Case Study—Ice Dam Remediation for Northeast Ski-Area Condominiums

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ABSTRACT

This is a case study describing the procedures for locating, prioritizing, and repairing the causes of ice dam formation at a complex of over one hundred Northeast ski-area condominiums. The testing, performed on four typical units, was commissioned by the Owner's Association to prove the feasibility of preventing ice dam formation without replacing all of the existing roofs and to determine the costs of this approach.

Ice dam formation is one of the predominate problems for buildings in cold climates. The causes of such formations are often misunderstood by building owners and construction industry professionals alike. Consequently, because the heat-loss sources usually cannot be visually detected, solutions to the problem are more apt to be attempts at limiting damage from the symptoms rather than preventing damage by eliminating the root causes of the ice dams. In addition to roof leaks, hazards from falling ice and potential structural damage to the building are additional reasons to prevent ice formation rather than just addressing leakage. Systems for limiting damage and preventing the intrusion of water from ice dams into the building envelope can be successful but are often more expensive and do not improve the energy performance of the structures. Eliminating the actual causes of ice dams, i.e., excessive warming of the roof surfaces in subfreezing weather, always saves energy. This case study looks at a complex of buildings where it was possible to utilize conservation measures to remediate ice dams. It is broad in the scope of its examples because these multi-family buildings with their complicated construction details include many warm air leakage and conductive heat loss problems that have led to ice formation during extreme winter conditions.

INTRODUCTION

Condominium owners at a complex in a northeastern ski area had experienced a number of "snow country" problems. At the head of their list were ice dams. While the buildings were intended to meet current insulation, roof/attic ventilation, and other environmental control standards, the actual assembly of the components of the thermal envelope has led to several cold weather related problems—ice dam formation, frozen pipes, occupant discomfort, and excessive energy usage. As new units were constructed over the ten-year construction schedule, some of the causes of these problems were successfully addressed through changes in design and construction practice. However, many of the original units were still in need of corrective measures, and many of the problems addressed in this study persisted in newer units or were only masked by the construction changes. Adding membrane under the shingles and improving flashing details limited the damage but did not provide a solution to the heat loss problems that caused the ice in the first place.

In 1997, the Owner's Association solicited proposals from five local contractors for work that would resolve the ice dam problem in all of the units. The proposals all focused on the areas in the buildings where the problem manifested itself—the cathedral ceiling areas. The methods proposed included new roofing, membrane installation, increased ventilation, added insulation, and flashing repairs. All of these proposals were expensive and included no guarantee that the problems would be eliminated. Because the association members were faced with selecting from such a broad range of approaches, they hired an independent architect to advise them on making an informed decision. The architect sought the author's services in diagnosing the specific causes of the ice dam formation so that he could recommend a solution that would eliminate the source of the problem. The consultation on which this case study is based led to the following process,

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which included contracted repairs to the existing insulation systems and an assessment of the resulting change in building performance.

EXPERIMENTAL DESIGN—THE PROCESS

To help the association members with their decision, the following process was proposed then adopted.

1. Preparation: Select accessible, typical condominium dwellings to serve as test units for determining the feasibility and economic value of selected corrective measures. Form a decision-making team composed of the architect, the diagnostician, the builder, and a designated member of the Homeowner's Association.
2. Phase I diagnostics and repairs:
   a. Perform nondestructive diagnostic procedures on the test units to identify and locate the largest causes of ice dams. The two major targets of this testing were air leakage (holes) and conductive heat loss (missing or inadequate insulation) areas that could warm the outer roof surface enough to melt the snow cover in below-freezing weather conditions.
   b. Based on the results of the nondestructive testing, develop small-scale access (destructive) for inspections of the specific construction details associated with the airborne and conductive heat losses that are warming the outer roof surfaces.
   c. Report on the findings, provide a list of possible causes of the problems, and propose corrective measures, including estimated costs for these repairs.
   d. Contract with a builder to make the repairs on the test units.
3. Phase II diagnostics and repairs:
   a. Operate the buildings without preventive measures including snow shoveling and the use of electric eave heaters.
   b. Assess the performance of the repairs, and perform a second series of nondestructive diagnostic test procedures to locate the remaining causes of the ice dams.
   c. Report on the findings, and propose corrective measures, including estimated costs for these repairs.
   d. Contract with the contractor to make the second round of repairs on the previously modified test units.
4. Collect the data from the work, and assess the costs as compared to the "new roof" options.
5. Report the results to the architect and the Owner's Association.
6. Plan and help to implement the analysis and repairs for the balance of the units (Phase III).

TEST PROCEDURES

The Phase I nondestructive diagnostic information was collected with infrared, snow/frost melt pattern, and ice formation analysis. The infrared testing was done at night with temperatures at or below 20°F. All four test units and several newer units were scanned to compare the original units to those with updated designs. Scans were done from outdoors, inside the living spaces, and inside the accessible attics. The thermography showed:

1. When done from inside the living spaces—conductive losses and cold air infiltration.
2. When done from inside the attics—conductive losses, warm air exfiltration from inside the units into the attics, and the temperature of the air flowing up from the cathedral ceiling vents spaces into the attics.
3. When done from the outside—conductive losses and warm air exfiltration. Snow-covered roof surfaces could not be included in this work.

Following the infrared work, photographic and video records of snow, frost, and ice patterns were made to complement the thermography. This was followed by physical inspections of easily accessible areas such as attic and basement areas. The owners had photos taken throughout the previous winter to supplement the initial test phase data, and ongoing monitoring of modified and unmodified units enabled documentation during various levels of snow accumulation and at various temperatures. (Note: In projects where it is not possible to access attic spaces or when melt pattern analysis is not feasible, creating a negative pressure in the units with a blower door test apparatus overcomes the stack effect in the building making all of the leaks inward. This allows them to be scanned from the inside. Pressurized fog analysis is also a useful tool in locating air-leakage sites). Finally, Phase I areas that could not be inspected without opening the building envelope were dismantled, and the inspections were completed.

Phase II nondestructive diagnostic information was collected with the same techniques as used in Phase I. Additional destructive testing was not required.

THEORETICAL CONSIDERATIONS

The process outlined above required two phases of testing and remediation work. In the first series of testing procedures (Phase I), only major conductive and air-leakage loss areas could be identified because the larger losses overwhelmed or "concealed" smaller ones. In the case of air leakage, large openings reduced the pressure differential across the barrier, and the smaller, more restricted openings had little or no flow. In conductive loss areas, large uninsulated sections of wall or roof concealed or reduced the apparent importance of relatively poor R-value areas. The initial (Phase I) testing gave an overall sense of the problem and determined that the primary causes of the ice formation were not failures in the insulation or ventilation systems in the cathedral roofs. It identified the areas requiring improvements and aided in prioritizing them. This procedure also provided a benchmark for comparative quality assurance procedures for the project.

After the Phase I improvements had been completed, the infrared and melt patterns in Phase II testing provided much more concise information about smaller, concentrated, heat-loss sites. The pressure differential across the remaining small openings increased, allowing them to be easily detected. The second round of testing also gave the contractor making the improvements feedback about the initial round of work. Usually, this was done prior to closing access areas and replacing finishes. By incorporating a review step and fine-tuning into the planning, there was less pressure to address potentially low-payback repairs in the first phase, resulting in cost savings on several occasions. This also allowed everyone involved to assess the impact of the initial work and to develop and try alternative techniques to overcome problems encountered in the first phase. Creating a cooperative effort where everyone worked together to accomplish practical goals resulted in a much lower probability of failure. For all of these reasons, it was clearly important that at least two series of tests be performed.

While this case study highlights the test methods, the construction details contributing to ice dam formation, the contractor's approach to the work, the details of the repairs, and the resulting effects on ice dam formation and energy usage, it also addresses the importance of communicating the goals of the work to the contractor providing the solutions. In these buildings, many of the causes of these ice dams could have been prevented at a much lower cost during the original construction if there had been an understanding of the intended function of the individual components of the thermal envelope. Bridging the gap between building science and field practice is one of the crucial challenges of achieving successful results in both new construction and this type of remedial work. The diagnostician or designer must be able to convey the problem and how the building materials can combat the problem and then support the installer by quality assuring the work during the process. "Seeing" evidence of the problems and successes through the use of photos, infrared scans, observed melt patterns, or with pressurized fog analysis is the most effective communication tool available.

