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Roof Ventilation to Prevent Problematic Icings at Eaves

James Buska **Wayne Tobiasson** **Alan Greatorex**

ABSTRACT

Attic ventilation 1/150 and 1/300 rules of thumb were established to avoid problems from indoor moisture. In cold regions another strong reason to ventilate roofs that slope to cold eaves is to prevent the formation of problematic icicles and ice dams. Building heat, not the sun, is responsible for the large icings that cause such problems, and roof ventilation is a direct and effective way of solving them.

The authors have instrumented buildings to determine attic ventilation needs to minimize icings and have developed design guidelines for natural and mechanical ventilation systems. These guidelines have been applied to roofs with cathedral ceilings, two of which are discussed in detail. Head losses in narrow airways complicate the ventilation of cathedral ceilings. It is particularly difficult to ventilate the valley areas of such roofs. However, as these case studies indicate, ventilation systems can be developed to eliminate problematic icings on complex roofs. Details often determine the success or failure of ventilation systems.

INTRODUCTION

Sloped roofs are ventilated to dissipate moisture and to diminish the adverse effects of solar heating on roof cladding and the occupied space below. These are important issues of durability and energy conservation. Attic ventilation 1/150 and 1/300 guidelines were developed to achieve these objectives (ASHRAE 1989; BOCA 1984; ICNO 1985). While any generalized guideline cannot be expected to provide the best answer for every situation, these have had a strong positive impact over the years.

In cold regions, another reason to ventilate the roofs of heated buildings that slope to cold eaves is to eliminate (or at least reduce) the magnitude and frequency of icicles and ice dams that form along their eaves. Icicles and ice dams can also form on unheated buildings, but they are usually small and infrequent. Chronic, problematic icings are much more likely to form on heated buildings. Figure 1 shows two adjacent identical buildings photographed at the same time. The eaves of one are festooned with ice while the eaves of the other are clear. As the snow on the chimney of the roof with clear eaves indicates, that building was not heated. Figure 1 serves to illustrate that chronic, problematic icings are caused by building heat, not by the sun.

PRIOR CRREL STUDIES

Several years ago the authors instrumented several buildings in upstate New York and determined that chronic problematic icings did not occur when attic ventilation (either

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

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natural or mechanical) was able to cool the attic to 30°F (−1°C) when the outside temperature was 22°F (−5.5°C) (Tobiasson et al. 1998). When it is warmer than 22°F (−5.5°C) outside, icings seldom form, and when it is colder than 22°F (−5.5°C) outside, it is easier to ventilate the attic with outdoor air. Since design should be based on the peak ventilation need, we recommended that to minimize icing problems, attic ventilation systems be sized to maintain an attic temperature of 30°F (−1°C) when the outside temperature is 22°F (−5.5°C).

These design guidelines were used by others to increase the amount of attic ventilation in 57 buildings suffering a range of icing problems from slight to severe (Figure 2). We had recommended attic ventilation improvements in conjunction with increased ceiling and duct insulation and reduction of air exfiltration. The designers chose to only improve attic ventilation for 51 of the buildings. Some insulation was added to HVAC ducts in the other six attics but that reduced the total heat losses into those attics only slightly. The improvements, essentially all of which were to the ventilation, eliminated chronic icing for 56 of the 57 buildings. Only a few small icicles formed on them occasionally after the new work. Some icing problems persisted along portions of the 57th building, where air intakes at the eaves could not be easily enlarged. We feel that this localized problem can be solved by increasing the size of air intakes in these areas. Improved attic ventilation, sized to meet the peak ventilation needs defined above, consistently eliminated the chronic icing problems suffered by these buildings.

In the process of this study, we determined some of the strengths and weaknesses of standing seam metal roofing systems in cold regions (Tobiasson and Buska 1993) and of difficulties associated with installation of electric heaters on metal roofs to clear paths through ice dams (Buska et al. 1997). We also developed guidelines for installing snow guards on metal roofs (Tobiasson et al. 1996). Such devices are needed in places to prevent electric heaters and other roof components, including the metal roofing itself, from being damaged by sliding snow. Snow guards may also be needed to prevent hazards associated with snow and ice sliding on, then falling from, such roofs.

