Thermal Metrics for High Performance Enclosure Walls: The Limitations of R-Value

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Abstract:

This document summarizes the theory behind thermal insulation and building system heat flow control metrics and presents a literature review of selected research into this area.

Review of the R-value as a Metric for High Thermal Performance Building Enclosures.

1 Introduction

The R-value was developed over 50 years ago to provide users and specifiers of insulation with an easy-to-compare, repeatable measure of insulation performance. Everett Schuman, an early director of Penn State's housing research institute, is often credited with first proposing (in 1945) and popularizing standardized measures of resistance to heat transfer. R-values were later widely applied to industrial and residential insulating materials and helped consumers make more energy-efficient choices. The strength of the R-value is that it is simple to measure, easy to communicate, and widely accepted.

Over recent decades a much broader range of insulation types, and application methods of insulation have been developed and deployed than were available when the R-value was conceived. As the building industry strives to reduce energy consumption for environmental and economic reasons, building enclosures with high thermal performance, reliably and affordably installed in the field are demanded. The R-value of the insulation products in many of the new building enclosure systems is increasingly unable to measure their actual thermal performance because system effects, sensitivity to construction defects, and airflow can play such a significant role in overall performance.

This document explores the thermal performance of opaque enclosures, and the need for a broader more holistic assessments than the R-value ratings of insulation products alone can provide. Its focus is lightweight framed wall systems insulated with solid body insulation, as this describes the enclosures of the majority of American homes. Although roof assemblies are not explicitly addressed, most of the discussion and research reviewed applies to light framed roofs as well.

1.1 Theoretical Background

Conductive heat flow is the basis for most of the heat flow calculation methods used in the building industry. One-dimensional steady state conductive heat flow through a homogenous material can be described by Fourier's law:

$$Q = (k / l)\ A\ \ T \qquad (1)$$

where

Q is the rate of heat flow.

k is thermal conductivity

l is the thickness

T is the temperature difference, and

A is the area through which heat flow is measured.

The R-value is the property of a homogenous *layer* or *assembly* of materials that characterizes its resistance to heat flow. R-value is defined by testing an assembly of known area exposed to a known temperature difference:

$$R = (T A)/ Q \qquad (1)$$

where

R is thermal resistance

T is the temperature difference

A is the area through which heat flow is measured, and

Q is the rate of heat flow.

If all heat flow was by conduction, and if all materials where homogenous and exhibited no temperature sensitivities, then it would be appropriate to assume that the R-value was equal to the inverse of thermal conductivity divided by thickness (R = l/k). However, heat transfer through most materials and assemblies is a combination of heat flow by the modes of conduction, radiation, and convection. The R-value measured in Equation 2 is an effective value that lumps all three modes into one metric.

However, radiation varies strongly with absolute temperature, and convection varies strongly with the size of the temperature difference, specimen orientation, and air permeability. Hence, the R-value is valid for specific test conditions, and may be a poor predictor of performance if the conditions of use vary significantly from those of the test. Just as significantly, if insulation is improperly installed, or if a product is installed in an improperly designed enclosure system, the performance of the complete enclosure can be very different than that of the product. In some cases the R-value labeled on a product will control the flow of heat with 1/2 or 1/3 the level expected by many professional specifiers and consumers. Hence there are a number of factors that influence the thermal performance of enclosures other than the R-value of the insulation product. These factors become even more important as high thermal performance enclosures are considered.

1.2 FTC requirements

Energy concerns became critical to modern society after the first oil shocks of the early 1970’s. During the response to these shocks a large number of energy-saving policies were implemented and it became economical to conserve energy rather than purchase it. One of the results was an explosion in the number of building insulation products. To provide consumers with reliable information about the many competing claims of R-value, the Federal Trade Commission (FTC) developed a rule, “Labeling and Advertising of Home Insulation,” almost universally known as the “R-value Rule.” This rule sets out how to conduct tests on insulation products and how to report the results to the public in terms of R-values.

For almost 30 years this rule has attempted to provide a level playing field for competitors and useful unbiased information for consumers. However, changing technology, better scientific understanding, practical field experience, heightened performance expectations, and a wide range of new products and systems have exposed some of the limitations of applying the FTC R-value Rule.

The FTC rule lists a number of ASTM test standards that are acceptable for use in determining R-value. There are several requirements for specimen preparation, having to do with aging of foam plastics and settling of blown insulations. The FTC requires that the tests must be conducted at a mean temperature of 75 °F (23.9 °C).

Although the R-value rule is expressly intended for home insulation products, its methodology is widely applied to all types of other insulation products intended for use in the commercial, institutional and industrial buildings as well.

1.3 Thermal Property Testing Methods

The most common thermal property testing methods are listed in the FTC rule, and these methods are used for many building products. These standards are:

- ASTM C 177-85 (Reapproved 1993), "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus;"
- ASTM C 518-91, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus;"
- ASTM C 1114-95, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus."
- ASTM C 236-89 (Reapproved 1993), "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box;" and
- ASTM C 976-90, "Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box."

Standards C177 and C518 are by far the most commonly used, as they can be quickly completed using small easy-to-handle samples (typically 12”x12” to 24”x24”). These test methods use an apparatus that places an air-impermeable hot and cold plate in direct contact with the test sample. In almost all cases, the specimens are installed horizontally. In the C177 standard, the energy required to maintain the hot plate at the target temperature is measured and used in Equation 1. In the C518 Standard, a heat flux transducer in series with the specimen is used to measure the heat flow across it and the specimen as target temperature conditions in the plates are maintained.

Figure 1: Commercial Apparatus for Conducting the C518 Standard Thermal Conductivity Test

The above-noted standard test methods return an *apparent thermal conductivity*, as they include mechanisms other than just conductive heat transfer. Apparent thermal conductivity is defined based on test results as:

$$k_{eff} = Q\,L/(\quad T\,A) \qquad (3)$$

where

k_{eff} is the effective thermal conductivity

Q is the measured rate of heat flow

L is the thickness of the sample (equal to the length of flow path)

T is the temperature difference, and

A is the area through which heat flow is measured.

Standards C236 and C976 were sometimes used in the past when an entire assembly was to be rated (in the form of an assembly R-value or U-value), but most insulation materials are sold as products, not assemblies. These test methods, with small variations, have been used for many years to research the actual performance of insulated building assemblies.

A newer standard,

- ASTM 1326-05 "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus"

replaces the C236 and C976, both of which have now been rescinded (although still used by some). Although the FTC rule has not been updated to expressly refer to it, it is assumed that the 1326 standard can be used to assess the thermal performance of full-scale building assemblies.

2 Heat Flow Through Building Enclosures

Heat flow through building enclosures is much more complex than heat flow through samples of materials. Building assemblies such as wood- and light-gauge-steel-framed enclosures are often highly three-dimensional, and may contain highly conductive components (such as steel or concrete). Airflow through an enclosure component, driven by wind, stack effect and mechanical equipment, will also transport significant amounts of heat. Finally, the assemblies may be built in a manner that does not replicate the method used during the R-value testing of the material in question. These factors can be grouped together in the following categories:

1. Thermal Bridging
2. Airflow Through Enclosures
3. Changes in Property over Time

All of these factors can significantly impact the heat flow control performance of an enclosure, and each will be discussed in the sub-sections below.

Heat flow varies over time as the outdoor air temperature varies (on an hourly, daily, and seasonal basis) and as the sun heats the outer surfaces. These dynamic variations are important for thermally massive enclosures (particularly concrete and masonry assemblies), but thermal mass is not addressed here.

Radiant barrier systems (RBS) are sometimes used to control heat flow in enclosure assemblies, especially in roof systems. This review focuses on solid body insulations, but many of the issues relate equally well to RBS.

2.1 Thermal Bridging

Insulation is often, almost always, installed between studs in light framed systems of wood and steel. In most cases no other insulation is provided for the assembly, although high-thermal performance systems often apply layers of insulation on the exterior or even interior of the framing in the form of semi-rigid insulation boards. Heat can flow much more easily through dense structural materials such as wood and steel than through the insulation between them. Heat flow also deviates from one-dimensional flow at corners, parapets, intersections between different assemblies, etc.

