CONVENTIONAL MEMBRANE DESIGN FOR THERMALLY EFFICIENT ROOF SYSTEMS

J. Roy Martin, Jr.
J. Roy Martin & Co., Anderson, S.C.

Few roof designers realize the increased problems which will be encountered as roof systems' thermal resistance is increased from the 3-6 R-value range of a few years ago to today's 12-20 R-value range. Though these problems can be mitigated by appropriate design, thermally efficient roof systems inevitably exact some sacrifice in the durability of a conventional built-up roof system.

Thermal splitting is the most important single risk threatening membranes over highly efficient insulation. There are other heightened risks, notably:

- Membrane shrinkage
- Accelerated membrane aging
- Increased blister growth rate
- Wind-blowoffs

This paper discusses these membrane hazards, remedial design features to reduce those hazards, and the impact of the protected membrane roof concept on roof system design in the coming era of energy-conscious design.

MEMBRANE SPLITTING

Like several other problems associated with more efficient roof insulation, the membrane-splitting hazard springs from the increased temperature range (higher in summer, lower in winter) experienced by membranes over thickened insulation of high thermal resistance rather than thinner, less efficient conventional roof insulation. Despite disagreements about the precise R value at which this effect is maximized, our discussion will assume that it has been reached. Membrane temperatures of 70°F above summer ambient highs and 15°F below winter ambient lows produce annual temperature ranges of 200°F or more, depending on local climate.

Not only greater temperature difference, but faster rates of temperature change occur over thermally efficient insulation. Cullen has shown that a mid-afternoon summer shower produces a sudden, extreme temperature drop. Although the precise effect of accelerated temperature change remains undocumented, it may be substantial – particularly as it affects thermal splitting.

Both membrane splitting and shrinkage are most severe in climates with frequent, wide temperature cycling. The Piedmont region of North and South Carolina has been cited by Cullen as possibly the nation's worst region for this phenomenon, yet the temperature seldom drops below 0°F. Neith splitting nor shrinkage are experienced in warmer areas, notably South Florida and Southern California.

High thermal stresses occur in bituminous membranes because they have very high coefficents of thermal expansion/contraction in the lower temperature ranges – 61.94×10^{-6} for one tested membrane, with $30\text{-}40 \times 10^{-6}$ common. Rissmiller has measured tensile stress as high as 77 lb./in. for a 100°F temperature drop (70°F to – 30°F). (We have established that such temperature drops are not unusual, though the rate would be slower in actual roof systems than in the laboratory.) A 77 lb./in. stress = 924 lb./ft. contractive stress exerted at the perimeter. At a parapet wall with little or no restraint, the outside line of insulation must resist this contractive stress, 3,700 lb. along a 4-ft. long board.

The membrane tested by Rissmiller broke at 291 lb./in. ultimate strength at – 30°F. Since membranes do rupture, a stress equivalent to the membrane's ultimate strength, roughly 3,500 lb./ft. or nearly 14,000 lb. on a 4-ft. long insulation board, must be exerted on the perimeter.

Membrane shrinkage, like splitting, occurs as a consequence of the built-up membrane's high coefficent of thermal expansion/contraction, coupled with repeated temperature cycling. It can only occur where the membrane is inadequately anchored to the deck or at the perimeter. Most contracting membranes subsequently wrinkle during cyclic expansion, and the wrinkles eventually crack or split.

Membrane aging is accelerated by the higher temperatures experienced by membranes over highly efficient insulation. Though still undocumented, accelerated membrane aging does appear to shorten membrane life, judged by our company's experience. Over the past 50 years, we have found that few bituminous membranes installed over high R value insulation in the Southeastern U.S. will last a normal 20-year service life. The precise loss in durability may vary with latitude and climate, but, in our opinion, reduced service life inevitably accompanies improved thermal efficiency.

Accelerated blister growth, like membrane aging, results from the faster and greater membrane temperature rise on hot sunny days. Although higher temperature will not originate a blister, it will accelerate blister growth, which results from expansion of the trapped air-water vapor mixture.

