TECHNICAL ASPECTS OF RETROFITTING

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Confronting a problem in retrofitting for improved roof-system thermal efficiency, the roof designer must step back and consider many other factors. Retrofit poses a much tougher problem than new construction, for you must either live with or bear the cost of rectifying unfavorable conditions that can be totally avoided with a new roof design.

The retrofit starts with an investigative analysis of the following:

- Nature and condition of existing roof-system components
- Roof system history
- Roof-system environment (interior R.H., exterior surface contaminants, structural loads, vibration, and other unusual considerations)
- New performance criteria (Improved thermal performance generally requires reduced U factor, but condensation and the insulation's location – i.e., above or below deck, etc. – also requires consideration.)
- Improved drainage (Many existing roofs pond water, and the retrofit must correct this problem to justify the owner's capital investment.)

As his first decision after assembling the foregoing information, the roof designer must choose between a retrofit and total tearoff-replacement. As its major advantage, tearoff-replacement offers an opportunity to inspect and repair the deck substrate prior to reroofing. Its major disadvantages include the major disruption of building operations and generally higher cost. Since tearoff-replacement is essentially a new system, it lies outside the scope of this paper and so will receive no further discussion.

PRINCIPLES OF RETROFIT

Good retrofit design depends on observance of three basic principles:

- Attachment
- Divorcement
- Ventilation

Attachment is a major consideration in all roof systems, despite the recent advent of "loosly laid" roof systems. A bituminous membrane has elastic properties only to about 1% deformation. If the membrane is partially unrestrained, local stresses will accumulate until the membrane either ruptures (splits) or tears the flashing free at the edges. In an inadequately restrained elastic system, the membrane can billow, dislodging gravel ballast, or it can wrinkle around the drains and other roof penetrations. Restraint is therefore necessary on all roofing systems.

Divorcement seems inconsistent with attachment, but, in fact, the two terms are not mutually exclusive. We hope to leave the problems of the old roof system far behind, and if we are roofing over that old system, then we must isolate the new system from the old system. Treatment of a tongue-and-groove wood deck illustrates the point. We expect the wood to dry and shrink with age. A dry absorbent sheet is first tacked to the deck, to prevent the membrane base sheet from adhering to the wood. The base felt is then nailed to the wood. The nails provide **attachment**, but the rosin sheet and spanning of the base sheet between nails provide **divorcement.**

Ventilation assumes the presence of moisture to be vented. This is a realistic assumption, and the designer needs to remember that a steam engine's power comes from the vaporization and consequent expansion of water. If the new roof system is designed for that extreme situation, it can handle anything less. There are several base sheets designed to meet this need. They are nailed through the bondbreaker, then vented via edge ventilation and/or interior roof vents.

In this manner, we satisfy all three requirements: attachment, divorcement, and venting.

GATHERING THE REQUIRED INFORMATION

The information process should begin with interviews of the building's occupants. Since some inspections – notably OSHA – have taken an adversary role, get authorization for the inspection and inform occupants that you are making an energy survey to make the building more efficient and comfortable.

The interviews will help to pinpoint problems encountered over the years. They may also disclose what repairs have been attempted. The interviews should also reveal what traffic the roof is subject to, exposure to chemical exhausts, etc.

Survey the roof system's needs as thoroughly as possible. Try to get original plans and specifications, plus later data on modifications or reroofing. These plans may reveal structural features not otherwise apparent, and may be valuable in determining the structure's design strength.

Non-destructive tests may help to pinpoint water entry points. Many leaks occur at flashings. If, for example, the survey reveals that the walls are defective, moving relative to the roof deck, resolve this, or similar problems, before attempting a retrofit.

Make roof test cuts before attempting a retrofit, as part of the information-gathering process. These test cuts should be several square feet in area, cut down to the deck. Identify components and observe their attachment to each other. Evaluate the deck itself. Its condition – detached, rusted, or spalled – will affect future decisions.

Strucutral framing must be investigated. If the retrofit will add any weight at all, calculations must verify that there is adequate safety factor. Since the major objective of a retrofit is to retard heat flow, the new roof might collect ice where previously the heat loss kept the water melted until it reached the drains. It might now be necessary to use heat cables to keep the drains and major drainage paths free of ice. This in turn, might suggest less insulation in valleys or around drains. If the retrofit includes addition of ballast you need calculations of ballast weight, plus the weight of the water that will be retarded as it flows to the drains. One inch of water depth adds 521 lbs. per roofing square (24.5 kg/m^2).

Through roof cuts and under-deck examination, you evaluate any impairment of design strength. If the deck is sagging or the joists are weakened, it may be possible to add new joists to the existing structure, leaving the old system in place (Illus. 1). An air space that vents laterally should be used, to create an attic. Over the new joists, a deck would be installed and roofed. A vented air space gets cold, so retrofit insulation would have to be placed below the old deck to be effective.

Determine winter design temperature, expected temperature and humidity. You can calculate points for plotting temperature gradient throught the roof system's cross section (Illus. 2). Ideally, in colder climates, the dewpoint is located above the vapor retarder to prevent condensation.

During the topside inspection, the inspector must observe potential problems created by addition of thicker insulation. Can existing curbs and walls accomodate additional thickness? Experience dictates flashing height at least 8 in. above the top of the cant strip, to prevent wind-blown water or snow from entering the flashing. If flashing height is already marginal, it may be impossible to accomodate added thickness.

Consider all aspects of drainage. Many post-World War II buildings have inadequate drainage. In fact, terms such as "cricket" or "saddle" (Illus. 3) have been all but forgotten. If practicable, inspect the roof during or just after a rain storm, to observe first hand how the roof sheds water.

Retrofitting and correcting drainage can go hand in hand. If a new deck is to be added, obviously the strucutral members can be designed to improve slope. More commonly the decking will remain where it is, so let's look at the case where the entire existing roof system can remain.

If the roof cuts indicate deck is safe, and it will retain mechanical fasteners, it is possible to chop holes through the old membrane for ventilation, fasten a divorcing sheet and venting base sheet, and apply new thermal insulation in steep asphalt. The insulation may be tapered to provide crickets and positive drainage.

Insulating fills compacted on the job can also be used to improve drainage, provided that the deck can stand the weight of the compacting equipment.

Venting cannot dry a wet roof system. Roof vents and venting sheets are capable of relieving vapor pressure (Illus. 4), but they are totally inadequate for drying saturated insulation or a very wet fill material. In this case, it is necessary to use power ventilation, where air is drawn into the wet space and exhausted in considerable volume. This might help to dry wet material, but the designer more realistically should consider this material as too wet, it will always be too wet, and the ultimate "R" value will remain drastically reduced from its dry value.

The environment in which the roof system will be expected to perform should be carefully observed, both during roof-top inspections and by determining the processes within and near-by the roof system.

Asphalts are soluble in most aliphatic and aromatic materials. Regular drippings of oil and grease from equipment must be diverted, or they will damage the roof. Excessive heat from exhaust stacks will melt both pitch and asphalt, as well as most plastics. All roofs get some foot traffic. But if conveyors regularly dump cement, fertilizer, or other debris on the roof, these piles should be periodically shovelled and wheelbarrowed away. In these cases, the membrane should be smooth, rather than aggregate or ballast surfaced. If the roof insulation is relatively soft, a final layer of wood fiber or perlite board could be installed directly under the membrane to improve impact resistance.

If the deck will be above 200°F (93°C), inorganic insulations should first be nailed or screwed to the deck, because bituminous adhesives are fluid above 150°F. If a temperature calculation confirms that the layers above this inorganic material are less than 150°F (66°C), conventional roofing practices can be followed.

PROCEEDING WITH THE RETROFIT

As the above information is compiled and interpreted, the designer will begin to formulate a plan. However, before the plan is executed, the owner had best be consulted to establish what his real goals are. Undoubtedly, he wants "to conserve energy," or to cut his fuel bills, but does he plan to occupy the building for a long period of time, or just for another year or two?

