#6938

# No Fault Cathedral Ceilings

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## ABSTRACT

*Cathedral ceilings have long presented interesting challenges to designers and builders as they seek to meet minimum energy codes, moisture control, and ventilation requirements. This paper presents a "no fault" design that was developed to solve all of the aforementioned problems using standard building materials and with slight modification of construction methods.*

*The design offers many advantages over more commonly used systems. The advantages include: long span capabilities, radiant barriers, dedicated ventilation space, built-in air retarder and vapor retarder, an insulation type that is unaffected by the convection current problems of fiberglass, dead air spaces, a dedicated space for mechanical and electrical equipment, and roof leak protection. While offering all of the previously mentioned advantages, ceiling thickness is normal and costs are competitive.*

## INTRODUCTION

Cathedral ceilings offer an attractive design alternative, providing a home with a feeling of spaciousness that flat ceilings cannot. Design and construction of energy-efficient cathedral ceilings present many problems, including the provision of (1) roof sheathing and joist cavity ventilation (cold roof), (2) adequate insulation levels (R-38 or more), and (3) air and water vapor retarders. The space available in conventional rafter-designed cathedral ceilings compromises insulation levels, which increases energy costs. Moisture-related problems can also develop if ventilation, moisture retarders, or air retarders are not provided, which can result in costly callbacks and repairs (Larsen 1991).

Many builders and designers have sought solutions to these problems, and their approaches have been diverse and sought with disagreement (*JLC* 1991). A solution was developed that provides for roof ventilation, control of indoor and outdoor moisture, a radiant barrier inside as well as outside the thermal envelope, and adequate insulation levels (R-40-50) while using readily available materials and standard roof assembly thicknesses.

## DESIGN AND CONSTRUCTION

The solution to providing adequate roof sheathing ventilation, insulation levels, and simple control of air and moisture migration is the use of wooden I-joists and plastic foam board insulation, in this case, foil-faced polyisocyanurate (Mulford 1987). Wooden I-joists are available in longer lengths and are straighter and stronger than dimensional lumber of similar size. Foil-faced polyisocyanurate insulation provides excellent R-value per inch of thickness.

### Framing

The wooden I-joists are used as recommended by their manufacturers and engineered for proper loading, spacing, and span distances. A laminated veneer lumber (LVL) ridge beam is used to span the width of the building; this supports the upper end of the rafters (see Figure 1). The base of the rafters rests on the wall top plate in a typical rafter framing detail (see Figure 2).

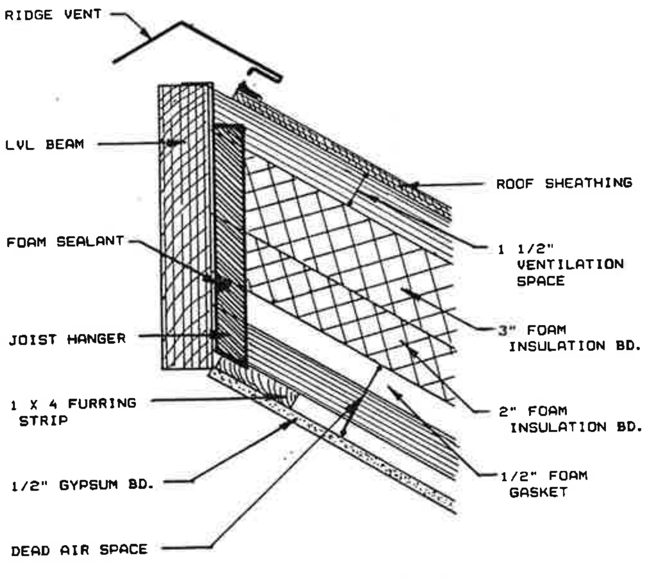

*Figure 1 Ridge detail.*

### Insulation

The rigid insulation was cut 1/8 inch undersize in width on a table saw from a 48-inch-by-96-inch sheet. Very little waste occurs, as the web of the wooden I-joist provides just enough thickness to make up for the saw blade kerf. The

