Guidelines for Ventilating Attics and Cathedral Ceilings to Avoid Icings at Their Eaves

Wayne N. Tobiasson, P.E. **James S. Buska** **Alan R. Greatorex**

ABSTRACT

Instrumented buildings and cold room studies indicate that the outside design temperature for sizing natural or mechanical ventilation systems to avoid problematic icings at roof eaves should be 22ºF (–5.6ºC). When it is colder outside, ventilating with outside air is increasingly effective, and when it is warmer, icings at eaves seldom grow.

The amount of fresh air needed to minimize icings is related to the size and slope of the roof, the temperature in the heated building below, and the thermal resistance in between.

In big open attics, essentially all of the resistance to airflow is created at inlet and exhaust openings. In cathedral ceilings, the resistance to flow up the narrow airways is also an important consideration.

Design aids are developed to make the task of sizing inlet and exhaust openings and, in the case of cathedral ceilings, the airway height, quick and easy. Recommendations are presented on when and where roof ventilation is necessary to avoid icings.

INTRODUCTION

Buildings in cold regions with roofs that drain to cold eaves may experience ice damming and icicles along their eaves in winter. Water that ponds upslope of ice dams may leak into the building since most steep roofs are configured to shed water—not hold back standing water.

Figure 1 shows two roofs located near Watertown, New York. The two photos of identically constructed buildings were taken within minutes of each other. One roof contains large ice dams and icicles, but the other is ice-free. Why? The snow on top of the chimney of one roof is the clue to the difference in behavior. That building was not being heated, while the other building was at room temperature.

Figure 1 illustrates that building heat—not the sun—is the primary cause of ice dams and icicles on roofs. When the sun melts snow on roofs, it also warms the eaves, and this tends to minimize the growth of icicles. Certainly, icings can form on unheated buildings and from solar heating, but they are usually small, infrequent, and do not cause chronic problems.

CRREL studies of ice damming (Tobiasson et al. 1998, 1999) conclude that a combination of insulation and roof ventilation is the most reliable approach to eliminate chronic

Figure 1 *Two identically constructed roofs photographed at the same time. The one on the right, with no icings, was unheated.*

Wayne N. Tobiasson is a civil engineering consultant and retired volunteer at the U.S. Army Corps of Engineers' Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), Hanover, N.H. **James S. Buska** is a research civil engineer and **Alan R. Greatorex** is a civil engineering technician at CRREL.

problematic ice dam formation. The importance of (1) installing insulation properly so that it is thermally effective and does not block air pathways and (2) providing a continuous air barrier between the living space and the attic are also acknowledged. By instrumenting several buildings with attics at Fort Drum in upstate New York—some with no ice dam problems and others with such problems ranging from minor to severe—guidelines for sizing attic ventilation systems to avoid such problems have been developed. The Fort Drum study (Tobiasson et al. 1998) determined that attic ventilation systems, natural or mechanical, should be sized to keep the underside of the roof below freezing when it is 22ºF (–5.6ºC) outside. When it is colder than that, it is easier to remove heat with outside air since that air is colder. When it is warmer than 22ºF (–5.6ºC), it is unlikely that meltwater will refreeze at eaves.

Fifty-seven buildings at Fort Drum were modified according to these guidelines. Those modifications essentially eliminated the chronic icing problems of the past. Since 1995, many other icing problems have been eliminated in other places using these guidelines. Buska et al. (1998) present some examples including one for a cathedral ceiling. Additional calculations for cathedral ceilings, along with cold room tests that verify those calculations, have also been reported (Tobiasson et al. 1999).

Our mathematical developments in these reports assume that all ventilation is by stack effect. We acknowledge that, at times, wind-induced ventilation can greatly exceed stack-effect ventilation. However, since winds cannot be relied on, we have based our approach on stack-induced ventilation.

Our measurements include the effects of daytime solar loading and nighttime radiational cooling, but our mathematical developments do not. Since our guidelines are solving ice damming problems, these simplifying assumptions appear to be reasonable for our purposes for snow-covered roofs.

Roofs that contain dormers, valleys, and other features that complicate ventilation are prone to ice damming in the vicinity of such features. At such locations, ventilation details deserve extra attention.

One purpose of this paper is to somewhat refine the "attic" calculations and present both the "attic" and "cathedral ceiling" findings in a simple graphical way so that they can be readily used without the need to make calculations. Another purpose is to discuss the counterpoint that insulation and tight construction alone can eliminate icings and, thus, ventilation is not needed.

DESIGN AIDS FOR ATTICS

Figure 2 shows a typical attic with insulation in the flat ceiling below. In this paper, our prior work on attic ventilation has been modified by using an average attic temperature of 27ºF (–2.8ºC), not 30ºF (–1.0ºC). This has been done to be consistent with our more recent cathedral ceiling calculations, which use an average airway temperature of 27ºF (–2.8ºC) based on 22ºF (–5.6ºC) outside air entering along the eaves and the requirement to limit the temperature of the air exhausting at the ridge to 32ºF (0ºC) to prevent melting of snow on the roof. We assume that enough ventilating air must pass through the attic to remove all of the building heat being added by conduction through the ceiling. Since some heat will be lost up through the snow on the roof or through the gable ends of the attic, our answer will call for somewhat more ventilating air than a more rigorous treatment of heat flows would determine.

