# VENTILATING CATHEDRAL CEILINGS TO PREVENT PROBLEMATIC ICINGS AT THEIR EAVES

**WAYNE TOBIASSON, THOMAS TANTILLO and JAMES BUSKA**
Cold Regions Research and Engineering Laboratory (CRREL)
Hanover, New Hampshire, U.S.A.

Building heat from an unventilated steep-slope roof system can cause bottom melting of snow on that roof's surface. This often creates icicles, ice dams, leaks and structural damage at cold eaves. A prior study of attics showed that, to minimize such problems, attic ventilation systems should be sized to keep the underside of the roof below freezing when it is 22°F (-5.6°C) outside. When it is colder than that, it is easier to ventilate with outside air, and when it is warmer than 22°F (-5.6°C), meltwater seldom refreezes at eaves. In this paper, mathematical expressions for sizing airways of cathedral ceilings of various slopes, lengths and insulating abilities are presented. Coldroom tests of 16-foot- (4.9-m-) long airways, some undersized and some oversized, show that the mathematics produces airways that do indeed perform as expected. In some of these tests, airways were blocked by expanding fibrous glass insulation. Air barriers and rigid insulation boards are shown to offer solutions to this problem. Design guidelines in the form of graphs make the task of sizing cathedral ceiling airways, as well as their inlet and exhaust openings, quick and easy.

**KEYWORDS**

Air Barriers, Airways, Cathedral Ceilings, Ice Dams, Icings, Insulation, Roofs, Snow, Ventilation.

## INTRODUCTION

When building heat melts the bottom of snow on a sloping roof in cold weather, the meltwater runs downslope to the cold eaves, where icings and ice dams are created (Figure 1). Adding insulation to the roof reduces the amount of heat available to melt snow, but even well-insulated roofs can suffer icing problems because snow is a good insulator. For example, a 70°F (21°C) building with an R30 roof that is covered with 12 inches (305 mm) of snow, which has an R value of 1 ft²h°F/Btu per inch (6.9 mK/W) (i.e., a total R-value of 12 ft²h°F/Btu [2.1 m²K/W]), will experience melting at the base of the snow pack when the outside temperature is 17°F (-8°C) or higher. Only when the outside temperature is lower than 17°F (-8°C) will the base of the snow on that roof be below freezing. With more snow on the roof, the likelihood off creating icicles and ice dams increases. Thus, insulation alone, while playing an important role in reducing icings, has limitations.

*Figure 1. Severe icings along the eaves of a poorly ventilated roof.*

By allowing cold outside air to bathe the underside of a roof deck, a significant portion of the heat that would melt snow can be removed, thereby eliminating most icing problems. When it is extremely cold outside, that cold air, when used for ventilation, can easily remove lots of heat. As it gets warmer and warmer outside, it takes more and more outside air to do the job. In addition, the stack effect (i.e., chimney draft), which causes that air to move up the underside of the roof deck, is diminished. Winds can also promote ventilation, but because they may not blow during critical periods, they generally are not considered in the design of roof ventilation systems.

Prior CRREL studies of sloped roofs have shown that it is hardest to ventilate with outside air when it is 22°F (-5.6°C) outside [1, 2]. When it is colder than that, it is easier to ventilate with outside air and when it is warmer than 22°F (-5.6°C), meltwater seldom refreezes at eaves. These studies conclude that the design of ventilation systems (natural or mechanical) for minimizing icings at eaves should be based on an outside temperature of 22°F (-5.6°C).

In these prior studies, guidelines were established for sizing ventilation systems for sloped roofs having attics. For such ventilation systems, all the resistance to airflow in the ventilation system is at the inlets and outlets. The big open attic spaces are assumed to offer no resistance. These guidelines have been used with success to solve chronic icing problems on numerous buildings. They define the size of inlets and outlets needed to achieve the desired result. (i.e., enough ventilation to keep the attic below freezing when it is 22°F [-5.6°C] or less outside).

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We caution that these guidelines may somewhat underestimate ventilation needs for roofs located in deep snow country (e.g., above 6000 feet [about 1800 m]) in the mountains of the North American West, owing to the extreme daytime solar radiation and extreme nighttime radiational cooling experienced there.

## CATHEDRAL CEILINGS

The attic guidelines cannot be used without adjustment for cathedral ceilings, because the narrow airways created above the insulation in such roofs (Figure 2) offer considerable resistance to airflow. However, we have used these guidelines with success to determine the size of attic ventilation systems, then multiplied them by three to five to size the airways of cathedral ceilings [3].

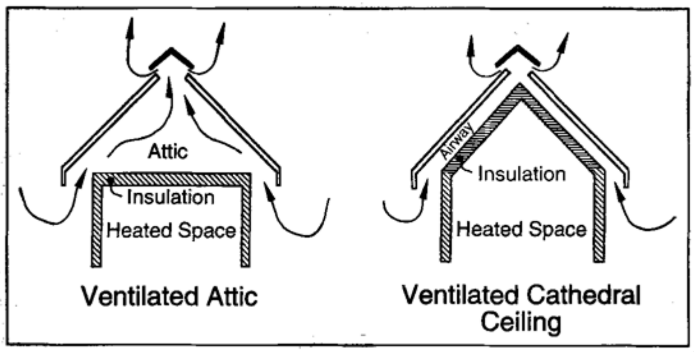


*Figure 2. Ventilated attics and cathedral ceilings.*

This study has allowed us to investigate this issue in more detail by developing the mathematics of flow in such airways and then assessing how well it applies to actual airways tested in a coldroom.

## MATHEMATICS

Figure 3 shows various roof and airway dimensions. The following mathematical relationships were developed from equations in the 1997 Fundamentals volume of the *ASHRAE* (American Society of Heating, Refrigerating and Air-Conditioning Engineers) *Handbook* [4]. Specific ASHRAE equations used are shown in brackets. For example, [C3E11] refers to Chapter 3 Equation 11 in that reference.

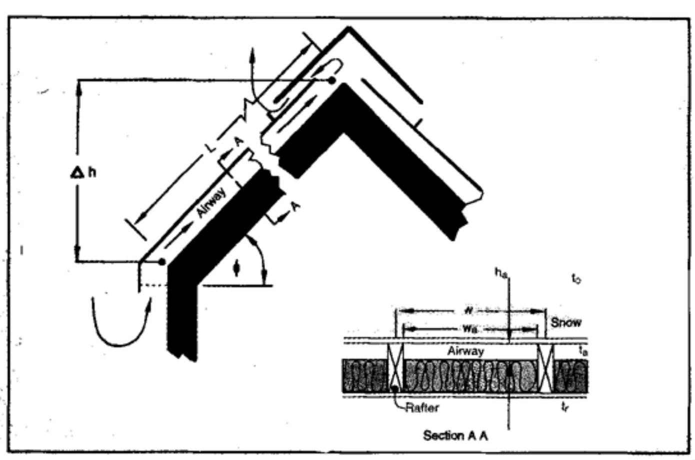


*Figure 3. Roof and airway dimensions.*

The amount of heat entering the airway from below is:

$$q_a = L(t_r - t_a)/R \quad [C3E11] \qquad \text{(eq. 1)}$$

where

- $q_a$ = heat added to airway, Btu/h per running foot of eaves.
- $L$ = airway length, ft.
- $t_r$ = temperature of heated space below roof insulation, °F.
- $t_a$ = average temperature of airway (or attic) air, (i.e., $(t_o + t_x)/2$), °F.
- $t_o$ = temperature of outside air entering airway (or attic) at eaves, °F.
- $t_x$ = temperature of air exiting airway (or attic) at ridge, °F.
- $R$ = thermal resistance of ceiling, ft²h°F/Btu.

[In SI (International System of Units) units, $q_a$ is in watts per running meter of eaves (W/m); L is in meters; temperatures are in °C and R is in m²K/W]

At the design condition, $t_o$ = 22°F (-5.6°C), $t_x$ = 32°F (0°C) (to prevent melting of snow on the roof) and $t_a$ = 27°F (-2.8°C). Thus, the amount of building heat entering the airway is:

$$q_a = L(t_r - 27)/R \qquad \text{(eq. 2)}$$

[In SI units, $q_a = L(t_r + 2.8)/R$]

The amount of heat removed by warming the airway air is :

$$q_r = 60\, Q\, c_p\, \rho (t_x - t_o) \quad [C25E8] \qquad \text{(eq. 3)}$$

where

- $q_r$ = heat removed by airway, Btu/h per running foot of eaves.
- $Q$ = airflow rate, ft³/min., i.e., cfm, per running foot of eaves.
- $c_p$ = specific heat of air, 0.24 Btu/lb°F @ 27°F
- $\rho$ = density of air. For the range of temperatures being considered this equals 39.71/(its temperature in °F + 460). $\rho = 0.0815\ lb_m/ft^3$ @ 27°F.