Wind blowoff becomes a greater risk with a thermally efficient roof system because of increased membrane contraction rate, which may break the adhesion either at the membrane-insulation interface or at the insulation-deck interface. In some areas, these conditions develop in a short time. They can result in a massive system failure. To reduce this risk, anchor the system solidly – both to the deck and at the perimeter.

ANCHORING THE SYSTEM

As indicated in the foregoing discussion, anchorage is a major safeguard against several hazards aggravated by improvement in roof-system thermal efficiency. Beginning at the deck, consider the vapor barrier first.

There is much difference of opinion concerning the criteria for determing when a vapor barrier should be used. The NRCA Roofing Manual states that, "It is possible, under some circumstances, that the vapor barrier can be omitted. However, this should be done with extreme caution and thorough study." The Manual states further that, "A vapor barrier improperly handled can create problems as well as solve them." Our experience indicates that these recommendations are sound. It is almost inevitable that condensation will occur at some time, unless an adequate vapor barrier is installed.

The caution against "improper handling" is a timely one. To be a true "vapor barrier," a system must not only have an adequate perm rating, but it must be securely attached to the deck and must be sealed "vapor tight" at all roof penetrations and perimeters. This must include double flashings at "hot" pipes and "movable" penetrations. Provide "double" drains at all interior drains (see Detail 1). Mount gutters at the vapor barrier level – not the roof level. (See Detail 2).

These provisions are consistent with use of the vapor barrier as a temporary roof. Except in rare instances, it is usually impossible to delay application of the roof until all trades have completed their work above the deck. To do so will often delay completion of the building by months. A viable alternative is the installation of a two-ply, bituminous coated-sheet vapor barrier. Interior drains and gutters can be installed as if this is the finished roof. All penetrations are made watertight. Such an installation can keep a building "in the dry" for months, until all work by other trades is completed. The vapor barrier can then be repaired as necessary and the roof system completed. We have employed this system for many years and have never experienced any problems attributable to abuse of the vapor barrier. The system avoids the problem of damage to the roof membrane and water damage to the insulation, which can be disastrous. Provision for drainage at the vapor barrier line serves the dual purpose of draining the temporary roof and disposing of water that may enter the system after the installation is completed. Without such provision where there is a viable vapor barrier, a small penetration of the membrane can result in massive damage to the insulation before the membrane damage is discovered.

The attachment of the vapor barrier to the deck is critical. If the deck can be solid mopped with steep asphalt, there usually will be no problem But if the vapor barrier must be secured by other means, then the attachment must be adequate to withstand contractive forces in the membrane. If the membrane is securely attached to the insulation, and the insulation to the vapor barrier, then all the force will be transmitted to the vapor barrier. If the attachment is inadequate at any of these three levels in the system, or between layers of insulation, then shrinkage is inevitable.

Inadequate attachment of insulation has probably caused as many roof problems in recent years as any single factor. To a large extent, these problems have involved steel decks. As a result of the Livonia, Michigan, fire, insurance authorities have severely limited the amount of asphalt that may be used between insulation and a steel deck. This policy has caused far more problems than it has prevented. Their criterion for attachment has been wind load which, in most areas of the country, is set at 30 lb./sq. ft. uplift. This means that a 3' x 4' piece of insulation is considered to be adequately attached if it can withstand an uplift force of 360 pounds. We saw earlier that the same piece of insulation may be subjected to a shear load of 3,696#, more than ten times as much! Under these circumstances, it can be expected that entire roof systems will be almost entirely separated from the deck very soon after being applied. Knowledgeable roofing contractors agree that most approved methods of insulation attachment are inadequate.

What methods then are adequate? They vary with deck type, but generally consist of two layers of insulation with the first layer being mechanically fastened and the second layer solidly mopped with steep asphalt. There are a number of variations and exceptions. for example, on concrete decks, it is possible to solid mop everything from the deck up with steep asphalt, which is usually adequate.

