NBS TECHNICAL NOTE 965

U. S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Effects of Moisture in Built-Up Roofing — A State-of-the Art Literature Survey

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Technical Note

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EFFECTS OF MOISTURE IN BUILT-UP ROOFING -
A STATE-OF-THE-ART LITERATURE SURVEY

by

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ABSTRACT

A literature review of the effects of moisture on built-up roofing was made. Quantitative data were summarized for some properties of membrane roofing including: permeability, absorption, thermal expansion, thermal resistance, tensile strength, modulus, and fungus attack resistance. Example calculations of possible temperature and moisture gradients for two typical roof sections were presented.

Nondestructive evaluative methods to locate moisture in roofing systems were summarized and include gravimetric, nuclear, capacitance, infrared imagery, electrical resistance, and microwave methods. A review of techniques to dissipate moisture in roofing is presented.

Key Words: Built-up roofs; bituminous roof membranes; moisture; moisture dissipation; nondestructive detection of moisture; performance criteria; roofing moisture.

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1. INTRODUCTION

1.1 BACKGROUND

Bituminous built-up membrane roofing is widely used in building construction in the United States. The area of built-up roofing constructed each year in the United States would cover approximately 3 billion ft^2 (280×10^6 m^2) or 108 mi^2 (280 km^2). A conservative estimate of the total amount of the nation's low-slope roofing is 25 billion ft^2 (230×10^7 m^2) or approximately 900 mi^2 (2,300 km^2). While built-up roofing in general performs satisfactorily, premature failures cause unneeded complications and inordinate expenses for owners, roofing contractors, and material manufacturers. Roof contractors and roofing manufacturers indicate that a probable failure rate of 4-5 percent may be accurate; however, others quote higher figures [1].* Many of these problems are attributable to moisture in one or more components of the roof system.

Buildings are among the largest energy consumers in the United States. Household and commercial sectors use approximately one-third of the total annual energy consumption [2]. New buildings constructed in compliance with current specifications use increased amounts of insulation to conserve energy. Increased attention is being directed to roofing materials and systems which must be effective in the envelope of conservation. The roof constitutes one of the largest uninterrupted elements of a building, and therefore reduced heat flow through the roof offers a major opportunity to conserve energy expended on heating and cooling. Moisture penetration into roofing insulation and membranes is detrimental to conservation of energy and materials, since moisture in insulation may drastically reduce its thermal resistance. Moisture in built-up roofing wastes energy required to manufacture those materials degraded by moisture since they must be replaced prematurely.

During the past few years roofing contractors, trade associations, manufacturers, and government agencies have been concerned with identifying the effects of moisture on built-up roofing. As a result of these concerns, more information is now available on deleterious effects of moisture in built-up roofing. Of special concern is premature loss of serviceability and reduced thermal efficiency of the insulation through intrusion of moisture in liquid or vapor form. It has been estimated that a decrease of 0.1 in the "U-factor" in the nation's low-sloped roofs would save nearly 20,000,000 barrels (3×10^6 m^3) of crude oil [3], or approximately 116×10^{12} Btu (122×10^{15} J) annually.

Bituminous built-up roofing usually consists of four major components which include the structural deck, a vapor flow retarder, thermal insulation, and a bituminous built-up membrane. The built-up membrane normally consists of 2 to 5 plies of organic or inorganic felts bonded together by interply layers of asphalt or coal tar pitch. The top ply is generally covered with a thicker coating of bitumen in which uniformly graded aggregate particles are embedded to enable a thicker flood coat to be placed and to protect the flood coat from degradation by solar radiation. Asphalt is currently used in approximately

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* Numbers in brackets indicate references listed in Section 10 of this report.

95 percent of the low-slope built-up roofing constructed in the United States and coal tar pitch is used in the remaining 5 percent [4].

A major objective of the Center for Building Technology of the U.S. National Bureau of Standards (NBS) is establishment of performance criteria and evaluative procedures. Performance criteria are derived from quantitative measurements of material properties. Roofing materials and systems comprise one important subset for which performance criteria are being investigated. Although bituminous membrane roofs have been used for over 70 years, criteria for satisfactory performance of constituent materials and systems are generally unavailable. Development of performance criteria will enable manufacturers, designers, constructors and owners to have greater assurance that roofing materials which are appropriate for the service intended will be specified and used.

The construction of built-up roofing has emerged in recent years from empiricism and use of trial-and-error techniques to more reliance on technology involving engineered properties and predictable performance. It is likely that this trend will continue and that future specifications for roofing will be more performance-oriented than in the past.

1.2 OBJECTIVES OF THE REPORT

The principal objective of this report is to review that literature which describes performance of roofing materials and systems specifically as they are affected by moisture. Because quantitative guidelines for roofing materials and products are sparse, further improvement in roofing membrane performance is impeded. Current specifications for roofing membranes are of the prescriptive type. Under these specifications, the type and number of plies are specified together with the amount of interply bitumen. Quantitative data and performance criteria are seldom specified.

Because special emphasis is now being placed on roofing performance, including thermal performance, various methods for surveying roofs to detect hidden moisture are becoming more widespread. These methods to locate moisture nondestructively in built-up roofing are reviewed together with current technology for dissipating moisture that has accumulated in roofs. This review is a secondary objective of the report. Physical principles and instrumentation used, either in situ on the roof or remotely, to monitor moisture in roofing systems are summarized.

Finally, a method for estimating heat losses and possible moisture migration and condensation in built-up roofs is presented. Moisture-temperature environments of roofing for several typical roof structures are presented to illustrate the method.

Additional testing of bituminous built-up roofing will be required if more quantitative information on moisture-related properties is to be determined. This report is intended to serve as a baseline of information to guide the development of additional research needed to define more completely the performance attributes of bituminous built-up roofing with regard to the effects of moisture on performance.

1.3 SCOPE OF THE REPORT

This report is limited principally to a review of the effects of moisture on built-up roofing systems and materials. It does not include effects of wind, hail, fire or other factors that significantly influence roofing performance. A review of pertinent literature on effects of moisture on selected performance attributes is complemented with summaries of nondestructive test methods that have demonstrated or exhibited potential for detecting moisture in built-up roofs. A comprehensive list of references provides access to more complete information and original sources.

1.4 SOURCES OF INFORMATION

Information for this report was obtained from a variety of sources and includes technical and scientific reports, journals, tests, trade association's and manufacturer's publications and personal correspondence. The authors contacted other roofing researchers and materials specialists from the United States and foreign countries and used recent reports abstracted in computerized information files.

Reports from organizations conducting building research including the National Bureau of Standards, the National Research Council of Canada, the Lund Institute of Technology (Sweden), and others comprise a portion of this document. In addition, roofing consultants and representatives from roofing materials and accessories manufacturers provided reports and data which have been included herein. Most references cited were written in English; however, foreign language articles and translations were also used. The report represents a synthesis of qualitative and quantitative information as assessed by an NBS team consisting of two chemists, a materials engineer and a civil engineer. References are included in Section 10 of this report.

2. THE ROOF STRUCTURE

The principal purpose of a roof is to protect the enclosed space beneath it. Roofs must therefore be constructed to withstand anticipated wind pressures [5] and climatic conditions including a variety of moisture and thermal conditions. Since the energy crisis, special emphasis is now placed on roofing to insure that heating and cooling losses are minimized over wide variations in temperature experienced in the U. S. Cullen [6,7] measured effects of substrates, surface color, insulation and surface treatment on solar heating and radiative cooling of built-up roofing specimens. Garden [8] reported that extreme temperature variations between night and day in a black roof material over insulation can exceed 140°F (78°C) and the seasonal variation can be over 250°F (138°C). In low-rise industrial buildings and many schools and multi-family residences, the roof often constitutes the largest structural component in which insulation can be most effectively incorporated to reduce heating and cooling loads. The four major roof elements - structural deck, vapor flow retarder, thermal insulation, and built-up membrane - perform special functions. These elements and their functions (figure 1) are reviewed here.

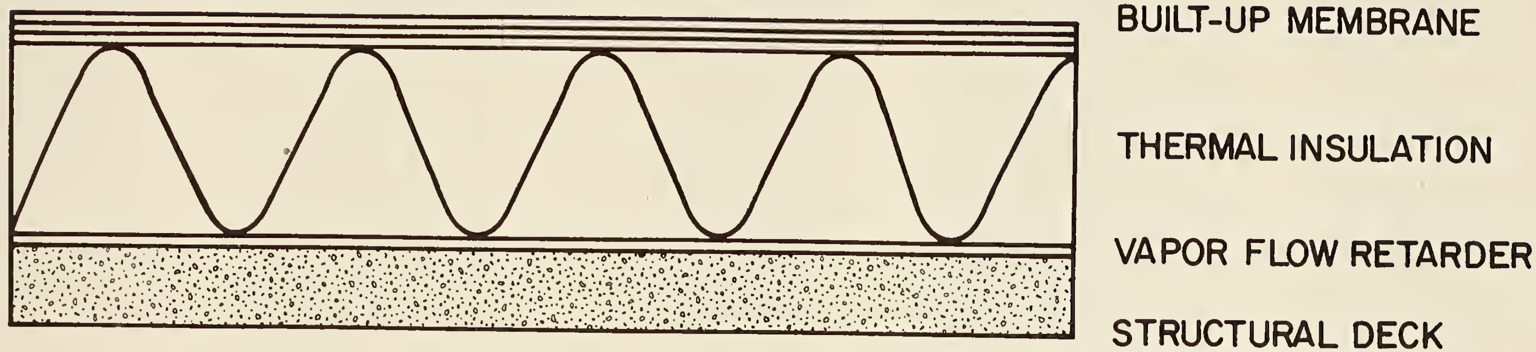

FIGURE 1. TYPICAL BUILT-UP ROOF SECTION

2.1 STRUCTURAL DECK

The structural deck supports its own weight as well as the insulation, the built-up membrane and roof-based mechanical equipment such as air conditioners and vents. Structural decks may be constructed of wood or plywood sheathing, preformed wood fiber, gypsum, precast or poured-in-place concrete, light gauge metal decking, or combinations of these and other materials. Metal decks are widely used in current practice.

Depending upon the material from which it is constructed, the deck may contain some water at the time of construction. Good roofing practice requires that this water be allowed to dissipate before application of the built-up membrane. It is recommended that decks be sloped at least 1/4 in per ft (20 mm per m) to drains to minimize chances for water to pond. The structural deck should not deflect excessively to induce ponding or low spots without drainage because standing water can lead to deterioration of the membrane. Well-drained roofs have, in general, longer service lives than those which pond water. For example, if ponded water can penetrate cracks, wrinkles, holes or other defects and then freeze, the expansive force of the freezing water can tear the membrane apart [9].

2.2 VAPOR FLOW RETARDER

Vapor flow retarders may be installed between the structural deck and the insulation especially over areas of high humidity, such as laundries and swimming pools, to reduce the amount of moisture penetration into the roofing system. Common vapor flow retarders have included plastic sheeting (such as polyvinyl chloride), hot-mopped felt-type moisture barriers, spray-on membranes and various composites.

2.3 THERMAL INSULATION

Thermal insulation is normally placed on top of the vapor barrier or directly on the structural deck to reduce heat losses through the roof. Less commonly, in some roofing systems insulation is placed on top of the membrane. Insulation materials for roofing may include: mineral aggregate board, vegetable-fiber board, glass-fiber board, foamed glass, polyurethane foam, corkboard, lightweight concrete, extruded and molded polystyrene, perlite concrete, cellular concrete, perlite-asphalt mixtures, perlite-mineral wool mixtures, and composites of foam plastic and mineral insulation.

2.4 BUILT-UP BITUMINOUS MEMBRANE

The built-up bituminous membrane is a composite material constructed of a number of felt plies bonded together with asphalt or coal tar pitch (often referred to as tar). The felt is generally an asphalt or tar-impregnated organic, asbestos or glass fiber material. The principal purpose of the membrane is to waterproof the building and to protect the insulation and structural deck from damage by sunlight and moisture. The felt provides reinforcement and strength in the composite membrane while the bitumen provides waterproofing. Mineral aggregate is usually embedded in a layer of bitumen on the top surface of the built-up membrane. The aggregate layer enables placement of a greater thickness of bitumen (flood coat), reflects solar radiation, increases resistance to fire and wind uplift, protects the bitumen and fabric from photo-oxidation, and protects the roof surface from light foot traffic. The aggregate often hides defects and, in general, must be removed to make repairs. Tibbetts and Baker [10] reported that a thin layer of small size aggregate will not give as good protection as a heavy layer of larger, uniformly graded material.

3. MOISTURE-INDUCED DAMAGE

Throughout its service-life, the roof system and its constituent materials are susceptible to moisture-induced damage and other problems [11-13]. Baker [11] noted that most roofers would probably agree that water in the wrong places has been responsible for most, if not all, of their roofing problems. Giles [14] categorized roofing failures in 251 buildings. Quantitative measurements of moisture-induced dimensional, chemical and mechanical changes in roof components as found in the literature are cited in Section 5.

Moisture can enter a roof by several mechanisms and cause damage. Damage may be immediate, such as through leakage of water into the building, or it may be slow to appear by vapor transmission but insidious in its effects. Regardless of its rate of appearance, moisture-induced damage provides significant motivation for increased understanding and research into the effects of moisture on roofing materials and systems. Repair of roofing failures and damage caused to the buildings because of failures attributed to moisture are expensive.

General effects of water on materials used in roofing include dimensional change, corrosion, leaching and efflorescence, biological deterioration and blistering, among others [11]. A major problem resulting from moisture in roofing systems other than general deterioration or rupture of the membrane is the loss of thermal resistance in some types of insulation.

3.1 MOISTURE INTRUSION DURING CONSTRUCTION

Moisture can enter roofing systems prior to construction, during construction or after construction. All materials may have some specific initial moisture content which can change by either direct moisture addition or hygroscopic action. This is particularly true for concrete decks and for insulating concrete [15-18].

Excessive moisture present in wood decks prior to construction may be damaging to the built-up roofing system. It has been reported [19] that under extreme moisture variation anticipated in service, the expansion of plywood would be roughly equivalent to the expansion of steel for a 150°F (83°C) temperature rise. Hutcheon and Jenkins [20] indicated that shrinkage of wood along the grain, upon drying from a fiber saturation level of about 30 percent to oven dry, may be 0.1 percent, while across the grain it can be of the order of 5 percent. The magnitude of these dimensional changes can be damaging if the insulation and the built-up roofing membrane cannot accommodate them.

Application of roofing over a concrete deck can trap moisture under the membrane. It has been reported that it usually takes approximately 90 days before the free water in freshly cast concrete is dissipated [21]. Other reports give longer times depending on conditions [17]. Lund [17] showed that the rate of drying of perlite concrete was considerably slowed by application of built-up roofing. He reported slow drying up to 285 days.

Moisture contents of roofing materials are generally monitored during manufacture. However, moisture is frequently absorbed while materials are in storage awaiting use in construction. Therefore, roofing materials should be protected during storage and transportation from exposure to precipitation, dew, and the absorption of water.

