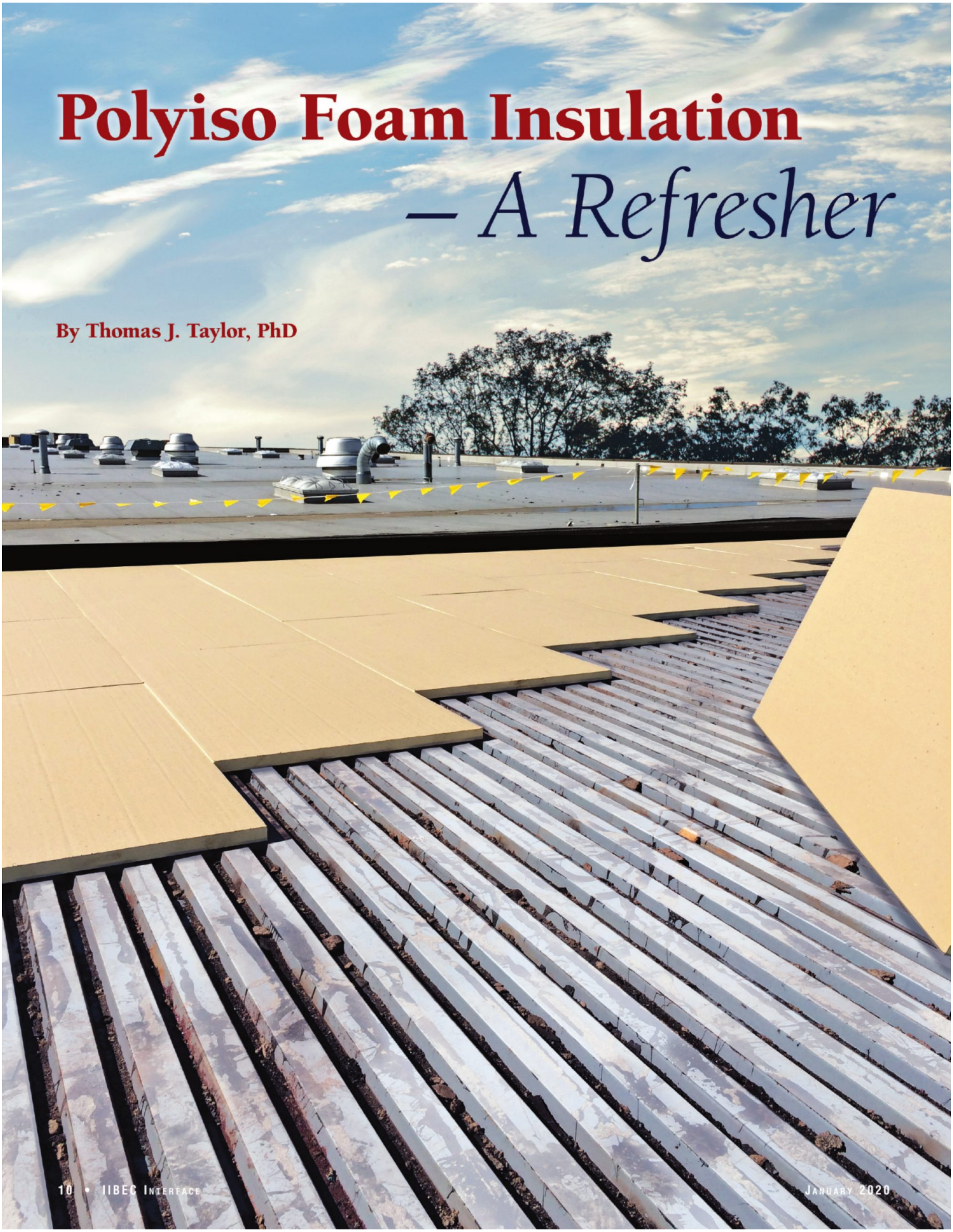
Polyiso Foam Insulation – *A Refresher*

By Thomas J. Taylor, PhD



ABSTRACT

Thermal insulation is an important part of commercial roofing assemblies, with polyisocyanurate foam, or polyiso, being the most common form today. As energy costs have risen, understanding the exact insulation value of this material (i.e., its thermal resistance or R-value) has become more important. Knowledge of thermal resistance can be used to specify heating, ventilation, and air conditioning (HVAC) equipment and to predict long-term energy use. The polyiso polymer represents less than 5% of the total insulation volume, with cell gas representing greater than 95%. Therefore, thermal conductivity of polyiso's cell gas is the critical factor determining R-value.

