Effects of Hail-Caused Dents on the Thermal Performance of Insulation under Single-Ply Roofing

By Steven R. Smith, PE; Robert Danielson, PE; and Cory Hurtubise, EIT

Figure 1. ***Heat flow meter test setup.***

Hail damage evaluations of single-ply roofing membranes present unique challenges. These roofing systems tend to be very hail resistant when the membranes are new; however, single-ply roofing membranes tend to lose strength and become brittle over time as they age.[1] Some membranes can develop anomalies related to weathering effects or mechanical contact that can appear similar to hail-caused conditions. Also, many single-ply systems are installed over mechanically fastened insulation. Roofing membranes can be torn or cut when hailstones strike the membrane over an underlying fastener or fastener stress plate.[2] Hail-caused fractures, tears, or cuts in single-ply roofing membranes can be identified during roof inspections conducted by trained inspectors.

When evaluating the effects of hail on single-ply roofing, another consideration is how hail might have affected the underlying insulation. Given the substantial hail resistance of many single-ply roofing membranes, it is possible for hail to dent the underlying insulation without damaging the roofing membrane. Property owners are often concerned about the effects of hail-caused dents in their roof insulation even when the single-ply membrane is not damaged by hail. The principal concern tends to be the thermal performance of the insulation. The absence of hail-caused damage to the membrane can reassure the property owner that the water-shedding ability of the roof has not been compromised. But will the owner incur noticeable increases in energy bills because the thermal performance of the roof insulation is reduced?

To address this question, Haag Research & Testing Co. (Haag) studied the effects that dents have on the thermal performance of roof insulation. The resistance to heat flow (thermal resistance) of common roof insulations, including polyisocyanurate (polyiso), extruded polystyrene (XPS), expanded polystyrene (EPS), and perlite, were measured in dented and nondented configurations. The thermal resistance of the insulation was then compared to the extent of denting. The research findings are most applicable to single-ply roofing systems because most other roofing types are rigid enough to protect the underlying insulation from being dented by hail.

HEAT FLOW PRIMER

Heat flow is a measure of thermal energy transferred between two bodies due to a difference in temperature.[3] Consider wearing a thick winter jacket on a cold January morning. The coat does not add any heat to your body; rather, it

Table 1. Insulation tested

Insulation	Thickness, in.
Polyiso	1
Polyiso	2
Polyiso	3
XPS	1
XPS	2
EPS	1
EPS	2
Perlite	1
Perlite	2

Note: EPS = expanded polystyrene; polyiso = polyisocyanurate; XPS = extruded polystyrene. 1 in. = 25.4 mm.

reduces the rate of heat transfer from your body to the surrounding air. Remove the coat, and heat rapidly transfers from the warm mass (you) to the cold mass (the air). Insulation under single-ply roofing reduces the rate of heat flow between the roof covering and the roof decking in much the same way. If the space inside the building is conditioned to maintain a constant temperature and the roof temperature is hotter or colder than the conditioned space, then air conditioning or heating equipment is needed to overcome the amount of heat energy transferred into or out of the building through the roof. Heat loss and heat gain also occur through walls, windows, doors, and so on. Infiltration and exfiltration of air through building openings such as doors, windows, and vents also affect heat gain or loss.

Conductive heat flow is the amount of thermal energy transferred through a material due to direct contact driven by differential temperatures across the material. This article focuses solely on the effects of conductive heat flow through the roof insulation.

TEST EQUIPMENT

Haag uses a heat flow meter (HFM) to evaluate the thermal performance of roof insulation and measures the thermal resistance to conductive heat flow (*R*-value). The HFM test chamber is thermally insulated and contains two temperature-controlled plates. Both plates are fitted with heat flow sensors and thermocouples. The upper plate is maintained at a constant higher temperature, and the lower plate is maintained at a constant lower temperature. The insulation sample is placed onto the lower plate within the chamber, and the upper plate is lowered onto the insulation sample. The thickness of the insulation (distance between the two plates) is measured by the HFM. During a test, a thermal equilibrium condition is achieved, and steady-state heat flow through the insulation is measured. **Figure 1** shows the HFM test setup.