[In SI units, $q_r = 1300\, Q(t_x - t_o)$ with $q_r$ in watts per running meter of eaves (W/m); Q is in m³/s per running meter of eaves; $c_p$ = 1.0 kJ/kg°C and $\rho$ = 1.30 kg/m³ @ -2.8°C]

When $t_o$ = 22°F (-5.6°C) and $t_x$ = 32°F (0°C),

$$q_r = 11.74Q \quad [\text{In SI units, } q_r = 7280\, Q] \qquad \text{(eq. 4)}$$

or

$$Q = 0.08521 q_r \quad [\text{In SI units, } Q = 0.000137\, q_r \qquad \text{(eq. 5)}$$

At the design condition (assuming steady state heat flow), the average temperature of the airway ($t_a$) is only 5°F (2.8°C) higher than the outdoor temperature ($t_o$). This small temperature difference, along with the insulating ability of snow, does not allow much heat to be lost up through the snow on the roof. Calculations suggest that between 10 percent and 25 percent of the heat added by typical buildings is removed up through the snow. We have made the conservative assumption that no heat is lost up through the snow. In this case $q_r = q_a$. Equating them and substituting $q_a$ in equation 2 for $q_r$ in equation 5 gives:

$$Q = 0.08521L(t_r - 27)/R \quad \text{[In SI units, } Q = 0.000137\,L(t_r + 2.8)/R] \qquad \text{(eq. 6)}$$

It is convenient to first calculate the inlet areas needed if this were an attic not a cathedral ceiling. For an attic where all the resistance to airflow is assumed to be at the inlets and outlets, the airflow rate (Q), is related to the net free area of inlets (or outlets, which should be about the same area) as follows:

$$Q = 60(0.65)(A_{i\ attic}/144)[(64.4)(\Delta h/2)(t_a - t_o)/(t_a + 460)]^{0.5} \quad \text{[C25E37]} \qquad \text{(eq. 7)}$$

where

- $Q$ = attic air flow rate, $ft^3$/min. per running foot of eaves.
- $A_{i\ attic}$ = net free open area at eaves, in.$^2$/running foot of eaves.
- $\Delta h$ = elevation difference between eaves and ridge, ft.
- $\Delta h$ = $L \sin \phi$ where $\phi$ is the roof slope, degrees.

[In SI units, $Q = 0.00204[L \sin \phi(t_a - t_o)/(t_a + 273)]^{0.5}$ with Q in $m^3/s$ per running meter of eaves; $A_{i\ attic}$ in $mm^2$ per running millimeter of eaves and $\Delta h$ in meters]

When $t_a = 27°F$ (-2.8°C) and $t_o = 22°F$ (-5.6°C) this reduces to:

$$Q = 0.1557\,A_{i\ attic}(L \sin \phi)^{0.5} \quad \text{[In SI units, } Q = 0.000208\,A_{i\ attic}(L \sin \phi)^{0.5}] \qquad \text{(eq. 8)}$$

Equating equations 6 and 8 and solving for $A_{i\ attic}$, when $t_r = 70°F(21°C)$ gives:

$$A_{i\ attic} = 23.51(L/\sin \phi)^{0.5}/R \quad \text{[In SI units, } A_{i\ attic} = 15.67(L/\sin \phi)^{0.5}/R] \qquad \text{(eq. 9)}$$

Because a cathedral ceiling airway creates additional head losses, its inlet, exhaust and cross-sectional areas each must exceed $A_{i\ attic}$, which only applies to attics. Thus, the height of the airway, $h_a$, in inches, must exceed 0.083 $A_{i\ attic} w/w_a$, where $w_a$ is the width of the airway in inches and w is the center-to-center rafter spacing in inches as shown in Figure 3. [In SI units, $h_a$, in mm, must exceed $A_{i\ attic}\, w/w_a$ where $A_{i\ attic}$ is in $mm^2$/mm and w and $w_a$ are in mm]. By calculating this value, which $h_a$ must exceed, the designer begins to appreciate the size of the airway needed for a cathedral ceiling.

The velocity of flow up an airway needed to produce the required cooling is the flow rate Q obtained using equation 6 divided by the cross-sectional area of the airway. Because these calculations are being made per running foot of eaves, it is necessary to express the width of the airway as a portion of every running foot of eaves available. In other words, the portion of every running foot taken up by the rafters must be considered. Thus,

$$v_a = 12Qw/h_a w_a \qquad \text{(eq. 10)}$$

where

- $v_a$ = average velocity of air flowing up the airway, ft./min.
- $w$ = rafter spacing, in.
- $w_a$ = airway width, in.

[In SI units, $v_a = 1000\,Qw/h_a w_a$ with $v_a$ in m/s and w, $w_a$ and $h_a$ in mm]

By selecting several candidate values for $h_a$ (all greater than the inadequate value discussed above), equation 10 can be used to determine the velocity of air in each candidate airway. The frictional head losses in each candidate airway can then be determined as follows:

$$h_f = 0.000276\,L\,v_a^2/R_e d \quad \text{[C2E27]} \qquad \text{(eq. 11)}$$

where

- $h_f$ = airway head loss, feet of air
- $R_e$ = Reynolds Number, dimensionless (must be less than 2000 for this laminar-flow equation to apply)
- $d$ = hydraulic diameter, feet

[In SI units, $h_f = 3265 L v_a^2/R_e d$ with $h_f$ in m of air and d in mm]

Since $R_e = 60 v_a d/\nu$, where $\nu$ is the kinematic viscosity of the airway air and $\nu = 0.5052\ ft^2/h$ for the 22°F to 32°F airway air,

$R_e$ = $118.76\,v_a d$ [In SI units, $R_e = 76.68 v_a d$]

and

$d$ = $0.1467 h_a w_a/(h_a + w_a)$ where $h_a$, $w_a$, and w are in inches and d is in feet. Note that we have multiplied the value of d in the ASHRAE 1997 Fundamentals [C32E24] by 0.88 according to recommendations in *Viscous Fluid Flow* by F.M. White for "skinny" rectangular ducts [5].

[In SI units, $d = 1.76 h_a w_a/(h_a + w_a)$ with all units in mm]

The total head available because of the stack effect produced by the warmer air in the airway is:

$$h_t = \Delta h\,(\rho_o - \rho_x)/(\rho_o + \rho_x) \quad \text{[C25E28]} \qquad \text{(eq. 12)}$$

where

- $h_t$ = total head available from stack effect (i.e., chimney draft), feet of air
- $\Delta h$ = elevation difference between the inlets at the eaves and the outlets at the ridge, (i.e., $L \sin \phi$), ft.
- $\rho_o$ = density of air entering the airway, 0.08239 $lb_m/ft^3$ @ 22°F
- $\rho_x$ = density of air exiting the airway, 0.08072 $lb_m/ft^3$ @ 32°F

This reduces to,
$h_t = 0.01027L \sin \phi$ [In SI units, $h_t = 0.03369L\sin \phi$ with L in m] (eq. 13)

If $h_t$ is less than $h_f$ for any of the candidate airways, that airway is not big enough. If $h_t$ exceeds $h_f$, then the remainder (i.e., $h_t - h_f$) is available for head losses at the inlets and outlets. Half of the remainder is available for the inlets and half for the outlets when they are about the same size, which is desirable.

Having already used equation 7 to determine the area of inlets for the attic situation, where the full head loss (i.e., $h_t$) occurs across the inlets and the exhausts, it is now possible to determine the area of inlets and exhausts for the airway by proportions. Because airflow through openings is proportional to the square root of the head loss across them, as in [C25E33], the area of inlets required for each candidate airway is

$$A_{i\ airway} = A_{i\ attic}[h_t/(h_t - h_f]^{0.5}$$

where

$A_{i\ airway}$ = area of inlet (or exhaust) openings for a cathedral ceiling, in.$^2$ per running foot [In SI units, mm$^2$ per running mm] of eaves or ridge.

In this manner, the size of several candidate airways, as well as their inlet and exhaust openings, can be determined. Selection of the best combination can vary among roofs, depending on economics, roof geometry, designer preference and other factors.

Design curves, based on these mathematical relationships, are presented at the end of this paper after the discussion of the coldroom tests used to validate these relationships.

## COLDROOM TEST APPARATUS

To validate the applicability of the equations in the previous section, a test roof with two side-by-side, 21¾-inch- (0.55-m-) wide, 16-foot- (4.9-m-) long airways was built in a coldroom at CRREL. The two airways could be configured differently and their heights could be varied. Figure 4 shows the dimensions of the test roof and where it was instrumented. Extruded polystyrene insulation boards were used to simulate the insulating value of snow on the roof.

