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CASE STUDY: INSULATED FLAT ROOF TOWNHOUSES
FAILED ROOFING & STRUCTURE DUE TO AIR EXFILTRATION/CONDENSATION

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INTRODUCTION

Purpose of Paper. In 1985, Tillyard & Partners Inc. were retained by a Brampton Ontario condominium corporation to investigate serious deterioration of the top storey ceilings and failure of the roof membrane of their insulated flat roofs. The purpose of this paper is to discuss:

- How this project was approached in terms of rationalizing the failures that occurred by the use of various investigative methods combined with the application of basic building science principles.

- The type of construction deficiencies and details which promoted the problem.

- The ramifications of adding insulation to an enclosed roof structure.

- The development of a solution that would accommodate the moisture loads; utilizing a microcomputer and spreadsheet software to assess thermal/vapour pressure gradients (hygrothermal analysis).

- The cost/benefit analysis in proving to building officials why the insulation levels required by the Ontario Building Code as applied to this project were not cost justified.

- The actual construction process which provided for a continuous air/vapour barrier which also acted as a temporary roof.

PCC #16: Description. Peel Condominium Corporation #16 (PCC #16) consists of 10 flat roof townhouse blocks containing a total of 73 three storey units. This condominium is located in Brampton Ontario, just north-west of Toronto. While having a heating degree day total of 7721 degrees F and a January outdoor design temperature of -4 degrees F, this part of the province is not considered to have a severe winter climate.

Built in 1972, the roof construction consisted of the following components (in to out) as shown in Figure 1:

- 1/2" drywall ceiling
- 2"x8" wood joists @ 24" c/c
- R-20 kraft-faced glass fibre batt insulation
- 1"x3" @ 24" c/c
- 1"x5" wood decking
- 4 ply built-up asphalt roof membrane

Venting of the joist cavity was attempted by leaving out the joist headers at the front and rear of the units. Air movement originated from the vents, located at the mansard roof soffit, approximately 11 feet down from the joist cavity.

The type of heating and ventilation equipment is noteworthy. Space heating is provided by electric baseboard heaters. The third floor bathrooms were exhausted by means of a fan, located in the roof cavity and exhausting out through the roof. The kitchens were not equipped with true exhaust fans. Dryers however, were vented. For the most part, the units were occupied by families.

Problem History. PCC #16 encountered moisture staining of the third floor ceilings during the first winter after construction had been completed and the units occupied. A roofing consultant was hired and concluded that the source of the moisture was due solely to dripping condensation from some uninsulated vent stacks. Remedial measures were implemented but did not stop the continued staining of the ceilings.

Over the next decade, the condominium coped with the problem, which eventually caused a premature failure of the roof membrane. In 1985, during repairs to the roofing, was the crisis most apparent, when one of the roofers put his foot through the roof deck and ceiling below. What had originally been a moisture problem had now become the start of a structural failure as well.

OBSERVATIONS AND RATIONALIZATION

Problem Assessment. After a review of the problem history and inspection of the various units in distress, it became somewhat evident that simple rain leakage was not the reason for the failure. It then became necessary to identify the sources of moisture and why it was able to cause the damage reported. There were a number of questions that had to be answered:

- What were the sources of indoor moisture and subsequent moisture loads?
- How was the moisture being transported into the flat roof cavity?
- Why could the moisture not be removed through ventilation within the roof space?

The infiltration rate plays an important part in determining the moisture load within the house. Though the amount of air infiltration is certainly dependent on the degree of air tightness of the building envelope, there needs to be a pressure difference to move this air into the structure. While wind is certainly a prime influence, houses often partially rely on the use of mechanical equipment to create a negative pressure difference to draw air into the space. This is usually accomplished by exhausting air out of the house via bathroom and kitchen fans, dryer venting, fireplaces and by combustion heating systems. Other than fireplaces, the major air consumer/exhauster is the fossil-fueled furnace/burner system. In order for these systems to work, they consume vast amounts of air for combustion and flue draft purposes. As this creates a negative pressure situation, outside air is drawn into the house through the multitude of unintentional openings. This process acts to remove moisture laden air up the chimney and also, dilutes the indoor air thus tempering the indoor humidity.

