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Moisture Detection in Roofing by Nondestructive Means— A State-of-the-Art Survey

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NBS technical note

David R. Jenkins
Robert G. Mathey
Lawrence I. Knab

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

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Moisture Detection in Roofing By
Nondestructive Means
A State-of-the-Art Survey

by

David R. Jenkins*, Robert G. Mathey**, and Lawrence I. Knab**

ABSTRACT

A literature survey is presented of nondestructive evaluation (NDE) methods for detection of moisture in roofing systems. The methods discussed include the use of capacitance-radio frequency instruments, capacitance-microwave instruments, nuclear meters, and thermal infrared scanners. For each method, the principles of operation are reviewed and the measured properties which are affected by moisture are identified. Factors other than moisture which may affect the response of the instruments are also described for each method. These factors produce responses which are similar to those due to moisture and include non-uniformities in the roofing system, roof construction details, and building equipment. The use of each NDE method in actual moisture surveys is reviewed.

It is emphasized in the report that the validity of roofing moisture surveys depends on both a knowledge of the factors noted above and a familiarity with roofing practice. Furthermore, cores of the roofing system at selected points are needed to confirm NDE observations.

To define operating conditions for infrared scanners, calculated temperatures of roof surfaces over dry and over wet insulation are presented for representative night and day conditions.

Key words: built-up roofing, moisture, moisture detection, nondestructive evaluation, nondestructive testing, roofing, thermal resistance.

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* Professor of Engineering, University of Central Florida, Orlando, FL, on assignment to the National Bureau of Standards under provisions of the Intergovernmental Personnel Act.

** Center for Building Technology
National Bureau of Standards
Washington, DC

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1. THE ROOFING SYSTEM: MOISTURE AND ITS DETECTION

1.1 GENERAL

Good roofing performance in industrial, commercial, and public buildings is important to the U.S. economy, since there are many buildings of these types and since they, in large measure, have large ratios of roof area to wall area. The built-up roofing installed each year would, it has been estimated, cover Washington, DC and part of its suburbs [1].

Most roofs do perform satisfactorily. However roof failures, which are estimated to be 5 to 15 percent of the total roofs in the United States, can be costly [1, 2]. While a number of failure processes may be involved, a roofing system has failed when moisture penetrates it. Penetrating moisture could lead to degradation in both the mechanical and the thermal properties of the materials comprising the system.

This report deals with nondestructive techniques for detection of moisture in roofing. Moisture data revealed by these techniques can be used to determine what action should be taken, be it roof repair or replacement, at a time when the moisture problem is of limited extent. It is far cheaper to solve moisture problems of limited extent than those that have expanded during years of neglect. Ideally, nondestructive evaluation should be a tool of preventive maintenance, and should supplement visual inspection of roofing.

A roof system consists of a structural deck, thermal insulation, and a waterproofing membrane. Depending on internal humidity conditions and geographic location, a vapor retarder between the structural deck and the insulation may be specified. Moisture can be present in the membrane, the insulation, or the deck but the bulk of the moisture is usually found in the insulation. In order to give an impression of the variety of materials which are used in roofs, the typical makeup of each of the roofing system components will be reviewed.

1.2 THE STRUCTURAL DECK

A sketch of a typical roofing system is shown in figure 1. Although most new structural decks are fabricated from steel, reinforced concrete or plywood decks are also common [3]. These materials have sufficient strength to be regarded as load bearing. Cold formed steel decks are available in wide rib, intermediate rib, and narrow rib configurations of the type indicated in the sketch (figure 1). Reinforced concrete decks may be cast-in-place, precast, or prestressed units. Plywood is generally used as a structural deck when the roof structural framing members are wood. Plywood is a better thermal insulator than reinforced concrete since it has a thermal conductivity value of about 1/10 that of concrete.

Wood fibers bonded with portland cement or other binder are pressed into planks or boards which are used as a deck material called structural cement-fiber (or mineralized wood fiber). Typically 2-inches thick, these planks are placed dry in the manner of precast concrete slabs. While the strength levels attainable with structural cement-fiber are not comparable with the strength levels of portland cement concrete, structural cement-fiber is a much better insulator. In fact, structural cement-fiber and plywood have similar values of thermal conductivity [3].

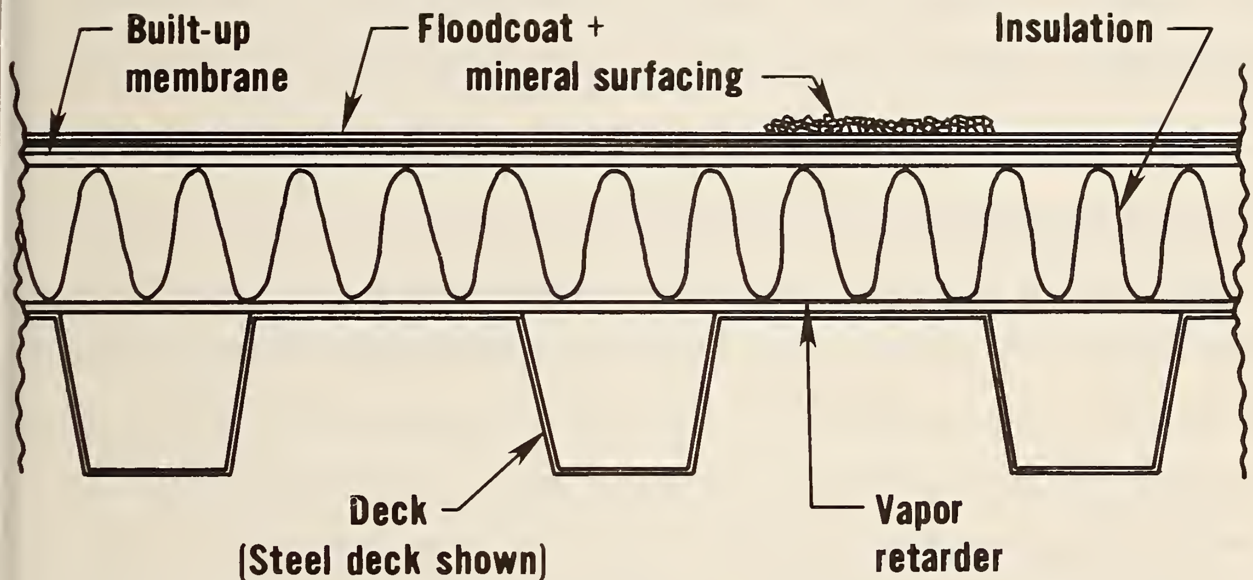

Figure 1. Typical Roof Cross-Section

As noted earlier, structural decks can retain original moisture or can become wet due to moisture migration. In particular, plywood and structural cement-fiber can hold substantial amounts of moisture. Moisture may migrate through steel (laps or joints), concrete, or plywood decks from the building interior and may, in turn, migrate to the insulation if a vapor retarder is not present. When conducting a nondestructive evaluation to detect moisture it should be remembered that moisture in the structural deck material itself may affect the results.