The HFM used in this study was a Netzsch Lambda 446, which has a published accuracy of ±1% to 2%.[4] (Note: The trade name is mentioned in the text to specify adequately the experimental procedure and equipment used. Its identification does not imply recommendation or endorsement by IIBEC.) The manufacturer visits the Haag laboratory annually to calibrate this HFM.

R-value measurements made during this research were performed by following ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.*[5] Haag is accredited by the International Accreditation Service (IAS) to perform ASTM C518 testing and is listed as Testing Laboratory 656 (TL-656) by IAS.[6]

TEST PROTOCOL

Insulation was cut to produce specimens measuring 11.8 × 11.8 in. (300 × 300 mm), which is the standard size for the HFM test chamber. Insulation types and thicknesses are summarized in **Table 1**.

HFM plate temperatures were selected in accordance with ASTM C1058, *Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation.*[7] The upper HFM plate was set at 145°F (63°C) and the lower HFM plate was set at 75°F (24°C) to represent the temperature of a hot roof in the summer and the typical air temperature in a conditioned space within a building, respectively.

Heat flow is measured in the HFM within a 4 × 4 in. (100 × 100 mm) region in the center of the test chamber (metered region). A template was used to precisely position a 1-in.-diameter (25-mm) steel ball bearing halfway into the insulation, forming semispherical dents in the insulation. A 4 × 4 in. (100 × 100 mm) grid pattern was made such that 16 symmetrical locations of the insulation within the metered region of the HFM would be dented. A random-number generator was used to select the order in which the locations were dented, and the same pattern was followed for each test run to account for possible variability due to geometric differences. The thermal resistance of the insulation was measured before and after denting. Seven different dent configurations were tested. **Table 2** summarizes these configurations, and **Fig. 2** presents two examples.

Table 2. Dent configurations

Test run	Dents added	Total dents
1	0	0
2	1	1
3	3	4
4	3	7
5	3	10
6	3	13
7	3	16

Figure 2. ***Polyisocyanurate insulation specimens for test run 3 (left) and test run 7 (right).***

Table 3. Equivalent dents per roofing square (SQ)

No. of dents in tested insulation specimen	Equivalent dents per SQ
1	900
4	3600
7	6300
10	9000
13	11,700
16	14,400

Note: SQ = 100 ft^2 (9.3 m^2).

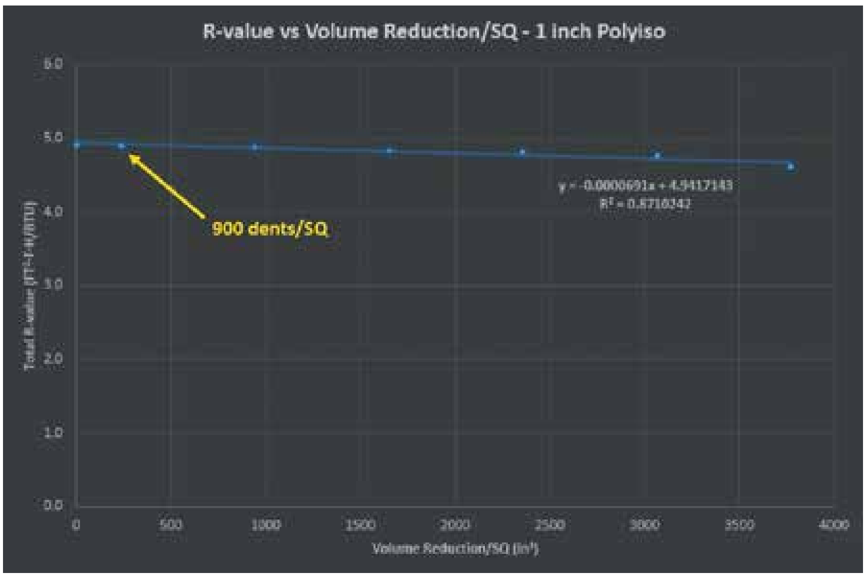

Figure 3. ***Plot of R-value versus volume reduction for 1-in.-thick polyisocyanurate (polyiso) insulation. Note: Although 900 hail-caused dents per roofing square (SQ = 100 ft² [9.3 m²]) is shown on the graph for reference, most hailstorms produce far fewer dents per SQ. 1 in. = 25.4 mm; 1 in.³ = 16,400 mm³.***

TEST RESULTS

The size of the metered region within the HFM is extremely small relative to the size of a roof. To correlate the test results with a meaningful roof measurement, the results were extrapolated to 1 roofing square, which is a standard roofing industry unit of 100 ft^2 (9.3 m^2). **Table 3** provides the number of dents in the tested insulation and the corresponding number of dents in 1 roofing square.