With respect to PCC #16, an understanding as to why an excessive moisture load existed was possible. The major reason was the lack of a combustion heating system to help ventilate the building. As noted previously, these units are electrically heated. When combined with the lack of a kitchen vent; the fact that most units had four to five family members and, additional moisture was entered into the air via portable humidifiers, it was expected that the units were excessively moisture loaded.

For many years, the moisture transfer process had been associated with water vapour diffusion. While this is still an important phenomenon that must be evaluated to identify moisture deposition, air exfiltration is now considered to be the major "vehicle" for condensation in roof constructions. A study of flat roofed, electrically heated houses in Ottawa, Ontario identified frequent condensation in the joist cavities, caused by a combination of points of air leakage from the living space and the lack of attic ventilation. (1)

The potential for flow of moisture laden air into the roof space can be appreciated through an understanding of the naturally occurring action of stack effect. Under winter conditions, the outdoor air is denser than the warmer indoor air. This produces differences in the pressures exerted on either side of the building envelope which are dependent on the building height. Therefore, a situation exists where there will be infiltration at the lower half of the building and exfiltration at the upper half. The transition point, known as the neutral pressure plane (NPP), will lie at the mid-height of the building if the size of the openings are evenly distributed over the building's height. This scenario is similar to PCC #16.

All things being equal, a furnace flue will move the NPP closer to the roof level. As the pressure differences which produce air flow vary linearly (to a degree) with the distance from the NPP, there is less chance of exfiltration/condensation at the roof line with houses with active flues.

To summarize, the absence of chimneys in the electrically heated units of PCC #16 led to lower air infiltration, resulting in higher than normal humidities (in concert with other factors) and a low NPP increased the stack pressures (exfiltration) at the third floor ceiling line. The only remaining requirement was the need for air leakage points from the inside space into the roof cavity.

Inspection Methodology. As the reported problems were so widespread,it was felt that the cause was not simply a failure of the roof membrane. Questioning of the occupants indicated that nearly all the failures took place during the winter and early spring. Roof leakage was not a problem during periods of heavy rain encountered during the rest of the year. Consequently, our efforts were directed towards identifying and evaluating the exfiltration/condensation phenomenon.

As discussed above, the potential for excessive indoor relative humidities certainly existed. Using comprehensive checklists and inspection forms, many of the units were inspected to evaluate sources of moisture: size of families, frequency of bathing and washing clothes, hobbies, number of indoor plants, drying laundry indoors without a dryer etc.

To gain additional information about the condition of the roof system, ceilings were taken down in some units that were experiencing severe problems. Extensive deterioration of the roof deck, saturated glass fibre insulation and other deck areas which were literally dripping wet, with moisture contents measured at over 30% were observed. The wood rot and fungus not only created a structural problem but also was a source of contamination of the indoor air via air-borne spores when the air flow is reversed due to wind etc. Other ceilings were observed to have had the batt insulation installed upside down with the vapour barrier on the cold side, thus creating a vapour trap.

As part of the investigation to identify air leakage sources, the architectural working drawings provided further information. Being a standard flat built-up roof, drains were provided to remove accumulated water. For the size of the roofs, the number of drains was insufficient. Also, being dead flat, the roofs did not drain very well and as a result, there was a considerable amount of water on the roof (and in the winter, presumably ice). This was a concern now knowing of the diminished structural capacity of the deck. It should be noted that the roof drains were situated directly adjacent to the firewalls separating the units. The opening for the drain pipe was overly large and obviously contributed to the air leakage problem.

While the bathrooms were mechanically ventilated, some of the third floor ceilings adjacent to these fan units (located in the roof space) had also failed. During the roof replacement, it was determined that the vent pipe connections of the fans were not air-tight, and as a result, had been feeding warm, moist air directly into the roof cavity.