Figure 2. Severe problematic icings developed all along the eaves of this dining facility.

VENTILATION, INSULATION, AND AIR LEAKAGE CONTROL

Ventilation can increase rather than solve moisture problems in roofs that are subjected to excess warm, moist air exfiltrating from occupied spaces below. Such air can also greatly increase heat losses through the roof, which directly diminishes the ability of ventilation systems to solve icing problems. Ventilation is likely to be successful only when air leakage up into the roof is minimized. Our attic ventilation studies convinced us that ventilation is often necessary to prevent, or in the case of existing buildings, solve, icing problems for reasonably well-insulated buildings. We promote air leakage control as an essential aspect of roof ventilation (Tobiasson 1994).

Adding insulation to a roof will also cool the base of snow on the roof, thereby reducing its potential to melt and its rate of melting. Just adding insulation may be enough to eliminate chronic icing problems in areas where snow remains on roofs for short periods only and its depth is not great. Using the 22°F (−5.5°C) outside, 30°F (−1°C) attic design condition discussed above, we have calculated that with one foot (0.3 m) of snow on a roof, the roof's thermal resistance needs to be about R45 (R7.9) to prevent snow melt. When a roof is covered with 2 feet (0.6 m) of snow, the thermal resistance needed increases to about R90 (R15.8) (Cushman 1996). In New England we have seen problematic icings on R40 (R7.0) roofs. While we do not yet know how "deep" into snow country unventilated roofs can successfully avoid chronic icing problems, we do know that wherever snow accumulates on roofs, ventilation of reasonably well-insulated roofs is a very effective way of preventing chronic icing.

On occasion, due to snow infiltration problems, roof complexity, costs, or whatever, ventilation may not be appropriate. However, in most situations, ventilation is the key to solving icing problems.

This paper presents two Hanover, New Hampshire, case studies where improved ventilation solved chronic icing problems.

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The original unventilated roofs of this building with cathedral ceilings had slopes of 6 on 12 (27°). Progressing upward through a section of the original roof, it consisted of an exposed 3 in. (76 mm) thick timber deck, 1½ in. (38 mm) of urethane insulation interrupted by 2×2 nailers that ran up the slope about 16 in. (0.4 m) on center. The 5/8 in. (16 mm) plywood attached to the nailers was tight against the upper surface of the insulation. Asphaltic underlayment and asphalt shingles provided waterproofing.

In most winters, large icicles and ice dams formed all along the eaves. After several crashed to the ground, creating hazards to low windows, to people, and to vehicles parked nearby, a solution was sought. A local architect recommended

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adding more insulation only. We advised against that for the reasons mentioned above. Based on our recommendations, the warm, unventilated roof was changed to a cold, ventilated roof with improved insulation. Figure 3 shows a cross section of the roof after these changes were made.

A primary hurdle in convincing the owners to open the roof to ventilation was aesthetics, since it was expected that the new system would look "top heavy." Sketches were developed to show that the eaves and rakes could be designed to retain their "lightness." This would necessitate extending the eaves several inches. We also promoted this for technical reasons since the 2 in. (51 mm) wide eaves were not enough to keep rain, meltwater, and ice off the brick walls below. The overhang was extended to about 8 in. (203 mm), which is more appropriate. We recommend against overhangs of less than 6 in.(152 mm) in cold regions. A 12 in. (305 mm) overhang is a good target when designing most cold ventilated roofs.

To size inlets and exhausts for attic ventilation, we use the following equation from Tobiasson et al. (1998):

$$A \doteq 0.227H/\Delta h^{0.5}$$

where

A = the net free area of inlets (or exhausts) needed (ft^2) to cool an attic by natural, stack-induced ventilation (multiply by 144 to convert to in.^{2}),

H = heat to be removed (Btu/min),

Δh = height difference between inlet and exhaust openings (ft).

(In SI units, $A = 0.000662\ H/\Delta h^{0.5}$ with A in m^2, H in W, and Δh in m.)

