Heat and Moisture Control Considerations with Steel Framing in Low-Rise Residential Construction

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ABSTRACT

Two important design considerations for steel-framed wall construction are heat and moisture control. To effectively control heat flow across steel-framed wall systems, it is necessary to provide a continuous thermal break external to the framing. It follows that a practical thermal insulation strategy will involve two layers of different types of insulation material.

In low-rise residential construction, it is common practice to avoid the use of a wood-based sheathing material and to regard the outer layer of thermal insulation as the exterior sheathing. Consequently, there is little, if any, capacity for moisture storage within the stud space. Given that air leakage as well as vapor diffusion occurs and that certain walls (e.g., upper walls on the leeward side of the prevailing wind direction) are likely to be particularly susceptible to the combined effects of exfiltration and water vapor diffusion, the possibility of condensation and moisture accumulation must be given serious attention as one or more moisture-related problems could develop.

This paper presents a strategy to effectively insulate and avoid moisture-related problems due to exfiltration condensation in residential wall systems. This work was the basis for revising the steel framing design recommendations that currently appear in both the IECC and the IRC 2000 codes.

INTRODUCTION

In November 1999, Pennsylvania's Governor Ridge signed into law the Uniform Construction Code (UCC) legislation, providing for a statewide building code. For residential buildings in Pennsylvania, the new International Residential Code (IRC) 2000 is to be adopted. Moreover, the act also requires the Pennsylvania Department of Labor and Industry (DLI) to promulgate regulations for the implementation of alternative, prescriptive methods for energy conservation.

In spite of its name, the IRC 2000 is intended to be a national code, and the space-conditioning energy provisions, which are contained in Chapter 11 of the IRC 2000, apply to all the climatic zones in the U.S. Chapter 11 in the IRC 2000 is a prescriptive version of the requirements of the 2000 International Energy Conservation Code (IECC). In December 1999, the Pennsylvania Housing Research Center (PHRC) was charged with the development of an alternative Chapter 11 that would be simpler, more flexible, and better focused on Pennsylvania. In terms of space-conditioning energy performance, this alternative Chapter 11 was to be equivalent to the 2000 IECC, which, in turn, is the successor code to the CABO Model Energy Code (MEC).

Chapter 11 of the IRC 2000 sets out specific requirements for the amount and location of thermal insulation for exterior walls framed with light-gauge steel studs. While these thermal requirements account for the unique nature of heat flow across steel-framed walls (i.e., thermal bridging), no provision has been made for the control of water vapor migration, by diffusion or air leakage, across the exterior wall assembly. Although the control of water vapor migration may seem to be beyond the scope of an energy conservation code, the likelihood of condensation within the stud space in steel-framed wall systems is very much dependent on the amount and location of the thermal insulation. In order to ensure the appropri-

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ate code recommendations for steel-framed exterior walls, the following needed to be done:

1. Check whether the IRC 2000 code requirements do provide for satisfactory heat and moisture control for the conditions that prevail in low-rise, new housing in Pennsylvania and, if not,
2. Develop the appropriate requirements for the Pennsylvania alternative Chapter 11.

The objective of this particular project was, therefore, to resolve both of the above needs within the time and funding constraints that prevailed. Fortunately, the PHRC had recently completed a project on steel stud-framed wall systems, and this prior work provided the basis for some of the discussion that follows (Bombino and Burnett 1999; Bombino 1999).

REVIEW OF RELEVANT CODE CLAUSES

The specific clauses from Chapter 11 of the IRC 2000 that define the required thermal insulation strategies to be used in above-grade exterior steel-framed walls are provided in Table 1. This constitutes all the relevant guidance that is given with regard to insulating steel-framed wall systems. No explanation is provided as to why these values are appropriate and there is no mention of any one of the following:

- the effective average R-value (including the vertical framing) for each combination of insulation and framing
- the spacing of studs and type of framing member (gauge, shape, openings, etc.)
- the thermal conditions that may prevail within the stud space
- the relative humidity of the air inside the building
- the air pressure differentials across the enclosure wall
- airtightness provisions
- water vapor diffusion provisions

These code requirements are relatively brief and are overly simplistic, especially when it is borne in mind that these clauses are intended to apply to any new house, anywhere within the U.S.

To superimpose a Pennsylvania context on these code requirements and to better visualize their likely impact, consider Table 2.