Insulation and the Lack of Ventilation. It was interesting to note that the original plan was to have the units heated by a gas-fired forced air furnace. The intent was to insulate the roof space with only an R-8 glass fibre batt. Apparently, in order to reduce construction costs, it was decided at the last minute to convert to electric heating. To meet Code requirements, the roofs were insulated with a thicker R-20 batt. Having this level and thickness of insulation now meant the underside of the roof deck would be maintained at a lower temperature (increasing the potential for moisture deposition) and also, the ventilation was essentially eliminated.

Even with the original design, the ability for these roofs to ventilate was in serious doubt. The designer had expected the air flow to run via one soffit vent, travel 11 feet up to the roof cavity (joist headers not installed), pickup any moisture and exit out the other side of the roof down 11 feet to the soffit vent and out. Even if the roof cavity had not been restricted with the R-20 batt, the fact that at some parts of the roof structure, the joists spanned from side to side (not front to back) meant that any air flow was seriously impeded.

As a note, with roof cavities which are heavily insulated, and located in extremely cold climates, it may not be prudent to rely upon ventilation for the removal of water vapour. In this situation, the outer components of the roof structure will be very close to the outdoor temperature. As air from outdoors is carried into the ventilation space, it can only pick up as much moisture that will take it to its saturation level (at the temperature of the condensing surface). It must be realized that outdoor air used for ventilation may already be saturated. Its ability to pick up moisture will depend upon it being warmed in the roof cavity.

By example, the moisture content of indoor air at 72 degrees F @ 40% relative humidity is 0.066 lb./lb. of dry air. If outdoor air at 15 degrees F is warmed only one degree from the dew point, it will be able to pick up only 0.0002 lb./lb. of dry air. Therefore, for every pound of air entering the ventilation space, only 3% of its moisture will be absorbed by the incoming air. (2)

SOLUTION DEVELOPMENT

Design Parameters. Following the inspections of the townhouse units, the cause of the failure was well understood. However, the development of the remedial measures had to take into consideration not only the deficiencies directly related to the problem, but also any other design problems that were identified and most important, ensuring that no new problems would be created by the retro-fit. In summary, the solution had to satisfy the following criteria:

1. Be airtight: The movement of air into the roof system would not be allowed.
2. Be thermally efficient: The design had to be thermally efficient to ensure comfort was not being compromised and heating bills were not excessive.
3. Accommodate existing moisture loadings: Past experience has found that it is often difficult to have people change life styles in order to reduce moisture loads.
4. Improve or accommodate the poor roof drainage: Many of the townhouse blocks lacked the proper number of roof drains. The resultant standing water had contributed to the deterioration of the roof membrane.

5. Be economical: While it is a requirement that a condominium have a Reserve Fund for the repair and/or replacement of common elements such as the roofing, PCC #16 was under funded and would not come close to paying for the major repairs necessary. Therefore, this meant that there would have to be a special assessment and each of the owners would have to pay a portion of the project cost.

Design Options. The investigation identified two different approaches towards developing a solution:

1. Rebuilding the roofs with standard trusses, sheathed and shingled.

2. Maintaining the built-up roof system.

Rebuilding the roofs with trusses etc. was a potential solution, which had been used on a previous project. If used on PCC #16, a question of what to do with the rainwater existed. The downspouts could have been connected to the development's storm sewer system. However, the sewer was situated under the only road on the property and the expense for excavation and the hookups was immense. Allowing the water to drain onto the ground was not permitted by the City of Brampton. Attempting to connect the eavestroughs to the existing internally located roof drains was not feasible due to the changing direction of the roof joists and existing firewalls. Therefore, this design option was considered to be impracticable.