1.3 DECKS WITH POURED-IN-PLACE INSULATION

In addition to the purely structural decks described above, there is an intermediate category of poured-in-place deck which combines some structural rigidity with good insulating properties [3]. The poured-in-place or "wet deck" materials include the insulating concretes and gypsum concrete. Both are relatively low strength materials which must be placed over steel or concrete decks or over formboard to produce acceptable structural integrity. The insulating concretes include those with expanded aggregate (vermiculite or perlite) and the so-called cellular concretes [4]. Vermiculite is an expanded mica aggregate and perlite is an expanded volcanic glass aggregate. They are combined with portland cement to give a concrete in the 15 to 50 lb/ft^3 (240 - 800 kg/m^3) density range. In cellular concrete, a preformed foam is added to a water-cement slurry. Here the air voids replace some of the aggregate, the proportion depending on the unit weight desired. All of the insulating concretes are good insulators having thermal conductivities when dry of 0.55 to 1.20 $Btu \cdot in/hr \cdot ft^2 \cdot °F$ (0.079 to 0.173 $W/m \cdot K$) [5]. Gypsum concrete, it should be noted, is a distinctly different material containing no portland cement [3]. It is placed over formboard and is reinforced by integral subpurlins and wire mesh. Gypsum sets rapidly and attains its strength rapidly, not requiring the extended curing time of portland cement. However, it may have a substantial moisture content for an extended period of time. Gypsum is a slightly less efficient insulating material than insulating concrete with a thermal conductivity, when dry of about 1.7 Btu•in/hr•ft^2•°F (0.25 W/m•K) [5].

All of the so-called "wet deck" materials discussed in this section can be pumped onto the roof surface, can be worked to provide slope-to-drain, and will have a virtually joint-free surface. In addition, all can hold substantial amounts of original moisture and can become wet due to moisture migration from the interior of the building or the structural deck.

1.4 INSULATION

Rigid board insulation in the roofing system provides a barrier to heat flow but has essentially no structural strength. Consequently, it must be supported on a structural deck. While insulation is usually installed in new construction, nearly one-quarter of the new or reroofed installations has no insulation at all [6]. Perlite insulation board, which is made from expanded volcanic glass aggregate, cellulosic fiber and asphalt, is the most commonly used material [6]. Glass fiber boards, made from compressed glass fiber wool with binder, is the next most commonly used insulation in new and reroofed installations [6]. The conductivity of perlite board is about 0.36 Btu•in/hr•ft^2•°F (0.052 W/m•K), while glass fiber board has a value of 0.25 Btu•in/hr•ft^2•°F (0.036 W/m•K) [3]. Ranking third in frequency of use are the closed cell foam plastic insulation boards polystyrene and polyurethane. The advantage of polystyrene and polyurethane is their high insulating value, particularly the latter, which has a thermal conductivity of 0.16 Btu•in/hr•ft^2•°F (0.023 W/m•K) [3]. Compared to the other insulations, these should be more impermeable to water because of their closed-cell-foam structure, but water can be forced to migrate into them. Composite insulation boards are available in which polyurethane is laminated with either perlite or glass fiber insulation. The mineral materials should be placed next to the deck to improve the fire rating.

Rigid board insulation will in general retain more moisture than other roof components. Thus, moisture in the insulation will most likely cause a response in the nondestructive evaluation instruments.

1.5 ROOFING MEMBRANE

The exterior membrane protects the other roofing components and the building from exterior water intrusion. The most common membrane is composed of roofing felts bonded by bitumen hot moppings and then floodcoated with bitumen. In the majority of roofing installations, three plies of felts are used [6]. However, four plies are used in many cases. Such membranes are called bituminous built-up membranes. Because bitumen weathers when exposed to direct solar radiation, mineral surfacing is generally embedded in the flood coat.

Roofing bitumens are asphalt or coal tar pitch. Asphalt is the heavy residue from vacuum distillation of petroleum. The softening point of this material is increased by passing oxygen through it in a "blowing" still. Four types of roofing asphalt are designated in ASTM D-312 [7] ranging from Type I for dead level roofs to Type IV for special steep slope applications. Coal tar pitch, which is used in less than 5 percent of the built-up roofing, is a coke oven by-product. It has properties similar to Type I asphalt. Coal tar pitch is used in low slope or dead level roofing [3]. It is noted that good roofing practice requires a slope of at least 1/4 inch per foot.

There are three types of roofing felts in use today, namely: organic, asbestos, and glass fiber [3]. Basically the felt is a porous mat which is saturated with asphalt or coal tar pitch. Organic felts are generally fabricated from fiberized wood and paper, with the wood fiber acting as the matrix builder. Asbestos felts are made in roughly the same manner as organic felts but with asbestos fibers forming the matrix. Glass fiber mats contain either filamentary or continuous strand glass fibers combined with a phenol-formaldehyde binder. Felts manufactured from the above materials are produced as (a) saturated felts, (b) coated sheets which are both saturated and coated with asphalt, and (c) mineral surfaced sheets which are coated sheets having mineral granules embedded in one surface.

Felts in the built-up membrane may contain moisture which has penetrated through cracks or breaks in the flood coat. Although the roofing felts can not hold large amounts of moisture as compared to insulations, the moisture could have a large effect on the nondestructive moisture detection instrumentation due to its location near the exterior surface. More important than moisture in the felts is the existence of cracking through the roofing membrane which would allow moisture to penetrate into the insulation. This is probably the major mechanism by which moisture collects in the insulation. Therefore, regions surrounding cracks or breaks in the membrane should be investigated for the presence of moisture.