Unprotected insulation boards and roofing felts should never be stacked outdoors or exposed to the weather. However, even protecting these materials with tarpaulins or other protective coverings may not prevent moisture absorption concentrated in the edges. Built-up roofing applied to such insulation boards will not bond at the wet edges. These wet edges also supply water to the felt above. For roofing constructed in this manner, wrinkling of the membrane at the joints of the insulation boards is almost inevitable.

Baker [22] reported that water trapped under or between the felts during construction or excessive amounts of condensation on the bottom of the felts following construction may cause blistering and ridging defects that rapidly deteriorate the roofing long before it degrades as a result of normal weathering. It is not yet known what quantities of moisture are undesirable for various roofing systems, but it is well established that organic felts can absorb moisture with consequent dimensional changes and deterioration [13]. Therefore, felts should not be applied if they are wet nor should they be applied over substrates still wet from dew, rain or other causes.

3.2 MOISTURE INTRUSION DURING SERVICE

Moisture can enter a roof system through leaks in the built-up membrane. Rain or melting ice and snow are common sources of water that can nourish roof leaks. Water from roof-based mechanical equipment can also cause problems after the roof is in service. Sometimes, detection of the location of the leak is impeded by a circuitous leakage path.

Other mechanisms for moisture intrusion into roofing systems have been identified. Researchers [6, 22] have observed that roof surface temperatures can be markedly different from ambient temperatures and, because of these temperature differences, moist air entrapped in the system can be cooled below the dew point temperature with resultant condensation of moisture, and potential for damage.

Moisture and its migration in built-up roof systems can be augmented through condensation within the system, from high inside relative humidity, and permeable interior construction. It has been reported that moisture gradients vary widely in roofing insulation over a constant temperature enclosure [22]. Different insulations absorb or are able to contain different amounts of moisture. In cold weather, the moisture content of the insulation is relatively high near the underside of the built-up roof. In warm weather, the upper portion of insulation may have a higher moisture content, especially in humid climates.

Lund and Granum [12] noted that moisture vapor transmission rates of bituminous roofing membranes are such that they do not normally transmit much moisture. However, others [23] reported that even small quantities of moisture, regardless of how it is transmitted, can damage the membrane. It has been reported that saturation of cellulosic felts with asphalt does not substantially affect the equilibrium moisture content which will ultimately be attained by that felt, but only affects the time required to reach that value [23].

Water vapor can be generated by many industrial processes. Examples of domestic sources of water vapor are noted in table 1 [24]. Given the right conditions, moisture from these sources may contribute to that already present in roofing components.

Table 1. Domestic Sources of Water Vapor [24]

Source	Pounds (Kg) of Water
Showers	0.5 (0.2) for each shower
Baths	0.2 (0.1) for each bath
Floor washing or mopping	3.0 (1.4) per 100 ft^2 (0.15 kg/m^2), each washing
Kettles and cooking	5.7 (2.6) per day
Clothes (washing, steam ironing, drying)	30.7 (13.9) per week

Hutcheon [25, 26] reported that the average family of four (in Canada) will produce, by its normal household activities, about 0.72 lb (0.32 kg) of water vapor per hour, but that this could rise to as much as 2 lb (0.9 kg) per hour on wash days. Wolfert [27] indicated that each member of a family contributed from 1-1/2 to 2 lb (0.7-0.9 kg) of water each day. McInnes and Masters [28] reported estimates indicating that up to 11 lb (5 kg) of water vapor are given out by a pair of lungs every 24 hours. These quantities of water vapor may contribute to the overall moisture content in the roofing system.

Mechanical humidification also generates moisture and can create vapor pressure gradients between the inside and outside [9]. The generally recommended use and effectiveness of vapor flow retarders to keep moisture vapor from built-up roofs is not consistent and is, in some cases, contradictory. According to Schreiber [30], a vapor retarder should be used only on insulated structures that have a maintained occupancy condition of 30 percent relative humidity, or higher. Leakage of moist air is often responsible for more serious condensation problems than water vapor diffusion, according to some reports [29, 31].

Moist air can leak through small holes in vapor retarders thereby reducing their effectiveness. In flat wood-frame house roofs with insulation applied between joists, damage to the roofs was attributed to moist air leakage through the ceiling [31]. Ventilation of moist air is important in preventing this damage. Hansen [32] recommended that efficient ventilation be provided above insulation installed in wood-framed flat roofs.

Tamura et al. [33] recognized that electric heating has become more prevalent and eliminates the need for chimneys and tends to decrease the natural exhaust of air from such houses. This gives rise to higher, potentially damaging, humidities in the living space. Based on a leakage opening of 0.02 percent of the total ceiling area and measured air pressure differences caused by stack effect, with inside conditions of 30 percent relative humidity and a temperature of 68°F (20°C) and an outside temperature of 0°F (-18°C), there is a potential for transfer of 15 lb (6.8 kg) per day of water into a 597 ft^2 (55.5 m^2) roof area [33]. Moist air leakage may also contribute to icicle formation, roof leaks, and spalling of mortar joints [34].

Poor roofing design resulting in inadequate drainage, as previously mentioned, can lead to accelerated deterioration of the roofing membrane by ponding water. Areas of ponded water may be wetted repeatedly during the service life of a roof and stresses attendant upon wetting and drying and differential thermal stresses may be consequently damaging. Shrinkage stresses, which occur when wetted membranes dry, when added to thermal stresses may contribute to roof membrane splitting.

Ponded water can promote plant growth. With time, plant roots can penetrate the roof membrane and cause the roof to leak. Growth of fungi and algae in moist areas of the roof can also be damaging according to Shuman [35].

Changes in the interior moisture content of a building during and after construction can be sources of distress. For example, salamander placement, different occupancy designs, and moisture exposure induced by plenum systems are possible causes of localized distress in membrane roofing [35].

Reports on the effects of moisture and subsequent deterioration in built-up roofing are numerous [21, 35-42]. Moisture which can get into the roofing system by any of the mechanisms cited previously can cause damage. Three potentially serious problem areas include: membrane wrinkling and ridging, membrane blistering, and excessive heat loss through wet insulation. Factors such as loss of strength, induced stresses attributable to wetting and drying, and other moisture-dependent attributes are discussed later in this report.

3.3 MEMBRANE WRINKLING AND RIDGING

Formation of wrinkles and ridges in membrane roofing is caused by moisture and has been described in the literature [21]. Moisture absorption causes elongation of felt strips, drying causes shrinkage [35].

Brotherson [38] concluded in a study that "wrinkle-cracking" failure is most probably caused by absorption of water and water vapor into the saturated felts used in the lamination of built-up roofs. He also concluded that moisture may enter the system from breaks in the surface of the membrane, due to mechanical damage, but is more likely to enter from below because of excessive humidities, either from the type of occupancy of the building or possibly from excessive moisture encountered during construction of the building. Fibrous, organic insulation are especially vulnerable to swelling and subsequent wrinkling of the membrane [35]. Griffin [21] noted that some insulations made of cellulosic fibers swell with moisture absorption and contract with drying as much as 0.5 percent with changes in relative humidity from 50 to 90 percent. These dimensional changes of the insulation lead to wrinkling of the membrane.

Membrane wrinkling usually appears as somewhat regularly spaced ridges that form over longitudinal and transverse insulation joints. As noted earlier, moisture in the membranes or in the insulation can concentrate near the joints. As the membrane is wetted, it expands, forming a ridge over the joint. Continued supply of moisture to the wrinkling site causes the wrinkle to enlarge as the membrane is heated [38]. When cooling occurs, the membrane and interply asphalt stiffen at low temperatures. Consequently, even during the evening or in winter, the membrane does not contract to its original length.

Ridges in roofing membranes have been formed [35] by causing persistent moisture migration into or out of the roofing by means of temperature gradients of less than 10°F (6°C). Where plastic flow in the bitumen layer between the membrane and insulation can occur, the ridge or buckle could flatten [43]. However, field experience corroborated by laboratory studies has indicated that when ridges were formed in roofing membranes from moisture-induced swelling, it was not likely that there would be sufficient natural drying for the ridges to recede appreciably [35].

Long [44] also demonstrated that the linear dimensions of built-up roofing membranes change with changes in humidity and temperatures. Felt type, felt direction and previous history influenced the changes in dimensions. In some cases, humidity changes caused greater dimensional change in the membrane than did variation in temperature.

A principal problem at wrinkles and ridges is loss of protective bitumen and cover aggregate which exposes the felts at the steep slopes. During hot summer days, the sun heats the asphalt to a semi-fluid state and eventually the bitumen flows away from the emerging ridge. This further exposes the top felt of the membrane to the destructive influence of sunlight and moisture. Repairing wrinkles and ridges is time-consuming and expensive and may only provide temporary protection until the roof is replaced [30].

One effect of the formation of ridges on a built-up membrane may be retarded drainage of surface water from the roof. On level roofs, continuous long wrinkles form ridges which can cause local ponding to compound the problem. Typical membrane wrinkling is shown in figure 2.

3.4 MEMBRANE BLISTERING

Blisters (figure 3) are voids in the membrane formed when water vapor trapped between the plies expands under the high temperatures that occur during service. Upon heating, water vapor contained in skips or voids between plies can exert pressures of several hundred pounds per square foot if confined within a constant volume, in accordance with the ideal gas law (pressure x volume = constant x absolute temperature). High interply vapor pressures create a potential for stress concentrations and resultant expansion of the blister.

Baker [11] indicated that water is not required to cause blistering although it is usually present and is frequently responsible for the lack of adhesion which is often the condition that allows a blister to start. Beijers [45] observed the same phenomenon when studying blister formation in bituminous pavements constructed over some concrete bridge decks. Mirra [46] reported that blistering of roofing over urethane insulation was caused by relatively large differences in thermal expansion of urethane and the built-up membrane.

Blisters may vary in size from relatively small, flat and unnoticeable, to very large. For example, blisters up to 40 ft (12.2 m) or more in diameter and several inches (cm) high have been observed [36]. Warden [47] proposed a theory of the mechanism of blistering. Blisters are formed when high temperatures increase vapor pressures at moist sites in the roof. The incipient blister may gain air and moisture at night. During hot days, the blister may expand, and during cold evenings, the blister will tend to contract. Continued cycling can enlarge the blister and lead to cracking and leakage. The presence of water or ice on a ponded roof or in a blister may also increase the size of the blister and increase the tendency of the membrane to split at low temperatures. Craig [48] noted water vapor pressures that could develop at specified roof temperatures under constant volume (table 2).

Table 2. Water Vapor Pressures Developed Under Constant Volume Conditions [48].

Water vapor pressure developed, lb/ft^2 (kPa)		Roof temperature, °F (°C)	
50	(2.4)	78	(26)
142	(6.8)	100	(38)
290	(13.9)	130	(54)
542	(25.9)	150	(66)
825	(39.5)	170	(77)

Figure 2. Membrane Wrinkling and Ridging (note water marks).

Figure 3. Blistering in Built-Up Membrane Roofing

Baker [11] indicated that when there is a temperature difference across a roof section, moisture originally distributed uniformly in the system tends to migrate to the cold side under the action of an imposed steady-state temperature gradient. This source of moisture can also nourish blisters. Construction practices can also leave a roof vulnerable to damage by blistering. According to Joy [36], strip mopping of bitumen under the first ply of saturated felt should never be used when condensation is possible. Complete coverage of the deck with bitumen is necessary. Joy [36] listed several factors that generally tend to increase the vapor pressure in a composite membrane of felts and bitumen, thereby increasing the tendency to blister. These factors include:

1. Large roof size with vents only at the perimeter.

2. Bright sun that appears, without wind, after several cold sunless days (this is typical of spring weather).

3. Liquid water (condensate) directly under the roofing, also probably in spring weather.

4. Dark thin roofing.

5. Thin insulation of low density and low specific heat on a wood or an insulating deck.

6. Rapidly declining barometric pressure.

3.5 HEAT LOSS THROUGH WET INSULATION

Moisture intrusion into roof insulation and concomitant excessive heat loss may be perceived as a failure of the roofing system. For example, an industrial or warehouse building, 100 x 150 ft, 10 ft high (30 x 46 m, 3 m high) has approximately 5,000 ft^2 (460 m^2) of wall area while the roof has an area of 15,000 ft^2 (1,400 m^2). For a building of these dimensions, the roof is the largest surface through which heat may be lost and the proper insulation of the roof offers an effective means of minimizing heating and cooling loads.

Wet insulation conducts more heat to the outside during winter and to the inside during the summer than dry insulation. Powell and Robinson [15, 49] measured the loss of efficiency of insulation after it had become wet. Their study showed that thermal resistance of wet insulation can be as low as 38 percent of the dry value. The owner of a building with wet roof insulation, often unknowingly, incurs an additional cost that can be significant. Wherever water replaces air, insulating values drop significantly because the thermal conductivity of water is approximately twenty times that of air and the thermal conductivity of ice is eighty times that of air. Keeping insulation dry helps insure a longer service life, better performance, lower operating costs, and a more economical building. The continuing development of insulating materials has raised problems other than thermal resistance and include water absorption, drying rates, water vapor transmission, dimensional stability, treatment of joints, and choice of thickness [30, 50-55].

Hedlin [56] reported on the severity of moisture attack on polystyrene, polyurethane, wood fiber, glass fiber and perlite fiber insulations used in protected membrane roofing. Protecting the insulations by sealing bottom and edge surfaces (by coated base sheet adhered with hot asphalt) and providing for moisture escape by evaporation and drainage was found to be effective in keeping moisture contents of some insulations at low levels. It was found that moisture gains varied widely depending on the type of insulation. Open pore insulations reached higher moisture contents than the closed cell types. Hedlin [56] found that, for wood fiber insulation, the average moisture content for all unsealed pieces was 30 percent by volume, whereas for sealed ones it was 1.7 percent.

Results of other tests evaluating moisture content and insulating properties of cast insulating concrete roof decks showed that substantial residual moisture remained in the wet cast decks for an extended period of time after construction [56]. During this period when residual moisture is present, heat gain or loss calculations based on dry state design data are in error due to the higher thermal conductivity of the wet cast deck.

4. PERFORMANCE CRITERIA

Roofs are subjected to a wide range of conditions. Major independent variables that influence the serviceability of roofing systems include time, temperature, moisture, wind and sunlight. Because moisture is so pervasive and has been identified as deleterious to roofing in many technical papers and in a special survey [57] conducted by the National Roofing Contractors Association, its reported effects on roofing have been selected as the special subject of this report. Section 5 summarizes reports of measured influences of moisture on selected performance attributes.

Mathey and Cullen identified 20 performance attributes for bituminous membrane roofing [58]. Their work followed laboratory testing and extensive field observations. Other research [59] had previously indicated that values of breaking load, elongation and thermal expansion for field-prepared specimens compared favorably with laboratory-prepared specimens. Koike [60] used a theoretical analysis to investigate the susceptibility of bituminous felt roof coverings to rupture when placed over cracks in substructure materials. Realistic criteria criteria for tensile strengths of roof membranes are necessary if these and similar investigations are to be meaningful.

Each performance statement proposed by Mathey and Cullen consists of a requirement which is qualitative and describes what the membrane is to accomplish. This is followed by a criterion or criteria which express quantitatively the acceptable levels for adequate performance. An evaluative technique or test method by which compliance with the stated criteria can be tested is then referenced or described.

