Evolving Ice Damming Solutions for a Changing Climate

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ABSTRACT

A recently completed mixed-scale residential development in the New England area experienced extensive ice damming at the roof surface during the winter of 2014-2015 that resulted in large ice formations and water entry.

Roofs are designed to withstand a certain amount of snow load and anticipate an average amount of snowfall each year. Industry standards and code regulations have been developed for general ice dam protection. In sloped roof assemblies, ice dams can occur under a variety of conditions. In winter months, warm air can leak from the interior to the exterior at locations like roof penetrations or roof-to-wall interfaces which can cause snow melt. Snow can also be melted by heat transferred from the interior to the exterior through conduction in addition to the melting that occurs from the sun's radiation.

With enough snow accumulation, snow will provide more resistance to heat transfer and will shade the roof surface from solar radiation to the point at which the predominant cause of melting is conduction rather than the sun's radiation. This, in combination with below freezing air temperatures, can enhance ice dam formation. Thermal analysis software was used to determine the point at which snow reaches an insulative value great enough to allow the roof surface temperature to reach 32 degrees Fahrenheit.

The presence of snow build-up in extreme winter weather enhances the ice damming process for longer amounts of time. Given the widespread ice damming issue throughout the New England area during the winter of 2015, the typical roof construction for residential buildings does not appear to protect against ice damming during extreme weather circumstances. The technical paper discusses ice damming fundamentals, how the changing climate may require a different approach to typical roof design and maintenance, and how thermal analysis is able to inform which approach to take.

INTRODUCTION

Despite having been completed in 2012, a residential development in New England experienced roof failure due to ice dam formations during the record-breaking winter of 2014 -2015 with snowfall accumulation totaling up to 3-feet during a single snow event. To an extent, as snow accumulates, the snow will provide more resistance to heat transfer and at the same time, shade the roof surface from solar radiation which, when combined with below freezing air temperatures can enhance ice dam formation. The property has a number of asphalt roof assembly configurations including cathedral ceiling and traditional insulated and ventilated attics. The largest ice dams on the property grew to be several feet in both height and width and were located adjacent to the cathedral ceiling assembly. Many ice dams required extreme removal techniques with the use of backhoes at grade to remove ice build-up in front of garage doors, and chainsaws to cut ice from the roof. While ice damming occurred during the early months of the year in 2015, only minor frosting was recorded on the roof shingles during the winter of 2015-2016. Weather conditions have notable impact on ice dam formation. On sunny days with air temperatures below freezing, solar radiation will intensify the development of ice dams. Cloud cover during the winter months will have a direct correlation to the intensity of the ice dam development over the winter season and may be a factor in why ice damming was more

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intense during the winter of 2014-2015 compared to other years.

The architectural drawings dated April 2012 meet the international residential building code requirements and accepted industry practices for roofing design which protect roofs against the occurrence and effects of ice damming. The development's asphalt roof shingles are shown to be installed over 15 pound asphalt impregnated roofing felt on 5/8th-inch exterior grade OSB sheathing. The roof ridges and valleys are detailed with a self-adhering membrane within the drawing set. This self-adhering membrane offers additional protection against water infiltration and ice build-up at critical building interfaces like ridges, valleys, and roof edges. The drawing set details the self-adhering membrane extending from the roof edge to 3-feet past the line of the exterior wall. This exceeds the code requirements which notes that the self-adhering membrane is to extend 24-inches past the interior surface of the exterior wall. The drawing set also requires self-adhering membrane to be installed 3-feet wide at the roof ridges and valleys. This detailing follows standard manufacturers' recommendations and meets the building code requirements. The drawing set also details a ridge vent at each roof ridge following standard manufacturers' details.

While a self-adhering membrane complying with ASTM Standard D 1970 was required by the design specification in accordance with the building code, a substitute product was installed in its place. During construction, the substitute membrane was not well-adhered and by 2016, was completely de-bonded in some areas which greatly reduced the membrane's performance capabilities. The product does not appear to have the tenacious adhesive layer required to be an effective self-adhering membrane as outlined in ASTM Standard D 1970. In addition, the substitute membrane was not installed per the code-compliant project architectural details or manufacturer's recommendations. At final installation, the membrane only extended 3-feet from the roof edge. Given the large overhangs on the development, this meant that the membrane did not extend 3-feet past the line of the exterior wall, as designed.

ICE DAM DISCUSSION

In order for ice damming to occur, the roof surface must be warm enough to melt snow that has accumulated on the roof. Water from melted snow flows across a roof surface while the snow accumulation offers insulating protection from the cold air temperature. Once the water reaches the edge of the roof, it is exposed to the cold air temperature or to cold roof surfaces that have not been insulated by snow build-up. At this point, water from the melted snow freezes. This cyclical melting and freezing process allows for ice dams to form at the roof edge and build up on the roof surface. Once an ice dam is formed, melted water from snow accumulated on higher roof surfaces continues to freeze at the roof edge which causes the dam to grow larger and at times form icicles. When a lesser amount of snow has collected on the roof, the accumulated snow on the roof surface melts before ice dams can form. Once the ice dams have formed, however, each additional layer of snow increases the risk for ice dam size growth.

Installing the self-adhering membrane where ice dams are more likely to occur, provides waterproofing so that melting water does not enter the building at those locations. A self-adhering membrane with a plastic facer acts as an impermeable waterproofing membrane whereas a roofing felt underlayment will shed water, but is not waterproof. Self-adhering membranes are designed to provide additional waterproofing performance at critical roof interfaces that are susceptible to water infiltration such as along roof ridges, edges, and valleys, and around penetrations. A self-adhering membrane also helps to control air flow, but it is its predominant quality as waterproofing that is the main reason for installing self-adhering membrane in those locations. The plastic facing of many self-adhering membranes can act as an air barrier if detailed so that penetrations through the membrane are sealed. However, air leakage is likely to occur through a roof assembly even with a self-adhering membrane installed on the exterior roof sheathing due to the roofing nails penetrating the membrane. This air leakage also contributes to the formation of ice dams.

