CONDENSATION IN FLAT ROOF SPACES: TWO CASE HISTORIES

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ABSTRACT

Ventilation is recognized as the only reliable means of ridding structures of excess trapped moisture. Toward this end codes stipulate minimum vent area requirements and specify types of air/vapor retarders. Failure to provide such air/vapor retarders and ventilation conditions can lead to disastrous and expensive consequences. As an example, the moisture trapped within a roof space can condense to induce decay of the wood structure; matting, moulding, and destruction of the insulation; shorting of the electrical fixtures; staining of the ceiling finish and/or destruction of the ceiling itself. This paper recounts the consequences of the failure to make adequate provision for the control of moisture in two flat mansard roof residential townhouse complexes in cold climates.

The first example recounts the deterioration that occurred in the timber flat roof structure as a direct result of the failure to provide an adequate air/vapor retarder and effective ventilation. Fiberglass batt insulation was wedged in the joist space when the complex was built. Condensate in the roof space resulted in decay in the timber members. Although the unit's owners were aware of moisture penetration problems, they were unaware of the cause or magnitude of the problem until seven years after construction. Extensive emergency structural repairs, at a cost of about $6,500 per unit, were required.

The second example reports the consequences of the failure to maintain adequate ventilation when conducting a roof thermal insulation retrofit. The 20-year-old roof structure was originally insulated above the roof deck. In an attempt to decrease heat loss, the joist space was filled, during retrofit, with blown-in fiberglass insulation. The work was completed in the fall and the unit's owners began experiencing moisture penetration almost immediately.

INTRODUCTION

The two case histories reported here highlight the importance of proper ventilation and adequate air/vapor retarders in residential flat roof timber structures in cold climates. In each case the lack of adequate ventilation has resulted in considerable expense, inconvenience, and even danger to the dwelling owners.

CASE HISTORY I

Description of Structure

The townhouses that are the subject of this case history comprise a 77-unit condominium

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located in Toronto, Ontario. They were built in the early 1970s with most units being first occupied in the winter of 1972-73. Each three-story unit contains either three or four bedrooms and measures approximately 20 ft (6.1 m) wide between party walls by 30 ft (9.1 m) deep between exterior walls. Much of the ground floor is occupied by the garage; the units do not have basements. Houses are arranged together in rows of up to approximately 20 units. To accommodate changes in grade, there are steps ranging between approximately 6 in (150 mm) and 3 ft (910 mm) between the roofs of some units in the rows.

All units are flat roofed with a cedar shake mansard extending approximately half-way down the top floor at all exterior walls. The original wood roof structure consisted of built-up felt and gravel roofing over 1 in (25 mm) decking; the decking was in turn supported by 2 x 8 (38 mm x 184 mm) joists spaced at 16 in (406 mm), which ran between each unit's exterior and center load-bearing walls. Suspended from the joists' soffit was a 1/2 in (12 mm) gypsum board ceiling. Above this ceiling and wedged between the joists was 6 in (150 mm) fiberglass insulation to provide the required R-20 (RSI-3.5) insulation value. The air/vapor retarder was an asphalt-impregnated kraft paper bonded to the underside of the batts. This air/vapor retarder was overlapped and stapled to the underside of the joists. No vents were provided on the roof. The roof structure's configuration and the condition at the center load-bearing wall is shown diagrammatically on Figure 1.

Venting of the above roof structure was supposedly accomplished through connection front and rear with the mansards. The mansard itself consisted of shaped and tapered 2 x 6 (38 mm x 140 mm) studs spaced at 16 in (406 mm). At the bottom of the mansard, the studs were the full 5 1/2 in (140 mm) in depth and rested atop the brick veneer. At the top the studs were only approximately 1 in (25 mm) in depth. The mansard face was finished with cedar shakes over 3/8 in (10 mm) plywood attached to the studs. Along the bottom of the mansard, a 1 x 4 (20 mm x 89 mm) soffit board was installed with 4 in x 16 in (102 mm x 406 mm) vents placed therein at approximately every 10 to 12 ft (3 to 3.7 m) along the building's length. Nominally these vents would have provided a venting ratio of approximately 1 in 500 had they been effective. In most units the mansard was interrupted front and rear by third floor windows. Between the windows there were short unvented portions of the mansard. The configuration at the eave and at the soffit is shown in Figure 2.

Preliminary Investigation

Since 1976 the owner had been plagued by moisture problems in the roof structure. Such problems manifested themselves as: condensation in or dripping from the ceiling electrical fixtures; persistent and recurring staining and softening of the gypsum board ceiling; failure of the ceiling taped joints; and telegraphing of nail head positions through the ceiling finish through rusting of the nails. Upon the advice of a series of roofing contractors, the owner ascribed these problems to failure of the roof membrane whereby water was migrating into the roof space from the exterior. The repairs undertaken prior to 1981 were commensurate with this diagnosis and, for the most part, proved fruitless in solving the chronic staining and softening problems.

By September 1980 roof membrane repairs had been periodically undertaken at considerable expense and to little avail for more than three years. However, at that time, a particularly large, sodden stain developed in the ceiling of a unit that, just a few months previously, had been subjected to major roof repairs plus partial mansard replacement. The ceiling had become so softened that during inspection by the owner portions crumbled away to reveal saturated, matted insulation and wet, soft lumber. Rightly suspecting the presence of decay, the owner sought the services of a consulting engineer to assess the nature and extent of the problem and to prescribe remedial measures.

Initial inspection of the problematic area via a 3 ft (0.9 m) by 4 ft (1.2 m) opening in the ceiling led to the following conclusions:

1. the structure was severely decayed to the extent that replacement was required;

2. until such replacement could be installed the roof must be immediately shored and the subject room should not be further occupied; and

3. in view of the history of the condominium complex, and in light of the common construction techniques employed therein, this condition was symptomatic of a more widespread problem.

Immediately thereafter, and with the cooperation of the owner, a series of test openings was made in the ceilings of ten units to better assess the extent of the problem. Within these ten units, a total of 14 openings were made in the ceilings to reveal the structure above. Each opening measured 3 ft (0.9 m) by 4 ft (1.2 m). Such units were selected to include houses that had and had not suffered water problems in the past; houses that had and had not been subject to previous roof repairs; houses that had and had not been well maintained since first occupied; and houses that represented all possible structural configurations in the complex. Within each unit, test openings were strategically located to coincide with locations of past problems and/or to expose all aspects of the underlying structure. The test openings revealed the following:

1. All ten roof structures were more or less heavily waterstained, including the roof boards, roof joists, insulation, and ceiling. This indicated that at some point in each and every unit's service life conditions had existed within the roof space that were conducive to decay.