The attributes which were identified as having potential impact on the total performance of the roofing system under in-service conditions include [58]:

1. Tensile Strength
2. Thermal Expansion

3. Flexural Strength
4. Tensile Fatigue Strength
5. Flexure Fatigue Strength
6. Shear Strength
7. Impact Resistance
8. Notch Tensile Strength
9. Moisture Effects on Strength
10. Creep
11. Ply Adhesion
12. Adhesion Resistance
13. Tear Resistance
14. Pliability
15. Permeability
16. Moisture Expansion
17. Weather Resistance
18. Wind Uplift Resistance
19. Fire Resistance
20. Fungus Attack Resistance

The concept of performance criteria and attributes in roofing is relatively recent and few citations regarding criteria are available in the published literature. Sandberg investigated performance criteria for roofs in Sweden [61]. Davis and Krenick [62] used the performance concept to describe a new cold-process roofing system. In a literature review, Sandberg listed 376 references that pertained to roofing [63]. Only two of these were categorized as germane to performance criteria [64, 65]. Table 3 indicates how the articles and reports from Sandberg's literature review were divided among six categories; some citations were germane to more than one category. Sandberg's categorization of roofing literature [63] provides additional evidence that moisture is considered by roofing technologists and others to be important to roofing performance. Because performance criteria for roofing attributes are currently being proposed and investigated, the factors affecting roofing performance identified in the literature and summarized in the next section of this report are grouped by attributes.

Table 3. Categorization of Roofing Systems Literature According to Sandberg [63]

	Category/Subject	No. of References
1.	Roofing and roofs in general	93
2.	Structural mechanics and design of roofs	26
3.	Heat, moisture, and ventilation	91
4.	Laying technique, workmanship	35
5.	Roofing materials, characteristics	123
6.	Roof failures causes	66
		434

Fewer attributes than the 20 identified in reference [58] are used in this report. This consolidation and its relationship to the attributes identified in NBS Building Science Series 55 [58] are shown in table 4. The consolidation was largely a matter of convenience and reflects the current lack of data on attributes such as notch tensile strength, pliability, and others.

Table 4. Listing of Roofing Attributes Reviewed

Attribute, this report	Corresponding attribute, BSS 55 [58]
Permeability and Permeance	Permeability
Absorption and Moisture-Induced Deformation	Weather Resistance
Temperature and Moisture-Induced Deformation	Moisture Expansion Thermal Expansion
Thermal Resistance	- - -
Strength Including Fatigue and Modulus	Tensile Strength Flexural Strength Tensile Fatigue Strength Flexure Fatigue Strength Shear Strength Impact Resistance Notch Tensile Strength Moisture Effects on Strength Creep Ply Adhesion Abrasion Resistance Tear Resistance Pliability Wind Uplift Resistance
Fungus Attack Resistance	Fungus Attack Resistance
- - -	Fire Resistance

5. EFFECT OF MOISTURE ON SELECTED PERFORMANCE ATTRIBUTES

While roof failures attributable to unwanted moisture in the system have been identified and described qualitatively by many authors, quantitative information regarding moisture-dependent properties and distress is not readily available. No single reference serves as a compendium of information on moisture-related performance of roofing products and systems. Nevertheless, roofing technologists and others have reported on the performance of roofing materials and systems and their reports comprise the basic commentary, if not quantitative data, cited here regarding effects of moisture on selected performance attributes of roofing. Effects of moisture on the following attributes are summarized in this section:

5.1 Permeability and permeance

5.2 Absorption and moisture-induced deformation

5.3 Temperature and moisture-induced deformation

5.4 Thermal resistance

5.5 Strength including fatigue and modulus

5.6 Fungus attack resistance

5.1 PERMEABILITY AND PERMEANCE

Ponded water and wind-driven rain are environmental conditions which may be detrimental to roofing membranes and insulation. Examples of these severe exposures to moisture and maintenance measures are documented in the literature [11, 21, 66]. Fortunately, the permeability of a properly constructed built-up roofing membrane is usually low enough to protect the insulation and the felts from moisture.

Bituminous materials, i.e. asphalts and coal tar pitches, used to coat roofing felts and fabrics are excellent waterproofing agents when applied in a continuous film of the proper thickness. Bituminous film thickness is influenced at the construction site by many factors including temperature of the substrate, application temperature, wind, viscosity, rate of change of viscosity, and workmanship. The current trend is to relate film thickness to the viscosity of the bitumen at the time of application [67]. Where the film of asphalt or coal tar pitch is of adequate thickness and is continuous, moisture will not enter the system. Adequate thickness of interply asphalt refers to an application rate of 15-20 lbs per 100 ft^2 (0.7-1.0 kg/m^2) as recommended by Rossiter and Mathey [4] and others [67].

The permeability of a membrane is quantified by the amount of water vapor which it transmits under standardized test conditions. The permeability of roofing materials, μ, is normally obtained by the "wet cup" and "dry cup" methods described in ASTM standard methods of test E 96 and C 355. Other principles and methods for measuring water vapor transmission are also documented in the literature [68]. Joy and Wilson [69] described the standardization of the dish or cup method which is widely used for measuring permeabilities of roofing materials. They reported significant differences in measured permeances for wet cup and dry cup methods at 50 percent relative humidities.

The mechanism of water vapor transmission through coatings and membranes is usually described by Fick's law:

$$W = \frac{\alpha \cdot \mu \cdot A \cdot T \cdot \Delta P}{t}$$

W = wt of moisture transmitted, lb (kg)

α = constant of proportionality

μ = permeability of coating, perm in (kg/Pa·s·m) at specified temperature

A = area through which moisture is transmitted, ft^2 (m^2)

T = time of transmission, days (seconds)

ΔP = difference in vapor pressure of moisture across coating, inches of mercury (Pa)

t = thickness of coating, inches (m)

Tator and Alexander [23] showed the effect of moisture transmission into, and absorption by, the components of an otherwise dry system using dry cup water vapor transmission measurements. They concluded that the ply adhesive and surface coating were the controlling components in the ultimate or near steady-state rate of moisture vapor pickup in the moisture vapor transmission test of a built-up roofing membrane. Typical permeance values of some roof materials have been reported by Joy [36] and are listed in table 5.

According to Tator and Alexander [23], cellulosic fibers commonly used in many roofing felts are more hygroscopic than those of asbestos and glass; however, if correctly installed, membranes composed of cellulosic felts have very low water permeabilities. For membranes installed incorrectly, penetration of small quantities of water vapor can result in condensation, differential movement of membrane components, and rot of other system components [22].

Jones and Garden indicated that to prevent moisture problems in a roofing membrane it is necessary to provide a continuous film of bitumen on both surfaces of felts in the membrane [70,71]. Masters et al. [72], noted that moisture may lead to degradation of building materials as a result of hydrolysis.

Table 5. Typical Permeance Values of Roof Materials [36]

Material Mass $lb/100 ft^2$ (kg/m^2)	Roofing and Barrier	Permeance: Dry cup perms* ($ng/P \cdot s \cdot m^2$)	Permeance: Wet cup perms*
15 (0.7)	Asphalt or tar-saturated organic felt	1.50 (86.0)	8.00 (459.0)
15 (0.7)	Asphalt-saturated asbestos felt	1.00 (57.0)	3.00 (172.0)
55 (2.7)	Asphalt-saturated and coated roll roofing	0.03 (1.7)	0.06 (3.4)
230 (11.2)	Four-ply built-up roofing (estimated)	0.01 (0.6)	0.02 (1.1)
	Polyethylene, 6 mil (0.15 mm)	0.05 (2.9)	0.04 (2.3)
	Insulation, 1 in (25 mm) thick, without joints		
100 (4.9)	Glass fiberboard	90 (5164)	100 (5730)
140 (6.8)	Fiberboard (wood or cane)	20 (1148)	30 (1721)
60 (2.9)	Corkboard	2 (115)	9 (517)
16 (0.78)	Polyurethane foam	1.1 (63)	1.1 (63)
18 (0.88)	Polystyrene extruded foam	0.7 (40)	0.7 (40)
73 (3.6)	Glass foam	0.0 (0.0)	0.0 (0.0)
	Roof Decks, 1 in (25 mm) thick, without joints		
	Concrete	0.6 (34)	3.0 (172)
	Wood (evergreen)	0.4 (23)	3.0 (172)
	Plywood (Douglas fir, exterior type)	0.2 (11)	0.6 (34)
	Metal	0.0 (0.0)	0.0 (0.0)

* Perm units in the British system are ($grain/ft^2 \cdot h \cdot in\ Hg$).

Water vapor will pass through many common building materials [73]. Factors such as temperature, humidity, felt type, bitumen type, age and exposure conditions of system, degree of moisture equilibrium and previous history, type of insulation, type of deck, and condition of vapor barrier, could also influence permeability of the roofing system [44].

Bituminous waterproof coatings usually have low water vapor permeance, normally not exceeding 0.5 perms. Powell and Robinson [49] measured water vapor permeability and water vapor permeance for 27 roofing specimens consisting of various combinations of insulation placed on materials normally used in structural decks. According to Powell, moisture in excess of the hygroscopic capacity of an insulation can impair significantly the insulating effect of a permeable roof insulation.

Researchers have cited damage caused by water vapor admitted by permeance of roofing materials. Cullen and Rossiter [55] cited reports that water vapor transmission is possible through polyurethane foams and that water vapor penetration into the foam can have an adverse effect on the strength, dimensional stability, and insulation value of the foam.

Stafford [74] corroborated the deleterious effect of high humidity on bituminous roofing material in water vapor transmission tests conducted in accordance with ASTM Specification E 96-72, Procedure B. A high relative humidity differential was held across the sample. The permeance was determined by measuring the amount of water vapor that passed through a sample when the conditions of 100 percent RH at 73°F (23°C) on one side and 50 percent RH at 73°F (23°C) on the other side were maintained. The materials tested by Stafford included seven experimental roofing membranes, two of which had permeance values of 0.014 and 0.031 perms (0.8 and 1.8 $ng/Pa \cdot s \cdot m^2$) while the remainder were considered impermeable (table 6). Blister craters were observed on the side which was exposed to the higher relative humidity

Warden [47] and Lund [12] hypothesized that moisture can be the cause of blistering in roofing materials of low permeability. Vapor pressures build up with increasing temperature within impermeable membranes and create blisters at points of weakness where adhesion between plies has been lost. Moisture is not readily released due to the resistance to moisture migration of intervening plies of felt and bitumen. In effect, low permeabilities of roofing plies decrease the potential for drying of trapped interply moisture.

Water vapor entrapped in an enclosed volume in the roof structure can result in large blisters given the right conditions of temperature and moisture. If moist air does not leak from a blister, the pressure within the blister will increase. According to Koike's calculations [75], a blister in an impermeable roofing membrane over a moist concrete roof slab would tend to increase 32 percent in volume if the temperature rises from 86°F (30°C) to 140°F (34°C) in five hours.

Hedlin [76] reported on moisture gains attained in less than two months by foam plastic roof insulations under controlled temperature gradients. The moisture content of polyurethane increased the most, followed by beaded polystyrene and extruded polystyrene [76]. The rate of moisture entry into these insulations increased with the applied vapor pressure gradient.

Table 6. Permeance of Typical Roofing Materials [74]

Description of Roofing Materials	Permeance Wet cup perms*($ng/Pa\cdot s\cdot m^2$).
Two-ply, type 15 perforated asphalt felt mopped with 140°F (60°C) softening point asphalt, 3 moppings of 20 lb (9 kg) per 100 ft^2 (9 m^2)	Nil
Two-ply, type 15 tarred felt, mopped with pitch, 3 moppings of 25 lb (11 kg) per 100 ft^2 (9 m^2)	Nil
One-ply, jute-reinforced kraft paper, mopped both sides with asphalt, 2 moppings of 20 lb (9 kg) each per 100 ft^2 (9 m^2)	0.014 (0.08)
One-ply, 33 lb (15 kg) base sheet, mopped both sides with asphalt, 2 moppings of 20 lb (9 kg) each per 100 ft^2 (9 m^2)	Nil
One-ply, 45 lb (20 kg) base sheet without surface mopping	0.031 (0.18)
One-ply, 45 lb (20 kg) base sheet mopped both sides with asphalt, 2 moppings of 20 lb (9 kg) each per 100 ft^2 (9 m^2)	Nil
One-ply, 33 lb (15 kg) self-seal base sheet, 1 coat 140°F (60°C) softening point asphalt on top side of base sheet	Nil

* Permeance units in the British system are ($grain/ft^2\cdot h\cdot in\ Hg$).

Hedlin used Fick's law to calculate permeabilities from the estimated conditions at the specimen faces. These calculated permeabilities were not found to be dependent on temperature gradient and were higher than those obtained with wet cup tests by 50 to 500 percent.

The effect of surface sealing to reduce permeability may keep moisture contents of even some porous insulations at low levels according to Hedlin [76]. Sereda and Hutcheon [77] hypothesized that the lack of an adequate mathematical expression to describe moisture migration is a serious limit to predicting heat flow in moist materials because the two flow mechanisms, of heat and moisture, are thoroughly inter-related. Martin [78] indicated that the most important factor in preventing condensation in flat roofs was to prevent the entry of moist air into the roof space. Moisture content gradients in roofing can vary seasonally since winter temperature differences of 80°F (44°C) or more between inside and outside can produce vapor pressure differentials of 30 lb/ft^2 (1.4 kPa) or more, according to Griffin [21]. Abraham [79] and Baker [80] provide additional data on properties of roofing asphalts and principles of roofing membrane design.

5.2 ABSORPTION AND MOISTURE-INDUCED DEFORMATION

As early as 1927, Miller [81] reported that organic felt gained weight when exposed to relative humidities ranging from 39 to 98 percent and the gain in weight increased with increasing relative humidities. Gumpertz [82] also recognized that organic fibers will absorb water, and resulting damage can include deterioration, collapse, or dimensional change and reduction of the thermal insulating value through the presence of free water. Freezing of absorbed moisture can also cause mechanical deterioration and contribute to premature failure in built-up roofing.

Moisture absorption can also contribute to failure of roof structural elements. For example, Dinwoodie [51] reported that most strength properties of timber above the fiber saturation point (28-30 percent moisture content) are approximately two-thirds of the corresponding strength at a moisture content of 12 percent and one-third that of oven-dried material. Mayo [83] reported that absorbed moisture was responsible for the collapse of a swimming pool roof constructed with pywood box beams.

Roofing felts are absorptive because they contain small voids and may contain materials that have an affinity for water [36]. The bitumen saturating process does not eliminate all the air. Brown [84] reported that bitumen fills approximately 75 percent of the air void volume in organic felts and 55 percent of the volume of voids in asbestos felts. Consequently, the water-holding capacity of "saturated" felts is high. Joy [36] measured water absorptions of 68 and 80 percent by weight in type 15 asphalt-saturated and tar-saturated organic felts, respectively. Jones and Garden [70] also reported that some felts can absorb and hold water, up to 80 percent of their weight. Equilibrium moisture contents for some roofing materials are listed in table 7, based on data from Mitchell [85].