At this development, an asphalt-impregnated roofing felt with self-adhering properties was installed at the roof edge. While this product provided water shedding performance, it did not provide waterproofing properties. While the installed membrane provided some protection against water infiltration, ice dams will still form under severe circumstances. As the snow builds up during extreme winter weather, its insulative properties increase. Additionally, the presence of snow accumulation in extreme winter weather allows the ice damming process to continue for longer amounts of time. It has been recorded that numerous properties in the New England area experienced large ice damming issues during the winter of 2014-2015. And so, even if the construction of the roofs at the development had followed the code-compliant design, providing as-designed waterproofing protection against melted snow, it is likely that ice damming still would have occurred.

ANALYSIS

Thermal analysis was performed to determine the conditions at which the roof surface temperature would reach 32°F or above during winter months when snow accumulation is present. When the surface temperature reaches 32°F or above, any snow accumulation has the potential to melt at the roof surface and form ice dams.

The thermal analysis was performed using THERM 7, a 2-dimensional heat transfer modeling software developed by Lawrence Berkeley National Laboratory. THERM illustrates conductive heat transfer through building materials and air temperatures, via a color legend. While the software can represent the effects of conduction, it cannot portray the effects of heat transfer through convection via air leakage. The software also excludes specific heat capacities and solar radiation which impact snow melt. Therefore, the analysis was limited to the impact of heat transfer through conduction. According to historic information provided by the property managers, the ice dams that occurred during the winter of 2014 – 2015 were most severe at certain roof conditions. Therefore, the roof section chosen for analysis represents the location that experienced the most severe ice dam formation. This roof section also has the greatest potential for heat transfer from the interior to the exterior through conduction. With a great amount of snow accumulation, conduction of heat from the interior in combination with the snow's insulative properties is contributing to ice dam formation.

The roof section used in the model is located at the roof valley above third floor units with the cathedral ceilings. A representative photograph of this location is presented in Figure 1 below. At this location, the roof surface is much closer to the interior ceiling surface than other units with occupiable, vented attic space between the interior ceiling and the roof surface. See Figure 2 for a building section comparison between the cathedral ceiling and the traditional attic.

Figure 1 This photo represents the location of the roof section used in the thermal analysis models.

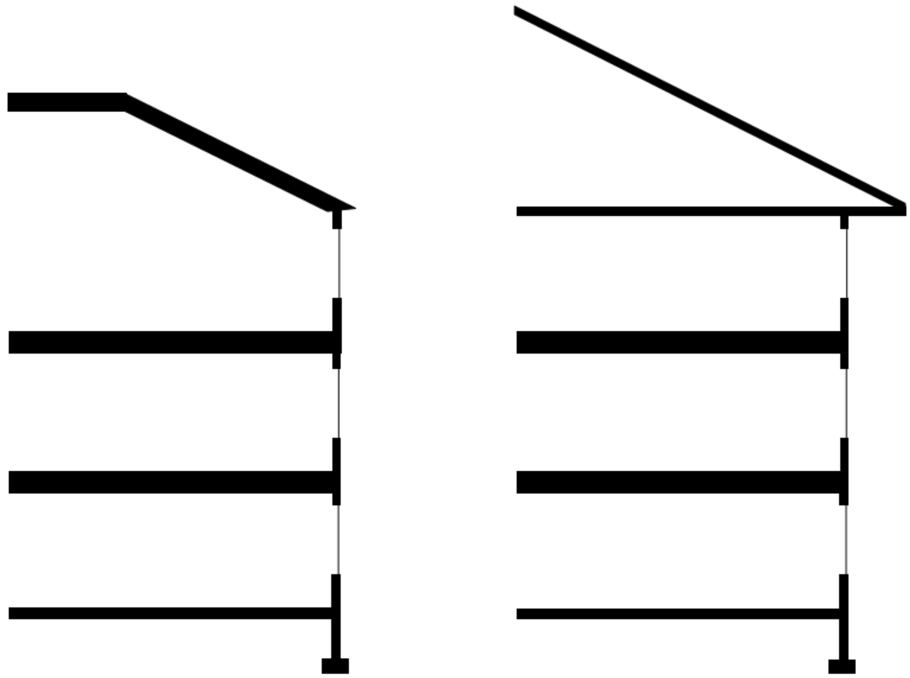

Figure 2 The left section represents the cathedral ceiling configuration and the right section represents the traditional vented attic configuration.

The worst recorded ice damming occurred at the property during January and February 2015. Historic weather data for the New England area gathered during that timeframe shows that the highest air temperature recorded was 57°F and the average air temperature was about 25°F. Exterior air temperatures were included in a series of models that ranged from the ASHRAE 2013 heating design temperature of 8°F to 57°F in order to simulate the conditions that occurred during January and February 2015. These temperatures were represented in the boundary condition assigned to the exterior surface across a series of models. An exterior surface film coefficient aligned for winter conditions of a 15 mph wind was also applied to the exterior condition within the models. The interior boundary condition represents a conservative thermostat set-point value occupants may see as desirable in winter months.

Material properties from the standard THERM database, supplemented with user-generated materials based on published data from several leading manufacturers were used to create the model. Additional materials from WSP's proprietary database of common materials based on values published in the 2013 ASHRAE Handbook – Fundamentals were also used to create the model. The material properties are a unique importance considering the performance differences between "fresh" and "packed" snow, described Table 1 below.

The region where the development is located recorded 64-inches of total snowfall in February 2015. Snow storms occurred in both January and February 2015 in which 24-inches of snow fell during each storm. This data indicated the potential maximum snow accumulation on the roof to include in the models. A series of models were created with a range of snow accumulation between 3- and 24-inches in 3-inch increments as this would more closely represent typical winter conditions. Due to the software's geometric sensitivity to modeling curved edges, the snow was modeled with straight edges. The straight edges also mimic snow accumulation that may occur at rising wall interfaces which is a common interface in the New England region.