Reported R-values represent an average over a wide temperature range across the insulation. As such, recent concern about the low-temperature R-value of polyiso might be leading specifiers and designers to use an inappropriately high value. Polyiso, like most other foams, can be expected to have an R-value that rises linearly with lower temperatures (i.e., it has an inverse relationship with temperature).

Recent data showing that the R-value at 40°F (4°C) is lower than expected could be the result of a deviation from the expected trend at, for example, 25°F (-4°C). While manufacturers reformulate to eliminate low-temperature anomalies, and while large industry studies show R-values to be consistently in line with labeled values, designers and specifiers are advised to continue to use those labeled values.

INTRODUCTION

Preventing water intrusion into the built environment due to precipitation has always been regarded as the basic function of roof assemblies. While this is undoubtedly true, reducing heat flow through the building enclosure is a very important secondary function. Maintaining interior thermal comfort has always been an important part of residential construction. However, it was not until the early 1970s that the use of thermally insulated roof assemblies on steel decks became commonplace in commercial construction,[1] due to the need to lower building energy costs.

Thermal insulation consists of low-density materials in the form of fibers, granules, or cells that contain air- or gas-filled pockets and voids, arranged to retard the passage of heat. Early forms of commercial roof insulation included boards containing expanded perlite and recycled newsprint, the mixture being bonded with asphalt. Fiberglass and mineral wool boards became increasingly prevalent, but these in turn were gradually supplanted by plastic foams. The latter can be further categorized into thermoplastic foams (typically expanded and extruded polystyrene) or thermoset foams (polyurethane, phenolic, and polyisoc). Polyiso foam started to become popular in the late 1970s[1] and, more recently, has come to represent around 75% of the commercial roof insulation market.

Polyiso has proven to be popular due to a combination of its cost effectiveness (i.e., cost per insulation unit), efficiency (i.e., insulation value per unit thickness), and fire resistance as compared to some insulation materials. However, as polyiso grew in popularity, so did an interest in understanding a more exact insulation value of these products. As energy costs have risen, the need to more accurately specify HVAC equipment has also increased. In addition, once a building is completed, it is important that the owner/tenant be able to better anticipate future energy costs from a budgetary perspective.

The aim of this article is to examine the factors influencing the R-value of polyiso. The prediction of long-term R-value and the influence of climate (e.g., temperature) have been of significant interest over the past few decades as building energy budgets have increased in importance. Recent discussions as to what R-value the designer should use and the importance of ambient temperature are reviewed and discussed herein.

AN INTRODUCTION TO POLYISO

While the purpose of this article is to review its thermal resistance, it is helpful to briefly describe the formation of polyiso foam. As with any foam material, the process begins with the plastic or polymer precursor materials in their liquid phase. A gaseous blowing agent(s) is introduced—either by some form of injection into the process, or through chemical reactions that create the polymer matrix. Initially, the blowing agent(s) are present as an extremely fine dispersion. In the case of polyiso, pentane is used as the blowing agent, and during the subsequent development of the polyisocyanurate matrix, heat is released. The heat causes the dispersed pentane to expand, forming gaseous cells. Growth of these cells ultimately results in cell impingement. The entire process is indicated schematically in *Figure 1*.

When the cells impinge, surface tension tends to cause the material between two cells to thin, and material between multiple cells to thicken. This results in so-called cell windows and struts, as indicated in *Figure 2*. The characteristics of the windows and struts—such as thickness, size, and number—influence the overall thermal resistance of the foam, along with the blowing gas composition, as discussed later.

In the section, "The Mechanisms of Thermal Resistance," we will note that polyiso cells are considered to be essentially >99% closed. So-called reticulated or open-celled foams have very few windows and consist mainly of struts only. Such foams allow air flow from one side to the other, while polyiso does not.