TABLE 1
The Relevant IRC 2000 Clauses and Their Requirements*

Climate Zone	HDD	Equivalent Steel-Frame Wall Cavity and Sheathing R-Value†
1	0 – 1999	R-11+R-5, R-15+R-4, R-21+R-3
2	2000 – 3999	R-11+R-5, R-15+R-4, R-21+R-3
3	4000 – 5999	R-11+R-9, R-15+R-8, R-21+R-7
4	6000 – 8499	R-13+R-10, R-19+R-9, R-25+R-8
5	8500 – 13,000	R-13+R-10, R-19+R-9, R-25+R-8

* Table N1102.1.1.2, Steel-Frame Wall Minimum Performance Requirements (R-Value).
† The cavity insulation R-value requirement is listed first, followed by the sheathing R-value requirement.

TABLE 2
IRC Code Provisions for Pennsylvania

<table>
<tr><th colspan="3">Building Location—Climate</th><th rowspan="2">Insulation Strategy: IRC 2000 Requirement*</th><th rowspan="2">Climate Zones and HDD Ranges Appropriate for Penn.</th><th rowspan="2">Percentage of Housing Starts in Penn.</th></tr>
<tr><th>Zone</th><th>HDD Range</th><th>HDD Gap</th></tr>
<tr><td>9</td><td>4000 – 4499</td><td>500</td><td rowspan="4">R-11 + R-9
or
R-15 + R-8
or
R-21 + R-7</td><td>Not Applicable</td><td>N/A</td></tr>
<tr><td>10</td><td>4500 – 4999</td><td>500</td><td rowspan="2">Southeast Penn. – Philadelphia Area (HDD = 1000)—S</td><td rowspan="2">56.5%</td></tr>
<tr><td>11</td><td>5000 – 5499</td><td>500</td></tr>
<tr><td>12</td><td>5500 – 5999</td><td>500</td><td rowspan="2">Central, Mideast, and SW Penn. – Pittsburgh Area (HDD = 1000)—C</td><td rowspan="2">41%</td></tr>
<tr><td>13</td><td>6000 – 6499</td><td>500</td><td rowspan="4">R-13 + R-10
or
R-19 + R-9
or
R-25 + R-8</td></tr>
<tr><td>14</td><td>6500 – 6999</td><td>500</td><td rowspan="2">NW and Northern Penn. – Erie / Bradford Area (HDD = 2000)—N</td><td rowspan="2">2.5%</td></tr>
<tr><td>15</td><td>7000 – 8500</td><td>1500</td></tr>
<tr><td>16</td><td>8500 – 8999</td><td>500</td><td>Not Applicable</td><td>N/A</td></tr>
</table>

* The cavity insulation R-value requirement is listed first, followed by the sheathing R-value requirement.

As shown in Table 2, the state of Pennsylvania can (for the purposes of these steel-stud provisions) be divided into three distinct climatic areas, as follows:

> Climatic Zones 10 and 11 – which straddle much of the Philadelphia area and contain more than 56% of all new house construction; labeled **Zone S** (south).
>
> Climatic Zones 12 and 13 – which straddle much of the Pittsburgh area and contain more than 40% of all new house construction; labeled **Zone C** (central).
>
> Climatic Zones 14 and 15 – which apply to the north of the state where less than 2.5% of all new construction occurs; labeled **Zone N** (north).

The IRC provisions make little climatic or strategic sense for central Pennsylvania. First, the climatic difference between the southeast (Philadelphia area) and much of the Pittsburgh (6000 HDD) area is not recognized, and, second, a 6000 HDD break point would have political implications as it would partition the city and its environs. In order to facilitate adoption of any new code-based regulation, it makes sense to take into account some of the political and economic realities.

THERMAL PERFORMANCE

Numerous studies have demonstrated that heat flow across the framing members can have a significant impact on the thermal performance of framed wall systems. Simply using the R-value of the thermal insulation to quantify the thermal performance of the wall assembly can be very misleading. To meaningfully evaluate the R-value of a wood- or steel-framed wall system involves determining, experimentally or analytically, representative R-values that include the thermal effects of all the constituent layers and parts as well as the framing members, i.e., the studs, top and bottom plates, and any blocking. It is not correct, especially with highly conductive framing, to merely add the R-values of the various in-plane layers.

A number of terms are currently used to identify the various composite R-values. For framed wall systems, the R-value of the portion of the wall between the studs and presumably unaffected by the framing, is known as the "center-of-cavity" R-value or R_{cc}; this value represents the portion of the wall with the highest resistance to heat flow. By including the effects of framing members at a regular spacing, i.e., the studs, as well as top and bottom plates and any blocking, a lower overall R-value is obtained; this is referred to as the "clear-wall R-value." By also including any additional framing, such as that at corners, around doors and windows, etc., one may establish a third value, namely, a "whole-wall R-value."