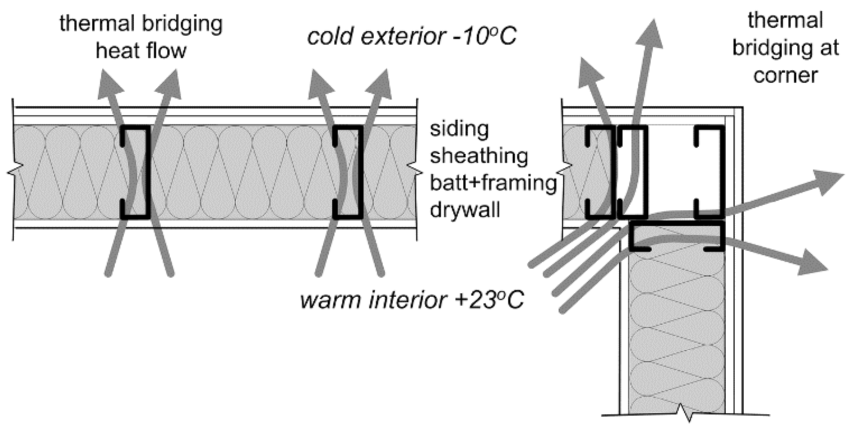


Figure 2: Thermal Bridging Through Steel Stud Wall

When heat flows at a much higher rate through one part of an assembly than another, the term "thermal bridge" is used to reflect the fact that the heat has bridged over / around the thermal insulation. Thermal bridges become important when they:

- cause cold spots within an assembly that might cause performance (e.g., surface condensation), durability or comfort problems
- are either large enough, intense enough (highly conductive), or frequent enough that they affect the total heat loss through the enclosure

Thermal bridging can severely compromise thermal control and comfort in some enclosure types. Heat flow through steel stud walls and metal curtainwalls is dominated by heat flow through the metal components. Failure to break these thermal bridges can reduce the R-value of the insulating components (the insulated glazing unit or batt insulation respectively) by 50 to 80%. Filling the voids in concrete block masonry with insulation is not very effective: adding R-15 insulation to the cores a 12" concrete block will increase the R-value of the wall by about R-2. Wood framed walls are not as badly affected as wood is a reasonable insulator, but reductions in R-value of more than 20% are common.

Thermal bridging has, and continues to be, extensively studied. Oak Ridge National Labs in particular have undertaken numerous measurements and simulations of full-scale walls and collated the results in a series of papers (Christian and Kosny 1995). They proposed several definitions that have since been widely accepted:

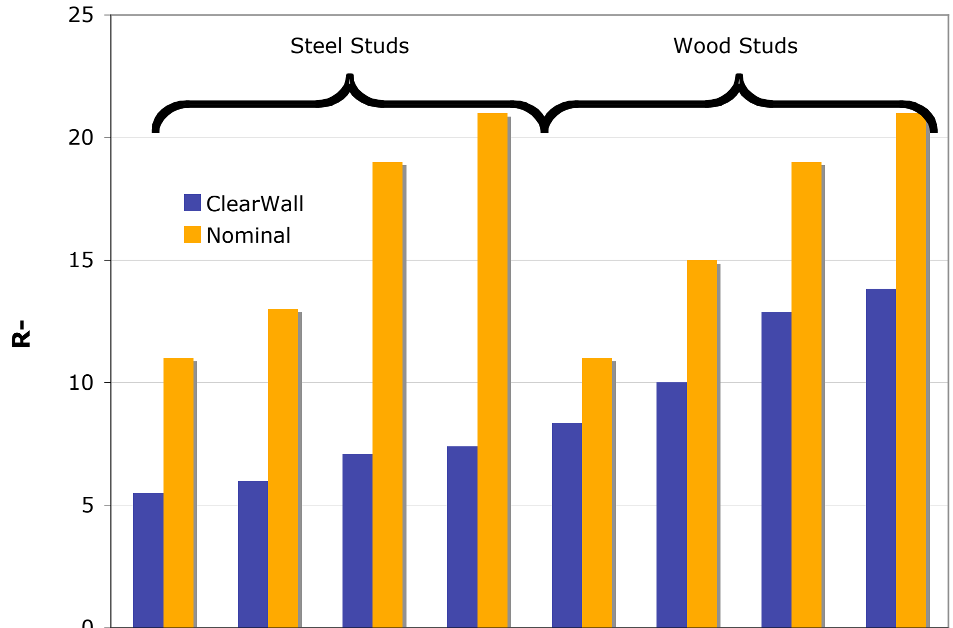
- The *Center-of-Cavity* R-value is based on the point in the wall's cross-sectional R-value containing the most insulation. Typically the value is for a 2-D horizontal cross-section at mid-height. This value is often equated with the "Nominal R-value" in practise as it is close to the R-value of the insulation installed between studs.

- The *Clear-wall* R-value is defined as the R-value for the enclosure area containing only insulation and necessary framing materials for a clear section with no fenestration, corners, penetrations, or connections between other enclosure elements such as roofs, foundations, and other walls.
- The *Whole-wall* R-value is calculated for the whole opaque wall including the thermal performance of not only the "clear wall" area, with insulation and structural elements, but also typical envelope interface details, including wall/wall (corners), wall/roof, wall/floor, wall/door, and wall/window connections.

The Clear-Wall R-value is used to define the thermal performance of enclosures in ASHRAE Standard 90.1. The impact of thermal bridging can be seen in the figure below. The impact of thermal bridging is most obvious for steel studs with high R-values of insulation in the studspace. For example, the R-value of 6 inch deep steel studs installed at 16 inch centers with cavity insulation of R-21 is reduced to R-7.4, a value only 35% of the nominal. Even for R-11 in a wood stud wall is reduced to 76% of nominal.

Thermal bridging becomes more important as the R-value of the studspace insulation increases and as the proportion of enclosure area occupied by studs increases. In the last 20 years, the use of 2x6 wood studs with R-19 batt and R-15 batt in 2x4 studs has increased tremendously. High performance enclosures with the stud space filled with high R-value per inch insulation such as spray foam are being built. Because of the higher studspace thermal resistance levels, thermal bridging has become more important.

At the same time that installed cavity R-values has been raised, the complexity of homes has increased and the ratio of framing (i.e., the framing factor) has increased to about 25% in enclosure walls (Carpenter and Schumacher 2003). The assumptions made in Clear Wall analysis (such as those in ASHRAE 90.1) mean that a 2x wood stud at 16" on center covers 9.4% of the wall area. Thus, true R-values of walls are lower than the clear wall analysis used in ASHRAE 90.1 and other references. The impact is highest for high stud space R-values and steel studs.



	R-11 3.5in	R-13 3.5in	R-19 6in	R-21 6in	R-11 3.5in	R-15 3.5in	R-19 6in	R-21 6in
ClearWall	5.5	6.0	7.1	7.4	8.4	10.0	12.9	13.8
Nominal	11	13	19	21	11	15	19	21

Figure 3: Nominal and Clear Wall Insulation R-values (after ASHRAE 90.1-1999) for Several Different Stud Materials and Insulation

The introduction of steel studs to the residential sector has created major thermal bridges that can dramatically reduce enclosure thermal performance. In short, steel stud walls can only control heat flow at levels expected of high performance walls with additional insulation over the exterior or the interior (Bombino and Burnett 1999). Bombino and Burnett considered the clear wall R-value of a number of realistic walls. One of the remarkable results of their study was that the addition of insulating sheathing layers reduced the thermal bridging effect to such an extent that some of the cavity insulation regained it effectiveness once more. For example, adding R-5 of exterior insulation to a 3.5 in thick steel stud wall increased its Clear Wall R-value by R-6. The effectiveness of an R-11 batt in a 3.5 in steel stud increased from 55% or R-6.6) to over 80% when R-10 exterior insulating sheathing was applied. They note that these calculation under-estimate the impact of exterior insulation, as no account has been taken of the insulation improvement provided at critical top and bottom tracks, rim joists, etc. (i.e., the effect on Whole Wall R-value would be even greater).

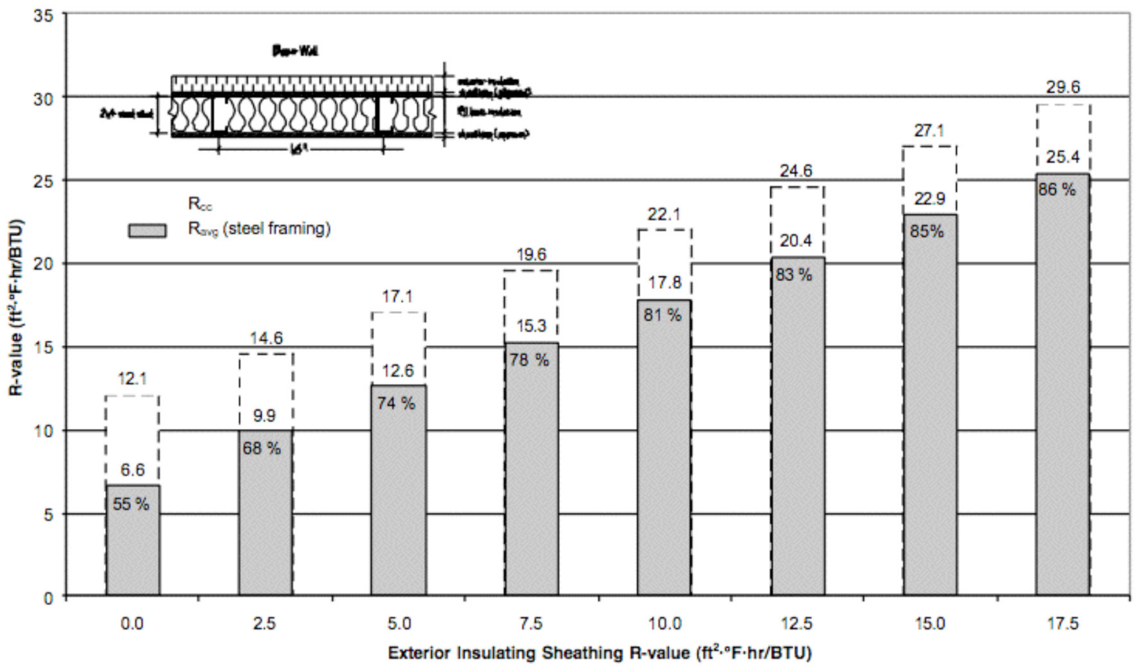


Figure 4: Impact of Adding Exterior Insulating Sheathing to 3.5 in Steel Stud with R-11 Batt (Bombino & Burnett 1999)

In the future, new steel stud designs, with many large perforations may reduce the thermal bridging effect somewhat, but insulation sheathing is likely to be required for all high thermal performance walls. Numerous researchers have investigated a bewildering array of web perforations to reduce the thermal transmission through the stud. The most successful results appear to come from research by Salonvaara and Nieman (1998) which demonstrated that it was possible to match the thermal performance of wood studs.