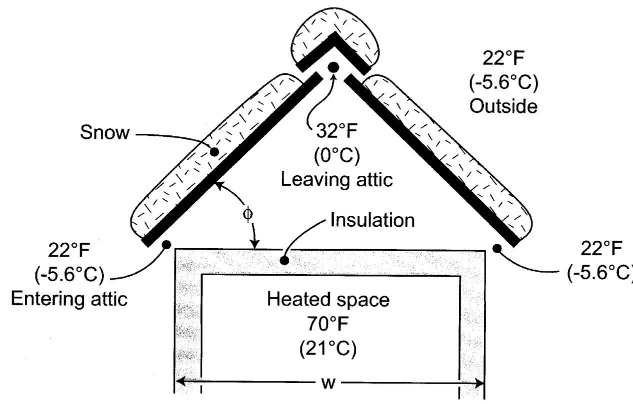

Figure 2 *A typical ventilated attic at the "design" condition.*

When our previous mathematical development for attics is modified to account for the above change in attic temperature, the area of inlets required along the eaves per running foot of attic to allow enough stack-effect ventilation to keep the entire attic below 32ºF (0ºC) is as follows:

$$A_i = 33.28(W/\tan\phi)^{0.5}/R \qquad (1)$$

$$\text{(in SI units, } A_i = 22.18(W/\tan\phi)^{0.5}/R\text{)}$$

where

A_i = net free open area of inlets along the eaves in in.^{2}/running ft (mm^2/running mm) of attic. Note that this is the *total value* for both eaves—half of this would be needed along each side of a typical gable roof. That same *total value* would also be needed for outlets along the ridge.

W = attic width, ft (m).

ϕ = roof slope in degrees. Table 1 relates slope in degrees to slope in inches per foot and provides the tangents and cosines of those slopes.

R = thermal resistance of the ceiling, ft^2·h·ºF/Btu (m^2 K/W).

For example, when a roof has a 3 on 12 (14º) slope, its attic has a width of 30 ft (9.1 m), and its ceiling has a thermal resistance of 25 ft^2·h·ºF/Btu (4.4 m^{2}K/W), the total net free open area of inlets along the eaves (and also the net free open area of outlets along the ridge) would be 33.28 $(30/0.25)^{0.5}/25$ = 14.6 in.^{2}/running ft (in SI units, 22.18 $[9.1/0.25]^{0.5}/4.4$ = 30.4 mm^2/mm). Along each eave

TABLE 1
Information on Roof Slope

Slope (in./ft)	Slope ϕ (degrees)	Tangent ϕ	Cosine ϕ
¼	1.2	0.021	1.000
½	2.4	0.042	0.999
1	4.8	0.083	0.997
2	9.5	0.167	0.986
3	14.0	0.250	0.970
4	18.4	0.333	0.949
5	22.6	0.417	0.923
6	26.6	0.500	0.894
8	33.7	0.667	0.832
10	39.8	0.833	0.768
12	45.0	1.000	0.707
14	49.4	1.167	0.651
16	53.1	1.333	0.600
18	56.3	1.500	0.555

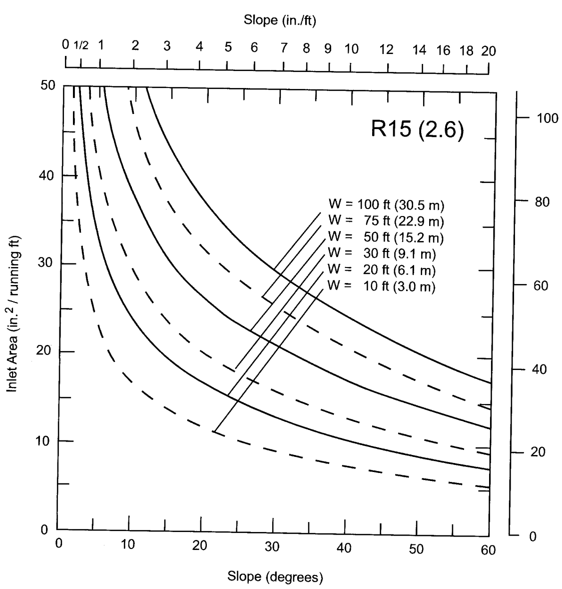

Figure 3 *Net free open area of inlets for attics with R15 (in SI units, R2.6) insulation.*

of the roof, the net free open area of inlets would need to be about 7.3 in^2/running ft (about 15.2 mm^2/mm).

In this example, the total area of inlets and outlets of about 29 in.^{2}/running ft (61 mm^2/mm) is about 1/150 of the attic area. This is double the current "1/300 rule" developed for moisture control in attics, not ice dam prevention. If this attic had more or less insulation, this ratio for ice dam avoidance would change. It would decrease to about 1/240 for R40 (in SI units, R7) and increase to about 1/90 for R15 (in SI units, R2.6). If the roof slope were to change, this ratio would also change. For flatter slopes, ventilation by stack effect diminishes, and much bigger openings are needed to achieve the ventilation necessary.