There are many elegant formulae and computer programs assessing pay-back, cash flow, or internal rate of return as ways to determine the "optimum" amount of insulation. In other cases, ASHRAE recommendations based in degree-days and cooling days, or legislated minimum amounts of insulation, are mandated. Any of these is acceptable, as long as you and the owner get what you have calculated.

There are many kinds of thermal losses in a roof system. Moisture degradation of thermal resistance is one example. A less obvious example is the occurrence of "thermal bridges," which occur when insulation boards are not tightly butted together. The loss of energy through open joints is hardly detectable when the insulation has an R of 3 or less, since most of the energy is flowing through the insulation. But when the R is 10 or greater, these open joints may be the **major** route for heat loss. In fact increasing a system from R-10 to R-20 might not save any energy at all!

Designers are beginning to accept the principle of two-layered roof insulation, with all joints staggered between layers to eliminate through-joints. There are several other benefits to the two-layer approach. Moisture laden air is prevented from reaching the cold underside of the roof membrane where previously liquid water would form. (Illus. 6). The water was absorbed into the roofing felts, causing a ridging called "picture framing." This problem is virtually eliminated in two-layer roof insulation systems.

Use of mechanical fasteners has greatly improved the anchorage and performance of roof systems. However, these nails or screws are thermal bridges (Illus. 7). In extreme cases, icicles have been observed on the bottom of piercing fasteners. These bridges are eliminated in the same manner as open-butt joints (Illus. 8). The fastener anchors the first layer of roof insulation only. This provides excellent attachment and wind resistance, even when the second layer is only mopped with bitumen.

Thermal losses also occur in "protected membrane" roofing systems. While the roof insulation will tend to be very water resistant and should retain its "R" value even when submerged, cold melt-water flow by the insulation causes convective heat loss. In addition, the water that cannot reach the drains gradually absorbs heat of vaporization, another perhaps unexpected source of lost energy. These losses can be minimized by putting some of the thermal insulation under the membrane, in the conventional position, and the rest in the "inverted" position. Ideally, the membrane should stay above freezing during the coldest weather, so water will flow to the drains, but there is no need for the membrane to be 70°F (21°C) when the melt-water is 32°F (0°C).

Under-deck insulation systems also have thermal bridges. Every wire, hole, beam, etc., that penetrates an under-deck insulation system carries away energy. Newer, high thermal systems are designed to insulate the structural members, eliminating thermal-bridges from the interior of the roof system (Illus. 9).

Many designers have learned to handle the concepts of "U" factor and how to design a roof system to meet the "Retrofit Criteria." Two factors have been sadly overlooked, however. One is the concept of **Mass**, or thermal lag. Heat-flow calculations generally use the "steady-state," in which the inside temperature is defined as 72°F (22°C) for example, and the outside winter condition might be 32°F (0°C). Thus, if the "U" factor were 0.05, there would be 0.05 BTU's flowing through each square foot per hour per °F, or (0.05) (72-32) = 2.0 BTU. Actually, a roof will super-cool on a clear winter night, and might be 12°F. Thus, per square foot 3.0 BTUs might be lost, 50% more than the designer anticipated.

The summer example is even more dramatic. If the hottest August day has an air temperature of 98°F, the black surface would be as much as 165°F. Thus, the temperature differential is not 98-72, but 165-72 or 93 x .05 = 4.65 BTUs, not 1.3 BTUs. That is an error of over 300%!

So called "thermal lag" resulting from heat absorption in massive materials moderates the temperature changes as solar radiation intensity varies with changing solar elevation. Thus, the temperature differential at the two faces of the roof insulation never gets as extreme as the above example, due to lagging which is omitted from a conventional "U" factor calculation.

The above examples also illustrate a second point. Black is the best radiator and absorber of energy. Use of light colored surfacings can dramatically reduce the above temperature differentials. Actual measurements indicated a black roof had a summer temperature of 166°F, while a gravel-surfaced roof was 144°F, and a roof surfaced with white marble chips was only 118°F.

These two aspects should therefore be considered in a retrofit design. Mass obviously implies weight, and this may be impossible on many structures. Light colors may be possible on many roofs, and should be considered more carefully, especially where air-conditioning claims a big part of an energy budget.

WHERE SHOULD THE NEW INSULATION BE PLACED?

The options are:

1. Below the structural deck
2. Above deck but below the waterproof membrane
3. Above deck and waterproof membrane
4. Some combination of the above three.

Here are the below-deck insulation advantages:

1. Less expensive materials can be used. Per unit of thermal resistance, glass fiber batts cost much less than any conventional roof insulations.
2. The insulation will not be as readily destroyed by a roof failure.
3. The insulation doubles as acoustical as well as thermal insulation.
4. Light reflective ceilings can reduce lighting demands compared with a darker, exposed roof deck.

Disadvantages include:

1. Interior spaces generally contain lighting fixtures, wiring, plumbing, hanging wires, and many other penetrations making it difficult to achieve a tight installation.
2. While vapor retardant facings can be laminated to the insulation, the laps and penetrations are impossible to completely seal. Water vapor can thus condense on the under-side of the deck and drip down onto the insulation.
3. As "R" value rises, thermal bridges of main strucutral elements become more significant. Recent novel designs have found ways to achieve "R" factors of 20 or more, on systems that include the strucutral elements (Illus. 9). (Dew Point maps have been prepared to help the designer decide where under-deck insulation will be most effective (Illus. 10).

Above-deck Thermal Roof Insulation:

In the original application, the roof insulation was placed on the roof deck to provide stiffness, spanning properties, and even to improve the fire properties. However, in the retrofit, these properties are less important. It is rarely acceptable to mop or nail new thermal insulation direct to the old membrane, as this violates both ventilation and divorcement. This is a common error with sprayed-on plastic foams. It is attractive to spray them directly onto a weathered roof since they are light in weight and adhere well to almost anything. Yet, moderate movement of the old system, or generation of only moderate amounts of moisture in the old system lead to delamination, splitting and failure.

Venting base sheets can be nailed through the old roof system, then vented to the atmosphere or, when nailing is not possible, controlled spot mopping can be used. These can be large blobs which cover 40-50% of the substrate. At least one available product has dime-sized holes through which the bitumen flows downward to give uniform spot attachment (Illus. 11).

If there is a strong vapor drive, such as when interior humidities are above 50% and outside winter temperatures are below 40°F (4°C), the old membrane should **not** be used as a secondary vapor barrier. Instead, it should be slashed so that the vapor can reach the venting base sheet. At least one ply of roofing felt should be mopped to the venting base sheet to make it impermeable and any penetrations should be sealed with bituminous mastic to be certain the vapor does not pass above this point.

Add enough thermal resistance above this point to be certain the venting base sheet is warmer than the dew point of the interior air. From the survey, the winter designed or observed humidity and temperature will reveal what the dew point is (see simplified table).

Venting base sheet temperature can be determined from the following formula:

$$T_{\text{vent Base layer}} = T_{\text{interior}} - \frac{R_{\text{v base}}}{R_{\text{total}}} \left(T_{\text{ interior}} - T_{\text{exterior}}\right)$$

An example is provided in the appendix to show how this equation applies, and how to calculate the insulation's required R value to satisfy the dew-point criteria.

Note that this may require **more** insulation than the economic thickness calculations.

As memtioned previously, the above-deck thermal insulation provides a simple means of improving drainage. While it is possible to leave the old roof system in place, old flashings should **always** be removed during the retrofit. First, the thickness of the system will be changing, and all lumber used as edge stops should be the full thickness of the new system. Second, edging and flashing failures are a major source of water entry. The lumber may be rotted, and total inspection is needed anyway. The new lumber must be coordinated with the new thickness of the system, especially when a tapered system is to be used.