2. Eight of the ten units had some active decay in their roof structures. Of these eight units, two were found to be so extensively decayed that collapse under any significant superimposed load was virtually assured.

3. In one unit the mansard sheathing was both waterstained and decayed.

4. In approximately half of units, the batt insulation felt damp to the touch and had been compressed due to long-term soaking. Therefore, the insulating capability of the batts had been severely impaired.

5. Three separate openings were made in the ceiling of one unit. The two located on either side of the center load-bearing wall revealed a roof structure so severely decayed that collapse was imminent. The third opening, which was located against the exterior wall and immediately above a soffit vent, revealed a roof that was not at all deteriorated. This third opening was no more than 15 ft (4.6 m) distant from the other two. The apparently sound condition of the roof at this third opening in contrast to the utterly destroyed condition elsewhere points up the significant error that one could make in concluding an entire unit's roof to be sound based on the condition of a relatively small opening.

6. In several units plywood roof decking was found over the top of seriously deteriorated roof boards and roof joists. In several such units it appeared that the joists were decayed at the time that the plywood was installed; however, determination of the age of the decay was not possible.

7. The air gap between the insulation and the roof deck was blocked at all center load-bearing walls. This had resulted from the 14½ in (370 mm) wide insulation being squeezed into a 13 in (330 mm) width since the roof joists are lapped at this location. This condition effectively blocks the ventilation of the entire roof structure, notwithstanding the fact that the mansard vents are also inadequate.

8. Where accessible for inspection, the air gap at the eaves between the insulation and the roof deck and between the insulation and the mansard sheathing was found to be open and unblocked.

9. In most units the presence of excess moisture in the roof space was manifest by the condition of the interior finishes. The evidence of such moisture's presence includes staining and/or softening of the gypsum board, failure of the taped joints, and staining at the nail heads.

10. The mansard sheathing was waterstained in places and exhibited some incipient decay.

As a result of this investigation the engineering consultant reported to the owner that a serious condition existed within the roof structures and that the structural safety could not be assured. Further, the owner was informed that said conditions could not be remedied by well-intentioned but nevertheless futile roof membrane maintenance. This was because the source of the moisture was internal rather than external. The common construction type throughout the complex and the past history of water problems are symptomatic of a widespread structural problem. Through extrapolation of the above observations it was concluded that

80% of the total roof structure was decayed to a greater or lesser extent. Further, it was predicted that approximately 16 units had roof structures deteriorated to the point where they were inadequate to support any superimposed load whatsoever and were therefore in imminent danger of collapse. A typical elevation of the townhouses is shown in Figure 3. It was recommended that remedial measures be designed and implemented immediately. Without such measures being taken, the municipal building authority indicated the homes were likely to be condemned.

Mode of Deterioration

The decay evident in these roof structures resulted from the roof spaces persisting in a warm, damp state. While the source of some moisture could be attributed to roof leaks, leaks from the roof drains, or leaks from the toilet stack vents, far and away the bulk of the moisture entered the roof space as moisture vapor from below, i.e., from the units' interior. Via vapor, diffusion and more importantly air leakage, this vapor penetrated the ceiling finish, the gypsum board ceiling, the air/vapor retarder, and the insulation to condense on the cold roof structure above. Decay began at the level of the roof deck and worked its way down the joists. In some cases 2 x 8 (98 mm x 184 mm) joists had been reduced in size to no more than 1 1/ 8 in (29 mm) x 5 3/4 in (146 mm); furthermore, the remaining residual cross section of these joists retained no structural capacity whatsoever. Penetration of the water vapor and its subsequent condensation had occurred at a slow enough rate that the condensate was more or less immediately absorbed by the wood structure. As such the condensate was not free to run down the sides of the joists to ruin the ceiling and thereby alert the individual owners to the significant problem developing above. The moisture penetration/condensation problem was aggravated by:

1. the very shallow air space between the insulation and roof deck;
2. the lack of any possibility of airflow perpendicular to the joists;
3. the blockage of the air space at the center load-bearing wall where the insulation had expanded upward to accommodate the overlapping joists' ends;
4. the blockage at the eaves between the roof and mansard air spaces, and
5. the widely spaced mansard vents, which, even if no blockage had occurred at the eaves or the center load-bearing wall, could have provided air changes to only the space between the two nearest joists.

Examples of the deterioration found during execution of the subsequent repairs are shown in Figures 4 and 5.

In other words, regardless of the rate at which moisture may have penetrated these roofs, its entrapment therein was so complete that decay of the wood structure and deterioration of the insulation and ceiling were almost inevitable. Given such conditions, one could expect to find waterstaining and decay in most roofs; observations during reconstruction confirmed this. Further, with such poor air/vapor retarders and degrees of moisture entrapment being common throughout the entire complex, one could also expect no correlation of the extent of decay with the types of ceiling finish or with the life-style or number of the occupants; observations during reconstruction also confirmed this.

In considering this condition, the particular asphalt-impregnated kraft paper air/vapor retarder merits some further mention. It was described above as integral with the fibreglass batt, overlapping its neighbors, and stapled to the joists' soffits. While such air/vapor retarders are no longer used, they were the norm for many years in North American residential construction. Even though such air/vapor retarders are conceded to be inferior to today's requirements, they have nevertheless performed well in other applications where adequate ventilation has been provided. Hence, in this sense, the primary cause of the deterioration of the subject roofs can be identified as inadequate ventilation. The corollary to this conclusion, therefore, is that such deterioration would likely have occurred in these houses, albeit at a somewhat slower rate, even if a air/vapor retarder fully consistent with contemporary standards had been provided. Therefore because the designer can never have assurance that over a building's life significant leakage cannot occur from the interior through the air/vapor retarder, it is incumbent upon that designer to provide in cold climates, means for ridding all roof and wall spaces of the invading water vapor.