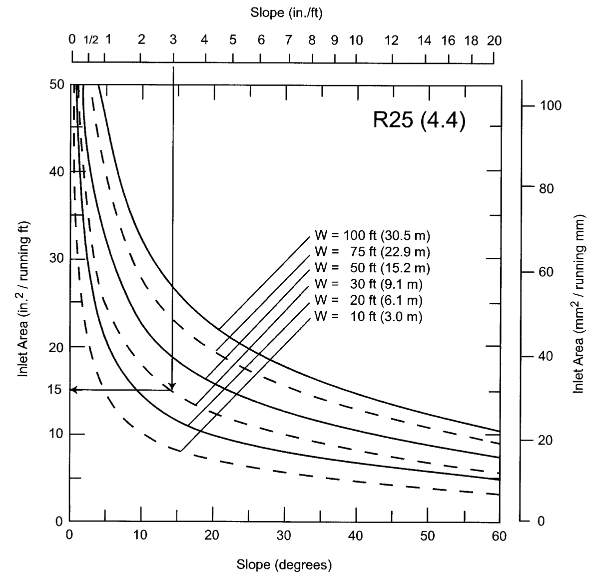

Figure 4 *Net free open area of inlets for attics with R25 (in SI units, R4.4) insulation.*

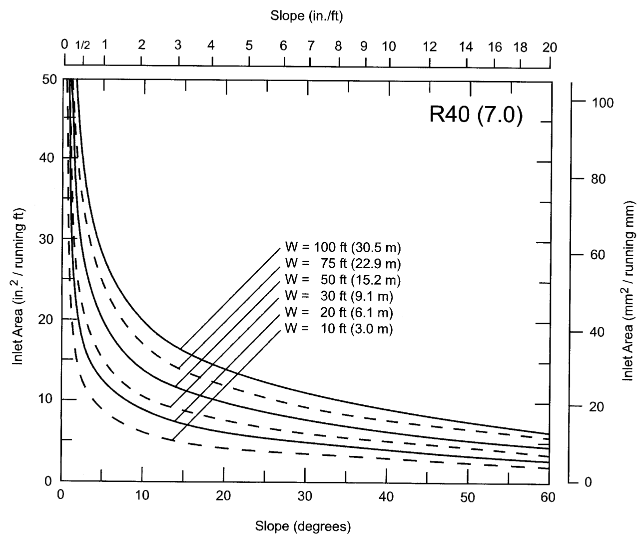

Figure 5 *Net free open area of inlets for attics with R40 (in SI units, R7.0) insulation.*

The above comparison with the current "1/300 rule" is made to indicate that it should *not* be assumed that if that rule is followed, the roof will not suffer icing problems.

Equation 1 is presented graphically in Figures 3, 4, and 5 for attics with ceiling thermal resistances of R15, R25, and R40 (in SI units, R2.6, R4.4, and R7.0), respectively. Arrows on Figure 4 illustrate the above example. For other ceiling thermal resistances, the answer can be obtained by interpolating among the three graphs.

By way of comparison, using Equation 1, the answer is 14.6 in.^{2}/running ft (30.7 mm^2/mm). That is a better answer since the inaccuracies associated with a graphical solution are avoided, but 15 in.^{2}/ft (31 mm^2/mm) is certainly close enough for design purposes.

DESIGN AIDS FOR CATHEDRAL CEILINGS

Figure 6 shows a cathedral ceiling with slope ϕ in degrees, length L in ft (m), airway height h_a in in. (mm), and ceiling thermal resistance R in ft^2·h·°F/Btu (m^{2}K/W). Figures 7, 8, 9, and 10 present the design aids developed previously (Tobiasson et al. 1999) for roofs with cathedral ceilings. Note that the answers are for each airway; therefore, for a typical gable roof, each side would be analyzed separately. Using the roof in the example used previously to illustrate the attic design aids, the horizontal projection of the 3 on 12 sloped airway would be the "attic" width of 30 ft (9.1 m) divided by 2. The length of the airway, L, would be 15 ft (4.6 m) divided by the cosine of the slope. From Table 1, the slope is 14°, its cosine = 0.970, and, thus, L = 15/0.970 = 15.5 ft (4.6/0.970 = 4.7 m). Since the R-value in the example is 25 ft^2·h·°F/Btu (4.4 m^2 K/W), and the roof slope is very near 15°, the middle graph of Figure 7 is used to determine airway height and inlet area. A range of combinations is available. First, it is clear that an airway only 1 in. (25 mm) high will not suffice. Not enough air can flow up such a narrow airway to provide the cooling required in this case. Next, it is clear that there is very little to gain by making the airway much over 1.75 in. (44 mm) high. For airway heights of 1.25, 1.5, and 1.75 in. (32, 38, and 44 mm), the required inlet areas are about 13, 9, and 8 in.^{2}/running ft (27, 19, and 17 mm^2/mm), respectively. The final selection among these alternatives would, in all likelihood, be based on lumber sizes, net free openings of commercially available soffit and ridge vents, and similar issues.