Since the built-up roofing membrane is, in effect, assembled on the construction site, the possibility of variations in membrane makeup exists. For example, the number of plies may not be the same throughout, the thickness of bitumen moppings between plies may vary, and the thickness of mineral surfacing may change from point-to-point. Variations of this type may cause a response in the nondestructive evaluation equipment which could be mistaken for water.

1.6 NONDESTRUCTIVE MOISTURE DETECTION

Nondestructive evaluation (NDE) techniques should provide information on whether moisture is present in a roof, the amount of moisture present, and the extent of the area affected by moisture.

From the foregoing, it is clear that nondestructive techniques for detecting moisture in roofs should be applicable to a variety of materials and material combinations. Although moisture may be found primarily in the insulation, it can be in the deck and in the ply-felts of the membrane. Due to the many point-to-point changes in roofing system construction which could be present, nondestructive evaluation instruments may display a change in response from one area of the roof to another that is not due to moisture. In spite of these difficulties, means for detecting moisture are available but they require careful evaluation and interpretation of instrument readings.

Nondestructive evaluation is an excellent supplement to visual inspection since moisture may be present even when the roof surface appears to be free of cracks, and dry. Persons familiar with roofing materials and their performance should conduct the roof inspections.

Two techniques which are destructive to some degree but are widely used in roofing moisture detection will be discussed briefly before describing the nondestructive methods. These techniques are used frequently in combination with the nondestructive techniques.

The first of these destructive moisture detection methods is the well known coring or gravimetric technique in which material is actually cut out of the roofing system. A limited number of cores for reference purposes is recommended with all nondestructive techniques and NDE survey results will indicate the key locations to be cored. Usually membrane and insulation are removed by means of a knife, saw, or hole-cutter. Moisture in the insulation is determined by the gravimetric method in which a quantity of insulation is weighed as it comes from the roof (samples or cores should be placed in plastic sealable bags on the roof) and then weighed again after oven drying. Of course, the roof must be patched by approved methods as soon as possible after taking cores. When coring is used in combination with nondestructive evaluation, generally only a few cuts into the roofing system have to be made.

The second technique is the resistance probe or resistivity measurement technique. It is relatively simple to use and is to some extent destructive since the roofing membrane must be punctured by the probes. Most instruments employ two closely spaced probes in one testing component and a meter-battery assembly which is quite small and portable. Probes are insulated except at the tips so that the region being measured lies between the tips of the probes. Consequently, the moisture content at various distances below the surface can be determined. However, it is not always clear just how much material is being sampled. This is a particular problem when dealing with a many-component roofing system which contains water.

Operation of the resistance probe is very simple. A voltage is impressed between the probes and the current is measured. The instrument should be calibrated using wet and dry insulation of the type being inspected.

The probes have been used for moisture detection in plaster, brick, or concrete. Somewhat similar procedures have been used for soil resistance determination where a 4-pin method is employed.

This report reviews the state-of-the-art for four methods of nondestructive evaluation of moisture in roofing. These methods include the use of capacitance-radio frequency instruments, nuclear meters, infrared scanning cameras, and capacitance-microwave instruments. The first three of these methods are available commercially, while the microwave systems discussed are not at present marketed for moisture detection surveys but they are included since they may have promise for the future. All of the methods have been used in the field.

An investigation at the National Bureau of Standards, which was recently completed, involved a comparision of NDE techniques under laboratory conditions [8]. The response of the instruments to increasing amounts of water in the insulation of built-up roofing specimens under controlled conditions of specimen construction and testing was evaluated.

2. CAPACITANCE-RADIO FREQUENCY INSTRUMENTS

2.1 DIELECTRIC PROPERTIES OF MATERIALS

Instrumentation of this type responds to changes in either the dielectric constant, k, which is a measure of the ability of a material to store electrical energy, or in the dielectric loss angle, δ, which is related to the energy lost in an alternating electric field. Insulators can be characterized by these dielectric properties as well as by resistance. The capacitance of a material, C, is the product of the dielectric constant and the capacitance of a vacuum, C_o, or

$$C = kC_o.$$

The dielectric constant also is a measure of the ease with which an electric field can be set up in a material. This is related to the behavior of the dipoles in the material. When an electric field is applied, the dipoles (which may be simplistically pictured as dumbbells with a positive charge at one end and a negative charge at the other) in a material are created or become aligned if they already exist but are randomly oriented. The amount of energy required for this alignment is expressed by the dielectric constant. Two kinds of dipoles can be found in roofing materials. In ionic materials such as dry roofing, the positive ions and the negative ions are displaced in opposite directions in an electrical field thus forming dipoles aligned in the field direction. In molecules such as water, randomly oriented permanent dipoles exist which tend to align or become preferentially oriented in an electrical field [9].

In an alternating electrical field which might be created by capacitance instruments, phase shifts between voltage and charge may occur. If there are resistive losses in the material, the voltage creating the field and the charge are out of phase. The dielectric loss angle is a measure of this phase difference. The power loss is also related to the dielectric loss angle. Another parameter, the dielectric loss factor, is the product of the dielectric constant and the tangent of the dielectric loss angle, that is

$$\text{Loss factor} = k \tan \delta$$

2.2 MOISTURE AND DIELECTRIC PROPERTIES

Water in a roofing system increases the dielectric constant since its randomly oriented dipoles require a large amount of energy to align them. For example, the dielectric constant for materials like dry roofing ranges from 1 to 5 while the dielectric constant for water is about 80. The dielectric constant changes very little with frequency until it undergoes a sharp drop in a frequency range centered at about 2×10^{10} Hz for water or other materials which have permanent dipoles. Water also affects the dielectric loss factor of dry material but this effect is frequency dependent. For example, the dielectric loss factor shows a marked variation in magnitude in both the radio frequency (1×10^6 to 30×10^6 Hz) range and again in the upper microwave range [9, 10, 11].

An estimate of the relation between volume fraction of moisture and the dielectric constant in wet roofing can be made by assuming that the dielectric constant of a mixture of materials is equal to the volume weighted sum of the individual dielectric constants, then

$$k_c V_c = k_w V_w + k_I V_I$$

where: k_c = Dielectric constant of the combination

k_w = Dielectric constant of water

k_I = Dielectric constant of insulation

V_w = Volume of water

V_I = Volume of insulation

V_c = Volume of the combination = $V_w + V_I$

Dividing through by V_c

$$k_c = k_w \frac{V_w}{V_c} + k_I \frac{V_I}{V_c}$$

which shows that the dielectric constant, k_c, of the combination varies linearly with the volume fraction of water, V_w/V_c, using the volume weighted sum approach. A similar relationship could be derived for the dielectric loss factor at a given frequency. Equipment characteristics may change this linear relationship at low moisture contents. In addition, a threshold level of moisture may need to be present before any instrument indication is apparent.