In the development of the flat roof system, it was known from the beginning that the existing roof membrane and decking would have to be removed. It was proposed to move the air/vapour barrier to the new structural deck level. This position is favourable for it allows the air/vapour barrier to be supported and more importantly, to be continuous over the entire roof space. With this approach, it was necessary to remove the existing fibre glass batt insulation from the roof cavity. The now uninsulated roof cavity could now be air sealed at the ceiling line to prevent any moist indoor air from entering into the space. This air sealing work at the ceiling would act as an initial restriction to air exfiltration. It was also felt that the air movement in the space between the joists would be minimal and it would be prudent not to encourage any indoor air transfer into the space. Therefore, all of the typical air leakage locations associated with the ceiling line were caulked with silicone. These areas included the tops of partitions, fan boxes and duct joints and holes in top plates for electrical wiring. Where the opening was too large to caulk (areas adjacent to the firewalls, boxed openings for the roof drain pipe), the area was blocked with plywood and sealed. The perimeter of the roof cavity was insulated with four inches of extruded polystyrene (itself an air/vapour barrier). To ensure that air infiltration around it would be minimal, each section of insulation was installed in a bed of silicone caulking. Prior to the installation of the plywood deck, the top surface of the perimeter insulation was caulked, thus completing the air seal.

To prevent the joist cavities from being compartmentalized, it was necessary to install wood purlins (2"x4") across the joists thus making the roof space one open cavity. Any moisture flow into this space would have a chance of being dispersed.

On the purlins, 1/2" roof sheathing supported with H-clips was installed. From the deck level, consideration had to be given as to the type of roof system to be installed; a conventional built-up roof or a protected membrane system. While the protected membrane roof is considered superior to the built-up roof, it could not be used on this project since the structure could not support the gravel ballast needed to cover and protect the polystyrene insulation.

As the standard built-up roof was to be installed, decisions had to be made in terms of the:

- Type of air/vapour barrier to be used.

- Type and R-value of the insulation.

- Type of waterproof membrane.

Air/Vapour Barrier Selection. While there are numerous types of suitable air/vapour barriers available, it was decided to use a 2-ply asphalt and felt membrane. Because of the membrane's waterproof characteristics, an entire block of townhouses could be rebuilt to this stage. As the air/vapour barrier was installed over the entire building, it protected the units until the insulation was installed and the built-up roof membrane could be applied in a continuous manner providing a better end-product. The work schedule was shortened since it was possible to do work that was not sensitive to the daily weather conditions. Had a another type of air/vapour barrier been installed that was not waterproof, it would mean that each day the roof membrane would had to have been applied.

Insulation Selection. In selecting an insulation, it was thought that the use of a sloped system would help promote roof drainage. However, due to the distances between the drains, massive thicknesses of insulation would have been required not only for proper slopes, but also for achieving a suitable overall thermal resistance. When the extra cost of raising the perimeter framing to accommodate the resultant thicknesses was included, it was decided to use flat insulation board.

From excellent past experiences, it was proposed to install rigid glass fibre insulation. Due to the significant extremes in temperature which would be encountered, it was felt that a product with very good thermal stabililty was necessary.

The amount of insulation required presented a problem. The Ontario Building Code required that for residential flat roofs, a minimum of R-20 insulation be installed. In our design, we had proposed to install the thickest single layer of rigid glass fibre insulation that was available from the manufacturer; 4.2 inches with an R-value of 15.5. In order to meet the OBC requirement, an additional 1-1/2 inch layer of insulation would have been necessary. The cost increment to supply and install this material was estimated to be $565. for the average sized roof area of a single unit (based on a cost of about $1.00 per sq. ft.). The calculated energy savings for this additional insulation was approximately 308 kWh per year. The dollar savings were estimated to be $15. per year, based on an electricity cost of $0.05 per kWh. Accordingly, this works out to a dismal payback of 37 years! It is certain that the roofs will be replaced again before this time.

When presented with the above analysis, the building officials agreed that the additional layer of insulation was not cost-justified.

Waterproof Membrane Selection. In the selection of the waterproof membrane, certain objectives had to be achieved with the final product. The major concern was the potential for standing water to remain on the roof. As described previously, the number and location of the roof drains allowed significant ponding on the roof surface. The slow deterioration of asphalt membranes is due to a combination of oxidation (due to solar radiation), temperature extremes and moisture. It is generally agreed that of the two bitumens used in built-up roofing, asphalt does not perform as well as coal tar pitch in wet environments.