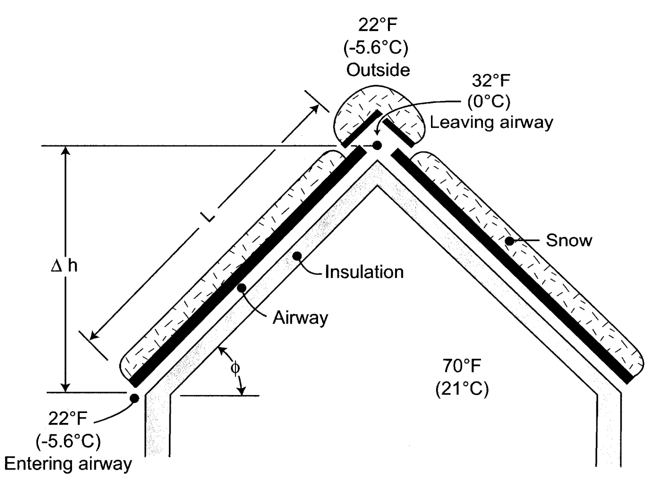

Figure 6 *A typical ventilated cathedral ceiling.*

Had the slope of this roof been 45°, the length of the airway would have been 21.2 ft (6.5 m) and sketching that line on the middle graph in Figure 9, between the L = 15 ft (4.6 m) and L = 30 ft (9.1 m) lines, a 1 in. (25 mm) high airway could be used, provided that the inlet area was about 9 in.^{2}/running ft (about 19 mm^2/mm).

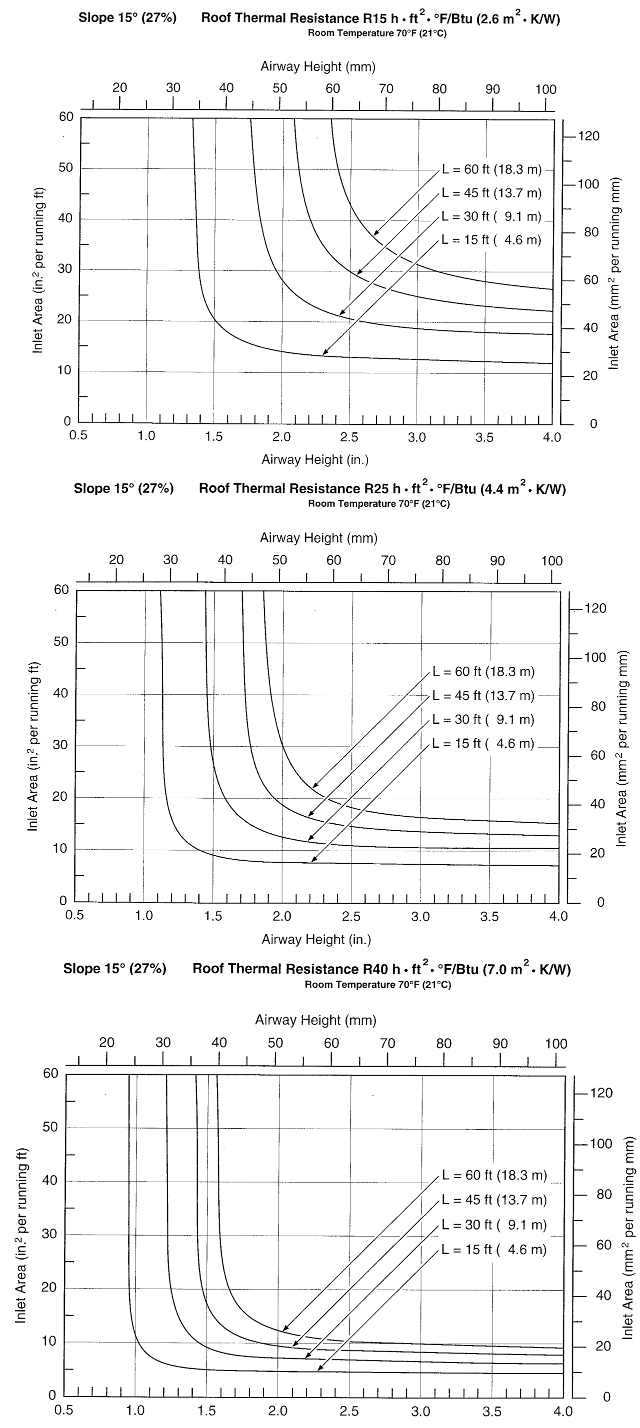

Figure 7 *Airway heights and inlet areas for cathedral ceilings with a slope of 15°.*