Absorption of moisture by roofing materials and insulation has been observed in laboratory as well as in field studies. In laboratory experiments, Brotherson [38] noted growth of ridges and blisters from moisture absorbed by felts. In less than 12 weeks of exposure to high humidity environment (62 and 95 pecent RH), the ridges and blisters had increased in size and new blisters had begun to show [38]. Tator and Alexander [23] noted that a 100 ft^2 (9 m^2) area of three-ply organic felt, steep asphalt membrane can potentially absorb over one pint ($5x10^{-4}$ m^3) of water during the fall and winter season. They also indicated that variations in the absorbed equilibrium moisture contents, and their vapor pressures, with changing environemtnal conditions seemed to correlate well with observed behavior [23].

Table 7. Equilibrium Moisture Contents [85]
At 75°F (24°C) and 90 Percent Relative Humidity

Material	Equilibrium Moisture Content (percent by weight)
Fiberboard	8.5 - 10.0
Gypsum	1.0 - 2.5
Steel	0
Wood	7.5 - 18.0
Concrete	1.0 - 2.0
Asbestos Formboard	6.0 - 7.0
Cellular Glass	0.1 - 0.5
Styrene	0.1 - 0.5
Urethane	2.0 - 4.0
Insulating Concrete	5.0 - 6.0
Perlite Board	2.5 - 3.5
Organic Felt, Asphalt Impregnated	2.5 - 4.0
Asbestos Felt, Asphalt Impregnated	1.0 - 2.0
Glass Felt, Asphalt Impregnated	0.1 - 1.0

Degradation may be accelerated when absorbed water is present and therefore limits for absorption may be specified. Absorptive materials may contain or absorb water which can expand upon freezing and cause mechanical disruption of the material. Harmathy [19] noted moisture absorptions that some building materials can hold in equilibrium with a certain environment. In a study of unusual deterioration of bituminous roofing materials under high humidity, Stafford [74] measured the following moisture contents:

Material	Moisture Content (percent by weight)
Two-ply, type 15 perforated asphalt felt mopped with 140°F (60°C) softening point asphalt, 20 lb/100 ft^2 (1 kg/m^2)	11.5 - 13.6
One-ply, 45 lb (20 kg) base sheet without surface mopping	11.9
One-ply, 45 lb (20 kg) base sheet mopped both sides with asphalt. 2 moppings of 20 lb each per 100 ft^2 (1 kg/m^2)	3.8 and 6.6

Shuman [35] found that roofing membranes expand or contract with changes in relative humidity regardless of temperature between -20 and 160°F (-29 and 71°C), but the total deformation depends upon the moisture history and the duration of changed environment. He observed that built-up roofing membranes changed length substantially less than single felts. Furthermore, he suggested that roofs which have withstood some severe cold waves without splitting may split when a very low relative humidity (which induces drying shirnkage) accompanies a less severe temperature drop.

Long [44] reported that, based on results of his laboratory study of roofing felt laminates, humidity changes caused more dimensional change than temperature. He measured dimension changes of uncoated felts and two-ply laminates of roofing felts and bitumen for temperatures of 10, 77 and 127°F (-12, 25 and 53°C) and for relative humidities of 0, 50 and 95 percent, and for water immersion.

Schaefer [86] described a series of tests conducted on extruded polystyrene insulation that had been exposed on roofs in Alaska and New Hampshire to environmental moisture and pressure gradients for a maximum of 36 months. For the conditions of testing, he noted that moisture absorption of 1.5 percent by volume can be expected in the field, and that the outer edges of insulation absorb much more water than the center. No physical deterioration of the insulation was reported for roofs that had been in service from 12 to 36 months.

Kaplar [87] conducted long-term moisture absorption tests of rigid thermal insulation materials submerged in water and after burial in moist soil. Porous and fibrous materials such as mineral wool, corkboard, perlite calcium silicate, and glass fiber board were generally more absorbent than closed-cell extruded polystyrene plastics. Special surface densification treatments on some of the extruded polystyrene boards appeared to be effective in reducing moisture absorption.

Rissmiller [88] noted from laboratory experiments that moisture is absorbed rapidly in roofing felts and that significant quantities of moisture are absorbed in a few hours (table 8). For absorption tests of at least 100 days

Table 8. Absorption-Expansion Data for Selected Roofing Materials [88]

Material	Moisture Absorbed[3] (Days)		Corresponding Expansion, percent[4]	
Coated organic felt (C.D.)[1]	0.4(1)	14.8(144)	0.36	2.16
Coated organic felt (M.D.)[2]	2.2(1)	21.4(365)	0.00	0.36
Type 15 Perforated tar-saturated organic felt (C.D.)	23.8(0.17)	67.8(272)	1.69	2.26
Type 15 Perforated asphalt-saturated organic felt (M.D.)	14.6(0.08)	69.3(88)	0.17	0.53
Type 15 Perforated asphalt-saturated organic felt (C.D.)	17.7(0.08)	4.6(89)	0.59	2.23
Type 15 Perforated asphalt-saturated asbestos felt (M.D.)	8.2(0.08)	21.5(89)	0.08	0.08
Type 15 Perforated asphalt-saturated asbestos felt (C.D.)	10.4(0.04)	25.4(64)	0.33	0.65
Type 15 Perforated asphalt-saturated asbestos felt (C.D.)	8.4(0.08)	21.7(91)	0.50	0.94
Type 15 Perforated tar-saturated organic felt (M.D.)	36.4(0.17)	70.9(242)	0.53	0.56
Impregnated glass mat (M.D.)	4.4(0.17)	14.8(104)	0.04	0.02
Impregnated glass mat (C.D.)	4.5(0.17)	18.3(103)	0.00	0.00
4-ply type 15 perforated asphalt-saturated organic felt (C.D.)	10.7(4)	35.4(421)	0.54	2.08

(1) C.D. - cross-machine direction.
(2) M.D. - machine direction.
(3) Percent by weight based on oven dry weight of membrane.
(4) Percent based on dimension of oven dry membrane.

duration, the following order of increasing absorption was observed [88]: coated organic roofing felt, impregnated glass mat, perforated asphalt-saturated asbestos felt, perforated asphalt-saturated organic felt, tar-saturated organic felt. Approximately 30-90 percent of the total moisture was absorbed during the first 5 days of water immersion.

5.3 TEMPERATURE AND MOISTURE-INDUCED DEFORMATION

As previously stated, bituminous roofing membranes and roof insulations are normally subjected to a wide range of temperature and moisture conditions. The influence of these factors on the dimensional stability of the roofing membrane is significant and must be considered in establishing performance criteria. Temperature and moisture are interdependent; the amount of water in roofing materials depends on humidity and temperature. The magnitude of temperature and moisture changes can cause relative dimensional changes that may induce shearing stresses and tensile stresses in felts and interply bitumen.

In his study on solar heating, radiative cooling and thermal movement, Cullen [6] measured roof surface temperatures to be as much as 80°F (44°C) hotter than ambient air temperature during the day and 20°F (11°C) cooler at night. Rossiter and Mathey [89] calculated roof surface temperatures for various insulation thicknesses. These temperature excursions may cause dimensional changes in all components of the roof. Cullen [6] and others have reported that thermal contraction of felt is not linear with temperature. Thermal contraction increases at a greater rate below the freezing point. Garden [90] showed temperature gradients through three roofs and two other temperature profiles are calculated in Section 8 of this report.

Mathey and Cullen have recommended, as a performance criterion for roofing membranes, a linear thermal expansion coefficient not exceeding 40×10^{-6}/°F (72×10^{-6}/°C) determined from the temperature range 0 to -30°F (-18 to -34°C) according to the ASTM Proposed Method of Test for "Coefficient of Linear Thermal Expansion of Roofing and Waterproofing Membrane" [58]. They recommended that tests should be performed in the transverse (crossmachine) direction since greater movement is generally expected in this direction.

The mechanisms responsible for thermal or moisture-induced dimensional changes include expansion of solid material or changes in gas pressure within the cells of foam material. Cullen and Rossiter [55] cited reports that indicated the linear coefficient of thermal expansion for polyurethane foam was $2.7\text{-}5.4 \times 10^{-5}$/°F ($4.9\text{-}9.7 \times 10^{-5}$/°C). Dimensional changes in this type of foam are caused primarily by changes in gas pressure within the cells.

Coefficients of linear thermal expansion for some common structural deck materials are listed in table 9 from data reported by Griffin [21].

Table 9. Linear Thermal Expansion Coefficients of Selected Decking and Counterflashing Materials [21]

Material	Linear Thermal Expansion Coefficient x 10^{-6}/°F (°C)	
Decking		
Steel	6.7	(12)
Aluminum	12.9	(23.2)
Wood	1.7-2.5	(3.1-4.5)
Plywood	3.0	(5)
Counterflashing		
Steel	6.7	(12.0)
Monel	7.8	(14.0)
Copper	9.4	(17.0)
Stainless Steel	9.6	(17.0)
Aluminum	12.9	(23.2)
Lead	15.0	(27.0)
Zinc, rolled	17.4	(31.3)

Mathey and Cullen [58] measured coefficients of thermal expansion for five types of roof membranes for three temperature ranges, 73 to 30°F (23 to -1°C), 30 to 0°F (-1 to -18°C), and 0 to -30°F (-18 to -34°C). Coefficients of thermal expansion measured for felt membranes are shown in table 10.

Data in table 10 indicate that some membranes expanded in the longitudinal direction and contracted in the transverse direction when tested in the temperature range 73 to 30°F (23 to -1°C). Moisture contents of the specimens were 2 percent or less. It is not clear how much of the variability in linear expansion/contraction coefficients is attributable to moisture or to the test method or to the inherent thermal expansion variability of felts.

Table 10. Typical Coefficients of Linear Thermal Expansion for 4-Ply Roofing Membranes [58] (x 10^{-6}/°F (°C), for Average of Three Specimens)

Type of Membrane	73 to 30°F (23 to -1°C) Long.	Transverse	30 to 0°F (-1 to -18°C) Long.	Transverse	0 to -30°F (-18 to -34°C) Long.	Transverse
Organic Felt & Coal Tar	-3.3 (-5.9)	4.4 (7.9)	22.3 (40.1)	36.0 (64.8)	19.3 (34.7)	29.5 (53.1)
Organic Felt & Asphalt	-3.4 (6.1)	-6.6 (-11.9)	2.7 (4.9)	12.6 (22.7)	13.9 (25.0)	37.4 (67.3)
Asbestos Felt & Asphalt	2.3 (4.1)	9.2 (16.6)	4.8 (8.6)	18.1 (32.6)	19.5 (35.1)	37.5 (67.5)
Glass Felt (Type I) & Asphalt	-7.1 (-12.8)	-5.3 (-9.5)	8.9 (16.0)	10.1 (18.2)	35.1 (63.2)	46.4 (83.5)
Glass Felt (New Product) & Asphalt	-7.3 (-13.1)	-3.9 (-7.0)	-4.2 (-7.6)	10.7 (19.3)	29.0 (52.2)	39.0 (70.2)

Data (table 10) also indicate that roofing felts contract at temperatures below 30°F (-1°C). Free water that freezes in water-saturated membranes would cause potentially disruptive stresses by expansion of ice within the interstices of the felt.

Cullen [6] noted that the thermal expansion coefficient of bituminous roofings increased as temperature decreased. Other roofing technologists have reported similar results [58, 91, 92]. Cullen [93] reported that the thermal deformation of 4-ply membranes was larger than that of the uncemented felts from which it was constructed. This indicated strong influence of the bituminous materials on thermal deformation. The linear expansion of asphalt was reported to be 120 x 10^{-6}/°F (216 x 10^{-6}/°C) while that of coal tar pitch was 90 x 10^{-6}/°F (162 x 10^{-6}/°C) [93]. Table 11 lists typical linear thermal expansion coefficients of 4-ply uncemented felts fastened by stapling at the ends and 4-ply built-up membranes composed of the felts. Membranes are especially susceptible to thermal shrinkage when exposed in cold climates. Hamada and others [94, 95] reported that thermal expansion and associated stresses were responsible for membrane blistering over urethane.

Hamada [96] noted that the coefficient of thermal expansion of asphalt increased with aging. In the temperature range 15 to 68°F (-10 to 20°C), unweathered material exhibited a thermal expansion coefficient of 0.5 x 10^{-5}/°F (0.9 x 10^{-5}/°C) whereas materials exposed outdoors for 2-1/2 and 6 months were 1.1 x 10^{-5}/°F (2.0 x 10^{-5}/°C) and 2.8 x 10^{-5}/°F (5.0 x 10^{-5}/°C), respectively.

Table 11. Typical Apparent Linear Thermal Expansion Coefficients for Roofing Felts and 4-Ply Built-up Membranes [93], Temperature Range 30 to -30°F (-1.1 to -34.4°C)

Expansion Coefficients for 4-ply Test Specimens x 10^{-6}/°F (°C)

	Roofing Felts		4-Ply Built-up Membranes	
Description	Longitudinal	Transverse	Longitudinal	Transverse
Asphalt-saturated organic felt (asphalt interply)	6.3 (11.3)	13.3 (23.9)	10.9 (19.6)	20.8 (37.4)
Asphalt-saturated asbestos felt (asphalt interply)	6.3 (11.3)	13.0 (23.4)	8.3 (14.9)	20.3 (36.5)
Asphalt-saturated glass felt (asphalt interply)	145.0 (261.0)	18.2 (32.8)	18.1 (32.6)	26.1 (43.0)
Coal-tar-saturated organic felt (coal tar interply)	6.5 (11.7)	15.2 (27.4)	19.45 (35.0)	29.4 (52.9)

5.4 THERMAL RESISTANCE

The thermal resistance of built-up roofing membranes, although not large, may be reduced by the presence of moisture. Insulation also loses thermal efficiency when it contains moisture. Complete enclosure of insulation boards to keep out moisture, however, is not yet practical, as Gumpertz [82] noted, because of the potential expansion of entrapped air and nullification of the sealing by cuts that are made during roof construction.

Loss in thermal reistance observed in moist insulation resutls from the high coefficient of thermal conducitivty of water relative to air [97]. Moist insulation is, in general, inefficient, resulting in a waste of money and energy. Some researchers [98, 99] computed temperature distributions that prevail in roofs of various cross-sections and materials.

The convection of heat at a conducting surface is affected by moisture as well as surface roughness, air movement, and conduction properties of the interiors of the materials. Surface conductance increases as air velocity over the surface increases and the insulation value of a material is not generally constant but decreases with increasing temperature [100, 101]. Heat conduction is complex and surface thermal resistance is dependent on emittance and temperature as well as air velocity.

Jesperson [102] investigated the effect of moisture on thermal conductivity. He reported that for some inorganic materials (mineral wools, cellular concretes and various clay products) the first few percent by volume of uncombined moisture caused a considerable increase in conductivity, but further supply of moisture had a more moderate effect on conductivity. For organic materials (cork and timber), the increase in conductivity with moisture content was approximately linear over the whole range of observation [102].

Hills [103] discussed condensation in flat roofs and Weber [104] and Vos [105] calculated the location of the dew point in roofs.

Experimental evaluation of the thermal transmittance of roofing materials was described by Lim [106]. Test methods normally used for determining the thermal resistance of materials employ some variation of the guarded hot plate test (ASTM C 177-73). In this method of test, the steady-state heat conduction is measured in a dry material. Quantitative data on the loss of efficiency caused by intrusion of moisture in roofing insulation have not in general been obtained from this test.