Data analyses revealed the *R*-value of some insulation specimens gradually changed in linear fashion as the number of dents in the insulation increased, whereas the *R*-value of other insulation types remained essentially constant. Because the vast majority of hailstorms dent roof insulation at a frequency much less than 900 dents per roofing square, the data were plotted and analyzed to obtain linear equations that model the effects the dents had on the thermal performance of the insulation. The equations were then used to estimate the effects that lesser dent frequencies would have on the insulation. **Table 4** summarizes the volume of dented insulation (semispherical dents) for 1-in.-diameter (25-mm) dents per roofing square. There was some degree of physical recovery (rebound) after the dents were made, and the extent of rebound varied by insulation type. The dent volume in Table 4 accounts for the initial dent volume without taking rebound into account.

The graph in **Fig. 3** plots the total *R*-value of 1-in.-thick (25-mm) polyiso insulation versus volume reduction due to denting. Figure 3 illustrates a gradual, linear reduction of *R*-value with increasing volume of 1-in.-diameter dents.

Similar analysis was conducted for each configuration of denting for each insulation type and thickness tested. **Figure 4** is a graph of the results for all four types of 1-in.-thick (25-mm) insulation tested. Measurements were deemed to be statistically significant when measured *R*-values deviated from

Table 4. Volume of 1-in.-diameter dents

Dents per SQ	Volume of dents, in.³
1	0.26
5	1.31
10	2.62
20	5.24
50	13.09
100	26.18

Note: SQ = 100 ft^2 (9.3 m^2).
1 in. = 25.4 mm; 1 in.³ = 16,400 mm³.

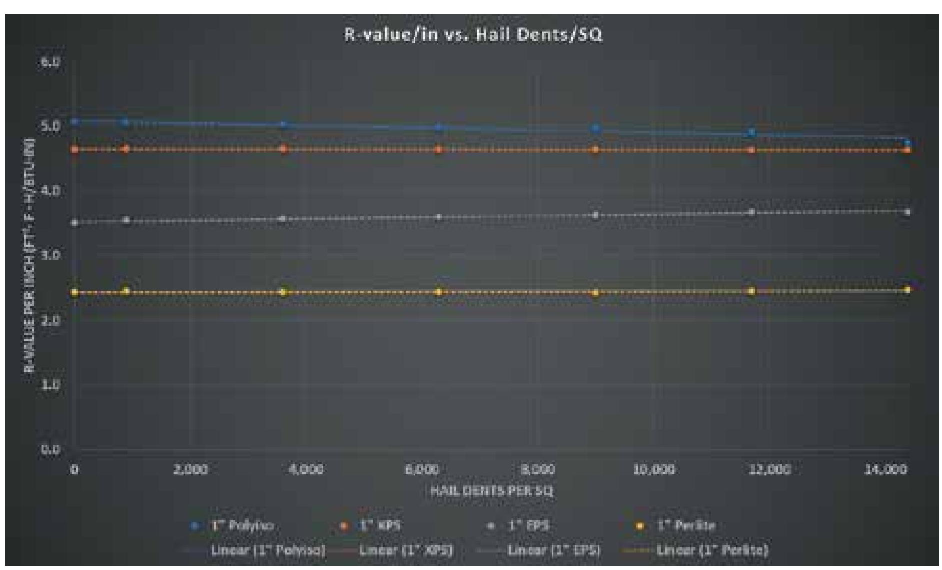

Figure 4. ***Plot of insulation R-values versus hail-caused dents per roofing square (SQ = 100 ft² [9.3 m²]). Note: 1 in. = 25.4 mm.***

the nondented specimens (test run 1) by more than 1%. Note that the plots of *R*-value for XPS and perlite are essentially flat and the changes in *R*-value for these insulations were insignificant. The plot for polyiso insulation has a slight downward slope (as previously shown in Fig. 3), and the plot for EPS has a slight upward slope. Analysis of data for polyiso and EPS insulations showed insignificant changes in *R*-value with four or fewer dents added (3600 dents per roofing square), and small but significant results with more than four dents in the metered region of the HFM. *R*-value measurements of XPS and perlite insulation remained within 1% of the test run 1 values even after test run 7, which represented 14,400 hail-caused dents per roofing square.