Using this equation we determined that a net free area of about 9 in.^{2} would be needed per running foot (0.019 m^2/m) of eaves for the widest portion of this building if it were configured as an attic, not a cathedral ceiling. For this "attic," those calculations give a venting ratio at the eaves of about 1/750. This is much less than the 1/300 ratio recommended by various guidelines for solving moisture-related durability and energy-conservation concerns for a roof this steep. Our calculations are for sizing the net free area of intakes at eaves or exhausts at the ridge of buildings with attics, not cathedral ceilings. If the airways above the insulation in this building were sized this way, they would only have to be about 3/4 in. (19 mm) high. But that would be a mistake, since those calculations do not consider head losses in a narrow airway, only head losses at the intakes and exhausts. A long narrow airway must be much higher and its inlet and exhaust openings must be larger than those needed by an attic of similar size and geometry.

Some guidelines (Marsh 1979) indicate that a 3/8 in. (10 mm) high airway will suffice, but we have had better success with a minimum height of 1½ in. (38 mm) and a target height of 2 in. (51 mm). Tobiasson (1994) recommends that airways usually need to be 2 in. (51 mm) high above cathedral ceilings forr oofs with a slope of 3:12 (14°) or more, provided that the airway is not much over 20 ft (6.1 m) long. Airways longer than about 20 ft (6.1 m) need to be even higher. For lower slopes, he indicates that it is usually appropriate to interconnect all individual airways by installing purlins on the rafters before the deck is laid, as shown in Figure 4. Based on that guidance we decided to use 2×6's for the vertical members shown in Figure 3. This created a 3½ in. (89 mm) high airway. Had 2×4's been used, the airway would have been only 1½ in. (38 mm) high. Because the 6:12 (27°) slope far exceeded the 3:12 (14°) slope where interconnected airways (see Figure 4) are recommended, we did not feel that interconnected airways were needed for this building.

This building has clerestory windows that cause the upper ends of the airways on one slope to terminate at the base of the clerestory wall, not at the ridge. A large roof exhaust structure (Figure 5) was needed for the airways all along that intersection. Since we had some concerns that snow drifts would form in this area, reducing ventilation, we and the architect involved gave that structure a rather wide brim. Large hoods for build-

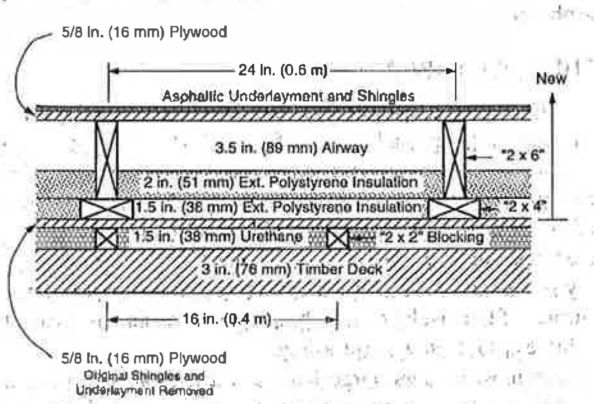

Figure 3 *Cross section showing the Howe Library roof ventilation modifications as constructed.*