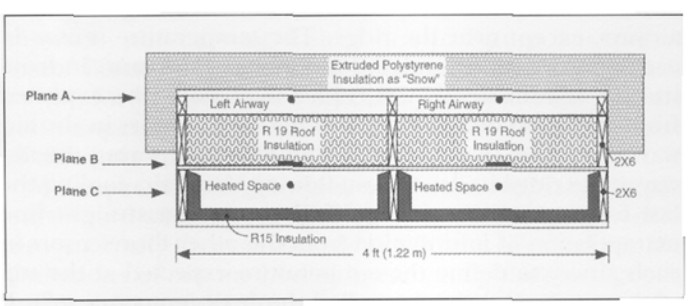


*Figure 4a. Test roof dimensions*

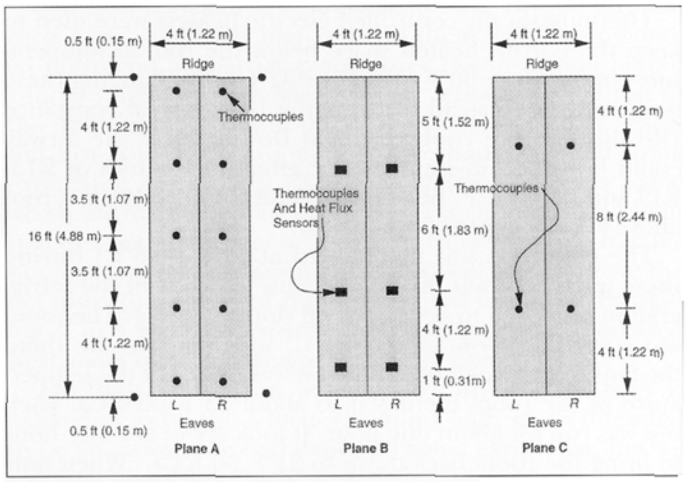


*Figure 4b. Location of instrumentation on test roof*

Figure 5 shows the test roof supported on a stripped down boat trailer. The tower also shown in that figure was equipped with a chain fall that allowed one end of the roof to be raised to create slopes up to 44 degrees . Tests were run at slopes of 0, 15, 30 and 44 degrees. In Figure 5 the roof is at a slope of 15 degrees. In Figure 6 it is at a slope of 44 degrees.

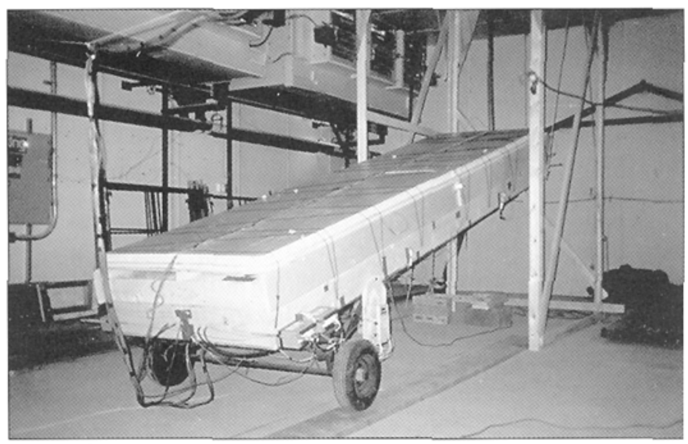

***Figure 5.*** *Test Roof raised to 15 degree slope in the coldroom.*

***Figure 6.*** *Test roof raised to 44 degree slope in the coldroom.*

Thermostatically controlled electric heaters were used to keep the narrow heated space below the roof at temperatures of 50, 70 or 90°F (10, 21 or 32°C). By changing these temperatures, instead of changing the thermal resistance (R-value) of the roof, the heat flowing into the airway could be varied to simulate the effect of R-values of R13, R19 and R36 ft$^2$h°F/Btu (2.3, 3.3 and 6.3 m$^2$K/W) in a roof above a room kept at 70°F (21°C).

The coldroom was maintained at 22°F (-5.6°C) during these tests. That was difficult because the fans in the refrigeration units had to be turned off during testing. The room was cooled to about 21°F (-6.1°C) with the fans on; then, the fans were turned off and a test was run until the temperature of the room increased to about 23°F (-5.0°C). Each test was run for about one hour. It took about another hour to bring the room back down to 21°F (-6.1°C). When only the slope of the roof was changed, tests could be cycled about every two to three hours. However, when the temperature of the heated space or the configuration of the airways was changed, cycle time increased considerably.

Data from 22 thermocouples, six heat flux sensors, two watt-hour meters and one watt meter were obtained once every two minutes during testing. Numerous test runs were made at various slopes, heated space temperatures, airway heights and "snow" depths.

## TEST RESULTS

### Introduction

It is well known that the "as-built" placement of batt insulation between rafters in cathedral ceilings and between ceiling joists in roofs with attics can be far from the idealized placement envisioned by designers. Many sloped roof ventilation systems are compromised by insulation that blocks air intakes at eaves or blocks airways above cathedral ceilings. The R19 (3.3 m$^2$K/W) fibrous glass batt insulation was installed with care so that it was in its intended position. This was done by building the "two-by-six" (51-mm-by 152-mm) roof frame upside down on the floor of the coldroom, then installing the insulation, the heat flux sensors, the 4-mil (0.1-mm) polyethylene vapor retarder and the ½-inch (13-mm) plywood "ceiling," then flipping the roof over.

### Unventilated Tests

One series of tests was done without airways. Half-inch (13-mm) thick plywood was placed over the insulated panels described in the previous section, and various amounts of extruded polystyrene insulation were placed on it to simulate snow on the roof. The edges of the test roof were also insulated using extruded polystyrene boards.

The "snow" insulation boards were held in place with bungee cords as shown in Figure 6. Those insulation boards were tight against the roof, but in hindsight, they also should have been sealed to it and each other with tape. The heat flux sensors and thermocouples indicated that the net insulating ability of those boards was only one-half to two-thirds of the thermal resistance of the boards themselves. Air movement at the seams and between them and the roof below is considered to be the cause of the reduction. We intended to run most of the tests with the equivalent of about 15 inches (381 mm) of snow on the roof to represent the "worst-case" condition of very little heat loss (and cooling of the airway) up through the snow. Because of air gaps between the roof and the "snow" insulation, we succeeded in creating only a moderate (about 6 inches [152 mm]) snow cover. Thus, these test airways did not get quite as warm as the worst case. Because of this shortcoming, these tests more closely represent lesser, "real-world" snow covers.

Figure 7 plots the net insulating ability of the "snow" for tests with no airway vs. the temperature at the base of the "snow." Assuming that the thermal resistance of snow is about 1 ft$^2$h°F/Btu per inch (6.9 mK/W), we can also think of the R-value shown in Figure 7 as snow depth in inches. The curving line in that figure is the trend line for those data points. Figure 7 indicates that, for these conditions (heated space at 70°F [21°C] and R19 [3.3 m$^2$K/W] insulation in the roof), it takes very little "snow" (only about 5 inches [about 130 mm]) to raise the temperature at the base of the snow above its melting point (32°F [0°C]) at the design condition (22°F [-5.6°C] outside). As more snow is present on the roof, the temperature at the base of the snow increases. The temperature there stays lower for roofs containing more insulation. However, for a roof with a thermal resistance (R-value) of 40 ft$^2$h°F/Btu (7.0 m$^2$K/W), problematic melting can occur when just a foot of snow is present.

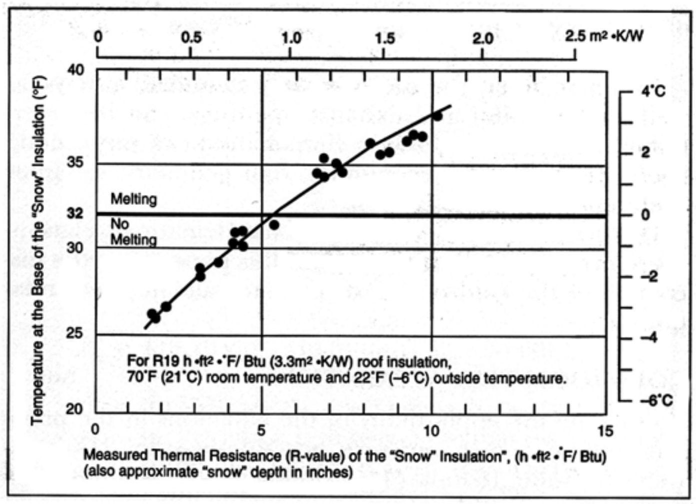


*Figure 7. Measured and calculated temperatures of "snow" on the test roof.*

### Airways

As shown in Figure 4, temperatures were measured at five places along the top of each airway from its eaves to its ridge. Figure 8 shows three typical temperature profiles. A uniform increase in temperature is evident along two of the airways, except near the ridge. The temperature sensor in each airway near the ridge was 6 inches (152 mm) in from its end. It consistently was colder than would be expected from the trend defined by the other four sensors in the airway. It appears that a loop of cold air was entering the airway at the ridge under the out-flowing warm air, cooling the last few feet of the airway. We have used a straight line extrapolation of information from the other four sensors in each airway to define the temperature expected at the top of the airway (hereinafter called the "exit temperature"). If the exit temperature exceeded 32°F (0°C), that airway was considered to be inadequate, since snow on the roof above would be melted, causing icings at the eaves.