In this work we are attempting to address all possible framed wall systems, and it can be assumed that the layers outside the exterior sheathing make the same contribution to retarding heat flow irrespective of framing material. For the purpose of this paper, only the sheathings, the insulated stud space or cavity, and the vertical studs at regular spacing are considered as variables. Of course, each in-plane layer has an R-value and the sum of these values will provide the center-of-cavity R-value. When the effect of the vertical framing is incorporated, an "average" R-value or R_{avg} is obtained, which is much more representative of the ability of this portion of the wall system to retard heat flow. THERM 2.0, a two-dimensional, steady-state, heat flow computer program was used to determine the average R-values of the various wall systems.

For steel-framed exterior walls, the IRC 2000 code requires a combination of insulation within the stud cavity and a continuous layer of insulation external to the framing. The continuous layer of thermally insulated sheathing is required to provide a thermal break to counter the thermal bridging of the steel framing members and, thereby, to improve the overall thermal performance of the wall system. Unfortunately, the amount of insulation required appears to be somewhat arbitrary and inconsistent with requirements for wood-framed walls when average R-values are considered.

Consider, for example, the thermal insulation alternatives for a building in a location with 5000 HDD. The IRC code requires R-18 cavity insulation for wood-framed walls and combinations of R-11 + R-9, or R-15 + R-8, or R-21 + R-7, stud cavity and exterior insulation, respectively, for comparable steel-framed walls. A comparison of the average R-value of these walls, listed in Table 3, shows that the thermal performance of these walls is somewhat different.

The result of these code requirements should be thermally more consistent. The provisions are stated solely in terms of the thermal insulation (hence, the thermal envelope)—an approach that can be very misleading and also ignores the

TABLE 3
Average R-Values of Wood- and Steel-Framed Wall Systems

Framing	Spacing	Interior Sheathing	Stud Space Insulation	Exterior Sheathing or Insulation	U-Factor* (Btu/h·ft^2·°F)	Average R-Value (h·ft^2·°F/Btu)
Wood 2×6	24 in.	½ in. gypsum	R-18	½ in. plywood	0.0564	17.7
Steel 2×4	16 in.	½ in. gypsum	R-11	R-9	0.0571	17.5
Steel 2×4	16 in.	½ in. gypsum	R-15	R-8	0.0541	18.5
Steel 2×6	24 in.	½ in. gypsum	R-21	R-7	0.0459	21.8

* U-value as calculated using THERM 2.0, including interior and exterior surface films.

contribution from other layers within the wall assembly. Preferably, a code should prescribe a target average R-value for the whole wall assembly. Furthermore, as shown in the next section, the combination of insulation specified is critical in order to avoid condensation within the cavity space.

In a previous study (Bombino and Burnett 1999), a series of thermal performance charts were developed. Some of these are provided as figures (Figures 1, 2, 3, 4, 5, and 6) in order to illustrate the relationship between the average R-value and the amount of insulated exterior sheathing for different sizes and spacing of steel studs. Background information, a better explanation, and much more detail is provided in PHRC Report #58 (Bombino and Burnett 1999).

PREVENTING CONDENSATION WITHIN THE STUD CAVITY

For any wall system, or for that matter any part of the building enclosure, moisture is a major concern because it can cause problems. To avoid a problem, all forms of moisture (solid, liquid, and vapor) from exterior, interior, and built-in sources need to be considered and controlled. Rain, being the largest and most obvious source of moisture, is usually foremost in the mind of designers and builders. However, it is water vapor in the air that can often lead to a problem in spite of the fact that it is not visibly a significant source of moisture. Accordingly, controlling water vapor is a very important design consideration for any enclosure system, especially for steel-framed wall systems. If any water vapor were to condense within the stud space, the steel members and the insulated sheathing—unlike wood—have little or no capacity to safely store moisture and may also be subject to corrosion or some other form of deterioration.

Within the stud space of any framed wall system, a primary design objective is to avoid accumulating enough moisture to generate a moisture-related problem. It is extremely difficult to quantify a single threshold level of moisture or the time period needed to initiate a problem because each situation is system, location, climate, and quality depen-