The problem of mechanical attachment and achieving a viable vapor barrier at the same time has been addressed by one manufacturer, who recommends installing a relatively thin first layer of insulation with mechanical fasteners, then the vaporseal, then the second layer of insulation solidly mopped to the vaporseal. This has several advantages in addition to the obvious one. Perhaps most important, it provides a temporary roof where one would not be possible otherwise. The major problem with this system is that the second layer of insulation must be sufficient to keep the dew point above the vapor barrier to avoid condensation at that point.

The recommendation for mechanical fasteners and two layers of insulation are complementary. With only one layer, the fasteners serve as a direct heat-transfer point from the membrane to the building interior, and condensation can occur. Fasteners have other problems prevented by using two layers. Two layered insulation should be specified for almost all installations.

Taping of insulation joints can sometimes make a substantial contribution to the integrity of the system. If the insulation has a top covering of felt, then taping will make that felt a continuous ply and, in effect, add a ply to the system. At the very least, the tape will reinforce the weakest part of the membrane. Tape should be applied at all junctures of insulation with nailers. This can help to prevent contraction.

Membrane splits usually occur above continuous insulation board joints parallel to membrane felt direction. One proposed remedy would orient insulation with the continuous joint at right angles to the membrane felt direction. Despite its apparent advantage this practice has not, to our knowledge, been proven effective.

The roof membrane is the one part of the roof system completely exposed to the elements. It is subject to large temperature changes, and it generates considerable contractive force. To prevent movement, it must be restraint between a wood nailer and a metal gravel stop nailed at 4-in. spacing. The membrane should be mopped various reasons, this is often insufficient. So it is necessary to anchor the membrane at the perimeter - and, for large roof areas, at intermediate points as well.

A standard gravel stop detail is usually adequate for membrane perimeter anchorage. This involves membrane restraint between a wood nailer and a metal gravel stop nailed at 4-in. spacicg. The membrane should be mopped to the nailer and the joint between nailer and insulation should be taped. The nailer anchorage must be designed to resist the contractive forces.

Except for gravel stops, most standard details are inadequate. Many are variations of parapet wall treatment, usually providing only nailing to support flashing. We have developed details for these systems which primarily involve securing the membrane between a nailer and a wood cant or bevel strip (see Detail 3). The wood nailer is installed over the vapor barrier, set in asphalt, and securely anchored. The joint between the nailer and the insulation should be taped. The membrane is then applied over and mopped to the nailer and turned up the wall. After the membrane is in place, a wood cant is set in asphalt and secured to the nailer. (This is the key point.) Membrane felts are installed over the cant before the flashing is installed. Where needed, a vertical nailer is installed to isolate the roof system from wall movement. The wood cant is installed over the membrane and nailed to the horizontal (and vertical) nailer, which is secured to the deck. This detail can be successfully adapted to many conditions, as long as this fundamental condition is retained.

So called "relief joints," purported to prevent thermal splits, allow roof contraction which will result in ridging and ridge splitting. We take the opposite position. Instead of relief joints, we install control joints in large roofs. This control joint is a modification of the wall detail, securing the membrane between two nailers (see Detail 4). The bottom nailer is installed above the vapor barrier and anchored to the deck. The membrane is run over the nailer and a second nailer placed above the first and nailed to it. Bevel strips are placed on both sides and a membrane applied over the entire joint. There is no exact method for spacing control joints, and most often that is determined by the shape and drainage system of the building. We feel that a spacing of 150 to 200 feet is optimum, where possible. They must be located parallel to the slope of the roof, at center points between drains. The only feasible location at right angles to the slope is on a ridge, and we frequently place one there on a building more than 200 feet wide. Control joints may appear to be redundant when there is adequate deck attachment. But, they are good insurance against movement.

MEMBRANE MATERIAL SELECTION

The selection of the type membrane to be used over high "R" value insulation is the most important single aspect of the system design. We have discussed the performance factors accentuated in these systems, and now we must select those membranes that will minimize these effects.