In this project, once the contractor had seen the evidence from the diagnostic procedures and gained an understanding of the problems that he had to address, he developed a very effective strategy for the necessary improvements. He was also prepared to make independent decisions when new or unexpected problems were encountered. The tests clearly showed that the vast majority of the heat loss problems contributing to ice dam formation were related to the integrity of the air barrier assemblies (air barriers are equated here with sealed "sheathing" or "closure" materials). In the worst cases, there was nothing between the interior (warm) and exterior (cold) spaces but the friction-fit unfaced batts (typical insulation), and in many cases the batts had gypsum board on the warm side but were unsheathed or open on the exterior side. It has been proved that air barriers are necessary to the performance of conventional batt insulation. Less frequently, the batts were closed in (sheathed) on both sides, but in all cases there were penetrations and unsealed joints in the sheathed surfaces. In order to prioritize the theoretical requirements for ensuring the continuity of air barriers and maximizing the thermal performance of the existing batt insulation, all of the thermal envelope conditions were referred to as one of three types:

1. *Unsheathed or open on both sides (no air barriers)*: This was cited as the worst condition and occurred in bathroom knee walls behind shower units, in ceiling to knee wall transition ceiling joist areas, over structural steel beams, party wall tops, and in the flat attics where the ceilings were dropped below (see Figures 1 and 2 at the end of this paper).
2. *Sheathed or closed on one side, usually the inside, but with penetrations (one air barrier)*: This occurred in knee walls, boxed floor and roof overhangs, typical rim joist areas, interior and exterior boxed chases (laundry duct chases, boiler flue chases, zero clearance fireplace boxes), overlapping attic "cricket" roof slopes (see Figure 3c), the attic floors, and in transition walls at vertical ceiling height changes.
3. *Sheathed on two sides (two air barriers)*: This was cited as the ideal condition and occurred in typical exterior walls and in some cathedral roof slopes.

The goal presented to the contractor for this project was to upgrade any conditions in types #1 and #2 above to type #3. In areas where the sheathing (air barrier) was missing, the surrounding air barriers were to be identified and materials selected to provide an airtight connection between the existing air barriers. The contractor's choice of materials was usually dependant upon the difficulty of the access to the work space. Where possible and practical, foil-faced rigid foam sheets were used, not only to complete the missing air barriers, but to provide added R-value. Accessible air-leakage gaps in existing air barriers were also sealed. All existing ventilation provisions were maintained and locations with no insulation were upgraded to match the original specified levels (R = 11 or 19 in walls, R = 30 in roof slopes, R = 30 in flat attic caps). These values met the minimum local code requirements at the time they were approved.

There was clear visual evidence of airflow through penetrations and the "open on both sides" (type #1, no air barriers) conditions from mold and mildew and heavily concentrated melt areas. These were easily located. There was little obvious physical evidence for the single-sided (type #2, one air barrier) condition. Not until Phase II, after the type #1 problems had been repaired, were the type #2 problems visible except with infrared equipment. For this reason, a study was performed at one of the typical examples of this condition: a bathroom knee wall. The temperatures on both sides of the wall and in the roof vents above this condition were monitored before and after installing a second air barrier on the exterior side of the wall. This test demonstrated that the wall performance was improved by reducing convection in the batts and reducing exfiltration through penetrations; therefore, the amount of heat that was "lost" into the roof slopes and attic above the knee wall was reduced. Roof melt patterns clearly corroborated these findings. The test was intended to show the owners that roof surfaces can be warmed by seemingly unrelated sources in walls and ceilings well below the affected roof area (Fennell 1998a).

RESULTS

Phase I Diagnostics

Four of the oldest units with full-time residents (nonrental units) were selected to maximize project access. The four dwellings comprised all of the units in one of the typical four-family clusters. The four-unit cluster chosen provided two end units and two middle units to evaluate and serve as baselines for comparison with other unmodified units. (The only other type of cluster layout was composed of three similar units: two end units and one middle unit).

Once the test units were established, an experienced local contractor was selected and the process was implemented. The video and photographic evidence was presented by the author to the owners, the contractor, the architect, and the property manager, hereinafter referred to as the team. From this review, the most severe areas of interior heat loss or roof surface warming were located. Architectural drawings were examined, and plans were made for the contractor to develop access to inaccessible areas. The contractor then made inspection openings in soffits, chases, attics, and dropped ceiling areas to allow visual identification of the actual construction details at the areas of significant heat loss. These problem areas were organized into the following four categories:

1. General energy conservation problems not related to ice dam formation such as missing insulation, unsheathed wall areas, or major air-leakage sites.
2. Pipe freeze-up causes such as uninsulated rim joists, unsealed penetrations, or second floor overhanging floor areas.
3. Ice dam formation causes—cathedral roof slope warming.
4. Ice dam formation causes—attic roof slope warming.

While remedying many of the energy conservation and freeze-up problems (items 1 and 2 above) was included in the work and resulted in fuel savings and reduced repairs, only the ice dam formation causes (items 3 and 4 above) will be addressed in this paper.

Cathedral Roof Slope Warming—Problems Identified in Phase I. In this project, cathedral roofs are areas where both the inside and outside of a sloped roof are finished surfaces (no attic space). These areas were typically at the lowest roof elevation and always had attics above them.

The cathedral roof construction, from the inside to the outside, consisted of gypsum board or horizontal tongue and groove wood paneling, 4 mil polyethylene vapor retarder, 2 × 12 wood rafters at 24 in. O.C., 9 in. unfaced batt insulation (R = 30), continuous molded polystyrene vent chutes, plywood sheathing, and asphalt shingles on roof felt. The soffits were narrow in most locations and had continuous ventilation strips in the bottom trim. The ventilation design included a ventilated ridge cap.

Most of the ice dams were located along the lower vented cathedral ceiling eaves and behind the zero-clearance fireplace boxes. Ice was concentrated at the valleys where the runoff from both roofs combines. In spite of the ice buildup and water infiltration, these lower roof areas were performing the best thermally. It was observed that the outside surfaces of the cathedral roof areas were generally cooler than the attic roofs above. This was indicated on the outside by snow and frost patterns. Typically, after light snowfalls (6 in. or less) or on frosty spring or fall mornings, the upper attic roofs were melted bare. Under the same conditions, the lower cathedral slopes were covered with snow or frost, showing only "spot" melt areas related to specific interior conditions. These patterns were constant from bottom to top on cathedral spans as long as 20 ft, stopping abruptly at a line where the vented attics began (see Figure 4).

The snow "melt" water flowing down from the warmer attic roofs froze when it reached the cooler cathedral roof creating ice dam formations and water infiltration (leakage) damage. In similar unmodified units, the property managers were forced to remove snow from the entire roof area to stop leakage as the snow depths increased. This revealed ice buildup on the roof surface extending all the way up the roof from the eaves to the attic floor height, indicating that the entire cathedral roof surfaces, not just the eaves, were cool enough to refreeze the melt water from the upper (attic) roof surfaces (see Figure 4). Interior infrared analysis of cathedral roof slope areas during the Phase I testing revealed the following:

- There was insulation in the slopes, but there was wind washing in the lower eave area, i.e., the cold air from the eave soffit vents is coming in under and through the lower slope batt insulation. As the outside air travels up the roof on the warm inner side of the insulation and through the insulation, it picks up heat and exits into vent space and eventually into the attics above. Interior infrared images showed a gradual temperature gradient from bottom to top in wind-washing cathedral roof slope areas. (This pattern was not visible after the rafter tails had been blocked and sealed except along the uninsulated gable walls.)
- The scans also showed cold air infiltration along the lower wall to ceiling connection of the gable (end units) or party walls (middle units), skylight rough openings and at the zero-clearance fireplace box walls (see Figu

10). This indicated that the air barriers in these areas were incomplete or unsealed (Janssens et al. 1992). As with the wind washing in the main cathedral areas, this was coldest at the bottom of the slope, indicating the exfiltration of warm interior air into the roof cavities at the higher ceiling (stack-effect) elevations. These theories were verified by the melt patterns above.

In the two end units, there are bathrooms with knee walls and dropped ceilings. Between the knee walls and the dropped ceilings are short cathedral slopes. Melt patterns showed that this short cathedral area was performing better than the attic roofs around it, except in the bay with a recessed fan/light fixture (see Figure 9). Interior infrared analysis and physical inspections of these areas during the Phase I testing showed the following:

1. The fan/lights in the guest bathroom (including a shower) slopes were a thermal disaster for the following reasons:
    a. The depth of the enclosure occupied the insulation space.
    b. The enclosure box and its connection to the gypsum ceiling (the air barrier in this case) were unsealed, leaking warm, moist bathroom air directly up into the vent space and insulation above. Cool air from the vent space and wind washing below the light leaked into the bathroom around the fixture trim.
    c. The 4 in. uninsulated flexible duct from the fan disrupted the insulation all the way up to the attic, and the warm room air flowed unrestricted up this duct against the roof sheathing. The long duct runs that vent to an exit point in the soffit on the other eave side of the building were exposed, thus dissipating any remaining heat into the attic space. The undampered termination cap was installed facing down in the eave soffit on the windward side of the building, encouraging the exhaust air to flow back up into the adjacent soffit vent strip and into the attic. This flow was visible during subzero weather.
    d. The light fixture had a high-wattage incandescent bulb that created a hot spot where there was little or no roof insulation. The infrared tests clearly showed the infiltration of cold air into the fixture; the outside melt pattern showed the fixture location and the warm air travel path in the roof's vent space above the fan.
2. The attics behind the bathroom knee walls and the boxed down soffit walls (see Figures 5 and 6) were unsheathed on the attic (cold) side. These attic-type roofs melted sooner than the surrounding cathedral slopes. Some were uninsulated or the insulation had fallen out of the stud bays. There was no air barrier in the plane of the knee walls between the floor and ceiling below. There were uninsulated recessed fixtures in the floor of this attic. While none of these surfaces were in the roof slopes themselves, they were assumed to be the causes of the warmed roof surfaces in these attics and in the cathedral slopes directly above them. Warmed ventilation air from the eave soffits below flowed through these attic spaces into the cathedral slope vent chutes starting at the tops of the knee walls. These interior "rafter tail" type conditions were not blocked below the vent chutes, allowing wind washing in the roof bays.