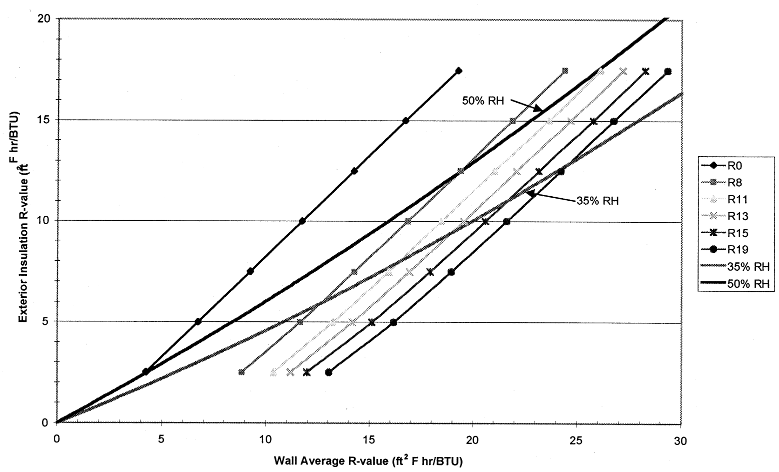


Figure 1 *Wall selection chart, 22°F design temperature, studs at 16 in.*

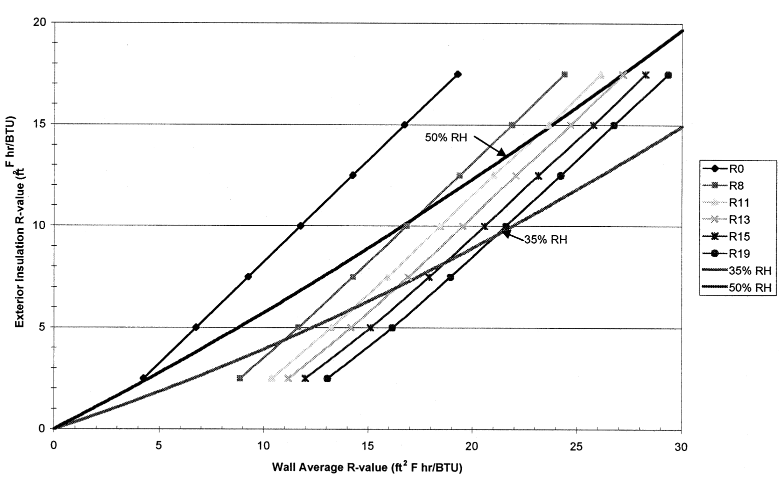


Figure 2 *Wall selection chart, 27°F design temperature, studs at 16 in.*

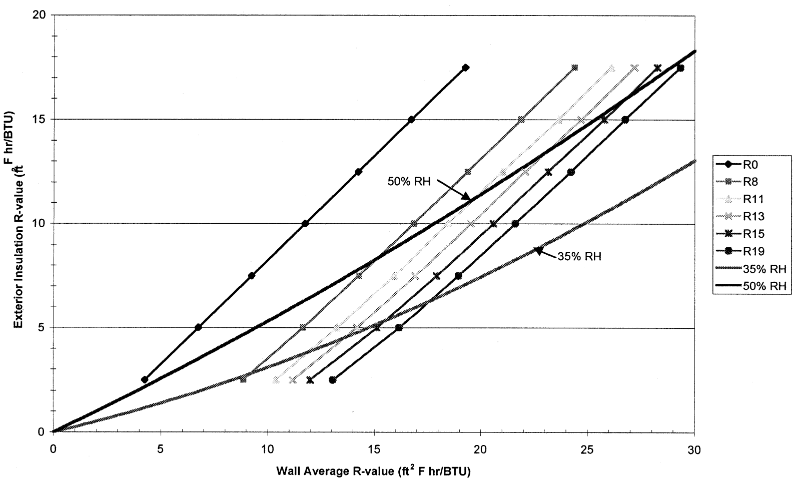


Figure 3 *Wall selection chart, 32°F design temperature, studs at 16 in.*

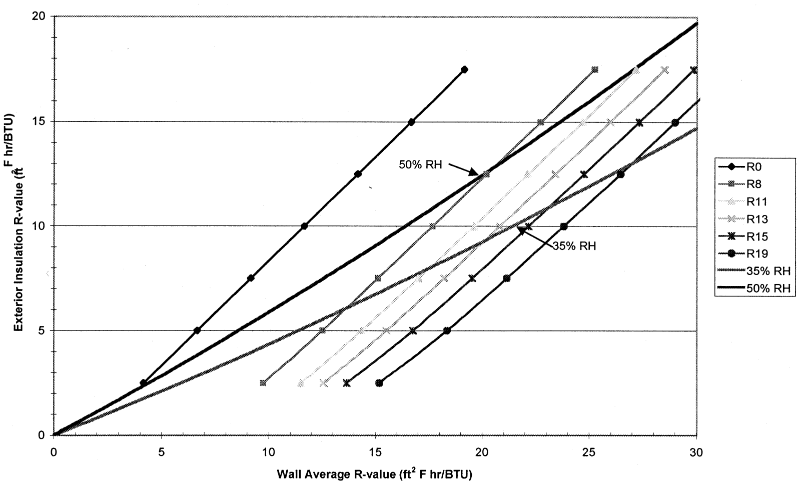


Figure 4 *Wall selection chart, 22°F design temperature, studs at 24 in.*

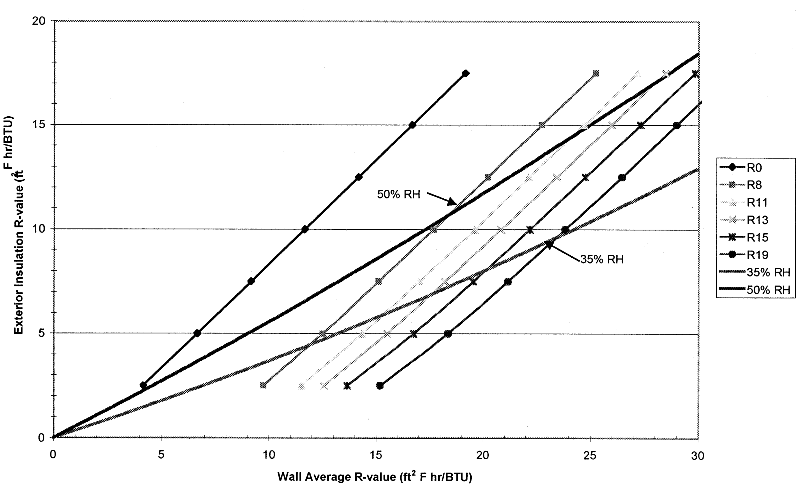


Figure 5 *Wall selection chart, 27°F design temperature, studs at 24 in.*

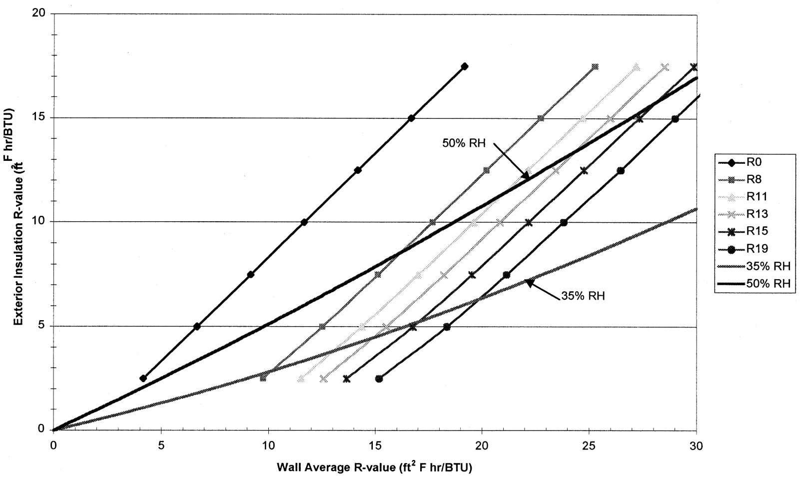


Figure 6 *Wall selection chart, 32°F design temperature, studs at 24 in.*

dent. For instance, although wall construction in houses is tighter than it used to be, walls are rarely airtight. It is difficult to identify a single representative air leakage rate through a section of wall. If airtight construction is not a practical goal for housing construction, then, for steel-stud construction, a conservative moisture-control strategy would be to avoid condensation (and thus the accumulation of condensate) within the stud space under averaged weather conditions over the coldest two or three months of the year.