Repair Approach

Design of repairs was undertaken in accordance with a two-fold philosophy:

1. First, to restore the roofs to structural adequacy and compliance with the Ontario Building Code.

2. Second, to prevent the recurrence of the problem. This was accomplished by installation of an adequate air/vapor retarder to minimize moisture vapor penetration into the roof space, coupled with a many-fold increase in the provision for ventilation.

Of the two-fold intent of this repair philosophy, the assurance of structural integrity was the easier to achieve. In brief, wherever roof joists' capacity had been wholly or partially lost through decay, then that lost capacity was restored by provision of additional joists. (A similar approach was adopted for assurance of the repaired house's thermal insulating capacities). Since the provision of adequate ventilation was also part of the repair philosophy, removal of decayed joists was not necessary. Ventilation would reduce the moisture content of the wood below the 15% to 20% required for continuing fungal attack. As this required inspection and evaluation of all joists and the entire area of insulation, it was obvious that complete removal and replacement of either the ceiling or the roof deck would be necessary. To prevent damage to the units' interior, because headroom restrictions prevented a lowering of the ceiling, and because major portions of the roof deck were known to be decayed, the upper surface emerged as the candidate for total replacement.

Adequate ventilation of the roof space was accomplished by raising the elevation of the roof deck to provide a minimum of 6 in (150 mm) of air space above the insulation. Further, reconstruction was specified in such a way that airflow could readily occur both parallel and perpendicular to the roof joists. Through a system of outriggers, two 4 in (102 mm) wide continuous vents were provided front and back at roof level; this provided an active venting ratio of no less than 1 in 50. In addition, the enlarged roof space was positively connected to all mansard structures through the relocation and/or removal of interfering existing cladding, blocking, or insulation. Finally, a continuous strip of 4 in (102 mm) vents was installed front and back to the bottom of the mansard (see Figures 6 and 7).

Since many ceilings were stained and deteriorated prior to the repairs, and since some damage was expected to be incurred by most ceilings because of the repairs, it was decided to incorporate the provision of a new ceiling into the design. Because it could be easily and inexpensively accomplished, it was further decided to include a new air/vapor retarder along with this ceiling. (Practice had shown that the original air/vapor retarder could not be relied upon and its heretofore unsatisfactory performance could be expected to be further impaired due to the rigors of construction). The new ceiling was 3/8 in (10 mm) gypsum board applied directly beneath the existing ceiling and screwed to the new and existing joists. To support ceiling edges, a paintable moulding was run around each room's perimeter. Sandwiched between the new and existing ceiling was a polyethylene air/vapor retarder whose thickness and installation method complied with the requirements of the local building code. In addition, since the new air/vapor retarder had to be interrupted by partitions at all room edges, all air/vapor retarder edges were sealed and caulked prior to application of the new ceiling and moulding (see Figure 8).

Construction

The contractor divided the construction into three distinct phases: first, the demolition of the existing roofs followed by reconstruction and reroofing; second, interior installation of new air/vapor retarder and new ceilings; and third, exterior closing and finishing including the installation of flashing and vents. For each unit the first phase was to take no more than one day. The second phase was scheduled to comprise parts of four to five consecutive working days and was to begin immediately following the roof reconstruction. The flashing and venting was scheduled to follow after roof reconstruction, but with the bulk of the work occurring after all reconstruction was complete.

The contractor moved onto the site on January 12, 1981, and undertook some preliminary work. Work began in earnest on the roof reconstruction on January 13. It was originally anticipated that two roofs per day would be completed; therefore, barring unforeseen material delays and inclement weather, the project completion date for roof reconstruction was March

6. Interior repairs would then finish some four or five working days later. Actual roof reconstruction was completed on March 27; all interior work was completed on April 6. Work regarding the flashing and vents began on January 22; all such work and the finishing was completed on May 14, 1981.

Total expenditures by the owner for construction were in the order of $385,000. To cover this and all other associated costs (engineering fees, legal fees, etc.) a levy of approximately $6,500 per unit was required. Observations during construction proved conclusively that the consultant's predictions and fears regarding structural adequacy were well founded. Of the 77 units, none was found to be free of significant waterstaining and 90% contained at least some decay. The most telling feature, however, was the fact that 19 of the 77 units contained some portion of roof structure so severely decayed that collapse under any applied load was a virtual certainty.

A total of 283 new joists were installed. This represents about 10% of the total number of existing joists. Approximately 8% of the total roof insulation was replaced. Wherever deterioration had occurred, the roof boards were always more severely decayed than the roof joists. Further, the decay in the joists began near the top of the members and worked down toward their soffits.

Previous Roof Repairs

During the course of the investigations by the consulting engineer and more particularly during the actual reconstruction, it became evident that certain previous repairs had not been satisfactorily completed, that inferior materials had been inappropriately installed, and that a new roof surface had been applied over what was already deteriorated roof structure. Such repairs had involved among other things the repairs or replacement of part or all of the membrane, the installation of plastic roof vents, repairs to cant strips and flashings, patching of roof deck, etc.

Following removal of the existing roof membrane, it was noted that on certain units the original 1 x 6 (20 mm x 140 mm) roof boards had been replaced during previous reroofing by new 1 x 6 (20 mm x 140 mm) roof boards. In all cases the 2 x 8 (38 mm x 184 mm) joists supporting the new 1 x 6 (20 x 140 mm) board were themselves decayed. Where the original roof had been so severely decayed that reroofing had not been possible without strengthening the decking, the more usual practice was to lay 1/2 in (12 mm) plywood over the decayed roof boards prior to installing the new roof membrane. In certain units where patches were needed prior to reroofing, used plywood was employed. On two units the patches were parts of old plywood shipping crates. In certain units where patches were needed prior to reroofing, discarded pieces of metal were employed. In some instances the patches were the lids from the cans in which the bitumen had been supplied; in other cases the patches were small pieces of sheet metal. In one unit the original 2 x 8 (38 mm x 184 mm) joists had been so severely decayed that during previous reroofing nonstructural scabs had been nailed alongside the joists to restore the roof to its required elevation. This was probably deemed necessary to prevent localized ponding. On three units the stack vent from the toilets had been cut off at roof level to function as roof drains. The original roof was a builtup felt and gravel membrane. All replacement membranes were also builtup felt and gravel. However, on certain roofs the gravel was never applied so that the asphalt-impregnated felts were left unprotected from ultra-violet degradation. Good practice dictates the use of sufficient gravel to completely cover the felts; the Ontario Building Code requires the use of 400 lb (180 kg) (approximately 1/2 in ,2mm.) of gravel for every 100 ft^2 (9.3 m^2) of roof. Without this gravel layer, the new roofs could not be expected to last a normal service life.