Moisture may also have a profound effect on the uniform electrical field which might be present in the dry insulation. Regions of high dielectric constant, such as wet regions, distort the field so that the spacing of the field lines is closer there than in dry regions. In cases where the moisture is not uniformly distributed, errors in interpretation could occur since the reading might not be representative of the entire roofing system. Water on the surface of a roofing system may also modify the electrical field. Again readings which are not characteristic of the roofing system could be obtained.

2.3 INSTRUMENTATION

Radio frequencies (1×10^6 to 30×10^6 Hz) are used in most commercial instruments for moisture determination. On the other hand, when large moisture contents are encountered, frequencies in the VHF range (100×10^6 to 300×10^6 Hz) can be used. Equipment is commercially available which measures either dielectric constant or dielectric loss factor [12]. Some manufacturers' literature indicates that moisture content readings should be accurate to less than $\pm$ 2 percent.

Instruments based on these principles have been used for 40 years by paper mills, textile mills, and wall board manufacturers to measure moisture in their products. Thus the various items of equipment are in an advanced state of development and have taken advantage of recent developments in electronics to enhance their dependability and portability. Available instruments make use of various electrode configurations. These electrodes, which are attached to a constant-frequency alternating-current source, establish a field in the material to be tested and influence the depth of penetration of the field. Current or power loss can be measured.

These instruments are lightweight and readings can be rapidly taken. When used in roof moisture surveys, readings are taken at selected points, for example, the intersection points of a grid laid out on the roof surface. A 5 ft x 5 ft (1.53 m x 1.53 m) grid has been used by one supplier of capacitance moisture determination service. Point measuring instruments which include capacitance, microwave, and nuclear types all have the same limitation in that they detect moisture in a relatively small region near the instrument and the result is considered to be representative of all material in that grid section.

Consequently, wet areas smaller than the grid dimensions might not be detected in the grid measuring approach.

Use of radio frequency equipment in roofing moisture detection should follow a general pattern that would also apply to other point measuring instruments. First, the wet-to-dry threshold reading should be established for a particular roofing system. This involves setting a dry base line reading for known dry areas based on coring results. Second, previous experience with roofing systems of similar construction would be used to relate the instrument reading to the amount of moisture present. Note that it is the relative reading or the amount that the wet reading differs from the dry that is significant. Third, the results of the readings taken at all points of the grid would be used to delineate the wet regions on a plan view of the roof. There are few references in the literature regarding the use of capacitance devices for measuring moisture in roofing applications. Two trade journal articles by a moisture detection service discuss the moisture problems in roofs and how their instruments may be employed [12, 13]. Technical publications are not available in the literature to verify the interpretation of their results.

3. CAPACITANCE-MICROWAVE INSTRUMENTS

3.1 DIELECTRIC PROPERTIES AT MICROWAVE FREQUENCIES

Microwaves, that is electromagnetic waves in the frequency range 10^8 Hz to 2.6 x 10^{10} Hz, have been employed in several different ways in moisture detection instrumentation. In all cases the propagation or reflection of microwaves is modified by the material involved and the modification can be related to the dielectric constant or the dielectric loss factor which were discussed in Section 2.1. While these instruments were not developed specifically for roofing moisture detection, all have had limited success in some type of moisture measurement application.

A discussion of the theoretical interaction of transmitted and reflected microwaves with dielectrics is presented by Hoekstra and Cappillino [11]. They demonstrate that either reflection or transmission modes could be used in detecting changes in the dielectric constant and dielectric loss factor and thus in detecting changes in moisture content. However, in both cases, for a fixed frequency input, it was found that specimen thickness had a marked effect on the result and thus had to be known. The authors predicted that for moisture detection, an input pulse containing a frequency shift (between input and output) would be related to moisture content. This concept was used in the device developed in the Boulder Laboratories of National Bureau of Standards and described in Section 3.2.

3.2 INSTRUMENTATION

One device, which was developed at the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers, is a microwave bridge or simply a waveguide with two arms [14] (see fig. 2). The sensing arm of the waveguide has one wall removed in a region which can be placed in contact with the material to be surveyed. The reference arm is instrumented so that the reference wave can be matched in phase and amplitude to the wave in the sensing arm. When the waves are recombined, one is 180° out of phase with the other and, if perfectly matched, the output is zero. During testing, the wave in the sensing arm can pass out of the waveguide into the test material, and its phase and amplitude are modified relative to the wave in the reference arm. The response in terms of phase shift and amplitude attenuation depends on the

