As you know, roofs represent large portions of low-slope building envelopes. And in light of declining energy resources, escalating energy costs and increasing concerns regarding climate change, roof systems' effects on energy consumption and environmental control are becoming increasingly important.

Heat flow through roof assemblies is impeded by exterior and interior air films, roof decks, thermal insulation and cover boards. A roof system's thermal performance is evaluated based on its steady-state thermal resistance, which is the ratio of the surface-to-surface temperature difference across the roof to the heat flow through the roof. Within a roof assembly, the single component that provides the greatest resistance to heat flow is thermal insulation. Therefore, the current and most effective way to reduce building energy demand through a roof system is via the effective use of insulating materials.

Background

The North American roof insulation market has evolved during the previous decades, developing insulation with R-values ranging from R-1 per inch to R-60 per inch. Apart from providing thermal resistance, roof insulation has expanded to fire protection, sound reduction, wind-uplift resistance, drainage and as a surface for installing waterproofing membranes.

MIND THE GAP

by Sudhakar Molleti, Ph.D.

During roof system design, the selection of insulation depends on several factors, such as R-value per inch, dimensional stability, compressive strength, aging of insulation, flexural strength, facer characteristics and moisture performance. At the roof assembly level, equally important are the compatibility of insulation with other roof system components and attachment within the assembly (loose-laid, secured with adhesives or mechanically fastened). Selecting appropriate insulation is a roof system designer's responsibility.

Insulation's thermal resistance referred to as "rated R-value" is reported by manufacturers at a mean temperature of 75 F. This value is obtained from laboratory tests conducted in accordance with ASTM C518, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." From this rated R-value, the amount of insulation required to comply with prescriptive code values can be estimated. The accuracy of such estimates depends on whether the insulation's thermal performance is fully realized.

In low-slope roof systems, insulation materials usually take the form of 4- by 4-foot or 4- by 8-foot rigid boards. As the boards are laid, gaps occur between the boards. These gaps have lower thermal resistance than the insulation itself. If insulation boards were continuous and heat flow one-dimensional, a roof assembly's thermal performance easily could be determined from the one-dimensional U-factor calculation approach. But with the presence of gaps in insulation joints, the heat flow analysis becomes more complicated.

The heat transfer that bypasses the conductive heat transfer between two regions, such as the gaps between the insulation boards, can be referred to as a thermal bypass. In other words, thermal bypass describes heat loss through intentional or unintentional openings in the roof assembly via air, heat and moisture movement.

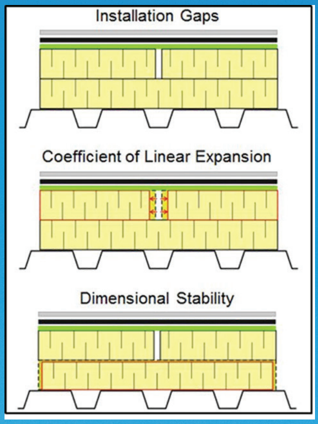
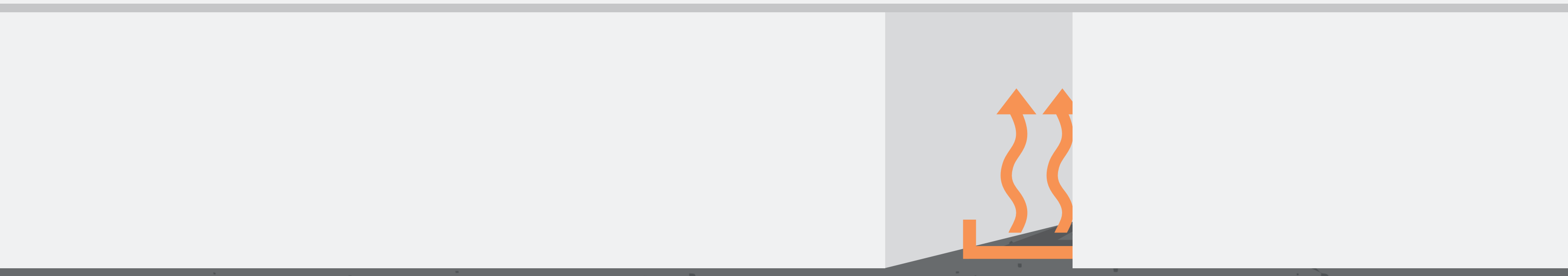