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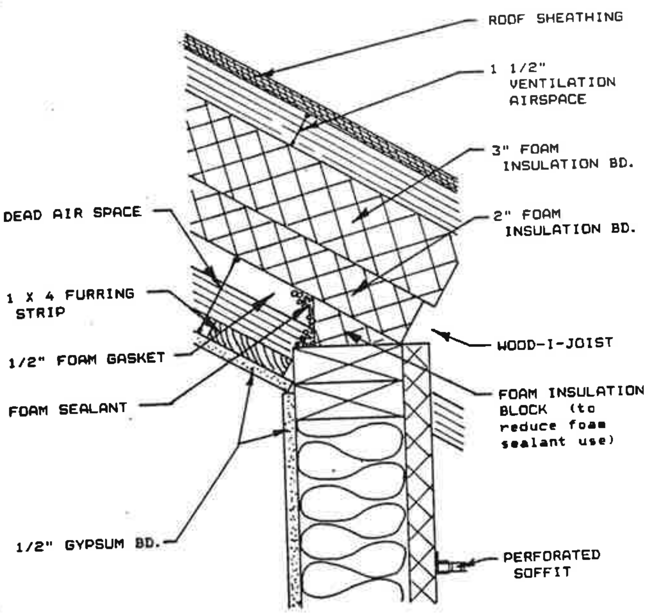

*Figure 2* *Ceiling-wall detail.*

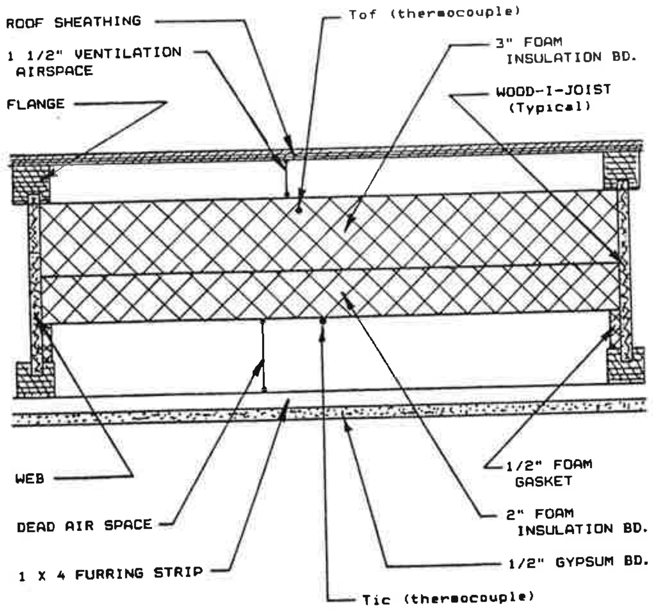

*Figure 3* *Ceiling cavity cross section.*

48-inch width of a standard board will provide two boards for rafter spacing of 24 inches on center and three boards for 16 inches rafter spacing. The upper end of the rigid insulation requires a plumb cut to match the ridge board. This was laid out on each board and cut quite easily with a hand saw.

The rigid insulation is inserted between the joists, fitting between the joist webs. The rigid insulation in this case was installed in two layers, a three-inch and a two-inch thickness. The thickness combination was based upon availability of the insulation.

Insertion of the rigid insulation was accomplished by two different methods. The first method involves simply sliding the boards (rigid insulation) in from the soffit end of the building. One person slides the boards in from the outside, while another person on the inside maneuvers them into their final position. The second method was to insert the boards from the inside, which was accomplished by using a stick to splay the bottoms of the wooden I-joists slightly (about ½ inch) and then tilting the boards into the rafter cavity diagonally.

After the upper layer of foam was slid into place, the joints between the rigid boards were taped with sheathing tape (oriented polypropylene with acrylic adhesive) to ensure no air or moisture leakage would occur. The seams were also taped on the lower layer of foam.