As a result of these observations the following conclusions are drawn regarding certain aspects of the reroofing previously done.

1. Much of the work had been improperly or incompletely performed such that the replaced roof membrane could not be expected to provide a normal service life.

2. The materials used to cover the decayed roof structure were neither new nor of good quality.

3. The existence of a significant decay problem within the roof structure would have been evident during any and all reroofing operations where the roofer found it necessary to replace and/or patch portions of the roof structure. Any new roof

membrane applied over such areas could not be expected to perform properly for any reasonable length of time.

The implications of these observations and conclusions with regard to the funds spent by the owner on the previous reroofing and the final reconstruction are twofold. First, inasmuch as the new roof membranes were knowingly and continually installed over obviously deteriorated structures, it is clear that a normal service life could not be expected of the new roof membranes; hence the owner did not receive the weatherproofing protection he had sought when he contracted for the reroofing. Second, had the owner been alerted to the developing roof decay problem when it had first become evident to the roofing contractor, then the final reconstruction could have been undertaken some years earlier. In addition to the savings the owner would have accured through not persisting with an inappropriate roof maintenance program up to and including the summer of 1980, significant savings in the final reconstruction would also have been realized as the decay would have been arrested at an earlier stage.

CASE HISTORY II

Description of Structure

This residential complex, as shown in Figure 9, is approximately 20 years old, is located in Alberta, and consists of 32 two-story townhouse units in four buildings. Each building is approximately 36 feet (11.0 m) wide by 110 feet (33.5 m) long. Each building consists of eight units with a flat mansard roof, and each unit has party walls on each of either two or three sides. The grounds consist of a car park, sidewalks, and landscaped areas. On-site observations confirmed that the originally constructed roof structure consists of a gypsum board ceiling, 2 x 8 (38 mm x 184 mm) timber joists, 1 x 6 (20 mm x 140 mm) roof deck boards, 3/4 in (20 mm) extruded polystyrene and four ply builtup roofing (BUR). There is no air/vapor retarder. Exterior walls consist of lower story brick masonry end walls with a combination of brick, stucco, glazing, and timber infill panels on the side walls. The upper story consists of a cedar shake mansard on all four sides with windows on side elevations only.

History

The roofs of the complex had been relatively problem free prior to 1982. In the summer of 1982 the owners elected to add insulation to the roofs in an effort to reduce heat loss and thereby energy consumption. In this regard an insulation contractor was engaged who proposed to blow loose mineral wool insulation into the then vacant joist space.

The insulation contractor anticipated, in the abscence of drawings to indicate otherwise, that the joists would span in the shorter 36 ft (11.0 m) east-west direction and, therefore, by installing insulation from each side would have a maximum 18 ft (5.5 m) to blow it. When the work began in early September of 1982, the contractor found, however, that the joists spanned in the north-south direction instead, and he could not, therefore, effectively install the insulation through the complete spans from the sides of the roof. The contractor decided to cut out eight sections of the roof on each building to install the insulation from above. These sections, shown on Figure 10, were patched by the insulation contractor after installing the insulation. All work was completed before October at a cost of about $34,000.

During the first week of October 1982, there was a severe rainstorm and 28 of the 32 units were subjected to water penetration from the roofs. The roof patches were deemed to be deficient and the insulation contractor then hired a roofing contractor to redo these patches. The roofing contractor also installed one rotating ventilator in each area that had been cut out, as well as installing additional roof scuppers through the roof flashings to assist in drainage of the roofs. This was required to connect drainage that had been interfered with by the patched area being higher than the surrounding surfaces. Interior water damage was repaired by a drywall contractor.

During a period of warm weather in February 1983, four units experienced water penetration again. The roofing contractor attributed this leakage to a thawing of frozen water trapped in the roof during the October repairs. At this time a roofing consultant was retained to inspect the roofs and report his findings. He reported that no mastic cement had been applied under the roof ventilator flanges or at seams in the ventilator stacks. He also reported finding moisture on the inside of the ventilator stacks, in the insulation as far horizontally as he could reach and on the top of the gypsum board ceiling, in seven of the eight ventilators he inspected.

In June 1983, a rainstorm resulted in water leakage in seven units (including the four units experiencing leakage in February). No further leakage occurred between June and August 1983 at which time the owner retained an engineering consultant to investigate the problem.

Observations

Observations made by the engineering consultant include the following.

1. The areas where cuts had been made by the insulation contractor were easily discernible. These consisted of a total of eight cuts per roof. Each cut was approximately half the width of the roof in an east-west direction, from the edge to the middle of the roof. The extent of the patched areas, over these cuts in a north-south direction, were approximately 5 ft (1.5 m) wide. A rotating ventilator had been installed around the middle of each patched area.

   The surfaces of the patches were higher than the areas surrounding these, as the patching materials had been built up above the original roof surface elevation. Asphalt was noted on the galvanized roof flashings adjacent to the patched areas. Obviously this was due to the patching operation.

2. A number of areas on the roofs were completely bare of gravel. The gravel in some areas had been left in piles instead of being spread evenly on top of the asphalt for its protection.

3. The asphalt exhibited blistering, or bubbling, in various exposed areas.

4. A total of four rotating 12 in (305 mm) diameter ventilators were removed for inspection on the two westerly buildings. Through these openings, the roof construction was examined and found to be as follows:

   - asphalt and gravel
   - four plies of asphalt felts
   - 3/4 in (20 mm) thick rigid insulation
   - roof deck consisting of 1 in x 6 in (20 mm x 140 mm) boards
   - 2 in x 8 in (38 mm x 184 mm) wood joists with loose, blown, mineral wool insulation filling the spaces between these
   - gypsum board ceiling

5. No evidence of polyethylene or any other kind of air/vapor retarder was found in the construction, either above or below the roof joists. However, the condition of the existing timber comprising the roof joists and roof deck was very good and did not exhibit any significant structural deterioration or decay. A typical view within the joist space is shown in Figure 11.