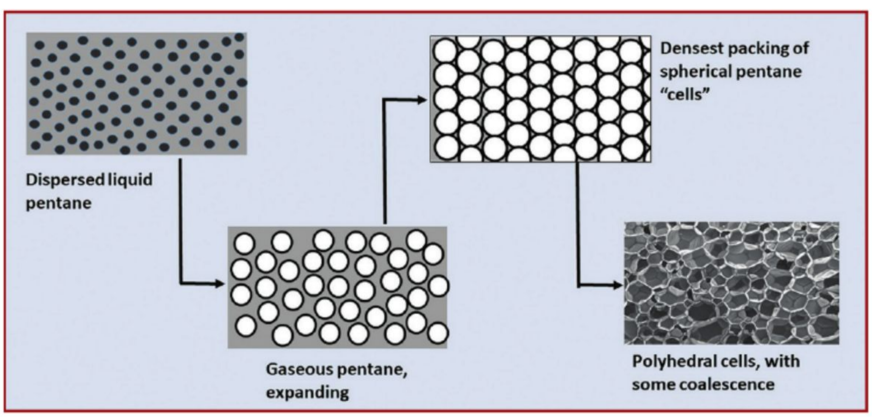


Figure 1 – The overall process leading to the formation of thermal insulation foam. Due to heat involved in the polymer reaction and/or applied heat, the gas expands until it is confined in polyhedral cells shown on the far right.

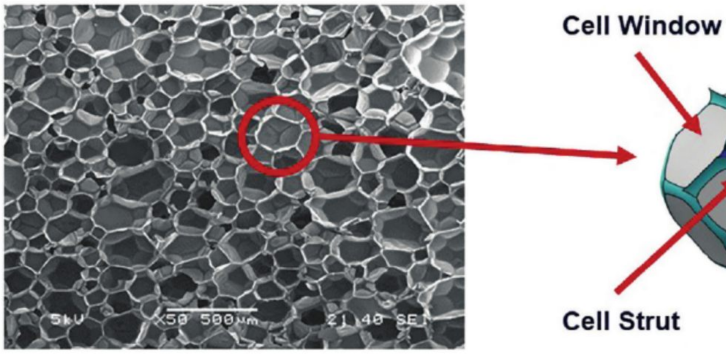


Figure 2 – The cross section of a piece of polyiso foam on the left, examined with a scanning electron microscope, and an idealized interpretation of a cell showing cell windows and struts on the right.

THE R-VALUE RULE

While knowledge of a material's R-value is important to the commercial building market for the HVAC specifier and building owners/occupiers, homeowners and individual consumers are generally unable to verify claims as to the thermal resistance. Schumaker et al.[2] noted that in the aftermath of the 1970s energy crisis, "fraudulent R-value claims became so widespread, the United States Congress passed a consumer protection law in response, the 'R-Value Rule' (16 Code of Federal Regulations [CFR] Part 460)."[3] The R-Value Rule "requires home insulation manufacturers, professional installers, new home sellers, and retailers to provide R-value information, based on the results of standard tests." As will be discussed later, the development of standard tests and interpretation of data from those tests has not been straightforward.

Polyiso is used as continuous insulation in residential wall systems and roof assemblies in many apartment and high-rise condominium buildings. It is not feasible for polyiso manufacturers to differentiate between products going into residential projects versus commercial applications. For this reason, manufacturers have elected to extend the R-Value Rule to all polyiso applications, not just applications on homes as the rule requires. Therefore, in practice, the rule covers all polyiso products.

THE MECHANISMS OF THERMAL RESISTANCE

The mechanisms of heat transfer through closed cellular foams have been reviewed by Glicksman and Torpey.[4] A brief overview of these mechanisms is necessary in order to better understand issues of R-value stability. There are three ways in which heat can travel through a material, these being convection, conduction, and radiation, as shown schematically in *Figure 3*.

Convection is the heat transfer due to the bulk movement of molecules within fluids such as gases and liquids, from a hot surface towards a colder surface. In foams such as polyiso, the cells are too small for any convection to occur. Also, the temperature difference across each individual cell is too small to cause convection.

Conduction – Closed-cell foams, such as polyiso, are composed of a polymer matrix of cells and a gaseous mixture within those cells.

- As stated earlier, the cell material (i.e., the polymer) represents less than 5% of the total foam volume and, therefore, the thermal conduction of that material accounts for a very minor fraction of the total heat transfer. Furthermore, the path along the polymer from the hot side to the cold side is convoluted. Manufacturers strive for low foam density, and polymer conduction is generally considered to be negligible.
- The gaseous mixture within the cells represents more than 95% of the total foam volume and can be as high as 98%. Thus, the gas phase accounts for essentially all of the thermal conduction through polyiso. It is the composition of the gaseous mixture that gives rise to difficulty in assessing a foam's R-value. The blowing agent used to create the foam will have a certain conductivity; however, over time, that blowing agent may diffuse out of the foam, and air could diffuse in. Due to its highly cross-linked nature, the diffusion of gas into and out of polyiso is slower than for thermoplastic foams, such as those based on polystyrene, and as a result, is harder to predict.[5]

Radiation – Thermal energy radiates from hot surfaces and is absorbed by materials, depending on their opacity and thickness. Polyiso does not totally block thermal radiation; cell walls are considered to be too thin to absorb thermal radiation; however, cell struts are thought to absorb and then re-radiate thermal energy. It is known that smaller cells—i.e., more cells per unit volume—are more effective at blocking thermal radiation than larger cells.