Figure 5: Thermally Efficient Steel Framing in Finish Housing (Nieminen & Salonvaara 2000)

Advanced Framing techniques, long promoted and practiced by Building Science Corporation through the Building America program, significantly reduce the number of framing elements by removing structurally unnecessary and/or redundant members. This results in a lower framing factor and hence a higher R-value. The framing factor for Advanced Framing is generally considered to be in the range of 10 to 15%, or at least 30% less than standard approaches (EERE 2000. For wood stud walls, this approach could be much more widely deployed to reduce thermal bridging. For steel stud walls, the reduction in framing factor offered by Advanced Framing is not sufficient to reduce the thermal bridging to acceptable levels for high performance enclosures unless new types of thermally resistant steel studs are involved.

The use of parallel-path and zone methods of calculating the impact of thermal bridging was once more common. Research has shown that highly conductive thin elements, such as steel studs, require a modified zone method (Kosny and Christian 1995). The ASHRAE handbook of Fundamentals has included these methods since 1997. Today, steady-state 2-D heat flow calculations are easy to conduct with freely available if sophisticated software. For most buildings, the enclosure is never studied with this level of detail, and the R-value of the insulation installed within the studspace is assumed to be a close approximation of the thermal performance of the enclosure. Clearly, in the case of steel framing, this is a gross error, and a significant error for high thermal performance wood enclosures.

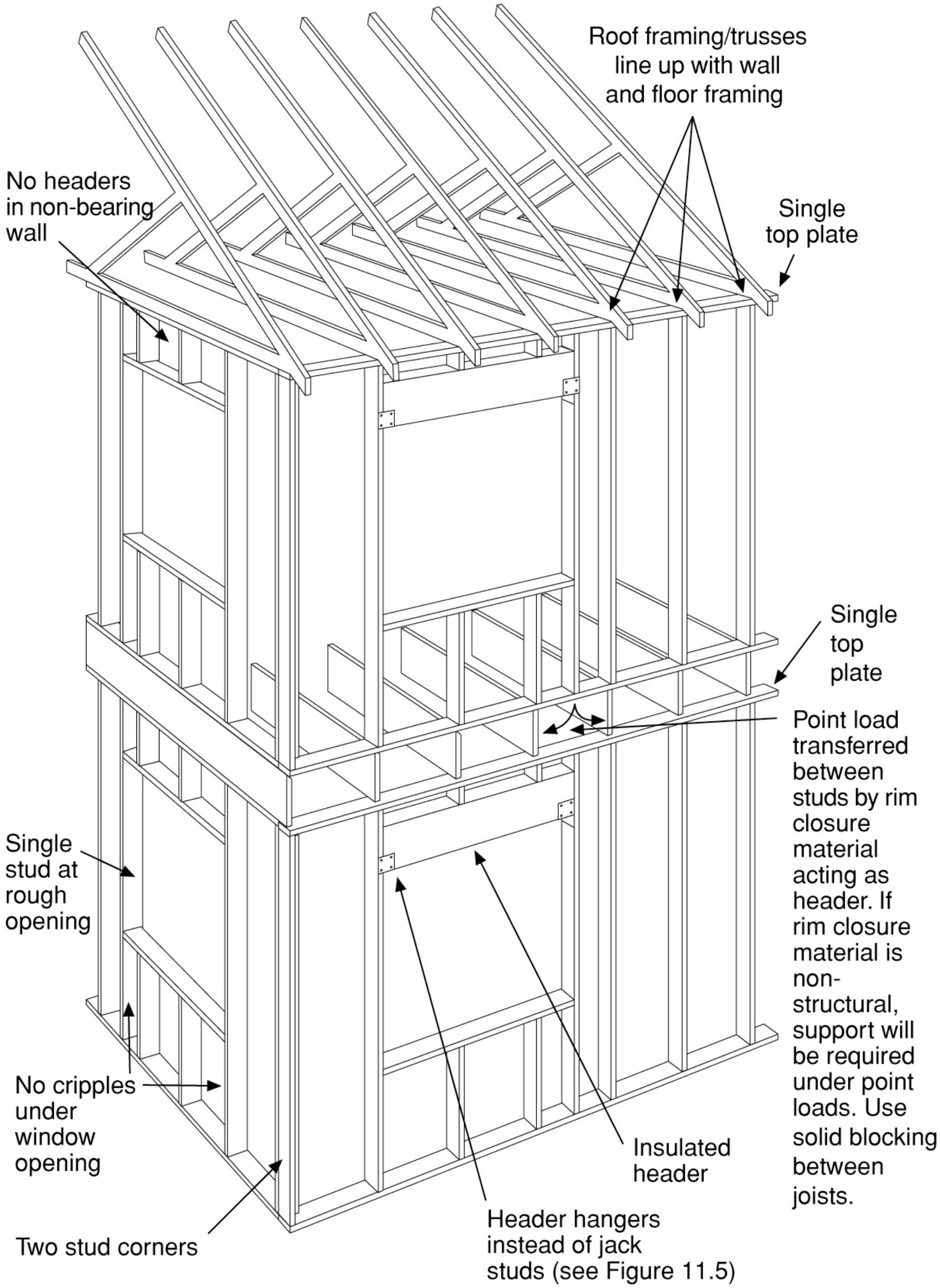


Figure 6: Advanced Framing Techniques Reduce Thermal Bridging as Well as Waste

2.2 Convective Heat Flow

Air can carry heat with it and hence convection is one of the primary modes of heat transfer. Figure 7 shows four different flow paths that influence the thermal performance of building enclosures.

The most well understood (Path 1: Infiltration / Exfiltration) is the flow path from inside to outside (or vice versa). Other flows are less well understood and more difficult to measure. Flow from the exterior, through the enclosure and back outdoors (Path 2: windwashing) can however be very important. In some cases, loops can form that move indoor air through the enclosure and back to the indoors (Path 3: when driven by wind pressures, this is called pumping). Air can also flow within and enclosure assembly, moving heat energy from the warm to the cold side (Path 4: natural convection).

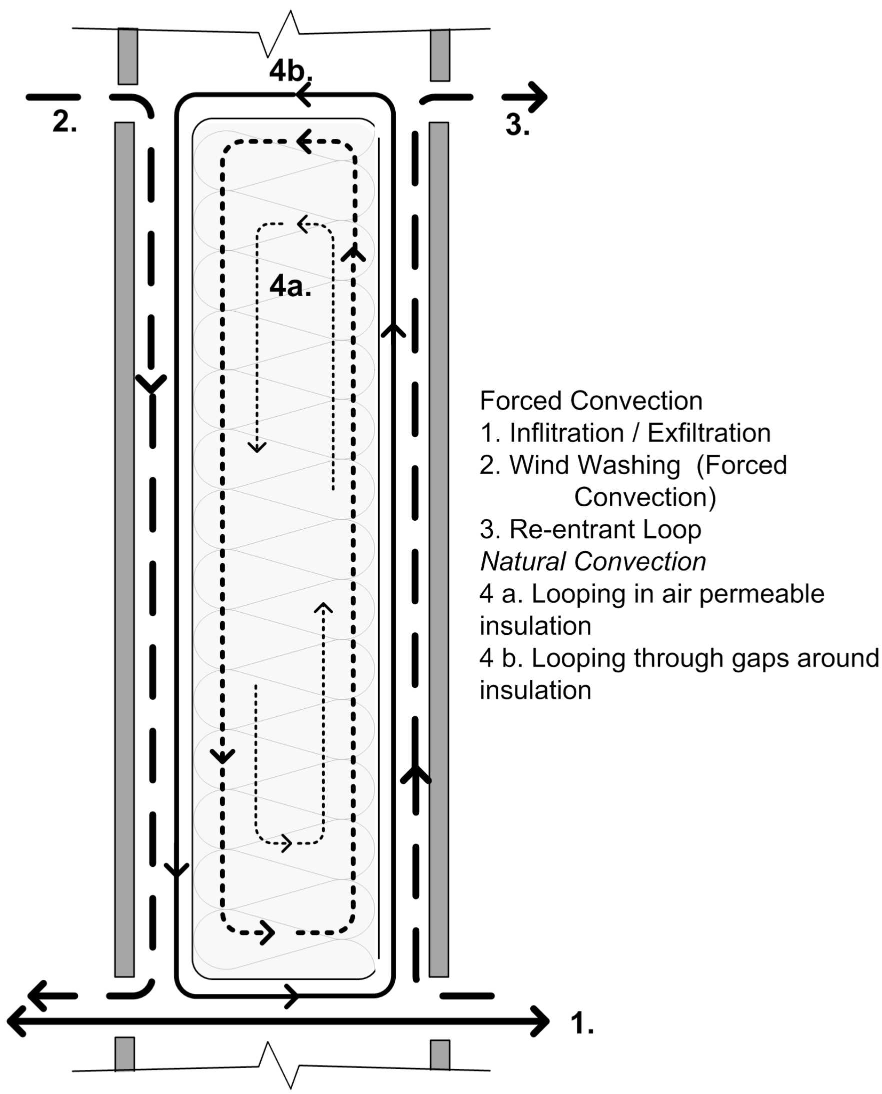


Figure 7: Common Convective Heat Flow Paths in Enclosures

2.2.1 Exfiltration and Infiltration Through Enclosures

Although flow path 1 is shown in Figure 7 as a simple and direct path, it is in fact often long and tortuous. The amount of air that moves along this path at a specific pressure can be measured by a blower door test (ASTM E779 2003) or a laboratory pressurization test (ASTM E283 2004). Building America requires that houses have an enclosure air permeance of less than 1.65 $l/(s\ m^2)$ @ 75 Pa.