Pressure-relief vents should be inserted through the new roof membrane, so that the new roof system is vented to the atmosphere.

This means there may be vents at two different levels in the roof system. One, to relieve the venting base sheet and old roof system, and the other to relieve an otherwise closed system between the two membranes (Illus. 12).

Above-Membrane Thermal Roof Insulation

This option generally requires careful repair of the existing roof membrane and flashings, after which thermal insulation is placed on top. Since the insulation weighs less than water, ballast is required to keep the insulation from floating away (Illus. 13).

It may be desirable to loosely lay a new roof membrane over the old system, if the old system is beyond economic repair. In this case, the flashings still require a great deal of attention, and the old system should still be vented. The ballast then serves to keep the membrane and the new insulation in place.

The ballast may be coarse aggregate or concrete pavers. When aggregate is used, it should be large enough so that it will not be dislodged by wind or ice, and enough must be used to prevent flotation (usually 5 psf/in. insulation thickness). If concrete pavers are used, the concrete must be good exterior mixture, with enough entrained air to be freeze-thaw resistant. The pavers might well be used to advantage in perimeter areas where uplift forces are greatest, and where blown gravel could damage windows. The pavers could also be used to delineate walkways, as it is much easier to walk and work on the pavers than on coarse, loose stone.

For the thermal insulation to succeed in the exposed above-membrane position, the water-resistance must be extremely good. To date, closed-cell extruded polystyrene seems best. The foam must resist moisture vapor drive, liquid water, and alternate wetting and drying cycles. The mechanical properties must also be very good, as the placing of the ballast will produce heavy point loads from wheelbarrows.

When pavers are used, damage is frequently observed at the flashings due to mechanical abuse. While above-membrane systems are "protected roof membranes," the flashings are **not** protected.

The pavers must be held back from the cant strip to avoid punctures (Illus. 14). In addition, the flashings must be designed to be stronger than the membrane, since the flashings will have more weather exposure and far more stress than the rest of the roofing system.

The ballast serves several useful functions: First, it has great heat capacity, providing thermal lagging. In addition, it protects the insulation from fire exposure. It can also serve as an ultraviolet and ozone screen to improve the durability of the thermal insulation.

Placing the thermal insulation on top of the waterproof membrane serves several purposes. The roofing membrane no longer is cycled thermally day to night and season to season. The membrane is also protected from human abuse, as well as hail, ultraviolet degradation, etc.

These advantages are balanced by some important limitations: The roof membrane will be wet and warm most of the year. Under these circumstances, rotting and vegetation growth are promoted. The membrane system must be designed to resist mold, root growth, and water absorption.

Thermal calculations based on "R" values will be incorrect as during wet weather the insulation will be bypassed by water which melts and flows across the membrane on the way to the drain (Illus. 15). Evaporative cooling will also take heat away, and of course all insulations lose some efficiency when wet, even polystyrene.

It is quite difficult to accurately estimate the weight of gravel ballast, and more difficult yet to insure that the gravel is uniformly distributed throughout the roof. Pavers, obviously, have neither of these drawbacks.

The requirements for ballast become a major consideration in a retrofit. The old roofing system, if left in place, could weigh 2 lbs. for a smooth roof to 7 lbs. (9.1kg/m^2 to 34 kg/m^2) for a gravel roof. Ballast weight could add 10-15 lbs. (plus the concentrated loadings during construction), and to this must be added the estimated weight of ice or water retained or retarded while flowing to the drains. One inch of water would add 5.2 lbs./ft.^{2}, so it is conceivable that a protected membrane system with three inches of polystyrene and ballast, applied over an existing roof system, could result in additional load of 27-30 lbs./ft^2 (132 - 146kg/m^2).

This loading exceeds the design requirements of most building codes, and would be beyond the normal capacity of most light frame steel buildings, as well as most timber buildings. This weight would be half the live load required for most floors, so it should not be a problem in most concrete structures, or roof-decks designed for future conversion to floors.

Intermediate Roofing Systems

Combinations of the above three insulating concepts are practicable ways of exploiting some of the advantages while minimizing disadvantages. Common examples include hung ceilings or the use of some under-deck batt insulation, with sufficient above-deck insulation to prevent surface condensation and to bridge to flutes of the deck.

Intermediate systems, where the above-deck, under-membrane insulation serves as a fire barrier and spans the deck and above-membrane insulation protects the membrane are also attractive (Illus. 16). By matching the vapor data to the climate, membrane temperature can be kept above the dew point, and the heat loss from melt-water can be minimized. In addition, less ballast is required for the thinner above-deck insulation.

TABLE 1

PSYCHROMETRIC TABLE: DEWPOINT OR SATURATION TEMPERATURE (F)

Relative humidity (%)	32	35	40	45	50	55	60	65	70	75	80	85	90	95	100
100	32	35	40	45	50	55	60	65	70	75	80	85	90	95	100
90	30	33	37	42	47	52	57	62	67	72	77	82	87	92	97
80	27	30	34	39	44	49	54	58	64	68	73	78	83	88	93
70	24	27	31	36	40	45	50	55	60	64	69	74	79	84	88
60	20	24	28	32	36	41	46	51	55	60	65	69	74	79	83
50	16	20	24	28	33	36	41	46	50	55	60	64	69	73	78
40	12	15	18	23	27	31	35	40	45	49	53	58	62	67	71
30	8	10	14	16	21	25	29	33	37	42	46	50	54	59	62
20	6	7	8	9	13	16	20	24	28	31	35	40	43	48	52
10	4	4	5	5	6	8	9	10	13	17	20	24	27	30	34

Dry bulb temperature (F)