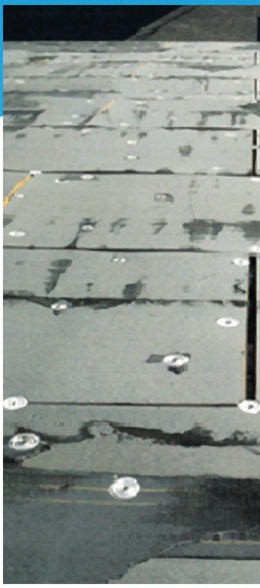
Figure 1: Causes of gap formation

Gaps in insulation joints are an unwanted but often unavoidable fact of life in low-slope roofing. Causes of gaps are listed in Figure 1 and can be attributed to the following:

- Gaps between the insulation boards occur as a result of installation procedures. During construction, it is common to see 1/16- up to 1/4-of-an-inch gaps between boards even though all attempts are made to place boards carefully. Deficiencies in manufactured boards can compound the issue.
- Roof assemblies are subjected to temperature

THERMAL BYPASS OCCURS THROUGH GAPS BETWEEN INSULATION BOARDS IN LOW-SLOPE ROOF ASSEMBLIES





variations, both diurnal and seasonal. Insulation boards will expand or contract under temperature variations depending on a coefficient of expansion. This effect of linear expansion is not permanent as the boards will revert to their initial dimensions when returned to the initial conditions.

- Gap formation also results from the dimensional stability of insulation boards. This is the degree to which a material maintains its original dimensions when subjected to changes in temperature and humidity. Unlike the coefficient of linear expansion, this is permanent deformation.

The gaps

Regardless of whether gaps are formed because of improper installation or panel defects, they are present in a majority of low-slope roof systems. Figure 2 shows in-situ examples of the extent of gap formation.

The effects of gaps on the overall effective R-values of roof assemblies depend on a gap's size, shape and location. There also may be lateral heat flow within a roof assembly (between the deck and insulation) that complicates the overall heat flow pattern. Even if a roof system designer believes a design has addressed the thermal performance requirement, most likely it has not.

Forming a consortium

Building energy codes, such as the International Energy Conservation Code® and the National Energy Code of Canada for Buildings, provide minimum performance requirements for the design of energy-efficient roofs. But none of these have any design considerations for thermal impact factors, namely thermal bridging and bypass. The prescriptive requirements in codes and standards mainly have focused on insulation requirements with limited emphasis on the thermal impact factors and their effect on energy loss. Reasons for the omission could include the absence of data and a lack of clear information demonstrating the significance of thermal bridging and bypass.

To enhance the energy efficiency of low-slope roof systems, the National Research Council Canada developed an industry consortium, Energy Resistance of Commercial Roofs, whose partners include 2001 Company, Waterbury, Conn.; Canadian Roofing Contractors Association; EPS Industry Alliance; International Institute of Building Enclosure Consultants; Natural Resources Canada—Program of Energy Research and Development; NRCA; Rockwool,® Milton, Ontario; Roofing Contractors Association of British Columbia; Sika Sarnafil,® Canton, Mass.; SOPREMA Inc.,® Drummondville, Québec; and TRUFAST,® Bryan, Ohio.

The consortium developed a project that had two major tasks:

- Evaluate the effective thermal resistance of current roof system designs and validate their compliance with energy code requirements using large-scale testing
- Quantify thermal bridging from metal fasteners and thermal bypass from gaps between the insulation boards

Following is an explanation of some of the experimental work conducted at NRC to quantify the implications of thermal bypass occurring because of gaps at the joints between insulation boards.

Setting parameters

When selecting the roof assemblies and components to be evaluated, we had to determine the thermal transmittance of roof assemblies that are designed to comply with the energy codes' prescriptive requirements. A three-step approach achieved this.

In the first step, the prescriptive thermal transmittance requirements for roofs as specified in the National Energy Code of Canada for Buildings and ASHRAE 90.1-2013, "Determination of Energy Savings: Quantitative

Board Thickness	R-25.21	R-30.21	R-35.21
Polyisocyanurate	2 inches + 2½ inches	2 inches + 3⅓ inches	2 inches + 4 inches
Expanded polystyrene	3⅛ inches + 3⅛ inches	3⅞ inches + 3⅞ inches	4⅝ inches + 4⅝ inches
Stone wool	2½ inches + 4 inches	4 inches + 4 inches	5½ inches + 4 inches

Figure 3: Design insulation nominal thickness for achieving respective R-value

Figure 2: Typical examples of gap formations in low-slope roof assemblies. Courtesy of 2001 Company, Waterbury, Conn., and Canadian Roofing Contractors Association.