In order to more accurately represent the insulative and conductive material properties of snow, snow was modeled in a "packed" and "fresh" state. The outermost 12-inches of snow were modeled as "fresh" snow throughout the models. The remainder of the snow accumulation was modeled as "packed" snow. The conductive properties of "packed" snow is greater than that of "fresh" snow as the air distributed within "fresh" snow, which provides reduction of thermal conductance, is eliminated. Table 1 below provides the assumptions and material properties assigned to the model during thermal analysis.

Table 1. Thermal Conductivity

Model Assembly Material	**Thermal Conductivity Value *k* (Btu/h-ft-°F)**
Fiberglass Insulation	0.0229
Pine Wood	0.0809
Air Cavity Slightly Ventilated (26°F air cavity temp., 12-inches of snow)	0.0139
Air Cavity Slightly Ventilated (40°F air cavity temp., 24- and 64-inches of snow)	0.0158
OSB	0.0537
Fresh Snow	0.0604
Packed Snow	0.2708

Table 1: Thermal conductivity values generated by material properties from the standard THERM database, supplemented with user-generated materials based on published data from several leading manufacturers. Additional materials properties from WSP's proprietary database of common materials based on values published in the 2013 ASHRAE Handbook – Fundamentals.

Infrared Representation of Results. Via a color legend, infrared images illustrate the gradation of building material and air temperatures between the interior and exterior. All images shown in Figure 3 below have an interior boundary condition temperature of 72°F which represents the third floor unit's interior set point temperature.

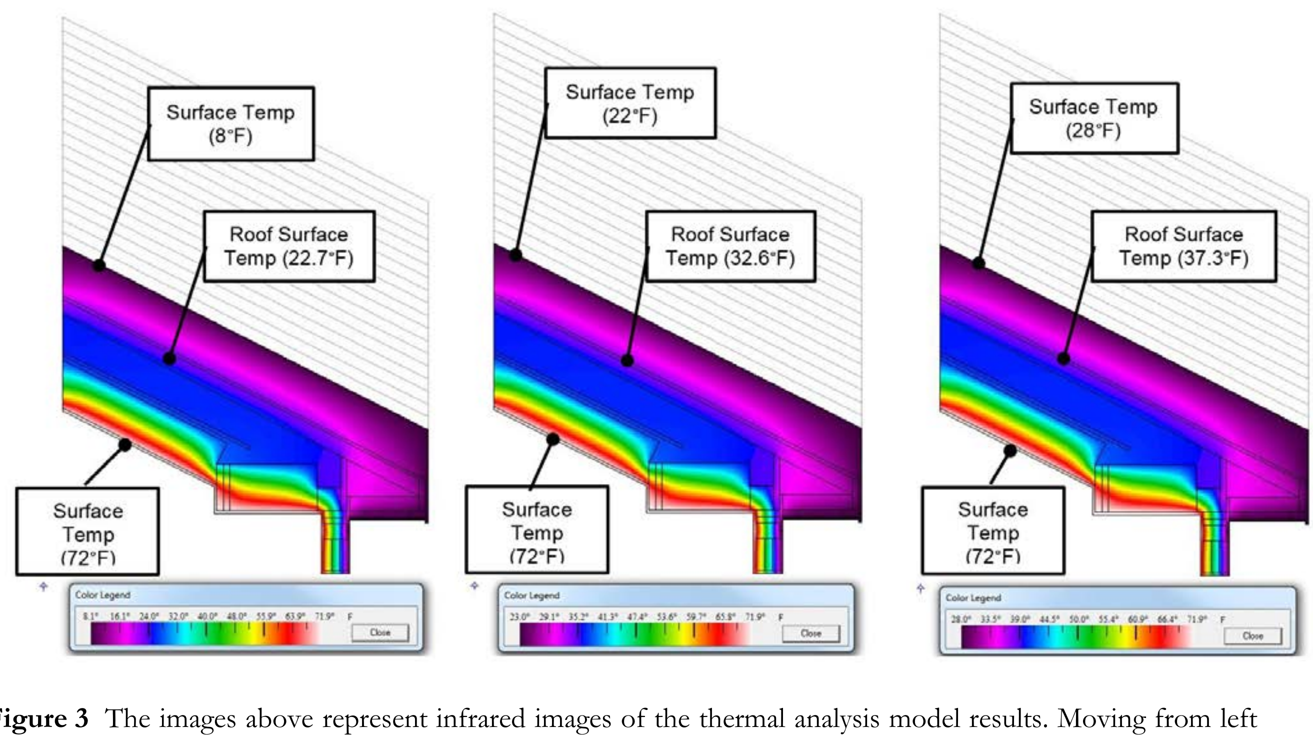

Figure 3 The images above represent infrared images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 12-inches of snow accumulation when exterior temperatures are 8°F, 22°F, and 28°F respectively.