ILLUSTRATION 1

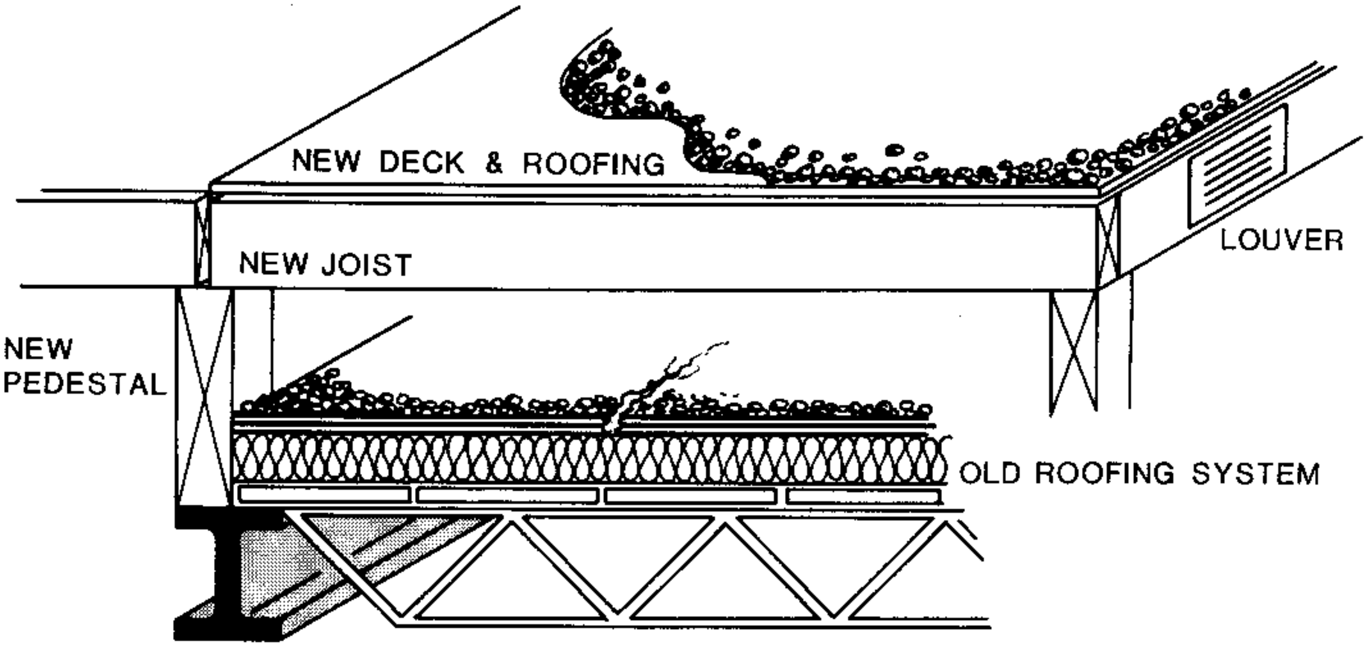
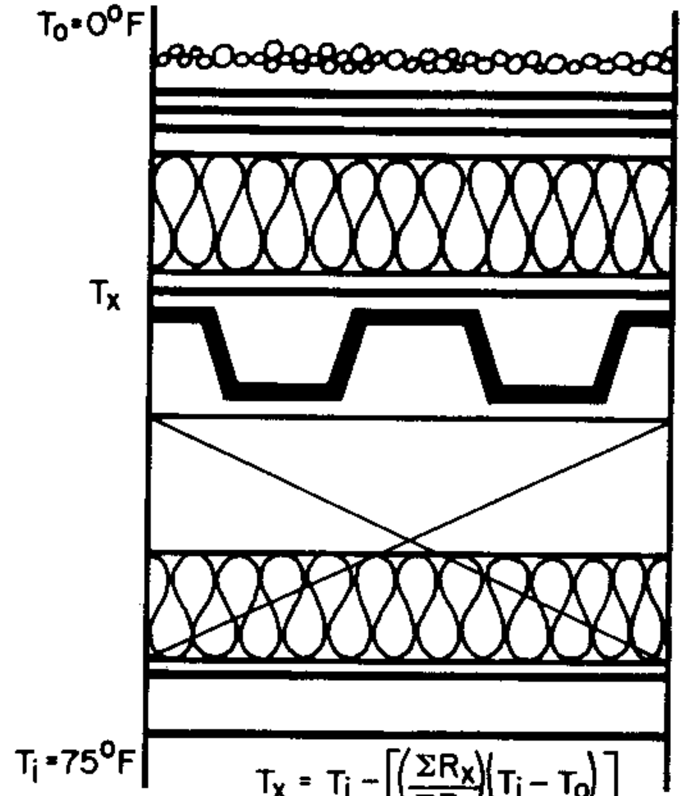


ILLUSTRATION 2

CALCULATION OF TEMPERATURE AT VAPOR RETARDER



	RESISTANCES	
OUTSIDE AIR	0.17	
MEMBRANE	0.33	
ROOF INSULATION	8.33	
VAPOR RETARDER	0	0
STEEL DECK	0	0
STILL AIR	0.94	0.94
BATT INSULATION	7.0	7.0
CEILING BOARD	1.62	1.62
INSIDE AIR FILM	0.61	0.61
	19.01 (ΣR)	10.17 (ΣR_x)

$$T_x = T_i - \left[\left(\frac{\Sigma R_x}{\Sigma R}\right)\left(T_i - T_o\right)\right]$$

$$T_x = 75^\circ F - \left[\left(\frac{10.17}{19.01}\right)\left(75 - 0\right)\right]$$

