PREMATURE FAILURE OF BUILT-UP ROOFING

BY
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BUILDING RESEARCH

THE PENNSYLVANIA STATE UNIVERSITY
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FOREWORD

The Better Building Report series was initiated to assist the builder of houses. It is now being expanded to include interests of the construction industry in general.

Failures of low-pitch and dead-level roofs have become a familiar and baffling problem. New roofs leak shortly after they are completed, and roofs and roof decks are damaged by condensation. In this publication Professor Frank A. Joy, whose research on water vapor phenomena has earned high respect, discusses some of the causes of roofing failures and suggests preventive measures. Other aspects of the roofing problem will be treated in later reports.

But the series will not be limited to studies of construction difficulties. It is expected to reflect such varied concerns of the building research group as new ideas for builders, new combinations of materials, heating, and the effects of air pollution on buildings.

E. R. QUEER, Director
Engineering Experiment Department

University Park, Pennsylvania
September 20, 1963
ACKNOWLEDGMENTS

For the inspiration to attack this problem, I am indebted to Dr. K. G. Martin of Melbourne, Australia, whose astonishing picture of felt puckering (Fig. 3) and helpful correspondence have stimulated the analysis herein.

The generous grants of the Armstrong Cork Company to the University have supported our basic studies of water vapor phenomena over a period of several years. Research on roof moisture sponsored by the Insulation Board Institute has been another vital element of experience bearing upon this problem.

F. A. Joy
Professor of Engineering
Research
PREMATURE FAILURE OF BUILT-UP ROOFING

Early failure of built-up roofing is causing increasing concern to builders, roofers, owners, and insurance companies as the trend to flat roof construction continues. Economy dictates flat roofs for large buildings, and the dead-level roof permits added efficiency in the design. Failure is more promptly detected and frequently more disastrous when the roof is dead-level, especially where a pool of water is intended or results from minor faults of construction or a drainage block. Dead-level roofs are a feature of many large buildings such as shopping centers, and it appears that size of the roof as well as its level design contributes to certain types of failure.

Many failures are due to faults of construction, particularly at flashings where the designer too often depends on the ingenuity of the workman to provide a proper dam. Such failures have obvious causes and logical remedies, and need not be considered here. But the obscure causes of blisters, wrinkles or ridges, and cracks require careful analysis in order to improve the design and, if possible, avoid the serious consequence of these defects.

Moisture entering the roof from the occupied space is one of the causes of roofing failure. Builders are familiar with this problem in walls and how to handle it by means of a vapor barrier. Naturally, they apply the same device in a flat roof, but the requirement is different because the exterior is vaportight and airtight. The problem could be effectively solved by a suspended ceiling with the space above it properly ventilated, but this adds to cost. Less expensive means must be considered. Moisture in the materials at the time of construction leads to other types of failure, and practical ways to avoid or offset this hazard must be devised. Air pressure under the roofing produces surprising blisters. When this action is fully understood, corrective measures can be applied.

This report emphasizes the phenomena involved in roofing failure and proposes some practical means to avoid such damage. For the reader not entirely familiar with roofing methods, a summary of current practice is presented in the final section.

THE ROOF SANDWICH

The essential members of a roof are the structure, or deck, and the roofing. In addition to strength, a wood deck provides considerable insulating value, as do some specialty products. On larger structures the deck is often poured or precast concrete, gypsum, or steel, having high strength and low insulating value. When more insulation is required, it is usually placed above the deck. The roofing is applied as a membrane "built up" with several plies of felt made of mineral or organic fibers, all bonded together in hot bitumen.

The most common ply sheet weighs 13 to 14 lb per 100 sq ft, and is made of felt treated with hot bitumen. Organic fiber felts, usually
called rag felts, are made of vegetable fibers. Most mineral fiber felts contain asbestos fibers, with a small addition of organic fibers. Instead of felt, a tissue of glass fibers bonded in a random arrangement is also used as the core material. The typical sheet, finished with a bitumen, is known as asphalt-saturated felt or tar-saturated felt. The glass fiber tissue, similarly treated, carries its own trade name. Saturated sheets may be "coated" in a range of weights for certain applications, and a coated sheet is sometimes recommended for the bottom ply of the roofing, called the "base sheet."

The function of felt or fabric in built-up roofing is to reinforce it and stabilize the bitumen, a job that it does well if it is placed dry and kept dry. Saturated felts are not truly saturated, however, since they contain small voids. Brown (1)* reports that the saturating process does not eliminate air, the bitumen filling 75% of the volume of voids in organic felts and only 55% in asbestos felts. Glass fiber tissue, being more open, is likely to be more completely filled by the hot bitumen. The open microvoids in the saturated felts would not be a significant fault except that they facilitate the entrance of moisture, which increases the air pressure, swells organic fibers, and weakens the bond of a bitumen to any fiber.

Tests of moisture content in saturated felts may be made by distillation (ASTM D 95-58) or approximately, in the case of asphalt felts, by heating to 221 F. ASTM Specification D 227-56 limits the moisture content of coal-tar saturated felt to 2.5%. Specification D 226-60 for asphalt-saturated rag felt limits the "loss on heating" to 4%, and D 250-60 for asphalt-saturated asbestos felt places this limit at 5%, including some volatile oils as well as moisture.