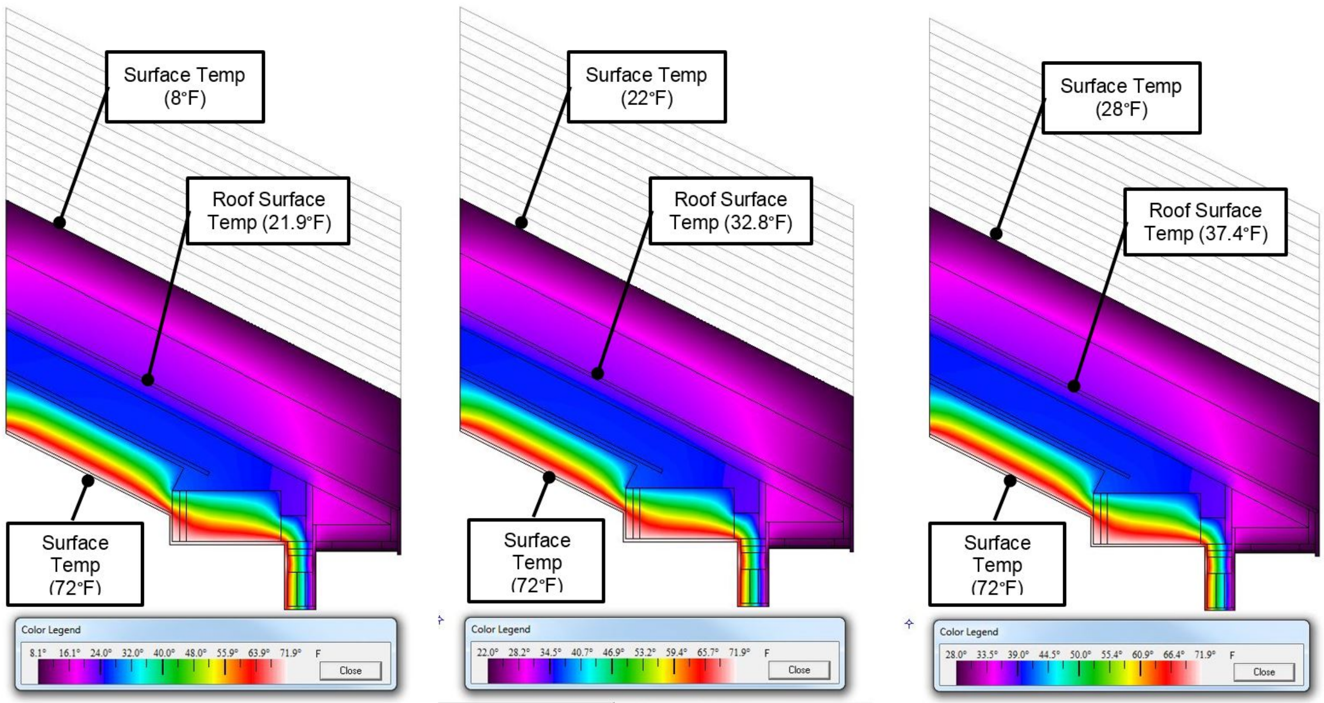

Figure 4 The images above represent infrared images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 24-inches of snow accumulation when exterior temperatures are 8°F, 22°F, and 28°F respectively.

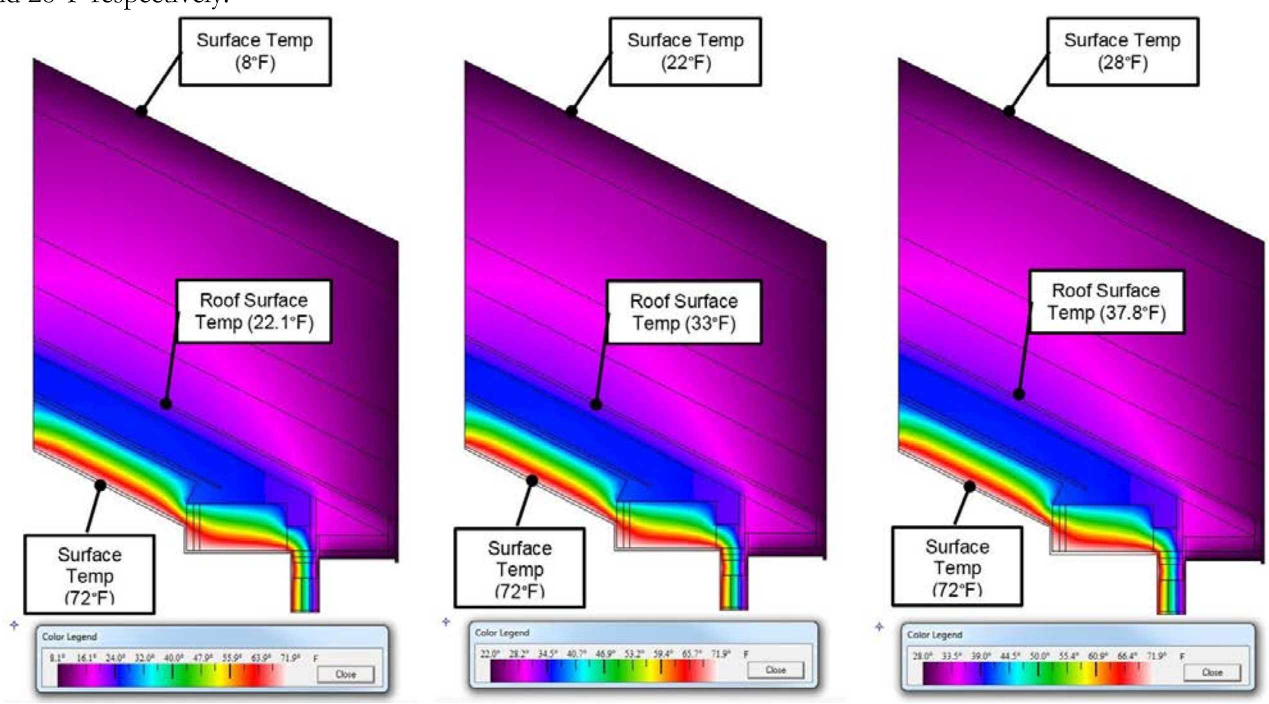

Figure 5 The images above represent infrared images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 64-inches of snow accumulation when exterior temperatures are 8°F,

22°F, and 28°F respectively.

The left-most images in Figures 3 - 5 have an exterior boundary condition temperature of 8°F. The middle images have an exterior boundary condition temperature of 22°F, and the right-most images have an exterior boundary condition temperature of 28°F. These temperatures were chosen as they are a few degrees above and below the average temperature recorded in January and February 2015 in the New England area. Additionally, although snow accumulation is more likely to occur between 25°F and 35°F, cool night-time and day-time temperatures will enhance the freezing and ice damming potential. It is important to note that the results of the models which uses the ASHRAE 2013 heating design temperature of 8°F demonstrate that the roof surface temperature does not reach above 32°F.

Although the color gradient appears to be identical in all three images, the temperature represented by the specific color changes within each image and associated color legend. For example, the light magenta color represents about 16°F in the left-most images and about 33°F in the right-most images. This indicates that the temperature within the roof assembly is increasing as the exterior temperature increases.