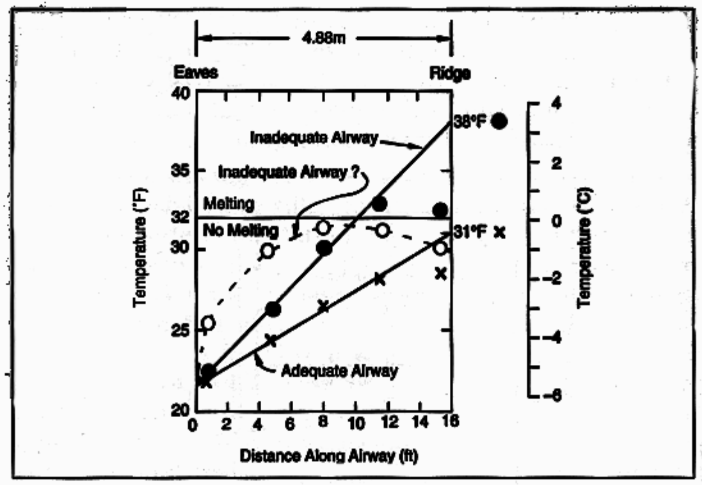


*Figure 8. Typical profiles of airways tested: one adequate, two inadequate.*

The airway represented by the upper straight line in Figure 8 ($h_a$ = ½ inch [13 mm], slope = 44 degrees) had an exit temperature of 38°F (3.3°C) and thus was inadequate. The airway represented by the lower straight line in Figure 8 ($h_a$ = 1 inch [25 mm], slope = 30 degrees) had an exit temperature of 31°F (-0.6°C) and thus was big enough to avoid snow melt and icings.

The third temperature profile shown in Figure 8 ($h_a$ = ¾ inch [19 mm] slope = 15 degrees) does not display the linearity that the others do. Those data points are connected by a curving dashed line to show this. This type of nonlinear temperature profile was present for some airways, most either blocked, narrow or low slope.

For these airways, the temperature profiles indicated that a large part of the cooling was attributable to cold air entering at the ridge rather than at the eaves. Anyone who has tried to start a fire in a cold wood stove can appreciate this tendency for cold, dense air to descend down a chimney. For these airways, classic chimney draft, from their eaves up to their ridge, was overpowered by this "reverse" chimney draft mechanism.

As cold air slowly descends down such airways, it is warmed. The warmed, lighter air then flows up the airway above the descending cold air. This counterflow within the upper portion of the airway reduces flow of outdoor air up the airway at its eaves. This reverse stack effect was present in 16 of the 42 airways tested. For seven of these airways, temperatures above 32°F (0°C) were present within them and thus they failed to perform. However, the temperature did not exceed 32°F (0°C) at any place along the remaining nine airways. The airway whose temperatures are shown by the curving dashed line in Figure 8 is one of them. When we do a straight line analysis of those data, as we did for the other two data sets shown in Figure 8, the exit temperature is about 39°F (3.9°C), and it fails in spite of never warming above 32°F (0°C).

We expect that slightly longer versions of these nine airways would warm above 32°F (0°C) and thus, we are reluctant to classify them as successful. While acknowledging the limitations of our method of linear extrapolation to generate an exit temperature, we have used that method to classify these nine airways as failures. Perhaps some short narrow airways, which we reject, can perform successfully. Such airways deserve further study.

Our first series of tests were to be side-by-side airways, each 1 inch (25 mm) high. One of them had a spun-bonded polyolefin air barrier placed over the insulation before 1-inch- (25-mm-) high spacers were screwed to the top of the three rafters to form the two airways. The other airway did not contain an air barrier. We had expected some expansion of the R19 (3.3 $m^2K/W$) fibrous glass batts, which are manufactured to fill the 5 ½-inch- (140-mm-) high spaces created between "2 x 6" rafters. The air barrier would resist this expansion and, we speculated, improve the net insulating ability of the fibrous glass insulation by placing it in a windless environment less prone to increased heat losses by air movement within the fibrous glass.

The batt insulation without the air barrier over it expanded to fill the 1-inch- (25-mm-) high space intended to be an airway. We had expected some expansion, but we did not expect this much.

The fibrous glass insulation in the adjacent airway was exerting similar expansion forces on the air barrier when we installed it. Had this air barrier been installed before the fibrous glass was installed, which would be the normal sequence on most real roofs, it is logical that it could have been installed somewhat tighter because no fibrous glass would be bowing it during its installation. We tried to install this air barrier very tightly, thus much of what we subsequently experienced can be expected, all things considered, on most real roofs. Figure 9 shows these two airways just prior to our placing the plywood roof deck on them. The unrestrained fibrous glass has risen more than 1 inch (25 mm) and is even forcing its way up around the straight edge, which rests on the top of the 1-inch- (25-mm-) high strips screwed to the "2 x 6" rafters to create the airway. The air barrier has also been forced up by the fibrous glass so that over most of the airway (between the two arrows on the straight edge) it is pressing against the bottom of the straight edge. Thus, the airway above the air barrier was of very limited size, and no airway existed when no air barrier was present.

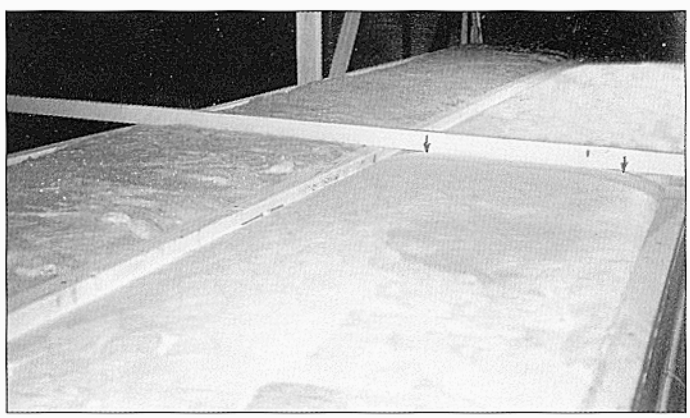

*Figure 9. One-inch- (25-mm-) high airways mostly blocked by expansion of fibrous glass insulation.*

Exit temperatures for tests with slopes from 15 degrees to 44 degrees ranged from 38 to 43°F (3.3 to 6.1°C) for the 1-inch (25-mm-) high airway blocked with fibrous glass insulation and from 37 to 41°F (2.8 to 5.0°C) for the 1-inch- (25-mm-) high airway not completely blocked by fibrous glass because of the presence of an air barrier. Both of these airways provided inadequate ventilation. They warmed above their limiting design temperature of 32°F (0°C).

Some as-built cathedral ceiling ventilation systems may be rendered ineffective by expansion of properly installed fibrous glass insulation into spaces intended to be airways. Certainly, some designers and builders are aware of this. They install forms of plastic or cardboard (or whatever) between rafters throughout cathedral ceilings, not just at eaves, where they are installed more commonly in attics.

We next increased the height of the spacers to 2 inches (51 mm). The fibrous glass without an air barrier continued to expand upward. As shown in Figure 10, it almost filled the 2-inch (51-mm) space intended to be an airway. Over the center half of the airway, it came within ½ inch (13 mm) of completely blocking it. This airway received some ventilation but exit temperatures were still quite high (35 to 39°F [1.7 to 3.9°C]).

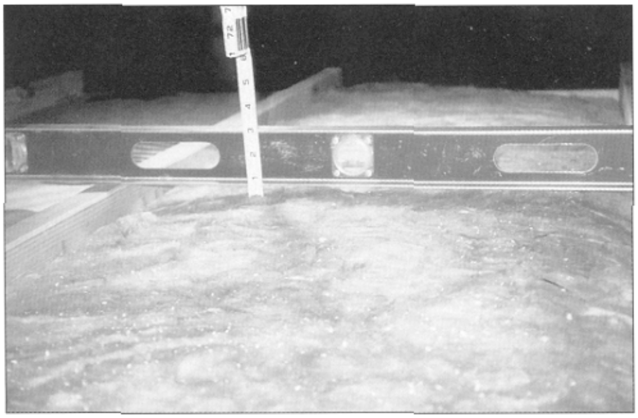

*Figure 10. Expanding fibrous glass came close to completely blocking this 2-inch (51-mm) high airway.*

In the adjacent airway, the air barrier resisted the fibrous glass expansion. As shown in Figure 11, at no place did this air barrier touch the underside of the roof deck. It was ¾ inch (19 mm) below the underside of the roof deck along the centerline of the airway.