Analysis," were summarized and consolidated into three categories: R-26, R-31 and R-36. It should be noted R-26, R-31 and R-36 are effective R-values that include outside and inside surface air films. Energy codes require that roof assemblies be designed to meet these minimum effective R-values to attain specific levels of energy efficiency. This design is achieved using R-values of the components measured at a standard average temperature of 75 F.

Next, the consortium's steering committee members selected three common conventional low-slope membrane roof assemblies, including three different conventional insulations: expanded polystyrene, polyisocyanurate and stone wool. Using the insulation R-values per inch provided by the manufacturers, the overall insulation thicknesses (top and bottom layers) for these three design categories were determined by the steering committee as shown in Figure 3.

All the selected assemblies contained two insulation layers. The most common layout for the assemblies installed with two layers of insulation is a configuration where the joints between the insulation boards are not lined up vertically but are in a staggered alignment, referred to as staggered joints. The study's primary focus was to quantify the thermal bypass resulting from gaps at the staggered joints.

To this end, several configurations were tested as summarized in Figure 4. To determine the thermal bypass occurring when the top and bottom joints are isolated from each other, gaps were initiated in a top and bottom joint orientation. In addition, staggered joints were tested to quantify any effect the top and bottom gaps could potentially have on each other. Gaps were introduced at a distance of 24 inches and 6 inches apart.

In summary, two-layer configurations were evaluated for the top gap, bottom gap and staggered gap configurations. Two gap widths, 1/4 of an inch and 1/2 of an inch, in addition to a butted joint with no gap between the insulation boards, were selected by the steering committee members.

Insulation boards can be installed in a single-layer configuration. Although two layers is the recommended practice, it is common to see single-layer installation in some parts of North America with milder climates. In consultation with consortium members, through-gap tests also were carried out on a single-layer insulation layout.

More than 75 experiments were conducted on thermal bypass, and all tests included a steel deck as the structural substrate, fiberglass-faced cover board and thermoplastic membrane as the waterproofing layer.

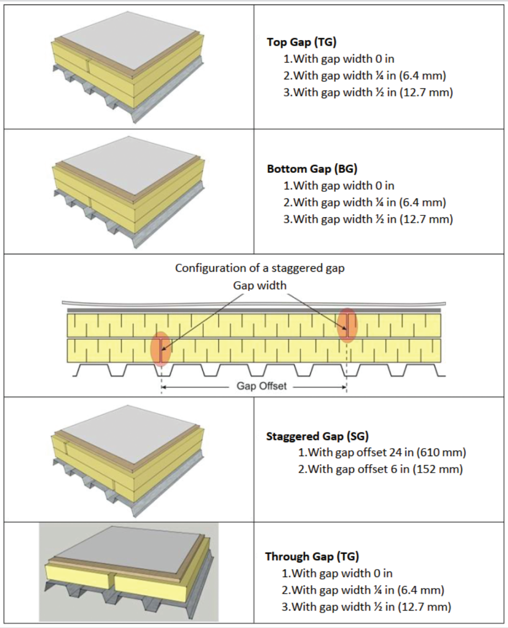


Figure 4: Tested gap configurations

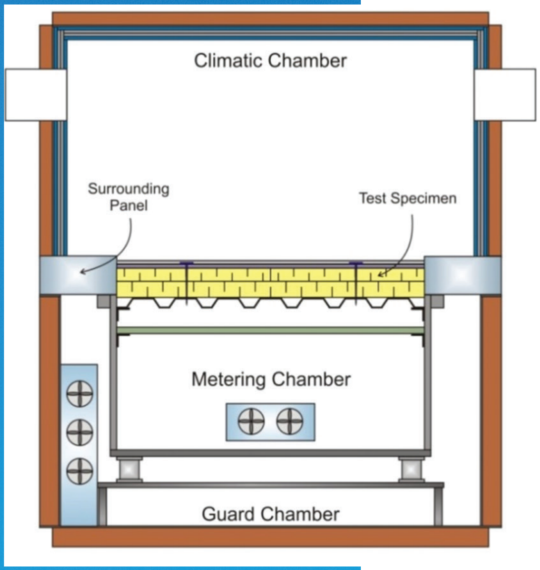


Figure 5: Guarded hot box

Measuring thermal bypass

Evaluating thermal bypass was accomplished using a 4- by 4-foot guarded hot box apparatus. It was designed, constructed and calibrated following ASTM C1363, "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." The testing allows for the isolation of a component from a full-scale roof assembly and the ability to conduct in-depth analysis of the thermal performance of that component and its interaction with other roof components. All experiments were conducted at a mean temperature of 75 F. Figure 5 shows the installation of staggered gap configuration in the guarded hot box.