For design, Section R322 of the IRC requires, with a few exceptions, that a vapor retarder with a permeance rating of 1 perm or less be installed on the winter warm side of the insulation. Clause N1102.1.10: Air Leakage in Chapter 11 of the IRC requires that all joints, seams, penetrations, etc., in exterior walls be gasketed, weather-stripped, caulked, or otherwise treated to limit uncontrolled air movement. With these two clauses the code acknowledges the fact that water vapor moves across walls by diffusion and that air leaks across walls. It is well known that both these phenomena can result in moisture accumulation within wall systems that subsequently leads to accelerated deterioration of materials and wall performance.

Thus, it should be prescribed that the insulation strategy not exacerbate a moisture problem due to water vapor migration by diffusion and/or air leakage. It is difficult to establish a threshold of what constitutes a moisture problem; however, we propose the following strategy.

Maintain the stud cavity layers above the dew-point temperature of the interior air during average weather conditions over the coldest two or three months of the year.

To accomplish this, the temperature at the inside face of the exterior sheathing layer, which is the coldest surface within the stud space, must be greater than the dew-point temperature of the interior air during average winter conditions.

For steady-state, parallel heat transmission, the temperature gradient across a wall assembly is linearly related to thermal resistance. Figure 7 illustrates the linear relationship between temperature and R-value.