MEASUREMENT OF THERMAL RESISTANCE

A detailed review of the measurement of thermal resistance of materials is beyond the scope of this article. However, most techniques rely on imposing a thermal gradient across a sample and measuring the heat flux through

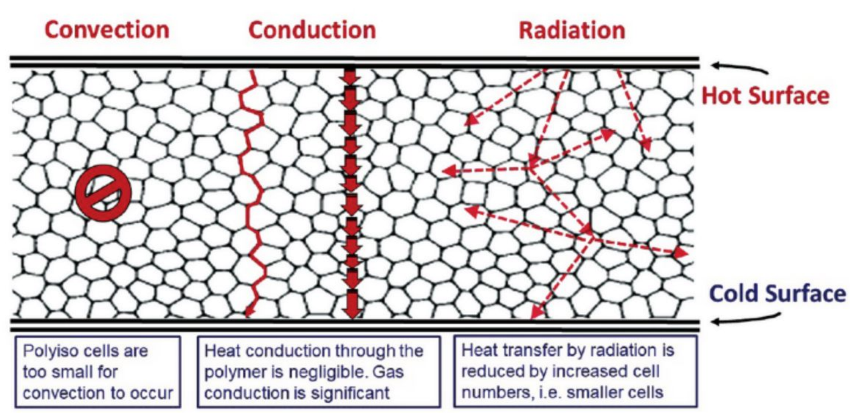


Figure 3 – Schematic showing the three main forms of thermal transfer through a closed-cell foam material.

the material from the hot side to the cold side. Polyiso is manufactured to meet ASTM C1289, *Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board*.[6] ASTM C1289 requires that R-value testing be in accordance with one of the following ASTM test methods: C177,[7] C518,[8] C1114,[9] or C1363/C1363M.[10]

ASTM C1289 specifies the thermal resistance at a mean temperature of 75°F (24°C) for various product thicknesses and requires that the values at 40°F (4°C) and 110°F (43°C) be made available upon request. Importantly, the temperature differential between the hot and cold sides must be at least 40°F (22°C). This means that R-values represent an average across a temperature range.

Overall Product Thickness, inch	LTTR R-Value per inch thickness	LTTR R-Value per product thickness
1	5.6	5.6
2	5.7	11.4
3	5.8	17.4
4	5.9	23.6

Table 1 – Minimum Long-Term Thermal Resistance (LTTR) Values established by the PIMA QualityMark™ Program.

THERMAL DRIFT AND LONG-TERM THERMAL RESISTANCE

As noted in the description of thermal conduction through a foam, the cell gas composition in polyiso foam changes over time as the blowing agent diffuses out of the cells and is replaced with air. Typically, blowing agents have a lower thermal conductivity than air, which results in the R-value drifting lower over time. Kalinger and Drouin have extensively reviewed such "thermal drift" and the development of test methods to predict a long-term R-value that can be reliably used by building designers.[5] They described the development and validation of a "long-term thermal resistance" or LTTR test method. While the LTTR method has continued to be used, in a study of foam aging, Singh and Coleman noted that the test requires care and the results are not readily verified by roofing professionals.[11]

An LTTR test method was published by ASTM International as standard C1303[12] in 1995. In 1998, the Standards Council of Canada and the Underwriters Laboratories of Canada published CAN/ULC-S770.[13] This was based on ASTM C1303 and research by Oak Ridge National Laboratories, and provides R-value data corresponding to a 15-year time-weighted average. Beginning in 2003, the Polyisocyanurate Insulation Manufacturers Association (PIMA) established a third-party certification program to enable participating manufacturers to report independently validated LTTR values. This is referred to as the PIMA QualityMark™ program, with six polyiso manufacturers participating. The LTTR values are considered "labeled R-values" to be used by building design professionals.