If air flows through an enclosure assembly with a temperature difference across it, energy is transported, according to the equation:

$$Q = c_O \cdot dm_{air}/d \cdot \quad T \qquad (3)$$

Where, c_O is the heat capacity of air,

dm_{air}/d is the mass rate of air flow, and

T is the size of the temperature difference between the air flowing out and the air that replaces it within the enclosure.

Substitution of the Building America leakage rate into Equation 3, the heat loss per unit temperature can be shown to be 0.18 W/m^2 °C (0.031 $Btuh/ft^2$ °F). This heat loss rate is about 60% that of a R-20 enclosure 0.28 W/m^2 °C (0.050 $Btuh/ft^2$ °F).

Although the flow can be measured once an assembly has been constructed, during design it is normally assumed that the enclosure will be completely airtight, as every enclosure should be designed with an air barrier system. Air barrier systems are far too often not included in the design and are never built in a perfectly airtight manner. Hence understanding exfiltration and infiltration requires an estimate of the type and size of design and construction defects.

Material R-values naturally do not take account of airflow through the material as a perfect air barrier is assumed. However, as some airflow always does occur, the impact on thermal performance is hotly debated. Some insulation products (such as sprayfoam) can provide both airtightness and insulation. Other products, such as densely packed cellulose, are less air permeable and hence less susceptible to air flow.

Even if the quantity of air that flows through an insulation product is known, the impact is difficult to assess. Yarborough and Graves (2006) conducted a bench top study of heat flow through air permeable insulation with imposed airflow using a modified ASTM C518 test approach. They found that the simple addition of heat flow from Equation 1 and Equation 3 is not sufficient to predict the measured thermal performance. This is expected because the temperature within air permeable insulation will vary as air flows through them, disturbing heat flow patterns. If air flow direction is opposite to that of the conductive flow of heat, some heat recovery occurs. This is sometimes termed "dynamic insulation" and has been studied in the past.

2.2.2 Internal Natural Convection Loops

Insulation products are not always installed as intended by their manufacturer's or in a manner similar to how the R-value is tested. One of the most common defects involves allowing air gaps around the insulation. Although this is quite common in friction fit batts (Figure 9), especially when facers are side stapled, gaps can also occur around air impermeable board insulation as well.

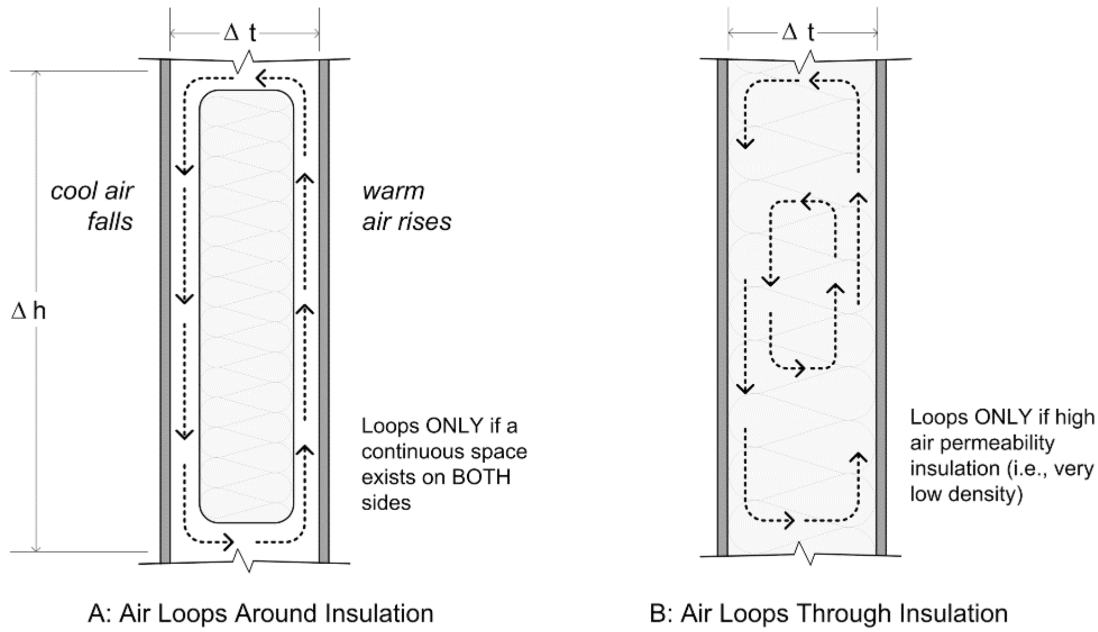


Figure 8: Convective loops can form around insulation or within insulation. A complete flow path is needed and the larger the temperature difference the larger the driving pressure.

To ensure that no flow paths connect air spaces on the warm side of the insulation to the cold side, insulation should always be placed in tight contact along at least one surface. Semi-rigid cavity insulation must be firmly attached to one side of the air space in which it is installed to avoid such convection loops. Full-bed or serpentine adhesive patterns are preferred to daubs when attaching board insulation to solid surfaces (e.g., when adhering foam insulation to a concrete wall) for the same reasons. Sealing joints between sheets of board insulation will also interrupt any potential flow paths. If the insulation is improperly installed or gaps form because of shrinkage flow paths can be formed. Low-density fibrous insulation should not be installed in walls with an gap on either the hot or cold side.

If insulation is sufficiently air permeable, loops can form within the insulation (Path 4b in Figure 7). To control this form of convection most fibrous insulation is made sufficiently air impermeable. In general, denser insulation is less air permeable, but special manufacturing processes can provide low density and good air resistance.

Batt insulation for installation between studs is manufactured slightly oversized so that when it is compressed by the drywall it is possible to avoid even small gaps. In the field, air gaps often form at the corners of batt insulation because of defects in installation. This common defect can allow significantly more heat flow than the rated R-value would suggest as it allows convective loops to form.

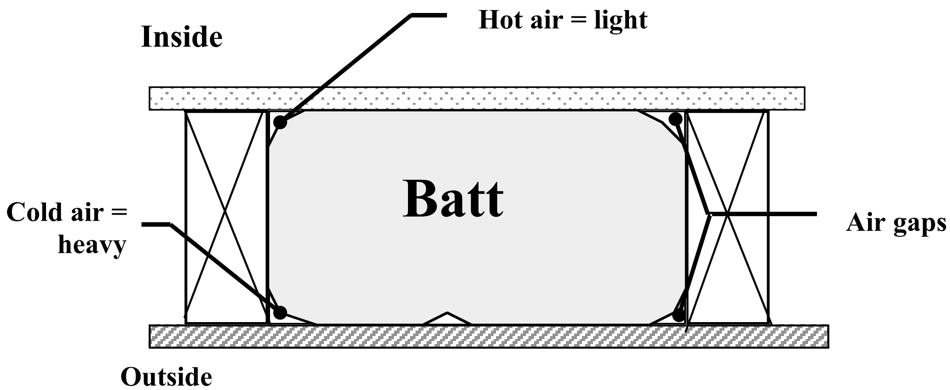


Figure 9: Gaps that Form at the Corner of improperly-installed Friction-fit Batts can allow Convection Loops to Form

The impact of these small gaps was studied by Bomberg and Brown (2003). They constructed walls with intentional and carefully controlled gaps that mimic defects known to occur in the field (Figure 10). The results of these tests (Figure 11) showed that the impact of convective loops increases with the size of the temperature difference, the size of the defect, and the air permeance of the insulation. For large gaps and large temperature differences, reductions in thermal performance of 25 to 33% were measured.