$$T_x = 35^\circ F$$

ILLUSTRATION 3

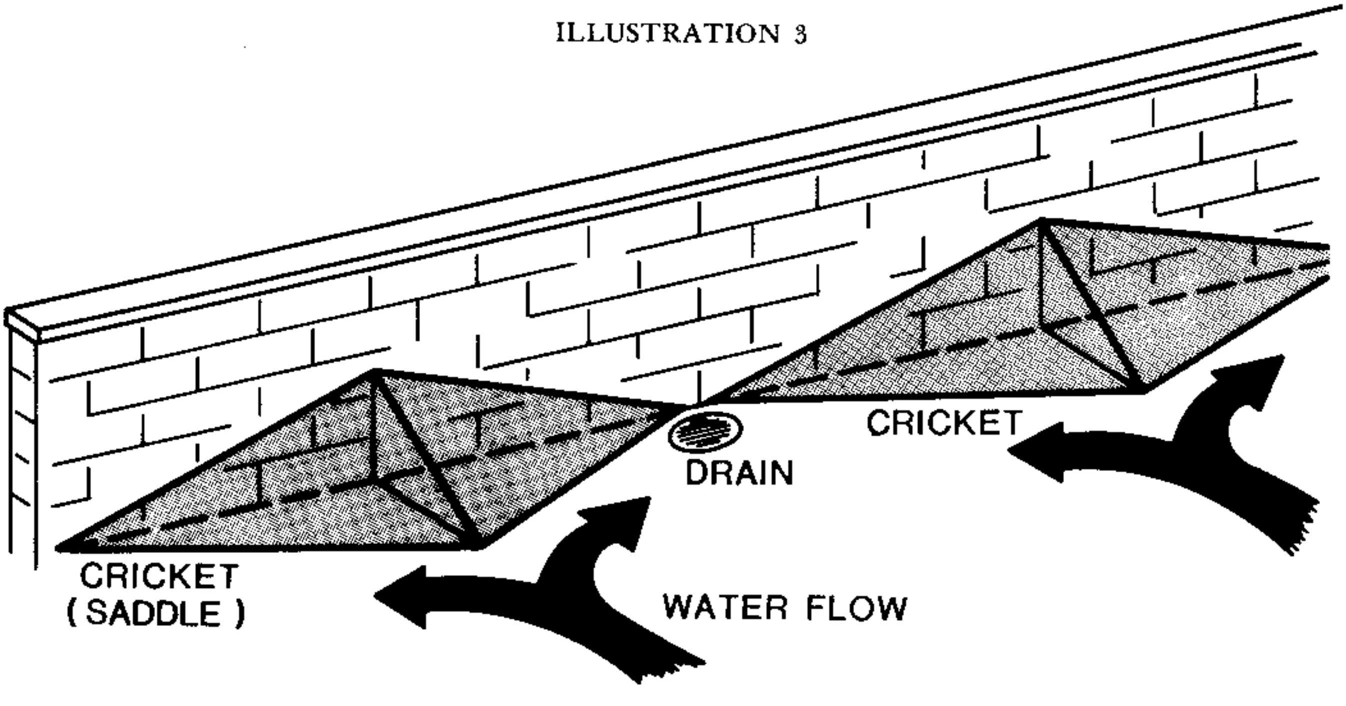


ILLUSTRATION 4

DIFFUSION OR PRESSURE RELEASE

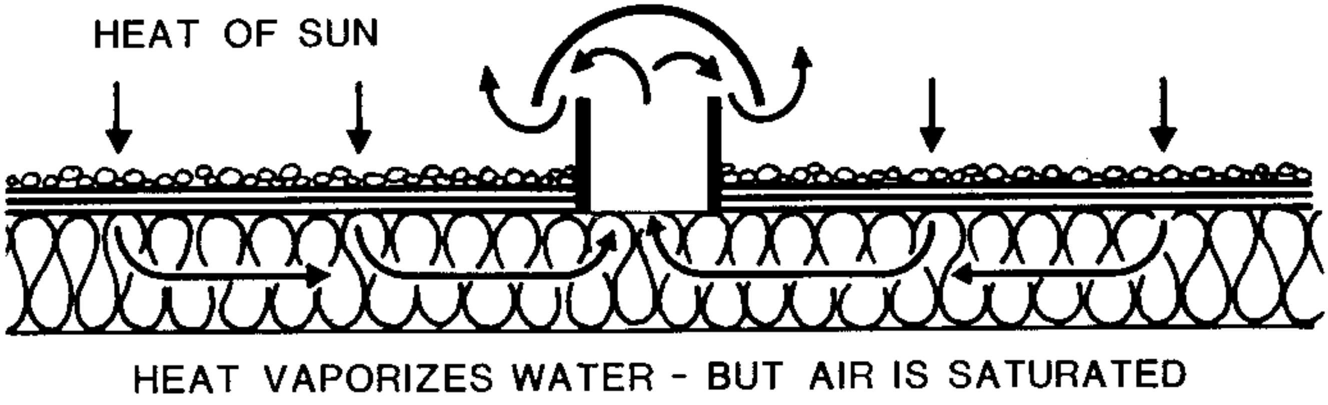


ILLUSTRATION 5

EVAPORATIVE POWER DRYING

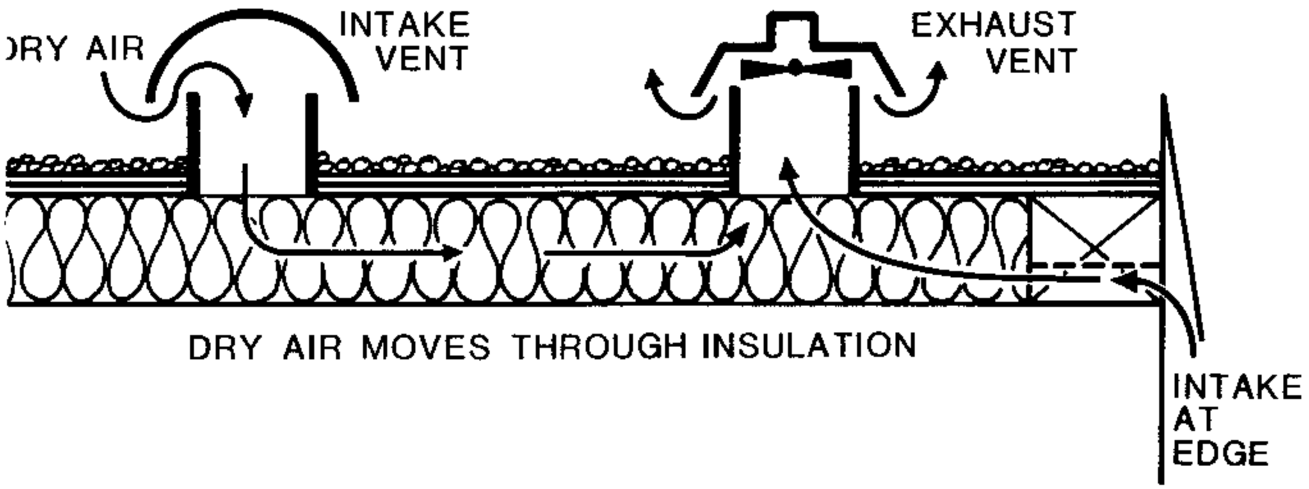


ILLUSTRATION 6

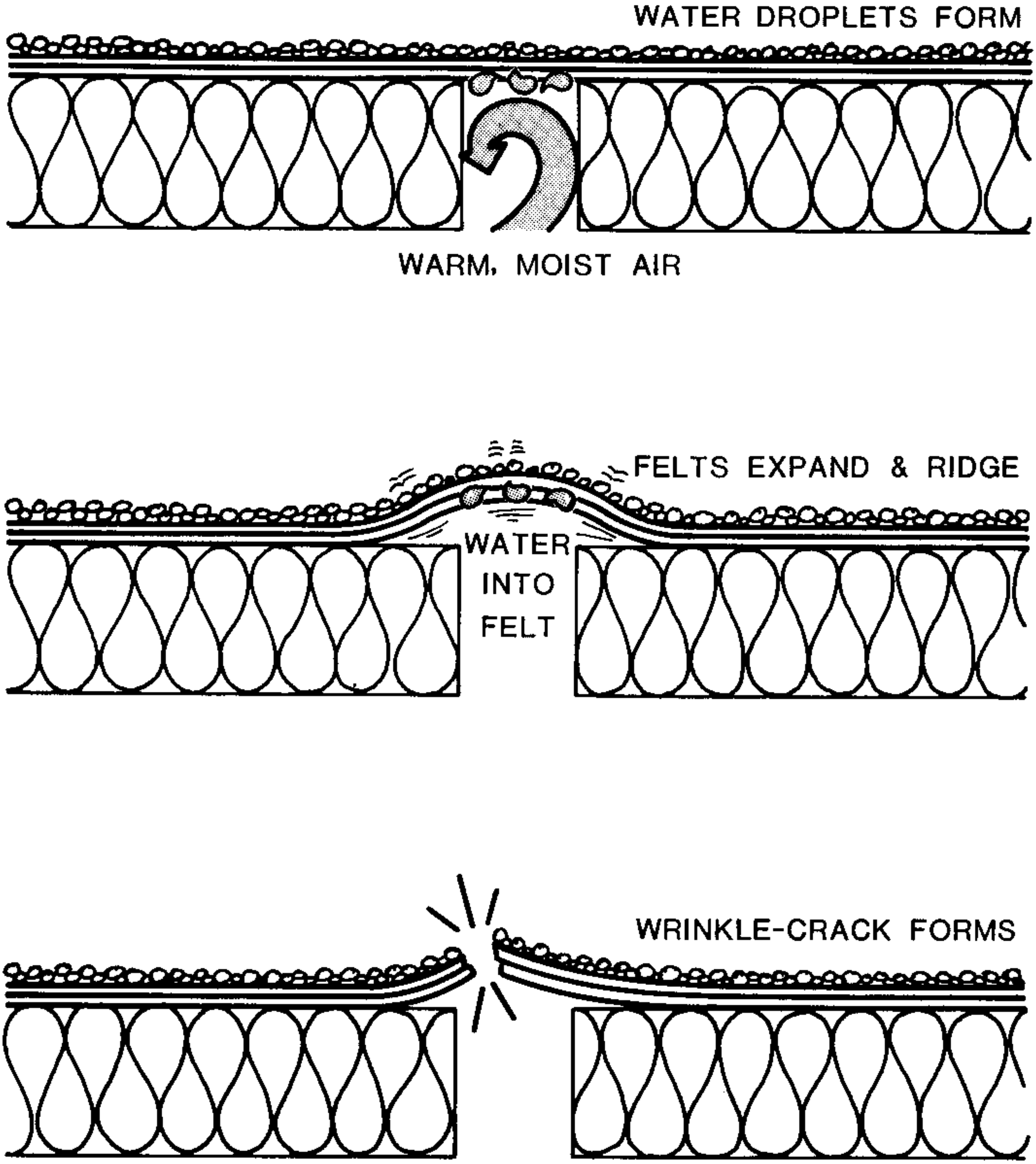
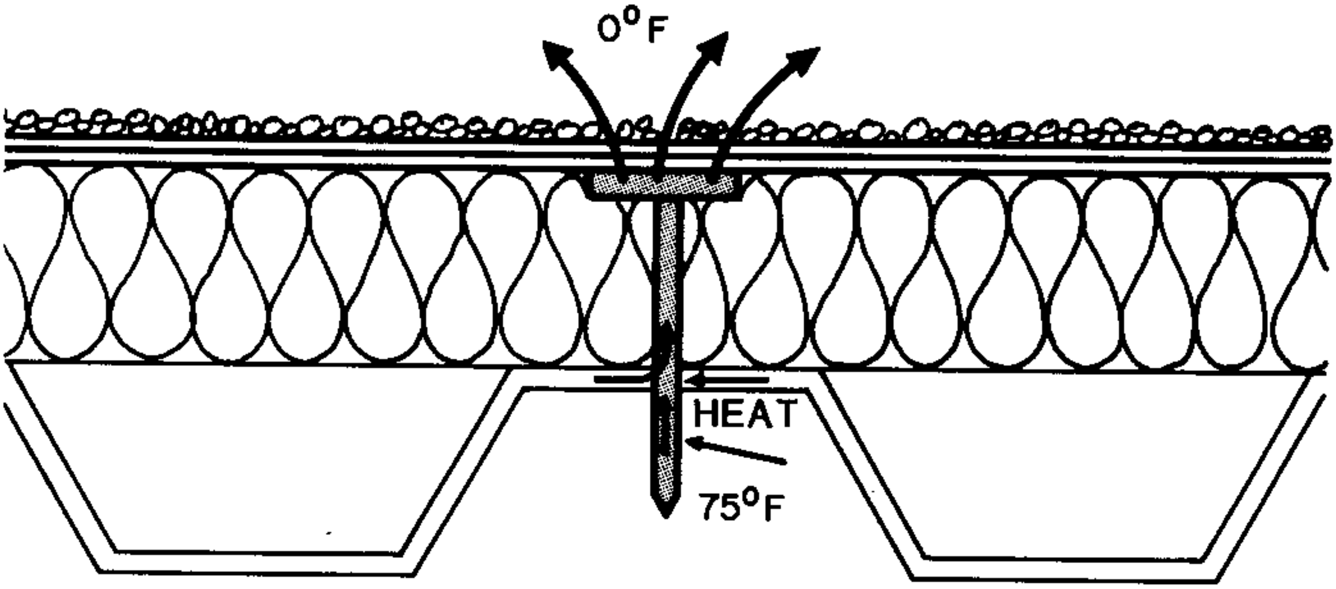