The crucial interface or surface for condensation is the inside face of the exterior sheathing. Using the relationship shown in Figure 7, the center-of-cavity temperature at the interface between the stud space and the exterior sheathing, t_{si}, may be expressed as follows:

$$t_{si} = t_o + \frac{R_{ext}}{R_{cc}} \times (t_i - t_o)$$

where

t_{si} = temperature of the inside surface of the exterior sheathing

t_o = outside ambient temperature

t_i = inside ambient temperature

R_{ext} = sum of the R-values of all layers including the exterior surface film outside the inside surface of the exterior sheathing

R_{cc} = sum of the R-values of all the layers of the wall including interior and exterior surface films, not including framing members

To maintain the stud space above the dew-point temperature of the interior air, it is required that $t_{si} > t_{dp}$, where t_{dp} is the dew-point temperature for the relevant interior conditions.

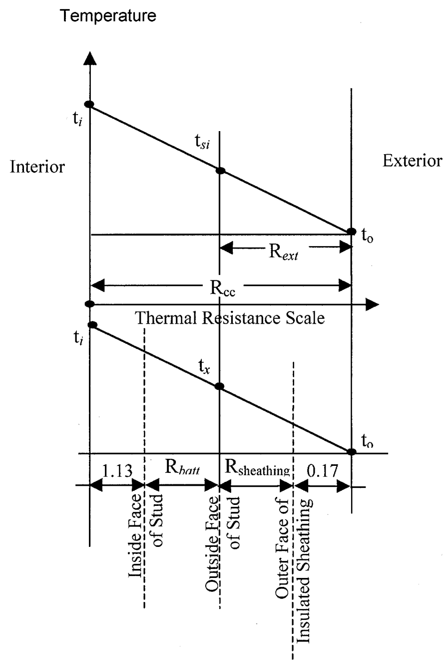
Hence,

$$t_{si} = t_o + \frac{R_{ext}}{R_{cc}} \times (t_i - t_o) \geq t_{dp}$$

and, by rearranging,

$$\frac{R_{ext}}{R_{cc}} \geq \frac{(t_{dp} - t_o)}{(t_i - t_o)} \quad .$$

This conditional criterion is a useful expression. The left-hand side is the ratio of the R-value of the materials beyond the



From Similar Triangles

$$\frac{t_{si}-t_o}{t_i-t_o}=\frac{R_{ext}}{R_{cc}}$$

and $t_{si} > t_{dp}$

$$\therefore \frac{R_{ext}}{R_{cc}} > \frac{(t_{dp}-t_o)}{(t_i-t_o)}$$

Critical Interface Criteria:

For $\frac{R_{ext}}{R_{cc}} > \frac{(t_{dp}-t_o)}{(t_i-t_o)}$, and

for RH = 35%, t_{dp} = 41°F, t_i = 70°F, it follows that:

Climate Zone	t_o	$\frac{R_{ext}}{R_{cc}} >$	
S	32°F	0.24	24%
C	27°F	0.33	33%
N	22°F	0.40	40%

Figure 7 *The avoidance of interface condensation.*

outside flange of the stud to the center-of-cavity R-value. For no stud cavity insulation, R_{ext}/R_{cc} approaches a value of 1, and for no exterior insulation, R_{ext}/R_{cc} approaches zero. The right-hand side is similar in form to the expression for temperature index (T.I.), e.g., T.I. = $(t_x - t_o)/(t_i - t_o)$, which is commonly used to assess condensation potential on windows.

For example, consider 70°F and 35% RH indoor conditions and, thus, t_{dp} = 41°F, with 27°F as the outdoor temperature:

$$\frac{R_{ext}}{R_{cc}} \geq \frac{41-27}{70-27} = \frac{14}{43} = 0.33$$

This result indicates that at least 33% of the insulation should be outside the critical surface (here the inside face of the exterior sheathing) so that the temperature of the critical surface will be greater than the dew-point temperature of the interior air for the selected conditions. This example could be repeated for numerous conditions, and various walls could be analyzed to determine whether they meet this specific criterion. In Figure 7, it is seen that for an interior relative humidity of 35%, the limiting ratios for the three climatic regions in Pennsylvania are 24%, 33%, and 40% for S, C, and N, respectively.

At this point, it should be clear that both thermal and moisture considerations are important and need to be simultaneously considered since the thermal design strategy has a significant influence on controlling water vapor condensation. For a builder or designer, it is desirable to be able to select a wall system that meets a target R-value, is thermally efficient, and is not likely to suffer from moisture problems arising from condensation within the stud space. For a specific building in a specific location (knowing the interior and exterior ambient conditions), and for representative steel stud framing options, a curve representing the conditional moisture criterion can be superimposed on the plots of R-value of the exterior insulation versus the average R-value of any of the various combinations under consideration. In Figures 1 through 6, both the thermal and conditional moisture (exfiltration/condensation) relationships are shown for walls on buildings in the S, C, and N climatic regions in Pennsylvania.