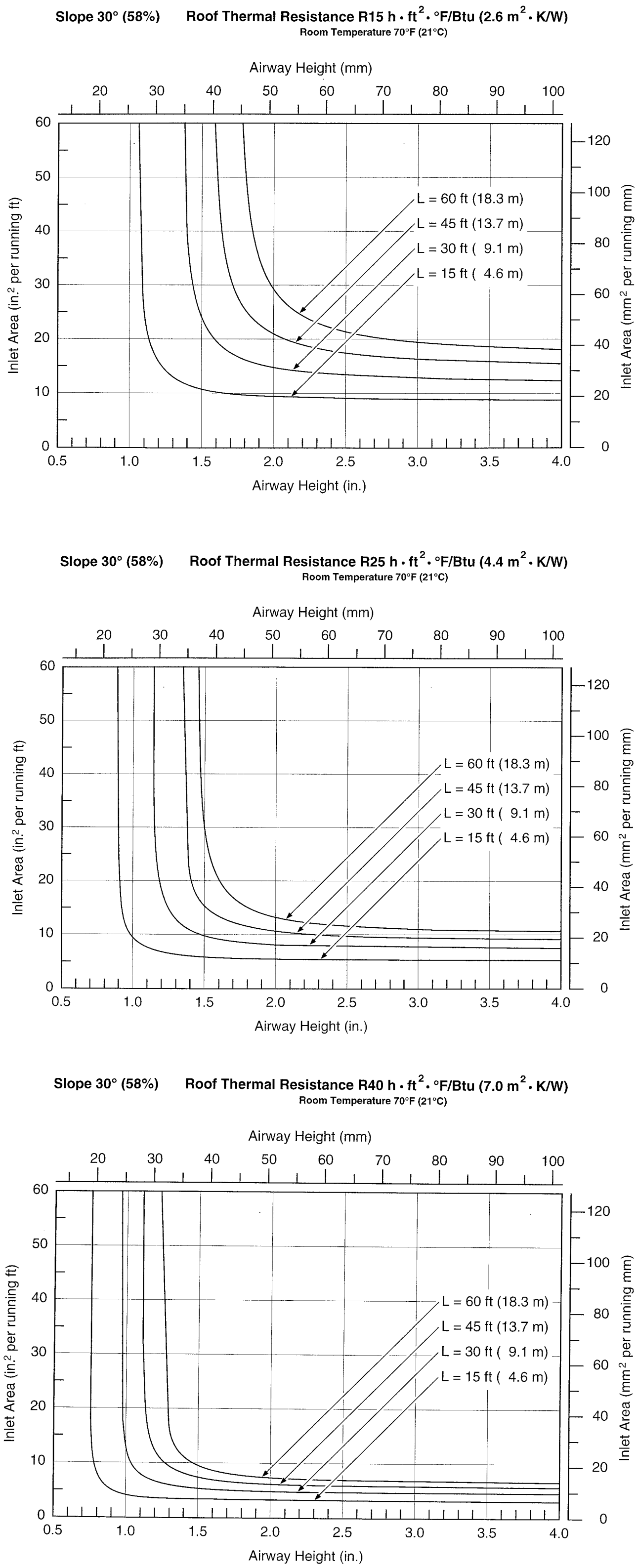

Figure 8 *Airway heights and inlet areas for cathedral ceilings with a slope of 30º.*

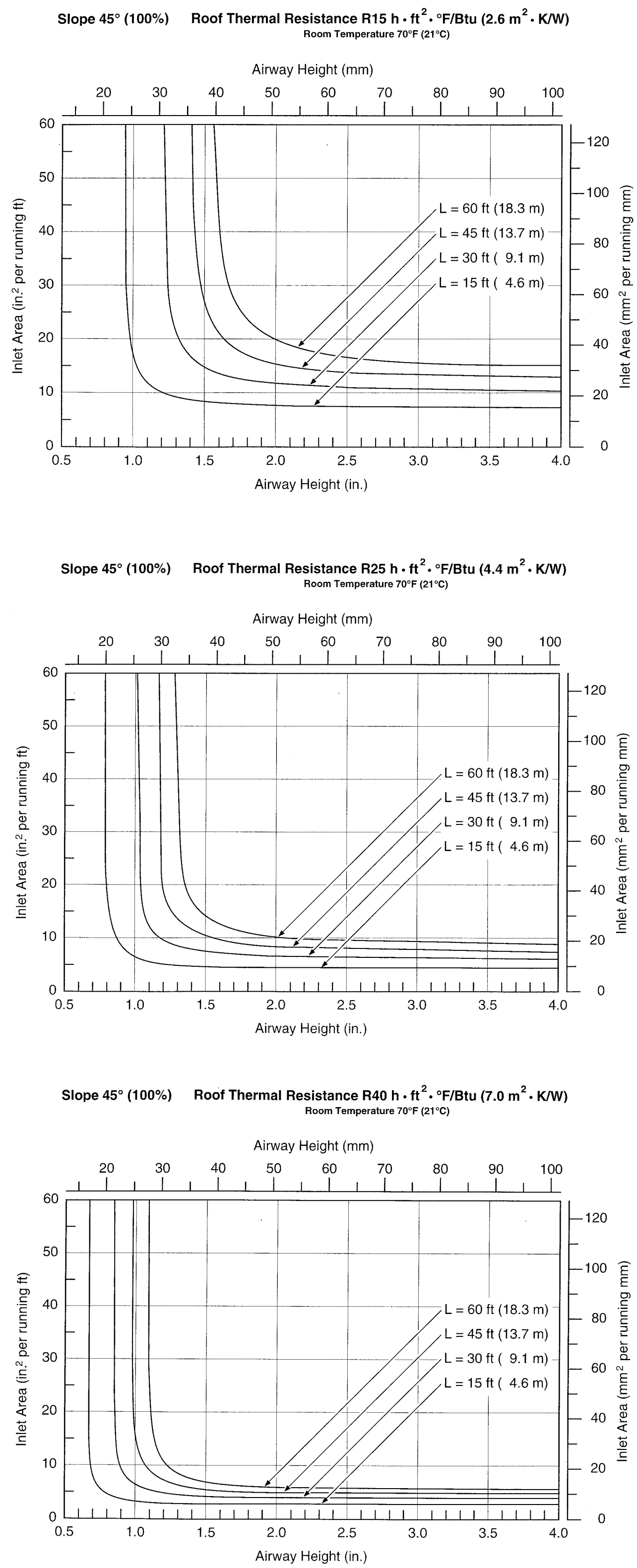

Figure 9 *Airway heights and inlet areas for cathedral ceilings with a slope of 45º.*