Attic Roof Warming—Problems Identified in Phase I. In this project, attic warming was the largest source of melt water, and, as a result, heat loss to the attics was the most significant cause of ice dams. Warm air rising into the attic melts the snow and creates the bare roof areas as shown in Figure 7. Assuming a constant snow depth, the volume of water generated for ice dam formation is directly related to the surface area of snow-covered roof that is melted by heat loss. However, the physical size of the heat loss source (i.e., the air-leakage hole size) is not necessarily directly proportional to the roof area it can melt. In the cathedral slopes, the area influenced by specific warm air leakage sites was limited by the area of the rafter bay that the leak was in and the volume of air that could flow out of the leakage area through the ventilation chute or space. In the case of the attic, a relatively small number of square feet of air-leakage area (hole or penetration size) could allow the unrestricted flow of conditioned air to warm the entire roof surface of the attic (for example, an open attic hatch). Heat from the attic floor's conductive losses was also distributed over the entire roof area. (Note that the use of strapping behind the gypsum board in both the cathedral and flat attic ceilings serves to create a cross-connection between communicating wall and ceiling framing bays and increases the air leakage from perimeter sources; see Figure 5).

The attic construction, from the inside (below the ceiling) to the outside, was as follows: gypsum board, 4 mil polyethylene vapor retarder in the bedroom ceiling areas (not in boxed chases or dropped ceilings), 1 × 3 strapping, 2 × 8 wood ceiling joists—24 in. O.C., a single 9 in. layer (R = 30), or two layers, one of 6 in. and one of 3.5 in. unfaced batt insulation (total R = 30). (Note: The second layer of batt insulation was turned across the framing and stopped at the intersection with the rafters, several feet short of the first layer (R = 19), which went to the edge of the ceiling bays where they met the slope insulation). The ridge had a continuous vent.

There was no ice formation observed on the upper attic roofs. Soon after a snow or frost event had occurred, a few hot spots would melt above specific areas such as the bathroom vents and the party walls (Figure 7); then, the entire roof would melt clear over the attics of all four units. The combined losses from the sources listed below resulted in attic temperatures as high as 55°F when outside temperatures were below 10°F. Infrared analysis inside the attics during the Phase I testing showed warm air leakage into the attics from numerous sources as well as reduced R-values in the loose-fill fiberglass and batt insulation (Wilkes 1992):

1. Dropped ceiling areas over bathrooms, closets, hallways, and recessed window tops had not been sheathed (no air

barrier) above or below the unfaced batts. Only strapping or friction supported the batts between the ceiling joists in these areas. In some cases the batts had fallen into the recess below.

2. Partition tops were unsealed at framing connections and at plumbing and wiring penetrations.
3. Party wall tops at the ceiling plane were unsealed and uninsulated. At the intersection of adjoining middle unit and end unit, the party wall was under an isolated "cricket" attic (a section of roof built over a lower roof slope to prevent water from running down the lower roof against a vertical wall where it cannot drain properly). One side of the party wall was above the rafter line of the adjoining unit (see Figures 8 and 11). The end unit side of the double wall was unsheathed (no outside air barrier) and not blocked or sealed at the lower top plate. The party walls were spaced apart by a 1 in. space, creating a continuous passage from the interior party walls below up into the cricket attic. The conductive loss through the top of the party wall was evident on the interior infrared tests as a cool band at this location. The scan from the attic showed the flow of heat up along the party wall and roof slopes. When viewed from the outside, the party walls and cricket roof areas had the highest rate of melting.
4. Attic hatches were unsealed and uninsulated.
5. Batt insulation was installed up to, but not over, the boxed I-beams and had no air barrier across the I-beam just below the sloped roof to attic ceiling transition. In some cases this adjoined a dropped ceiling area at the hallway and in all cases opened into the dropped bathroom and closet ceilings. The lack of a continuous air barrier kept these interior spaces warm (open to the interior partitions below) and "connected" to the roof slope vent and attic spaces (see Figure 1).
6. The flat cap (attic) areas showed conductive and warm air leakage losses at the butt joints in the batts and around the framing members at the flat to slope transitions. Light fixtures, bathroom fans, and duct runs also created gaps in the insulation. This was true in both single-layer and crossed double-layer configurations. The insulation did not extend into the party walls (approximately 10 in. wide) or out to meet the top of the roof slope insulation. At the intersection of adjoining middle and end units where the roofs overlapped (termed the "cricket" area), the vents of the end unit slopes originated at the unsealed tops of these party walls (see Figure 8).
7. The tops of the boiler chimney chases were open to the attic (see Figure 2).

Phase I Repairs

Based on a report of the results of the nondestructive and destructive test procedures, the team reviewed the problems and agreed to make the following repairs:

Cathedral Roof Slope Warming—Phase I Repair Methods.

1. The eave soffits on all units were opened, and blocking was installed between the rafters above the walls to eliminate wind washing. Unsheathed walls were covered with rigid foam and air sealed. Narrow empty roof bays at the gable ends, skylight double rafters, and party walls were insulated as far up as possible from the bottom access and sealed to reduce infiltration (see Figure 6).
2. The large zero clearance chimney boxes were opened, and the inside of the exterior walls were sheathed and sealed with rigid foam; the roof slopes were insulated and sheathed along the plane of the slope to continue the insulation over the box to the outside wall. These procedures prevented the infiltration of cold air into the box and the flow of warm air up into the roof slope vent chutes.
3. The interior roof slope perimeter was sealed in the wood paneled units. The skylight casings were removed and the jambs sealed to the rough openings to prevent cold air infiltration at the bottom and warm air leakage into the roof above them. The beams at the top of the cathedral slopes were air sealed from below.
4. Insulation defects in the knee wall and boxed chases were repaired. Sheathing was installed and sealed on the second side of each of these one-sided conditions, and unblocked floor-to-floor rim joist areas were sheathed to prevent heat loss in these lower attic spaces from flowing up into the roof vents above. It was recommended that the recessed light in the floor of this attic be changed to a fluorescent surface-mounted fixture.
5. Additional glazing was added to the outside of one of the test unit skylights. Ice dam formation below the modified and unmodified skylights was monitored to determine if additional R-value would reduce conductive losses enough to eliminate melting on the glass in cold temperatures.
6. The fan/lights in the guest bathroom slopes were reinstalled as surface mount units in the same location. The original holes behind these new installations were insulated, and the air barrier was completed. Rigid foam was used to insulate the roof over the duct in the reduced rafter space above the fan. In the attic, the duct was relocated under the insulation until it exited. A wall cap with a damper was installed at the end of the duct run, and the soffit vents for 4 ft on either side of the vent location were sealed to stop warm, moist air from re-entering the attic (see Figure 9).

Attic Roof Warming—Phase I Repair Methods.

1. Insulated attic hatches with gaskets and drawdown latches were installed.
2. Foil-faced rigid foam sheathing was installed and sealed to adjoining air barrier materials in the short slopes and flat ceilings above all of the drop ceilings. This insulation and air barrier system was boxed around the I-beam. The top

plates of interior partitions inside the dropped ceiling spaces were air sealed. Insulated exterior walls above the ceiling plane were treated similarly (see Figure 1).

3. In the flat ceilings of the attic, air sealing was done at all accessible penetrations under the batt insulation. The air barrier and insulation were extended into the party walls. Gaps in the batt insulation were to be filled with loose-fill insulation. An additional layer of loose-fill insulation or a continuous vapor-permeable air barrier film was to be installed on top of the batts to reduce convection in the batts.

4. The top of the insulated metal furnace flue was sealed to prevent the heat from flowing into the roof slope vent spaces.

Phase II Diagnostics and Repairs

Phase II nondestructive diagnostic information was collected as in Phase I. The results showed more detailed information about the locations and severity of the remaining heat losses as the overall heat flow had been significantly reduced. Specific melt spots in the snow cover were now visible and could be associated with interior construction details. Due to the improvement from the first round of repairs, the flow of melt water had been dramatically diminished and was concentrated below the areas of remaining heat loss. As a result of monitoring the depth and location of ice dam formations early in the season, the ice pattern was used as an indicator of the volume of melt water that was coming from each problem area above. (This was useful in prioritizing the cost-effectiveness of Phase II repairs.) Later in the season, the ice depth evened out along the length of the eaves (except at the valleys, which still had the largest ice accumulation) due to the melt water spreading horizontally as it was held back behind the earlier ice formations.

Cathedral Roof Slope Warming—Phase II Problems and Repairs. Phase II testing was completed late in the winter of 1997-98. The cathedral roof slopes appeared to be clear of problems except for two areas: below the skylights and along the party walls. Based on the infrared and melt pattern analysis, the following assessments were made.