ILLUSTRATION 7



THERMAL BRIDGE THROUGH NAIL

ILLUSTRATION 8

THERMAL BRIDGES INSULATED

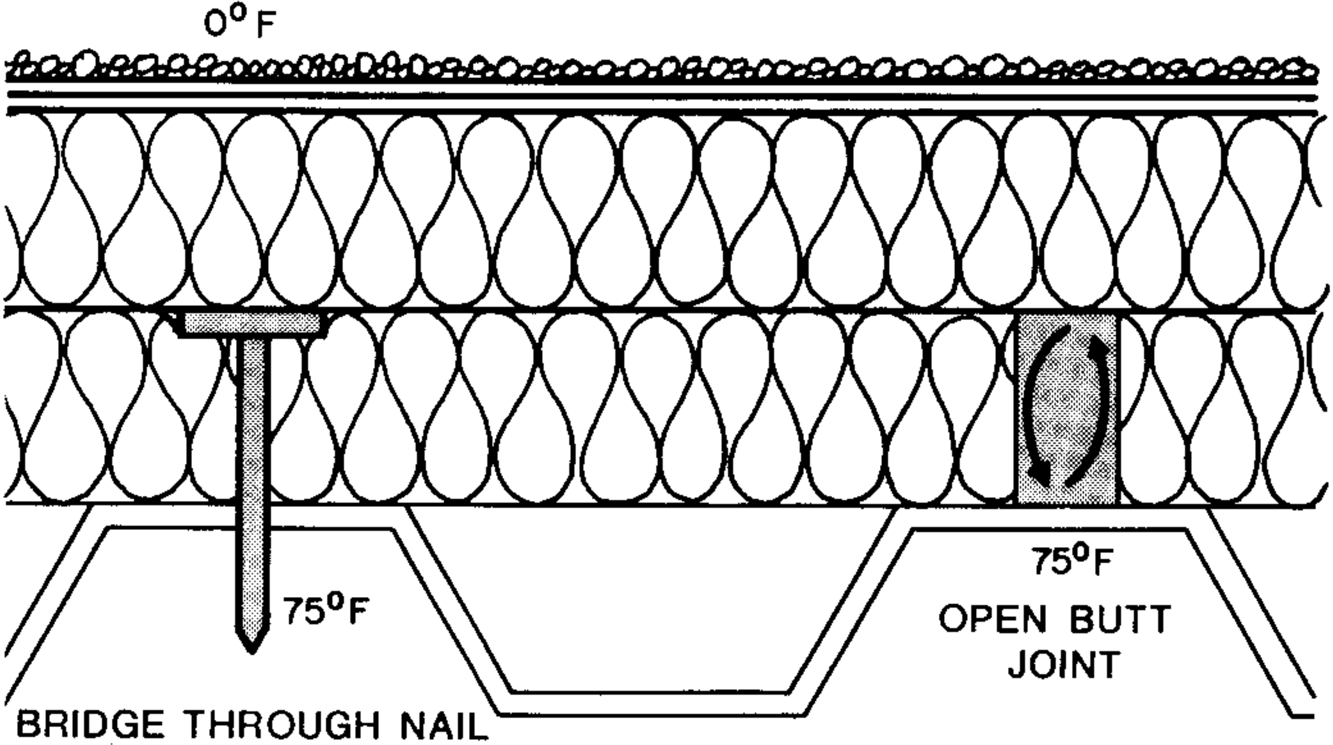
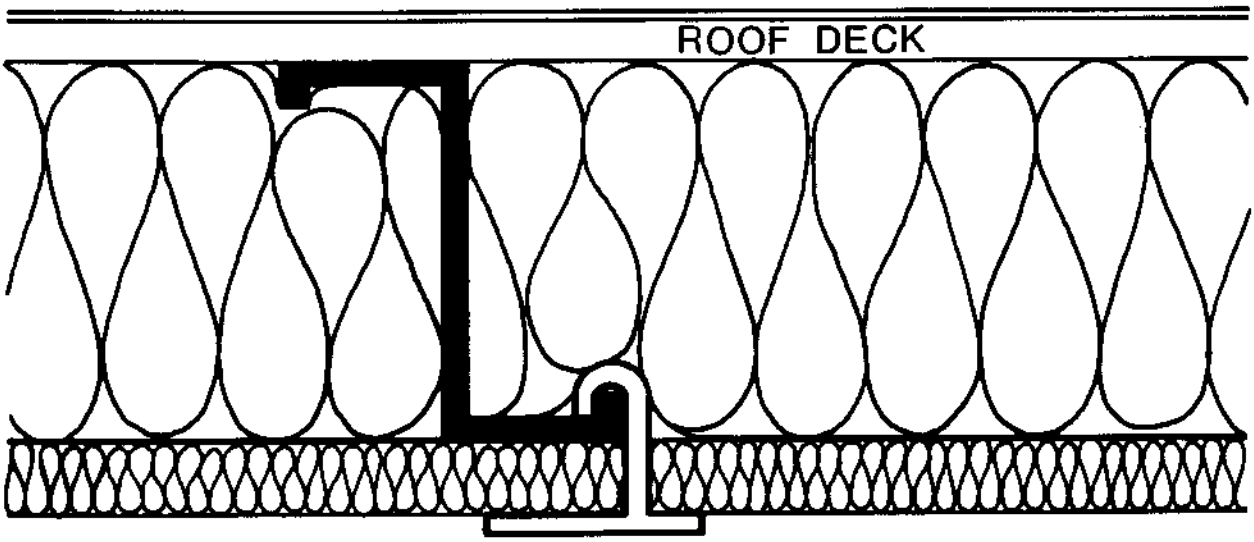


ILLUSTRATION 9



PURLIN IS WELL INSULATED

ILLUSTRATION 10

	Winter, median of annual extremes	Maximum allowed indoor relative humidity (constant)	Maximum allowed indoor relative humidity daytime (intermittent)
Zone 3	+10°F or higher	40%	45%
Zone 2	−10°F to +10°F	30%	35%
Zone 1	−10°F or lower	20%	35%