While consideration was given to using sloped insulation or sloping the entire plywood deck, the technical and labour complexities prevented the use of these options. Therefore, it was decided that a four ply coal tar pitch membrane would be installed. Although more expensive than asphalt, this choice was made upon its ability to maintain its long-term waterproof characteristics in a wet environment and also because of the membrane's self-healing abilities in hot weather. To help withstand the accelerated weathering at corners of the roof due to wind scouring, these areas were double poured.

Hygrothermal Analysis. While not nearly as serious as the air exfiltration/condensation phenomenon, the designer must also consider the water vapour diffusion process through the proposed building assembly. This evaluation is coupled with the thermal aspects of the component since both water vapour and temperature combine to cause condensation. This evaluation process is called "Hygrothermal Analysis". While it assumes steady state heat and vapour flow, which is not usually the case, it can be used to indicate the potential for condensation to occur within the roof system for a given set of environmental conditions.

With the aid of a microcomputer and spreadsheet software, the relationships between the indoor and outdoor environmental conditions and the thermal and vapour resistance of the roof components could be easily evaluated. The "what if?" abilities of the software permitted quick analysis of changes in insulation levels or its placement as well as alternatives for the air/vapour barrier. The effects of different humidities and temperatures could also be evaluated with little effort.

The basis for hygrothermal analysis is that for condensation to occur, the vapour pressure for continuity (VPC) of the air must exceed its saturated vapour pressure (SVP) at the corresponding temperature of the particular component. It should be noted that under equilibrium conditions, condensation does not take place at the exact location where the VPC exceeds the SVP, but rather at the next interface (4).

An important aspect of the analysis is to appreciate that there may be instances where condensation may indeed be formed. It is therefore necessary to determine the amount of moisture that could be deposited, and assessing if it is cause for concern. The condensation rate is easily determined by calculating the vapour flow to and the vapour flow from the condensation interface.

In the case of PCC #16, the condensation rate was estimated to be about 0.022 grain/ft^2/hr. For a 24 period, this works out to 0.528 grains/ft^2, or 0.0000754 lbs./ft^2. If the rigid glass fibre insulation (density of approximately 6 lb/ft^2) were to take up this moisture, the increase would be:

$$0.0000754 / 6.0$$
$$=0.0000125$$
$$=0.00125\%$$

This is an infinitesimal change which will have no deleterious effect on the insulation or membrane.

Final Design. With the analysis completed, the final design which was implemented was as shown in Figure 2:

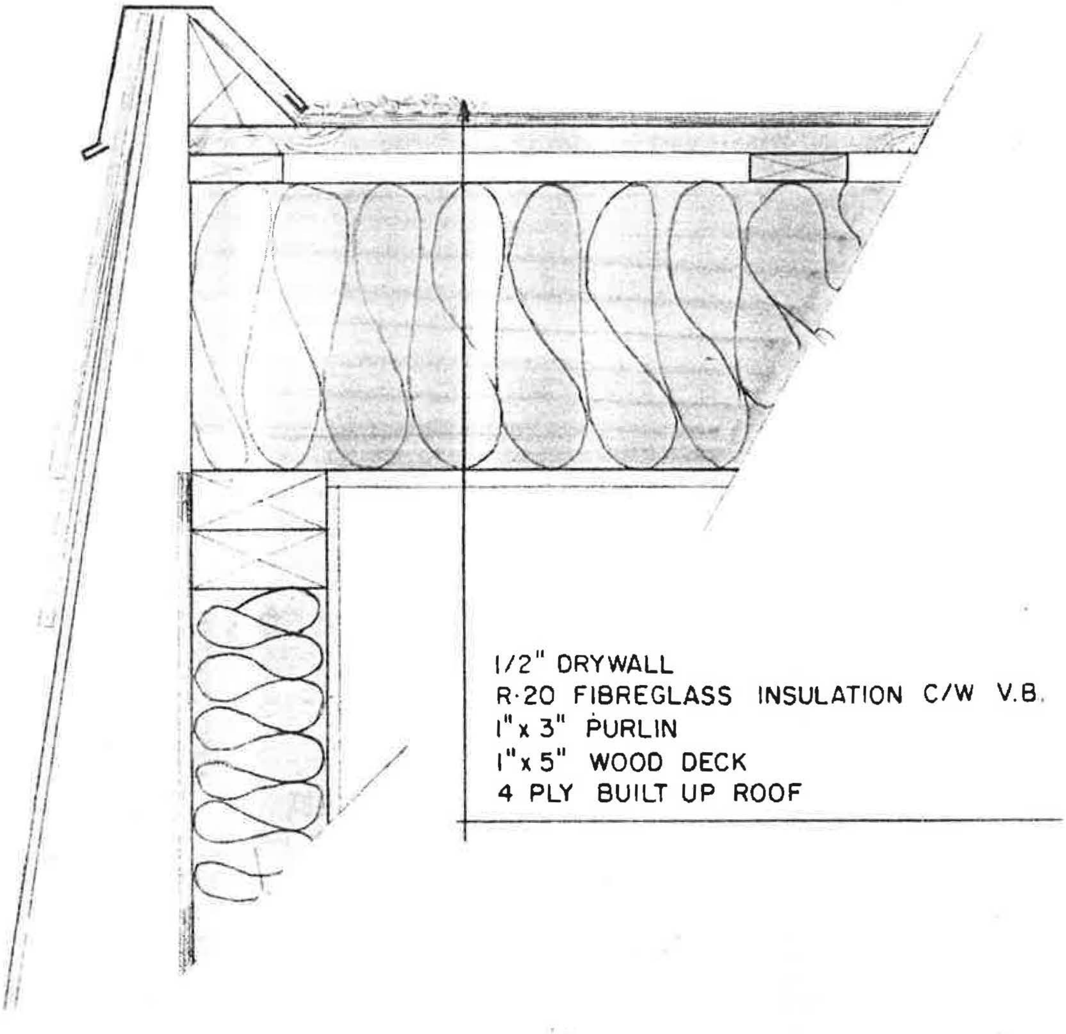
- 1/2" drywall ceiling, all openings sealed
- 2"x8" wood joists @ 24" c/c
- 2"x4" purlins running perpendicular to the joists
- 1/2" plywood sheathing, secured with H-clips
- 2 ply asphalt bitumen and felt air/vapour barrier
- 4.2" (R-15.5) rigid glass fibre insulation
- 4 ply coal tar pitch built-up roof membrane

For the ten blocks of approximately 41,200 square feet, the final contract amount was $329,200.; or $7.99 per sq. ft.