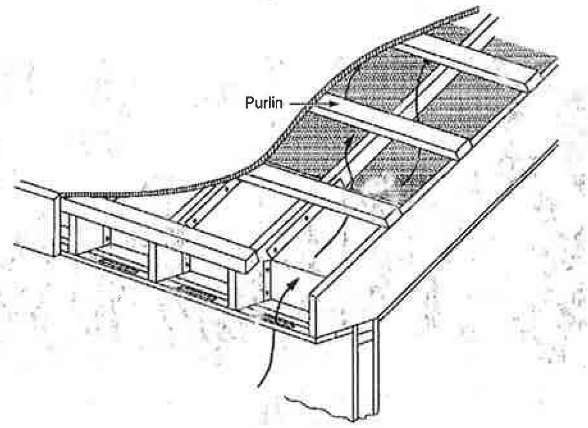

Figure 4 *Use of cross-purlins to interconnect the airways of a low-slope roof.*

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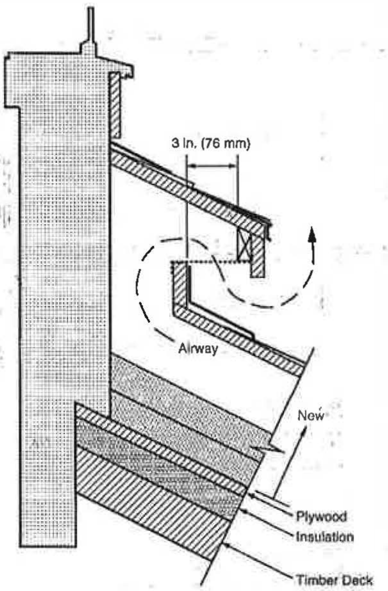

Figure 5 *Large roof exhaust structure used where airways terminated at clerestory wall.*

ing exhaust fans interrupted our new roof exhaust structure in several places. The 2×6's were notched in these area, as shown in Figure 6, to allow air in the dead-ended airways to gain access to adjacent airways that lead to our new exhaust structure. Similar notching was used to open airways that dead ended at the chimney (Figure 6).

The cold ventilated roof of this building has performed as we expected. One author has periodically driven by it during the past five winters since it was completed and has yet to see any problematic icicles or ice dams at its eaves. Some snowdrifts form at the base of the clerestory wall on occasion, but even then most of the exhaust structure there remains clear. No complaints have been aired by those who felt it might look "top heavy." In fact, several individuals have indicated that "it looks better now." It certainly looks better to us since the original 2 in. (51 mm) overhang looked and acted wrong.

Fig re 6 ... tches in 2×6's allow cross-ventilation at ... nney and at large building exhaust hoods. ... exhaust structure shown in Figure 5 not ... lled.

As an aside, the as-built roof cross section shown in Figure 3 was not our primary recommendation. We felt that a tighter, and thus a better insulating/waterproofing system, could have been achieved by using about 2½ in. (64 mm) of monolithic spray foam instead of numerous insulation boards. Our spray foam recommendation is shown in Figure 7. The curved uninterrupted upper surface of the spray foam would serve as a secondary drainage trough for any moisture that might get by the primary waterproofing system. Such moisture would work its way deep into any system of individual boards. While the extruded polystyrene boards themselves would remain dry, that moisture could do harm to other components of the roof in time. We estimated that the spray foam alternative, with 2×4 verticals, not 2×6 verticals, would be only a bit more expensive, and, considering the "insurance" it would add, we recommended it. However, these secondary benefits were not enough to convince the owners to spend the extra money.

We continue to recommend the use of spray foam in some situations. One such roof was built based on our recommendations; but, unfortunately, our attempts to document its installation and performance were thwarted.

HANOVER POLICE FACILITY

The designer's intent was to minimize snow melt on the roof during cold weather by keeping the underside of this roof cool. This was to be accomplished by allowing cold outdoor air to enter all along the eaves, flow upslope above the insulation, then exit all along the ridge (see Figure 8). Unfortunately as-built ventilation was minimal. The roof was too warm, snow on it melted during cold weather, ice dams formed along the cold eaves, and water backed up behind these dams. That water leaked into the building at valleys where it was difficult to achieve watertightness.

We first inspected this building in December 1989 to determine the cause of roof leaks that had occurred the prior

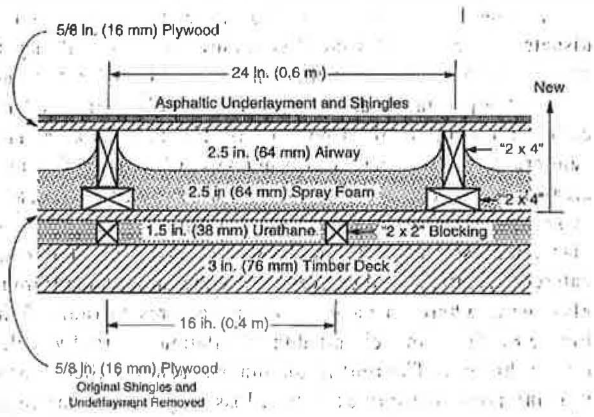

Figure 7 *Spray foam recommendation for improving roof ventilation of Howe Library.*