Most of the temperature gradation occurs within the insulation at the interior-side of the roof assembly. However, even with 12-inches of snow accumulation on the roof, the roof surface reaches the melting point when the outside temperature is 22°F or above. This implies that at 12-inches of accumulation, the snow closest to the roof surface can begin to melt when the exterior temperature reaches 22°F. These conditions can attribute to the formation of ice dams.

Isotherm Representation of Results. Isotherm images help to illustrate temperature differences within the assembly. The path of an isotherm indicates the line at which a certain temperature is present within an assembly. These diagrams can also illustrate surface temperatures and overall thermal resistance values of assemblies.

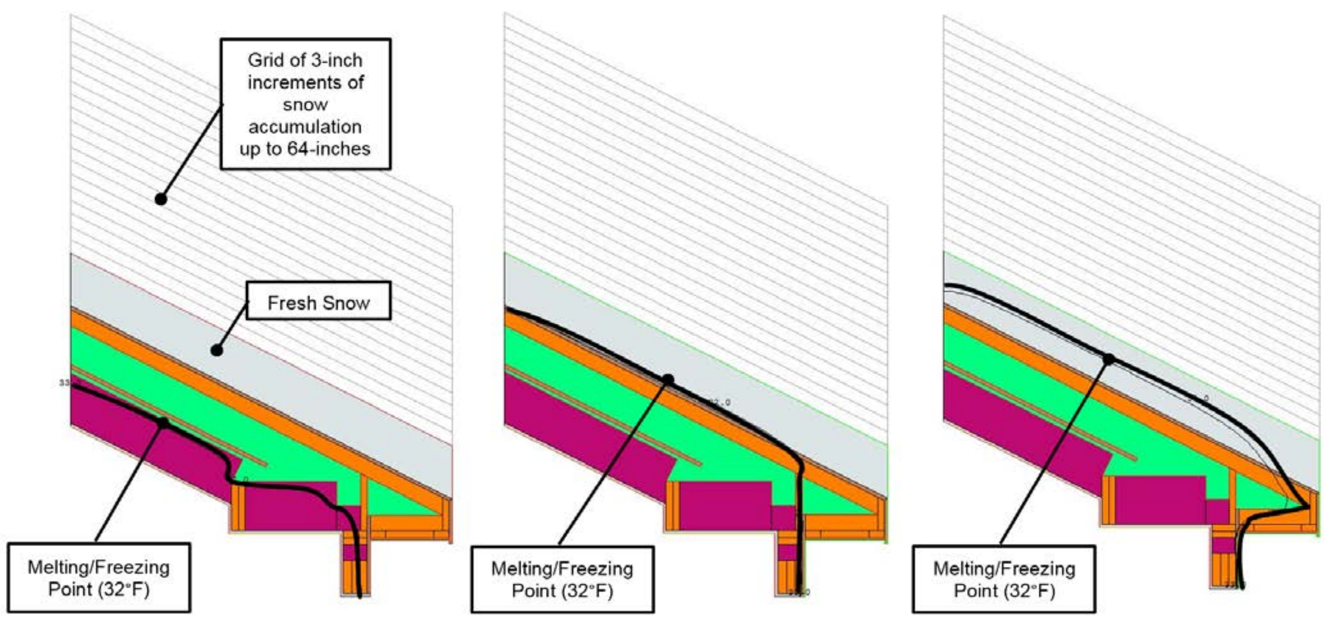

Figure 6 The images above represent Isotherm images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 12-inches of snow accumulation when exterior temperatures are 8°F, 22°F, and 28°F respectively.

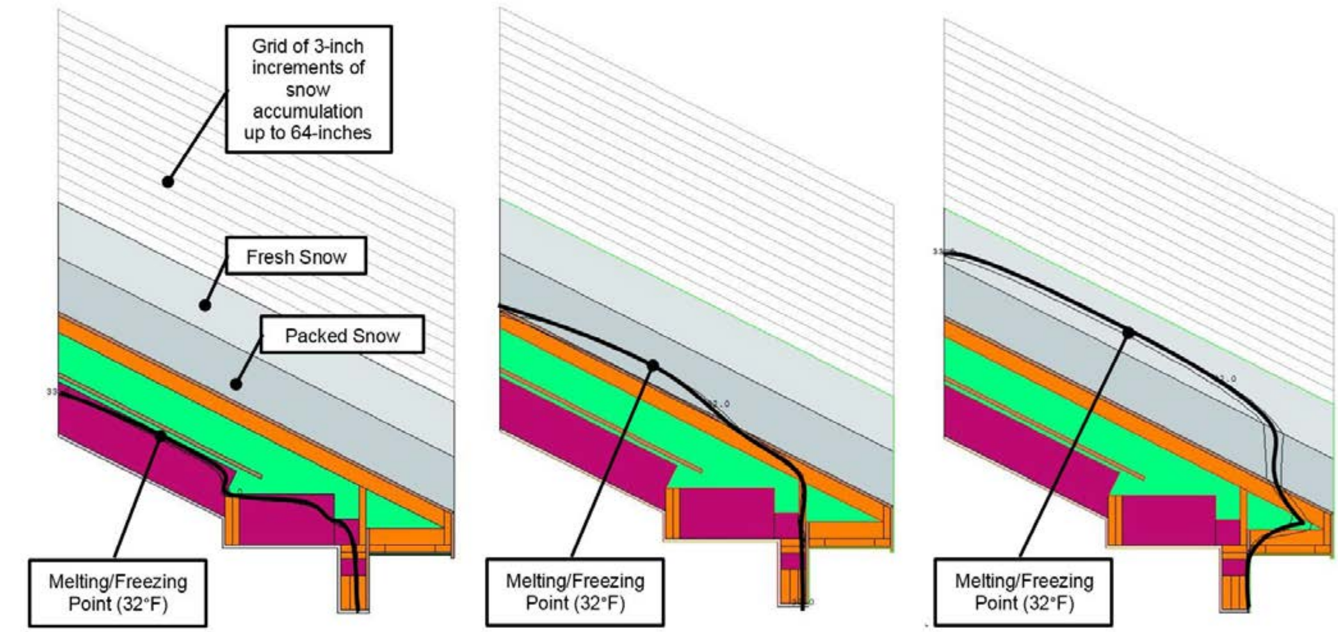

Figure 7 The images above represent Isotherm images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 24-inches of snow accumulation when exterior temperatures are 8°F, 22°F, and 28°F respectively.