Powell [15, 107] found in laboratory studies of the effect of moisture on the heat transfer performance of insulated flat-roof constructions that appreciable amounts of moisture in permeable roof insulations seriously reduced their insulating value under both simulated winter and summer exposure conditions. For some insulations containing considerable but probably not untypical amounts of moisture, such as insulating concrete, the effective thermal resistances observed were as little as one-quarter of the values observed for the dry insulation, under the same summer exposure conditions, and about one-half the dry values under winter exposure conditions.

Powell [15] measured the average thermal resistance, R_t, of roofing specimens over the test periods. He then calculated the dry thermal resistance on the basis of laboratory test resutls for the dry components. He suggested a minimum acceptable value of the ratio of the average to the dry resistance to be 0.6; however, he recommended conducting field tests on full-scale buildings and comparing these results with laboratory results on the relatively small specimens studied. Although Powell made his recommendation in 1971, such tests have yet to be conducted.

Sereda and Hutcheon [77] indicated that the capability to predict heat flow in moist materials is restricted partially because of the lack of an adequate mathematical expression to describe moisture migration.

Aamot [108] studied the thermal efficiency of protected membrane roofs influenced by external, natural causes. His study indicated that sunshine and snow increased the efficiency (defined as theoretical energy loss/actual energy loss), while rain reduced it. Wind was important to surface heat exchange; however, its influence on efficiency was small.

Gammie [109] showed the effect of moisture on k-factors (thermal conductance) of several types of insulation including: rock wool, glass fiber, cork board, and wood fiber board. For example, Gammie [109] indicated that the k-factor for glass fiber insulation containing 8% moisture by volume was approximately 1.7 times that of dry fiber glass insulation.

Changes in thermal conductivities of moist insulation are dependent on the physical arrangement of the water in the insulation. Joy [110] calculated the effect on thermal conductivity of 10 percent water, by volume, in insulation having 90 percent air space and thermal conductivity, based on dry insulation, of 0.30 Btu$\cdot$in/h$\cdot$ft^2$\cdot$°F (0.043 W/m$\cdot$°K) for various arrangements of water. He reported thermal conductivities for 10 percent water arranged in series, bead, foam and parallel configurations as 0.34, 0.38, 0.57, and 0.73 Btu$\cdot$in/h$\cdot$ft^2$\cdot$°F (0.049, 0.05, 0.105 W/m$\cdot$°K), respectively. In the series arrangement, water is located in one or several layers perpendicular to the direction of heat flow. In the parallel system, the water is located in continuous shafts parallel to the direction of heat flow. In the bead arrangement the water is located in small beads uniformly spaced throughout the insulation. In a foam arrangement, the water films surround the insulation particles or fibers thereby forming a honeycomb or foam structure. For insulation containing 10 percent ice, by volume, the series, bead, foam and parallel arrangements resulted in calculated thermal conductivities of 0.34, 0.39, 1.39, and 2.05 Btu$\cdot$in/h$\cdot$ft^2$\cdot$°F (0.049, 0.056, 0.201, 0.296 W/m$\cdot$°K), respectively. Using a thermal conductivity probe, Joy [110] measured thermal conductivities of three types of insulation containing various quantities of water or ice at 8 and 80°F (-13 and 27°C). In all cases, thermal conductivities increased substantially with increasing moisture contents.

Moisture sensitivity and thermal efficiency for insulation are interrelated. However, insulation is selected with consideration for other factors such as dimensional stability, suitability as a substrate for the built-up roofing membrane, fire safety requirements, cost and availability.

5.5 STRENGTH INCLUDING FATIGUE LIFE AND MODULUS

The strength of bituminous membrane roofing is dependent on many factors, such as moisture content, age, and exposure conditions, among others. For example, Polychrone [111] noted that the resistance of bituminous substances to deformation varies with strain and with rate of strain. He hypothesized that the incidence of splitting failures could be decreased by increasing the tensile strength of the roofing membrane by increasing felt weights or by developing stronger membranes.

Tensile strengths of bituminous roofing membranes and of constituent materials have been measured for a variety of conditions by several researchers [36, 44, 78]. Martin [78] measured tensile strengths of cellulosic, asbestos and glass fiber roofing felts for varying rates of deformation ranging from 12 in/min (5 mm/s) to 0.002 in/min (0.8 µm/s). Tensile strength (lb/in width or N/m) decreased with decreasing rates of movement for all materials tested.

Maximum tensile strength at the lowest rate of movement (0.002 in/min or 0.8 µm/s) was about 33-44 percent of the strength measured at the highest rate of movement. Tensile strength decreased linearly with the logarithm of the rate of movement.

Jones [112] reported that the breaking strains of many of the membranes prepared in the laboratory decreased with temperature, but even at very low temperatures (-40°F; -40°C) the breaking strains ranged from 0.8 to 2.0 percent.

Mathey and Cullen [58] suggested as one preliminary performance criterion a breaking force (tensile strength) of not less than 200 lb/in (35.0 kN/m) in the weakest direction of the membrane when tested at 0°F (-18°C); however, this strength was for dry materials. If moisture degrades materials, as has already been noted for improperly protected organic felts [113], breaking force (tensile strength) will also be adversely affected. Jones and Garden [70] observed the effect of membrane type and direction on breaking strains and loads.

Laaly [113] investigated the influence of moisture on stress-strain properties of type 15 asphalt-saturated organic and asbestos felts at room temperature and 50 percent relative humidity. In another investigation, he [114] reported that moisture reduced the breaking force (tensile strength) of asphalt-saturated organic felt by a factor of about six and freeze-thaw cycles reduced the breaking load further. He found that type 15 asphalt-saturated organic felt absorbed approximately 60 percent by weight of distilled water during immersion at room temperature for 520 hours. This moisture reduced the tensile strength of the felt to 16 percent of its original strength. Even a single cycle of wetting for ten days and drying at room temperature to original weight resulted in a decrease in strength in the machine and cross-machine directions of approximately 19 percent [113].

Cash [115] presented a hypothesis and theory for built-up roofing splitting failures. In developing his theory of thermal warp, he showed the effect of insulation type, bitumen, and membrane-insulation orientation on strength. Although he showed modulus of elasticity of roof membranes to be a function of temperature; no comparable data relating modulus to moisture were given.

Little quantitative data regarding the tensile fatigue life of built-up roofing membranes are available. Occurrence of freezing and thawing of bituminous built-up roofing was also investigated by Laaly [114] who measured the temperature of bituminous roofing membrane and its relation to ambient conditions [116]. Laaly [113] and Rissmiller [88] have both noted that absorption of water of roofing membrane samples is relatively rapid and, as a consequence, strength reductions are rapid.

Sushinsky and Mathey [117] conducted tensile and flexural fatigue tests under load control and cyclic midspan displacement control, respectively. Cyclic loads equivalent to 80, 60, and 40 percent of the ultimate tensile load were applied. At 80 percent of the static tensile load, the fatigue life at 0°F (-18°C) was substantially lower than that at 70°F (21°C) (130 load repetitions vs 70,000 repetitions). The effect of moisture on the fatigue strength of membranes is not known.

5.6 FUNGUS ATTACK RESISTANCE

In developing preliminary performance criteria for bituminous membranes, Mathey and Cullen [58] recognized that any appreciable reduction in performance or appearance resulting from decay should be prevented during the expected service life of the membrane. Bituminous built-up roofing should be resistant to attack by fungi and microbiological organisms. The asphalt or coal tar pitch which is applied to base sheets and between plies helps to protect organic felts from attack by micro-organisms. In most instances, fungus attack and micro-biological degradation require moisture [118].

The potential for fungus attack and the rheological properties of oxidized asphalts such as those used in roofing can be changed by overheating [119] and by aging and weathering [120, 121]. Greenfeld [122] observed that outdoor weathering of mineral stabilized asphalt coatings oxidized the asphalt which then became more water soluble as oxidation progressed. Campbell and others [123] showed that extent of asphalt oxidation was a function of exposure time and was dependent on temperature and relative humidity. Roofs which pond water [124] may become stagnant pools that can collect dirt and support algae growth if minimum slopes to obtain drainage are not constructed.

Stafford [74] showed in a laboratory study that moisture could damage felts exposed to 100 percent relative humidity. Craters and minor blistering were observed on the side exposed to moisture; however no evidence of fungus attack was reported.

Moisture contents of about 35-50 percent are required for wood rotting fungi to flourish [118]. In addition, a source of infection, a suitable substrate (food), oxygen, and suitable temperature are also necessary [118].

Beech and Newman [125] reported, in a Scottish study, that there was evidence of a degree of moisture hazard in one-third of the roof spaces inspected although there was no significant occurrence of decay or insect attack.

In bituminous coatings used in underground pipelines, Jones [126] noted that after prolonged exposure to ideal microbial growth conditions, thin films of bituminous materials sometimes show distress and structural deterioration. Thick sections of solid asphalt, e.g., 0.25 in (6.4 mm) or more, have been found to be essentially immune to microbiological attack.

Air-blown asphalts used for built-up roof construction are generally more resistant to microbiological attack than straight run asphalts and claims that microbial attack was causing roof deterioration have not been impressive, according to Jones [126].

Where moisture is present in roofing systems in some cases of poor construction, weathering degradation products could react with roofing aggregates, fillers and dust to make a substrate buffered to an ideal pH for fungal growth [126]. Jones [126] noted that the most likely area of microbial attack, if it does occur, would be in organic felt fibers after they had been exposed by weathering degradation of the asphalt coating; however, ultraviolet degradation of the fibers would ordinarily be faster than microbiological attack.

Martin [127] conducted mildew susceptibility and soil burial tests on bituminous fabrics commonly used in construction of built-up roofing. As a result of the positive findings, inspections of old roofs in Melbourne, Australia were made but no evidence of microbiological deterioration was found. The literature reviewed for this report indicates that adequately coated roofing membranes are resistant to fungus attack provided that they are kept dry. Similar protection appears to be appropriate for preserving insulation and structural decks.

6. MOISTURE DETECTION METHODS

It has already been noted that moisture in the wrong places can damage built-up roofs. In addition, roof maintenance, repair and replacement necessitated by moisture problems require a higher degree of expertise related to specification, design and field control than that required for a new project [30]. It is important to be able to detect moisture in roofs. Knowledge about the amount and location of moisture in roofing will enable better decisions to be made regarding replacement and maintenance strategies. Premature replacement of a roof can mean wasting 75 to 80 percent of a perfectly good roof system [128].

The individuality of building design and the proliferation of products and systems have complicated roofing construction problems. Since the thermal transmittance (U-value) of the roof is computed from the series resistance of the various layers or components of the system, moisture and concomitant high thermal conductance in any layer or component can reduce the thermal efficiency (theoretical energy loss/actual energy loss) [108].

Careful inspection of the roof surface is important because there are many possible paths for water to enter the roof system of a building. Van Court [129] and others [66] have provided check lists and guidelines to follow in conducting visual, on-site roof inspections. Gammie [109] summarized specific uses of data obtained from inspection. He noted that moisture inspection in roofing can be useful in the following tasks:

1. Finding leaks
2. Saving fuel
3. Reducing repair costs
4. Preventing repetition of costly design or construction errors
5. Heading off future problems
6. Establishing a realistic preventive maintenance program
7. Testing new construction
8. Providing a basis for realistic future bidding.

It has been reported [130] that Sweden now requires thermal scanning of all new construction including the roof and is considering making the periodic re-inspection of existing buildings mandatory. Hedlin [131] has reported that a variety of devices such as nuclear moisture density meters and infra-red imagery can be employed to make roof inspections more effective. Anderson [132] indicated that a range of moisture contents is normal for roofing materials exposed to high relative humidities. Consequently, moisture detection methods must be able to discriminate a range of moisture contents directly or indirectly.

Selection of instrumentation for measurement of moisture in materials in highway and airport pavements included the following considerations reported by Ballard [133]: availability, sample size, effect on sample, accuracy, speed of measurement, durability, reliability, time stability, hazards, temperature stability, instrument life, and remote sensing. Comparable considerations are valid for roof inspection instrumentation.

In addition to regularly scheduled inspection, special roof inspections should be made for the following [66]:

1. After exposure of roofs to unusually severe weather conditions such as very strong winds, hail or long periods of rain.

2. Immediately prior to preparation of projects for maintenance, repair, or reroofing. This will usually require the removal of samples of the roofing and insulation materials for analysis and inspection. Cullen [66] recommended removal of samples of sizes 4 in (102 mm) wide by 36 in (914 mm) long or 12 in (305 mm) square extending down to the roof deck.

3. To ascertain or verify the backlog of essential maintenance and repair.

The service life of a roof can be extended substantially through inspection and maintenance. Periodic inspections of a roof can reveal defects that can be corrected to forestall major problems. Inspections should be made at least once each year and always in the spring, according to Cullen [66]. Roof age and conditions should be made part of the permanent records for each building.

This section reviews and summarizes some of the emerging techniques used for detecting moisture in roofing. In addition, some methods of moisture detection that are useful in nonroofing applications are discussed briefly together with the constraints that impede their application in detecting moisture in roofing. The methods which are summarized include: gravimetric, nuclear, electrical capacitance, infra-red imagery, electrical resistance, and microwave measurements. All of the methods are nondestructive except for the gravimetric method. Many of the methods for detecting moisture are sold as a service by roofing inspection companies and therefore exact details of any partiuclar company's method and equipment for moisture detection are often proprietary.

Nondestructive moisture measurement techniques are relatively recent developments and, consequently, do not have an extensive record of use and performance. Furthermore, no comparative data on the suitability of the various nondestructive methods of moisture inspection for roofs are available. Nondestructive roof inspection methods require some samples to be taken from the roof; however, sampling is not usually extensive. Samples taken from roofs leave repairs that are potential sources for moisture intrusion and subsequent damage.

Nuclear, capacitance and infra-red imagery techniques are currently being used in surveys of roof moisture but their accuracy has not been validated. Electrical resistance moisture detection is not generally applicable as a non-destructive evaluation method because the membrane generally has to be penetrated by probes and subsequently patched. Microwave moisture detection techniques are not currently used on roofing.

Since many of these techniques are expensive to employ, it is important to give consideration to the benefit/cost of using these techniques. For example, in many cases it may be a more economical procedure to make estimates of the roof condition and move ahead with remedial action rather than employ expensive moisture detection techniques.

6.1 GRAVIMETRIC MOISTURE DETECTION

Standard methods for moisture content determination in soils and paving materials were formerly based on gravimetric techniques; however, more rapid and automatic methods are currently used [133]. New methods of moisture detection that do not require destructive sampling are also useful in building conservation and in assuring preservation of historic structures [134]. Nevertheless, gravimetric methods of moisture detection in roofs are still widely used to substantiate estimates of moisture content established by non-destructive methods.

Gravimetric methods of moisture detection usually involve surface inspection of the roof and subsequent sampling of a portion of the roof to determine wet and dry weights of roof samples. The roof conditions, penetrations, condition of flashing, presence of moist or damaged components, and general state of repair are observed and recorded during site inspections. The roof and its features are usually drawn to scale and the roof features and condition are entered into a log book that provides a historical record of the roof.