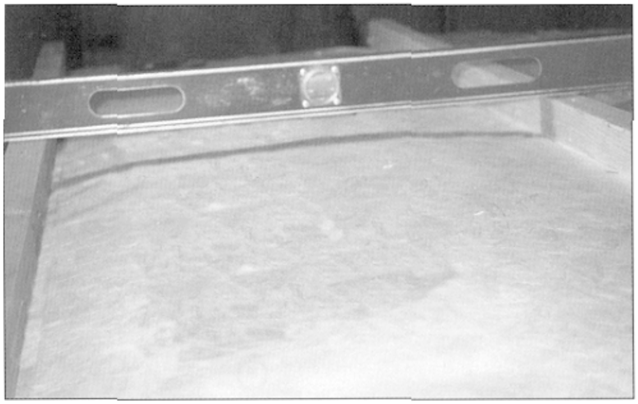

*Figure 11. Air barrier reduced the intrusion of fibrous glass insulation into this airway.*

Results for this and another airway with an air barrier are presented in Figure 12. At a slope of 15 degrees the airway shown in Figure 11 (lower line in Figure 12) warmed to above 32°F (0°C) but at test slopes of 30 and 44 degrees it passed the test (i.e., it remained below 32°F [0°C] throughout its length). With the bowing of the air barrier, its average height was about 1 inch (25 mm).

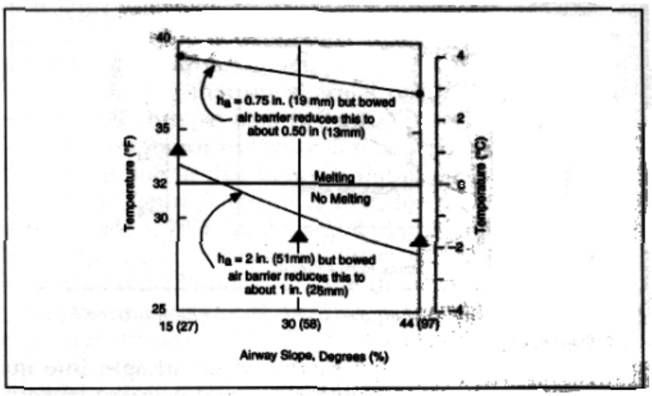


*Figure 12. Exit temperatures for two airways with bowed air varriers.*

The ability of an air barrier to retain a full-width airway is probably limited to airways at least 1½ inches (38 mm) high when rafters are about 2 feet (0.6 m) on center. When rafters are 16 inches (0.41 m) on center, it may be possible to achieve full width airways using 1¼-inch (32-mm) (perhaps 1-inch [25-mm]) spacers above a tightly stretched air barrier.

We investigated one other means of creating "guaranteed" airways using an air barrier over fibrous glass insulation. We removed the air barrier previously discussed and installed a new air barrier on top of 2-inch- (51-mm-) high spacers. We then added ¾-inch (19-mm) spacers over it. Figure 13 shows how little that air barrier was bowed by the relaxed fibrous glass. The airway was at least ½ inch (13 mm) high across its width. Figure 12 shows that this narrow airway provided inadequate ventilation. Nonetheless, providing space below the airway for expansion of fibrous glass insulation can be beneficial. Air barrier bowing can decrease the effective height of an airway by 1 inch but, by providing space into which the fibrous glass insulation can expand below the air barrier, this loss can be reduced to about ¼ inch (6 mm). Thus, providing space for fibrous glass expansion can create a ¾-inch (19 mm) deeper airway when its bottom is an air barrier.

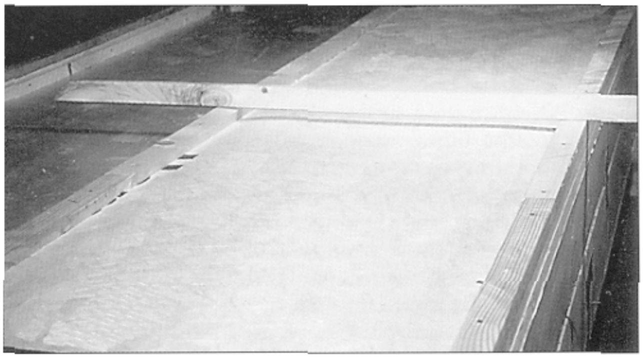

*Figure 13. This air barrier, placed over already expanded fibrous glass, was only bowed upward ¼ inch (6 mm).*

This approach could be used in newer buildings by buying insulation sized to fit one size rafter smaller than is actually present. In other words, for "2 x 8" rafters, R19 (3.3 $m^2K/W$) insulation, intended to fill the space between "2 x 6" rafters, would be used. With the air barrier installed before the insulation (in a new roof system), the insulation could be installed to fill the space below the air barrier. This "expanded" insulation would have a slightly lower thermal resistivity (i.e., unit R-value), but because there are 2 inches (51 mm) more of it, its total R-value would increase. Our heat flux sensors indicated that the expanded fibrous glass insulation had a thermal resistance of 23.8 $ft^2h°F/Btu$ (4.2 $m^2K/W$), while the same insulation used as intended by the manufacturer had a thermal resistance of 20.6 $ft^2h°F/Btu$ (3.6 $m^2K/W$). The unit values (i.e., thermal resistivity) of the expanded and normal fibrous glass were 3.17 $ft^2h°F/Btu$ per inch (21.8 mK/W) and 3.75 $ft^2h°F/Btu$ per inch (25.8 mK/W).

In addition, the in-place R-value of fibrous glass would be closer to its "advertised" value when it is covered by an air barrier than when flowing air has direct access to it [6]. Of course, the primary reason for using the relaxed insulation in this way is to create a reliable, large airway above it for the purposes of ventilating the roof. Additional studies are needed to quantify the net thermal gain by insulating roofs in this way, but it is clear that it is a reliable way of creating guaranteed airways. The use of an air barrier for this purpose is also quite appealing because most moisture problems in roofs are caused by air leaks, not by diffusion [7]. The installation of air barriers for creating guaranteed airways also clearly reduces the potential for moisture problems in framed roofs. Such an air barrier also should, to some degree, serve as a secondary line of defense against roof leaks caused by flaws in the roof system and ingestion of driving rain and blowing snow at ridge vents (several on the market have that tendency).

Another way of creating guaranteed airways is to use rigid insulation boards for the bottom of airways [8]. Once the roof is framed and the deck installed, spacers are attached to the sides of the rafters at the top. Rigid insulation boards are then cut to fit between the rafters. The spacers keep the boards some distance below the deck, creating the airway. We used 1-inch (25-mm) boards of extruded polystyrene for this. The previously mentioned tendency of fibrous glass batt insulation to expand upward did not cause noticeable bowing of these boards at rafter spacings of 21¾ inches (0.55 m). Although rigid insulation boards do not provide as reliable resistance to air leakage as continuous air barrier sheets, rigid insulation boards certainly improve the air leakage resistance of such roofs. Because they are not bowed upward as air barrier sheets are, some of the precautions related to fibrous glass expansion, as discussed previously, are unnecessary.

We constructed guaranteed airways ½, 1 and 2 inches (13, 25 and 51 mm) high using spacers and extruded polystyrene insulation boards. The boards increased the amount of insulation in these tests from about R19 to R24 (3.3 to 4.2 $m^2K/W$). Figure 14 shows the ½-inch- (13-mm-) high airway.

Results of these three tests are presented in Figure 15. The 2-inch- (51-mm-) high airway performed adequately at slopes from 15 to 44 degrees. The 1-inch (25-mm) airway did not suffice at 15 degrees but it did at slopes of 30 and 44 degrees. This is consistent with the findings for the nominal 1-inch (25-mm) airway created with 2-inch (51-mm) spacers and a bowed air barrier as shown in Figure 11. The ½-inch (13-mm) airway was inadequate at all slopes, as was the nominal ½-inch (13-mm) airway with an air barrier (Figure 13). The slopes of the lines for the 1- and 2-inch- (25- and 51-mm-) high airways in Figure 15 are understandable: As slope increases, these airways perform better. The ½-inch- (13-mm-) high airway, also shown in that figure, does not follow this trend. We expect that the air flow complexities mentioned when discussing Figure 8 explain why this inadequate airway behaves as it does.