By studying the graphs in Figures 7 through 10, it is possible to get an appreciation for just how much the length of the airway, the slope of the roof, and its thermal resistance influence the inlet areas and airway heights needed to keep cathedral ceilings from suffering chronic icing problems.

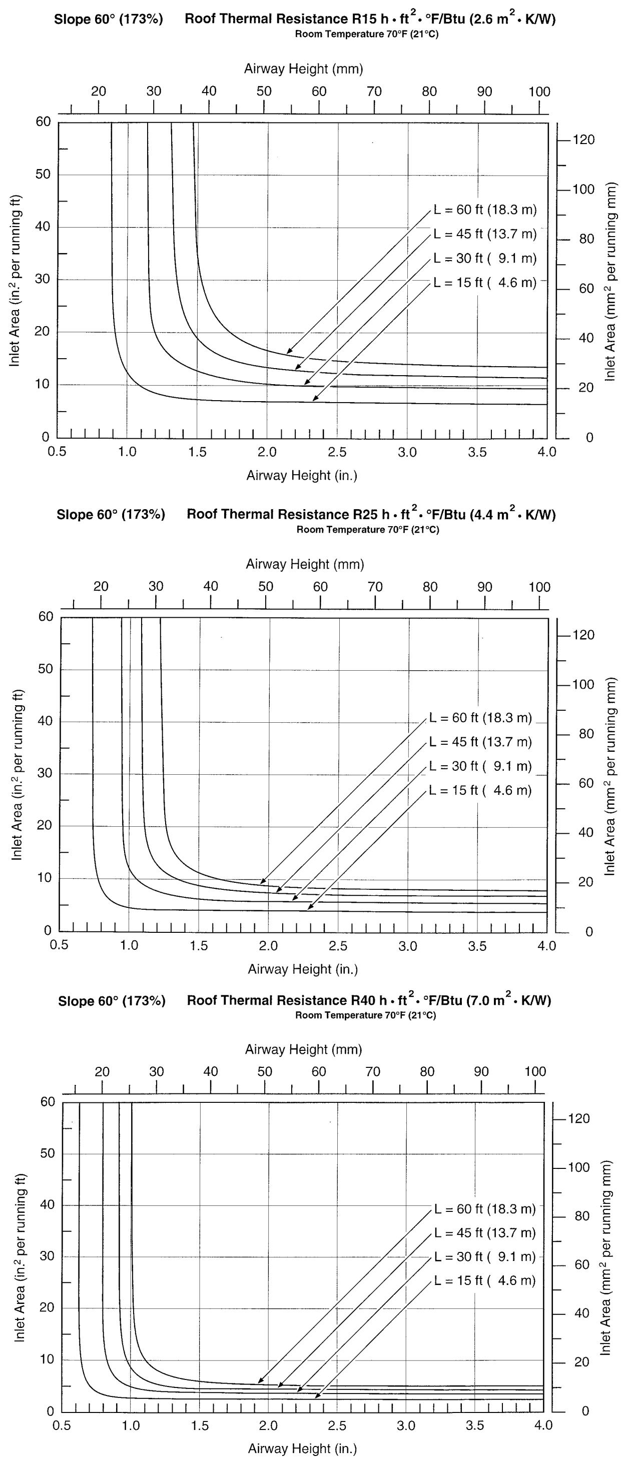

***Figure 10** Airway heights and inlet areas for cathedral ceilings with a slope of 60º.*

IS ROOF VENTILATION NECESSARY?

We and others at CRREL have done several studies to show that edge venting and the various commercially available breather vents are not effective in ventilating low-slope "compact" membrane roofing systems (Tobiasson et al. 1983; Tobiasson 1994). We define "compact" as a system with its insulation above its deck and having no airspaces or intermediate framing members. Those studies indicate that such roofs do not need to be ventilated and the penetrations of their waterproofing membranes needed to install such vents often do more harm than good.

"Framed" roofs have all or some of their insulation below their deck between framing members. Low-slope framed roofs have a relatively high risk of incurring condensation problems. Risks can be reduced by using, instead, a compact roof or a hybrid roof (i.e., part "compact" above the deck and part "framed" below) (Tobiasson 1994).

Air barriers and vapor retarders are the primary lines of defense against condensation problems in building envelopes in cold regions. When air exfiltration is prevented, condensation problems seldom occur. When condensation problems develop, air leakage paths are usually found to be the cause.