In contrast to these acceptable figures, the water-holding capacity of saturated felts is high. Both tanned felt and asphalt felt will act somewhat like a sponge when wetted, and they swell much more across the sheet than along its length. The data in Table 1 were obtained on rag felts of both types, randomly chosen from available stocks. The figures are typical, and they indicate an expansion of 0.5 to 0.6 in. across a 36 in. strip of felt when it is wetted. The reason for the greater expansion in this direction is that the manufacturing process tends to orient fibers parallel to the strip, and their thickness swells more than their length. In fact, the saturating process puts tension into the sheet so that it is prestressed along the strip length, and the elongation of the wet fiber merely reduces the tension in it (2). There is a significant correlation between this cross-strip expansion and roofing ridges that develop in parallel lines, as explained in the section on roofing wrinkles.

Insulation may also absorb moisture, with damage to its thermal value and dimensional stability. Even destruction by fungi is an ultimate danger to some types. Therefore, it must be applied dry and kept dry in
service. Above humid spaces, especially those where a manufacturing process like textile spinning and weaving requires a warm and humid atmosphere, insulation that is fibrous or permeable to water vapor should be protected on its lower side by a vapor barrier that strictly limits vapor entrance and condensation in winter weather. This barrier usually consists of one or two plies of asphalt-saturated felt, bonded to the deck with hot asphalt and liberally mopped on top to secure the insulation. It should be airtight as well as vaportight. Air movement into porous insulation from a humid space in winter is a sure means of wetting the insulation near the point of entrance.

The typical assembly above the deck is, then, a sort of sandwich. The large volume of air in fibrous insulation is enclosed between covers forming a container that is more or less airtight. Every temperature change produces a pressure change in this sandwich. Even when the insulation is cellular and not permeable to vapor or air, cracks between pieces of the insulation may be sealed air spaces in which this pressure change occurs. Though the pressure is the same in a large or small sealed space, effects on the roofing are likely to be different.

PRESSURE UNDER ROOFING

The phenomenon of changing pressure in the roof sandwich, as a result of temperature change, should be clearly understood. The total effective pressure under the roofing is the sum of two pressures, that of dry air and that of water vapor. In a tightly sealed space containing only dry air, the pressure will rise 20% when the temperature changes from 40°F to 140°F. This wide range of temperature is possible between night and day in or under dark roofing, which is colder than the weather air at night and much hotter than the weather air in the bright sun. At the same time, if a very small amount of liquid water is present (about 1 oz in 8 cu ft of space), its vapor pressure will increase 24-fold, from 0.12 to 2.89 psi. Starting at 40°F with normal atmospheric pressure in the sealed container, the total effective pressure at 140°F will be 5.7 psi higher, which is about twice the pressure rise of dry air alone. These pressure relations are shown in Fig. 1.

High pressure (820 lb per sq ft) could be definitely expected in a thin roof sandwich on a wood deck if the sandwich were actually airtight and would hold together. But perfect tightness over a large area is virtually impossible, considering all the factors that are bound to enter the roofing job. The roofing itself is likely to be airtight, but the

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TABLE 1. Moisture in Asphalt-saturated and Tar-saturated Rag Felts

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No. 15 Asphalt Felt</th>
<th>No. 15 Tarred Felt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight per 100 sq ft, lb</td>
<td>14.2</td>
<td>13.3</td>
</tr>
<tr>
<td>Loss of weight on heating, %</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Gain of weight in water, %</td>
<td>68</td>
<td>80</td>
</tr>
<tr>
<td>Expansion along strip in water, %</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>Expansion across strip in water, %</td>
<td>1.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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vapor barrier at the bottom probably is not. And a seal between roofing and barrier at the perimeter of the roof or around roof obstructions is rarely attempted. In fact, perimeter vents of proper design can be highly desirable.

Vents through the vapor barrier reduce its efficiency. Although they permit the escape of air from porous insulation during the day, they also allow its return at night. In the winter season, air entering from the humid space below carries water vapor into the insulation, where it condenses under the cold roofing. When the air escapes the next day, it is drier. This breathing action deposits more water in the insulation each day, and since the water tends to remain near the point of leakage, this location exhibits water damage before other roof areas. Likewise, high pressure often develops within or between plies of the roofing felt, and blisters occur in spots of poor adhesion.

Vents relieve the pressure in the sandwich, but a spot far from a vent does not get much relief while the temperature is rising fast. Figure 2 shows the expansion of air at constant normal pressure. This is one of the factors that determine net moisture gain or removal in the daily breathing cycle.

MOISTURE IN ROOF MATERIALS

Water, as vapor or liquid, can enter the roof sandwich in so many ways and its effects are so serious, it is not surprising that many early failures are reported. The sources of water may be listed in the order of their prevalence somewhat as follows.

(1) Construction practices. These include improper shelter and excessively long storage of materials on the site before use, and roofing work during foul weather. The rush job, where insulation and roofing are applied on a freshly poured masonry deck or above a closed shell where plastering continues inside, is another bad practice.