Gap width and height

To understand the relationship between gap size and insulation thickness, a preliminary series of testing was conducted on R-26 and R-31 assemblies for the three gap configurations: top gap, bottom gap and staggered gap. For the staggered gap, tests were conducted with the gap offset 24 inches. Before we investigated the different gap configurations, experimental testing also was done with insulation butt joints (those boards that were adjoined with zero gap between them). The measured data for these tested configurations were almost identical to the opaque assemblies (the full board of insulation).

The R-31 configuration included 2- and 3⅓-inch-thick insulations as indicated in Figure 3. In the top gap configuration, the gap height was 2 inches, and in the bottom gap, it was 3⅓ inches. The staggered gap configuration is the combination of these two gap heights. In the opaque assembly, the insulation boards are continuous without any gaps.

We made the following observations:

- Effective thermal resistance decreases with increasing gap width.
- Effective thermal resistance also decreases with increasing gap height.
- The combination of gap width and gap height lowers the effective R-value.

The results show the presence of gaps reduced the effective thermal resistance of the R-31 configuration from 3% to 6% depending on the gap features.

To compare the performance of the various tested configurations, the results were normalized by examining the percentage decrease in the effective R-value of the assemblies. It should be noted the results discussed here are a simplified analysis of actual results to show relative effects of thermal bypass and provide a comparison among the different test results. The gaps were developed in a single 4-foot-long joint within a 4- by 4-foot assembly area.

The measured results in Figure 6 indicate the percentage decrease in effective R-value of an assembly is found to be linear with increasing gap height and width. Irrespective of gap position, the effective R-value of an assembly decreased with increasing insulation thickness (or gap height). Similarly, with higher gap widths, the thermal performance showed a decrease in effective R-value. For staggered gaps, the total gap height is equal to the thickness of insulation, and the measured data indicated the data trend remains the same: With increased gap width and height, there is an increase in thermal losses. The decrease in effective thermal resistance was found to be consistent irrespective of the insulation type.

Effect of gap offset

Within the two-layer staggered insulation layout, the effect of the gap offset on the overall thermal performance of the roof assembly also was investigated. Two offsets, 24 inches and 6 inches were evaluated with the R-31 configuration for each insulation type. Figure 3 provides the insulation thickness for each insulation type to achieve the target design value of R-31. During roof system installation, it is common practice to offset insulation board joints in the multilayer insulation layout by 24 inches. The 6-inch offset is the investigative parameter to compare the performance to the 24-inch offset.

Figure 7 shows the relationship between a roof assembly's gap offset and overall thermal performance. Assemblies with the 6-inch gap offset showed an average of 3% lower effective R-value compared with assemblies with the 24-inch offset irrespective of insulation type and gap widths. The measured trend was with increasing gap width, the overall thermal performance of the assembly decreased. The effect of gap height also is visible in the measured data. As gap height increased from 5.3 inches in polyisocyanurate configurations to 8 inches in stone wool configurations, there was a decrease in overall roof assembly thermal performance. The impact of gap height ranged from 4.7% to 6.2% (average of two gap offsets) decrease in the effective R-value with 1⁄4 of an inch gap width and from 6.1% to 8.2% decrease with 1⁄2 of an inch gap width.

Gap impact factor

The gap impact factor is the outcome of all the assembly tests conducted with each insulation type in each design category of R-26, R-31 and R-36, maintaining a constant 24-inch offset between insulation board joints. Once again, it should be noted our results show a simplified analysis applicable to the tested case of a 4-foot-long single joint within a 4- by 4-foot area.

Figure 8 on page 46 summarizes the gap impact factors developed for two gap widths relating the gap height (or insulation thickness) with the effective R-value. The percentage decrease in effective thermal resistance because of gaps was found to be linear, and gap height and gap width were identified as having an effect on thermal performance. In a two-layer insulation layout, the presence of gaps in either the top or bottom layer or both layers decreased the overall thermal performance of the assembly with increasing gap height.