For decades, framed roofs have been ventilated as an acknowledgment that the elimination of air exfiltration is seldom achieved in framed construction. Vapor retarders, air barriers, foam sealants, and such have led to tighter building envelopes, and, thus, the need to ventilate away moist exfiltrating air has diminished. If framed walls built "tight" do not need to be ventilated, why use framed roofs? One argument is that the forces that promote air exfiltration are greatest at the top of buildings. Thus, large portions of walls may be subjected to air *infiltration*, which, in cold regions, is less apt to create condensation problems.

Other reasons for ventilating sloped roofs relate to thermal—not moisture—issues. By ventilating between the insulation and the roofing material (e.g., asphalt shingles), those materials remain cooler and their useful life is prolonged. However, evidence is accumulating that the expected benefits are minimal and the need to ventilate roofs for this reason is now being questioned (TenWolde and Rose 1999). Nonetheless, most manufacturers of asphalt shingles currently require ventilation below their products. Problems such as shingle splitting are often blamed on missing or inadequate ventilation. A lot of valuable findings and perspectives on this issue are not available due to their proprietary nature. However, it appears that the lack of adequate ventilation is not the primary cause of most of these problems.

Ventilation is also promoted to reduce cooling loads. Some studies support this benefit, but others do not. TenWolde and Rose (1999) acknowledge that attic ventilation may reduce cooling loads somewhat, but they indicate that there are several more direct ways of doing that. In cold regions, cooling loads are not usually a big issue. Since ventilation can somewhat increase heat losses in cold weather by removing solar heat gain on a bare roof and diminishing the insulating benefits of snow on a snow-covered roof, there is some incentive not to ventilate roofs in cold regions. However, as previously stated, our investigations of ice dams and icicles at eaves have convinced us that ventilation is a very effective way of resolving problematic icings.

TenWolde and Rose (1999) calculate that the rate of snow melt is very slow. They conclude that at an outside temperature of 22ºF (–5.6ºC), it would take about 2.5 days to melt an inch of 7 lb/ft^3 (100 kg/m^3) snow. They use a thermal resistivity of 0.25 h·ft^2·ºF/Btu·in. (1.7 m·K/W) obtained from the *1997 ASHRAE Handbook—Fundamentals*. Mellor (1964) discusses the thermal conductivity of snow and how it varies with snow density. He presents the results of several studies that collectively indicate that 7 lb/ft^3 (100 kg/m^3) snow has a thermal resistivity of about 1.7 h·ft^2·ºF/Btu·in. (11.7 m·K/W)—about seven times the value mentioned above.

However, we do not feel that the snow density of 7 lb/ft^3 (100 kg/m^3) is realistic for most snow on most roofs. From our involvement in the development of the snow load information in the national standard used in the United States by structural engineers (ASCE 2000), we expect the density of that snow to be closer to 15 lb/ft^3 (210 kg/m^3). From Mellor (1964), the thermal resistivity of this snow would be about 0.9 h·ft^2·ºF/Btu·in. (6.1 m·K/W).

Using this value, the base of the snow would begin to melt at the 22ºF (–5.6ºC) outside "design" temperature when there are only 9.5 in. (0.24 m) of snow on the roof, not 16 in. (0.41 m) as TenWolde and Rose (1999) determine. We conclude that significantly less snow is needed on a roof to initiate melting than their calculations indicate.

TenWolde and Rose (1999) determine the amount of heat flowing up through a ceiling with R30 (in SI units, R 5.2) insulation when the temperature in the attic above is 30ºF (–1ºC). Then they assume that all this heat is available to melt snow. In fact, when there is just enough snow on the roof to raise the temperature at the base of the snow to 32ºF (0ºC), there is *no* melting since the heat entering the snow from below equals the heat lost out of the upper surface of the snow. With 16 in. (0.41 m) of snow on the roof, the base of the snow is at 32ºF (0ºC) and the heat flow up into the snow from below exceeds the heat lost out of the surface of the snow. Melting then occurs. In this case, the heat flow up into the snow is about 1.19 Btu/h·ft^2 (3.8 W/m^2) and the heat flow up out of the snow is about 0.69 Btu/h·ft^2 (2.2 W/m^2). The difference of about 0.5 Btu/h·ft^2 (1.6 W/m^2) melts snow. Since it takes about 144 Btu to melt a pound (334 kJ to melt a kg) of snow, meltwater is being created at about 0.0035 lb/h over every square foot of roof (0.017 kg/h·m^2). If the upslope length of the roof is 20 ft (9.1 m), 0.07 lbs of meltwater are available to build an ice dam along each foot (0.10 kg/m) of eaves every hour. In a day that totals about 1.7 lb/running ft (2.5 kg/running m), in a week it becomes about 11.8 lb/running ft (17.6 kg/running m), and in a month it becomes about 50 lbs/running ft (74 kg/running m), which, considering that it forms within existing snow at the eaves, is about a cubic foot of ice per running foot (0.09 m^3/running m). On a 45º slope, the face of this ice dam would be about 17 in. (0.43 m) high. That is a big dam.

Since cold weather often lasts weeks or months over much of the United States, these calculations tend to support our contention that ice dams of some size can be expected to develop even on relatively well-insulated, but unventilated, roofs in cold regions. Our observations, measurements, and laboratory studies indicate the same thing.