1. Wind washing in the lower slope was eliminated except in minor spot locations at inaccessible soffit areas. No additional work was performed in these areas.

2. Infiltration and heat loss at the zero-clearance fireplace boxes were significantly reduced. The complexity of this triangular ornamental box and the limited work access made the work difficult at best. Some infiltration was still evident where the front face of the box met the two outside walls; however, the amount of warm airflow out of the top of the box into the roof slope vents was virtually eliminated. No additional work was performed in these areas.

3. Infiltration of cold outside air along the wall to roof intersection of the cathedral gable walls had been eliminated. In the two middle units, these walls form the party walls with the two end units. Even after air sealing procedures, the narrow strip of roof over the party walls remained as one of the two most serious melt areas, in part because they are directly above the valleys. With the wall to roof intersection sealed, it is assumed that the heat source causing this melt pattern was heat coming up from the wall cavities rather than directly from inside the room itself. The air barrier in the cathedral ceilings did cross over the party walls that have double 2 × 4 walls with a space between them (see Figure 11). Because these bays are inaccessible from the interior and opening the roof was deemed to be too expensive, the decision was made to block the flow of air from the walls into the attic by sealing the roof bay at both ends. This did not preclude the option of opening the roof at a later date, and it promised to limit the heat reaching the roof and attic by cutting off the stack effect from the double wall and creating a dead air space rather than a constant warm flow. As the bottoms of these roof bays had been sealed when the eaves were blocked and sealed, this only required sealing the readily accessible top of the vent space from the attic.

4. The fan/light in the guest bathroom showed no infiltration on the infrared scan, and the melt area in the roof had been significantly reduced considering that the duct was still routed through the roof bay. While totally relocating this fan would have been the optimal solution, the degree of improvement achieved without major renovations was acceptable.

5. The repairs in the kneewall attics were performing well. Both the infrared and melt patterns showed significantly less warming at cold temperatures. The remaining warming, visible only at near-freezing temperatures, was believed to be caused by the recessed entry porch light.

6. Air infiltration around the skylights was virtually eliminated; however, ice formation was noted immediately below the skylights. As the infrared and melt pattern testing did not indicate roof warming, and similar construction on both sides of the skylights had not developed ice, it was assumed that the source of melt water in this specific area was from the skylight itself. A Phase II test was developed utilizing a piece of double-glazed tempered glass installed over one of the existing inoperable skylights. If this test alleviates this problem, better insulating glass or an outside storm panel will be proposed. This unit and the unmodified skylight on the next unit were monitored to determine the following:

    a. Would additional glazing R-value prevent ice formation below the skylights?

    b. Was the melt caused by the glazing only, or by the curb and framing losses around the skylight?

    The result of this test was inconclusive. Late-winter conditions did not produce enough snow to effectively compare the volume of ice produced below the modified and unmodified units. Photos of earlier snow cover indicated that the snow pack went clear up to the skylight curbs. This indibarrier) above or below the unfaced batts. Only strapping or friction supported the batts between the ceiling joists in these areas. In some cases the batts had fallen into the recess below.

2. Partition tops were unsealed at framing connections and at plumbing and wiring penetrations.
3. Party wall tops at the ceiling plane were unsealed and uninsulated. At the intersection of adjoining middle unit and end unit, the party wall was under an isolated "cricket" attic (a section of roof built over a lower roof slope to prevent water from running down the lower roof against a vertical wall where it cannot drain properly). One side of the party wall was above the rafter line of the adjoining unit (see Figures 8 and 11). The end unit side of the double wall was unsheathed (no outside air barrier) and not blocked or sealed at the lower top plate. The party walls were spaced apart by a 1 in. space, creating a continuous passage from the interior party walls below up into the cricket attic. The conductive loss through the top of the party wall was evident on the interior infrared tests as a cool band at this location. The scan from the attic showed the flow of heat up along the party wall and roof slopes. When viewed from the outside, the party walls and cricket roof areas had the highest rate of melting.
4. Attic hatches were unsealed and uninsulated.
5. Batt insulation was installed up to, but not over, the boxed I-beams and had no air barrier across the I-beam just below the sloped roof to attic ceiling transition. In some cases this adjoined a dropped ceiling area at the hallway and in all cases opened into the dropped bathroom and closet ceilings. The lack of a continuous air barrier kept these interior spaces warm (open to the interior partitions below) and "connected" to the roof slope vent and attic spaces (see Figure 1).
6. The flat cap (attic) areas showed conductive and warm air leakage losses at the butt joints in the batts and around the framing members at the flat to slope transitions. Light fixtures, bathroom fans, and duct runs also created gaps in the insulation. This was true in both single-layer and crossed double-layer configurations. The insulation did not extend into the party walls (approximately 10 in. wide) or out to meet the top of the roof slope insulation. At the intersection of adjoining middle and end units where the roofs overlapped (termed the "cricket" area), the vents of the end unit slopes originated at the unsealed tops of these party walls (see Figure 8).
7. The tops of the boiler chimney chases were open to the attic (see Figure 2).

Phase I Repairs

Based on a report of the results of the nondestructive and destructive test procedures, the team reviewed the problems and agreed to make the following repairs:

Cathedral Roof Slope Warming—Phase I Repair Methods.

1. The eave soffits on all units were opened, and blocking was installed between the rafters above the walls to eliminate wind washing. Unsheathed walls were covered with rigid foam and air sealed. Narrow empty roof bays at the gable ends, skylight double rafters, and party walls were insulated as far up as possible from the bottom access and sealed to reduce infiltration (see Figure 6).
2. The large zero clearance chimney boxes were opened, and the inside of the exterior walls were sheathed and sealed with rigid foam; the roof slopes were insulated and sheathed along the plane of the slope to continue the insulation over the box to the outside wall. These procedures prevented the infiltration of cold air into the box and the flow of warm air up into the roof slope vent chutes.
3. The interior roof slope perimeter was sealed in the wood paneled units. The skylight casings were removed and the jambs sealed to the rough openings to prevent cold air infiltration at the bottom and warm air leakage into the roof above them. The beams at the top of the cathedral slopes were air sealed from below.
4. Insulation defects in the knee wall and boxed chases were repaired. Sheathing was installed and sealed on the second side of each of these one-sided conditions, and unblocked floor-to-floor rim joist areas were sheathed to prevent heat loss in these lower attic spaces from flowing up into the roof vents above. It was recommended that the recessed light in the floor of this attic be changed to a fluorescent surface-mounted fixture.
5. Additional glazing was added to the outside of one of the test unit skylights. Ice dam formation below the modified and unmodified skylights was monitored to determine if additional R-value would reduce conductive losses enough to eliminate melting on the glass in cold temperatures.
6. The fan/lights in the guest bathroom slopes were reinstalled as surface mount units in the same location. The original holes behind these new installations were insulated, and the air barrier was completed. Rigid foam was used to insulate the roof over the duct in the reduced rafter space above the fan. In the attic, the duct was relocated under the insulation until it exited. A wall cap with a damper was installed at the end of the duct run, and the soffit vents for 4 ft on either side of the vent location were sealed to stop warm, moist air from re-entering the attic (see Figure 9).

Attic Roof Warming—Phase I Repair Methods.

1. Insulated attic hatches with gaskets and drawdown latches were installed.
2. Foil-faced rigid foam sheathing was installed and sealed to adjoining air barrier materials in the short slopes and flat ceilings above all of the drop ceilings. This insulation and air barrier system was boxed around the I-beam. The top

plates of interior partitions inside the dropped ceiling space were air sealed. Insulated exterior walls above the ceiling plane were treated similarly (see Figure 1).

3. In the flat ceilings of the attic, air sealing was done at all accessible penetrations under the batt insulation. The air barrier and insulation were extended into the party walls. Gaps in the batt insulation were to be filled with loose-fill insulation. An additional layer of loose-fill insulation or a continuous vapor-permeable air barrier film was to be installed on top of the batts to reduce convection in the batts.
4. The top of the insulated metal furnace flue was sealed to prevent the heat from flowing into the roof slope vent spaces.

Phase II Diagnostics and Repairs

Phase II nondestructive diagnostic information was collected as in Phase I. The results showed more detailed information about the locations and severity of the remaining heat losses as the overall heat flow had been significantly reduced. Specific melt spots in the snow cover were now visible and could be associated with interior construction details. Due to the improvement from the first round of repairs, the flow of melt water had been dramatically diminished and was concentrated below the areas of remaining heat loss. As a result of monitoring the depth and location of ice dam formations early in the season, the ice pattern was used as an indicator of the volume of melt water that was coming from each problem area above. (This was useful in prioritizing the cost-effectiveness of Phase II repairs.) Later in the season, the ice depth evened out along the length of the eaves (except at the valleys, which still had the largest ice accumulation) due to the melt water spreading horizontally as it was held back behind the earlier ice formations.

Cathedral Roof Slope Warming—Phase II Problems and Repairs. Phase II testing was completed late in the winter of 1997-98. The cathedral roof slopes appeared to be clear of problems except for two areas: below the skylights and along the party walls. Based on the infrared and melt pattern analysis, the following assessments were made.