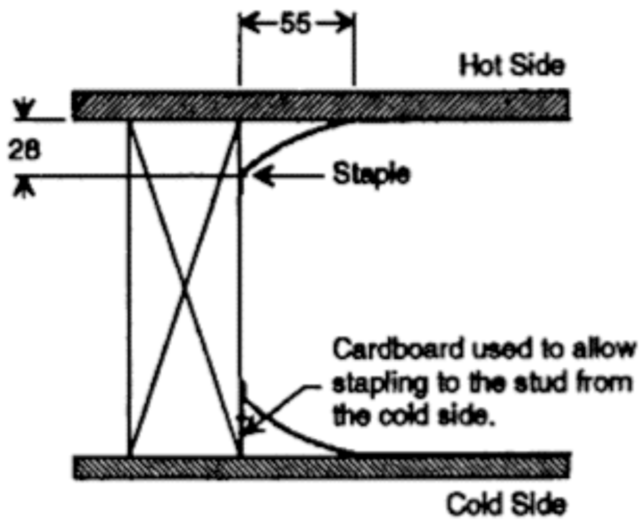


Figure 10: Experimentally Tested Idealized Gaps in Bomberg & Brown (1993) representing a 6% installation defect (dimensions in mm)

Table 3. Thermal resistance measured for frame walls insulated with three different MFI products installed with three different levels of defects.

	Product 1			Product 2			Product 3		
T_{cold}	0%	3%	6%	0%	3%	6%	0%	3%	6%
−5°C	3.15	3.08	2.87	3.29	3.22	3.10	2.95	2.80	2.53
−20°C	—	3.07	2.62	3.37	3.23	2.97	—	2.76	2.24
−35°C	3.38	2.96	2.35	3.43	3.12	2.75	3.14	2.68	2.00

Figure 11: Thermal Resistance (Metric RSI, $R_{imperial}$=5.67*RSI) of 2x6 Wall Assemblies with Simulated Batt Insulation Defects (from Bomberg et al 1993)

The temperature measured through one of the assemblies tested by Bomberg is shown in Figure 12. This plot demonstrates the airflow that begins to loop around the batt at the corners also sets up some flow within the insulation itself: the temperature at mid-depth is significantly colder in the bottom third of the wall than the top third, while the temperature in the middle is what would be expected.

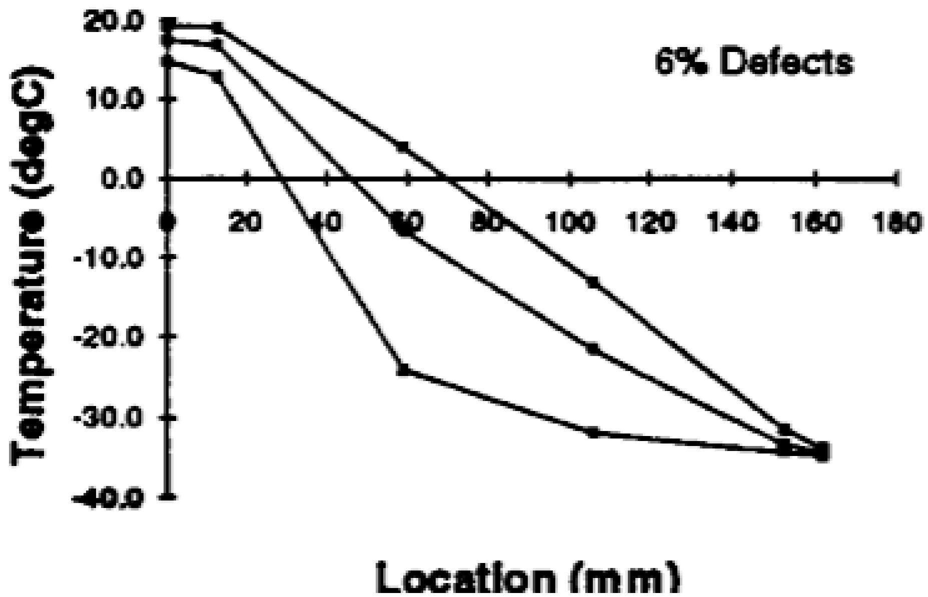


Figure 12: Temperature Plot through Insulated Wall with Defects (from Bomberg et al 1993)

Lecompte (1991) investigated convective loops within and around higher density mineral wool and around air-impermeable rigid foam insulation. He tested the heat flow across wall systems when gaps of various sizes were allowed behind and in front of board insulation. For air gap sizes that might be observed in the field behind rigid boards (e.g., 3/16" or 5 mm) with gaps between the boards of 1/4" (6 mm) heat flow increases of 30% can be expected. If the gap behind the board increases to 3/8" (9.5 mm) heat flow will be more than double than if convection is suppressed.

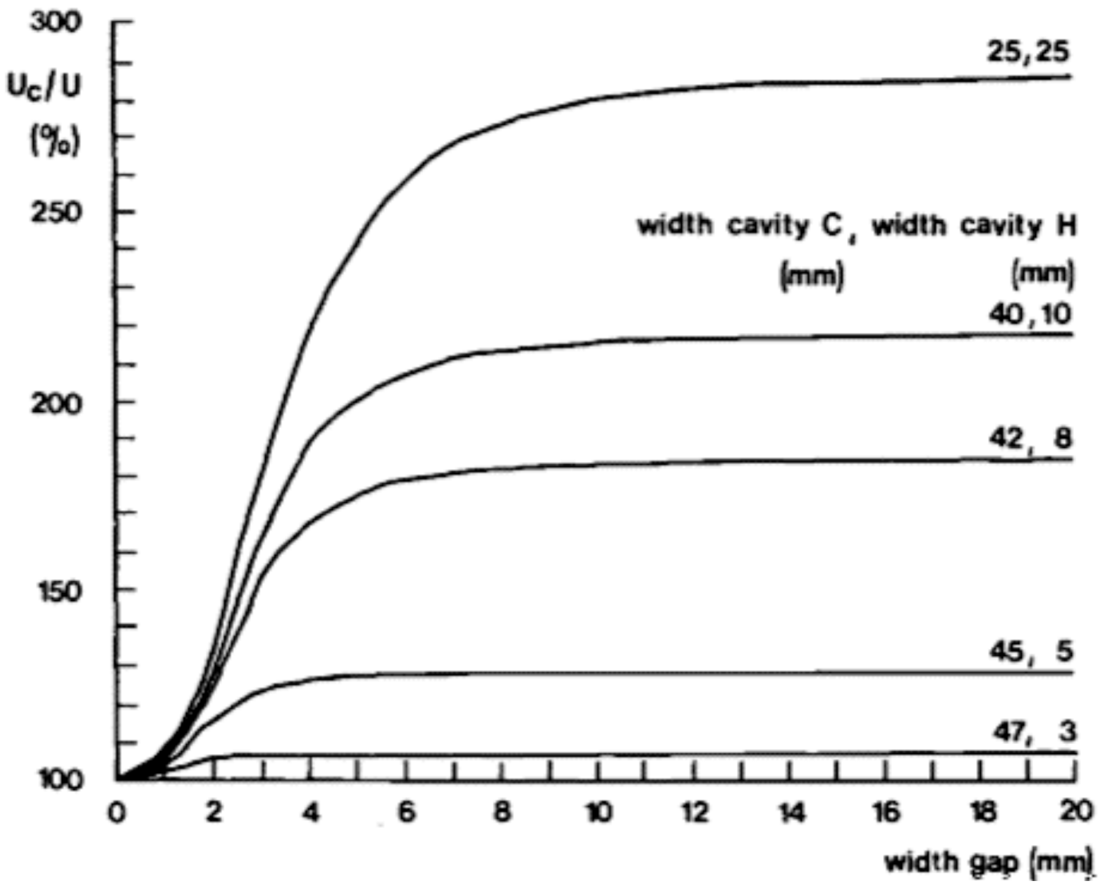


Figure 13: Increase in U-value (i.e., heat flow) because of convective looping around vertically installed air impermeable insulation as a function of Cold (C) and Hot (H) vertical cavity size and gap width between sheets (from Lecompte 1991).

Trethowen (1991) also conducted studies of natural convection looping. In his experiment a 5/8" (15 mm) cavity was provided on both sides of an air impermeable EPS board insulation installed in a wood stud wall (Figure 14). A variable width of gap at the top and bottom of the studspace was used to investigate workmanship effects. With a gap of 1/8" at the top and bottom heat flow was almost twice that when the gap was sealed, a 50% reduction in thermal performance. He concludes that installation of rigid insulation with an air cavity on either side in vertical applications requires essentially perfect workmanship and no shrinkage to achieve the rated thermal performance.