A result of particular interest was the slight increases in the *R*-value of EPS insulation as more dents were added. In a part of our research that is outside the scope of this article, we examined EPS insulation under magnification before and after making a dent to better understand any physical changes that occur when EPS insulation is dented. We noted some of the EPS beads developed creases and had slightly separated from adjacent beads. These mechanisms could impede conductive heat transfer between individual beads to some degree, which could explain the slightly higher *R*-values that were measured. Also, the EPS tested was low density and relatively compliant, allowing most of the dent volume to rebound after denting. For this reason, compression of the EPS at the dents did not significantly alter the density of the insulation where dented. **Figure 5** presents micrographs of dented and undented EPS.

Table 5 summarizes the total *R*-value change for each of the tested insulation configurations on a per-dent-volume basis for 1 roofing square of insulation. Although the changes in *R*-value were small, variations in *R*-value on a per-thickness basis for polyiso and EPS insulation varied enough to be significant.

APPLICATION

The data and analysis developed and presented to this point of the study indicated that very small changes in *R*-value were observed for the polyiso and EPS insulation specimens as a function of the dent volume when the dent volume was extreme. Given the miniscule extent of the measured *R*-value changes, the effects of the indentations in the insulation would be essentially inconsequential to the thermal performance of roofs. This conclusion will be illustrated in a number of ways in the paragraphs that follow.

In the event that the insulation under a single-ply membrane roof is dented after a hailstorm, the change of insulation *R*-value can be estimated using the values in Table 5 and performing a thorough inspection of the roof. Hail-caused dents in roof insulation can typically be felt by hand during a roof inspection.[8] Depending on the frequency of the dents, an inspector can locate all of the dents in a roofing square. If dents are very frequent, a smaller sample of the roof can be examined and the total number of dents per roofing square estimated from that sample.

The dent volume can be estimated based on the volume of a semisphere (Eq. [1]).

$$\text{Dent Volume} = \tfrac{2}{3}\pi \cdot r^3 \qquad (1)$$

where r = dent radius, in.

The dent radius for Eq. (1) can be determined in several ways. If the dents are similar in size, the roof can be cut open at a representative dent and the dent diameter measured. If the hail-caused dents substantially vary in size, the diameters of multiple dents can be measured, with the dent volumes computed for each diameter size and then summed together. Alternatively, an average dent diameter can be determined from measurements, and the dent volume estimated based on the average radius.

Once the total dent volume per roofing square is determined, the dent volume can be multiplied by the appropriate value in Table 5 to obtain the total estimated change in *R*-value on a per-square basis. For example, if there were 50 dents per roofing square, each measuring 1 in. (25 mm) in diameter, the estimated dent volume would be 13.09 in.^{3} (214,500 mm^3). If the roof had 3 in. (76 mm) of polyiso insulation, the estimated total *R*-value per roofing square would decrease by 0.001. Based on our test results, 3 in. of polyiso had a nondented *R*-value of 13.467, and 50 hail-caused dents per roofing square would theoretically reduce the *R*-value to 13.466, or a reduction of about 0.007%. An *R*-value change this small would be well within the measurement uncertainty of modern HFM equipment, making the results statistically insignificant.

THERMAL ANALYSIS

Fourier's law describes the rate of conductive heat transfer through a material expressed using Eq. (2).[9]

$$q = \tfrac{k}{s} A \cdot \Delta t \qquad (2)$$

where

q = heat transfer rate
k = thermal conductivity of the material
s = thickness of the material
A = heat transfer area
Δt = temperature difference across the material

The *R*-value of a material is inversely proportional to its thermal conductivity. The total *R*-value of the insulation is the *R*-value on a per-inch basis multiplied by the overall thickness of the insulation. If multiple insulation types are