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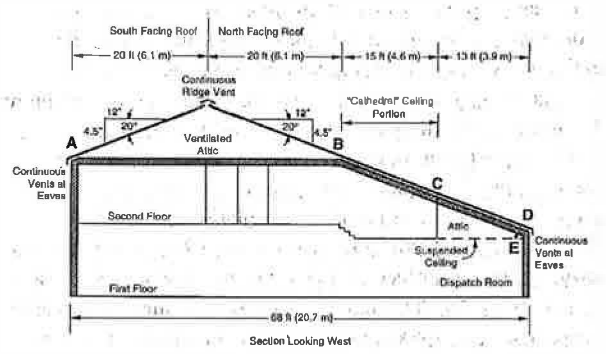

Figure 8 *Cross section through east-west wing of the Hanover Police Facility.*

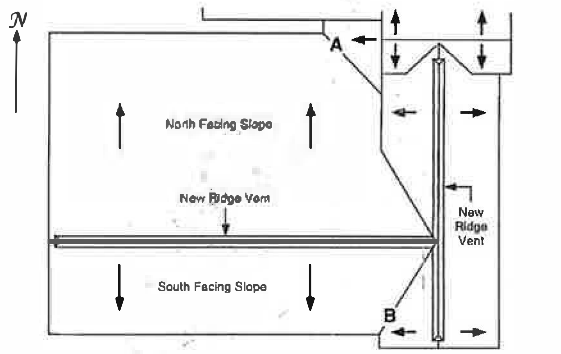

Figure 9 *Plan view of Hanover Police Facility showing slopes and location of roof leaks (A and B) at valleys.*

two winters near the two roof valleys (Points A and B in Figure 9). Large icings (Figure 10) and roof leaks were causing serious problems in the dispatch center located below point A in Figure 9. The occupants complained of cold drafts. They also had to chop ice off the eaves and shovel snow from the roof to minimize hazards and leaks. Figure 11 shows the paths of meltwater that is produced on several roofs, then drains into this problematic valley.

Figure 8 shows the complicated ventilation pathways through a cross section of this facility. A ventilated attic, containing a large amount of HVAC equipment, exists below the upper portion of the north roof and the entire south roof. The attic has intakes all along its south eaves (at A in Figure 8), a small gable vent at its west end, and a continuous ridge vent. The middle portion of the north roof has a sloped, cathedral ceiling with a 2 in. (51 mm) ventilated air space above the insulation (between points B and C in Figure 8). The lower portion between point C and the continuous vents along the north eaves (at D in Figure 8) also had a 2 in. (51 mm) air space above the roof insulation and a warm unventilated attic below. In this attic area the insulation was placed between the roof rafters, and a clear polyethylene vapor retarder was stapled below.

Although the attic above the suspended ceiling in the dispatch room is within the heated portion of the building, it was 15°F (8.3°C) cooler than the rooms below when the outside temperature was 20°F (−6.7°C). With portions of the ceiling removed, cool air poured into the dispatch area. The vapor retarder was installed very poorly. It was missing in some areas, it contained many gaps—some several inches wide, and in several areas it was hanging down rather than stapled in place. We used a smoke gun to verify that cold outdoor air entered this attic near the eaves by passing through the fibrous glass batts where no vapor retarder was present (point E in Figure 8). This short-circuited the insulation and roof ventilation in this area. The roof insulation was also installed poorly in many areas, causing extra heat losses up through the roof. The poor job of placing insulation suggested that the 2 in. (51 mm) ventilated air spaces above the insulation were not clear. By reaching up around insulation batts, we determined that

Figure 10 *Icings and ice dam at eaves of problematic valley over dispatch center. Icicles in the valley were removed the day before this picture was taken.*

Figure 11 *Roof surfaces that drai lley over dispatch center.*

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expanded polystyrene spacers were present in some areas. Such spacers are used to ensure that the insulation batts do not block the airway. However, these spacers were not present everywhere and no cold airflow was detected by a bare hand placed up many supposedly ventilated spaces. The space above the suspended ceiling was also crammed full of heating and ventilating equipment and electrical lines. Some duct insulation had fallen off, allowing additional heat to warm the roof.