Similarly, with an increase in gap width, there was a decrease in the effective R-value. For example, in a two-layer insulation layout with the top and bottom layers 3 inches each, the presence of a 1⁄2-inch gap in the bottom layer reduced the overall thermal performance of the assembly 4.2%. If the same gap existed in both layers, the effective R-value was lowered 6.5%. With gap height ranging from 2 to 9 1⁄2 inches, a 1⁄4-inch gap width lowered the overall thermal performance of the roof assembly from 2.4% to 6.9% and a 1⁄2-inch gap width led to a thermal bypass of 3.5% to 9.3%.

Through vs. staggered gap

A through gap results when a gap in a single-layer insulation layout develops as a result of scenarios explained in Figure 1. The gap that forms between insulation and

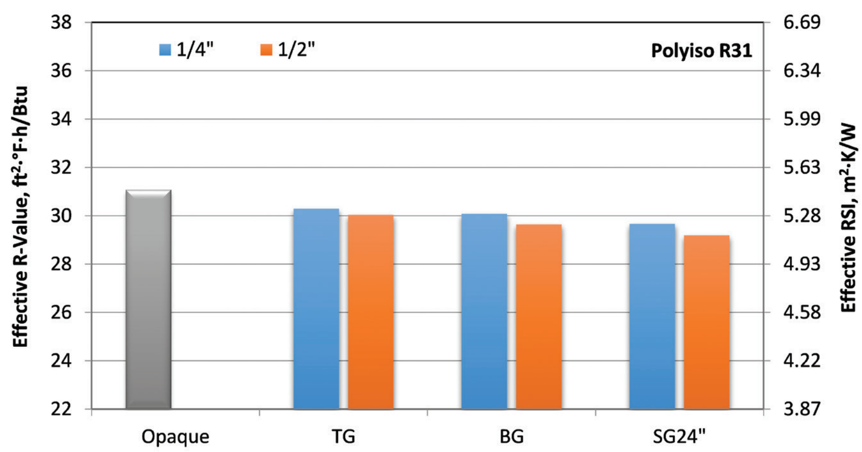


Figure 6: The effective thermal resistance of a roof assembly with gaps between the insulation

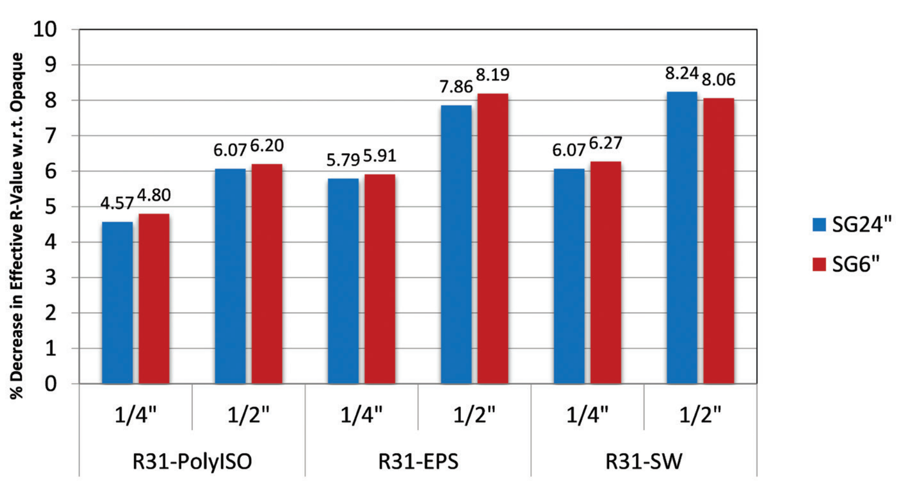


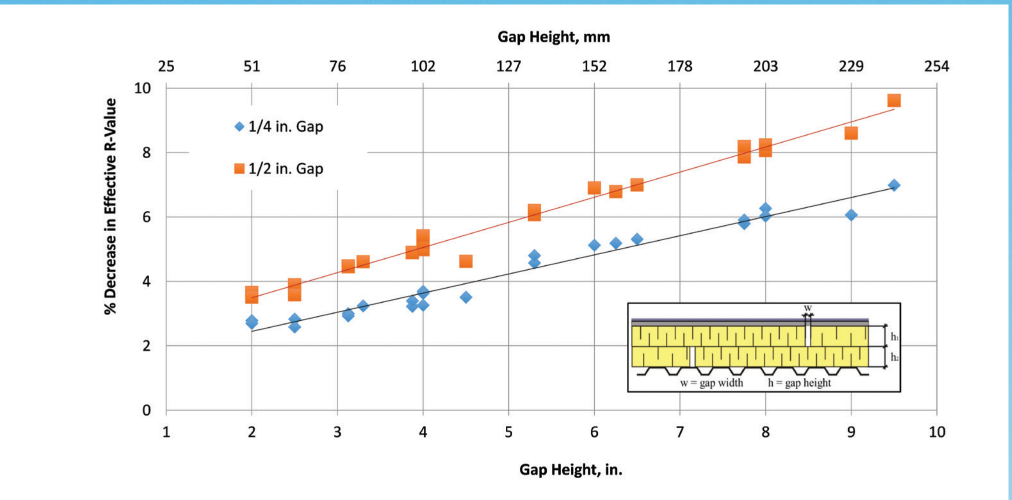
Figure 7: Effect of gap offset in staggered joint configuration