(2) Flashing leaks. More than 75% of roofing complaints turn out to be sheet metal roof-edge problems (1), and it is generally true that this failure of a flat roof will flood a considerable area within a roof sandwich containing porous insulation.

(3) Condensation. In most large buildings located where the winter temperature drops to 0°F, water vapor originating in the interior raises the dew point well above the roofing temperature. Vapor permeates into the roof and condenses there unless it is effectively stopped by the structure or a vapor barrier before it reaches the cold zone.

(4) Roofing damage and defects. Roofing damage here includes cuts and abrasion resulting from traffic. The most common defects relate to the bitumen, which may be of poor quality, unsuitable for the application, or improperly applied -- too little, too hot, or too cold. When water stands on a dead-level roof as it may for long periods in some spots, especially if snow-covered, any fault in the top "pour coat" will allow water to reach the top ply of felt, with progressive damage.
FIG. 1. Pressure rise in a space of constant volume.

FIG. 2. Expansion of air at constant pressure.
FIG. 3. Shrinkage of saturated organic fiber felt in weather exposure. (Photo from K. G. Martin. See Ref. 2.)
Moisture swells wood or other organic fibers, and a repeated cycle of moisture sometimes produces progressive movement. This phenomenon is especially important in rag felts that are not fully saturated with bitumen. Dramatic evidence of such movement has been presented by Martin (2) who exposed a number of saturated felts to the weather. His specimens, 36 in. square, were laid in hot bitumen on top of an existing built-up roof. Shrinking started promptly and ranged up to 23% reduction of width across the unrolled strip, in the first year. Figure 3 shows a typical specimen of Martin's saturated organic fiber felt with 60% reduction of area after five years. He describes the behavior as puckering of the felt, in a ratchlike action produced by rain-sun cycles.

Evidently the fibers were not protected from water as the felt was supplied in the roll, and mopping on only one side has not protected them in this test. The sequence of events may be described as follows. In rain, the fibers expand and separate. Since the bottom is then anchored by cool bitumen, expansion of the top is accommodated by puckering of the surface. Later, in the hot sun, drying produces shrinkage of the fibers, but the bitumen is then fluid and the whole sheet slips on its base into a smaller area. This cycle is repeated every time it rains, the sheet getting thicker and smaller.

A similar action can occur within the roof sandwich when the bottom ply of felt is exposed to condensation. When water from one source or another has entered porous insulation, condensation may be found above the insulation in cold weather, on the first ply of roofing, and below the insulation in warm weather, on the vapor barrier. It may even be in both locations in mild weather, as the moisture moves up and down each day, always toward the cooler side.

"Strip mopping" under the first ply of saturated felt should never be used where condensation is possible. In fact, any unsealed spot under the first ply is a place for condensed water to enter the felt. One such bare spot under the first ply may be found over an insulation joint not tightly closed. If the bitumen mopped on the insulation is too hot and scanty, it runs into the crevice without filling it, leaving a narrow strip of the first felt uncovered so that it can receive water and expand. By capillarity, the liquid water penetrates this felt layer farther and farther from the point of entrance. In winter the penetration is increased by repeated freezing, which also expands the felt. Slowly but surely, the roofing is detached by splitting of the first ply or by the destruction of its bond to the insulation below it. Swelling is eliminated in felts made wholly of mineral fibers, and is greatly reduced in blends containing no more than 15% of organic fibers.

Excessive moisture in any component of the roof sandwich at the time of construction will lead to early damage. Wood or cane fiber insulation can tolerate considerable moisture because of its natural affinity for water, but it is apt to pick up excessive moisture if stored long on the job without good protection. Such insulation leaves the factory with no more than 8% moisture; depending on the climate, it should have no more than 8% to 10% when installed. Moisture in roofing felts should also be strictly limited. When any doubt exists, two or more outer layers from the roll should be discarded.
Bad weather during the roofing job also leads to a bad job unless work habits are carefully planned and controlled. These include storing all materials under cover from rain, wind, and snow; applying a permanent roof only on a deck that is dry; careful sealing of exposed insulation or felts at the end of a day's work; and assurance that precipitation (rain or dew) during the night is thoroughly removed from any damp surfaces before they are closed in.

Moisture in the felt as the result of faulty application is a start of trouble. As noted in the preceding section, the pressure of saturated air can rise as much as 5.7 psi at 140°F, a temperature apt to be exceeded in the roofing many times during a year. The limited void space within a sheet of felt does not reduce the pressure. In a rare case, such as a warehouse for metal products that is heated in winter, roofing felts that are damp when applied will dry and shrink both in summer and in winter, placing the roofing under tension until it cracks -- and leaks badly.

ROOFING BLISTERS

The basic factors in typical roofing failures have been described as moisture, temperature, and pressure. These tend to combine in various ways to produce certain distinctive types of failure, among which blisters are the most amazing.