During our inspection we found that the snow was thinner above the "cathedral ceiling" portion of the north-facing roof than it was above the lower attic. Stripes of thin snow a rafter-space wide above the cathedral ceiling portion indicated that some rafter spaces were hotter than others (i.e., they were not as well ventilated as others).

The south eaves of the upper ventilated attic were not blocked by batts of ceiling insulation as is often the case. A smoke gun verified that air was flowing out the continuous ridge vent. Since the ceiling of the second story was insulated and the attic ventilated with cold outside air, this attic should have been cold. Even though it was 20°F (–5.5°C) outside during one of our inspections, the attic temperature was 55°F (12.8°C). At that time, this was only 2°F (1°C) colder than the temperature of the lower warm attic that had R30 (R5.3) insulation above it. Clearly, the roof over the ventilated attic was too warm, making it the source of much of the meltwater causing icings at the eaves. One reason this attic was so hot was that the ceiling vapor retarder contained gaps and holes that allowed warm indoor air to rise up into the attic. A second reason was that some of the insulation batts were poorly placed. A third, and perhaps the primary, reason for this warm attic was the amount of heating equipment and ducting up there. That hardware was insulated, but its insulation was minimal and some was loose. We measured a temperature of 99°F (37.2°C) under the insulation of one duct near a gap in that insulation.

While in the upper attic, we could look down the north roof to the point where it joins the cathedral ceiling portion (point B in Figure 8). Expanded polystyrene insulation spacers were present there between some rafters to ensure ventilation above the insulation. However, between other rafters no spacers were present and the insulation appeared to, at least partially, block the space intended to be ventilated. Between a few rafters we could see wooden blocking that appeared to completely block off the space intended to be ventilated. The plans called for "discontinuous blocking" at this location. Discontinuous blocking was also called for at another location lower on this roof (C in Figure 8). At least some of this blocking was not discontinuous. However, even where discontinuous, the drawings indicated that the blocking cuts the width of the ventilated space in half, reducing its height to less than one in. (25 mm). The as-built ventilating ability of this roofing system was very limited.

As mentioned previously, our experience was that a 2 in. (51 mm) deep ventilated space between rafters above batt insulation for a roof such as this should be limited to a length of about 20 ft (6.1 m). By the time cold outside air has traveled about 20 ft (6.1 m) in such a narrow space, it is no longer very effective at cooling the roof. The narrow ventilated space of this roof was 30 ft (9.1 m) long and, as suggested by the guidelines used when sizing the Howe Library airway, a higher airway was needed than was provided.

In 1989, to solve these problems, we recommended that the insulation and vapor retarder be properly installed to resist heat flow and prevent air leakage across the building envelope. We also indicated that the roof needed more ventilation to keep its surface below freezing in cold weather. Because of the difficulty of gaining access to the areas needing attention, we acknowledged that rehabilitating the existing system would be difficult. We suggested that it might be less expensive and better to build another roof above the existing roof with the intervening 3 to 4 in. (76 to 102 mm) space properly ventilated.

The Town of Hanover repaired some of the air leakage problems and vapor barrier problems but chose not to fix the ventilation problems. Instead, they hired a contractor to periodically shovel snow off the roof for four more winters. By then they needed a new roof as the snow removal operations had damaged the asphalt shingles beyond repair. During that period they also tried to reduce the leakage problems in the problematic valley (point A on Figure 9) by covering it with metal roofing. A ¾ in. (19 mm) air-space was provided under the west-facing portion of the metal roofing in this area. That air space was open at the eaves, but there were no exhaust openings for that air. The portion of the north-facing roof above the lower attic was covered with metal roofing. Since the roof was still warm and poorly ventilated, this accomplished little. Icings and leaks persisted.