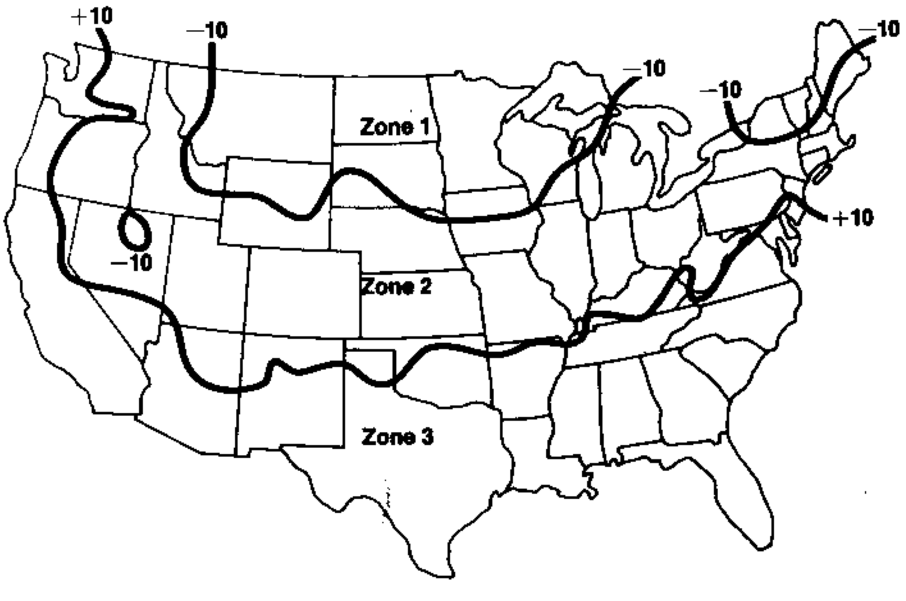


ILLUSTRATION 11

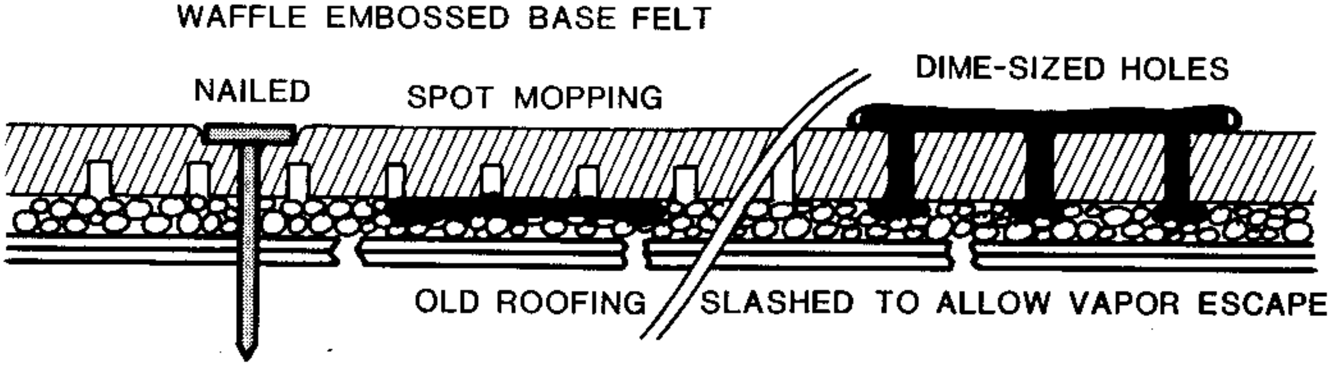


ILLUSTRATION 12

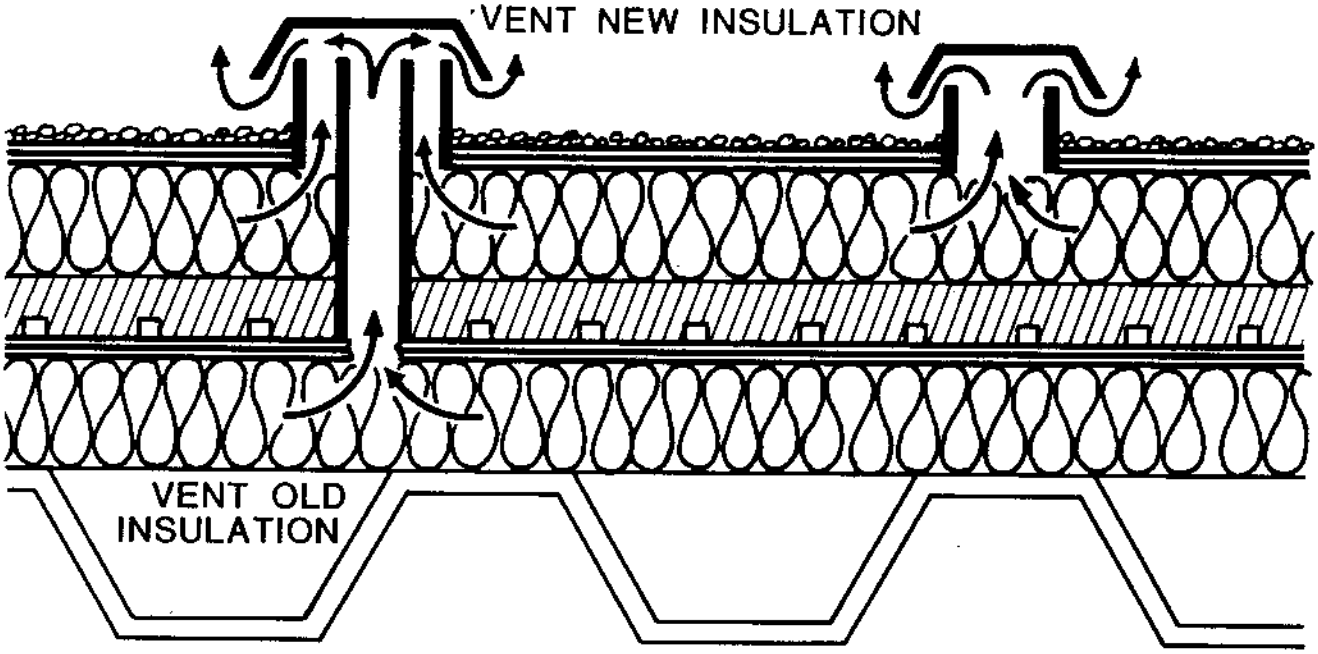


ILLUSTRATION 13