Blisters have been reported as large as 50 sq ft in area and a foot high. Sometimes they are soft, and sometimes so firm that a man can walk on them. Obviously they contain gas under pressure, and samples have revealed air, often with high humidity, but rarely with any significant contamination by other gases. They are a natural result of the pressure of air, with or without water vapor, which is to be expected in a roof sandwich. The growth of a blister has been watched over a long period, but more commonly they are not seen until the roof leaks. Leakage does not occur promptly, and a large blister may continue for years without leaking. A roof often has many small blisters, not easily seen, but there is a good reason for their growth.

The mechanism of blistering has been discussed by Lund (3), who emphasized the separation of roofing plies when improperly bonded, and by Warden (4), who developed the theory of trapped air and moisture within porous insulation, based on the air temperature at the time of construction. Both properly emphasize the high temperature of the roofing on a bright summer day and the resulting expansion of trapped air, especially when water is also involved.

Blisters between plies of the roofing are by nature not high. They are quite common, and are generally unnoticed on a gravel-topped roof except that it feels spongy when walked on. But a small blister between plies may easily develop into a big one if it receives air under pressure from below or by suction, from top or bottom, through a small crevice.

The basic cause of pressure in the roof sandwich is a temperature rise, as shown in Fig. 1, which applies to a sealed space containing air and a bit of liquid water. The roof sandwich, however, behaves somewhat
differently. The volume increases when blisters develop, and vapor pressure is always a part of total pressure, higher if there is liquid water but important without liquid when the insulation is porous and contains hygroscopic moisture. Also, it is hard to imagine that the whole roof sandwich is a tightly sealed space. Indeed, it appears that limited leakage of a sandwich containing porous insulation actually favors blister formation and is essential to their growth. This anomaly needs explanation.

Pressure in the roof sandwich, like pressure in a leaky tire, can be temporarily produced without perfect closure. Peaks of pressure may very well be higher with limited vents, since small vents ensure a close approach to full atmospheric pressure at the start of each heating cycle, whereas the pressure in a perfectly tight space depends on its temperature and the barometric pressure on the day it was closed.

The factors that tend to increase the peak of pressure in a nontight sandwich, listed in their order of importance, are the following:

1. Large roof size with vents only at the perimeter.
2. Bright sun that appears at noon, without wind, after several cold sunless days. This is typical of spring weather.
3. Liquid water (condensate) directly under the roofing, also probable in spring weather.
4. Dark thin roofing.
5. Thin insulation of low density and low specific heat on a wood or insulating deck.
6. Rapidly falling barometer.

All of these factors may cooperate to produce the maximum lift, but a pressure high enough to lift the roofing in a weak spot requires only one or two of them.

Roofers have reported that balloonlike blisters more often occur on large roofs. This would not be true of spaces tightly sealed; rather, it is consistent with the assumption of incidental edge venting. In a large roof, the path from the central area through insulation to an edge vent is long and restricted, and there is more air to be released as the temperature rises. Actually, the pressure rise near the perimeter blocks escape from the center. Furthermore, with the same construction technique, it is reasonable to expect that incidental edge vents increase in proportion to the length of all edges, whereas the volume of the sandwich is proportional to the roof areas. Thus, for a given shape, the volume of air to be released per foot of perimeter is doubled when the perimeter is doubled.

The pressure in a leaky sandwich depends on the rate of temperature rise as well as its magnitude. The rate of heating the air in the sandwich is increased by factors 2, 4, and 5 in the preceding list. A dark roof, of course, absorbs radiant heat rapidly. Low mass and low specific heat of the sandwich components increase the rate of temperature rise.

Thick insulation has mixed effects. Considering a 2 in. thickness of insulation, it is evident that the top inch heats first while the
FIG. 4. Typical pressures in wet insulation in spring weather.
bottom inch of cooler air cushions the pressure rise. Ultimately, when all is heated, more air will have been forced out of the available vents, but the time will be longer and the path through the insulation to the vent will be more open than would be the case with 1 in. of the same insulation.

Condensate location will be on top of the insulation when the roofing is consistently colder than the building interior. This water, heated by radiation from the sun, provides the maximum vapor pressure. Downward vapor movement, with condensation on the vapor barrier, is a means of heat transfer to speed the temperature rise at the bottom of the air space, provided the deck below the closed space has considerable insulating value.

Barometer drop is a minor factor for a nontight sandwich, since it is usually slow, but it could be an important factor if the sandwich were tightly sealed. The range of barometric pressure at one location may be as much as 2 in. of mercury, and if the roof happened to be sealed on a day when the barometer was very high, a subsequent drop could produce a lift up to 140 psf under the roofing, in addition to the effects of temperature. It is possible that prompt blistering of the roof membrane above nonporous insulation with minor crevices could be traced to this cause.

When the temperature rise in the roof sandwich is fast, the pressure change will approximate that in a sealed container. Figure 1, with a base condition of 40 F and atmospheric pressure, shows the pressure rise at constant volume for increasing temperature. Volume change at constant pressure, as shown in Fig. 2, indicates the volume of air to be vented or to form blisters. Between the three curves shown, interpolation for any relative humidity may be made. It should be noted that a temperature rise in the roof sandwich does not reduce the relative humidity as it could in an "empty" vessel. Water vapor is released into the heated air from the damp insulation, which has so much surface that the relative humidity is nearly constant even when there is no free water.