1. Wind washing in the lower slope was eliminated except in minor spot locations at inaccessible soffit areas. No additional work was performed in these areas.
2. Infiltration and heat loss at the zero-clearance fireplace boxes were significantly reduced. The complexity of this triangular ornamental box and the limited work access made the work difficult at best. Some infiltration was still evident where the front face of the box met the two outside walls; however, the amount of warm airflow out of the top of the box into the roof slope vents was virtually eliminated. No additional work was performed in these areas.
3. Infiltration of cold outside air along the wall to roof intersection of the cathedral gable walls had been eliminated. In the two middle units, these walls form the party walls with the two end units. Even after air sealing procedures, the narrow strip of roof over the party walls remained as one of the two most serious melt areas, in part because they are directly above the valleys. With the wall to roof intersection sealed, it is assumed that the heat source causing this melt pattern was heat coming up from the wall cavities rather than directly from inside the room itself. The air barrier in the cathedral ceilings did cross over the party walls that have double 2 × 4 walls with a space between them (see Figure 11). Because these bays are inaccessible from the interior and opening the roof was deemed to be too expensive, the decision was made to block the flow of air from the walls into the attic by sealing the roof bay at both ends. This did not preclude the option of opening the roof at a later date, and it promised to limit the heat reaching the roof and attic by cutting off the stack effect from the double wall and creating a dead air space rather than a constant warm flow. As the bottoms of these roof bays had been sealed when the eaves were blocked and sealed, this only required sealing the readily accessible top of the vent space from the attic.
4. The fan/light in the guest bathroom showed no infiltration on the infrared scan, and the melt area in the roof had been significantly reduced considering that the duct was still routed through the roof bay. While totally relocating this fan would have been the optimal solution, the degree of improvement achieved without major renovations was acceptable.
5. The repairs in the kneewall attics were performing well. Both the infrared and melt patterns showed significantly less warming at cold temperatures. The remaining warming, visible only at near-freezing temperatures, was believed to be caused by the recessed entry porch light.
6. Air infiltration around the skylights was virtually eliminated; however, ice formation was noted immediately below the skylights. As the infrared and melt pattern testing did not indicate roof warming, and similar construction on both sides of the skylights had not developed ice, it was assumed that the source of melt water in this specific area was from the skylight itself. A Phase II test was developed utilizing a piece of double-glazed tempered glass installed over one of the existing inoperable skylights. If this test alleviates this problem, better insulating glass or an outside storm panel will be proposed. This unit and the unmodified skylight on the next unit were monitored to determine the following:
   a. Would additional glazing R-value prevent ice formation below the skylights?
   b. Was the melt caused by the glazing only, or by the curb and framing losses around the skylight?

The result of this test was inconclusive. Late-winter conditions did not produce enough snow to effectively compare the volume of ice produced below the modified and unmodified units. Photos of earlier snow cover indicated that the snow pack went clear up to the skylight curbs. This indicated that the heat loss through the skylight curbs was not a significant contributor to the ice buildup below them.

Attic Roof Warming—Phase II Problems and Repairs. The main attic roofs had improved but not as much as was expected, given the magnitude of the initial improvements. Most of the attic roof now held snow, the exceptions being the cricket attic areas where the roofs of two units overlapped and above the middle unit party wall. The small isolated attics (cricket attics) just over the party walls between the middle and end units (see Figure 8) were especially problematic as this area was directly above the valleys that concentrated the volume of melt water and ice in one spot. This was a good example of the need to plan for two rounds of testing and repairs. The small cricket area had not originally appeared as a unique problem from the rest of the attic roofs when the Phase I testing (infrared and melt pattern analysis) was performed. Only after correcting the main attic heat loss problems could the crickets be identified as unique problem areas. While these attics were relatively small, they still provided conditions conducive to ice dam formation as well as roof leakage. As a result of the second round of tests in the attics, the following fine-tuning details were identified and addressed:

1. The flat cap areas were performing well over the majority of the large ceiling surface area. The contractor had elected to fill large gaps in the original insulation, add batts over fixtures and bathroom fan ducts, and to use an air barrier material over the batts for convection and exfiltration control. This was successful in improving the performance of the ceiling insulation except around the edges. At the party walls and rafters, the air barrier material stopped at the face of the open framing. It was clear that the air barrier needed to be sealed to the wall and roof sheathing to work as a secondary air barrier to stop exfiltration from ceiling penetrations. Sprayed urethane foam was used to make these complex connections around the rafters, vent chutes, and double party wall stud framing. Cutouts around plumbing and chimney penetrations were also sealed (see Figure 2).
2. Infrared testing showed that there was still heat flowing into the attic from the top of the cathedral slopes. This was coming from the vent space in the roof bays over the party walls, the narrow spaces between the doubled skylight rafters, and at the boxed-down I-beam at the slope to ceiling transition. While the beam had been air sealed from below, there was little or no insulation over the steel. Because the batt insulation had originally been installed from below, the air barrier and insulation did not pass over the beam. To deal with the reduced space between the top of the beam and the vent chute, the available space was filled with urethane foam to provide an air barrier and an adequate R-value. This foam seal was carried over to meet the air barrier material that covered the attic ceiling batt insulation. The foam was also used to seal the tops of the narrow spaces between the doubled skylight rafters and the tops of the party wall bays (see item #4 below).
3. The infrared scans showed that the backs of two dropped ceiling area walls were still cold. Further investigation determined that the outside of these walls was unsheathed and open to a vented soffit above the windows. Some of the batts had fallen out of these bays. This area communicated with the attic above. The walls were retrofitted with sheathing and sealed as in the other dropped-ceiling areas.
4. The tops of the cathedral slope bays over the party walls were sealed. These three bays had been the largest sources of heat in the attics after the Phase I repairs. The bays had batts in them, but no vent chutes or interior sheathing. They were open over their entire length into the walls below. As a part of the foam contractor's work, these bays were filled as far down the slopes as possible. The two party wall roof bays were the primary source of the warming in the small cricket attics.

DISCUSSION

Following the Phase II repairs, a final round of scans and melt pattern reviews was made. Conversations with the builder, the management group, and the owners in conjunction with this review provided feedback and data about the performance of the buildings and the roofs through the end of the winter season. The snow melt patterns showed significant reduction of roof surface warming, especially above the party wall and in the valleys below the crickets. Only a few melt spots were visible in the two middle units above chimney boxes—presumed from their location to be caused by exhaust gases rising from the boiler's through-wall vent up along the wall and into the soffit vents above. There was an apparent reduction in ice dam formation compared to adjacent unmodified units.

The results of the Phase I and Phase II procedures were the elimination or significant reduction of the major causes of roof warming and the subsequent ice dam formation. The improvements accomplished in an already existing and complex group of buildings without major demolition and cost were significant. The per-unit cost of the repairs was less than the original proposal for new roofing and flashing; it promises a short payback from energy and maintenance savings (Fennell 1998b). The ice formation has been reduced to a level that eliminates the need for the annual routine of raking snow, installing eave heaters, and repairing water and shingle damage. The information gathered and the understanding of the root causes of many of the building problems will be useful in the planning of future improvements throughout the rest of the condominium community.

SIGNIFICANCE FOR FUTURE PROJECTS

This project demonstrates that it is possible to create solutions to ice dam formation and the related water infiltration damage by using energy conservation measures involving minimal disruption to the interior and exterior finishes of the building. This conservation-oriented approach has the additional benefit of being extremely cost-effective.

The earlier proposals, which addressed the ice dam leakage by improving the roofing, all were targeting the symptoms of the problem. The fact that none of these reputable contractors proposed to address the root causes of the ice dams underscores the need for promoting a more energy-conscious approach to the industry. Many building owners misunderstand the source of their problems and fail to consider the potential payback of repairing the thermal envelope rather than the roof.

This study indicates the need for proper planning and implementation of the thermal envelopes in new construction. It is far less expensive to install the effective thermal envelope components during the original construction than to properly install them in a retrofit situation. It is hoped that the examples identified in this case study might help designers and builders avoid similar problems in their own work and encourage them to use performance-based quality assurance techniques at the time of construction when it is easy and inexpensive to fine-tune the integrity of the thermal envelope. This study may also serve as a useful process outline for troubleshooting existing buildings with related problems.

Using this as a model, condominium association owners and operators can see that the root causes for this common problem can be identified and eliminated with a proven team approach. The figures in this document can serve as examples of frost and snow melt patterns that are the visual manifestations of flaws in the thermal envelopes of their buildings. The project has also demonstrated that pursuing an energy conservation approach can be a better investment for the homeowners than implementing damage control measures.

CONCLUSIONS

This case study demonstrates that for a specific project, remediation of the existing thermal envelope was the most cost-effective way to avoid ice dam related damage. It presents a viable approach for building owners to utilize in the assessment and repair of conditions that lead to ice dam formation and its related water damage. The feasibility of successfully preventing damage caused by ice dams through the means of a science-based approach has been proven. This approach did not resort to major reconstruction, nor did it rely only on waterproofing solutions to roof leakage. It conserves fuel, is environmentally sound, and can be less expensive than replacing the roof and installing infiltration-proof membranes.