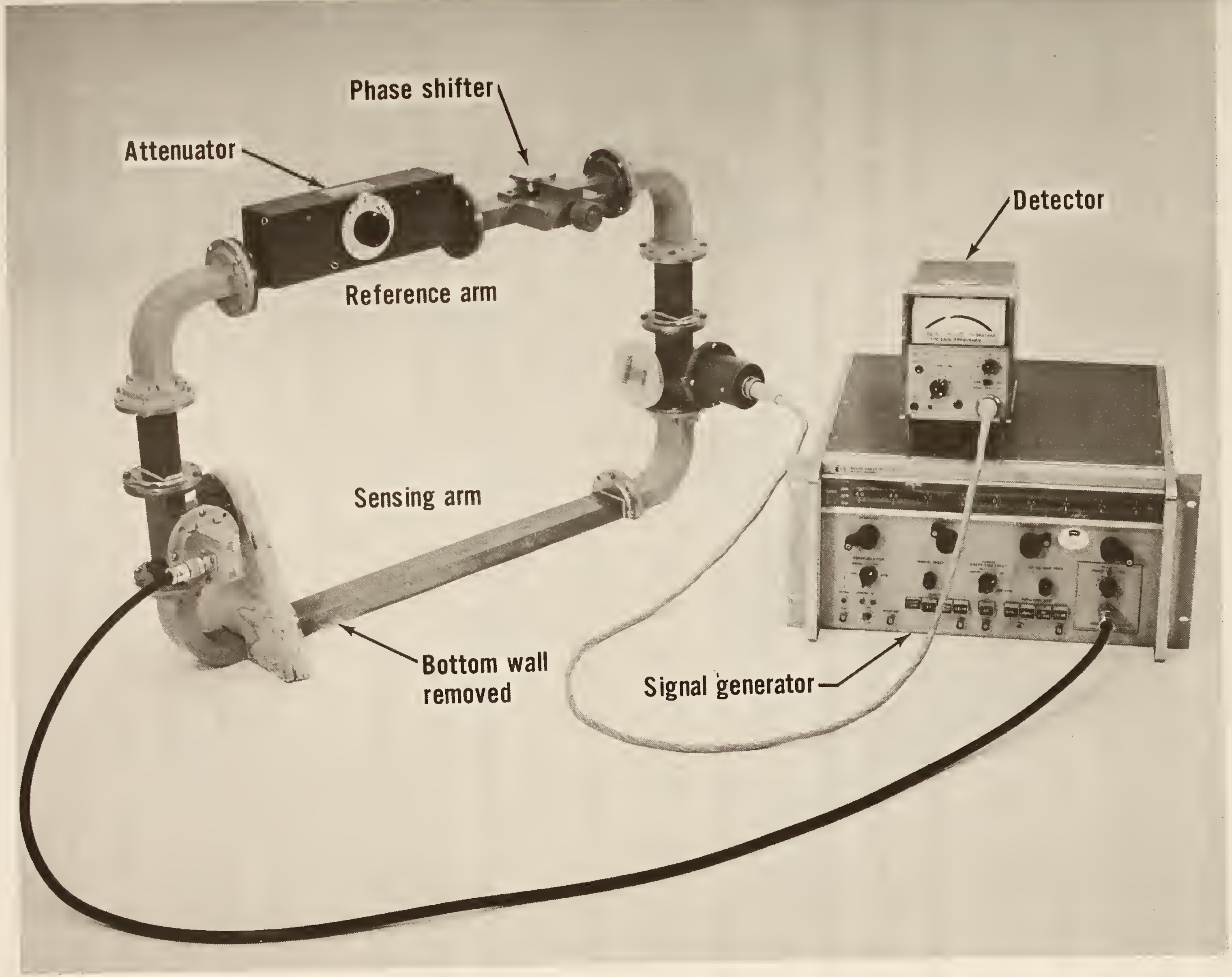

Figure 2. Microwave Bridge Moisture Detection System

dielectric constant and the dielectric loss factor, which are functions of moisture content of the test material. The system has been used to assess the degree of cure in concrete by measuring its moisture content. The equipment is not commercially available. It has been tried in roofing applications, but with erratic results caused, probably, by the layered structure of roofing systems.

A commercially available device, which is similar to the one described above, utilizes a resonant microwave cavity [15]. An opening in the side of the cavity allows the test material to influence the resonant frequency. Rather sharp resonances are obtained, thus making it relatively easy to detect a frequency shift due to changes in the dielectric constant of the material. This easily portable and stable instrument is used in the paper industry.

Another non-commercial microwave system was developed by the Boulder Laboratories of National Bureau of Standards. This is a frequency modulated, continuous wave (fm-cm) instrument operating in the 1×10^9 to 2×10^9 Hz frequency band. It transmits a signal which is reflected from an object or surface in a roof and is compared with an undisturbed reference signal [16]. The device is represented by the block diagram of figure 3. Microwave frequency is varied linearly with time for both the roof signal and the reference signal. If the roof signal arrives later at the mixer than the reference signal, the frequencies will be different and the frequency difference can be detected. The time of travel of the roof signal depends on the dielectric constant of the material traversed. A signal proportional to the product of the two frequencies is displayed. Peaks occur at points corresponding to interfaces in the system being analyzed and the spacing of the peaks depends on the specimen thickness and dielectric constant. If, for example, the specimen thickness is