In general, damp insulation receiving heat from the sun is hotter on top and the vapor pressure is higher there, with consequent vapor transfer downward. But total pressure at any level is the same at a given time, as indicated in Fig. 4, which also suggests typical pressure conditions for wet insulation at the high and low points of the daily temperature cycle under a clear sky in the spring season.

Blisters develop at a time of high roofing temperature. Bitumen, especially the coal-tar pitch of low softening point favored for dead-level roofs, loses its strength rapidly above 130 F, at the time when pressure in the roof sandwich is high. A blister starts at a spot of weakness in the bond of roofing to insulation, or more often between plies of the roofing, especially within its bottom ply where water has weakened the felt structure. There is little more than the weight of the roofing and slag to hold it down when the bridge strength of the plies above it is lost at high temperature.
The blister will grow rapidly, swelling like a balloon, if the peak pressure of the cycle has not been reached. As the size increases, the pressure required to continue the growth may actually diminish, since the total lift increases with the area lifted and the anchorage at the rim of the blister is proportional to the length of that line. Thus, for a small circular blister containing a given pressure, the lift per inch at its rim doubles when its diameter is doubled. This vicious circle will continue until the anchorage greatly improves or the pressure drops. Better anchorage is found at the limits of the wet and split felt or the ply separation, and "dual anchorage" may occur where the compressed air penetrates one of the lifted plies and there are two bonds to be sheared simultaneously instead of one.

Pressure in the blister drops when the rate of temperature rise in the sandwich as a whole diminishes, or when the liquid water close under the roofing is all evaporated and transferred downward, bringing a sharp reduction of vapor pressure. In its later stages, the growth rate of a large blister between roofing plies is inhibited by the restriction to upward air flow offered by plies under it. Growth ends when the blister leaks air as a result of excessive flexing. If this leak is an inch or more above the drain level, raintightness may be maintained though airtightness is not. A leak at the base of a blister admits water, and this is apt to be the first warning of this strange dome on the roof.

On a smaller scale, the same mechanism of rapid pressure rise may produce a blister between plies of the roofing even when the roof insulation is well vented and has no vapor barrier. It must start with trapped air, with or without moisture. But as already noted, there is always some air and some moisture in saturated felts, and when the mopping is too cold or is not properly broomed, the trapped air is greatly increased. Since the bonding of plies is also poor in this case, the pressure rise under sun heating lifts the upper plies. If such a space is not vented, there is a slight lift during the day and a return at night, never attracting attention except that the roof feels spongy on a hot day. But a very small vent through the lower plies leads to growth. When the sun goes down, the crown stiffens, and as the pressure slowly drops, more air is drawn into the enlarged space. Rapid heating the next day continues the growth until another larger vent develops either above or below the air pocket.

Large blisters may collapse under a load of snow or rain, but smaller ones usually hold their shape. In the daily cycle of temperature, the blister cools rapidly as the sun goes down, and the dome develops structural strength as it cools. This facilitates growth in the next cycle, within the limitation noted. If both axes of a permanent blister exceed 3 ft, it is probable that internal curtains assist in its support when the pressure drops. Such a curtain is a strip of felt separated at the overlap and partly detached from the dome by its own weight when the dome is hot. Left in a more or less vertical position when the dome cools, the strip helps to support the weight of the dome.
Sometimes called ridges or mole runs, roofing wrinkles are different from typical blisters in appearance and genesis. Air pressure is not a necessary factor, though it may assist in their formation. They grow slowly and are rarely more than 2 in. high. Frequently they appear in straight parallel lines matching the unstaggered joints of insulation boards below the roofing. There may be other wrinkles at right angles, also above insulation joints, in a distinct "waffle" pattern.

An affected roof is likely to reveal some evidence of wrinkles over a large area, though the appearance is not uniform. Wrinkles may be narrow and low, often going unnoticed until erosion of the gravel top leaves them bald. Eventually, due to traffic or flexing, a crack develops somewhere in the wrinkle and rain leaks in. Inspection under an unbroken wrinkle is also likely to reveal water, which may be rain leakage or condensed vapor that has entered from below.

These wrinkles are the most serious problem that confronts the roofer today. They develop above insulation, and he blames that product. They are found where there is a vapor barrier as often or perhaps more often than where none is used, and the roofer is sure that the vapor barrier caused the failure. Perhaps, in a sense, the vapor barrier does contribute to wrinkle formation, in the same way that it does to blister formation. It permits pressure in the sandwich, and where the vapor barrier has a spot of air leakage, breathing provides extra vapor entrance. But pressure is not the basic cause of a wrinkle. Rather, it is water, assisted by elevated temperature.

Wrinkles are usually caused by water in the bottom ply of rag felt, which probably entered as vapor from below and condensed under the roofing. But the water may have been in the insulation when the roof was built, or it may be rain leakage. Water in the top ply would have the same effect, but the top ply is better protected by a heavy coat of bitumen. Asbestos fiber felts also swell when wet, but the expansion is smaller.