6. The openings in the roof deck at the ventilators had been effected by removing two adjacent 1 in x 6 in (20 mm x 140 mm) boards, i.e., a width of approximately 12 in (305 mm). From above this a section of insulation, approximately 18 in (457 mm) wide had been removed. The opening in the insulation had been closed by spanning this with 3/8 in (10 mm) plywood, and there was no indication that this was fastened down by any means other than the weight of the covering of felts, asphalt, and gravel. As a result, walking on the patched areas caused them to move easily and to "ripple."

7. Originally vents had been installed in the mansard roof soffits in one building (the southwest building) but not in the other three. It was found that a total of 73 three-inch (75 mm) diameter vent holes had been provided in the south-west building, and this was the only venting provided originally in the four buildings.

8. The amount of ventilation on each building had been increased by the installation of eight 12 in (305 mm) diameter ventilators.

Evaluation

The engineering consultant concluded the water penetration experienced to date was a result of deficient workmanship or materials when waterproofing the roof patch areas and installing the roof ventilators. Condensation may have been a minor contributing factor to the February 1983 leakage.

The roof patches installed by the insulation contractor were grossly deficient as evidenced by the fact that 28 of the 32 units experienced significant water penetration for the first time about one month after the work was completed. The 3/8 in (10 mm) plywood used in patching the holes was not fastened down to the roof deck. This is considered improper; however, the prime cause of the October 1982 leakage was considered to be a failure in bond between the old roof and the new cold applied plastic cement used in the patching operation.

The engineering consultant agreed that the February 1983 leaks during a spell of warm weather were at least partly due to thawing of rainwater trapped in the roofs prior to the roofing contractors repairs. Thawing of condensate could also be a contributing factor. The June 1983 leaks at the time of a rainstorm are, however, attributed to the work of the roofing contractor. Some of the roof patches, rewaterproofed with hot tar and felt by the roofing contractor, were leaking and , as well, the unsealed joints of the ventilators, or the ventilators themselves, may have been contributing factors.

The water leakage problems experienced to date may however be deemed minor problems when compared to the potentially very serious and costly problem inadvertently created by the retrofit.

It has been noted that vents had not been supplied for three of the four buildings of this complex. The reason for the mansard soffit vents on the one building is unknown, although they may have been intended to vent the mansard only. This general absence of ventilation was quite acceptable for the original roof construction, as it was designed to have no enclosed air space between the roof membrane (i.e., the four plies of asphalt felts) and the rigid insulation.

The current situation is quite different, however. The insulation installed by the insulation contractor will have created air spaces below the roof deck in some areas, but not in others. The variation, the engineering consultant believed, will have been aggravated by water leakage compressing the insulation in these wetted areas and also due to the effect of the ventilators drawing air through the new wool insulation. For a building in Alberta the air spaces between a conventional roof membrane and insulation below are required to be vented in accordance with the 1981 Alberta Building Code. The unobstructed vent area for this type of roof shall be not less than 1/150 of the insulated ceiling area. It is not possible to determine if there are any areas of the roof space above the new insulation that are completely unobstructed with regard to air movement, but the likelihood is considered very small and only possible on the southwest building where there are vents in the soffits of the mansards. As it was the insulation contractor's intention to fill all the joist spaces, it is considered very unlikely that there are any areas, even in the south-west building, which are completely unobstructed with regard to venting. Thus it is considered that the amount of ventilation for these roofs is totally inadequate.

Figure 12 shows the roof cross sections and Tables 1 and 2 show the temperature gradients before and after retrofit. These demonstrate that the temperature of the lower surface of the timber deck can be expected to be lowered during winter conditions from about 42 ^{o}F ($6^{o}C$) to about -10 ^{o}F ($-23^{o}C$) by the addition of insulation in the joist space. Condensation, particularly in the absence of an effective air/vapor retarder, is inevitable.

Conclusion

In the opinion of the engineering consultant, the installation of proper venting in these roofs is not a worthwhile economic consideration for the current situation. For vents to function properly would require that there be no obstruction at mansard/joist joint and no lateral obstruction to air movement along the underside of the deck. It is not known if obstructions exist due to original construction details; however, it is believed that the new mineral wool insulation alone will effectively block ventilation.

To ensure ventilation would require that the existing roofing and timber deck be removed and a new, raised deck installed with adequate ventilation. This alternative could also allow for additional insulation to be installed. This was of course the initial desire of the owners, which ultimately led to the water penetration problems.

Given that the cost of providing effective ventilation was prohibitive, the engineering consultant recommended to the owner that the mineral wool insulation in the joist space and the ventilators be removed to restore the roofs to their original configuration.

CONCLUSIONS AND RECOMMENDATIONS

Each owner within the buildings described here has painfully gained first-hand knowledge of the implications of inadequate ventilation and poor quality workmanship. The problems have been thrust upon them in a fashion they'll not forget.

Nevertheless, it is from situations like this that the building community can and must learn if similar occurrences are to be prevented elsewhere. For the designer/builder/purchaser of new construction or retrofit, these case histories underscore the care and attention to detail that must be taken in selecting materials and specifying construction techniques. Air/vapor retarders must be properly installed and sealed to prevent as much as possible any migration of moisture into the roof space. The roof space itself must be large enough and built in such a way that air circulation between all areas therein, and between it and the exterior, can occur. Blockages of such air spaces whether by insulation or solid blocking must not be allowed. Where building codes rightfully require smoke and/or fire separations, provisions must be taken to ensure that each and every roof space compartment is independently and adequately vented. Vents should be installed wherever possible to take advantage of the natural convective effects and/or the pressure differentials that occur on opposite sides of a building during wind. The fact of such vents' presence is in itself not enough - they must be unobstructed and functional. The venting ratios stipulated in building codes are minimums; when in doubt, designers should take pains to "over-vent."

In addition to the above, the owner of an existing structure should be aware of certain other considerations (and experience would suggest this to be particularly so for flat-roofed structures such as these townhouses). Whenever and wherever chronic and persistent moisture problems occur, it must be recalled that the source could well be internal. Whenever this is the case, then all monies spent on external membrane repairs are wasted; indeed, such expenditures may only delay the diagnosing of the true problem such that eventual rectification can be even more costly. Therefore, given a situation of persistent condensation in or dripping from ceiling electrical fixtures, of persistent staining and softening of the gypsum ceiling, of chronic failure of the ceiling taped joints, or of telegraphing of corroded nail heads through the ceiling finish regardless of the frequency of repainting, it is strongly recommended that a representative sample of the roof structure be opened for detailed inspection. Should evidence of moisture penetration or condensation be noted, then assessment of the wood structure by a competent and experienced engineering consultant technologist is essential to assure the structure's continued structural adequacy. Where conditions similar to those described herein are noted, major modifications must be undertaken to assure long-term structural adequacy and to preclude recurrence of the moisture induced problems.