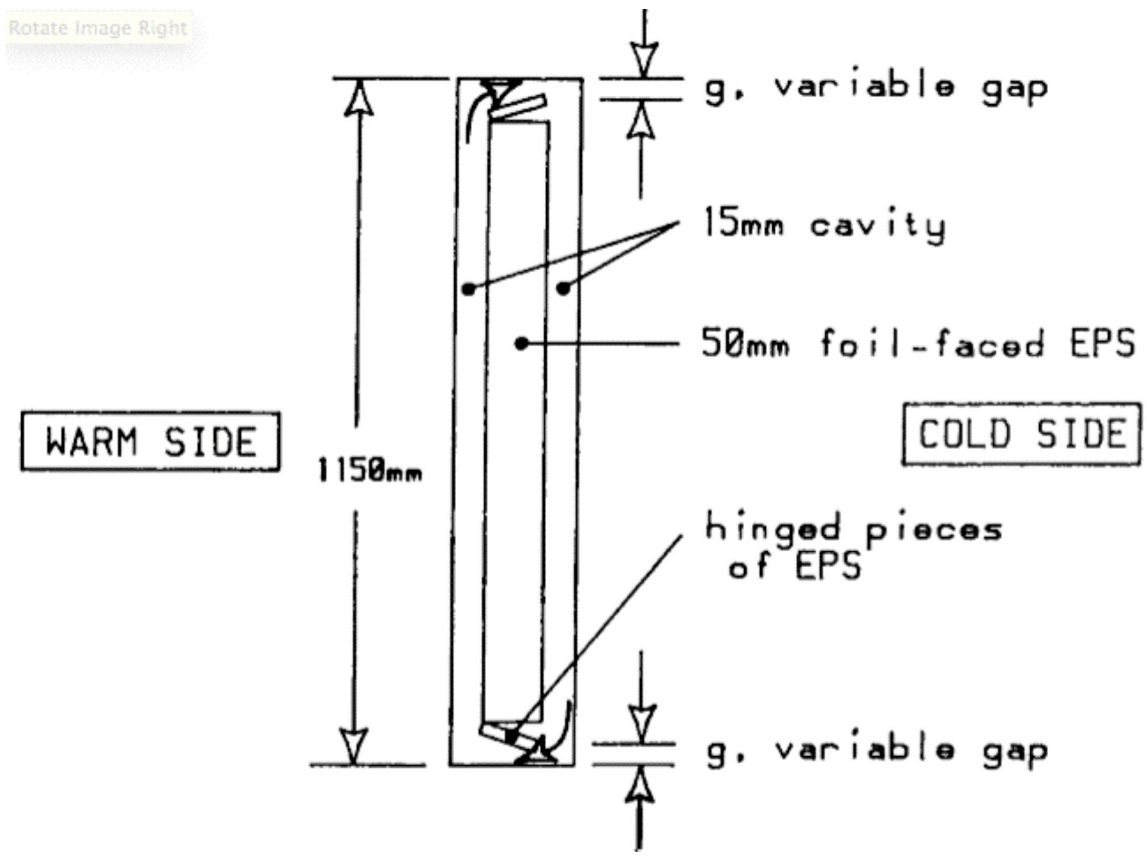


Figure 14: Experimental Setup to Test Convective Heat Loss around Air Impermeable Insulation (from Trethowen 1991)

2.2.3 Wind Washing and Pumping

Air can flow from the outside (or inside), around or through insulation, and then return to the outside (or inside). These flow paths are labeled Path 2 and Path 3 in Figure 7. Although the density differences that drive natural convections can be the force that causes this flow, it is much more common for such the flow to be driven by wind pressures. Wind pressures can often impose gradients of 10 Pa and more, particularly around corners, whereas natural buoyancy pressures tend to be closer to 2 or 3 Pa. When the flow occurs because of exterior wind gradients, the effect on heat loss is called *wind washing* (Figure 15).

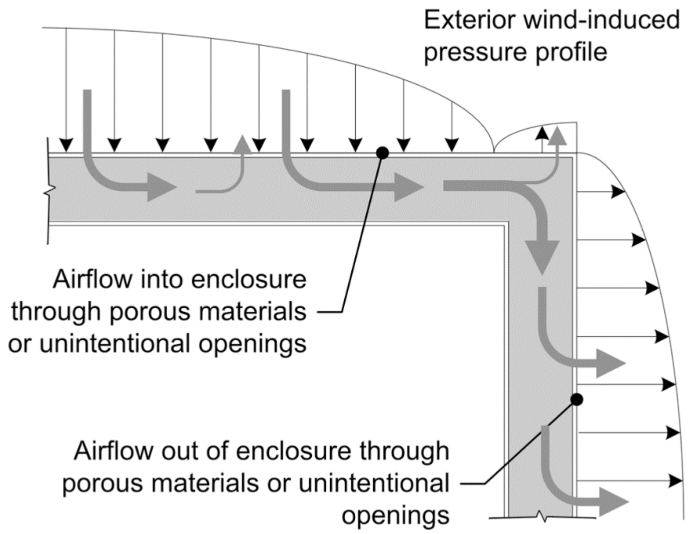


Figure 15: Airflow through and/or behind insulation driven by exterior wind gradients is termed windwashing

If the flow is generated by the deformation of a large membrane, such as a roof membrane or housewrap, under gusting and dynamic wind pressures the mechanism is termed *pumping* (Figure 16). Although this mode of heat flow has been observed in field forensic examinations, research of its impact on heat flow has not been reported in the literature.

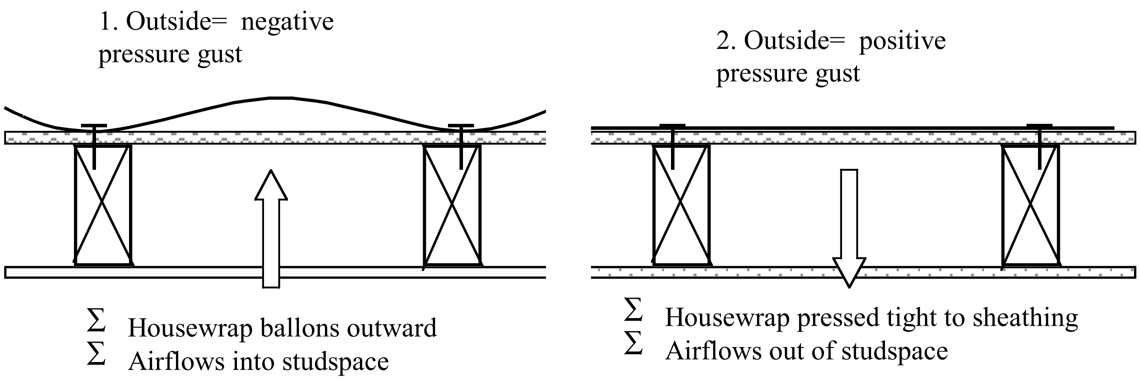


Figure 16: Loose-applied membranes can pulse and flutter in dynamic wind conditions, thereby causing air "pumping"

The impact of wind washing on thermal performance has been studied in Scandinavia. Finnish research (Uvloskk 1996) demonstrated that heat loss due to windwashing can increase by 10 to 30% depending on windspeed (Figure 17). In Scandinavia, secondary, outer layers of airflow resistance located outside air permeable insulation are called wind barriers or convection barriers To control wind-driven convective heat losses Uvloskk recommends limiting the maximum permeability of this wind barrier to between 25 and 100 x 10^{-6} m^3/Pa. Most rigid foam insulations and housewraps (both with taped joints) can provide this level of control.

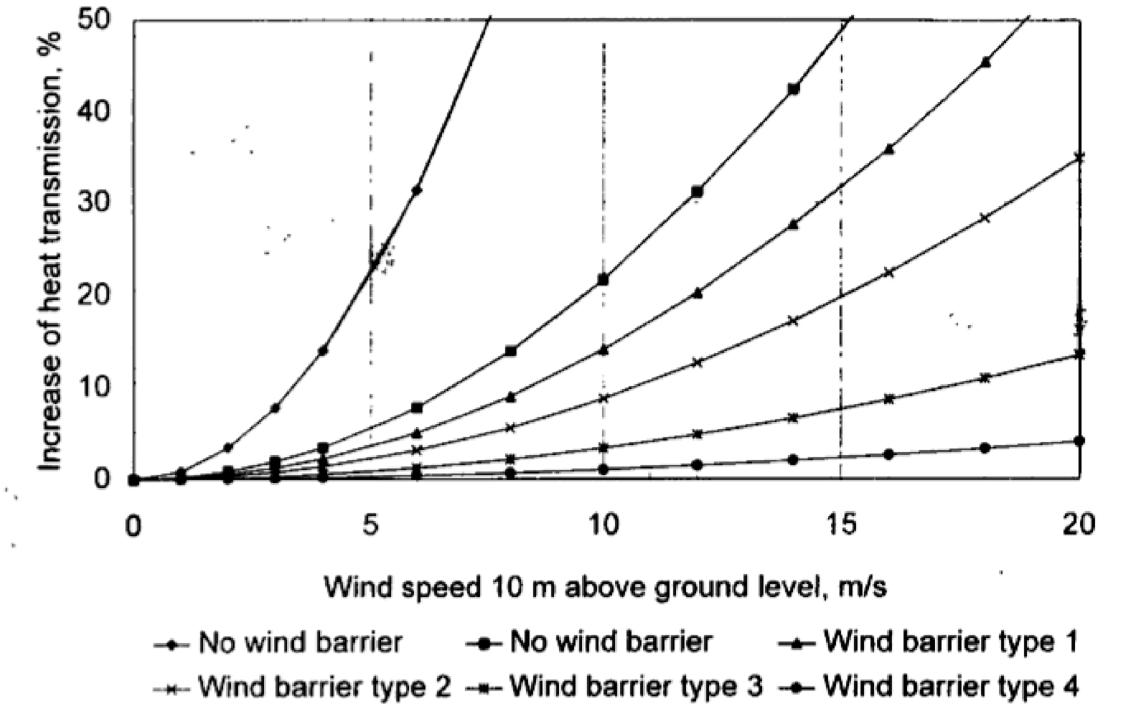


FIGURE 11. Estimated increase of heat loss through a timber frame wall, because of forced convection. Construction variant 1. The values are *average values* regarding both the wall area of the house and wind approach angle. The measurements with no wind barrier represent two ways of mounting the thermal insulation into the wall cavity. The permeance fo the four wind barriers including joints are 4.9E-5, 1.9E-5, 0.73E-5 and 0.22E-5 m^3/m^2 s Pa, respectively.