The type bitumen to be used is crucial. Our experience and research in the field indicates that coal tar pitch membranes are more subject to contraction and thermal splitting than comparable asphalt membranes. However, if structural design considerations compel very low roof slopes where there will be considerable ponding, pitch should be used. Its performance under water is far superior to asphalt.

The recent trend toward exclusive use of steep or Type III asphalt, both by some manufacturers and some roofing contractors is detrimental to membrane performance in our opinion. We use the lowest melt-point asphalt consistent with slope. The blowing of asphalt is in many respects similar to the aging process in service. Why "age" it in a blow before using it when you expect accelerated aging on the roof? Use Type III and IV asphalt only where required to prevent slippage.

The amount of bitumen to be used in interply mopping deserves consideration. Much emphasis has been given in recent years to the specified minimum weight of bitumen per ply. The result is that often much more is used by the contractor to be sure that the test cut will satisfy minimum weight. This is generally believed to make a better roof, to improve performance.

To the contrary, Cullen has demonstrated that excess amounts of bitumen do not increase, in fact, may decrease the bond between the felts – i.e. increasing interply bitumen weight does not reduce the possibility of delamination. Moreover, Rissmiller has demonstrated that thermal load is directly proportional to the ratio of bitumen to felt – i.e., increasing interply bitumen weight increases the thermal load resulting from a given temperature drop. A reduction in interply mopping weight thus appears in order. Cullen has suggested 15# as optimum.

Felts used in bituminous membranes vary so widely that it is difficult to make a selection.

Asbestos felts have very low tensile strengths, and asbestos-felt membranes have very low thermal shock resistance. Their use is not recommended except for (a) steeply sloped, smooth-surfaced roofs, or (b) roofs in moderate climates where thermal shock is not a factor.

Coated organic felts were introduced into built-up membranes as base sheets to eliminate "ridging." When their use was expanded to entire membranes, the result was thermal splitting and increased blistering. Except as a base sheet, we see no justification for their use in built-up membranes, except in steep slope applications where a smooth surface is necessary. If a good vapor barrier is installed, a base sheet should not be used in the membrane.

Four-ply #15 asphalt organic felt systems have been an industry standard for many years, considered by many to perform adequately. That has not been our experience. Applied over high "R" value insulation, they frequently develop thermal splits, shrink if not adequately restrained, and age prematurely. Few will last for a 20 year service life in areas notorious for thermal splitting. In areas where conditions are less severe, they may perform much more satisfactorily.

These systems do not develop thermal splits across the run of the felt. If it were possible to develop a system with the same qualities in both directions as they have in the longitudinal, it should perform satisfactorily.

The last several years have seen a proliferation of glass felts. Each manufacturer has his own specification, some more than one. There are differences in glass type, fiber size and length, method of production, weight of felt, and weight and type of coating. These differences make it impossible to analyze glass felts as a group.

Perhaps most important, they do not absorb moisture, thereby eliminating problems associated with water. This alone is a tremendous advantage. Most have a much greater tensile strength/weight ratio than other felts and some are nearly isotropic. This should make it possible to design a membrane with the same strength in both directions. When glass felts were first introduced there were tremendous splitting problems in some areas. Some manufacturers are using the qualities of a four ply #15 asphalt organic system in the transverse direction as their performance criteria. This is inadequate, and we anticipate thermal splits. Where thermal splits are not a problem these systems should perform adequately.

In summation, we believe that glass felts have the potential to give satisfactory performance over high "R" value insulation, if the system is designed for a sufficiently high thermal shock factor.

As a final comment on Thermal Shock Factor, which we believe is of paramount importance as an index to a membrane's resistance to thermal splitting, we see a great need for the roofing industry to develop some means of generating reliable data of this type. Despite the controversy surrounding it, the Thermal Shock Factor, as proposed by Cullen and Mathey, remains our only means of predicting a membrane's performance in this regard. The current trend toward publishing Thermal Shock Factors is welcome. But we have serious reservations about the practical value of some published numbers, and, in some cases, we doubt their reliability. Designers should demand dependable data to back up the claims made for new membranes.