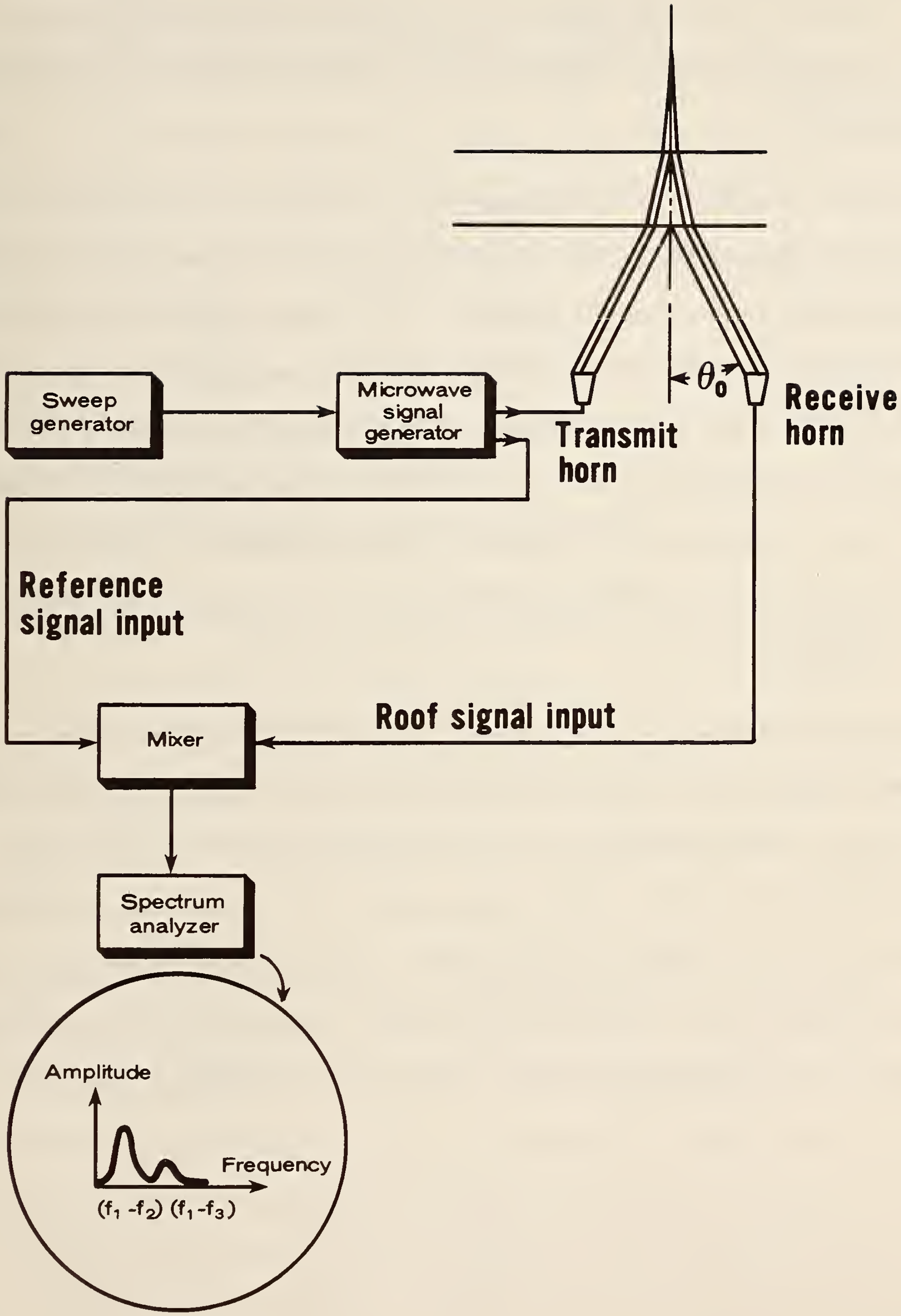

Figure 3. Block Diagram of the FM-CW Electromagnetic System

known, the dielectric constant can be calculated from the distance between peaks. The system has been used for measuring coal layer thickness. As noted earlier, the application of this system for detecting moisture in roofing is being evaluated.

Impulse radar is another possible approach for detection of moisture in roofing although probably too bulky for field application at present. This system uses short duration pulses which are comparable to frequencies ranging from VHF to microwave and the differences in travel time or in amplitude for various echos are measured. The dielectric constant of the material traversed can be calculated from the results [17]. It is used primarily in geophysical applications for subsurface profiling [18]. Studies at CRREL showed the impulse radar could detect both variation in moisture content in built-up roofing and degree of cure in concrete [17].

All of the systems discussed in this section should be regarded as being in the development stage from the point of view of moisture detection in roofing. While they may not be suitable for routine moisture surveys at this time, they have potential for possible future development. In roofing practice, these systems would be point measuring instruments. Thus they would be used by taking readings at the intersections of a grid laid out on the roof surface and would have the disadvantages inherent in all point measuring instruments.

4. NUCLEAR METER

4.1 NEUTRON SCATTERING AND THERMAL NEUTRON DETECTION

Nuclear meters are used in the measurement of both moisture content and density in soils, portland-cement concrete, asphaltic concrete, and roofing materials. These meters, in brief, consist of a radioactive isotope source, a detector or counting device, and readout equipment. For some meters the radioactive isotope source is shielded. In commercial meters, the isotopes used are radium 226-beryllium, cesium 137, or americium 241-beryllium which are packaged in such a way that the radiation hazard is relatively low. These isotopes produce primarily two types of radiation, namely: gamma rays from cesium 137 or fast neutrons from radium-beryllium and americium-beryllium.

Gamma rays or gamma photons are used exclusively in density measurement and, while this is applicable to roofing materials, it is not the primary interest here. If the source is cesium 137 and the detector is a gamma photon detector, density would be measured by a backscattering process in which the photons collide with atoms in the material and follow an irregular path to the detector [19, 20].

Fast neutrons from radium-beryllium or americium-beryllium are involved in moisture content measurements. Referring to figure 4, fast neutrons from the source enter the material and are both scattered and slowed down by collision with the nuclei of the atoms composing the material. Nuclei of all materials slow down the neutrons by momentum exchange but the speed reduction is greatest for collisions with hydrogen nuclei which have about the same mass as the neutrons. Some of the slow neutrons or thermal neutrons are scattered in such a way that they reach the slow neutron detector and are counted for a specified