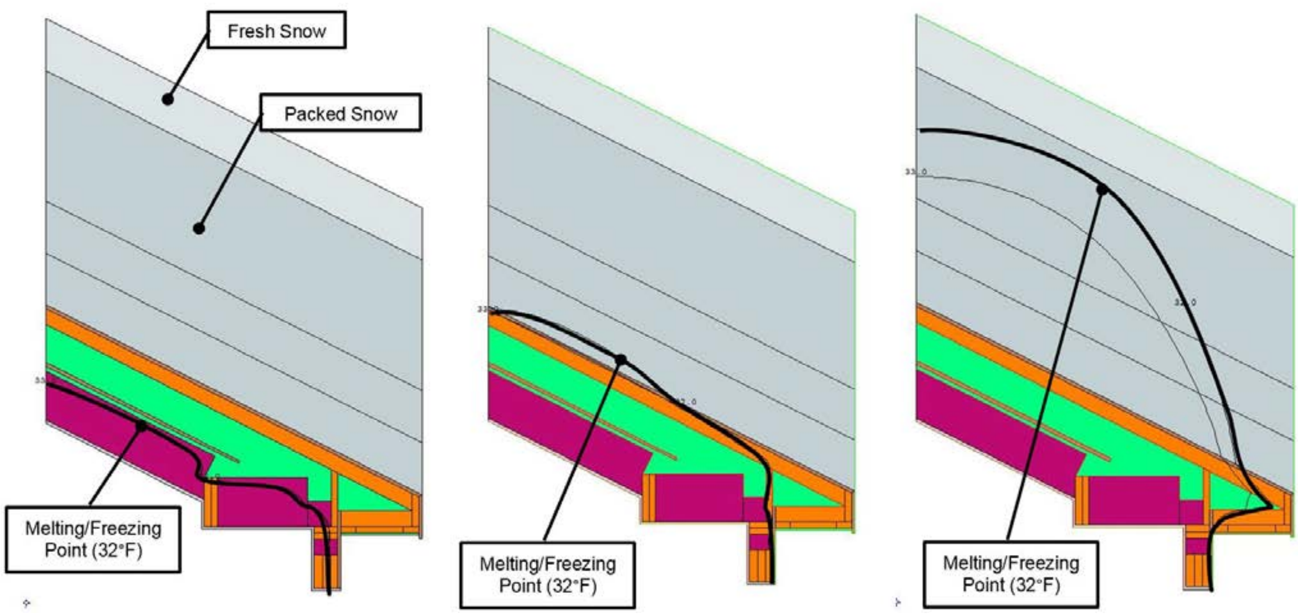

Figure 8 The images above represent Isotherm images of the thermal analysis model results. Moving from left to right, the images represent roof conditions of 64-inches of snow accumulation when exterior temperatures are 8°F, 22°F, and 28°F respectively.

Like in the infrared images, all isotherm images shown in Figures 6 – 8 above have an interior boundary condition temperature of 72°F which represents the third floor unit's interior set point temperature. The left-most images have an exterior boundary condition temperature of 8°F. The middle images have an exterior boundary condition temperature of 22°F, and the right-most images have an exterior boundary condition temperature of 28°F.

The bold line represented in the figures above represents the path of melting point temperature within the assembly. Note how the melting point temperature moves from within the insulation in the left-most images, to the roof surface in the middle images, to within the snow accumulation in the right-most images. This indicates that as the outside temperature increases, the roof surface temperature increases. Any surface below the line at which melting/freezing point occurs is above 32°F. Even with 12-inches of snow accumulation on the roof, the roof surface reaches the melting point when the outside temperature is 22°F or above. This implies that at 12-inches of accumulation, the snow closest to the roof surface can begin to melt by conduction alone when the exterior temperature reaches 22°F. These conditions can attribute to the formation of ice dams. Although attic ventilation at both the cathedral ceiling and the occupiable attic configurations will impact the temperature of the roof surface and will keep the surface at the roof below freezing (many times at a smaller snow accumulation depth), as temperatures at the exterior becomes warmer, the surface temperature will no longer be below freezing and conduction-driven melt will occur.

Heat Flux Representation of Results. Heat flux vector figures illustrate the amount and rate of heat transferred through building materials, which can be helpful to identify potential thermal bridges. The larger the arrows are in length and the greater number of arrows in a concentrated area indicate more heat transfer is occurring at those locations.