We acknowledge the limitations of the simple calculations discussed above. For example, solar warming, diurnal temperature changes, and changes in the boundary conditions as snow is melted are not considered. Our observations and those of others (Mackinlay and Flood 1997; Gillan 1998) indicate that, without the "catalyst" of additional heat gain from a warm building below, the sun and diurnal temperature changes seldom create large icings except at very high elevations such as in the High Sierra. However, when combined with heat gain from below, they probably explain why we have observed, on occasion, even faster growth of icings than these simplified calculations predict.

We acknowledge that air exfiltration, insulation flaws, and other weaknesses in building envelopes and other heat sources under roofs can cause large chronic icings. However, our investigations indicate that large icings also can occur on well-insulated but unventilated roofs.

The perspective of TenWolde and Rose (1999) has prompted us to give thought to when and where in cold regions, roof ventilation (for the purpose of ice dam control) could be eliminated. In places that experience infrequent snowstorms, several midwinter thaws, and where the depth of snow on the roof is relatively shallow (e.g., seldom more than about 12 in. [about 0.3 m]), the mechanism for ice dam formation is limited, particularly for well-insulated roofs. In such areas, roof ventilation would not be essential for ice dam control. In places where heavy snow loads are to be expected and the climate allows such loads to remain on well-insulated roofs for many weeks or months, the need for ventilation to limit ice dam growth is much greater.

We find it convenient, relative to icings, to relate the need for ventilation in the contiguous United States to the ground snow load at a location and the amount of roof insulation. Ground snow load has been mapped for the United States (ASCE 2000). That map, which was made by two of the authors of this paper, Tobiasson and Greatorex, is also in many model codes and the new International Building Code (ICC 2000). Table 2 presents our recommendations for when and where ventilation for ice dam control is needed for residential size roofs. For bigger roofs, the potential for formation of ice dams increases and there are more situations where ventilation is required. We solicit feedback on Table 2. Table 3 presents ground snow load values for some cities across the

TABLE 2 *

To Avoid Problematic Icings, Ventilate Residential Size Roofs Under the Following Conditions

Ground Snow Load, lb/ft^2 (kN/m^2)	
Less than 10 (0.48)	No need to ventilate to avoid ice dams.
10 to 15 (0.48 to 0.72)	Ventilate if the thermal resistance of the roof is less than R10 (1.8).
16 to 30 (0.77 to 1.44)	Ventilate if the thermal resistance of the roof is less than R20 (3.5).
31 to 45 (1.48 to 2.16)	When the elevation is above 6000 ft (1830 m) ventilate all roofs. Below that elevation, ventilate if the thermal resistance of the roof is less than R30 (5.2).
46 to 60 (2.20 to 2.87)	When the elevation is above 3000 ft (920 m) ventilate all roofs. Below that elevation ventilate if the thermal resistance of the roof is less than R40 (7.0).
61 (2.92) and up	Ventilate all roofs.

* This table should be considered a work in progress at this time. Feedback on it would be appreciated.
See Table 3 for ground snow loads at some representative U.S. cities.

TABLE 3 *

Ground Snow Loads for Some Cities in the United States

Ground Snow Load lb/ft^2 (kN/m^2)	Cities
10 (0.48)	Norfolk, VA; Memphis, TN; Portland, OR; Tulsa, OK
15 (0.72)	Louisville, KY; Salt Lake City, UT
20 (0.96)	Philadelphia, PA; Detroit, MI; Cheyenne, WY
25 (1.20)	Washington, DC; Chicago, IL; Omaha, NB
30 (1.44)	Hartford, CT; Milwaukee, WI; Idaho Falls, ID
35 (1.68)	Madison, WI
40 (1.92)	Boston, MA; Albany, NY; Green Bay, WI; Sioux Falls, SD
50 (2.40)	Minneapolis, MN; Portsmouth, NH
60 (2.87)	Portland, ME; Duluth, MN
70 (3.35)	Bangor, ME; Marquette, MI

* Warning: Do *not* use these values to interpolate to other places in between.
These values are from site-specific snow load case studies conducted by W. Tobiasson and A. Greatorex of CRREL.

nation to help the reader visualize about where the boundaries in Table 2 lie.

TenWolde and Rose (1999), in spite of developing many cogent arguments against ventilation, recommend attic ventilation in cold regions and mixed climates for several reasons—not just ice dam control—"as an additional safeguard." We agree.

They feel that ventilation of cathedral ceilings in cold and mixed climates is "still a contested issue" and argue that cathedral ceilings, properly insulated and sealed against vapor diffusion and air leakage, can be built without ventilation when "measures are taken to control indoor humidity." We feel that in at least those cold places where ice damming is likely (as defined in Table 2), cathedral ceilings should meet the above requirements *and* be ventilated.

CONCLUSIONS

Our observations, measurements, and calculations indicate that there are times and places when roofs above attics and cathedral ceilings should be ventilated to eliminate the problems associated with the growth of large ice dams along their eaves. Table 2 in this paper provides recommendations as to when and where ventilation is needed for this purpose. Equation 1 or Figures 3, 4, and 5 can be used to size inlet and exhaust openings of attics. Figures 7, 8, 9, and 10 can be used to size inlet and exhaust openings and airway heights for cathedral ceilings. With these aids, these tasks are quick and easy.

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