SUMMARY

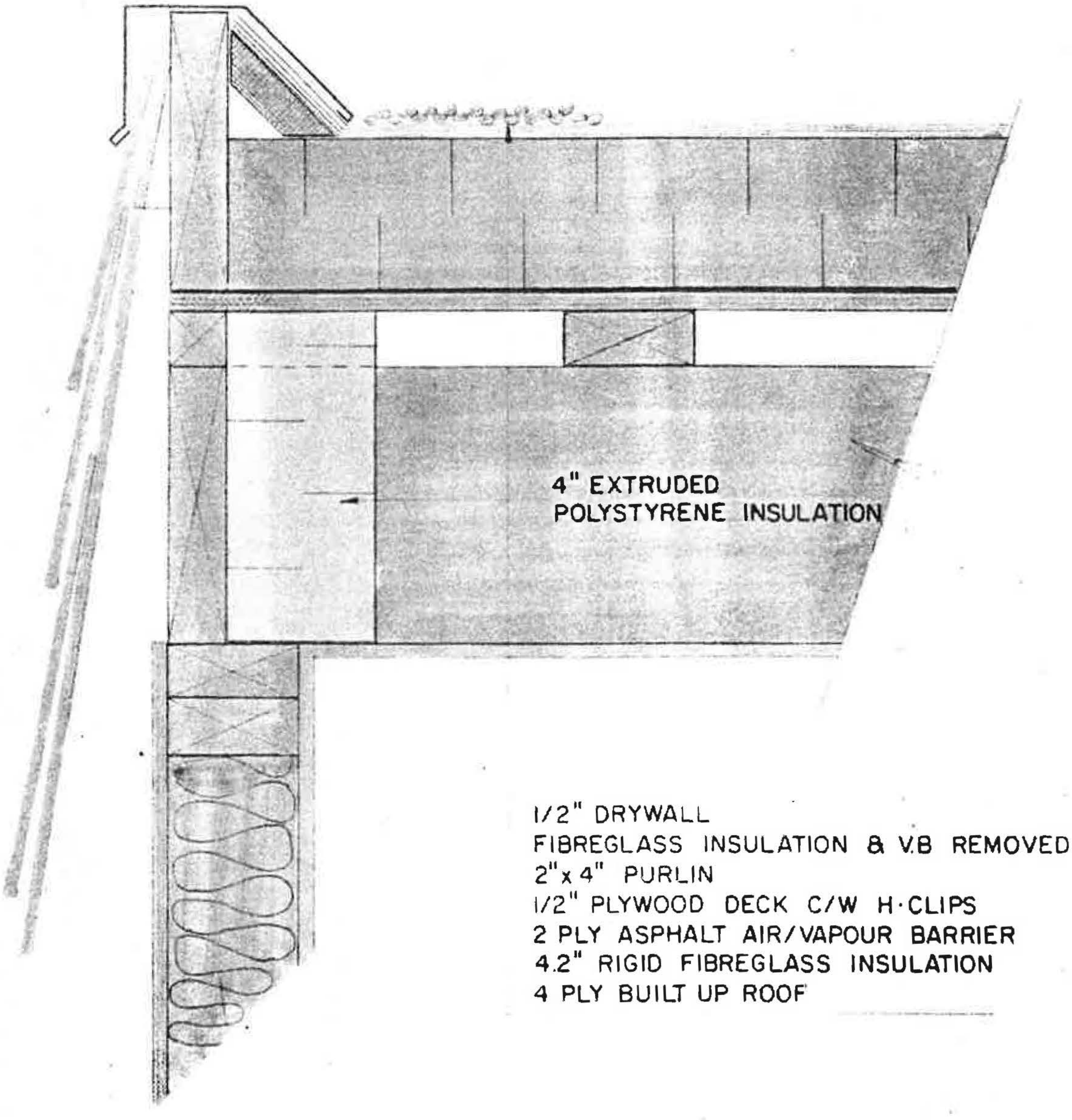
The roof system of PCC #16 was destined to fail from the very beginning. By not appreciating the potentials for condensation due to the need for air tightness (in terms of design detailing and actual construction) and cold side ventilation, the designer had imposed a severe burden upon the roof and its structure.

This paper has presented an evaluation and design development methodology which is based on the philosophy that the cause of the distress should be first rationalized through a process of applying the observed conditions to basic first principles dealing with building envelope performance. The remedial measures can then be tailored to handle the anticipated thermal and moisture environments.



ORIGINAL ROOF DESIGN

FIGURE 1



UPGRADED ROOF DESIGN

FIGURE 2

APPENDIX A

COST/BENEFIT ANALYSIS FOR ADDITIONAL ROOF INSULATION

Problem: What is the cost/benefit analysis if an additional 1-1/2 inches of rigid fibre glass roof insulation is installed in order to meet the Ontario Building Code requirements?

Unit Roof Area:	565 sq. ft.
R-value without 1.5" insulation:	18.81
R-value with additional insulation:	24.31
Electricity cost (100% efficient):	$0.05 per kWh
Insulation cost:	$565.
Degree Days:	7721

ENERGY SAVINGS= (20x7721)/1.0 x ((565/18.81)-(565/24.31))
= 1,049,400 Btuh
= 308 kWh

DOLLAR SAVINGS= 308 X $0.05
= $15.40 per year

PAYBACK= $565/$15.40
= 37 years

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