MEMBRANE SURFACING

The surface of a thermally efficient roof system has a very great effect on membrane performance. The worst surfacing is a mop coat of steep asphalt, especially with ponded water. It is an open invitation to disaster, almost regardless of anything else that may have been done, in practically every area of the United States.

Several factors make this surfacing method unacceptable. The black surface assures maximum absorption of the sun's rays and high radiation at night, thus assuring maximum temperature swings. These greatly increase the potential for thermal splits and membrane contraction. The high temperatures, combined with direct exposure to the ultraviolet rays of the sun, will greatly accelerate bitumen aging. The smooth surface is also highly vulnerable to mechanical, hail and wind damage.

Fortunately, the answer to most of these problems is relatively simple. Cover the surface with a heavy application of heat-reflective white gravel, which lowers day time membrane temperatures. The gravel will cover the asphalt, if applied in sufficient quantitiy, and protect it from the ultraviolet radiation, retarding the aging process, even if there is standing water. The gravel will also protect against mechanical, hail, and wind damage, and provide some protection from blowoffs.

Between these extremes, there are other alternatives. Aluminum or white coatings are highly desirable when a smooth surface is necessary, but they offer incomplete protection and must be renewed frequently. Cap sheets with white granule surfacing have been used successfully and weigh much less than gravel. Cold coatings with embedded white granules offer some advantages.

In summary, any surfacing technique that improves on the black smooth surface will increase the performance of the membrane, with white gravel clearly the most desirable.

PROTECTED MEMBRANE ROOFS

The Protected Membrane Roof (PMR), introduced in the mid-1960's, reverses the positions of membrane and insulation in the conventional roof assembly. Instead of its conventional position atop the insulation, a PMR membrane is sandwiched between the insulation above and the deck below. The most popular version of the PMR comprises a bituminous membrane applied direct to the deck with foam plastic insulation embedded in a mop coat of bitumen and covered with a layer of loose stones or concrete pavers acting as ballast against flotation and wind uplift.

This system's advantages spring chiefly from the membrane's protected location. It is shielded from all the elements, except water, and is well able to resist attacks from that source. Membrane temperature remains relatively constant, near interior temperature. This means an almost complete absence of contraction force and resulting thermal splits and membrane shrinkage. An additional effect is that blisters do not grow. A minor void or bare spot between the felt plies will remain just that and cause no problem. Accelerated aging will not occur. Protected from the ultraviolet rays of the sun and maintained at a relatively constant low temperature, the membrane will have a very slow rate of oxidation. In tearing off insulated roofs, we find that seldom, if ever, does a bituminous vapor barrier show evidence of aging, even though many have been completely covered with water for years. We routinely leave them in place as a part of the new system. Protected membranes should perform in the same way.

The variety of materials that can be used in these membranes is almost unlimited, and those to be used are determined primarily by the designer's preferences. Since most are commonly used bituminous products, familiar to roofers, they present no problems in application.

The system is compatible with the construction process, allowing the roofer to get a building "in the dry" in a very short time and often to continue to work in weather that would be intolerable for a conventional system. Installation of the insulation may be delayed, but the membrane obviously must be protected or repaired as necessary. The completed system is much less subject to mechanical damage and lends itself well to the installation of paving blocks or other similar material in walkways or work areas.

Like any roof system, the protected membrane roof has its disadvantages. A major problem has concerned anchorage – specifically the weight of stone or other material necessary to prevent the insulation from floating. The insulation is usually embedded in a heavy flood coat of asphalt, but great care must be exercised to insure that each piece is secure. Unless that is done and an adequate amount of stone is used, the insulation will sometimes "float" during a heavy rain. The stone also serves to protect the insulation from solar radiation. Only foamed plastic insulation has so far been successfully used, and it is rapidly degraded by sunlight.