Water absorption in saturated felts was discussed in the first section, where it was noted that swelling across the strip is many times greater than swelling along the strip. It is usual to place insulation boards with their short joints staggered and their long joints in an unbroken line, and to lay the felts all parallel to these straight lines. Thus the felt axis that swells more is placed across the unstaggered joints, and this suggests one reason why wrinkles are more likely to develop over these joints.

Saturated felt, as it is furnished, is not protected from moisture entrance and swelling. It appears, moreover, that mopping is not a dependable protection unless the weight, temperature, and other specifications are fully met at every spot, including the insulation joints.

The mechanism of wrinkle formation seems to require water (condensation) in one or more plies of felt, which may be expected in cold
weather, then a period of quick heating that softens the bitumen and permits the wet felt to swell and expand the roofing membrane, also releasing its bond to the base. As a result, the roofing rises, and it takes the form of a straight ridge over the joint because that is the line of wetness and poor attachment to the insulation. This action is probably repeated to some extent every day in spring and early summer when moisture moves upward at night and the following day is warm.

Although the swelling of wet roofing felts is the principal reason for wrinkle formation, water in plant fiber insulation may also assist in several ways. Geddes and Perot (5) note that fiberboard insulation swells and shrinks with moisture content, irrespective of the method of manufacture. They emphasize the importance of dryness all the way from the factory to the final enclosure under roofing. Their problem was warping of a damp board lying in the sun, but the same basic effects of moisture change can be expected after the board is covered by roofing if its movement is not properly restrained.

Bonding the insulation to the roof deck by a strong adhesive or proper nailing minimizes but does not eliminate lateral movement if the boards are laid with excessive moisture, or even if they are dry and the joints are not tight. Construction methods tend to leave the long joint more open, and a partial filling of bitumen may not resist the pressure of the swelling boards.

But the most serious fault in the assembly results from stacking the boards outdoors on the job for an excessive period in wet weather. A tarpaulin is not a dependable cover, and it may even promote moisture gain if the stack is close to water-soaked ground. In such conditions moisture rapidly enters the edges of the boards through their paper wrapping. Inward diffusion is slow, and moisture probably does not reach the middle of the board through the 12 in. path to the center. But the edges may have a water content of 20% or more. A wet edge spoils the bond to the deck (or vapor barrier), to the roofing, and to the adjacent edge of another board, leaving the edge free to move and to contribute water to the felt above it. A waffle pattern of ridges may be expected.

Brotherson (6) has studied the development of roofing ridges on a small structure in the laboratory under accelerated conditions. He concludes that water in the roofing felts and high temperature (above 90 F) are the essential requirements for ridge formation. The water expands the felts, and high temperature softens the bitumen to make the roofing pliable. In his test, a ridge first appeared over an unmopped strip spanning the insulation joint. Ultimately ridges appeared everywhere, with some separation of the first and second plies. No vapor barrier was used. Noting the entrance of condensed moisture into the bottom ply, Brotherson recommends that a No. 43 coated base sheet be specified for the bottom ply of built-up roofing. This is good, but vapor entrance properly should be stopped below the insulation. Here again, if there is any measure of airtightness in the roof sandwich, some air and vapor pressure will assist the lifting action.
On some buildings there is no condensation problem, and no vapor barrier is used. These include dehumidified warehouses and factories where the product requires a dry atmosphere. Buildings of low occupancy or for storage of dry materials, if heated in winter, have no roof blisters or ridges. Instead, the roofing dries and shrinks if it was too damp when laid down. Insulation also must be dry at the start, since its shrinkage will pull the roofing.

Drying of these materials under the heat of the sun and low interior vapor pressure proceeds slowly but surely, with shrinkage stress developing in the roofing. Normally, it will crack at lines of greatest stress, at the joints of insulation. But an exceptionally strong multi-ply roofing has been known to slip on the insulation when summer heat weakens its anchorage, pulling several inches from all roof edges and opening bad leaks.

Just as a carpenter is careful to check the moisture in wood flooring, so should the roofer make sure that his materials are not too damp for the job. And the engineer must provide the proper specifications.

CONDENSATION CONTROL METHODS

Water vapor phenomena include a few basic principles which, although generally well known, may be noted here for convenience.

Condensation occurs on a surface colder than the dew point of vapor near it. Vapor diffuses through air and many solid materials from a region of high vapor pressure (or dew point) to a region of lower vapor pressure, made low by removal of vapor as condensate or as adsorbed moisture in hygroscopic materials like wood fibers. Water vapor is also transferred by air movement, a very important mechanism that brings vapor to a cold condensation area or removes it from a wet zone when the air supply has a low vapor content (or dew point). The capacity of air to "hold" and carry moisture, though small, increases rapidly with temperature. Table 2 shows a 150-fold rise in the range from 0 F to 150 F.

A "vapor barrier" is an obstruction to vapor diffusion, but it rarely blocks the vapor completely. The permeance of the barrier, or the permeance of any other obstruction, is measured in perms. A one-perm barrier allows 1 grain of moisture to pass through 1 sq ft of its substance in 1 hr when the vapor pressure difference at its surfaces is 1 in. of mercury. For example, 1 lb of water vapor will go through 100 sq ft of a one-perm barrier in one week when the barrier is the only vapor resistance between a room at 80 F with 50% relative humidity and a condensation area at 20 F.