In locations where moisture damage is evident or suspected, samples of the roof extending down to the roof deck are cut out and immediately placed in a moisture tight container. Samples of wet roofing should be weighed as soon as possible after removal from the roof and sensible moisture - that moisture which can be seen or felt - should be described as to its location whether between plies, within the insulation, or elsewhere. Small quantities of water may be difficult to detect by touch; therefore, sensitive scales or analytical balances should be used for samples dried to constant weight.

One method employs heating the roof samples to 100-110°C (212-230°F) for 24 hours to drive off moisture without decomposing other constituents.

Other methods involve heating the samples to 150°F (66°C) for 48 hours [135]. Moisture content is frequently reported as a percent by weight (standard practice in soils testing) or as a percent of the bulk volume of the roofing materials sampled.

The gravimetric method uses oven drying and therefore measures free or partially bound water. The accuracy and precision of the gravimetric method are influenced by presence of volatile materials which may be driven off while the sample is being dried. Normally several hours are required to dry the sample to constant weight to determine the moisture content.

Evidence of voids in the interply asphalt (usually highlighted by a glossy sheen) and lack of adequate asphalt coating on any of the components should be reported as part of the roof inspection and moisture detection program that accompanies gravimetric moisture determination. Condition of the insulation including presence of moisture, evidence of degradation, moisture marks, and delamination should also be noted. Woodhouse et al. [136] reported that a device employing fiber optics and its own light source has been used in Great Britain for visually inspecting roofing materials and building cavities. A small hole (1/2 in, 13 mm) is drilled to admit the device into the roofing to conduct the inspection.

6.2 NUCLEAR MOISTURE DETECTION

Nuclear methods of moisture detection are nondestructive and are based on a method of identifying hydrogen atoms. Pawliw and Spinks [137] used nuclear meters to detect moisture in concrete nondestructively. Hydrogen atoms are present in several chemical compounds in roofing materials, including asphalts and coal tar pitches and, therefore, the selective detection of hydrogen in moisture is complex.

Huett [138] described the operating principles of nuclear moisture meters. Nuclear moisture detectors operate by producing fast neutrons that emanate from a source and travel outward until they collide with atoms in the surrounding media [138]. In collisions with the surrounding material, fast neutrons are slowed and some are reflected back to the vicinity of the neutron source. If a detector which counts backscattered slow neutrons is placed near a source of hydrogen atoms, which are effective neutron moderators, the counting rate of the detector will reflect the content of hydrogen atoms. Instrumentation establishes the ratios between fast and slow neutrons within the neutron cloud formed at the investigation and presents them in the form of counts per minute [133]. The quantity of slow neutrons counted is an indirect measure of hydrogen atoms and moisture content.

In one method the lowest recorded backscatter reading on the roof is located and is assumed to account for hydrogen atoms other than in water. Any readings in excess of that base are considered to be due to water content. Nuclear readings are made on a grid, such as 10 ft (3 m) centers, and each reading samples approximately a 4 ft^2 (0.37 m^2) area.

Hedlin [139] observed that uncertainty as to whether moisture is present can arise because the nuclear gage does not distinguish between the variability due to structural features and nonuniformity of roofing applications and that caused by moisture. Link and Miller [140] corroborated these findings. One report [138] indicated that use of nuclear moisture meters to detect moisture in roofing can be time-consuming and data reduction and analysis are complicated. Nuclear moisture gages are sensitive to sample density, sample composition, surface roughness, and homogeneity of the sample [133]. Because the nuclear technique detects hydrogen in all materials including water, it is sometimes necessary to run correlation studies prior to use of the gages on roofs in service. Early attempts to use nuclear methods erroneously cited flashing areas as high moisture regions. However, it was later determined that the nuclear gages were detecting the higher hydrogen content present in increased quantities of bitumen in the vicinity of the flashing.

Nuclear instrumentation forms the basis for at least two currently used methods of nondestructive moisture inspection in the U.S. Contour maps of alleged moisture are prepared from the grid of counts. Subjective descriptions of moisture (e.g., dry, damp, moist, wet, saturated) are provided to suggest priority of repair or replacement. It has been estimated that one two-man crew using a nuclear moisture detection device can survey over 30,000 ft^2 (2,800 m^2) of roof in a day.

Neutron scatter methods require approximately 1-5 minutes per measurement and the electronic system requires occasional recalibration. The equipment has been reported to be stable, reliable and portable [133].

Hedlin [139] reported the use of commercial nuclear soil moisture-density meters to measure moisture content of thermal insulation in flat roofs and to map wet areas. He reported that variations in bitumen and gravel thickness and moisture distribution caused uncertainty in these measurements. In field tests in Canada, the standard error of estimate was 3 lb/ft^3 (50 kg/m^3) for moisture contents up to 15.6 lb/ft^3 (250 kg/m^3) and 6.2 lb/ft^3 (100 kg/m^3) for moisture contents up to 25 lb/ft^3 (400 kg/m^3) [136]. Moisture readings varied depending on whether the moisture was uniformly distributed or concentrated near the top or bottom of the insulation. The Canadian study [139] utilized laboratory prepared deck types and top coverings with perlite-fiber insulation with moisture contents ranging from dry to 41 lb/ft^3 (650 kg/m^3) (symmetrically distributed through the insulation). To estimate the accuracy, moisture measurements were made by the nuclear method and by cutting samples and oven drying them to determine their moisture contents which ranged from near dry to near saturation.

6.3. CAPACITANCE METHODS

The capacitance method of moisture determination depends on the fact that most materials have characteristic dielectric constants. Furthermore, a mixture of materials has an apparent dielectric constant that is proportional to the sum of the product of the dielectric constant of each constituent and its concentration in the mixture.

The measurement of capacitance for soil moisture has been identified by Ballard [133] as one of the simplest, most rapid, and least expensive methods. Capacitance of a condenser in which mixtures of materials are the dielectric has been measured by use of various electronic circuits [141]. Capacitance methods have been used to measure water film thickness, amount of water in soil, amount of moisture in baled cotton, and composition of mixtures [141]. A U.S. patent application for a method of detecting moisture in multiple layer roofs has been filed [142].

Anderson [143] described the use of an electronic inspection procedure that utilized the principles of electrical capacitance to detect unseen roof moisture. A direct measurement of the dielectric constant is used in detecting moisture in roofing.

The dielectric constants of most materials used in roofing range from 1-4, whereas the dielectric constant of water is 80. Sensors utilizing capacitance circuits are used in much the same manner as nuclear backscatter gages to obtain a grid of readings on the roof. Departures of dielectric constant from a norm obtained from intact, dry roof areas, are indicators of moisture in the roof.

Capacitance equipment and instrumentation are said to be portable and enable dielectric measurements to be made in a minute or two [133]. Measurements are made in a grid pattern on the roof surface which must be dry when dielectric measurements are made. No comparative data are currently available to enable an assessment to be made of the precision of this method relative to other non-destructive methods of detecting moisture in roofing.

6.4 INFRA-RED IMAGERY OR THERMOGRAPHY

Infra-red imagery or thermography is one recent method used to detect heat loss through roofs [144, 145]. Thermography is often implemented by flying over roofs to be inspected with an aerial camera using infra-red film. Fly-overs can be relatively rapid and jet aircraft have been used in some experiments at high altitudes. However, the amount of moisture or extent of roof degradation is difficult to assess at high altitudes because of lack of detail.

Lower altitude survey flights at 200-500 feet (60-150m) above roof level are now being used with helicopter-mounted aerial cameras. The detail observable by this means is limited only by the state of the technology. Large areas of roofs and numbers of buildings can be scanned in a relatively short time [129, 130, 146].

Hand held infra-red cameras have also been used to detect moisture in roofing [147-149]. Infra-red imagery techniques measure energy emitted from radiating hot spots [150].

Infra-red imagery depends on detection of infra-red radiation or thermal radiation which occupies a specific region of the electromagnetic spectrum and extends from 0.75 m to approximately 1,000 m [148]. The intensity of infra-red radiation emitted by an object is dependent on its temperature and can be manipulated, like visible light, using lenses, prisms and mirrors, and can be photographed by means of special cameras and film. Photographing the thermal radiation emitted from a body forms the basis for the method of nondestructively detecting moisture in roofs [151].

Successful application of the method depends on the intensity of infra-red radiation being emitted by the object of interest. Link [152] reported that water has a heat capacity that may be as much as 5,000 times that of some insulations such as fiber glass. A photograph of the roof made using an aircraft-mounted or hand held infra-red camera will show areas from which the most heat is emitted.

Anomalies are created by roof features other than moist roofing components or degraded insulation. For example, variations in material cross-section, presence of vents, roof hatches, and heat loss from walls and flashing require special interpretation. Structural members and shadowing may also cause anomalies [153]. According to Link [135] it is most advantageous to obtain thermal infra-red imagery at the time of maximum temperature contrast during nighttime hours.

The infra-red sensor system, for either the hand held or helicopter-mounted camera, is sensitive to changes in energy. The apparent temperature of a material can be approximated by the following equation derived from Planck's radiation law [153]:

$$T_{app} = \frac{1}{\frac{1}{T} - \frac{(\Delta\lambda)\ln\Sigma}{C \ln \frac{\lambda_2}{\lambda_1}}}$$

where:

T_{app} = apparent temperature, °K

T = actual temperature, °K

$\Delta\lambda$ = width of wavelength band $(\lambda_1-\lambda_2)$, m

Σ = emissivity

C = 14380

λ_1, λ_2 = wavelengths bounding spectral band

Infra-red photographs are sometimes made at night when roof features, heated during the day, emit heat by radiation causing maximum temperature contrasts to occur. Some use is made of a schedule of photographing roofs during summer days, say from 10 a.m. to 4 p.m., when moist areas of roofing would be transmitting more heat through the roofing system than dry areas; however, reflection of solar energy and added complexities in the thermal regime on roofs make daytime imagery interpretation more difficult.

Bjorklund and others [154, 155] described a program of infra-red imagery used to detect heat lost through poor insulation or wet insulation of buildings in the vicinity of Lincoln, Nebraska. Van den Berg [156] noted that it is not possible to tell the difference between water on the surface of the roof and water under the felts from airborne infra-red imagery. He noted that infra-red thermography will not quantify heat losses, nor is it always cost-effective, but it does serve as a useful tool when used with discretion. Moisture detection services using infra-red imagery are available commercially from several firms.

Thermography research is being conducted by the U.S. Army Cold Regions Research and Engineering Laboratory (Hanover, NH), the U.S. Army Waterways Experiment Station (Vicksburg, MS), and other agencies. Use of special infra-red imaging equipment and videotape equipment may lead to further improvements in the use of thermography for moisture detection and subsequent inspection to assess moisture dissipation.

6.5 ELECTRICAL RESISTANCE

Water is a good electrical conductor and moisture can be detected by changes in electrical resistivity that are observable when a material becomes wet.

Electrodes are generally inserted in materials in which moisture is to be measured. A current is passed through the electrodes and the electrical resistance across the gage length is measured. The reading obtained is related to the moisture-resistance calibration curve for that material. This method has been applied satisfactorily to wood and other materials for which correlations can be established [133, 157].

For some materials, moisture measurement using electrical resistivity provides a fast, accurate, simple operation with reliable equipment. Surface-mounted electrodes covering various areas and depths of influence are available; however, they have not been widely used to detect moisture in roof systems. Moisture in roofing may occur at locations below the effective measurement zone for these transducers. Presence of metals and other highly electrically conductive materials may also preclude widespread use of this method for detecting moisture in roofing.

One variation of the electrical resistance principle of detection utilizes a special tape that is attached to the surface of the material in which moisture is to be monitored. The tape consists of two parallel wires contained in a specially treated cloth ribbon. When the cloth becomes moist, it enables current to flow between the two wires and causes an electronic monitoring unit to issue an alarm. The fixed location of this sensor and difficulty in retrofitting it are significant impediments to its use in existing roofs. As currently used, this method cannot specify precisely the location and quantity of moisture.

6.6 MICROWAVE MOISTURE DETECTION

The absorption of microwave energy of nonmetallic solids is related to moisture content. For many materials, a linear relationship exists between moisture content and the logarithm of microwave attenuation [133, 158]. Hoekstra and Cappillano [159] analyzed nondestructive sensing of water content by microwaves and indicated that use of this method was extremely difficult because of the dependence of reflection and transmission on both the water content (dielectric constants) and thickness of the sample. They noted that a calibration made at one particular sample thickness was invalid if the thickness of the sample changed.

The mathematics of microwave attenuation is described by the following equation [133]:

$$I = I_o \exp(-2\pi\eta\frac{\ell}{\lambda})$$

where I = transmitted intensity

I_o = initial intensity

λ = wavelength

ℓ = thickness of material

η = refractive index

Hoekstra and Cappillano noted that if microwave measurements were made periodically at fixed locations on roofs, deviations from the dry roof system would certainly be found by microwave attenuation; however, a requirement would be that reflection from the roof should be relatively uniform [159]. Deviations from average readings would be detected and probably could be attributed to water. Microwave heating has been used to determine separation-causing water content in tires [160] and presence of water in shelter panels [161] and in air cell cavities of rubber anechoic tiles [162].

Ballard reported [133] that microwaves between 30 and 300 mm were most suitable from an economic standpoint. Microwave response is sensitive to polar materials, thickness and bulk density variation and to small changes in temperature. No major use of microwaves for detecting moisture in roofs has been noted from the literature reviewed.

7. MOISTURE DISSIPATION

After moisture gets into roofing membranes and insulation, it is, in general, difficult to dissipate. There are several reasons why wet roofing may not dissipate the moisture. These include the leakage paths that may admit water but do not provide rapid egress for water vapor. In addition, membranes have very low permeability to water vapor transmission.

Excessive moisture accumulated during cold weather normally will remain in the insulation or membrane until warmer weather and even then drying is not assured [35]. For drying to occur by convection, the drying air must come in contact with wet roofing materials and a path for ventilation must be provided.

Much has been written about methods for venting, although benefits are not always quantified [27, 163-166]. It is therefore better to keep moisture from roofing constituents than to attempt to dry out the roof by methods which are used but have not been proven to be effective for all conditions.

Methods for drying usually include some form of venting from the insulation through the built-up roof to the outside. Venting passages through the insulation have also been used in attempts to dry built-up roofs and insulation. The effectiveness of vents in drying wet roofing components is controversial. Not all owners or consultants concur on the benefits derived from venting [164]. Baker and Hedlin [163] reported that some roofers and consultants claim success in drying wet roofs, some have noted little if any benefits, and some owners have reported that vents made a bad situation worse because moisture could enter the roofing system through them.

Moisture dissipation can take place through breather vents which are vertical pipes or stacks which penetrate the roofing membrane, are open to the outside air, and are shielded from precipitation by a cover. Drying occurs through movement of air by air pressure differences (convection) or by vapor pressure differences (diffusion).

Some suppliers of vents recommend that 2 in (50 mm) stack vents be spaced so that there will be one vent for each 1000 ft^2 (93 m^2) of roof. According to Baker and Hedlin [164], stack vents should be combined with perimeter venting and intentional venting passages though the insulation should be provided. They report that ventilation from the outside can remove accumulated moisture above a vapor barrier if stacks and vents are weatherproof and are located in exposed areas of the roof to take maximum advantage of wind.