Designers should carefully investigate the insulation's in-place thermal value. These materials often lose thermal value with age and water absorption. To insure adequate thermal efficiency of the building throughout the life of the roof, it is necessary to base computations on the thermal value of the insulation after these changes have occurred.

Ballasted protected membrane roofs weigh more than most conventional systems. This can be easily accommodated in a new design, but may result in increased structural costs. It can be a major obstacle, however, in retrofit.

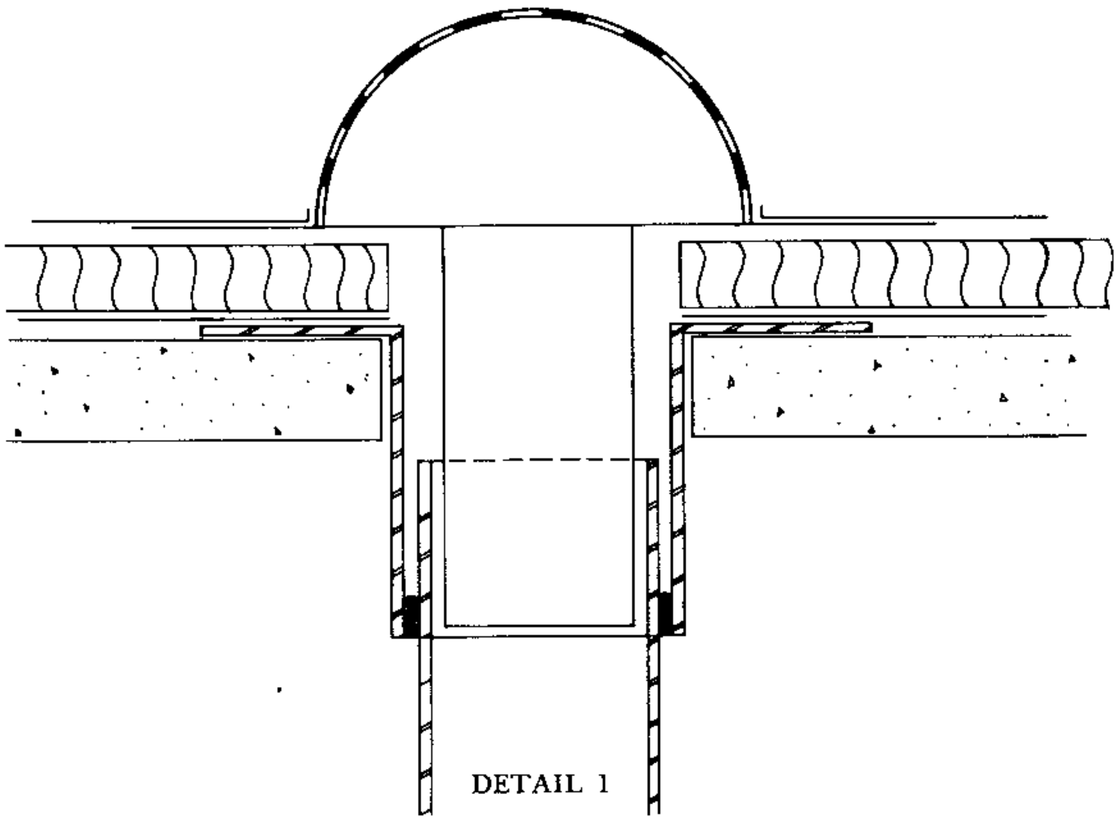
SUMMARY

Thermally efficient roof systems with conventional bituminous membranes are subject to conditions quite different from uninsulated built-up roofs. These conditions will amplify almost all problems normally encountered and in addition will often produce thermal splits and contractions. Extreme care must be exercised in the design of the systems to minimize these effects. The three system components – vapor barrier, insulation and membrane – should be carefully selected to fit conditions and to be compatible with each other. Special attention is required to insure that all components are securely attached in all respects.