The rigid insulation is held tightly against the top flange of the wooden I-joist with a gasket made of 1/2-inch polyisocyanurate foam board. The gaskets are cut 1/4 inch taller than the space left between the bottom side of rigid insulation and the top of the lower wooden I-joist flange (see Figure 3). The gaskets press in with little effort, creating a tight seal between the inner building envelope and the ventilation space.

Where the rigid insulation did not seal tightly, at the ridge board and at the wall plate, an aerosol spray-applied foam was used. The foam was applied along the gaps in sufficient thickness to ensure a tight seal.

## Interior/Exterior Finish Details

The exterior of the roof is a conventional construction assembly consisting of 1/2-inch plywood sheathing, number 15 roofing felt, and asphalt singles. The interior of the ceiling was furred with 1 by 4-16 inch o.c. (to reduce the span of the ceiling finish), with 1/2-inch gypsum board, latex primer, and a flat latex top coat as the finished ceiling surface.

## Design Performance

The total R-value of the no-fault cathedral roof-ceiling assembly is 39.10 (see Table 1). This compares well to a conventional cathedral roof-ceiling assembly using 2 by 12-16 inch o.c. and fiberglass batt or blanket insulation, whose R-value is 29.09 (see Table 2). The 1/2-inch web thickness of the wooden I-joist contributes to the higher R-value of the no-fault cathedral roof-ceiling by minimizing the effects of thermal bridging when compared to solid wood framing. The greater strength and stiffness of wooden I-joists also provided the ability to use a smaller depth and a wider spacing, in this case 2 by 10-24 inch o.c.

A conventional cathedral ceiling is approximately one-third cheaper to construct than the no-fault design (see Table 3), primarily because the cost of the rigid board insulation is more expensive than fiberglass insulation.

The no-fault cathedral ceiling design is more expensive to construct, but when the performance gain is factored into

### TABLE 1
### R-Value Calculations for Cathedral Ceilings

| No Fault | R(cavity) | R(web) |
|---|---|---|
| Outside air film | | .17 |
| Asphalt shingles | | .27 |
| ½-in. plywood sheathing | | .63 |
| Outside air film | .62 | |
| Polyisocyanurate (5") | 36.00 | |
| Rafter (9¼"*1.25) | | 11.56 |
| Foil-faced dead air (3½") | 2.95 | |
| ½-in. gypsum board | .45 | .45 |
| Inside air film | .62 | .62 |
| | **$R_c$ = 40.64** | **$R_w$ = 13.70** |

U-value = $1/R_c$ * % cavity + $1/R_w$ * % web
U-value = 1/40.64 * .98[a] + 1/13.70 * .02[a]
U-value = .0256 Btu/h·ft$^2$·°F
R-value = 39.10 °F·ft$^2$·h/Btu

[a] Framing factor based on 24" o.c. spacing and 1/2" web thickness

| Conventional | R(cavity) | R(rafter) |
|---|---|---|
| Outside air film | | .17 |
| Asphalt shingles | | .27 |
| ½-in. plywood sheathing | | .63 |
| Outside air film | .62 | |
| Fiberglass insul. (10") | 30.00 | |
| Rafter (11¼"*1.25) | | 14.06 |
| ½-in. gypsum board | .45 | .45 |
| Inside air film | .62 | .62 |
| | **Rc = 31.89** | **Rr = 16.20** |

U-value = $1/R_c$ * % cavity + $1/R_r$ * % rafter
U-value = 1/31.89 * .90 + 1/16.20 * .10[b]
U-value = .0344 Btu/h·ft$^2$·°F
R-value = 29.07 °F·ft$^2$·h/Btu