None of the test units has experienced failures (leaks) since the Phase I modifications were performed two years ago. Even though the final improvements were not completed until late in the second winter, these units have functioned successfully, realizing lower operating costs through two winter seasons.

In addition to achieving the original goal, the owners have attested to the fact that their units are quicker to warm up, have not had any frozen pipes, are more comfortable, and use less energy.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions of the following people to this paper: Katherine Fennell, Harold Garabedian of EVermont, and Paul Richmond of Cold Regions Research and Engineering Laboratory.

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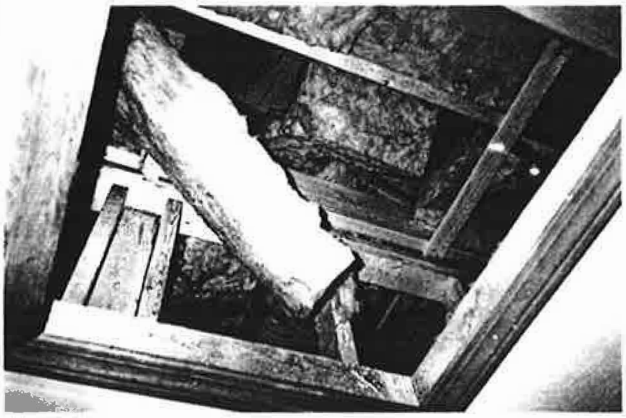
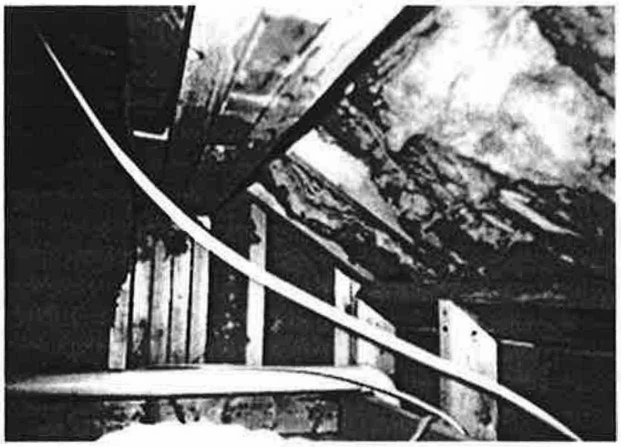


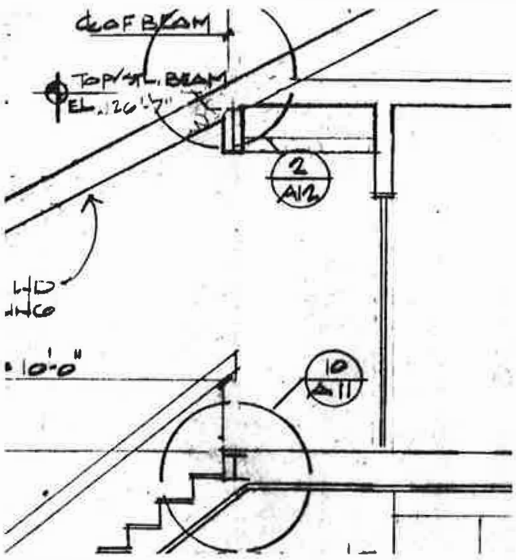
Existing attic insulation over closet dropped ceiling—no air barrier.

Attic insulation along I-beam on right over second floor hallway—incomplete air barrier.



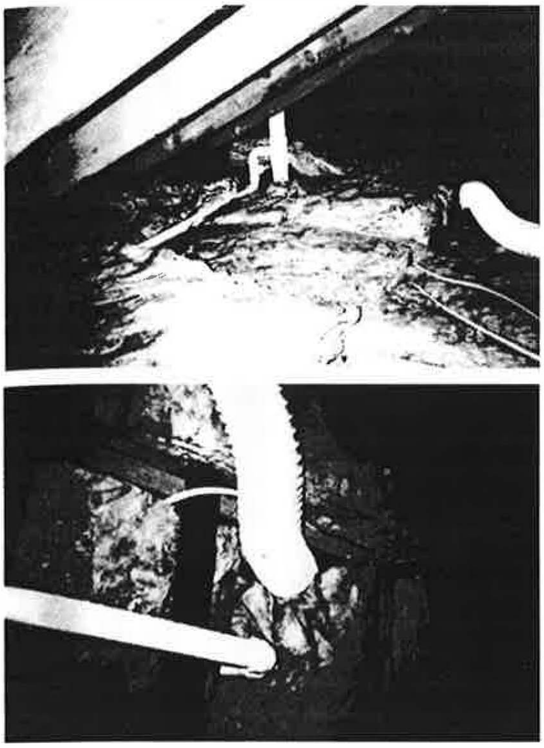
Attic insulation over bathroom—no air barrier in slopes or cap.

View down into dropped ceiling along party wall—no air barrier under batts or on party wall framing.



Section in middle unit at dropped ceiling over second floor hallway.

Figure 1 *Dropped ceilings.*



Attic batt insulation showing gaps and unsealed penetrations.

Boiler flue passing through unsealed opening in the attic floor allowing the steady flow of heated air into the attic from the chase.

Infrared image of gaps in batts and along attic framing members.

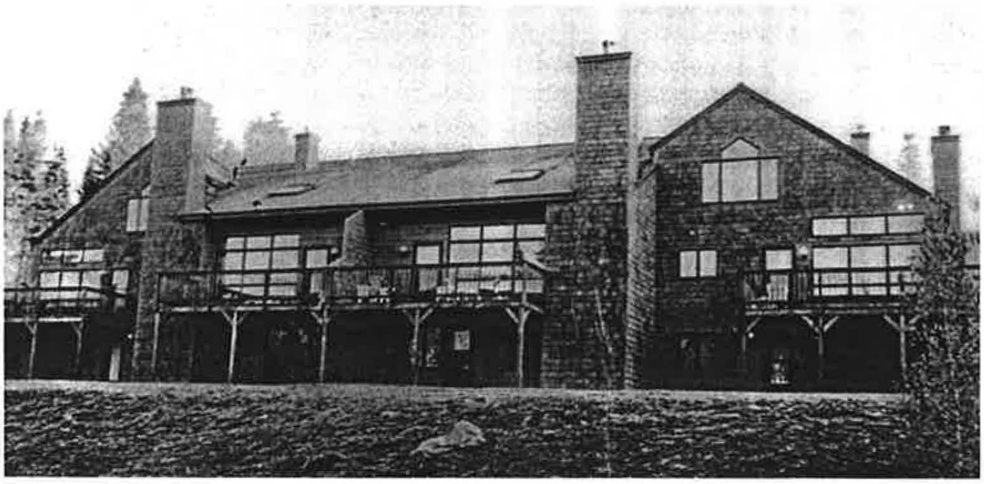
Example of the voids found in the attic insulation.

Unsealed spaces below attic batt insulation are open to partition and party wall stud bays.

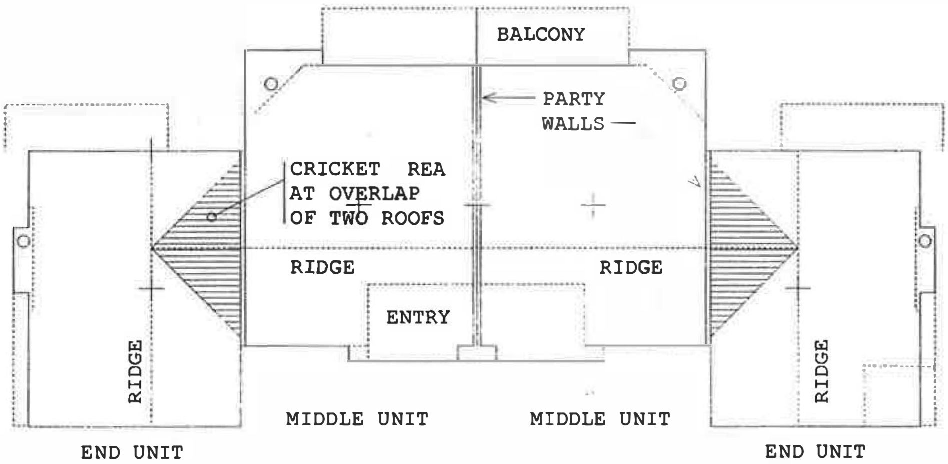
Attic batt insulation showing gaps and unsealed penetrations.

Figure 2 *Inside attics.*

(a) Front view of the four test units.



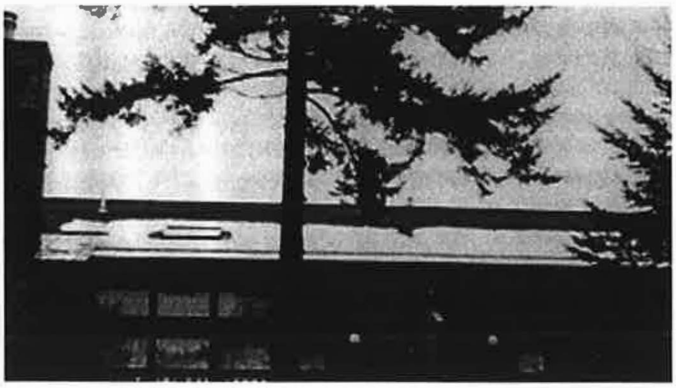
(b) Rear view of the four test units.