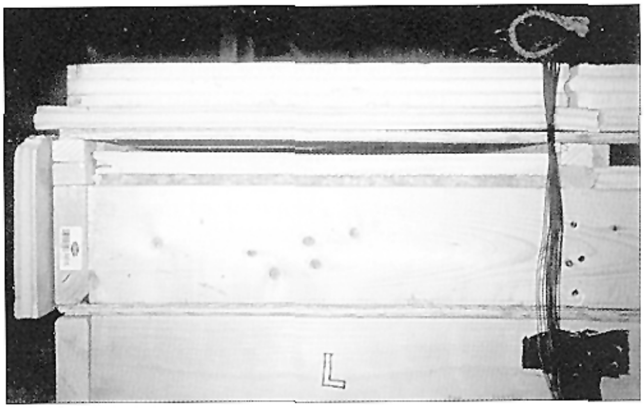


*Figure 14. One-inch- (25-mm-) thick extruded polystyrene insulation boards(the light horizontal band below the dark airway) were not bowed by the fibrous glass insulation below. This airway is only ½ inch (13 mm) high. The insulation boards guaranteed its existence. Also note that a gap exists between the plywood roof deck and the "snow" insulation over the right third of this airway. That may explain why the snow insulation provided less thermal resistance than expected.*

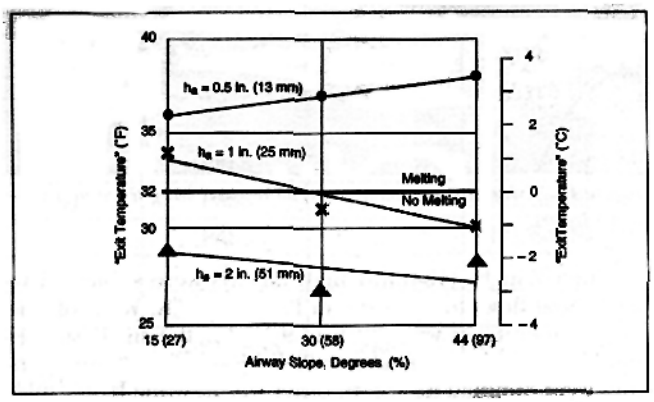


*Figure 15. Exit temperature for airways with bottoms of extruded polystyrene insulation boards.*

## INLETS AND EXHAUSTS

As Figure 14 shows, the ends of the test airways did not contain inlet and exhaust structures, which would have somewhat reduced airflow up the airways. To obtain an appreciation of how much such features would decrease the ability of these airways, a few tests were re-run with these added. Figure 16 shows the inlet and exhaust structures before they were installed. Each contains two strips, each providing 9.2 square inches of net free openings per running foot (19.5 $mm^2$/running mm). Some tests were run with one strip covered with tape, and others were run with both strips open. Figure 16 shows one strip open and the other covered with tape except at its upper end, so its presence can be detected in the photograph. Figure 17 shows the exhaust structure mounted at the top of an airway that is being tested at a slope of 44 degrees. One of those strips is covered with tape.

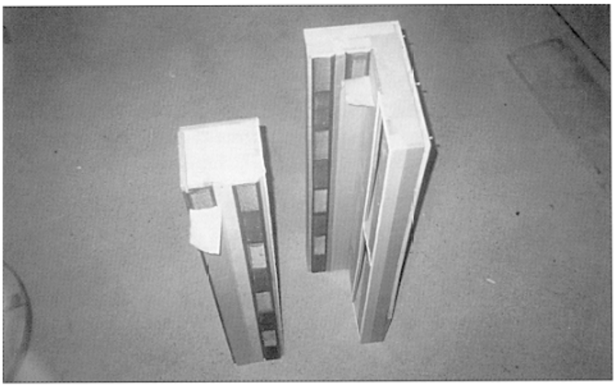

*Figure 16. Intake and exhaust structures before being installed on the test roof.*

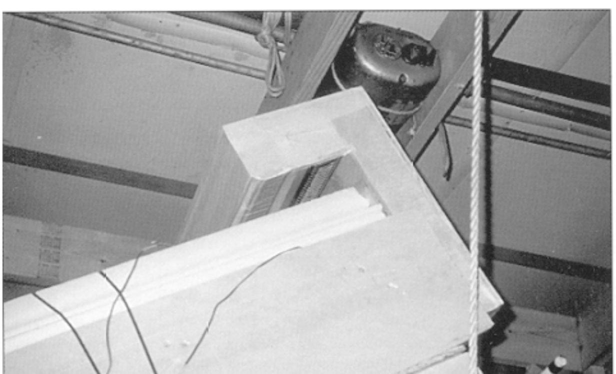

*Figure 17. Exhaust structure mounted on airways being tested at a slope of 44 degrees.*

When ½-inch- (13-mm-) high airways were subjected to large heat flows to simulate an R13 (2.3 $m^2K/W$) roof, the exit temperatures were 39°F (3.9°C) for the smallest inlet openings and just a bit above 32°F (0°C) when these openings were doubled in size. In other words, while larger inlet and outlets improved flow, the improvement was not enough to make these airways perform adequately. With no inlet or exhaust constrictions, this airway had an exit temperature just below 32°F (0°C), and it just met the design goal. These differences in performance show the importance of appropriately sized inlets and exhausts.

For this airway, our calculation procedure indicates that even the unconstricted airway should have failed to meet the design requirement. Our calculations tell us that this airway needs to be about 20 percent higher when it has inlets providing a net free opening of about 20 square inches per running foot (42 $mm^2$/mm). Said in another, more positive, way, these three tests indicate that our design method is less than ¼ inch (6 mm) too high in its prediction of required airway depth.

Other tests were run with these inlets and outlets in place for 1-inch- (25-mm-) high airways over a somewhat better insulated (R19 [3.3 $m^2K/W$]) roof. The exit temperature for all these tests remained unchanged at 31°F (-6°C). Our calculation procedure indicates that, with the smallest inlets and exhausts in place, this airway should have just failed. Instead, it just passed. Our calculation procedure calls for an airway about 25 percent higher.

The inlet and exhaust tests suggest that our calculations call for slightly higher airways than are necessary. Considering some of the assumptions made in our design procedure (e.g., no heat is lost up through the snow on the roof), we think that this finding is reasonable. However, since comprehensive tests of inlets and exhausts were not conducted, we do not consider it appropriate to assume that our design always calls for slightly higher airways than are needed.

## SUMMARY OF TEST FINDINGS

Of the 42 16-foot- (4.9-m-) long airway configurations tested, 25 were inadequate and 17 were able to provide enough ventilation to keep the airway from warming to 32°F (0°C), according to our exit temperature pass-fail criterion. As shown in Table 1, all but three test findings match the mathematical results obtained with our equations. The three tests that passed, but were expected to fail according to the mathematics, attest to the limitations of our assumption that no heat is being lost up through the snow on the roof. In these three tests, the roof was not well insulated (R16 [2.8 $m^2K/W$]), and thus, these airways had to remove a lot of building heat. Heat losses up through the "snow" insulation on them helped remove enough heat to allow these airways to perform successfully.

Using our pass-fail criterion, the equations accurately predicted the performance of almost all airways. Because all tests were for airways only 16 feet (4.9 m) long, we do not have test results to verify the mathematics for longer airways. We expect that the mathematics also works well for longer roofs but these tests do not answer that question.

Our pass-fail criterion can be questioned for nine of the 42 test airways (see Table 1) because we failed airways that never warmed above 32°F (0°C). There was a reverse stack effect in portions of these airways. The mathematics presented in this paper does not describe this mechanism of cooling. Additional studies are needed to better understand such airways.

| Airway Height (in. [mm]) | R-value of roof ft²h°F/Btu (m²·K/W) | Slope (degrees) | Test | Math | Agreement |
|---|---|---|---|---|---|
| 2 in. (51 mm) but mostly blocked by fibrous glass insulation (see Figure 10). | 13 (2.3) | 15 | *F | F | YES |
| | | 30 | F | F | YES |
| | | 44 | F | F | YES |
| | 19 (3.3) | 15 | F | F | YES |
| | | 30 | F | F | YES |
| | | 44 | F | F | YES |
| | 36 (6.3) | 15 | F | F | YES |
| | | 30 | F | F | YES |
| | | 44 | F (?) | F | YES (?) |
| 2 in. (51mm) but closer to 1 in. (25 mm) due to bowing of air barrier (see Figure 11). | 13 (2.3) | 15 | F (?) | F | YES (?) |
| | | 30 | JUST F | F | YES |
| | | 44 | JUST PASS | JUST PASS | YES |
| | 19 (3.3) | 15 | F (?) | F | YES (?) |
| | | 30 | PASS | JUST PASS | YES |
| | | 44 | PASS | PASS | YES |
| | 36 (6.3) | 15 | JUST PASS | JUST PASS | YES |
| | | 30 | PASS | PASS | YES |
| | | 44 | PASS | PASS | YES |
| ¾ in. (19 mm) but closer to ½ in. (13 mm) due to bowing of air barrier (see Figure 13). | 24 (4.2) | 15 | F (?) | F | YES (?) |
| | | 30 | F | F | YES |
| | | 44 | F (?) | F | YES (?) |
| ½ in. (13 mm) with flat bottom (see Figure 14). | 16 (2.8) | 15 | F (?) | F | YES (?) |
| | | 30 | F | F | YES |
| | | 44 | F | F | YES |
| | 24 (4.2) | 15 | F | F | YES |
| | | 30 | F | F | YES |
| | | 44 | F | F | YES |
| | 45 (7.9) | 15 | F(?) | F | YES (?) |
| | | 30 | F (?) | F | YES (?) |
| | | 44 | F (?) | F | YES (?) |
| 1 in. (25 mm) with flat bottom | 16 (2.8) | 15 | PASS | F | NO, See Note 1 |
| | | 30 | PASS | F | NO, See Note 1 |
| | | 44 | PASS | F | NO, See Note 1 |
| | 24 (4.2) | 15 | F | F | YES |
| | | 30 | JUST PASS | JUST PASS | YES |
| | | 44 | JUST PASS | PASS | YES |
| | 45 (7.9) | 15 | PASS | JUST PASS | YES |
| | | 30 | PASS | PASS | YES |
| | | 44 | PASS | PASS | YES |
| 2 in. (51 mm) with flat bottom | 24 (4.2) | 15 | PASS | PASS | YES |
| | | 30 | PASS | PASS | YES |
| | | 44 | PASS | PASS | YES |