Many owners and designers somehow feel that switching to a metal roof is the way to solve ice dam problems. Quite often this does not solve that problem, and the expensive, new metal roof introduces additional problems, such as the hazards associated with sliding snow. Metal roofing can be used when solving icing problems but only when the roof is well insulated and preferably also ventilated to prevent refreezing of snow meltwater at cold eaves. Metal roofing may also need snow guards to prevent snow from sliding (Tobiasson et al. 1996).

In 1994, the town decided to follow our earlier recommendation and create a "cold" ventilated roof with improved valley ventilation using the cross-purlin scheme shown in Figure 4. New continuous air inlets, eaves to ridge airways, and continuous air exhaust structures would be added above the existing roof.

The new metal roofing and old asphalt shingles were removed and vertical 2×4 sleepers were placed up slope 24 in. (0.6 m) on center creating 3½ in. (89 mm) high airways from the eaves to the ridge. To achieve cross-ventilation, 2×4 cross-purlins were placed on their side on the sleepers 24 in. (0.6 m) on center. Figure 12 shows this system during construction. The cross-purlins eliminated the need for the kind of Howe Library rafter notching (Figure 6) that would have been needed in valley areas and where skylights blocked individual

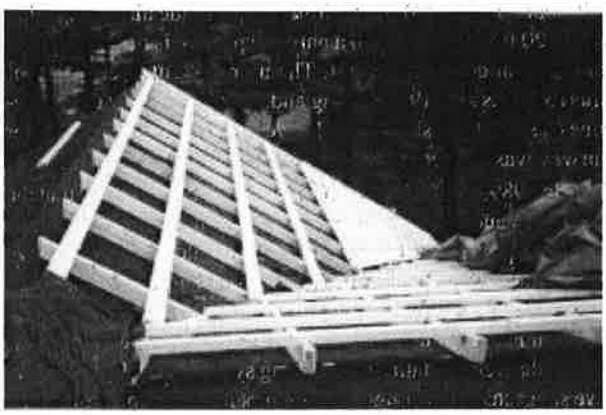

Figure 12 Cross-ventilation provided by sleepers and cross-purlins in valleys.

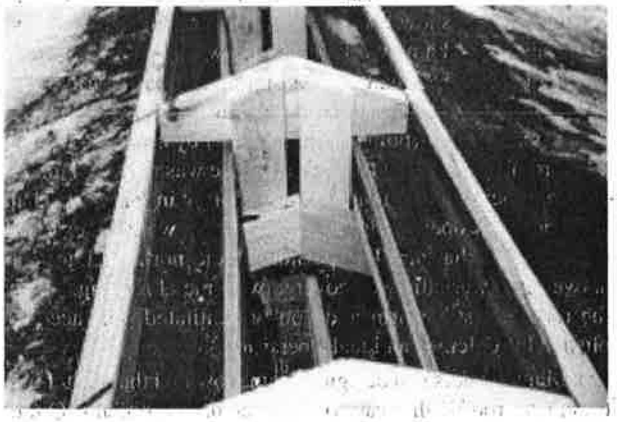

Figure 13 Continuous ridge vent structure ventilates both the old attic and the new airways.

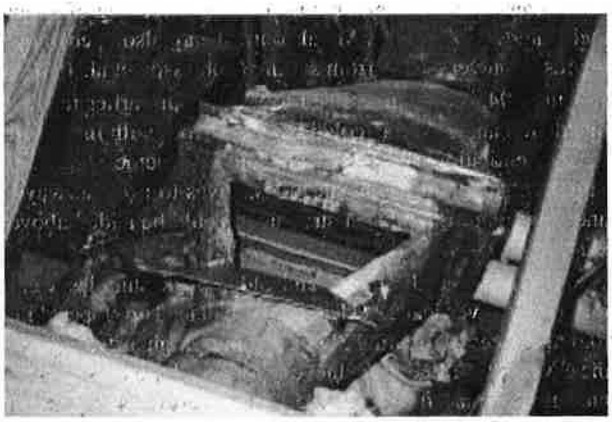

Figure 14 Inspection opening on heating duct. It was "only" open about 2 in. at the top. We bent it back further to show it better.

airways. Cross-purlins are a very effective method of providing ventilation in valleys, as shown in Figure 12. The continuous ridge vent structure (Figure 13) exhausted both the existing ventilated attic and the new airways created by the sleepers and cross-purlins. It was framed to interconnect each individual airway.