CODE PROVISIONS

In order to arrive at a set of recommendations, it is necessary to identify or reiterate certain basic considerations, as follows.

- When an insulated exterior sheathing such as EPS or EXPS or some other higher-density insulation board is used in place of a wood-based sheathing, then the stud space has no or very little moisture-storage capacity. The steel has none, the insulated sheathing has none, and only the air in the stud space can provide some degree of safe storage for water vapor. This is a very different situation from a wood-framed wall assembly, even one that does not have a wood-based exterior sheathing.
- For detached single-family houses, an indoor air temperature of 70°F may be considered a reasonable value during the winter.
- For detached single-family houses, a relative humidity of 35% for the indoor air may be considered a reason-

able upper limit for the value of the mean interior air moisture content in winter. Note that in multi-unit housing of more than three stories, a higher RH value would have to be used as this threshold value.

- Air exfiltration occurs and, in winter, the resultant quantity of water vapor transported is usually much greater than, but additive to, that due to water vapor diffusion.
- Three mean exterior ambient temperatures, namely, 32°F, 27°F, and 22°F, are representative of the mean daily temperatures for a 60-day period over December, January, and February in the three geographic and climatic regions (there are six in the IRC 2000) previously identified as covering Pennsylvania: S, C, and N.

Insulation strategies that satisfy a code-specified minimum average R-value and avoid an exfiltration-induced moisture problem may be derived directly from the set of design charts provided in Figures 1 through 6. In using these charts, some provision has to be made for the following:

- The prescriptive provisions in the IRC 2000 code specify a minimum required R-value based solely on the sum of the layers of thermal insulation for the appropriate climatic zone (e.g., R-16, R-18, and R-21 for zones S, C, and N, respectively). For steel-framed walls, a portion of the insulation must be a continuous layer located external to the framing to counter the thermal bridging. When average R-value is considered, the same base or datum requirement should apply to both steel- and wood-framed walls, with the exception that steel-framed walls require a minimum percentage of insulation exterior of the framing. If an averaging or framing factor is to be applied to the steel, then it follows that a similar provision for the framing factor for wood needs to be incorporated into the calculations. If wood framing was to be used, then each of the above R-value requirements could be met using 2×4 or 2×6 studs with glass fiber batt insulation within the cavity—and OSB or plywood exterior sheathing would probably also be used. Thus, as shown in Table 4, to meet the R-16, R-18, and R-21 requirements of the IRC 2000, it follows that the datum level to be met by an equivalent steel stud system must be R-14.3, R-17.8, and R-20.0, respectively. Moreover, the wood-framed options will also have an exterior sheathing, albeit a "non-insulated" sheathing. In fact, the R-value of dry OSB or plywood exterior sheathing will be about 0.63, which is not an inconsiderable amount. Because the steel stud option must always involve an insulated exterior sheathing, it follows that provision for the use of a wood-based sheathing should also be made with the wood framing options.
- As shown in Figure 7, to avoid condensation within the stud space, or more specifically on the inner face of the exterior sheathing, it is theoretically necessary to ensure that this surface temperature is greater than the dew-point temperature of the interior air. This criterion can be expressed as follows:

$$\frac{R_{ext}}{R_{cc}} \geq \frac{(t_{dp} - t_o)}{(t_i - t_o)}$$

as either a fraction or a percentage.

However, as is also evident in Figure 7, the contribution to the overall R-value for the wall assembly involves more than just the contributions from the stud cavity insulation and the sheathing. To compensate for the other contributors, the following has been assumed:

1. The interior surface film R-value = 0.68, and the 1/2-in. gypsum board R-value= 0.45; thus, 1.13.
2. The exterior surface film in winter R-value = 0.17. Given that we cannot accurately represent all likely cladding systems, it is slightly conservative to ignore the contribution from the cladding and airspace.

It follows that for R_{batt} known or specified, an expression for $R_{sheathing}$ can readily be derived.

On the basis of these listed assumptions and provisions, the combinations, summarized in Table 4, for single-family houses have been developed (Burnett 2000). For code purposes, some rounding off should be made. It is important to be aware that these insulation strategies and any related code recommendations are driven by two requirements, namely, a minimum effective R-value (according to the IRC 2000 Table N1102.1) and a moisture control criterion. In some instances, the latter requirement is dominant, and it is for this reason that walls with either 2×6 steel studs or the closer 16 in. spacing are at a relative disadvantage.

CONCLUSIONS

When Table 4 is compared with the tabulated values for the IRC 2000 (Table 1), the following is evident.