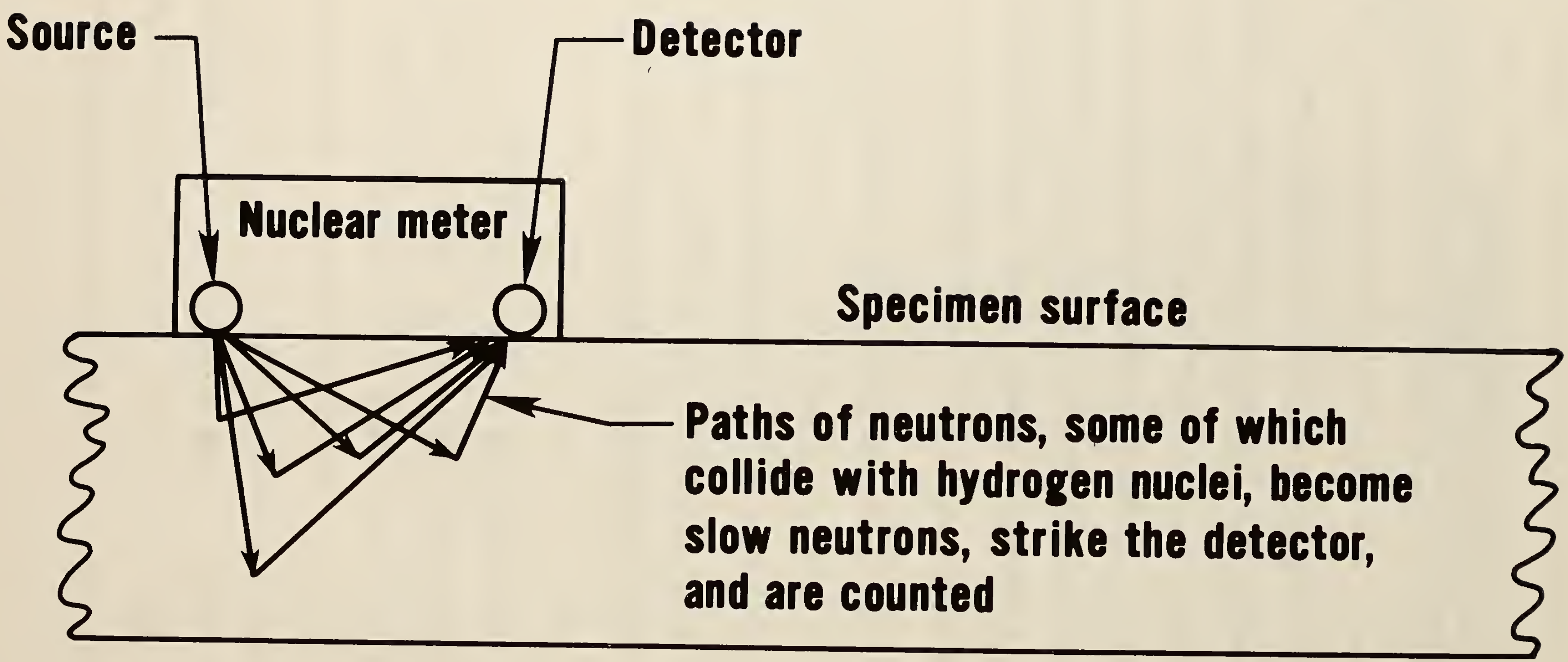

Figure 4. Backscattering Mode of a Nuclear Meter

period of time. The thermal neutrons reaching the detector are much more likely to have collided with a hydrogen nucleus than other atomic nuclei since the scattering cross-section of hydrogen is greater than for other atoms likely to be present. In short, the activity of the detector is principally due to neutron collisions with hydrogen nuclei. Generally, the detector measures the backscattering of slow neutrons which have collided with hydrogen nuclei in the surface region, since nuclei at a large distance from the source have little influence. However, the depth of measurement may be 2 to 8 inches (0.05 to 0.20 m) in soils [19, 20].

4.2 MOISTURE AND NEUTRON SCATTERING

The presence of water in a material, such as roofing or soil, furnishes hydrogen nuclei for this slowing process. Since the activity in the detector is related to the total amount of hydrogen present in the surface region, the interpretation of the reading as being due to moisture alone may not be valid. The asphalt in a membrane or other hydrocarbons in the insulation may contribute to a reading. Suppose that a series of readings has been made on a roof and the lowest reading is treated as the dry insulation reading. If a nuclear meter reading is made at a selected point and the reading is greater than the "dry" reading, this might be caused by a higher moisture content or, it might be due to a greater bitumen thickness [21].

4.3 APPLICATION TO ROOFING

The nuclear meter is a "point" measuring device because backscattering from surface material in the immediate neighborhood of the instrument is measured. Since the neighborhood is "small" compared to the area of a grid, it may not be representative of the entire area. When measurements are made at the intersections of a grid on the roof surface, wet areas smaller than the grid dimensions could be missed. A 10 ft by 10 ft (3.05 x 3.05 m) grid is frequently used with the nuclear meter.

Although not directly related to moisture determination in roofing, it should be noted that gamma ray and fast neutron sources have been used in the soils and concrete fields since the early 1950's. Typical of early work in back-scattering of slow neutrons in concrete is that of Pawliw and Spinks [22]. They found that the volume of material which has an influence on backscattering varied with the water content. Representative of early work on soil moisture determination is that of Davidson, Biggar, and Nielsen [23], Gurr [24, 25], Ferguson and Gardner [26], and Rawlins [27]. The researchers just cited, [23-27], employed a gamma ray transmission technique. Commercially available nuclear meters, rather than the laboratory set-ups noted above, have been widely used for soil moisture and soil density measurements in the field. Waterways Experiment Station of the U.S. Army Corps of Engineers has evaluated many of these devices and they concluded that soil water contents can be determined rapidly by nuclear meters with sufficient accuracy for most field work [20]. However, individual instrument calibration curves were required to obtain this accuracy [28]. In general, the success of the nuclear meter in the soil area encouraged its application to roof system moisture measurement. Application of the nuclear meter to identify wet roof areas began in the early 1970's. Some of the disadvantages of the method are that a reference dry reading must be established for each roof and that variation in thickness of mineral surfacing can cause uncertainty in meter reading [21].

In field use of nuclear meters, the user is interested in establishing a wet-to-dry threshold reading and in determining how roof construction variables affect the readings. One approach to obtaining this information is contained in a comprehensive set of roof observations and analyses carried out by Waterways Experiment Station [29]. Roofs of several different types and at various locations were surveyed using a 10 ft x 10 ft (3.05 m x 3.05 m) grid for taking readings. Core samples were taken on each roof at various positions including edges, center span, and expansion joints. A statistical data reduction scheme for the nuclear meter readings was followed. The analysis dealt with roofs which had wet areas, i.e., had some wet as well as some dry cores. In each of these cases, the threshold reading was determined from bimodal frequency versus meter reading histograms, i.e., histograms for dry areas and histograms for wet areas. The threshold reading was defined as the lowest reading expected in a wet area. Clearly, this procedure requires a substantial amount of data analyses.

Another interesting result of the study was a demonstration that readings near the edge of the roof or near expansion joints were greater than readings away from edges or joints. This was probably due to greater bitumen thickness near edges or joints. Suggested average correction factors are given for these areas where membrane thickness may be greater than average.

While statistical approaches like the above are valuable, verification of wet and dry regions by taking cores is also very important. The number of construction variables which occur in roofing is sufficient that statistical prediction alone should not be depended on.

There have been a number of field studies in which areas of roofs identified as wet by infrared scanner systems also gave wet indications by nuclear meters. This is true for both airborne infrared scanner results, [29, 30] and on-the-roof hand-held infrared scanners [31, 32, 33]. In these field studies, it should be noted that the nuclear meter was not regarded as the primary moisture detection instrument but was simply compared with the infrared system.

5. THERMAL INFRARED

5.1 BACKGROUND INFORMATION

Infrared instrumentation of the scanner type has been widely used in roof moisture detection, in assessing the relative heat loss through walls, and in aerial reconnaissance. These instruments, called thermographic instruments, sense the intensity of radiation from a surface, such as a roof surface, and display a monochrome image whose density corresponds to radiation intensity. The radiant energy levels can be interpreted as surface temperatures if the emittance of the surface is known. Since the surface temperature, for fixed emittance, is responsible for the instrument indication, it follows that moisture must cause a change in surface temperature for its presence to be known.