Figure 17: Influence of Windwashing on Heat Flow Through a 2x6 Studwall with Mineral Wool Insulation (from Uvloskk 1996)

2.3 Temperature Dependency

For low density and air permeable insulation products heat flow by radiation and convection can account for the majority of the heat flow. The relative proportion of heat flow by radiation and convection are, however, highly temperature dependent. This temperature dependency can have significant practical implications.

2.3.1 FTC Mean Temperature

The FTC R-value Rule requires testing to be conducted at a mean temperature of 75 °F (24°C), although it does not specify a temperature difference or an orientation for the samples. However, ASTM C1058 "Standard Practise for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation" which is referenced by the Rule, provides only one set of test temperatures with a mean of 75 °F: a hot side of 100 °F ±9 and a cold side of ±50 °F. This is not the only set of temperatures that are allowed, but it is one of the most commonly chosen.

Hence, a sample may be tested in a horizontal orientation (this orientation is almost universally the only one available amongst our survey of equipment manufacturers) with a top side temperature of 95 °F and a bottom side temperature of 55 °F. This test arrangement minimizes convection (which flows upward with rising air much more effectively than downward), and imposes only a moderate temperature difference (which reduces the role of radiation).

In the marketing of industrial insulation products it is common to provide R-value ratings over a wider range of temperatures. These tests are also generally only conducted horizontally with heat flow from top to bottom to reduce convective heat flow that might occur in air-permeable insulation. Because of the role of radiation, the thermal resistance of insulations usually decrease with increasing temperature.

A more realistic test for an attic application would be a large airspace on top, a top side temperature of either 140 °F (for summer) or -10 °F (for cold winter) with a bottom side temperature of 75 °F. For wall insulation, a more representative test would be conducted vertically, include no airspace, and be exposed to an exterior temperature that is similar to the attic test. Conducting tests under these more realistic conditions would more accurately show the impact of radiation transfer and convective loops through any air permeable materials.

Radiation plays a powerful role in heat transmission across air spaces and through semi-transparent and porous media. Radiation exchange between two flat surfaces facing each other varies with the fourth power of absolute temperature according to the Stefan-Boltzman equation:

$$q_{1-2} = \cdot F_E \cdot (T_1^4 - T_2^4) \qquad (4)$$

where,

q_{1-2} is the heat flux from surface 1 to 2,

F_E is the emissivity factor

is the Stefan-Boltzman constant.

T_1 and T_2 are the absolute temperatures of the surfaces.

Hence, at high temperatures radiation transfer is much more significant than at cold temperatures. For summer-time performance of roof insulation applications (which often operate at 140 °F / 60 °C and higher), poor radiation control will result in a significant negative impact on performance.

Data published by manufacturers over wider temperature ranges shows the impact radiation can have. For example, the R-value per inch for Type 1 expanded polystyrene (a relatively air-impermeable board product) varies from R-4.2/inch at a mean of 25 °F (-4 °C) to R-3.25/inch at a mean of 110 °F (43 °C) (thermalfoams.com 2008). This is an almost 25% change in R-value over a range of temperatures experienced by many buildings. Equation 4 would predict that radiation will transfer almost 40% less heat at a mean temperature of 25 °F (-4 °C) than at 110 °F (43 °C) and likely accounts for much of the change.

2.4 Material Property Changes over Time

2.4.1 Aging of foams

Rigid foam insulations use blowing agents to form the hollow pores that help reduce their density and thereby decrease their thermal conductivity. These blowing agents often have a thermal conductivity lower than air and hence increase the effective R-value of the product. However, if these gases leak out by diffusion over time, the R-value of the foam product will eventually drop until it equals the R-value of the same foam structure with the pores filled with air.

In some types of foam, such as expanded polystyrene (EPS), the blowing agents (such as pentane) leave the foam relatively quickly. Measuring the thermal conductivity after 28 days is often sufficient to approach the long-term equilibrium for EPS. However, for closed-cell foams that employ blowing agents, such as polyurethane, polyisocyanurate, and extruded polystyrene, the aging continues for decades.

The temperature of the foam influences the rate at which gas will diffuse out, and hence the aging process will depend strongly on the temperature in a non-linear manner (i.e., exposure to relatively short periods of time at high temperatures will result in a significant amount of diffusion). To accelerate the diffusion of gases, some non-standard methods condition samples at high temperatures. Hence, the use of the insulation below a dark colored roof in a sunny and warm climate will significantly increase its aging compared to the same insulation used on the interior of a basement wall (which rarely sees warm temperatures).

To address the aging issue, a time-averaged R-value, termed the *Long Term Thermal Resistanc*e (LTTR), was developed that tests thin slices of insulation (which accelerates aging). The method has been standardized in ASTM C1303-07 Standard Test Method for Predicting Long-Term Thermal Resistance of Closed-Cell Foam Insulation. The method is purported to provide a 15 yr aged R-value.

The LTTR method is not without controversy. Many claim that the quoted LTTR values are still a significant over estimate of the thermal performance. A recent article in Professional Roofing Magazine reported research that showed measured R-values below the manufacturers published LTTR at ages of only a year.

2.4.2 Settling of loose-fill and blown insulation

Fibrous insulation is widely blown into attics and into walls. If these materials settle in horizontal applications, the density increases and the thermal performance may degrade. If the loose fill insulation is installed in walls, then settling will result in uninsulated portions at the top of each studbay. Hence, installing blown and loose-fill insulation requires careful control of minimum density. The required density varies strongly with each product type and application. Blown-in cellulose insulation’s product specification, ASTM C739-05 “Standard Specification for Cellulosic Fiber Loose-Fill Thermal Insulation,” includes some information and methodology relating to the assessment of settling and its impact on thermal performance. Although testing by the Danish Building Research Institute showed that cyclical humidity variations significantly influence settling in wall installation (Rasmussen 2003), this is not yet part of industry standard methods.

There is a generic standard test method to assess settling "ASTM C 1374 Standard Test Method for Determination of Installed Thickness of Pneumatically Applied Loose-Fill Building Insulation," but it does not deal with many of the issues of vibration (Yarborough et al 1983) and moisture effects on settling, nor is it included in the FTC R-value reporting requirements.

It would appear that the settling issue is not really a thermal metric problem, but a long-term and installation material property specification issue.

3 Implications for High Thermal Performance Enclosures

The strengths of the current building enclosure thermal metric (the R-value) is that it is simple to measure, communicate, and widely accepted. It was however created to describe the thermal property of a single material or property under very specific and easily reproducible conditions. Its weakness is that it oversimplifies the reality of enclosure assemblies (multiple materials, tolerances, etc.) and does not account for the real temperature conditions these materials are exposed to (large temperature differences, lower cold side temperatures and higher warm side temperatures). It therefore neglects important physical phenomena that occur in real building assemblies. The current industry focus on a material product standard, R-value, has resulted in the use of inappropriate metrics for the control of heat flow.

There are clearly many factors that influence the thermal performance of enclosures that are not currently widely understood or included in, or both. As the control of heat flow across an enclosure increases, the impact of factors such as thermal bridging, convective loops, wind washing, and air leakage become much more important. Imperfections that could in the past be ignored because they had a small impact on thermal control must now be understood and dealt with to meet the goals of high thermal performance building enclosures. As the industry demands higher levels of thermal performance the short comings of the R-value metric make it increasingly difficult to properly distinguish which products will perform best in different application, and even to quantitatively predict heat flow with accuracy.

From this review of physics and previous research, it can be concluded that any metric for high thermal performance enclosures must deal with:

- The effective thermal conductivity of insulation materials, including variations with temperature, settling, and off-gassing.
- The influence of thermal bridging, especially for highly conductive structural components and realistic framing factors,
- The susceptibility to construction defects that can result in convective loops, and
- The control of air leakage and wind washing.

Some of these factors can be controlled at design, and their influence on thermal performance is predictable (eg. thermal bridging). Others, such as convective loops and air leakage, are the result of a combination of design and workmanship and hence their impacts on thermal performance are more difficult to predict.

4 References

ASTM C 177-85 (Reapproved 1993), "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus." ASTM International, West Conshohocken, PA.

ASTM C 236-89 (Reapproved 1993), "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box." ASTM International, West Conshohocken, PA. ASTM International, West Conshohocken, PA.

ASTM C 518-91, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." ASTM International, West Conshohocken, PA.

ASTM C 739-05 “Standard Specification for Cellulosic Fiber Loose-Fill Thermal Insulation.” ASTM International, West Conshohocken, PA.

ASTM C 976-90, "Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box." ASTM International, West Conshohocken, PA.

ASTM C 1058 “Standard Practise for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation.” ASTM International, West Conshohocken, PA.

ASTM C 1114-95, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus." ASTM International, West Conshohocken, PA.

ASTM C 1374 “Standard Test Method for Determination of Installed Thickness of Pneumatically Applied Loose-Fill Building Insulation.” ASTM International, West Conshohocken, PA.

ASTM E283-04, “Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen.” ASTM International, West Conshohocken, PA.