These modifications were completed in January 1995. The winter of 1994-95 was mild. We observed no icing problems then and none were reported to us. The winter of 1995-96 was severe, producing major ice dams and icings on many roofs and some ice dams even on well-ventilated roofs. Some icicles and ice dams formed along the eaves of the Hanover Police Facility even after the ventilation improvements of the year before. Minimal icing occurred on the east eaves of the facility and along the north eaves of the main east-west roof, indicating that the improved ventilation was working. The amount of icing that occurred along the south eaves of the main roof and in the valley over the dispatch center was more than we expected.

We inspected this facility again in February 1996. The main attic was still quite hot. Hot air was leaking up through the ceiling insulation at some penetrations, and some ceiling insulation was displaced and not very effective. Gaps in the vapor retarder allowed hot indoor air to infiltrate into the attic. Hot air was blowing out of inspection openings cut in metal heating and ventilating ducts (Figure 14). Metal flaps covering these rough-cut inspection openings were not sealed properly, and duct insulation was missing at all five locations where such inspection openings had been created. Heating and ventilating ducts contained very little insulation, and, thus, they were losing a lot of heat to the attics. Some of this insulation was still falling off some of these ducts. Great quantities of heat was being lost into this attic from sources that were relatively easy to fix. These deficiencies were corrected in November 1996. The rest of that winter (1996-97) the roof suffered no icing problems. However, it was not a very harsh winter. Our observations suggest that the roof will no longer suffer chronic icing problems.

While we felt that correcting these deficiencies would solve the icing problem, we also recommended that a small test section be installed on the south-facing slope of the attic. One and one half inches (38 mm) of extruded polystyrene insulation were added to the underside of the original roof deck to further reduce attic heat losses up into the new ventilated space above (Figure 15). This is a somewhat inefficient place to add insulation since the attic below is ventilated with cold outdoor air. However, all the timber trusses and HVAC equipment in the attic made it quite difficult to add insulation to that already on the attic floor and on the hot HVAC equipment in the attic.

We visually inspected the attic insulation test section periodically during the winters of 1996-97 and 1997-98. On occasion we noticed increases in snow over the test section, indicating that the extra insulation was keeping the roof slightly cooler there. We noticed some differences in icing

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Figure 15 *Extruded polystyrene insulation added to the underside of a portion of the original roof deck.*

along those eaves, but the chronic icings of the past have not reoccurred. We have tentatively concluded that the attic does not need additional insulation, but it probably needs additional air leakage control. The test section remains in place, and we periodically drive by the roof to see if any differences occur there under more severe icing conditions.

CONCLUSIONS

Ventilation coupled with additional insulation and reductions in air exfiltration can eliminate chronic icings along the eaves of roofs in cold regions. Ventilation may not be needed to solve such problems in areas where roofs are covered by only a little snow for short periods, but "deep" in snow country, ventilation is the key to solving ice damming problems at eaves.

Improved ventilation can increase exfiltration of warm, moist indoor air up into attics and cathedral ceiling airways. Attention must be given to minimizing such exfiltration since it can significantly reduce the effectiveness of ventilation provisions.

Our method for sizing inlet and exhaust openings of attic ventilation systems should not be used to size such openings and the airways of cathedral ceilings. Unless those openings and airways are much larger, the head losses in them will result in reduced ventilation rates and inadequate airway cooling. Improved guidelines are needed for the sizing of ventilation systems of cathedral ceilings.

Simple roofs are relatively easy to ventilate, but roofs with valleys and other complications often require provisions such as cross-purlins to interconnect airways and move cold ventilating air into these areas.

Heat losses from warm HVAC equipment located in attics must be considered when sizing ventilation systems. Such equipment should be carefully inspected for heat leaks, and such leaks should be eliminated in conjunction with attic ventilation improvements.

When ventilation improvements do not fully accomplish the desired result, the ventilation system may be undersized or blocked airways, air exfiltration, and other inadequacies in the building envelope may need to be eliminated.

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