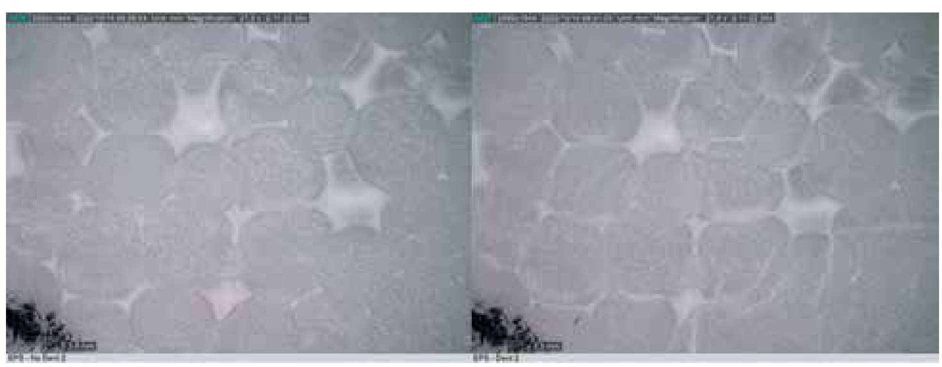

Figure 5. ***Expanded polystyrene (EPS) specimens: undented (left) and dented (right).***

Table 5. Total *R*-value change per SQ by dent volume

Insulation	Thickness, in.	*R*-value Change/in.^{3}
Polyiso	1	-0.0000691
	2	-0.0000732
	3	-0.0000857
EPS	1	0.0000337
	2	0.0000291
XPS, perlite	1	insignificant
	2	insignificant

Note: SQ = roofing square = 100 ft^2 (9.3 m^2). EPS = expanded polystyrene; polyiso = polyisocyanurate; XPS = extruded polystyrene. 1 in. = 2.5 cm; 1 in.^{3} = 16.4 cm^3.

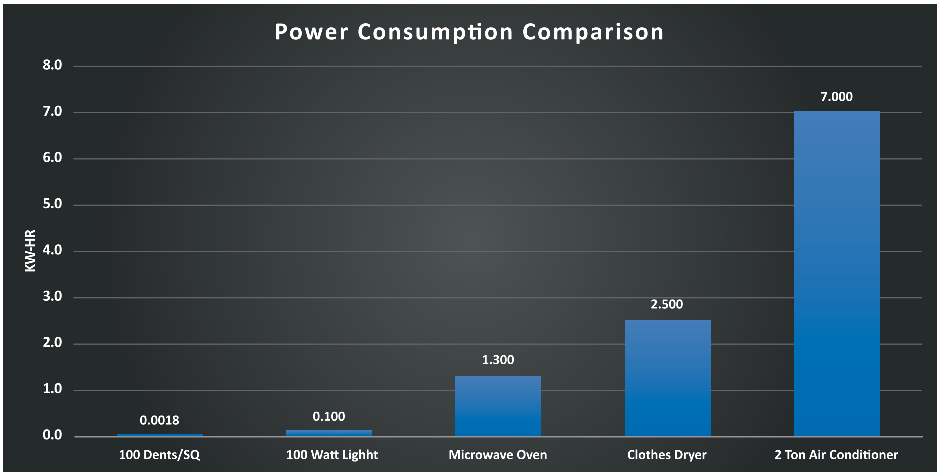

Figure 6. ***Power consumption comparison: hail-dented roofing square (SQ = 100 ft^2 [9.3 m^2]) versus selected appliances.***

Table 6. Number of dents to reduce *R*-value of 3-in.-thick polyisocyanurate insulation by 0.5

Dent diameter, in.	Required dents/SQ
1	22,286
1.25	11,411
1.5	6604
1.75	4159
2	2786

Note: SQ = roofing square = 100 ft^2 (9.3 m^2). 1 in. = 2.54 cm.

present in the roof system, the total *R*-value of each insulation type must be determined separately and then summed together to compute the total *R*-value of the system.

Fourier's law can also be expressed on a per-roofing-square (SQ) basis by using the total *R*-value and substituting 100 ft^2 for the heat transfer area, as shown in Eq. (3a). The same equation expressed in metric units is shown in Eq. (3b). When using Eq. (3a) or (3b), it is important to note the standard imperial units of *R*-value are ft^2•°F•h/BTU and the metric units are m^2•°K/W.

$$q/SQ = 100/Total\ R\text{-}value \cdot \Delta t \quad (3a)$$
$$q/m^2 = 9.3/Total\ R\text{-}value \cdot \Delta t \quad (3b)$$

Because roof insulation reduces the conductive heat flow between the roof surface and the building interior, a significant reduction in the insulation *R*-value can result in a significant increase in the heat transfer into or out of the building. To determine whether hail-caused dents in roof insulation resulted in a significant increase in the overall heat flow, the heat flow rates before and after the insulation was dented by hail must be computed and then compared.