[b] Framing factor based on 16" o.c. spacing

### TABLE 2
### Cost Comparison[a]
### (No Fault and Conventional 2 x 12 - 16" o.c.)

| No Fault (R = 39.10) | Materials | Labor (hrs) |
|---|---|---|
| 13 - wooden I-joists 10" x 18' | $ 333.45 | |
| 13 - wooden I-joists 10" x 10' | 185.25 | 10 |
| 1 - LVL beam 1 3/4" x 12" x 26' | 97.50 | 2 |
| 26 - joist hangers | 26.00 | |
| 18 - 3" rigid insulation 4' x 8' | 432.00 | |
| 18 - 2" rigid insulation 4' x 8' | 361.00 | |
| 3 - ½" rigid insulation 4' x 8' | 20.70 | 14 |
| 1 - roll sheathing tape | 15.00 | |
| 4 - cans aerosol foam | 20.00 | |
| 456' - furring 1' x 4" | 68.40 | 8 |
| | Sum = $1,559.00 | = (hrs) 34 |

Materials = $1,559.00
Labor ($20.00 x 34) = 680.00
Total = $2,239.00 or $3.89/ft$^2$

| Conventional (R = 29.07) | Materials | Labor (hrs) |
|---|---|---|
| 19 - rafters 2" x 12" x 18' | $342.00 | |
| 19 - rafters 2" x 12" x 10' | 190.00 | 14 |
| 4 - ridge board 2" x 12" x 14' | 56.00 | 4 |
| 38 - joist hangers | 38.00 | |
| 576 - ft$^2$ fiberglass | 288.00 | 10 |
| 36 - posi-vents | 47.00 | |
| 2 - boxes prop rods (100 ea) | 12.00 | |
| 1 - 6 mil poly (12'x 100') | 30.00 | 4 |
| 4 - 1 part urethane sealant | 16.00 | |
| | Sum = $1,019.00 | = 32 |

Materials = $1,019.00
Labor ($20.00 x 32) = 640.00
Total = $1,659.00 or $2.88/ft$^2$

[a] The finished exterior—1/2" plywood, #15 roof felt, and asphalt shingles—and the finished interior—1/2" gypsum board and paint—as well as fasteners were not included in the cost comparison since they are similar for both construction details.

the design consideration, the costs are similar. The no-fault design has an R-value of 39.10; when divided by the square-foot cost of construction, it costs $.10 ft$^2$/R. The conventional framing method has an R-value of 29.07; when divided by the square-foot cost of construction, it also costs $.10 ft$^2$/R.

## IN-SERVICE PERFORMANCE

A thermocouple was placed in the ceiling at two locations within a rafter bay to evaluate in-service performance. One thermocouple ($t_{ic}$) was placed within the lower cavity against the bottom side of the rigid insulation, and the second thermocouple ($t_{of}$) was placed in the rigid insulation at a depth of 4½ inches from the inside surface (see Table 3), ½ inch from the outside surface of the rigid insulation, to reflect heat movement through the rigid insulation and not air temperature through the ventilation cavity (see Figure 3). Using Equations 6 and 7, chapter 20, *1989 ASHRAE Handbook—Fundamentals*, in-service performance was evaluated.

The equation for temperature drop is

$$t_1 = R_1\,(t_i - t_o)\,/\,R_t$$

where

$t_i$ = indoor temperature,
$t_o$ = outdoor temperature,
$R_1$ = resistance at an interface, and
$R_t$ = total resistance.

TABLE 3
In-Service Performance of Thermocouples
(Temperatures in °F)

**Performance at 4½" rigid foam insulation ($t_{of}$)**

| | $t_o$ | $t_i$ | $t_1$ | $t_{1-2}$ | $t_{ic}$ | $t_{1-2}-t_{ic}$ | % Gain |
|---|---|---|---|---|---|---|---|
| 1 | 23.0 | 64.4 | 37.11 | 27.29 | 30.60 | 3.31 | 12.1% |
| 2 | 22.2 | 64.2 | 37.65 | 26.55 | 33.20 | 6.65 | 25.0% |
| 3 | 22.4 | 63.2 | 36.57 | 26.63 | 30.20 | 3.57 | 13.4% |
| 4 | 21.0 | 65.0 | 39.44 | 25.56 | 27.60 | 2.04 | 08.0% |
| 5 | 7.0 | 62.2 | 49.48 | 12.72 | 13.20 | .48 | 03.8% |
| 6 | 24.0 | 63.6 | 35.50 | 28.10 | 33.00 | 4.90 | 17.4% |
| 7 | 25.0 | 63.2 | 34.24 | 28.96 | 31.60 | 2.64 | 09.1% |