ASTM E779-03, “Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.” ASTM International, West Conshohocken, PA.

Bombino, R. and Burnett, E.F.P., *Design Issues with Steel-stud-framed Wall Systems*, PHRC Research Series: Report No. 58, The Pennsylvania Housing Research Center, University Park, PA (May 1999), 44p.

Carpenter S.C. and Schumacher C.J. “Characterization of Framing Factors for Wood-Framed Low-Rise Residential Buildings” *ASHRAE Transactions* v 109, Pt 1. Feb. 2003.

Christian, J.E., and Kosny, J., "Toward a National Opaque Wall Rating Label" *Proceedings Thermal Performance of the Exterior Envelopes VI* , ASHRAE ISBN 1-

883413-29-X, December 1995.

Energy Efficiency and Renewable Energy Clearinghouse, *Wall Insulation*. DOE, Washington DC, October 2000.

Graham, Mark, S. “Research reveals the LTTR method may be over-reporting results,” *Professional Roofing Magazine*, January 2006.

Kosny, J. Christian,J.E. " Reducing the Uncertainties Associated with Using the ASHRAE Zone Method for R-value Calculations of Metal Frame Walls.” *ASHRAE Transactions* v.101, Pt 2, 1995.

Rasmussen, T. “Verification of Density Predicted for Prevention of Settling of Loose-fill Cellulose Insulation in Walls,” *Journal of Thermal Envelope and Building Science*, Vol. 27, No.1 p. 46-69, 2003.

Salonvaara and Nieminen, “Hygrothermal Performance of a New Light Gauge Steel-Framed Envelope System,” *Journal of Building Physics*, Vol 22 No 169-182, 1998.

Thermal Foams, Inc., Buffalo, New York. www.thermalfoams.com

Trethowen, H.A., “Sensitivity of Insulated Wall and Ceiling Cavities to Workmanship,” *J. of Thermal Insul.,* Vol 15, October 1991.

Uvslokk, S., “The Importance of Wind Barriers for Insulated Timber Frame Constructions,” *J. Thermal Insul. & Building Envelopes*, Vol. 20, July 1996.

Yarbrough, D.W. and Graves, R.S. “The Effect of Airflow on Measured Heat Transport Through Wall Cavity Insulation,” Presented at the ASTM Symposium on Heat, Air, and Moisture Transport in Buildings, Toronto, Canada, 2006.

Yarborough, D.W., Wright, J.H., McElroy, D.L., and Scanlan, T.F., “Settling of Loose-Fill Insulations Due to Vibration,” in *Thermal Insulation, Materials and Systems for Energy Conservation in the 80’s*, ASTM STP 789, F.A Govan, D.M. Greason, and J.D. Mcallister Eds., American Society for Testing and Materials, 1983, pp. 703-714.

Appendix A: The FTC Rule

Excerpts from: LABELING AND ADVERTISING OF HOME INSULATION 16CFR460

Authority: 38 Stat. 717, as amended (15 U.S.C. 41 et seq.).
Source: 44 FR 50242, Aug. 27, 1979, unless otherwise noted.

Sec. 460.1 What this regulation does.

This regulation deals with home insulation labels, fact sheets, ads, and other promotional materials in or affecting commerce, as "commerce" is defined in the Federal Trade Commission Act. If you are covered by this regulation, breaking any of its rules is an unfair and deceptive act or practice or an unfair method of competition under section 5 of that Act. You can be fined heavily (up to $10,000 plus an adjustment for inflation, under Sec. 1.98 of this chapter) each time you break a rule.

[44 FR 50242, Aug. 27, 1979, as amended at 61 FR 54549, Oct. 21, 1996; 61 FR 55840, Oct. 29, 1996]

Sec. 460.2 What is home insulation.

Insulation is any material mainly used to slow down heat flow. It may be mineral or organic, fibrous, cellular, or reflective (aluminum foil). It may be in rigid, semirigid, flexible, or loose-fill form. Home insulation is for use in old or new homes, condominiums, cooperatives, apartments, modular homes, or mobile homes. It does not include pipe insulation. It does not include any kind of duct insulation except for duct wrap.

Sec. 460.3 Who is covered.

You are covered by this regulation if you are a member of the home insulation industry. This includes individuals, firms, partnerships, and corporations. It includes manufacturers, distributors, franchisors, installers, retailers, utility companies, and trade associations. Advertisers and advertising agencies are also covered. So are labs doing tests for industry members. If you sell new homes to consumers, you are covered.

Sec. 460.4 When the rules apply.

You must follow these rules each time you import, manufacture, distribute, sell, install, promote, or label home insulation. You must follow them each time you prepare, approve, place, or pay for home insulation labels, fact sheets, ads, or other promotional materials for consumer use. You must also follow them each time you supply anyone covered by this regulation with written information that is to be used in labels, fact sheets, ads, or other promotional materials for consumer use. Testing labs must follow the rules unless the industry members tells them, in writing, that labels, fact sheets, ads, or other promotional materials for home insulation will not be based on the test results.

Sec. 460.5 R-value tests.

R-value measures resistance to heat flow. R-values given in labels, fact sheets, ads, or other promotional materials must be based on tests done under the methods listed below. They were designed by the American Society of Testing and Materials (ASTM). The test methods are:

1. All types of insulation except aluminum foil must be tested with ASTM C 177-85 (Reapproved 1993), "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus;" ASTM C 236-89 (Reapproved 1993), "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box;" ASTM C 518-91, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus;" ASTM C 976-90, "Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box;" or ASTM C 1114-95, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus." The tests must be done at a mean temperature of 75 deg.Fahrenheit. The tests must be done on the insulation material alone (excluding any airspace). R-values ("thermal resistance") based upon heat flux measurements according to ASTM C 177-85 (Reapproved 1993) or ASTM C 518-91 must be reported only in accordance with the requirements and restrictions of ASTM C 1045-90, "Standard Practice for Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements." These incorporations by reference were approved by the Director of the Federal Register in accordance with 5 U.S.C. 552(a) and 1 CFR part 51. Copies of the test procedures and standard practice may be obtained from the American Society of Testing and Materials, 1916 Race Street, Philadelphia, PA 19103. Copies may be inspected at the Federal Trade Commission, Consumer Response Center, Room 130, 600 Pennsylvania Avenue, NW, Washington, DC 20580, or at the Office of the Federal Register, 800 North Capitol Street, NW, Suite 700, Washington, DC.

    1. For polyurethane, polyisocyanurate, and extruded polystyrene, the tests must be done on samples that fully reflect the effect of aging on the product's R-value. To age the sample, follow the procedure in paragraph 4.6.4 of GSA Specification HH-I-530A, or another reliable procedure.
    2. For loose-fill cellulose, the tests must be done at the settled density determined under paragraph 8 of ASTM C 739-91, "Standard Specification for Cellulosic Fiber (Wood-Base) Loose-Fill Thermal Insulation." This incorporation by reference was approved by the Director of the Federal Register in accordance with 5 U.S.C. 552(a) and 1 CFR part 51. Copies of the test procedure may be obtained from the American Society of Testing and Materials, 1916 Race Street, Philadelphia, PA 19103. Copies may be inspected at the Federal Trade Commission, Consumer Response Center, Room 130, 600 Pennsylvania Avenue, NW, Washington, DC 20580, or at the Office of the Federal Register, 800 North Capitol Street, NW, Suite 700, Washington, DC.
    3. For loose-fill mineral wool, the tests must be done on samples that fully reflect the effect of settling on the product's R-value. When a settled density procedure becomes part of a final GSA Specification for loose-fill mineral wool, the tests must be done at the settled density determined under the GSA Specification.

2. Aluminum foil systems with more than one sheet must be tested with ASTM C 236-89 (Reapproved 1993) or ASTM C 976-90, which are incorporated by reference in paragraph (a) of this section. The tests must be done at a mean temperature of 75 deg.Fahrenheit, with a temperature differential of 30 deg.Fahrenheit.
3. Single sheet systems of aluminum foil must be tested with ASTM E408 or another test method that provides comparable results. This tests the emissivity of the foil--its power to radiate heat. To get the R-value for a specific emissivity level, air space, and direction of heat flow, use the tables in the most recent edition of the American Society of Heating, Refrigerating, and Air-

Conditioning Engineers' (ASHRAE) Handbook. You must use the R-value shown for 50 deg.Fahrenheit, with a temperature differential of 30 deg.Fahrenheit.

4. For insulation materials with foil facings, you must test the R-value of the material alone (excluding any air spaces) under the methods listed in paragraph (a) of this section. You can also determine the R-value of the material in conjunction with an air space. You can use one of two methods to do this:

1. You can test the system, with its air space, under ASTM C 236-89 (Reapproved 1993) or ASTM C 976-90, which are incorporated by reference in paragraph (a) of this section. If you do this, you must follow the rules in paragraph (a) of this section on temperature, aging and settled density.
2. You can add up the tested R-value of the material and the R-value of the air space. To get the R-value for the air space, you must follow the rules in paragraph (c) of this section.

[44 FR 50242, Aug. 27, 1979, as amended at 55 FR 10055, Mar. 19, 1990; 55 FR 12110, Mar. 30, 1990; 61 FR 13665, Mar. 28, 1996; 63 FR 71587, Dec. 28, 1998]

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