As an example, we can evaluate a 10,000 ft^2 (930 m^2) roof having 3 in. (76 mm) of polyiso insulation that receives 100 1-in.-diameter (25-mm) dents per roofing square after a hailstorm. From Table 4, the reduction of insulation volume due to denting is computed to be 26.18 in.^{3} (429,000 mm^3) From Table 5, the total *R*-value reduction is estimated to be −0.0022 (26.18 × −0.0000857). Consequently, the total *R*-value of the system would be reduced from about 13.467 to about 13.465 after denting. This reduction is less than 0.02% and sufficiently insignificant that it is unmeasurable by modern HFM equipment. The *International Energy Conservation Code*[10] specifies *R*-values of roof insulation to the nearest whole number. Consequently, reducing the *R*-value by 0.02% will not influence whether the insulation will meet code requirements after the storm. In this example, to reduce the *R*-value by 0.5 (which

If conditions such as solar radiation level, air temperature, and wind speed were constant, an equilibrium roof temperature would be attained.

could present possible code-compliance issues), the number of 1-in.-diameter (25-mm) hail-caused dents per roofing square would have to exceed 22,000. In other words, every square inch of the roof would need to be dented.

The roof temperature and building interior temperatures must be determined to examine the effect that the *R*-value change computed in the previous example would have on air-conditioner power consumption. The roof temperature on a hot, sunny day can be measured directly or estimated by knowing the solar reflectance and the thermal emittance of the roof. Solar reflectance is the ratio of solar energy reflected by a surface and the total solar energy onto the surface. Thermal emittance is the ratio of radiant energy emitted by an object compared with that of an ideal black body (a theoretical body having zero reflectance and perfect emittance). The Solar Reflectance Index (SRI) combines solar reflectance and thermal emissivity into a single value, which is often used to rate the thermal performance of roofing products.[11] ASTM E1980, *Standard Practice for calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*,[12] explains how to compute SRI.

If conditions such as solar radiation level, air temperature, and wind speed were constant, an equilibrium roof temperature would be attained. A downloadable spreadsheet tool[13] from the Heat Island Group, Lawrence Berkeley National Laboratory, can be used to compute the equilibrium roof surface temperature based on solar reflectance and thermal emissivity, and compute the SRI from the provided reflectance and emissivity values based on ASTM E1980. The tool assumes a 98°F (36.7°C) outdoor air temperature for the calculation. Many roofing manufacturers publish the reflectivity and emissivity of their products in new and aged conditions. For this example, we will assume an aged, white-colored thermoplastic polyolefin (TPO) roofing membrane with a reflectivity of 0.65 and an emissivity of 0.85. The estimated equilibrium roof temperature with moderate wind convection coefficient is 127.5°F (53.1°C).

Using the roof surface temperature of 127.5°F (53.1°C), and assuming the interior of the building is maintained at 75°F (23.9°C), the temperature difference across the insulation is calculated to be 52.5°F (29.2°C). This result assumes that the insulating effects of the roof decking and all other components in the roof system (apart from insulation) are negligible. Using Eq. (3a) and the example of 100 1-in.-diameter (25-mm) dents per roofing square, the initial heat flow through the insulation is calculated to be 389.84 BTU/hour (114.25 W) per square, and the heat flow through the insulation after it is dented by hail is 389.90 BTU/hour (114.27 W) per square, an increase of 0.06 BTU/hour (0.02 W) per square. The roof size is 100 squares; therefore, the total increase in heat flow through the entire roof due to the hail-caused dents is approximately 6 BTU/hour (1.76 W).

To put the magnitude of this estimate into perspective, **Fig. 6** compares the 100 hail-caused dents per roofing square example to the power consumption of several common appliances.[14] Interestingly, operating a single 100-W light bulb for one day would consume about 55 times the energy associated with the increase in thermal energy through the roof due to the hail-caused dents. The hail-related thermal energy increase would be roughly equivalent to having the light bulb on for about 26 minutes a day or running a 2-ton (7-kW) air conditioner for about 22 seconds per day, although these comparisons overestimate the effects of the dents because the roofing square example assumes the roof remains at peak temperature for 24 continuous hours each day.

