.

Recommendation #3: Revise *RBES* Table R402.1.2 as follows:

TABLE R402.1.2
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT

PACKAGE#	FENES-TRATION U-FACTOR	SKY-LIGHT U-FACTOR	CEILING R-VALUE	WOOD FRAME WALL R-VALUE[f]	MASS WALL R-VALUE	FLOOR R-VALUE	BASEMENT & CRAWLSPACE WALL R-VALUE	SLAB R-VALUE & DEPTH	HEATED SLAB R-VALUE
1	0.32	0.55	49	13+10 <u>**R20+5**</u>	15/20	30	15 continuous or 20 cavity	15, 4ft	15, edge and under
2	0.28	0.55	49	25 <u>**R15+5**</u>	15/20	30	15 continuous or 20 cavity	15, 4ft	15, edge and under

Table footnotes unchanged except footnote f as follows:

f. The first value is cavity insulation, the second value is continuous insulation, so "R13+10" means R-13 cavity insulation plus R-10 continuous insulation. ~~R25 can be met through any combination of insulation R-values, cavity, or cavity and continuous insulation.~~

REASON: The added R-value solutions are thermally equivalent and provide two alternates for 2x4 and 2x6 walls consistently for each of the two packages. The moisture control suitability of these added assemblies for Vermont (Climate Zone 6) is justified in US and Canadian building code provisions. In particular, the R20+5 solution has been recognized as an acceptable assembly in the moisture vapor control provisions of Part 9 (Housing) of the Canadian National Building Code (NBC) since the 1995 edition with an absence of reported problems, even under recent National Research Center re-evaluation for the 2015 NBC. Regarding footnote f, the last sentence is stricken because the methodology proposed does not comply with wall assembly thermal performance principles serving as the basis of the code and also accepted engineering practice recognized in the ASHRAE Handbook of Fundamentals. R25 is not equal to R20+5 or R15+10. Adding only the separate component R-values together without considering their location and role in the thermal pathway is fictional math and does not represent the physics of heat flow through the assembly.

Appendix A:

Excerpts from final draft Vermont *RBES*:

TABLE R402.1.2
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT[a]

PACKAGE#[i]	FENESTRATION *U*-FACTOR[b]	SKYLIGHT[b] *U*-FACTOR	CEILING *R*-VALUE[h]	WOOD FRAME WALL *R*-VALUE[f]	MASS WALL *R*-VALUE[g]	FLOOR *R*-VALUE	BASEMENT[c] & CRAWLSPACE WALL *R*-VALUE	SLAB[d] *R*-VALUE & DEPTH	HEATED SLAB[d] *R*-VALUE
1	0.32	0.55	49	13+10	15/20	30[e]	15 continuous or 20 cavity	15, 4 ft	15, edge and under
2	0.28	0.55	49	25	15/20	30[e]	15 continuous or 20 cavity	15, 4 ft	15, edge and under

For SI: 1 foot = 304.8 mm.

a. R-values are minimums. *U*-factors are maximums. When insulation is installed in a cavity which is less than the label or design thickness of the insulation, the installed *R*-value of the insulation shall not be less than the *R*-value specified in the table. Insulation R-value layers can be added to meet the required R-value.

b. The fenestration *U*-factor column excludes skylights.

c. Basement and crawlspace insulation can be met through either R-15 continuous insulation or R-20 cavity insulation, either interior or exterior.

d. "4 ft" can be horizontal or vertical coverage including slab edge. "Edge and under" requires complete coverage. Up to 8 lineal feet of exposed slab edge may be insulated to R-10.

e. Or insulation sufficient to fill the framing cavity.

f. The first value is cavity insulation, the second value is continuous insulation, so "13+10" means R-13 cavity insulation plus R-10 continuous insulation. R-25 can be met through any combination of insulation R-values, cavity, or cavity and continuous insulation.

g. The second *R*-value applies when more than half the insulation is on the interior of the mass wall.

h. Installing R-38 over 100 percent of the ceiling area requiring insulation shall be deemed to satisfy the requirement for R-49 insulation wherever the full height of uncompressed R-38 insulation extends over the wall top plate at the eaves. (See section R402.2.1).

i. The Public Service Department has developed alternative prescriptive packages deemed to be equivalent, provided in the accompanying 2015 RBES Handbook.

TABLE R402.1.4 EQUIVALENT *U*-FACTORS[a]

FENESTRATION *U*-FACTOR	SKYLIGHT *U*-FACTOR	CEILING *U*-FACTOR	FRAME WALL *U*-FACTOR	MASS WALL *U*-FACTOR[b]	FLOOR *U*-FACTOR	BASEMENT WALL *U*-FACTOR	CRAWL SPACE WALL *U*-FACTOR	SLAB & UNHEATED SLAB *U*-FACTOR & DEPTH
0.32	0	0.026	0.045	0.060	0.033	0.05	0.050	0.066, 4 ft

a. Nonfenestration *U*-factors shall be obtained from measurement, calculation or an approved source.

b. When more than half the insulation is on the interior, the mass wall U-factors shall be a maximum of 0.057 in Climate Zones 6 through 8.

402.6 Vapor retarders. Class I or II vapor retarders are required on the interior side of frame walls.

Exceptions:

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

402.7 Class III vapor retarders. Class III vapor retarders shall be permitted where any one of the following conditions is met:

1. Vented cladding over fiberboard.
2. Vented cladding over gypsum.
3. Insulated sheathing with *R*-value 7.5 over 2 × 4 wall.
4. Insulated sheathing with *R*-value 11.25 over 2 × 6 wall.

402.8 Material vapor retarder class. The *vapor retarder class* shall be based on the manufacturer's certified testing or a tested assembly. 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.

R402.2.15 Wood framed walls. Efforts must be made to protect insulated cavities from airborne water vapor and condensation. Air sealing the interior face of the assembly, controlled mechanical ventilation (targeting 30% relative humidity), exterior continuous insulation and proper consideration of the vapor permeance of materials are all design elements that can contribute to this protection. Adequate protection from condensation within a standard 6" assembly is likely with R-11.25 or higher exterior insulating sheathing; R-5 exterior insulating sheathing likely does not prevent condensation within a standard 6" assembly and may increase its likelihood. Consultation with design professionals on these details is strongly encouraged.

Excerpt from *2015 IRC*:

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.