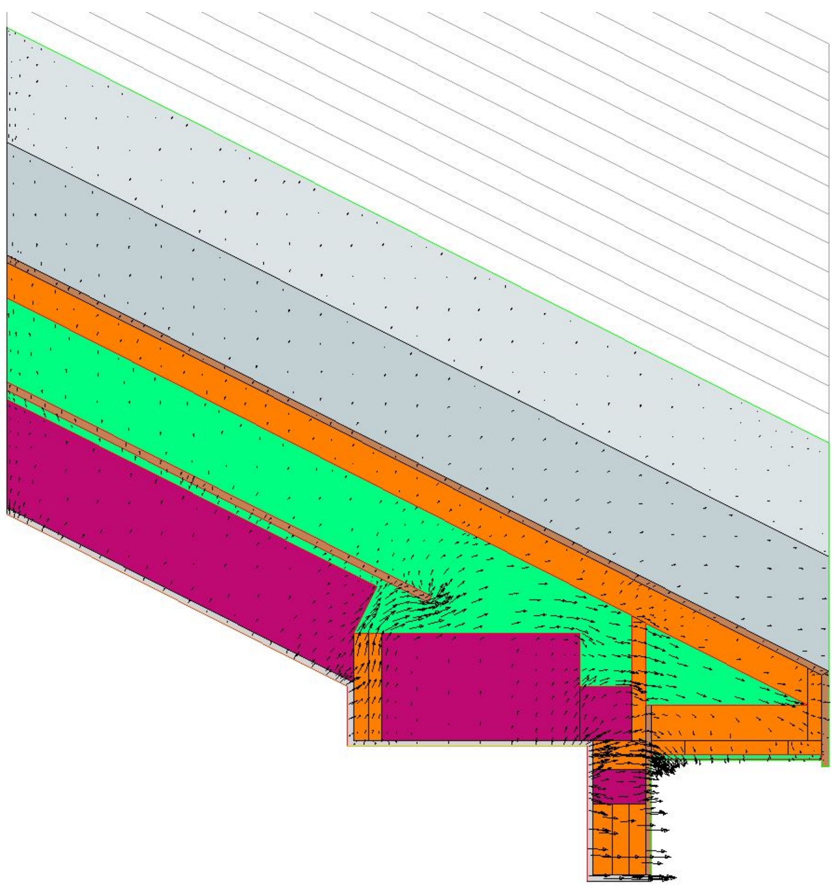

Figure 9 Heat flux vector image with 24-inches of snow accumulation at 22°F exterior temperature. The image above represents typical results achieved by the thermal analysis models.

As indicated by the concentration of vectors shown in Figure 9, heat loss is occurring at the wood trusses within the roof assembly. Although wood is not a highly conductive material (when compared to materials such as metal), it is more conductive than the batt insulation. Even if insulation is added to the underside of the roof surface, there is still risk that conduction through the wood rafters would still drive some degree of ice damming, although it may be less than the current rate of conduction.

RECOMMENDATIONS

Given the widespread ice damming issue throughout the New England area during the winter of 2015, the typical roof construction for residential buildings does not appear to protect against ice damming during extreme weather circumstances. This may require a different approach than typical roof design and repair process. Short term and long term options are outlined below.

Short Term

Short term recommendations include repairing the roof in such a way that it is returned to the design intent. This includes installing a code-compliant self-adhering membrane per the drawing set. Install self-adhering membrane at the roof penetrations for a more robust flashing detail that corresponds with improved manufacturer roofing details instead of what is detailed in the drawing set.

Repair the ridge vents that have been compressed under the weight of previous snowfall, or have been covered by roofing felt below the asphalt shingles, in order to restore natural ventilation. Consider installing additional back slant vents approximately three feet from the roof ridge to enhance natural ventilation.

Consider installing non-combustible insulation around dryer vent pipes. This will help to minimize the zone of influence of the heat given off by the dryer vent. While snow melt will continue to occur in the winter, the zone would be localized to the immediate vent surround. If possible, to avoid any zone of melting occurring on the roof, re-route dryer vents to exhaust on the exterior wall instead of the roof. In addition, once covered by snow on the roof surface, the dryer vents cannot exhaust properly which may increase lint build-up and fire risk. This could be eliminated by exhausting the dryer vents on an exterior wall or by extending the dryer vent pipe without surpassing the allowable vent run by code.

Finally, in an effort to reduce the risk of ice damming occurring under extreme winter conditions, develop operations for an extreme-weather maintenance plan. As noted previously, the greater the snow accumulation and the greater the length of time the accumulation is present, the larger the ice dam. Snow removal may be necessary to reduce the risk of ice damming. The maintenance plan would include the safe removal of snow build-up after it reaches a certain depth. In order to ensure a safe removal process, new roof tie offs will likely need to be installed and identified on plans provided to those performing maintenance; a firm certified in ice dam removal should be used and the roofing product manufacturer should be contacted for guidance on snow removal.

Table 2 below indicates roof surface temperatures given certain inches of snow accumulation on the roof surface and certain outside air temperatures. The temperatures in red are temperatures where the roof surface is above the freezing point. Remove the snow before the conditions create a roof surface temperature above 32°F. However, regardless of snow removal for ice damming concerns, snow accumulation should not exceed the designed snow load for the roof. Following the temperatures represented in the table, Figure 10 graphically indicates the conditions at which snow removal is required at the roof surface in order to reduce the risk of ice dam formation. In Figure 10, the change in the graph slope at 15-inches is associated with the change in material properties from 12-inches of fresh snow to a combination of fresh and packed snow (3-inches fresh, 12-inches packed).

Table 2. Temperature (°F) of Roof Surface at Cathedral Ceiling Valley

Inches of Snow Accumulation on Roof Surface	**Outside Air Temperature (°F)**													
	8	18	19	20	21	22	23	24	25	26	27	28	29	57
64” (52” packed 12” fresh)	22.1	29.9	30.6	31.4	32.2	33	33.8	34.5	35	36.4	36.6	37.8	38.6	60.3
24” (12” packed, 12” fresh)	21.9	29.6	30.4	31.1	32.7	32.8	33.5	34.3	35.1	36.5	37.3	37.4	38.2	60.2
21” (12” packed, 9” fresh)	20.4	28.4	29.2	30	30.8	31.6	32.4	33.2	34	34.9	35.7	36.4	37.2	59.9
18” (12” packed, 6” fresh)	18.5	26.8	27.6	28.5	29.3	30.1	31	31.8	32.6	33.5	34.3	35.2	36	59.4
15” (12” packed, 3” fresh)	16.1	24.7	25.6	26.5	27.3	28.2	29.1	29.9	30.8	31.7	32.6	33.5	34.3	58.9
12” (fresh)	22.7	29.5	30.3	31	31.8	32.6	33.4	34.2	35	35.7	36.5	37.3	38.1	60.4
9” (fresh)	19.5	27.6	28.4	29.2	30.1	30.9	31.7	32.5	33.3	34.2	35	35.8	37.4	59.7
6” (fresh)	16.7	25.3	26.1	27	27.9	28.8	29.6	30.5	31.3	32.2	33.1	33.9	34.8	59
3” (fresh)	14.6	22.3	23.2	24.1	25	25.9	26.8	27.8	28.7	29.6	30.6	31.5	32.2	58.2

Table 2 Roof surface temperatures at various conditions generated by author’s analysis (temperatures above 32°F are shown in red).