(c) Basic four-unit layout.

Figure 3 *Project overview.*

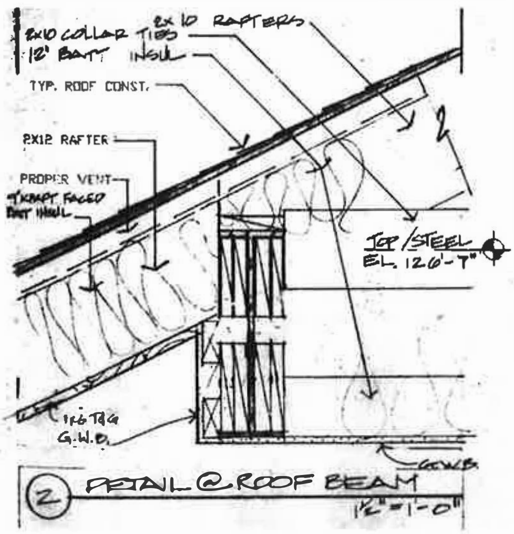
Snow melt pattern on end units showing melt on attic roofs above cathedral slopes—foreground and background units, same pattern.



Snow melt pattern on middle units showing melt on attic roofs above cathedral slopes—melt spots at party wall, behind chimney, and at bath vent.

Roof with snow removed showing ice on entire cathedral area and ice dams along eave edge.

Cathedral roof area showing melt above skylight rough opening leakage and above fireplace vents.



Detail of beam at top of cathedral slopes.

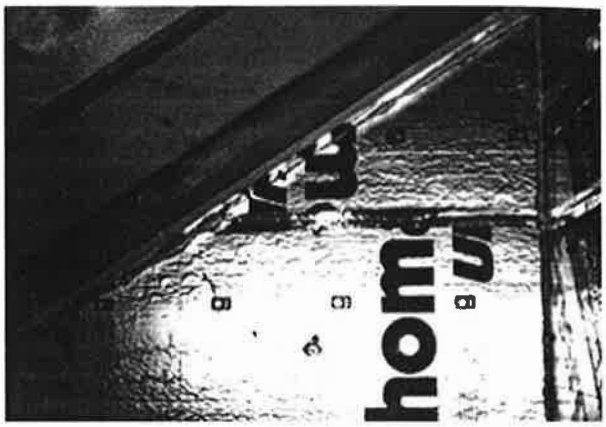
Frost melt pattern showing melt line along beam at top of cathedral slope.

Figure 4 *Cathedral roofs.*

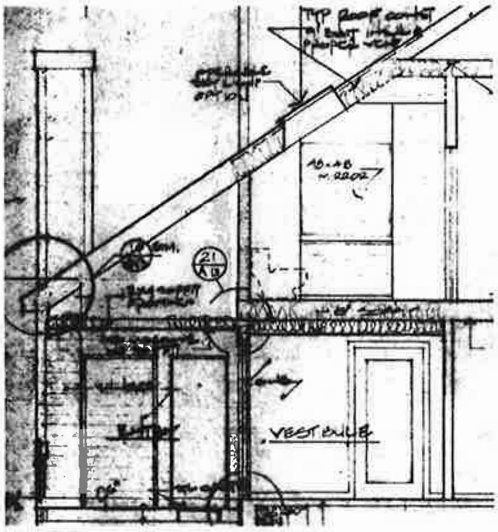
Cold air bypass below roof insulation at strapping above unsheathed kneewall bay.

Frost pattern above entry at bathroom kneewall attic.

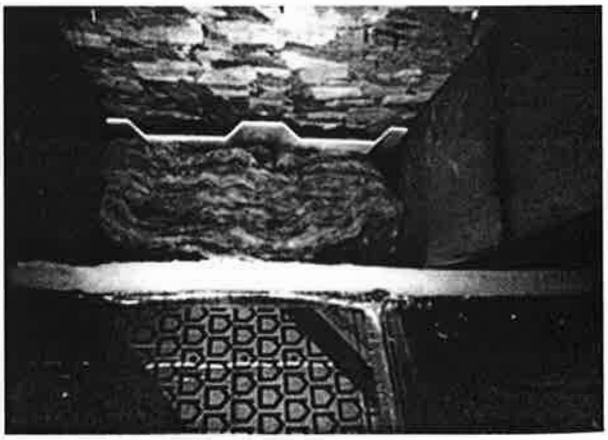
Original kneewall insulation without sheathing—none in floor thickness.



Kneewall insulation after air barrier sheathing retrofit.

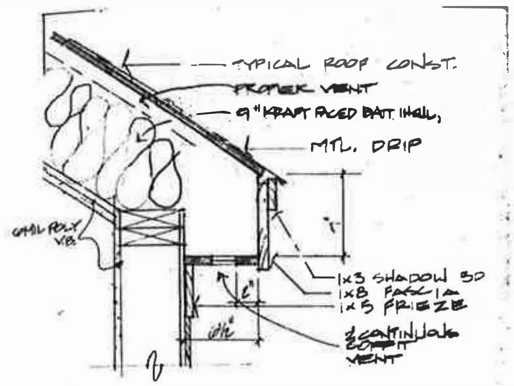


Section showing unsheathed kneewall attic cover entry—fan/light usually in skylight location.



Insulation above knee wall open to wind washing through and under batts.

Figure 5 *Kneewall attics.*



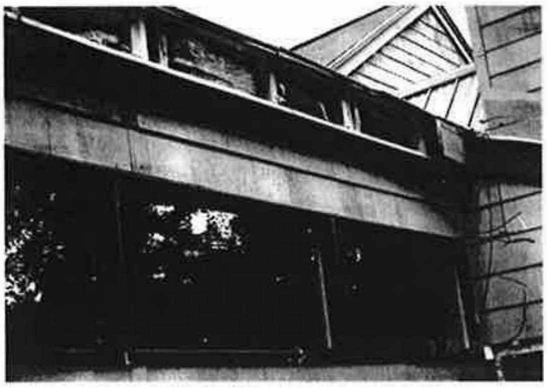
Section at top of party wall in cricket attic.

Unsheathed wall inside soffit.

Open soffit and rafters—before.

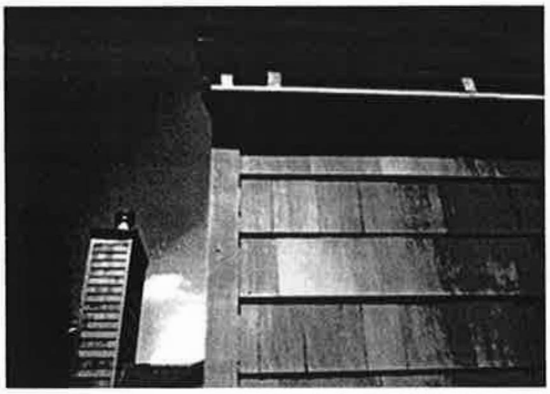
Soffit walls and blocked rafters—after.

Figure 6 *Soffits.*



Typical existing soffit bays including uninsulated narrow skylight double rafter bays—note inaccessible bays at top of fireplace box.

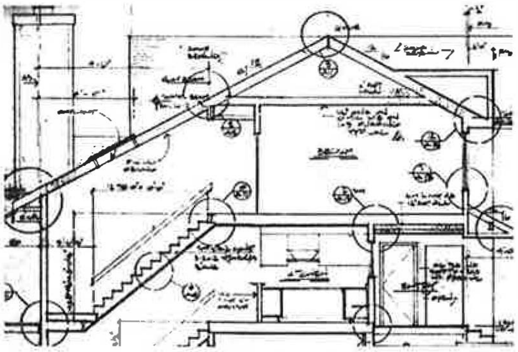
Typical soffit bay after blocking and sealant.



Uninsulated rake bay over gable end wall before retrofit of insulation and air sealing.

Multiple units with common pattern of melted attics above snow-covered cathedral slopes.

Original melt pattern showing attic melt above cathedral slopes.



Section showing cathedral and attic areas of a middle unit.

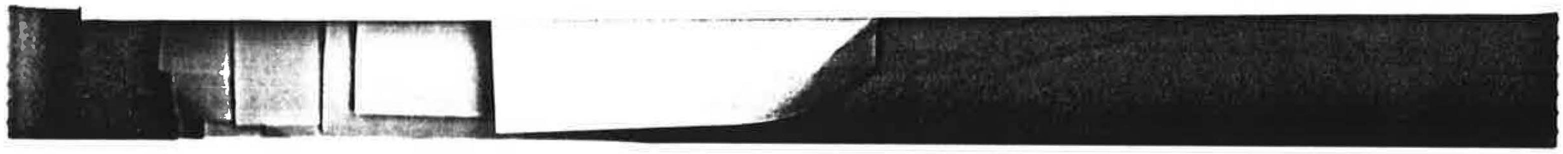
Background—unmodified units with attic melt. Foreground—modified with none.