Owners of existing structures must be aware of the possible consequences when additional insulation is imprudently added to a flat roof structure. Poor workmanship aside, allowance for adequate ventilation must be included in any insulation retrofit.

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TABLE 1
Temperature Gradient Before Retrofit

	R		ΔT		T	
	R	RSI	oF	oC	oF	oC
Indoor Room Air					70	21.1
Indoor Air Film	0.61	0.11	8.5	4.7		
Lower Surface of Gypsum					61.5	16.4
Gypsum (1/2") (12)	0.45	0.08	6.3	3.5		
Upper Surface of Gypsum					55.2	12.9
Air Space (8") (200)	0.93	0.16	13.0	7.2		
Lower Surface of Deck					42.2	5.7
Deck (3/4") (2)	0.93	0.16	13.0	7.2		
Upper Surface of Deck/ Lower Surface of Insulation					29.2	-1.6
Insulation (3/4") (20)	3.75	0.66	52.3	29.1		
Upper Surface of Insulation/ Lower Surface of BUR					-23.1	-30.6
BUR (4 ply)	0.33	0.06	4.6	2.6		
Upper Surface of BUR					-27.7	-33.2
Outside Air Film	0.17	0.03	2.3	1.3		
Outside Air					-30	-34.4
	7.17	1.26	100	55.6		

TABLE 2
Temperature Gradient After Retrofit

	R		ΔT		T	
	R	RSI	°F	°C	°F	°C
Indoor Room Air					70	21.1
Indoor Air Film	0.61	0.11	2.4	1.3		
Lower Surface of Gypsum					67.6	19.8
Gypsum (1/2") (12)	0.45	0.08	1.8	1.0		
Upper Surface of Gypsum/ Lower Surface of Insulation					65.8	18.8
Insulation (8") (200)	19	3.35	75.3	41.9		
Upper Surface of Insulation/ Lower Surface of Deck					-9.5	-23.1
Deck (3/4") (2)	0.93	0.16	3.7	2.0		
Upper Surface of Deck/ Lower Surface of Insulation					-13.2	-25.1
Insulation (3/4") (20)	3.75	0.66	14.8	8.2		
Upper Surface of Insulation/ Lower Surface of BUR					-28.0	-33.3
BUR (4 ply)	0.33	0.06	1.3	0.8		
Upper Surface of BUR					-29.3	-34.1
Outside Air Film	0.17	0.03	0.7	0.3		
Outside Air					-30	-34.4
	25.2	4.45	100	55.5		