Average percent above predicted R-value = 12.7%

$R_t = 40.64$ $R_{tof} = 36.43$

**Performance at inside rigid insulation surface ($t_{ic}$)**

| | $t_o$ | $t_i$ | $t_1$ | $t_{1-2}$ | $t_{ic}$ | $t_{1-2}-t_{ic}$ | % Gain |
|---|---|---|---|---|---|---|---|
| 1 | 23.0 | 64.4 | 4.10 | 60.30 | 59.20 | −1.10 | −01.8% |
| 2 | 22.2 | 64.2 | 4.15 | 60.05 | 61.40 | 1.35 | 02.3% |
| 3 | 22.4 | 63.2 | 4.04 | 59.16 | 60.60 | 1.44 | 02.4% |
| 4 | 21.0 | 65.0 | 4.35 | 60.65 | 59.40 | −1.25 | −02.1% |
| 5 | 7.0 | 62.2 | 5.46 | 56.74 | 58.60 | 1.86 | 03.3% |
| 6 | 24.0 | 63.6 | 3.92 | 59.68 | 61.00 | 1.32 | 02.2% |
| 7 | 25.0 | 63.2 | 3.78 | 59.42 | 60.60 | 1.18 | 02.0% |

Average percent above predicted R value = 1.2%

$R_{tic} = 4.02$

The equation for calculated temperature at the interface is

$$t_{1-2} = t_1 - t_2.$$

Temperature readings at the thermocouples indicate that the roof-ceiling assembly performance is better than the calculated R-value. The in-service performance is 12.7% better near the exterior surface of the rigid board insulation (see Table 3). The readings were taken randomly using a hand-held digital thermometer and 30-gauge thermocouple wire during the month of March 1992. The thermocouples were located on a north roof face to eliminate solar heating as a factor.

The cathedral ceiling has proved to have a very low air leakage rate. Precise air leakage is difficult to measure, but blower door testing was done before and after construction of the home addition. The pre-addition blower door reading was 3.91 cubic feet per minute at 50 pascals (cfm 50), and after the addition was completed, the house tested at 2.89 cfm 50. The house was 25% tighter with a 35% increase in exterior surface area. The improvement is due to removal of 50% of the old house roof, exterior blown-in foam wall insulation, and the no-fault roof-ceiling. Visual inspection with a smoke pencil produced no visible leaks. Potential leakage points checked were at wall ceiling intersections, the ridge intersection, and the ceiling-mounted light fixture's electrical boxes. Since there is little or no evidence of air leakage, it is a safe assumption that little vapor transmission through air transport is taking place. Four foil surfaces exist on the rigid insulation board surfaces, which will essentially prevent moisture movement via diffusion.

## CONCLUSION

The no-fault cathedral ceiling design has proved to be an excellent method of construction. It is cost-effective while at the same time energy-efficient. Construction is simple; no new skills, tools, or equipment are required; and materials are readily available at the local retail lumber dealer. Ventilation of the lower roof sheathing surface, as well as the air retarder and vapor retarder, is built in. A radiant barrier is provided on the upper and lower side of the insulation, providing reduction of summer cooling loads and winter heating loads. Space below the insulation for mechanical and electrical equipment (electrical wiring) without penetrations into the infiltration barriers is also possible, eliminating convective heat loss or gains. Finally, diffusion of moisture into the insulation cavity is unlikely, due to the four foil surfaces of the rigid board insulation.

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