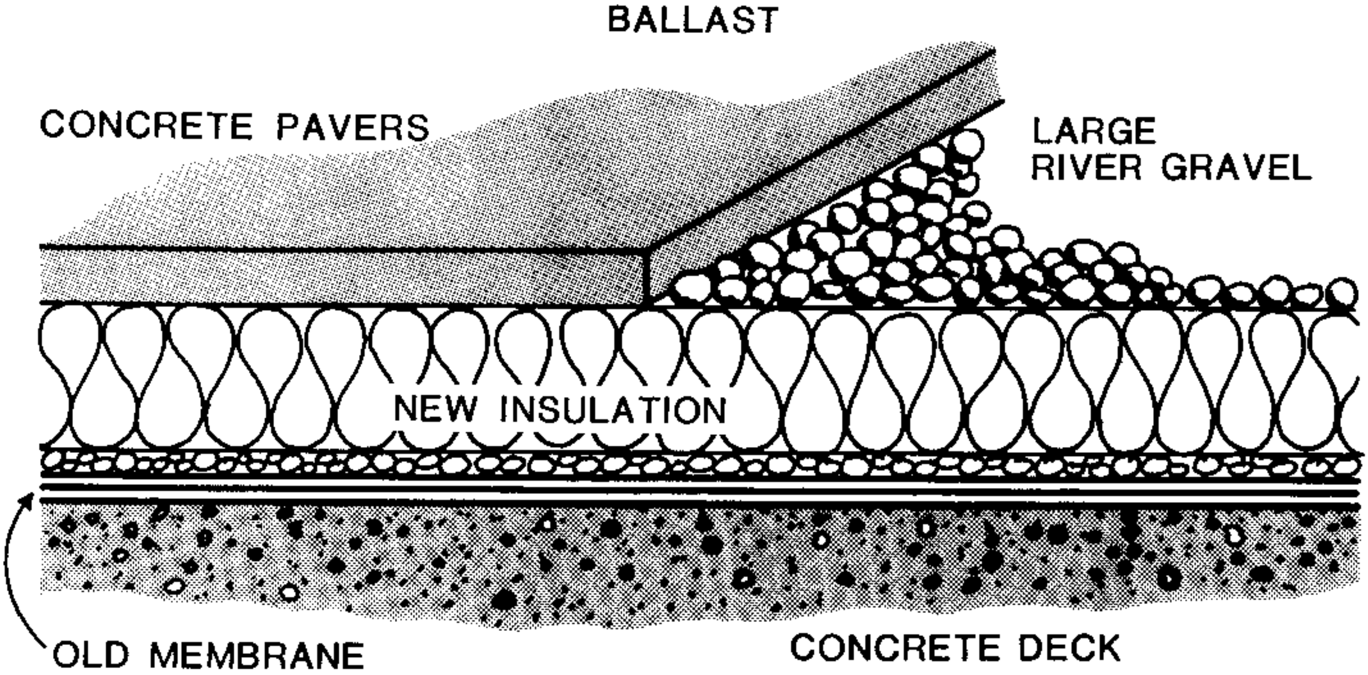


ILLUSTRATION 14

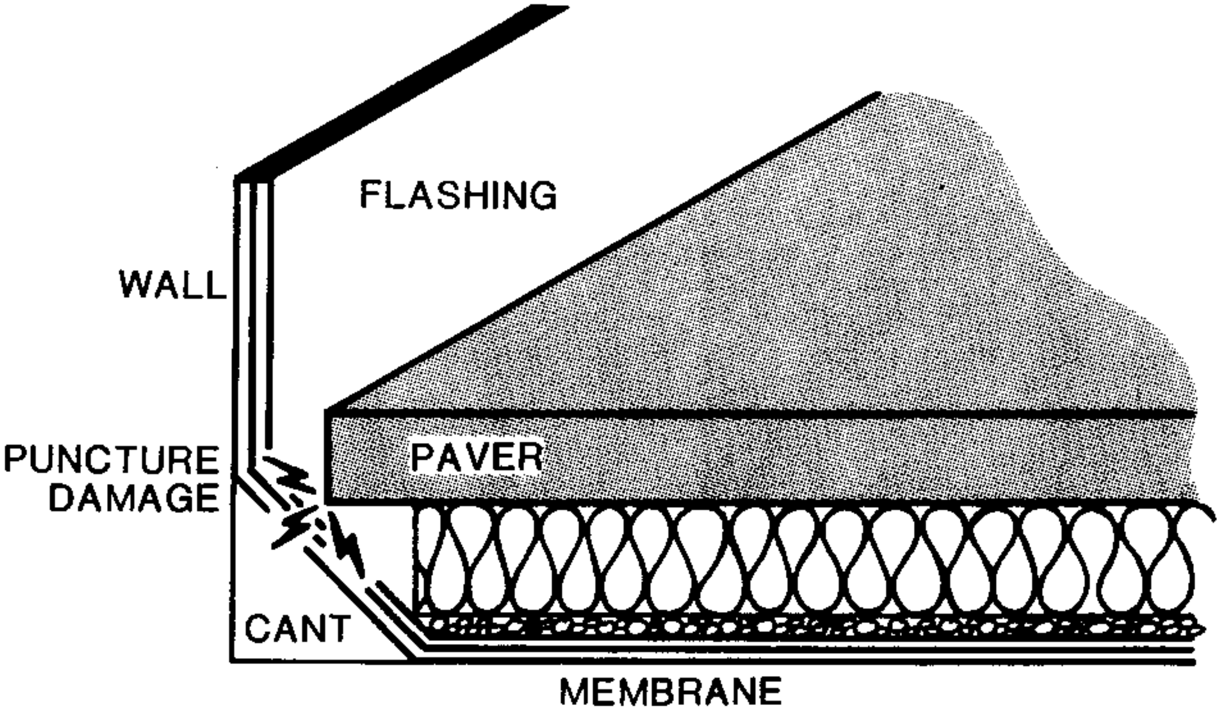


ILLUSTRATION 15

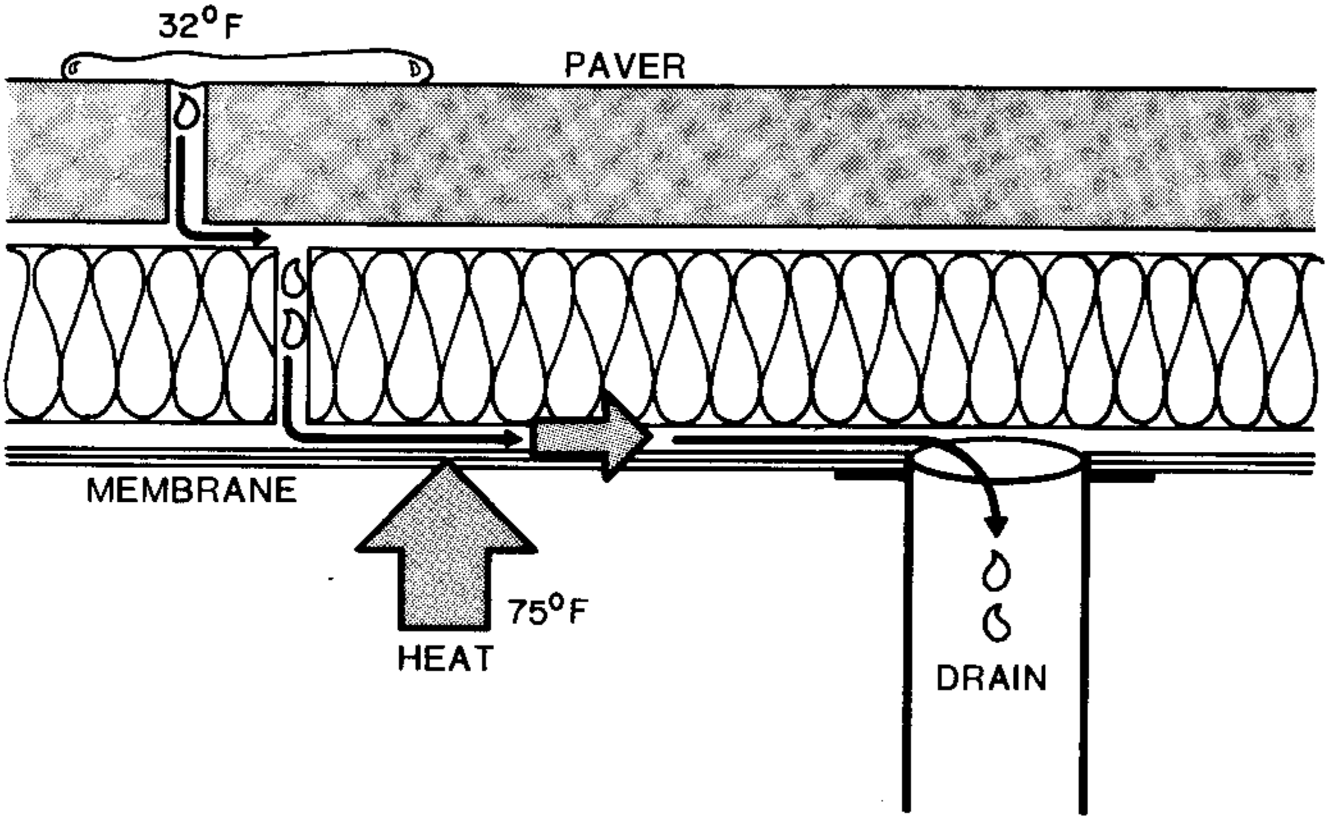


ILLUSTRATION 16