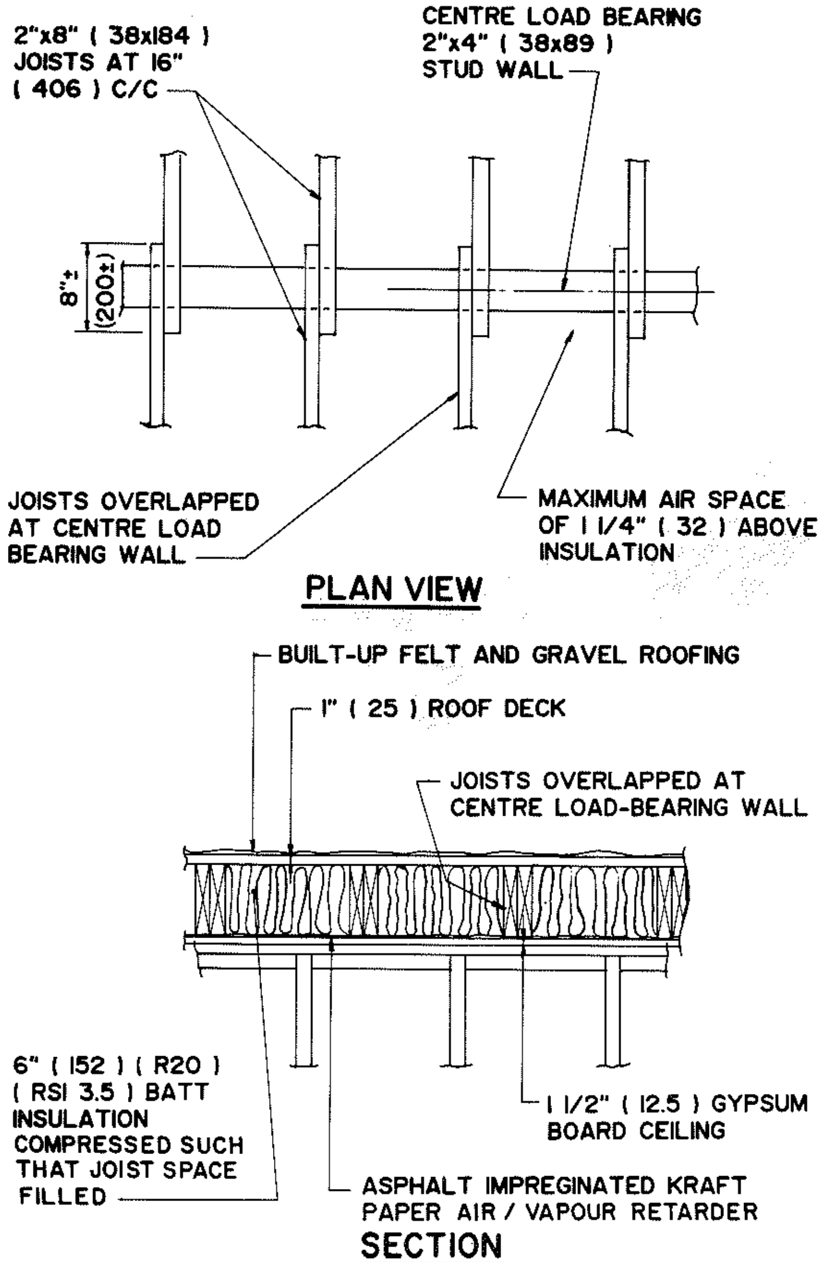

Figure 1. Condition at center load-bearing wall

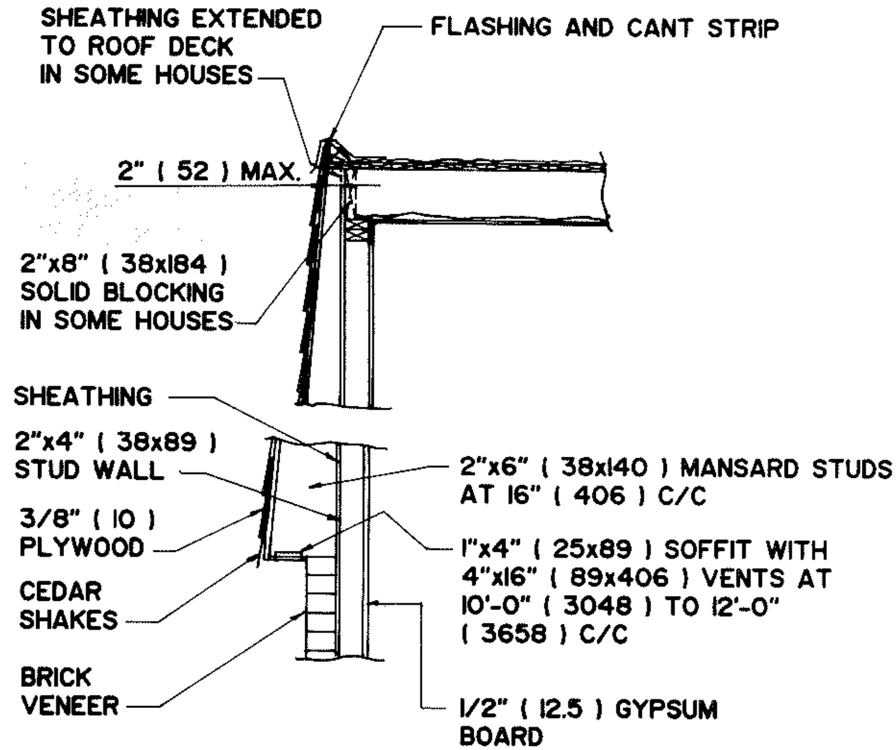

Figure 2. Condition at eave

Figure 3. Typical elevation

Figure 4. Severely decayed roof joist

Figure 5. Decayed roof boards and roof joists

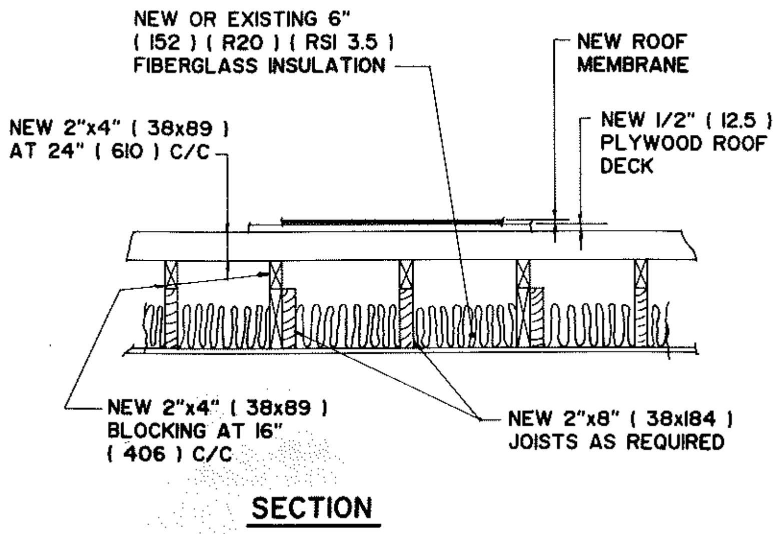

Figure 6. New raised roof structure

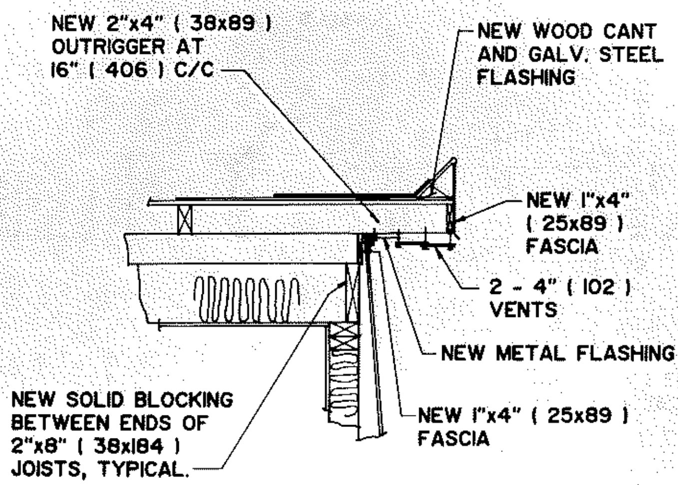