A one-perm barrier is generally acceptable for conventional frame walls of a residence with an exterior finish through which vapor can readily escape to the weather or in which moisture can be stored without harm during the winter season. In typical roof construction, however, the built-up roofing has a permeance so low that it should be considered
as zero; the only place for moisture storage is in the insulation, and the storage charge is high.

Furthermore, in industrial buildings the atmosphere ranges widely -- from the conditions in unheated and dry storage warehouses, to 80°F and 85% relative humidity for cotton weaving. Obviously, the vapor barrier requirements vary correspondingly. If there is no period in the year when vapor transmission will be downward, with satisfactory drying of the insulation, it may be necessary to specify zero permeance for the vapor barrier.

Typical permeance values of some roof materials are listed in Table 3 to indicate their range. Design values, however, must consider a number of factors not essential to present here.

A vapor barrier in a flat roof is both blessing and bane. If it stops vapor, it also stops air and allows damaging pressure under the roofing. If it is not airtight, the roof sandwich breathes to and from the room below, and this action brings in water. What, then, can be done to control condensation? Some means that may be used are the following.

(a) Insulation that is impermeable to moisture or air, such as foamed glass, may be applied with complete filling of crevices between the insulation blocks so that the roof sandwich contains no air or moisture. Great care is required in sealing crevices, and a rigid deck is needed to keep them sealed. Irregularity of the deck surface and of the top insulation surface must be avoided. With proper specifications and care, a dependable job is possible.

(b) A hung ceiling that is insulated and has a ventilated loft above it assures dry insulation and no pressure under the roofing. A suitable vapor barrier under the insulation sharply reduces the ventilation requirement, and is essential where a high-humidity atmosphere is to be maintained. This system is dependable, but it involves a taller building, a heavier roof load, and added construction cost.

(c) A double roof, which in principle is the same as a hung ceiling, saves height and weight.

(d) Suitable venting of the roof sandwich will relieve pressure and prevent blisters which are the result of air pressure in the sandwich. With highly porous insulation, vents that will avoid pressure are readily arranged; but their natural breathing action has limited capacity to remove moisture, and a nearly perfect vapor barrier is required. With insulation of lower porosity, special air channels within the roof sandwich will minimize the necessary number of vents and permit a choice of their location. Channels also increase the moisture removal capacity of the breathing process, but the vapor barrier requirement over a high-humidity space is still stringent.

(e) Forced ventilation within the roof sandwich, preferably with channels, avoids damaging pressure and ensures moisture control. Proper
TABLE 2. Saturated Vapor Content of Air

<table>
<thead>
<tr>
<th>Temperature, ( \text{deg F} )</th>
<th>Saturated Vapor, ( \text{lb per 1000 cu ft} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.068</td>
</tr>
<tr>
<td>30</td>
<td>0.278</td>
</tr>
<tr>
<td>60</td>
<td>0.831</td>
</tr>
<tr>
<td>90</td>
<td>2.14</td>
</tr>
<tr>
<td>120</td>
<td>4.93</td>
</tr>
<tr>
<td>150</td>
<td>10.34</td>
</tr>
</tbody>
</table>

TABLE 3. Typical Permeance Values of Roof Materials

<table>
<thead>
<tr>
<th>Weight, ( \text{lb per 100 sq ft} )</th>
<th>Permeance*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Cup, perms</td>
</tr>
<tr>
<td><strong>Roofing and Barrier</strong></td>
<td></td>
</tr>
<tr>
<td>15 Asphalt- or tar-saturated rag felt**</td>
<td>1.5</td>
</tr>
<tr>
<td>15 Asphalt-saturated asbestos felt</td>
<td>1.0</td>
</tr>
<tr>
<td>55 Asphalt-saturated and coated roll roofing</td>
<td>0.03</td>
</tr>
<tr>
<td>230 Four-ply built-up roofing (estimated)</td>
<td>0.01</td>
</tr>
<tr>
<td>Polyethylene, 6 mil</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Insulation, 1 in. thick, without joints</strong></td>
<td></td>
</tr>
<tr>
<td>100 Glass fiberboard</td>
<td>90</td>
</tr>
<tr>
<td>140 Fiberboard (wood or cane)</td>
<td>20</td>
</tr>
<tr>
<td>60 Corkboard</td>
<td>2</td>
</tr>
<tr>
<td>16 Polyurethane foam</td>
<td>1.1</td>
</tr>
<tr>
<td>18 Polystyrene extruded foam</td>
<td>0.7</td>
</tr>
<tr>
<td>75 Glass foam</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Roof Deck, 1 in. thick, without joints</strong></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>0.6</td>
</tr>
<tr>
<td>Wood (evergreen trees)</td>
<td>0.4</td>
</tr>
<tr>
<td>Plywood (Douglas fir, exterior type)</td>
<td>0.2</td>
</tr>
<tr>
<td>Metal</td>
<td>0.00</td>
</tr>
</tbody>
</table>

* Composite values obtained from the references and from the writer's experience.