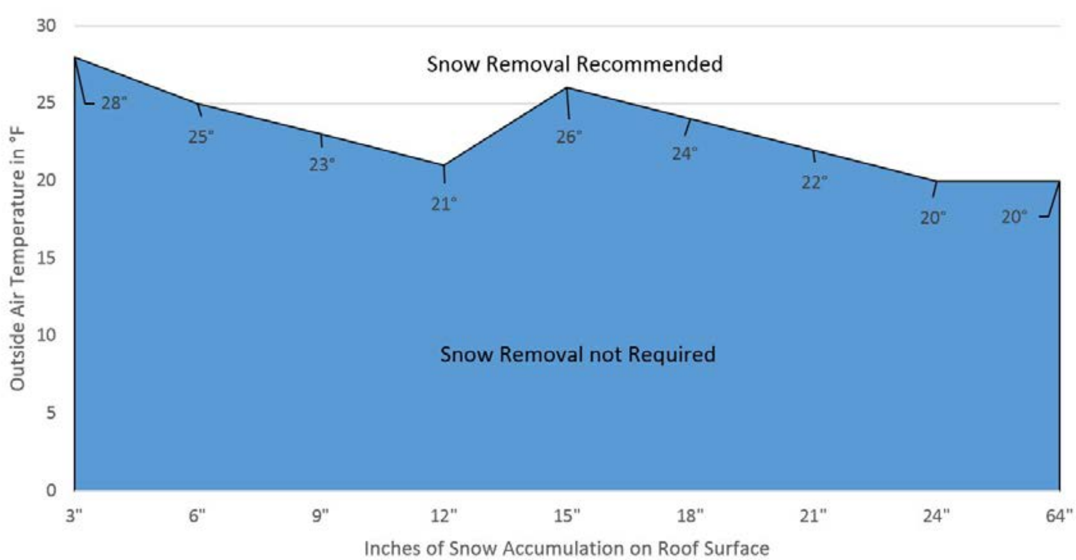

Figure 10 The shaded area above indicates conditions at which roof surface temperature is below 32°F. Consequently, shoveling is not required at these conditions. Once conditions outside the shaded area occur, snow removal is recommended to reduce the risk of ice dam formation as the roof surface temperature is at or below 32°F.

Long Term

In the long term, as the roof covering reaches the end of its useful service life and requires roof replacement, install roofing felt and self-adhering membrane per code requirement and best roofing practices. Upgrade the roof sheathing from an OSB to a kiln-dried pressure treated plywood when sheathing is replaced – note that if the OSB is in good condition, it can remain and only deteriorated sheathing requiring replacement should be upgraded to plywood when replaced. This would improve the performance of the design and allow the roof to exceed industry best practices.

Extensive Long Term

Other considerations include insulating within the attic space below the roof sheathing. This would reduce the amount of heat transfer through the roof structure which would therefore reduce the amount of snow melt. This would also offset the potential imbalance of the snow's insulation value, to an extent, that would occur as snow accumulates on the roof surface. Consider installing insulation that can provide air sealing as well as insulative properties. Also, in order to be most effective, insulation should be installed to encapsulate the roof trusses.

Installing heat trace at the roof edge is often suggested to melt the ice dam formations. While this method would melt both ice and snow, it has the potential to increase the severity of the ice damming process if the snow accumulation provides enough insulation to fuel the ice damming cycle and therefore, is not recommended to be installed.

Finally, one other repair option to consider would be to install insulation on the outboard side of the roof sheathing at the time when the roof shingles are at the end of their useful service life. Continuous, outboard insulation would reduce the amount of heat transfer from the interior through conduction. Outboard insulation is anticipated to provide the greatest benefit to conditions like the cathedral ceiling where the roof assembly is more shallow and currently allows for increased conductivity than the roof assembly with the occupiable attic condition. Provide a ventilated air space between the outboard side of the insulation and a layer of secondary roof sheathing so that the assembly is similar to several manufactured sheathing systems. Install an air-tight roof membrane on the existing roof sheathing which would eliminate air leakage through the roof system. This would lower the risk of snow melt at the roof surface which would, in turn, reduce the risk of ice damming occurring. If this repair option is chosen, run analysis to verify what thickness of insulation should be installed to provide the optimal protection, and insulative values. Once the thickness has been determined, the roof structure would then need to be studied to determine whether the trusses should be reinforced to accommodate the added weight of the insulation and re-roof system. Installing continuous insulation in this way will provide a better-performing long term solution. But in the near term, repairing the roofs to meet the original design with improved snow removal operations process will help resolve the ice damming issues.

CONCLUSION

The findings showed that the roof surface temperature reaches 32°F at certain winter conditions depending on the amount of snow accumulation and the outside air temperature. Once the roof surface reaches about 32°F, the snow closest to the roof surface may begin to melt which could lead to ice damming. Therefore, develop a snow removal plan that would allow the safe removal of snow from the roofs once the conditions, outlined above, are met. For example, if the snow accumulation on the roof is 12-inches deep, shovel the snow when the outside air temperature is above 23°F.

If the self-adhering membrane is replaced, as recommended, it will help to protect the roof from water infiltration that could occur as snow accumulation of 6-inches or less begins to melt. Since the snow accumulation, at 6-inches, is not that deep, there is a greater chance of the entire snow accumulation melting faster than the time it takes ice dams to form. Therefore, water infiltration becomes a bigger concern than ice dam formation. Shovel the roof before the conditions create a roof surface temperature above 32°F. However, regardless of snow removal for ice damming concerns, snow accumulation should not exceed the designed snow load for the roof.

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