Figure 7. Condition at cantilever eave

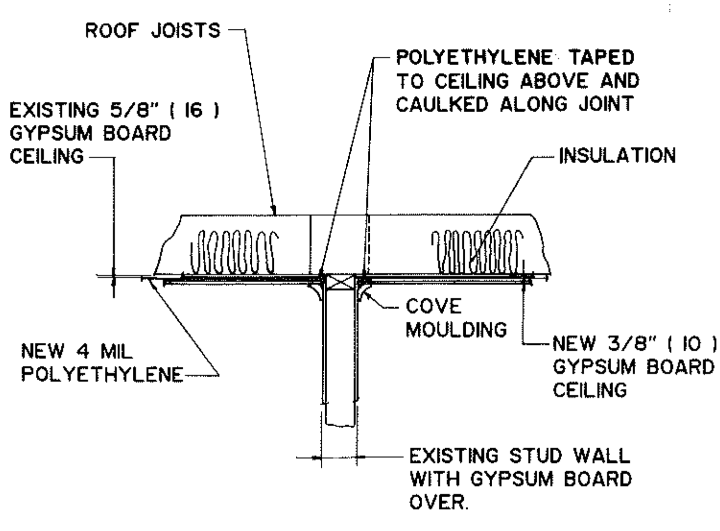

Figure 8. Detail of new ceiling installation

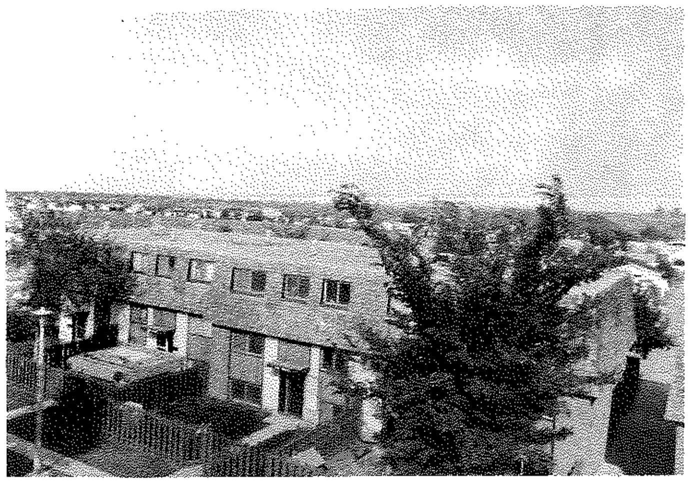

Figure 9. Typical elevation and roof after retrofit

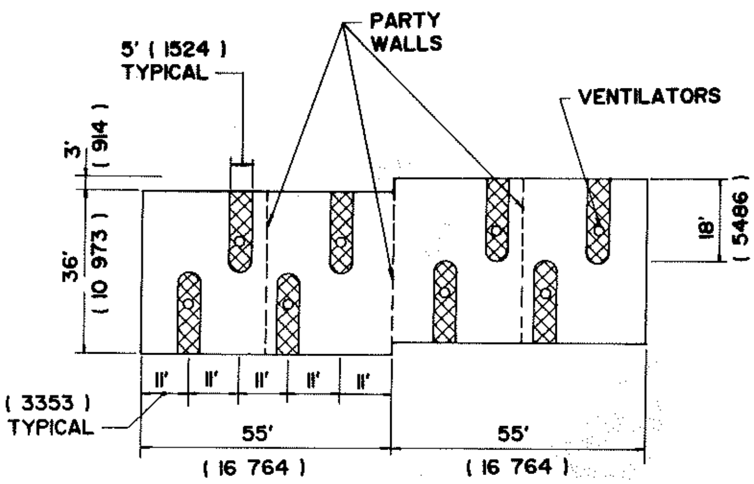

Figure 10. Roof plan

Figure 11. Typical view of joist space through ventilation stack

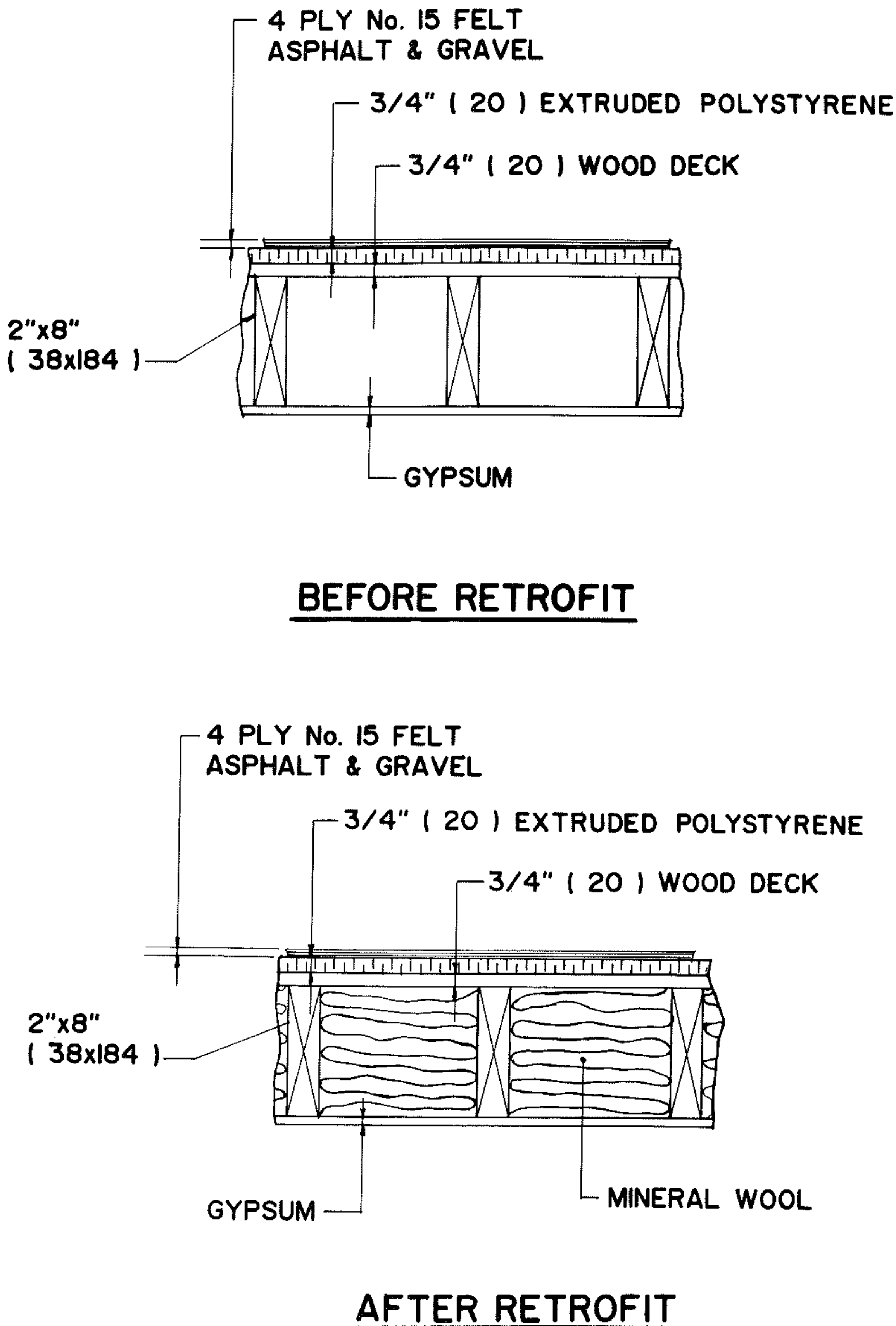

Figure 12. Roof cross section