Independent testing of polyiso obtained through distribution suggested that the labeled R-values were overstating product performance.[14] In 2011, the ASTM C1289 specification was updated to incorporate changes in the underlying CAN/ULC-S770 test method and to allow for the use of ASTM C1303.[15,16] Beginning in 2014, the PIMA QualityMark™ program was similarly updated, and the R-values required of

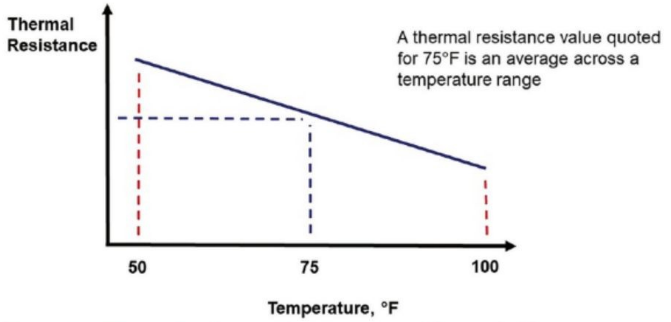


Figure 4 – Thermal resistance is not measured at a single temperature but across a gradient. In this case, the quoted 75°F value is an average between 50°F and 100°F.

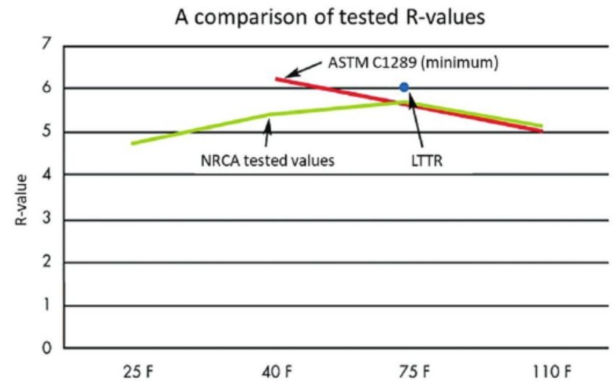


Figure 5 – Mean thermal resistance versus temperature for NRCA test of 16 polyiso samples, average values.

participating manufacturers, shown in *Table 1*, were promulgated.

These minimum LTTR R-values represented about a 7% reduction from prior values but were deemed by PIMA to be based on the best available knowledge at the time as to polyiso thermal drift and its measurement. The PIMA QualityMark™ program requires each manufacturing facility to submit to an annual verification of LTTR values.[17] During verification, independent third-party representatives visit each facility and select a minimum of five boards for testing. The overall process is administered by FM Global.

R-VALUE AND TEMPERATURE

As noted previously, the measurement of R-value requires application of a temperature gradient across a sample of the board, typically 12 x 12 inches. The ASTM C1289 specification requires the gradient to be at least 40°F (22°C); and, in practice, many testing laboratories use a gradient of 50°F (28°C). Therefore, for the purposes of reporting the thermal resistance at 75°F (24°C), the cold side is at 50°F (10°C), while the hot side is at 100°F (38°C).

Importantly, while the thermal resistance is assumed by many to be the actual value at 75°F (24°C), for example, it is actually an average value across a temperature range. If the gradient is 50°F (28°C), then the result is an average between 50°F (10°C) and 100°F (38°C), as indicated in *Figure 4*. As described previously, the thermal resistance of foams is dominated by the thermal conductivity of the cell gas. While gases become less thermally resistant at higher temperatures, the relationship cannot always be assumed to be linear. Phase changes and, in the case of polymer foams, interactions between the cell gases and the polymer matrix can change the expected linear relationship.

The National Roofing Contractors Association (NRCA) reported that testing at mean temperatures of 25°F (-4°C), 40°F (4°C), 75°F (24°C), and 110°F (43°C) suggested that thermal resistance at 25°F (-4°C) and 40°F (4°C) was both lower than suggested in the C1289 specification and showed polyiso to have a lower thermal resistance at low temperatures versus higher temperatures.[18] *Figure 5* shows the NRCA data averaged for the 16 samples investigated. The NRCA data were shown in more detail by the Building Science Corporation (BSC),[19] which noted that the temperature gradient used was 50°F (28°C). Furthermore, BSC tested additional samples and confirmed the general observation that R-values were lower at colder temperatures. A similar observation