construction details, such as at the expansion joint, parapet (see Figure 2), curbs, drains, etc., also could be considered a through gap. In consultation with consortium members, the through-gap tests were carried out on a single-layer insulation layout with 3⅓-inch-thick polyisocyanurate insulation.

Figure 9 compares the thermal performances of a through gap versus staggered gap. With a ¼-inch-wide through gap in a 3⅓-inch-thick insulation board, there is a drop of 9% in the effective R-value of the roof assembly relative to the opaque assembly without any gaps. If the gap width increased to ½ of an inch, the effective R-value reduced 13.5%. It should be noted this value is specific to a 3⅓-inch-thick gap height, and with increasing gap height, there is potential for higher thermal losses. This is a greater loss in R-value than a staggered gap configuration of a 10-inch gap height.

For a roof assembly of similar thickness with a staggered gap configuration, the percentage loss in effective thermal resistance would be 3.2% and 4.5% for the ¼-inch and ½-inch gap, respectively, as determined from gap impact factors shown in Figure 9. The through gaps result in nearly triple the amount of R-value loss as the staggered gap. Therefore, we recommend two-layer insulation layouts with staggered arrangement be standard practice in the roofing industry.

Figure 9: Gap impact factor



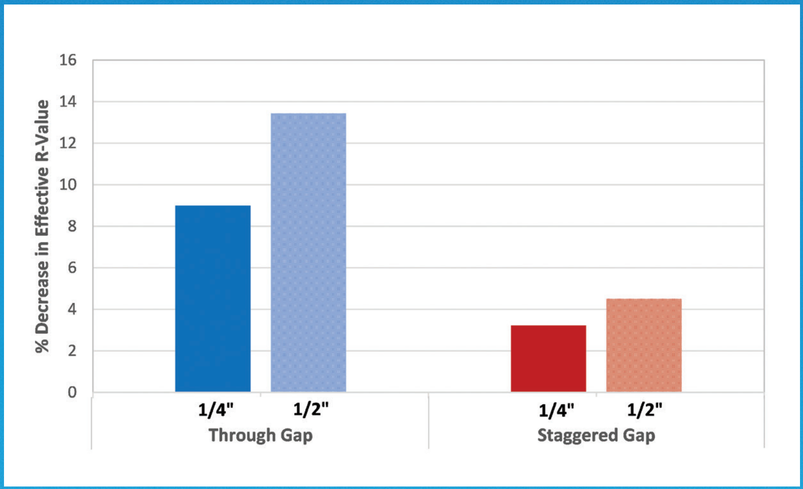


Figure 8: Through gap versus staggered gap percent decrease in effective R-value

Valuable data

In low-slope commercial roofing, the formation of gaps in insulation joints and at construction details is inevitable. The question of how much thermal bypass results at these gaps has never been addressed or quantified. The consortium study examined the significance of gaps between insulation boards and produced the thermal bypass data. Gap height and width were identified to affect a roof assembly's thermal performance.

With increasing gap height, there is a decrease in a roof assembly's effective thermal resistance. A through gap is the worst-case scenario for insulation gaps, and single-layer insulation layouts should be avoided in roof system design. A two-layer staggered insulation layout should be recommended design practice because it can considerably minimize thermal loss in the event of gap formation between insulation boards.

Energy codes are pushing for higher thermal performance values in low-slope roofs, specifically in the form of continuous insulation. The question is: Does thermal bypass in roofs either in the form of gaps in the insulation joints or at the construction details comply with the definition and/or requirements of continuous insulation? And if not, should roof system designers account for thermal bypass during the design stage to comply with the code thermal requirements?

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