Venting is necessary to prevent rotting of wood [118, 167] in environments where moisture contents are high. Baker and Hedlin [163] note that there are recommended standards governing the type and amount of venting required; however, the principle involved is often misunderstood. Furthermore, each vent projection through a roof is a potential source of leakage if flashing is improperly constructed or if the vent is damaged by traffic on the roof.

Handegord and Baker [92] noted that combining roof drains and vents reduces the number of roof penetrations and the likelihood of leakage from poor workmanship. They [92] reported that most venting of moisture vapor will probably take place during the summer under the influence of solar heating that promotes migration of moisture to the lower membrane. Handegord [168] reported that moisture removal in a flat roof system can only take place by diffusion and wind-induced ventilation, and the effect of both mechanisms will probably be small. Furthermore, removal of moisture to the outside in flat roofs involves lateral migration to special roof or perimeter vents by forces that cannot be controlled or predicted with any degree of certainty.

The British Code of Practice (CP 144, Part 1, 1968) states that flat roofs should have ventilation provided and gives a minimum rate of ventilation of 1/2 in (13 mm) square opening per 1 ft (0.3 m) run of eaves on opposite sides of the building [103].

Dickens and Hutcheon [31] indicated that provision of fans to pressurize roof spaces offers an opportunity for positive ventilation in summer. In one instance, fans were kept running during the following summer to counteract air leakage into the roof space from the heated area by slightly pressurizing the space. Dickens and Hutcheon [31] indicated that the use of ventilation may actually increase the rate of moisture accumulation in roofs by promoting air leakage through the warm side. In such cases it may be preferable to avoid any attempt to ventilate the roof space in winter in order to minimize air leakage. Hedlin and Cole [169], in an experiment in Canada, showed drying of insulation on a 2 percent slope and with use of vents. Insulation with air space below dried faster than insulation without air below. Drying occurred more rapidly as roof slope increased.

Experimental work evaluating roof vents tested for nearly six years in Canada [164] indicated that slow drying of wet insulation did take place. Results of this study confirmed that, where there is no vapor barrier, vents to the outside from the roof system should not be used unless it can be definitely established that no air leakage paths will be created.

In one field experiment [163] using four different types of rigid insulation (panel size: 2 ft x 4 ft x 2 in, 610 x 1220 x 50 mm), slow drying of wet insulation appeared to have taken place. Glass fiber, perlite, and bead polystyrene insulation was used with vents installed at the insulation surface, or at butt joints in the center for the test panel, or over a hole in the insulation. Baker and Hedlin [163] indicated that stack or breather vents can provide only for drying of small quantities of moisture over a relatively long period of time. Breather vents can relieve vapor pressure. Hansen [32] suggested using 2 x 2 in (50 x 50 mm) purlins and continuous soffit vents to improve venting in wood-framed flat roofs.

Plonski [170] described a 2-year experimental program on ventilated and unventilated flat roofs constructed over two different spaces with relative humidities of 72 percent and 30-40 percent. He observed that ventilated concrete roofs dried during summer and winter; however, drying of unventilated construction (above the moist space) progressed more slowly. He noted that concrete roof planks over a vapor barrier did not dry much [170].

Hedlin [171] studied the effect of design features on moisture dissipation and moisture content in protected membrane roof insulations and found that the severity of moisture absorption can be reduced by protective measures. Fibrous and closed cell plastic insulation 6 to 24 in square and 2 in thick (150 to 610 mm square and 50 mm thick), were placed on experimental roofs where they were weighed periodically over periods of up to five years.

Hedlin found [171] that moisture gains were reduced by increasing the deck slope from 2 to 8 percent. Sealing the bottom surface in bead polystyrene also reduced moisture gain. Slots 0.25 in deep x .33 in wide (6 mm deep x 8.4 mm wide) in the lower insulation surface on a 4 in (100 mm) square grid were not found to reduce moisture uptake. Moisture content of some fibrous specimens sealed on the bottom and edges remained at less than 4 percent by volume; others sealed and with paving stone cover flashed to divert water remained at less than 1.5 percent. Significant drying occurred over several months when specimens were placed wet on the roof in winter. Moisture contents of wood fiber, glass fiber, and perlite fiber insulations ranged as high as 60 percent by volume before drying in winter. Polyurethane moisture contents were consistently low and remained below two percent by volume [171].

It is not known how moisture migrates through different types of insulation. Likewise rates of moisture migration are unknown and remains an issue for additional research.

8. ANALYSIS OF THERMAL AND VAPOR PRESSURE GRADIENTS IN SELECTED ROOFS

Keeping moisture from roofing components is the best method of preventing condensation in the roof and thereby retaining material integrity and thermal insulation characteristics. Moisture is prevalent in the environment and is normally contained in roofing materials and insulation and in the air surrounding these materials. Moisture fronts can migrate within the roof system. This section shows example calculations and provides a rational framework within which approximate temperature and moisture regimes can be estimated.

Several references describe the mechanics of heat transmission through entire buildings as well as through roof and wall sections [172-175] and insulation [176, 177]. Basic data on material properties such as specific heat, thermal conductivity, sometimes as a function of density, can be obtained from the ASHRAE Handbook of Fundamentals [100] and from literature published by building materials manufacturers. The mechanism of condensation in composite roof and wall sections has also been studied and is widely reported in domestic and foreign technical literature [178-200]. Use of mathematical or analog models to predict temperatures, moisture levels and dew point locations enables the roofing technologist to study the effect of initial moisture content, insulation levels, season of completion, diffusion resistance of linings, and cavity ventilation, according to Trethowen [201]. Diffusion resistance, particularly of coated slab materials, may be different for vapor migration in one direction than in the other [202]. Wilson [203], reporting on performance of flat roofs in Scotland, observed that of 80 listed causes of defects, 32 were attributed to inadequate control of roof space condensation. Clogged drains or occasional high rates of precipitation can also have serious consequences for porous types of insulation used in protected membrane roofs [204].

The temperature at any cross-section through the roof system may be approximated, if inside and outside temperatures are known. The temperature drop through any number of components of the roof is proportional to the total thermal resistance, R_T, through the components.

For a roof composed of a structural deck, vapor barrier, insulation and built-up membrane, the temperature change Δt_1 accumulating through component C_1 with cumulative thermal resistance R_1 is:

$$\Delta t_1 = \frac{R_1}{R_T} (t_i - t_o) \tag{8.1}$$

where: R_1 = thermal resistance of the section in question,

R_T = total thermal resistance of the roof system,

$(t_i - t_o)$ = temperature difference between inside and outside.

It has already been noted that moisture from condensed water vapor has been detected in components of built-up roofs. Condensation that may take place is related to the temperature and relative humidity of the air in the system. Relative humidity is the ratio of the mole fraction of water vapor in a given moist air sample to the mole fraction of water vapor in an air sample which is saturated. As temperature increases, the amount of water vapor which can be held in a unit volume of air increases. Chilling moist air can result in condensation of moisture on cooler surfaces.

The mechanism for vapor transmission and partial vapor pressure computation is quite complex; however, Fick's law can be used to calculate water vapor transmission through materials. In many computations, the permeance coefficient M is used to determine the total weight of vapor transmitted. The weight of water, W, transmitted is expressed by:

$$W = M \cdot A \cdot \theta \cdot \Delta p \qquad (8.2)$$

where:

W = weight of water transmitted, lb (kg)

A = area of cross section of the flow path, ft^2 (m^2)

θ = time during which the transmission occurred, hours (seconds)

p = difference of vapor pressure between ends of the flow path, inches of mercury (Pa)

M = permeance coefficient, perms, or (grains/$ft^2 \cdot h \cdot$in Hg) ($ng/Pa \cdot s \cdot m^2$)

Not all of the water vapor in air will pass through a layered roofing system if some of it is needed to supply the equilibrium hygroscopic moisture of the constituent materials. It is generally recognized that when air temperatures are depressed below the dew point, some portion of the water vapor, if present, may condense in the insulation or elsewhere in the built-up system.

Equilibrium hygroscopic moisture content at 90 percent relative humidity can be calculated from:

$$M_c = \frac{\rho_1 x_1}{12} \cdot \frac{W_{h1} - W_{d1}}{W_{d_1}} + \frac{\rho_1 x_2}{12} \cdot \frac{W_{h2} - W_{d2}}{W_{d_2}} \qquad (8.3)$$

where: M_c = equilibrium hygroscopic moisture content, lb/ft^2 (kg/m^2)

ρ_i = dry density of ith component, lb/ft^3 (kg/m^3)

x = thickness of each material, in (m)

W_{h_i} = constant weight of ith component of the specimen at 76 ± 2°F (24 ± 1°C) and 90 ± 3 percent relative humidity

W_{d_i} = constant weight of ith component of the specimen after oven drying

In built-up roofs, entrapped moist air will follow conventional laws relating pressure, temperature, and volume. The ideal gas law indicates that at a constant volume the pressure of a confined gas increases in direct proportion with the rise in absolute temperature. The degree of confinement that occurs in a built-up roof membrane or even in a blister is difficult to assess, however.

Wind blowing against a building can also create a pressure difference that may drive moist air into roofing. The theoretical pressure difference due to this "chimney effect" is:

$$P_c = K\,P\,h\,\left(\frac{1}{T_o} - \frac{1}{T_i}\right) \qquad (8.4)$$

where: P_c = theoretical pressure difference across enclosure due to chimney effect, in (m) of water

P = absolute pressure, lb/in^2 (Pa)

h = distance from neutral zone, or effective chimney height, feet (m)

T_o = absolute temperature outside, °R (°K)

T_i = absolute temperature inside, °R (°K)

K = constant of proportionality

Most materials, including vapor barriers, allow some vapor to pass through them. In fact, the vapor-pressure gradient through a roof can be computed in a manner analogous to that for temperature gradient. Hence, the vapor pressure, p_x, at plane x can be estimated from the following relationship:

$$p_x = p_i - \frac{\Sigma\,(1/M)_x}{\Sigma\,(1/M)}\,(p_i - p_o) \qquad (8.5)$$

where: p_x = vapor pressure

p_i = interior vapor pressure

p_o = exterior vapor pressure

$\Sigma\,(1/M)_x$ = sum of vapor resistances from interior to plane x

$\Sigma\,(1/M)$ = total vapor resistance

Equations (8.4) and (8.5) can be used to calculate vapor flow to and from any plane in the roof. Vapor migration is usually less serious in summer than it is in winter. Moisture calculations are given for the roof section shown in figure 4. It is noted that equation 8.5 applies to steady state vapor diffusion conditions and is applicable to building assemblies including roofs which do not contain condensation.

The heat transfer calculations which follow are similar to those presented by Griffin [21] and illustrate how temperatures can be estimated for roof sections shown in figures 4 and 5, respectively. These calculations assume a steady state condition of heat flow. It is noted that in these calculations a membrane surface temperature (t_s) was used instead of an exterior air temperature (t_o). The purpose is to allow the model calculations without considering all factors which influence membrane surface temperatures. A method for calculating membrane surface temperature under steady state conditions was presented by Rossiter and Mathey [89].

Example calculations of vapor flow, similar to those presented by Griffin [21], are given on page 52 and illustrate vapor pressures at various locations in the roofing system shown in figure 4. These calculated values should be considered as approximate because of the complex mechanism of vapor migration. In the calculation for summer conditions the outside temperature was taken as 90°F (32°C).

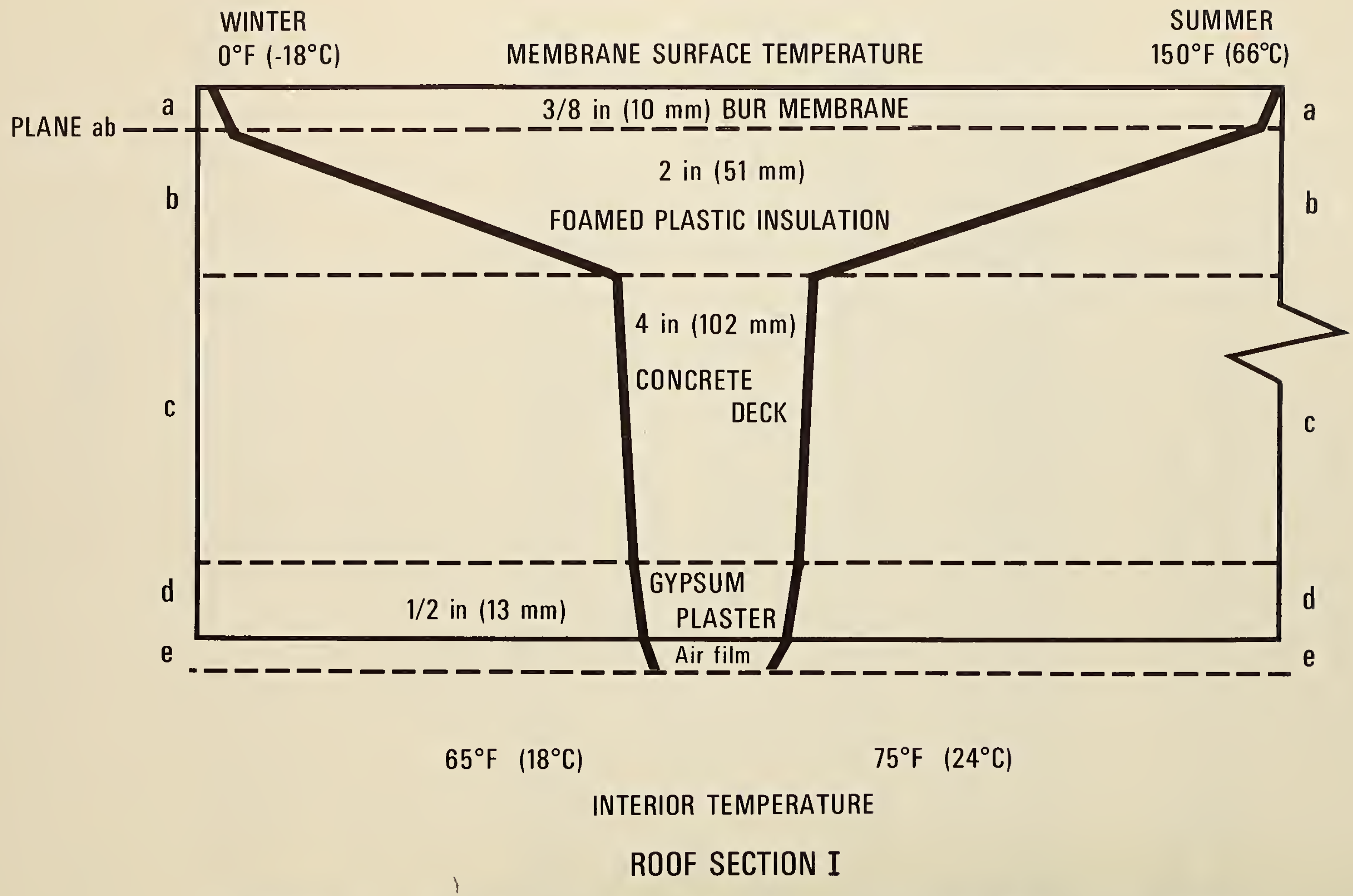

FIGURE 4. TEMPERATURE PROFILES THROUGH ROOF SECTION I .