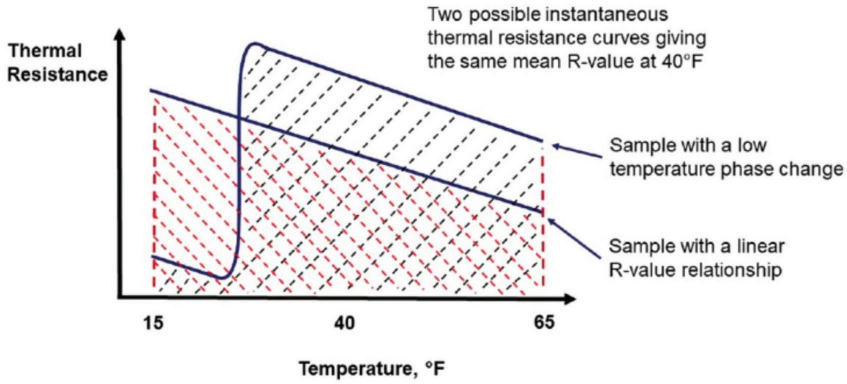


Figure 6 – Two possible instantaneous thermal resistance versus temperature responses that can result in the same reported mean R-value at 40°F (4°C). The hatched areas refer to areas under the curve—mean R-Value being the area under the curves divided by the temperature span (i.e., 50°F [28°C]).

was reported by Schumaker et al.[2] and by Berardi and Naldi.[20] However, the measurements were conducted using typical temperature gradients, and the precise temperature at which R-values begin to fall has not yet been identified. The laser flash method of determining thermal conductivity without applying a thermal gradient[21] has not been used to characterize polyiso to this author's knowledge.

Figure 6 shows two possible instantaneous thermal resistance versus temperature responses that can result in the same apparent mean R-value at 40°F (4°C). These responses represent instantaneous thermal resistance values and not means over a temperature range. The instantaneous R-value at 40°F (4°C) differs between the two curves. However, the mean R-values, calculated as the area under each curve divided by the temperature range (50°F [28°C]), are the same. Until the low-temperature thermal performance of polyiso is fully characterized such that the temperature at which the R-value departs from expected trends is identified, it would be a mistake to change from using existing labeled R-values. If, for example, the R-value departs from the expected trend at 20°F (-7°C), then the existing reported data could be appropriate for most locations. This will be discussed in more detail in the following section.

LOW-TEMPERATURE R-VALUE AND THE BUILDING DESIGNER

PIMA has shown that as a national average, taking into account outdoor summer temperatures for all seven climate zones and an indoor design temperature of 68°F (20°C), mean reference temperatures range between 68 and 76°F (20 and 24°C).[22] Therefore, the labeled R-value, determined at a mean temperature of 75°F (24°C), is a representative value that can be used to compare insulation performance. PIMA similarly showed that taking into account winter temperatures, mean reference temperatures range between 45°F (7°C) and 70°F (21°C). The PIMA data are summarized in *Table 2*, and they suggest that building design professionals designing roofs for ASHRAE climate zones 6 and 7 may need to use the R-value reported for a mean temperature of 40°F (4°C).

An often-overlooked factor in discussions as to which temperature R-value to consider is that of the energy source used for heating. It has been noted that electricity costs are about four times the cost of natural gas on a British Thermal Unit of energy-equivalent basis.[23] Therefore, the building designer needs to consider whether heating or cooling costs are likely to dominate. The various energy sources for heating

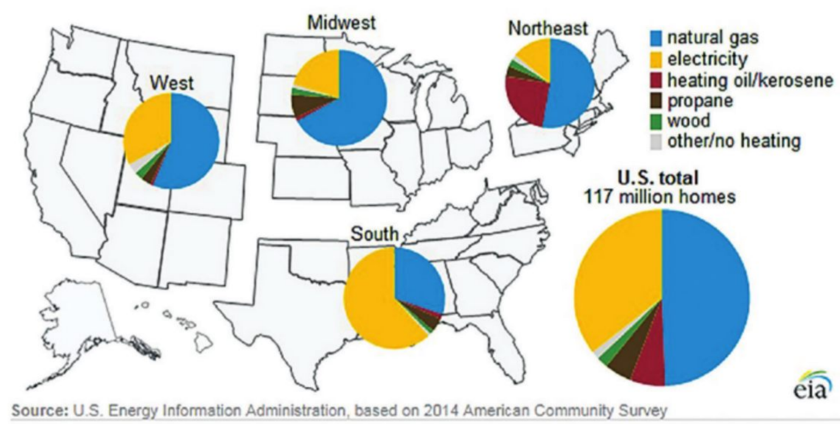


Figure 7 – Share of homes by primary space-heating fuel and census region (source EIA, 2015).

Climate Zone	Outdoor Winter Temperature, °F	Winter Mean Temperature, °F	Outdoor Summer Temperature, °F	Summer Mean Temperature, °F
1	71	70	82	76
2	56	62	82	76
3	49	59	81	75
4	39	54	78	73
5	36	52	68	68
6	28	48	67	68
7	22	45	66	67

Table 2 – Mean reference temperature by ASHRAE climate zone for winter and summer conditions, assuming an indoor design temperature held constant at 68°F (20°C).