Note 1: Since this roof did not contain much insulation, the airway had to remove lots of heat from the building. The math does not consider heat losses up through the "snow" above the airway. In these tests enough heat was being lost that way to allow the airway to pass the test, even though it failed the math.
*F = Failed to provide adequate cooling.
F(?) = Failed according to our way of establishing the "exit temperature" but temperatures within this airway never exceeded 32°F (0°C).
YES (?) = Using our method of analysis there is agreement but considering measured temperatures only, there is disagreement.

*Table 1. Summary of test findings and comparison with mathematical results.*

## DESIGN GUIDES

While acknowledging that some of our tests suggest that airways of somewhat lower height may perform adequately in some circumstances, we are reluctant to adjust the mathematics to account for this. Thus, at this time, we take the conservative approach and recommend that the equations presented in this paper be used to design airways for cathedral ceilings to avoid problematic icings at their eaves.

Figures 18 through 21 present the mathematics in a user-friendly format for buildings with an interior temperature of 70°F (21°C). Each figure contains information for airways at one slope (15 degrees in Figure 18, 30 degrees in Figure 19, 45 degrees in Figure 20 and 60 degrees in Figure 21). Each figure consists of three graphs: one for roofs with a thermal resistance of 15 ft²h°F/Btu (2.6 m²K/W); one for roofs with a thermal resistance of 25 ft²h°F/Btu (4.4 m²K/W); and one for roofs with a thermal resistance of 40 ft²h°F/Btu (7.0 m²K/W). The four lines on each graph represent airways 15, 30, 45 and 60 feet (4.6, 9.1, 13.7 and 18.3 m) long. Knowing the slope of the roof, length of the airway and thermal resistance of the roof, the height of the airway and the net free area of inlet and exhaust openings can be determined. There are numerous combinations of airway height and inlet and exhaust areas that will achieve the desired result. These curves can be used for buildings with an indoor temperature other than 70°F (21°C) by modifying the R-values shown on them as follows:

In IP units, with temperatures in °F, multiply the R-value in ft²h°F/Btu by $43/(t_i - 27)$.

In SI units with temperatures in °C, multiply the R-value in m²K/W by $23.9/(t_i + 2.8)$.

As examples, if the indoor temperature ($t_i$) is 60°F, the R-values on the curves (i.e., 15, 25 and 40) increase to 20, 33 and 52, and if the indoor temperature is 80°F, they decrease to 12, 20 and 32 ft²h°F/Btu. (In SI units, with $t_i$ = 15.6°C, the thermal resistance values on the curves [i.e., 2.6, 4.4 and 7.0 m²K/W] increase to 3.4, 5.7 and 9.1 m²K/W respectively. If $t_i$ = 26.7°C, they decrease to 2.1, 3.6 and 5.7 m²K/W.)

The curves in Figures 18 through 21 were developed for airways located between 1½ inch- (38-mm-) wide rafters spaced 16 inches (406 mm) on center. When rafters are spaced farther apart, the airways occupy a slightly larger portion of the roof area and will perform slightly better. However, because the improvement is minimal, it is suggested that the curves be used unmodified for other rafter spacings.

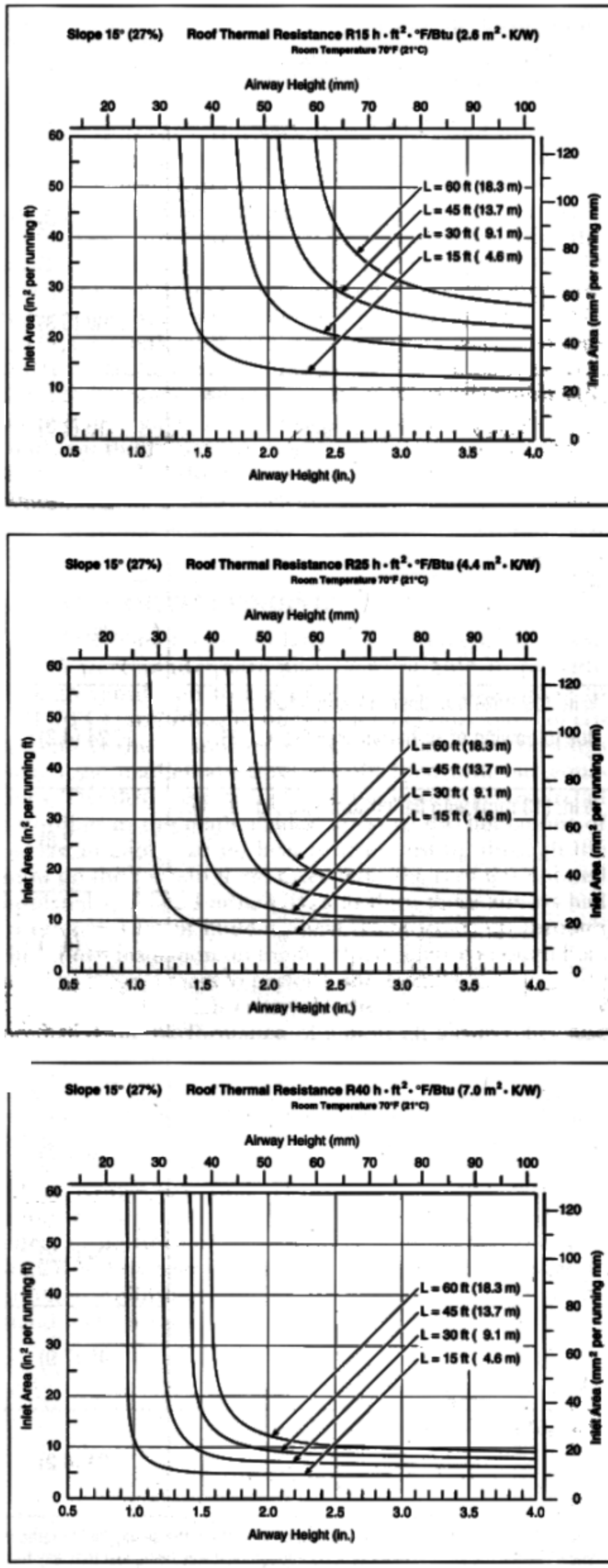


*Figure 18. Airway heights and inlet areas for cathedral ceilings with a slope of 15 degrees.*