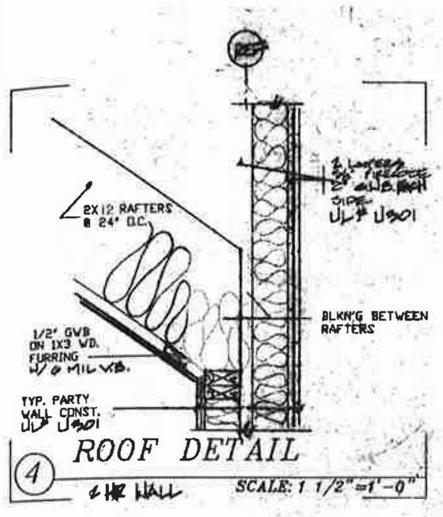
Infrared image showing heat in attic end wall.

Attic melt pattern reduced to spots after the Phase I repairs.

Attic melt pattern with snow remaining on short cathedral slopes.

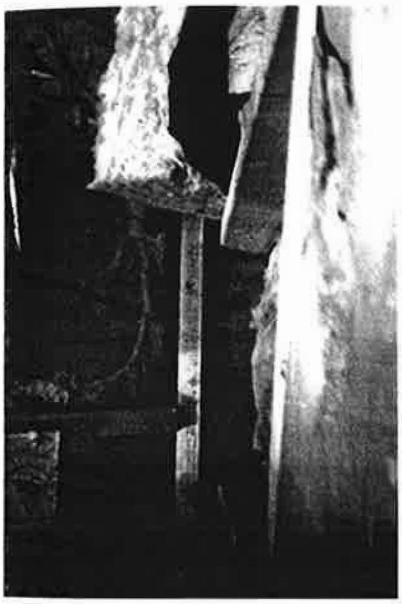
***Figure 7** Outside attics.*





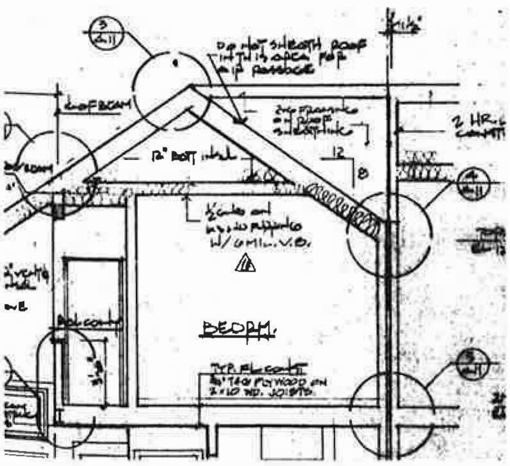
Section at top of party wall in cricket attic.

Melt pattern at end unit cricket area above valley.



Looking down along middle unit end wall into open top of party wall.

Cricket party wall condition after air sealing with rigid foam.



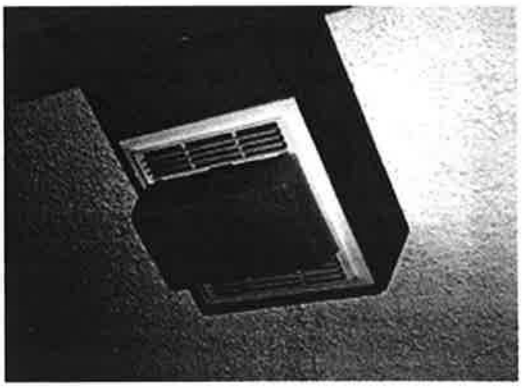
Section showing isolated cricket attic and location of detail 4/A11 shown above.

Interior infrared image of cricket attic area.

Figure 8 *Cricket attics.*

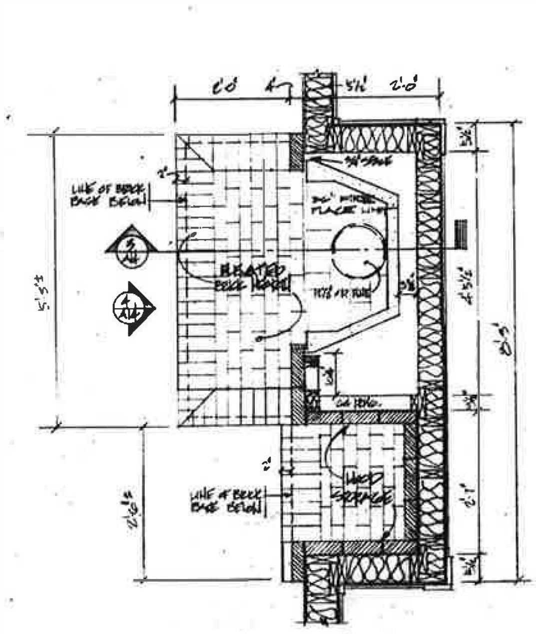
Melt pattern showing location of bathroom fan/ light and heat flow in vent space above.

Infrared scan of fan/light prior to retrofit.

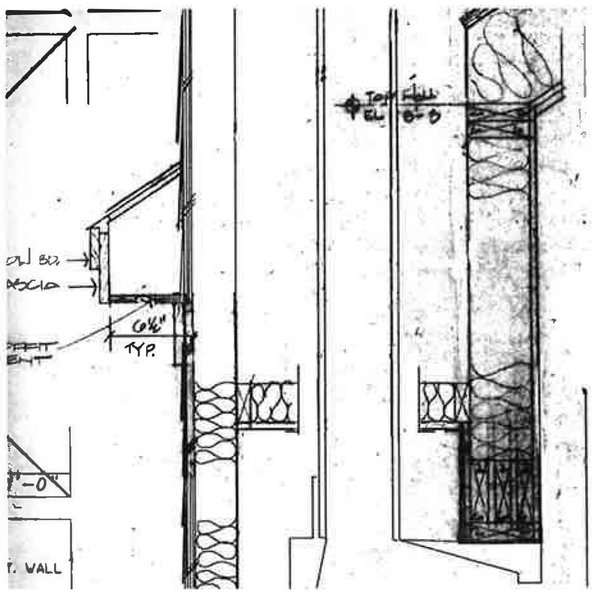


Recessed fan/light after being relocated to a surface-mount position.

Figure 9 *Bathroom fans.*

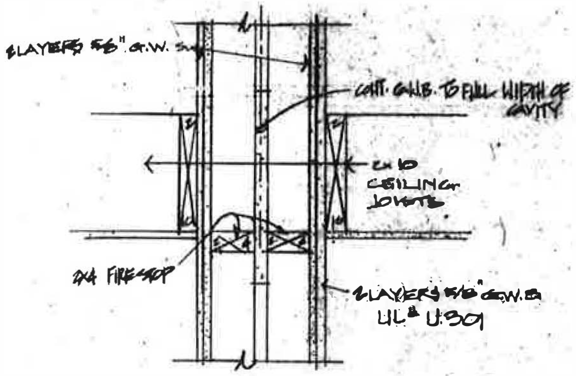


Plan of end-unit fireplace showing unsheathed and unsealed wall insulation.

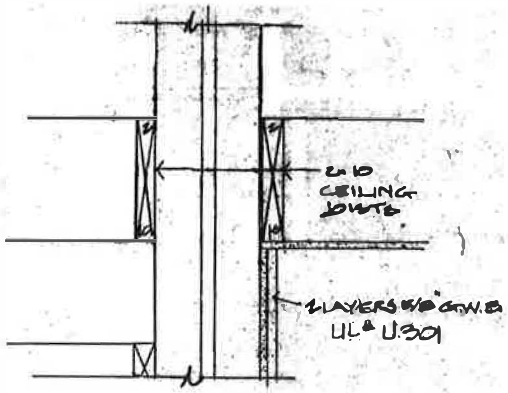


Section at fireplace box showing warm air paths to roof vent space.

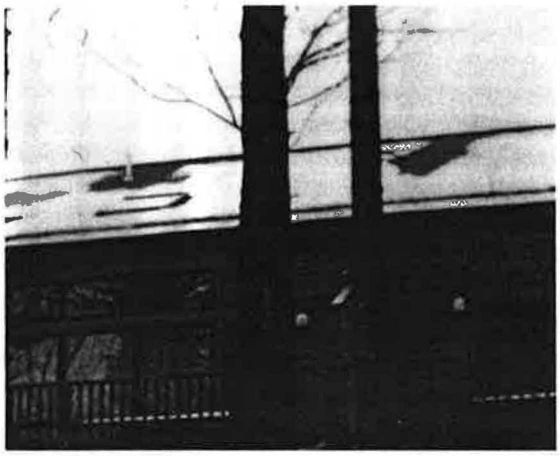
Figure 10 *Fireplace enclosures.*



Party wall detail as designed at attic level showing closure.



Party wall detail as built at attic level showing open center.



Melt pattern—left side over bathroom vent, right side over center party wall.

Top of one party wall in the attic.

Before (top) and after (bottom) shots of open and sealed party wall tops in attic.

Figure 11 *Center party walls.*