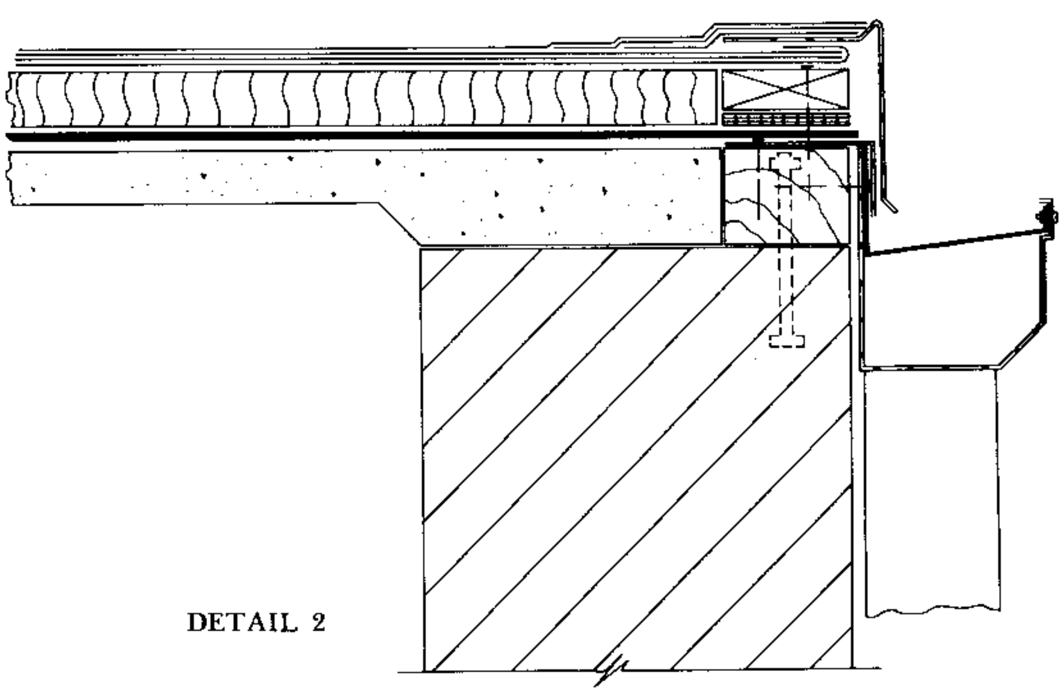
Even with optimum system design, the service life of a thermally efficient roof system will not equal a conventional system's service life.

The protected membrane roof concept appears to solve many of the problems associated with thermally efficient systems, but has some unique requirements. It cannot be embraced as a cure-all.

Roof system designers must recognize that some bituminous membranes currently marketed will not perform when applied over high "R" value insulation, and others have yet to prove their performance.