- Table 4 provides a much better (better structured, more detailed, more comprehensive) basis for wall design strategies for steel stud framing, at least for Pennsylvania.
- In general, the listed R-values are not that dissimilar from the IRC 2000 requirements except when moisture-control provisions are dominant and the insulated sheathing requirements increase.
- When moisture-control considerations dominate, the insulated sheathing requirements become onerous.
- It is largely the use of 2×6 steel studs with larger amounts of batt insulation (R-15 but especially when R-19 or more is provided) that is adversely affected.
- It would appear that neither the IRC 2000 nor the 2000 IECC makes proper provision for moisture control.

It needs to be appreciated that the above conclusions apply only to the common situation where steel framing has only thermal insulation as the exterior sheathing. In the event that sufficient moisture storage is provided, either as a layer of wood-based sheathing or somehow within the stud space, then the situation has to be reassessed.

The steel-stud industry needs to be aware of the implications of these proposals because they will have an impact on

TABLE 4
Thermal Insulation Combinations for Use with Steel Framing in Pennsylvania—Single-Family Detached Housing

				Insulation Combination Options (≥ Min. Avg. R-value)			
				Studs at 16 in. spacing		Studs at 24 in. spacing	
Penn. Alternative Zones	**IRC 2000 Climatic Zones**	**Mean Winter Design Temp.**	**Minimum Average R-Value**	**Stud Space + Min. Ext. Sheathing R-value**	$\frac{R_{ext}}{R_{cc}}$	**Stud Space + Min. Ext. Sheathing R-value**	$\frac{R_{ext}}{R_{cc}}$
S	10 and 11	32°F $\left\{\frac{R_{ext}}{R_{cc}} \geq 24\%\right\}$	14.3[*] (16[†])	R-0 + R-12.6	86%	R-0 + R-12.6	86%
				R-8 + R-7.5	46%	R-8 + R-6.7	43%
				R-11 + R-6.0	34%	R-11 + R-5.0	30%
				R-13 + R-5.1	27%	R-13 + R-4.4[‡]	24%
				R-15 + R-5.1[‡]	24%	R-15 + R-5.1[‡]	24%
				R-19[††] + R-6.3[‡]	24%	R-19[††] + R-6.3[‡]	24%
C	12 and 13	27°F $\left\{\frac{R_{ext}}{R_{cc}} \geq 33\%\right\}$	17.8[**] (18[†])	R-0 + R-16.1	89%	R-0 + R-16.1	89%
				R-8 + R-11.0	55%	R-8 + R-10.1	53%
				R-11 + R-9.4	44%	R-11 + R-8.3	41%
				R-13 + R-8.3	37%	R-13 + R-7.1	34%
				R-15 + R-7.9[‡]	33%	R-15 + R-7.9[‡]	33%
				R-19[††] + R-9.7[‡]	33%	R-19[††] + R-9.7[‡]	33%
N	14 and 15	22°F $\left\{\frac{R_{ext}}{R_{cc}} \geq 40\%\right\}$	20.0[**] (21[†])	R-0 + R-18.1	90%	R-0 + R-18.1	90%
				R-8 + R-13.1	59%	R-8 + R-12.3	58%
				R-11 + R-11.5	49%	R-11 + R-10.4	47%
				R-13 + R-10.5	43%	R-13 + R-9.3[‡]	40%
				R-15 + R-10.7[‡]	40%	R-15 + R-10.7[‡]	40%
				R-19[††] + R-13.1[‡]	40%	R-19[††] + R-13.1[‡]	40%

[*] Average R-value of a wood-framed wall with 2×4 studs at 16 in. o.c., 1/2-in. gypsum, R-16 batt insulation, 1/2-in. plywood sheathing, including interior and exterior surface films.
[†] The IRC 2000 prescribed stud cavity insulation for wood-framed walls.
[‡] Exterior insulation requirements are governed by moisture control criteria, and thus these walls have average R-values greater than the minimum required for thermal purposes alone.
[**] Average R-value of a wood-framed wall with 2×6 studs at 24 in. o.c., 1/2-in. gypsum, R-18 or R-21 batt insulation, 1/2-in. plywood sheathing, including interior and exterior surface films.
[††] Requires 2×6 studs.

designers, builders, and consumers. It also needs to be pointed out that there is a comparable issue with regard to the use of steel floor systems, especially over basements and crawl spaces or any partially conditioned or nonconditioned space. In these situations floor insulation, i.e., fiberglass batts between the joists, is not an effective option for energy conservation. It follows that, in houses with ground or first floors with steel floor joists, the basement and/or crawl space walls must be insulated, at least in those areas with climates comparable to Pennsylvania.

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