The procedures discussed previously provide a means to approximate the theoretical change in insulation *R*-value based on testing new roof insulation. In the event roof insulation is dented by an actual hailstorm, the change in insulation *R*-value for the particular roof in question can be determined by taking samples of the insulation and having them tested in a laboratory. A thorough examination of the roof must be performed to estimate the volume of hail-caused dents per roofing square. Following the procedures outlined previously, the approximate loss of *R*-value can be computed to better understand the effects the hail-caused dents had on the thermal performance of the insulation.

Larger hail-caused dents will have a more meaningful effect on the insulation *R*-value than smaller dents of the same frequency. Therefore, we estimated for hail-caused dents of various sizes the number of dents needed to reduce the *R*-value of a roof by 0.5 on a per-square basis, which could have potential effects on energy code compliance issues. **Table 6** summarizes the approximate number of hail-caused dents per roofing square that would theoretically reduce the *R*-value of 3-in.-thick (76-mm) polyiso insulation by 0.5.

It is worth emphasizing that our research focused on dents in insulation that did not rupture the insulation, which could result in a thermal short. Severe hail-caused dents that break through the insulation would need to be evaluated by a laboratory to determine the effects on the insulation in such extreme cases.

CONCLUSION

An extreme amount of hail-caused dents can slightly reduce the *R*-value of polyiso insulation, and the change in *R*-value is linearly proportional to the volume of the dents. A key finding of our study is that, unless an extraordinary amount of the insulation was dented, hail-caused dents would be unlikely to reduce the *R*-value of a roof insulated by polyiso to the point that any meaningful code compliance issues would occur. This conclusion may reassure those practitioners who have concerns that hail indentation of roof insulations has serious deleterious effects on thermal performance.

Another benefit of the study is that it provides a protocol for laboratory testing of hail-dented insulation to determine whether a measurable change in insulation *R*-value has occurred. Our research also showed the *R*-values of XPS and perlite insulations are essentially unaffected by hail-caused dents and the *R*-value of EPS insulation could slightly improve after a hailstorm. If insulation were ruptured by hail, laboratory testing would be necessary to evaluate the impact on the performance of the insulation.

ACKNOWLEDGMENTS

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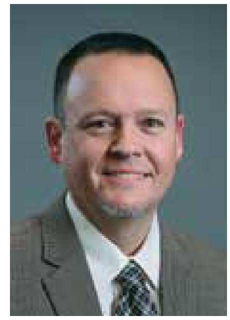
ABOUT THE AUTHORS

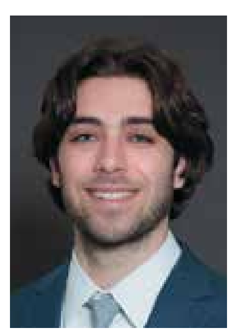


Steven R. Smith, PE

Steven R. Smith, PE, *has a BS in mechanical engineering from the University of Texas at Arlington and is licensed as a professional engineer in six states. Smith has been with Haag Engineering since 1998 and is the director of Haag Research and Testing Co. He has inspected more than 1000 roofs for hail- and wind-caused damage. Smith is a member of the American Society of Mechanical Engineers, the National Roofing Contractors Association, and the Asphalt Roofing Manufacturers Association.*

Robert A. Danielson, PE

Robert A. Danielson, PE, *has a BS in agricultural engineering from Texas A&M University and is licensed as a professional civil engineer in 14 states. Danielson has been with Haag Engineering since 2009. He has inspected more than 1000 roofs for hail- and wind-caused damage. Danielson is a member of the American Society of Agricultural and Biological Engineers and American Society of Civil Engineers.*



Cory Hurtubise, EIT

Cory Hurtubise, EIT, *has a BS in civil engineering from the University of Texas at Arlington and is an Engineer in Training in Texas. He has been with Haag Research & Testing Co. for about five years. Hurtubise has performed hundreds of laboratory tests, including simulated hailstone impact tests, wind simulation tests, R-value tests, product tests, and roofing sample evaluations. He has also contributed to several research papers.*