DETAIL 1



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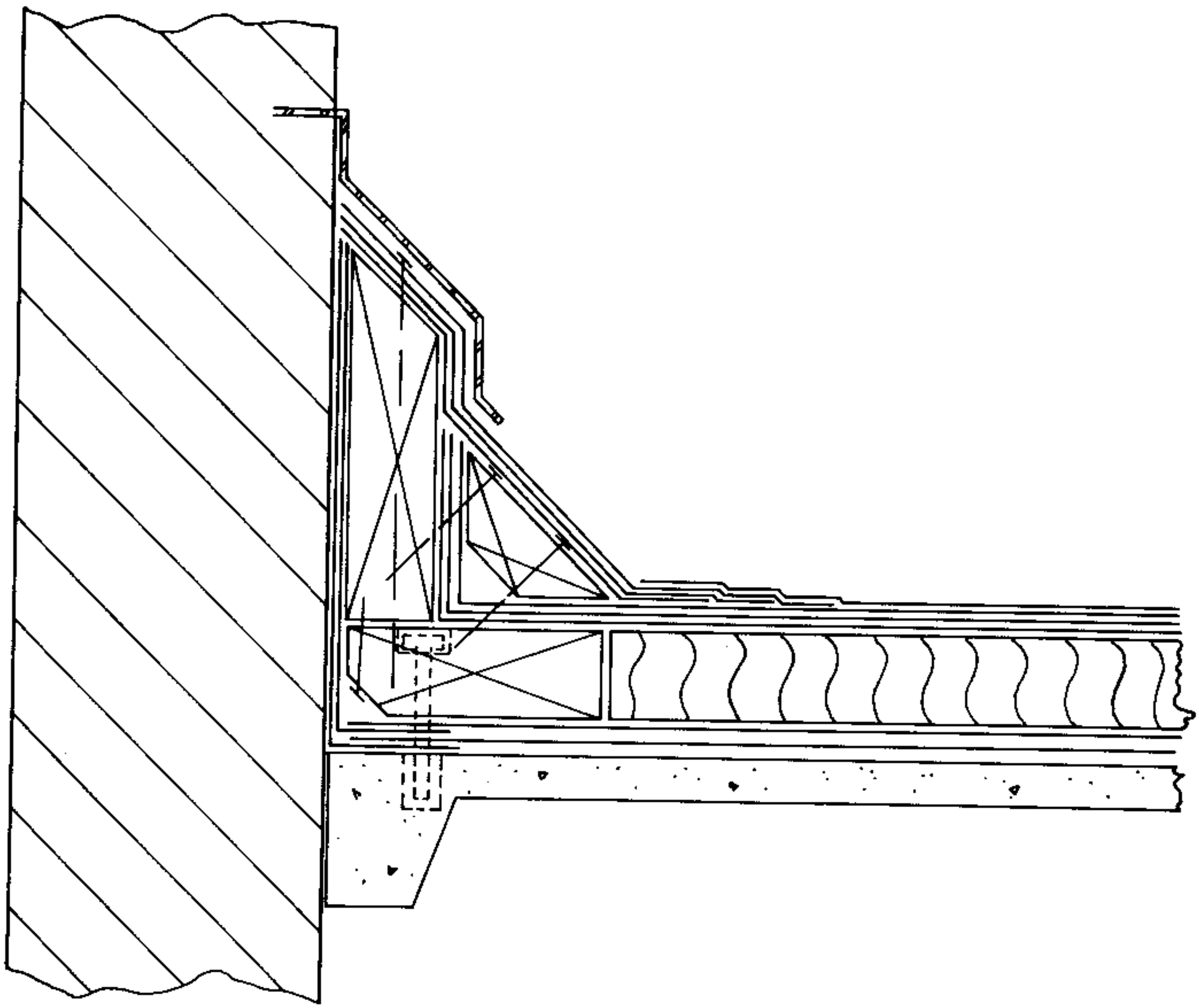

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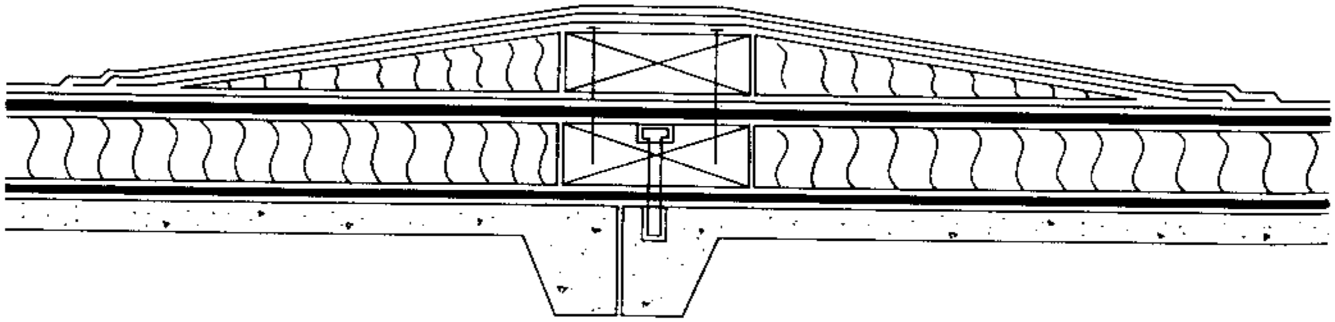

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