** Any felt made largely from plant fibers.
design will limit the cost of construction and operation. This is a promising method.

(f) Water drains from channels under the insulation are a means of removing condensate as liquid after it moves to the bottom of the sandwich in summer. This process is idle in winter, when the condensation occurs. Consequently, the vapor barrier must be adequate to limit the moisture entrance in one season to an acceptable quantity, and all parts of the roof sandwich must tolerate water well. Complete drainage would be difficult to achieve, but a metal deck of special design can be effective. Drainage is simplified under a roof that is not dead-level.

These are some of the possible ways to keep roof insulation dry and effective and the roofing undamaged by pressure and water. They require further research and imaginative development, for which there is an urgent need.

CURRENT ROOFING PRACTICE

A set of specifications covering all kinds of roof decks, slopes, insulations, vapor barriers, and roofing would be a voluminous document and outside the scope of this report, but a brief review of current practice is in order.

Under specified conditions, the tightness of roofing over any standard type of deck, with or without insulation, may be insured or "bonded" for as many as 25 years. Although the policy is limited to the hazard of rain entrance, it is likely to specify condensation control methods that are expected to guard the roofing from premature failure.

The typical "20-year bonded roof" has four plies of No. 15 felt (weighing 15 lb per 108 sq ft, covering a "square" or 100 sq ft as normally applied) with a "solid" or continuous mopping of bitumen under each ply and a heavier poured top coat in which gravel, slag, slate, or marble chips may be embedded. For tarred felts, coal-tar pitch is used for mopping and top coat. Asphalt, a petroleum product, is used for asphalt felt. On a dead-level roof, the pitch system was once used exclusively and is still preferred by many roofers. Pitch has a low softening point, around 135 F, and will seal itself where minor damage has occurred. "Dead-level asphalt" will do the same. A 25-year bond is sometimes available with one more ply, and a 15-year bond with one ply omitted. Also, there is a range of requirements among makers and in different locations.

For one square, the mopping under each ply of felt should be at least 30 lb of pitch or 25 lb of asphalt. The top coat requires 75 lb of pitch or 60 lb of asphalt, in which 400 lb of gravel or 300 lb of slag is embedded. Typical weights for these constructions are given in Table 4.

Slag and gravel are interchangeable when available or preferred. Either reduces damage from traffic and from surface cracking or "alligating" due to sun radiation, and the weight reduces wind hazard.
TABLE 4. Typical Weights for a Four-Ply Roof

<table>
<thead>
<tr>
<th>Pitch and Gravel</th>
<th>Weight, lb per 100 sq ft</th>
<th>Asphalt and Slag</th>
<th>Weight, lb per 100 sq ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 tarred felts</td>
<td>60</td>
<td>4 asphalt felts</td>
<td>60</td>
</tr>
<tr>
<td>4 moppings of pitch</td>
<td>120</td>
<td>4 moppings of asphalt</td>
<td>100</td>
</tr>
<tr>
<td>Pour coat, pitch</td>
<td>75</td>
<td>Pour coat, asphalt</td>
<td>60</td>
</tr>
<tr>
<td>Gravel</td>
<td>400</td>
<td>Slag</td>
<td>300</td>
</tr>
<tr>
<td>Design total</td>
<td>655</td>
<td></td>
<td>520</td>
</tr>
</tbody>
</table>

In addition, white marble chips will markedly reduce the roof temperature in summer.

When no insulation is required, the essential built-up membrane may be placed on one or more plies of dry felt nailed to a deck with crevices. In case of fire, this will prevent bitumen from dripping into rooms and increasing the damage by adding fuel. On a wood deck the bottom ply is often "red rosin sheathing paper" for maximum drip protection. All dry plies must be suitably nailed or fastened by other devices. On a deck assembled from precast concrete slabs that are not nailable, the crevices are calked and the mopping is held back at least 2 in. from all joints. The use of a dry ply is satisfactory where there is no condensation hazard.

Roofing applied over insulation is usually mopped down without dry plies. Some highly porous roof insulation is made with a coating or a securely attached sheet on its top side, on which hot bitumen can be mopped without penetration.

A vapor barrier under the insulation is often neglected in roof specifications. Its value continues to be controversial, for there are numerous examples of failure where a barrier has been applied. A presumed vapor barrier is one ply of No. 15 felt with a hot mopping of steep asphalt on both sides. Two plies, with the first ply dry on its lower side, give about the same effective vapor resistance, since the hot mopped bitumen, not the felt, is the essential vapor block. For more severe service, as in textile mills, some specifications require one or two plies of 55 lb roll roofing instead of No. 15 felt. If properly assembled in warm weather, one ply should have a vapor permeance in the 0.03 perm range. The deck construction determines whether the vapor barrier, like roofing, should be mopped over a nailed dry base sheet and whether pitch of low softening temperature may be used.

Some of these practices have been adopted to correct obvious faults, but they have introduced other faults, not so obvious. Revision will be in order when the nature of the problems presented in this report is recognized and testing has demonstrated the merit of new designs.
REFERENCES