Sample #	1	2	3	4	5	6	7	Average	Standard Deviation
R-value, per inch	5.774	5.444	5.371	5.828	5.522	5.889	5.058	5.555	0.297

Table 3 – Full thickness R-value data obtained at 75°F (24°C), from a study sponsored by the NRCA. A total of seven boards were tested.

are shown geographically in *Figure 7*.[24]

Given the doubt about the temperature at which polyiso thermal resistance deviates from the expected trend, the design professional is advised to continue to use labeled R-Values for those projects in zones 6 and 7. It is also noteworthy that polyiso manufacturers are working to convert over to technologies that do not have any low-temperature deviation.

LABELED R-VALUE AND THE BUILDING DESIGNER

Independent testing from limited sampling of polyiso boards obtained through distribution has been used to suggest that R-values may be lower than labeled or LTTR values.[25] The study was sponsored by the NRCA, which obtained seven samples of recently manufactured 2-in.-thick boards by six U.S. manufacturers from job sites. As shown in *Table 3*, the average insulation value was R-5.555, which was below the labeled value of R-5.7.

Based on this and the 40°F (4°C) data, the NRCA recommended that designers use an R-value of 5.0 per inch in heating conditions and 5.6 per inch in cooling conditions. As noted previously, the use of low-temperature average R-values is suspect until the point at which low-temperature R-values' fall is clearly identified. Also, the exact details of the testing have not been fully described. For example, it is well known that polyiso boards continue to cure while warm for several days after manufacture. It is important that boards be sampled from within a bundle and not taken from the top or bottom of a package where curing will not have been complete due to faster cooling of those boards.

An appropriately conservative approach could be to use 40°F (4°C) R-value data supplied by manufacturers for those projects that are going to be located in predominantly cold locations. This should be evaluated on a case-by-case basis, but it would be focused on those projects located in ASHRAE climate zones 6 and 7.

In contrast to the NRCA study, the results of a 2015 PIMA QualityMark™ verification testing are summarized in *Table 4*.

Overall Product Thickness, inch	1	2	3	4
Published LTTR/inch	5.7	5.7	5.8	5.9
Verified LTTR/inch	5.78	5.74	5.85	5.95

Table 4 – Results from the PIMA QualityMark™ Program for 2015. A total of 33 samples were tested for each thickness at a mean temperature of 75°F (24°C).

These values, obtained from a third-party process described previously, are reassuring—especially given the large number of samples involved (33 x 4 = 132). The PIMA QualityMark™ program exists to ensure that member manufacturers are held accountable for producing product that meets label values. If the program functions as intended (i.e., to verify actual monitored LTTR values as compared to published LTTR values, and alerts manufacturers as to discrepancies that need to be corrected), then it could be a mistake to recommend that designers use lower values than those promulgated by the industry through PIMA. Such a recommendation also does a disservice to most of the industry members who meet or exceed labeled values and discourages efforts by others to improve these values.

CONCLUSIONS

1. Thermal conductivity of polyiso, like most other foams, is dominated by the thermal conduction of the cell gases.
2. The thermal resistance of gases is inversely proportional to temperature (i.e., sub-ambient R-values should be higher than those at higher temperatures).
3. Contrary to popular understanding, R-values are reported as an average across a temperature range and do not represent a value at an exact temperature. For example, the reported R-value at 75°F (24°C) is normally measured across a range from 50°F (10°C) to 100°F (38°C) and should be noted as a mean R-value.
4. There is evidence that some polyiso boards produced today have R-values that fall at low temperatures. However, the point at which that occurs is not yet known. Building designers and specifiers are advised to continue to use reported R-values at 40°F (4°C).
5. Results from limited sampling of polyiso boards have suggested that actual R-values can be lower than labeled values for some manufacturers. This is contrary to extensive testing by the industry. IIBEC