Temperatures in Roof Section I (example calculations)

Material (Section I)	Thermal Resistance Winter °F·h·ft²/Btu (K·m²/W)	Summer °F·h·ft²/Btu (K·m²/W)
a) 3/8 in (10 mm) BUR membrane	0.33 (0.06)	0.33 (0.06)
b) 2 in (51 mm) foamed plastic insulation	8.00 (1.41)	8.00 (1.41)
c) 4 in (102 mm) concrete deck	0.32 (0.06)	0.32 (0.06)
d) 1/2 in (13 mm) gypsum plaster	0.09 (0.02)	0.09 (0.02)
e) Interior still air film	0.61 (0.11)	0.92 (0.16)
(Heat flow up in winter, down in summer) ΣR =	9.35 (1.65)	9.66 (1.70)

	Winter	Summer
Membrane surface temperature, t_s =	0°F (-18°C)	150°F (66°C)
Inside temperature, t_i =	65°F (18°C)	75°F (24°C)

Temperature at plane x = $t_x = t_i - \frac{\Sigma R_x}{\Sigma R}(t_i - t_s)$

Winter Temperatures

t_i = = 65°F (1°C)

$t_{de} = 65 - \frac{0.61}{9.35}(65)$ = 61°F (16°C)

$t_{cd} = 65 - \frac{0.70}{9.35}(65)$ = 60°F (16°C)

$t_{bc} = 65 - \frac{1.02}{9.35}(65)$ = 58°F (14°C)

$t_{ab} = 65 - \frac{9.02}{9.35}(65)$ = 2°F (-17°C)

$t_s = 65 - \frac{9.35}{9.35}(65)$ = 0°F (-18°C)

Summer Temperatures

$t_s = 75 - \frac{9.66}{9.66}(-75)$ = 150°F (66°C)

$t_{ab} = 75 - \frac{9.33}{9.66}(-75)$ = 147°F (64°C)

$t_{bc} = 75 - \frac{1.33}{9.66}(-75)$ = 85°F (29°C)

$t_{cd} = 75 - \frac{1.01}{9.66}(-75)$ = 83°F (28°C)

$t_{de} = 75 - \frac{0.92}{9.66}(-75)$ = 82°F (28°C)

t_i = 75°F (24°C)

Vapor Pressure in Roof Section I (example calculations)

Materials (Section I)	Permeance, M perms ($ng/Pa \cdot s \cdot m^2$)	Vapor Resistance 1/M
a) 3/8 in (10 mm) BUR membrane	0.20 (11.00)	5.00 (0.09)
b) 2 in (51 mm) foamed plastic insulation	0.80 (46.00)	1.25 (0.02)
c) 4 in (102 mm) concrete deck	0.98 (56.00)	1.02 (0.02)
d) 1/2 in (13 mm) gypsum plaster	22.00 (1262)	0.05 (0.00)
e) Interior still air film	- (-)	- (-)
(Vapor flow up in winter, down in summer)	Σ (1/M) =	7.32 (0.13)

Vapor Pressure Calculations (RH x Saturated Vapor Pressure)

Summer

90°F (32°C), RH = 43%; p_o = outside pressure = 0.43 x 1.42 = 0.61 in Hg (2.07 kPa)

75°F (24°C), RH = 40%; p_i = inside pressure = 0.40 x 0.875 = 0.35 in Hg (1.19 kPa)

$\Delta p = p_o - p_i$ = 0.26 in Hg (0.88 kPa) - vapor pressure difference

Winter

65°F (18°C), RH = 35%; p_i = 0.35 x 0.622 = 0.22 in Hg (0.74 kPa)

0°F (-18°C), RH = 90%; p_o = 0.90 x 0.0376 = 0.03 in Hg (0.10 kPa)

$\Delta p = p_o - p_i$ = 0.22 - 0.03 = 0.19 in Hg (0.64 kPa)

Vapor pressure at plane x = $p_x = p_i - \dfrac{\Sigma\,(1/M)_x}{\Sigma\,(1/M)}\,(p_i - p_o)$

<u>Winter Vapor Pressures, in Hg (kPa)</u>

$$p_i = 0.22\ (0.74)$$

$$p_{cd} = 0.22 - \frac{0.05}{7.32}(0.19) = 0.22\ (0.74)$$

$$p_{bc} = 0.22 - \frac{1.07}{7.32}(0.19) = 0.19\ (0.64)$$

$$p_{ab} = 0.22 - \frac{2.32}{7.32}(0.19) = 0.16\ (0.54)$$

$$p_o = 0.22 - \frac{7.32}{7.32}(0.19) = 0.03\ (0.10)$$

<u>Summer Vapor Pressures, in Hg (kPa)</u>

$$p_o = 0.35 - \frac{7.32}{7.32}(-0.26) = 0.61\ (2.07)$$

$$p_{ab} = 0.35 - \frac{2.32}{7.32}(-0.26) = 0.43\ (1.46)$$

$$p_{be} = 0.35 - \frac{1.07}{7.32}(-0.26) = 0.39\ (1.32)$$

$$p_{cd} = 0.35 - \frac{0.05}{7.32}(-0.26) = 0.35\ (1.19)$$

$$p_i = \quad = 0.35\ (1.19)$$

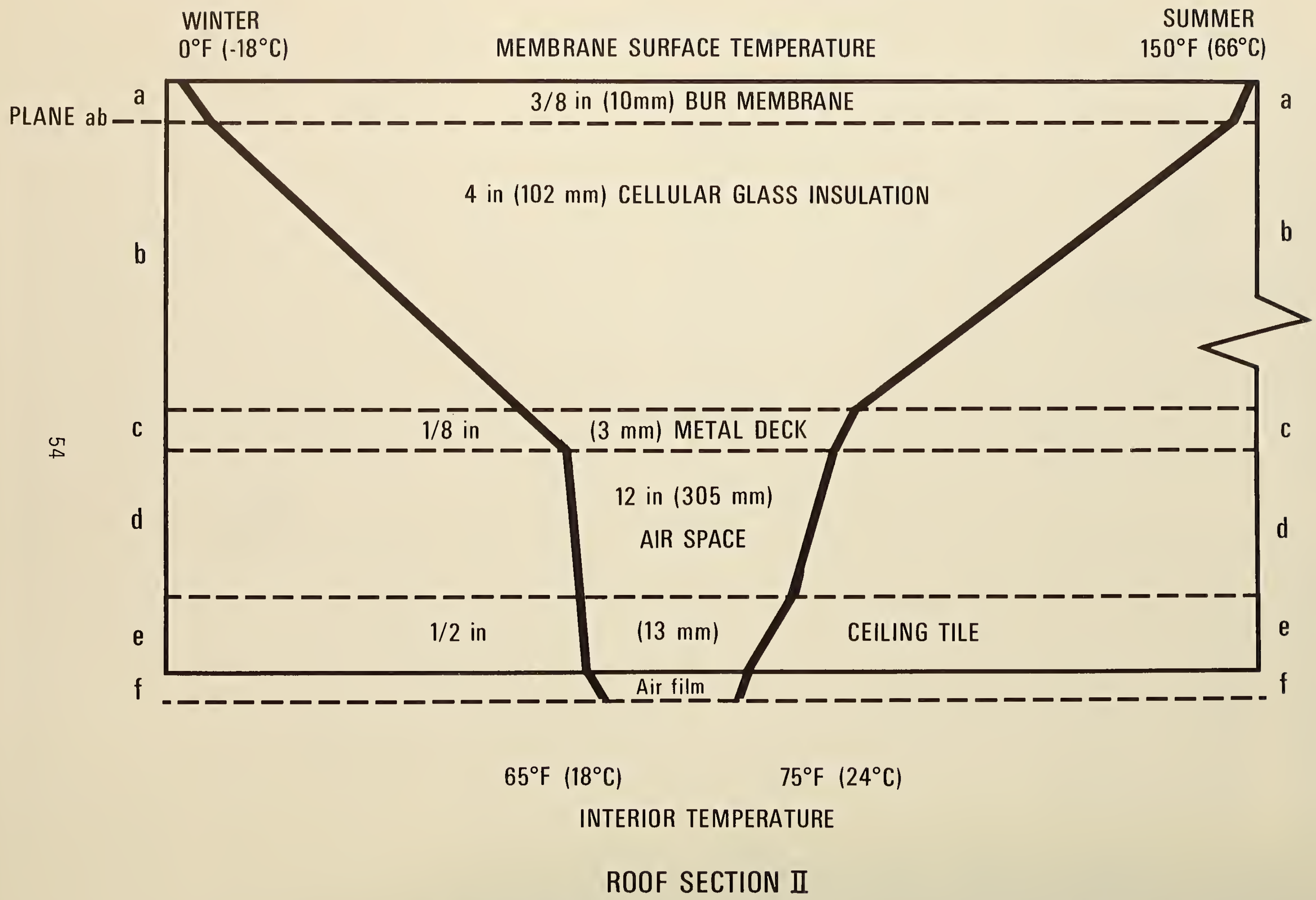

FIGURE 5. TEMPERATURE PROFILES THROUGH ROOF SECTION II.

Temperatures in Roof Section II (example calculations)

Material (Section II)	Thermal Resistance Winter °F·h·ft²/Btu (K·m²/W)	Summer
a) 3/8 in (10 mm) BUR membrane	0.33 (0.06)	0.33 (0.06)
b) 4 in (102 mm) cellular glass	10.00 (1.76)	10.00 (1.76)
c) Metal structural deck (steel)	0.67 (0.12)	0.67 (0.12)
d) 12 in (305 mm) air space (drop ceiling)	0.61 (0.11)	0.92 (0.16)
e) 1/2 in (13 mm) wood fiber tile	1.35 (0.24)	1.35 (0.24)
f) Interior still air film	0.61 (0.11)	0.92 (0.16)
(Heat flow up in winter, down in summer) $\Sigma R =$	13.57 (2.39)	14.19 (2.50)

	Winter	Summer
Membrane surface temperature, t_s =	0°F (-18°C)	150°F (66°C)
Inside temperature, t_i =	65°F (18°C)	75°F (24°C)

Temperature at plane x = $t_x = t_i - \frac{\Sigma R_x}{\Sigma R}(t_i - t_s)$

Winter Temperatures

$t_i =\ = 65°F\ (18°C)$

$t_{ef} = 65 - \frac{0.61}{13.57}(65) = 62°F\ (17°C)$

$t_{de} = 65 - \frac{1.96}{13.57}(65) = 56°F\ (13°C)$

$t_{cd} = 65 - \frac{2.57}{13.57}(65) = 53°F\ (12°C)$

$t_{bc} = 65 - \frac{3.24}{13.57}(65) = 49°F\ (9°C)$

$t_{ab} = 65 - \frac{13.24}{13.57}(65) = 2°F\ (-17°C)$

$t_s = 65 - \frac{13.57}{13.57}(65) = 0°F\ (-18°C)$

Summer Temperatures

$t_s = 75 - \frac{14.19}{14.19}(-75) = 150°F\ (66°C)$

$t_{ab} = 75 - \frac{13.86}{14.19}(-75) = 148°F\ (64°C)$

$t_{bc} = 75 - \frac{3.86}{14.19}(-75) = 95°F\ (35°C)$

$t_{cd} = 75 - \frac{3.19}{14.19}(-75) = 92°F\ (33°C)$

$t_{de} = 75 - \frac{2.27}{14.19}(-75) = 87°F\ (31°C)$

$t_{ef} = 75 - \frac{0.92}{14.19}(-75) = 80°F\ (27°C)$

$t_i =\ = 75°F\ (24°C)$

The model calculations for temperatures and vapor pressures may be used to indicate the possibility of condensation occurring within the roof system for a given set of environmental conditions. For example, in Roof Section I, it may be assumed that the critical plane for condensation for winter conditions is the interface (plane ab) between the relatively permeable insulation and the impermeable built-up roofing membrane. The temperature and vapor pressure at this interface are calculated as:

$$t_{ab} = 65 - \frac{9.02}{9.52}(65) = 2°F\ (-17°C)$$

$$p_{ab} = 0.22 - \frac{2.32}{7.32}(0.19) = 0.16 \text{ in Hg } (0.5 \text{ kPa})$$

From a psychrometric table it is determined that the saturated vapor pressure at 2°F is 0.04 in Hg (0.14 kPa), which is less than the calculated value of 0.16 in Hg (0.54 kPa). This indicates that for the given conditions condensation would probably take place at (or even below) the interface (plane ab). Condensation may be expected to occur when the value of the saturated vapor pressure is less than the calculated vapor pressure.

By calculating the vapor flow to and the vapor flow from the insulation-membrane interface (plane ab), the condensation rate at the interface may be approximated. The vapor flow to the interface is calculated by dividing the pressure differential ($p_i - p'_{ab}$) by the total vapor resistance of the materials below the plane ab. The vapor flow from the interface is calculated by dividing the pressure differential ($p'_{ab} - p_o$) by the total vapor resistance of the materials above plane ab. The vapor pressure, p'_{ab}, is taken as the saturated vapor pressure for the temperature of the plane, since the saturated vapor pressure is lower than the calculated vapor pressure.

$$\text{Vapor flow } \underline{\text{to}} \text{ plane ab} = \frac{0.22-0.04}{2.32} = 0.076 \text{ grain/ft}^2\text{•hr } (1.5\text{x}10^{-8}\text{kg/s•m}^2)$$

$$\text{Vapor flow } \underline{\text{from}} \text{ plane ab} = \frac{0.05-0.04}{5} = 0.002 \text{ grain/ft}^2\text{•hr } (0.04\text{x}10^{-8}\text{kg/s•m}^2)$$

The condensation rate is the difference between the vapor flow to plane ab and the vapor flow from plane ab, i.e. 0.074 grain/ft^2•hr (1.4x10^{-8}kg/s•m^2). Were the temperature and humidity to remain constant for 24 hours, the total quantity, Q, of water condensing in each 100 ft^2 (9.3 m^2) of roofing would be for example:

$$Q = 0.074 \frac{\text{grain}}{\text{ft}^2}(24 \text{ hr})(100 \text{ ft}^2) = 178 \text{ grains} = 0.025 \text{ lb } (11.4 \text{ g})$$

It is again noted that these model calculations should be considered as approximate because of the complex nature of moisture migration in building assemblies.

9. ACKNOWLEDGMENT

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A literature review of the effects of moisture on built-up roofing was made. Quantitative data were summarized for some properties of membrane roofing including: permeability, absorption, thermal expansion, thermal resistance, tensile strength, modulus, and fungus attack resistance. Example calculations of possible temperature and moisture gradients for two typical roof sections were presented.

Nondestructive evaluative methods to locate moisture in roofing systems were summarized and include gravimetric, nuclear, capacitance, infrared imagery, electrical resistance, and microwave methods. A review of techniques to dissipate moisture in roofing is presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Built-up roofs; bituminous roof membranes; moisture; moisture dissipation; non-destructive detection of moisture; performance criteria; roofing moisture.

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