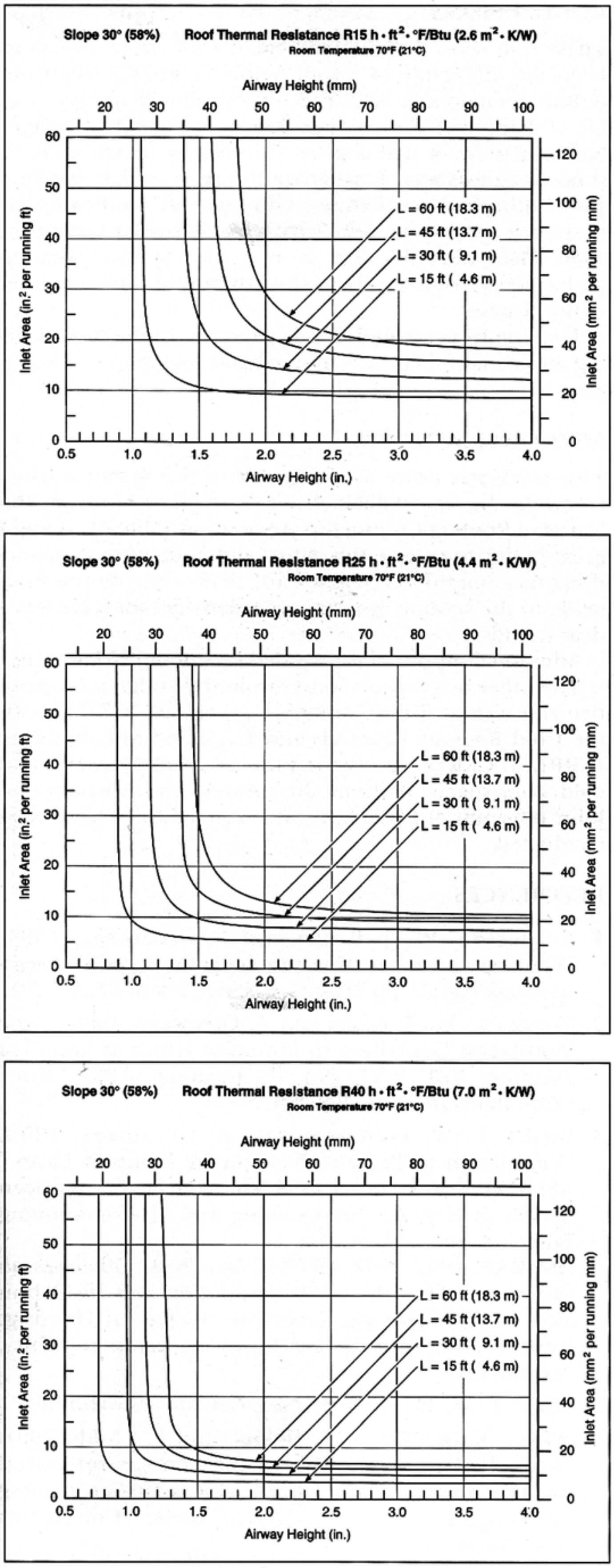


*Figure 19. Airway heights and inlet areas for cathedral ceilings with a slope of 30 degrees.*

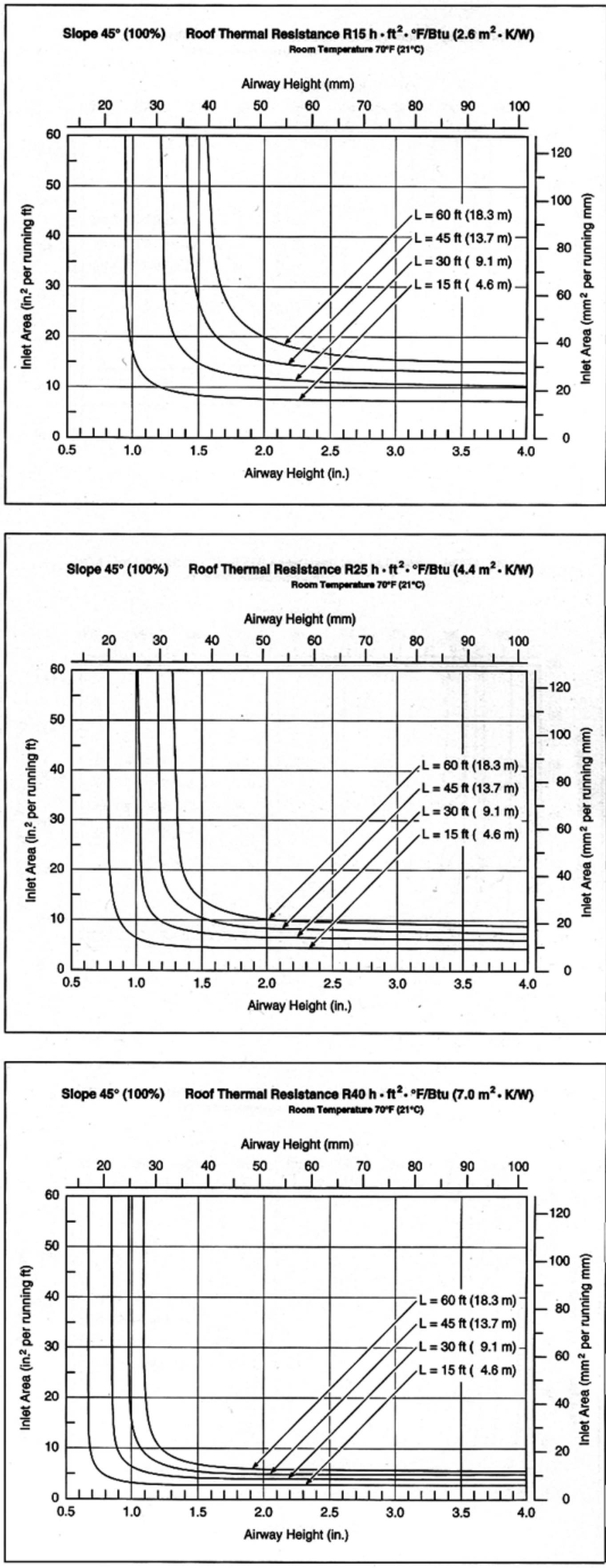


*Figure 20. Airway heights and inlet areas for cathedral ceilings with a slope of 45 degrees.*

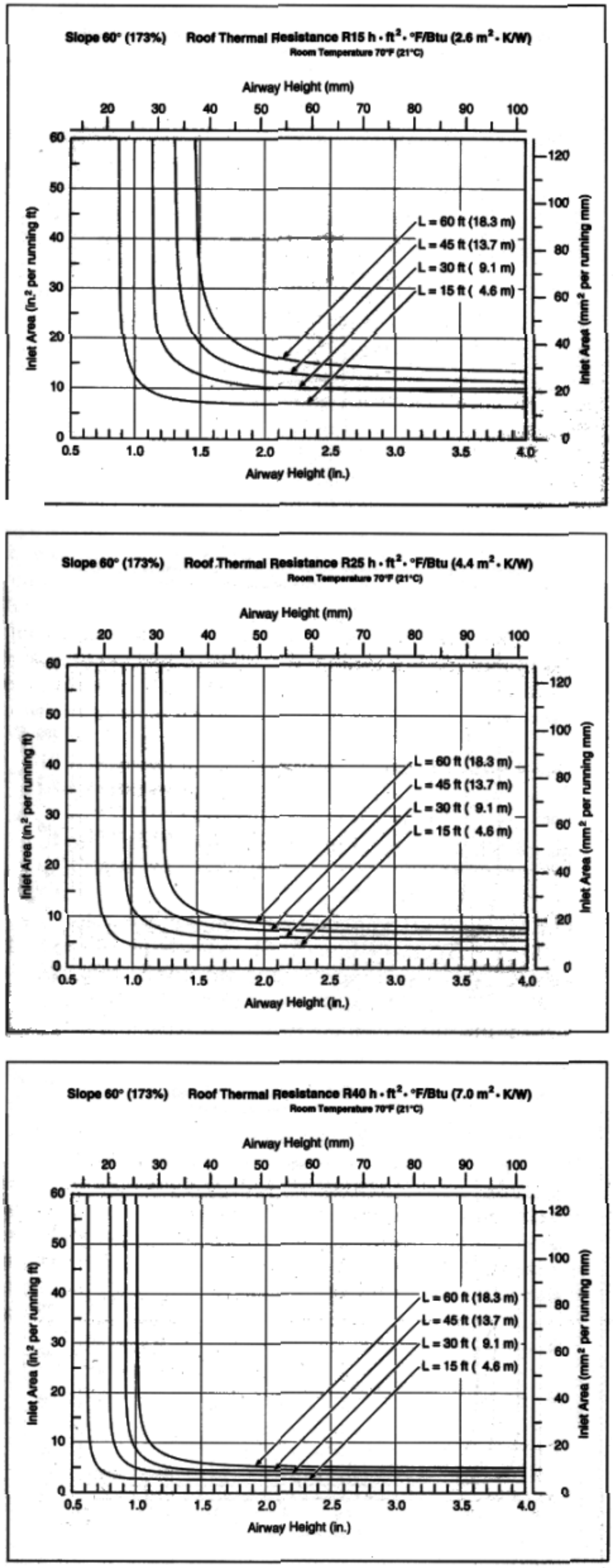


***Figure 21.** Airway heights and inlet areas for cathedral ceilings with a slope of 60 degrees.*

## CONCLUSIONS

These tests show that the mathematics for sizing airways to keep the underside of a roof below 32°F(0°C) when the outside temperature is 22°F(-5.6°C) produces airways capable of doing that. Rather large airways are needed. Some of our tests indicate that smaller airways may be adequate in some circumstances. Further studies are needed to define such additional possibilities. Our tests also indicate that there are numerous pitfalls to achieving clear airways in roofs. Many difficulties can be overcome by incorporating air barriers or rigid insulation boards in roofs as the bottom of the airways.

The graphs presented in this paper make the task of sizing airways and their inlet and exhaust openings quick and easy.


## ACKNOWLEDGMENTS

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