REFERENCES

1. Rene Dupuis. "Perspectives From 40 Years in Commercial Roofing." *National Legal Resource Center Conference*. Austin, TX. Sept. 12, 2014.
2. Chris Schumaker, John Straube, Lorne Ricketts, and Graham Finch. "The Effects of Temperature on Insulation Performance: Considerations for Optimizing Wall and Roof Designs." *Proceedings of 31st RCI International Convention and Trade Show*. 2016. pp. 165-173.
3. Federal Trade Commission. Trade Regulation Rule Concerning the Labeling and Advertising of Home Insulation. https://www.ftc.gov/enforcement/rules/rulemaking-regulatory-reform-proceedings/r-value-rule.
4. Leon R. Glicksman and M. Torpey. "Factors Governing Heat Transfer Through Closed Cell Foam Insulation." *Journal of Thermal Insulation*. December 1989. pp. 257-269.
5. Peter Kalinger and Michel Drouin. "Closed Cell Foam Insulations: Resolving the Issue of Thermal Performance." *Interface*. IIBEC, Inc. August 2002. pp. 23-26
6. ASTM C1289, *Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board*. ASTM International. www.astm.org.
7. ASTM C177, Standard *Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*. ASTM International. www.astm.org.

8. ASTM C518, *Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*. ASTM International. www.astm.org.
9. ASTM C1114, *Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus*. ASTM International. www.astm.org.
10. ASTM C1363/C1363M, *Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*. ASTM International, www.astm.org.
11. Sachchida N. Singh and Paul D. Coleman. "Accelerated Aging Test Methods for Predicting the Long Term Thermal Resistance of Closed-Cell Foam Insulation." *Proceedings of the Polyurethanes Technical Conference*. Orlando, FL. Sept. 2007. pp. 266-280.
12. ASTM C1303, *Standard Test Method for Estimating the Long-Term Change in the Thermal Resistance of Unfaced Rigid Closed-Cell Plastic Foams by Slicing and Scaling Under Controlled Laboratory Conditions*. ASTM International. www.astm.org.
13. CAN/ULC-S770, *Standard Test Method for Determination of Long-Term Thermal Resistance of Closed-Cell Thermal Insulation Foams*. Underwriters Laboratories of Canada. https://canada.ul.com/wp-content/uploads/sites/11/2015/02/Standards_Bulletin_2015-02_S770-15_EN.pdf.
14. Mark S. Graham. "Testing LTTR. Research Reveals the LTTR Method May Be Over-Reporting Results." *Professional Roofing*. January 2006. p. 12
15. Mark S. Graham. "New LTTR Values. PIMA Updates Its QualityMark™ Program." *Professional Roofing*. August 2013. p. 12
16. Mark S. Graham. "A Question of Accuracy." *Professional Roofing*. May 2014. pp. 46-50.
17. PIMA Performance Bulletin, Measuring the R-Value of Polyiso Roof Insulation. PIMA. https://www.polyiso.org/resource/resmgr/performance_bulletins/2018/PIMA_PerfBull_MeasureRValue_.pdf.
18. Mark S. Graham. "R-value Concerns. R-Values Are Found to Be Below LTTR." *Professional Roofing*. May 2010. p. 24.
19. BSC Information Sheet 502, Understanding the Temperature Dependence of R-Values for Polyisocyanurate Roof Insulation. Building Science Corporation. https://www.buildingscience.com/file/3455/download?token=O_zsQygM.
20. Umberto Barardi and Matteo Naldi. "The Impact of the Temperature-Dependent Thermal Conductivity of Insulating Materials on the Effective Building Envelope Performance." *Energy and Buildings*. Vol. 144, 2017. pp. 262-275.
21. W.J. Parker, R.J. Jenkins, C.P. Butler, and G.L. Abbott. "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity." *Journal of Applied Physics*. Vol. 32, 1961. p. 1679.
22. PIMA Report. "Thermal Resistance and Mean Temperature: A Report for Building Design Professionals." PIMA. July 6, 2015.
23. Thomas J. Taylor and Christian Hartwig. "Cool Roof Use in Commercial Buildings in the United States: An Energy Cost Analysis." *ASHRAE Transactions*. Volume 124, Part 1. 2018. pp. 88-95.
24. U.S. Energy Information Administration. "Share of Homes by Primary Space-heating Fuel and Census Region." *American Community Survey*. 2014. https://www.eia.gov/todayinenergy/detail.php?id=23232.
25. Mark S. Graham. "Testing R-Values. Polyisocyanurate's R-values Are Found to Be Less Than Their LTTR Values." *Professional Roofing*. March 2015. p. 14.


Tom Taylor

Tom Taylor is an advisor in the Building and Roofing Science Group for GAF, of which he was previously the executive director. He is experienced at evaluating the relationships between individual roofing materials and the overall roof system and building enclosure performance. He is a frequent presenter at industry meetings and has over 20 years' experience in the industry, working for manufacturing organizations in a variety of product development roles. He received his PhD in chemistry and holds approximately 35 patents.