Briefly, infrared scanners consist of a sensing or camera-like unit and a display or recording unit. The elements of the camera unit are shown schematically in figure 5 and these components scan the viewed area and focus the individual "points" on a sensor or radiation detector. As shown in figure 5, the radiant flux which is related to the temperature of the selected viewing area passes through an infrared transparent lens and a mechanical-optical scanner. The mechanical-optical scanner, which consists of rotating or vibrating mirrors or prisms, provides a vertical and horizontal scan of the

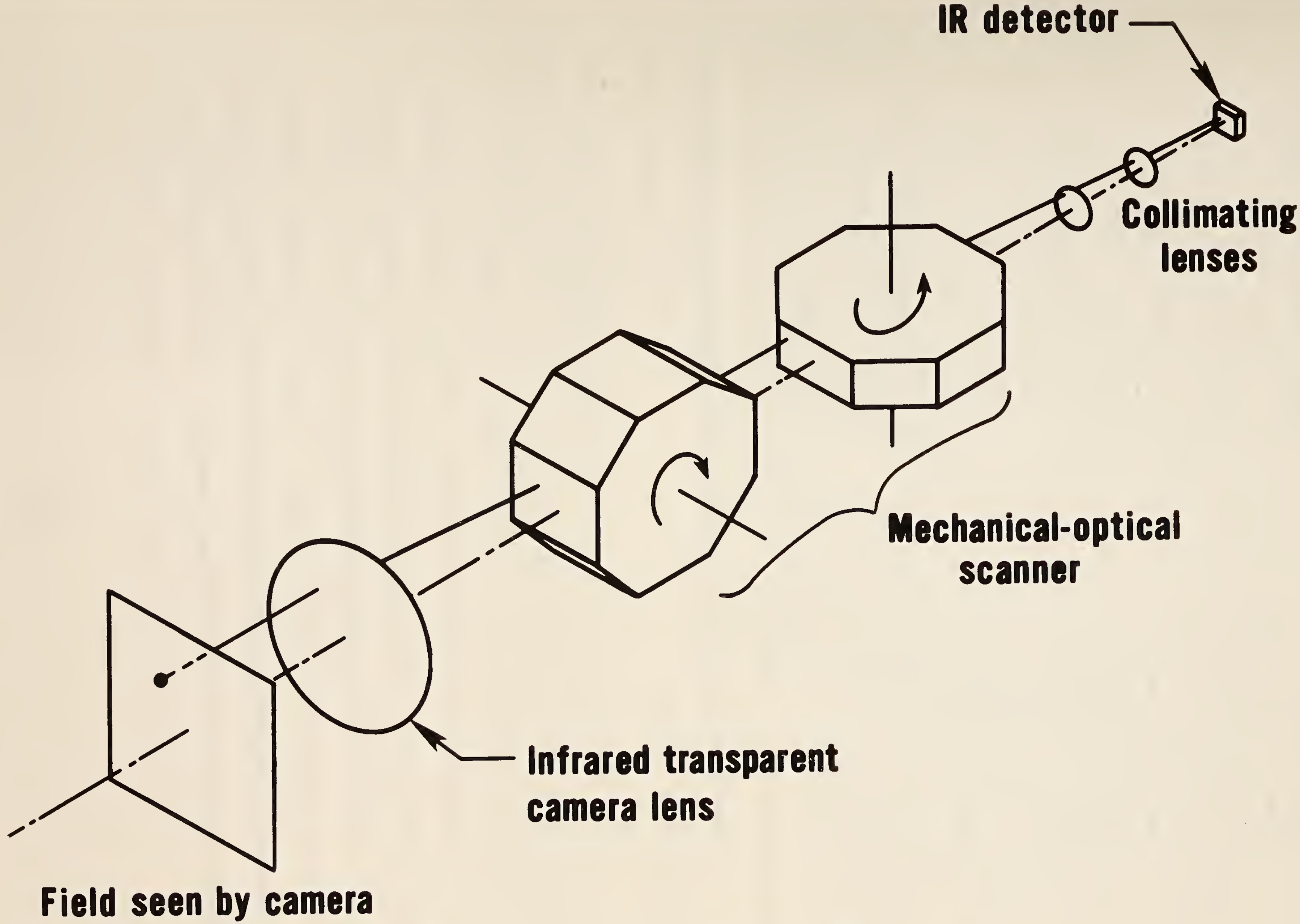

Figure 5. Schematic of Infrared Camera

virtual image from the lens. In airborne scanners, this mechanical-optical system scans in the lateral direction only and scanning in the other direction is provided by motion of the aircraft along the flight path. Finally, the infrared beam from a small region of the total image is focussed on a photo-voltaic detector which is sensitve to infrared radiation. Commercial infrared cameras often use either an indium-antimonide or a mercury-cadmium-tellurium detector. Systems using the former detector sense radiation in the 2×10^{-6} to 5.6×10^{-6} m wavelength band while systems which use the latter operate in the 8×10^{-6} to 14×10^{-6} m wavelength band. The signal output of the detector is used to modulate the beam intensity of a cathode ray tube (CRT) in the display unit. Grey tones in the CRT image correspond to various radiation intensities (or apparent radiance temperatures). Operation of the system is much like that of a video or television system and thermograms are made by photographing the "picture tube" display.

There are four characteristics of infrared scanners which make them distinct from the NDE methods of the previous sections. First, simultaneous measurements of apparent roof temperatures can be made over large areas in the field of view and not just at selected grid intersections. Second, the quantity measured is well defined and thus ambiguities do not arise over the volume of material sampled, although differences in material thicknesses may affect response. Third, observations can be made at a great distance from the roof surface as in the remote sensing mode. Fourth, the ability to detect moisture in a roofing system depends upon heat flow through the roof.

5.2 THE THERMAL RADIATION PHENOMENON

A few observations on the physical mechanism of thermal radiation may be helpful in relating physical properties to the radiation intensities. Energy, in the form of thermal photons, is emitted from any surface which is at a temperature above absolute zero. The intensity of the radiation is greater at higher surface temperatures and has a different distribution of wavelengths depending on the surface temperature. This is shown in figure 6 for a black body. The black body, an idealization, is more properly defined as a perfect absorber, that is, no photons are reflected by the body itself. In a black body, all energy leaving the surface is emitted, not reflected. One practical observation that comes from figure 6 is that working with a surface at higher temperatures results in much higher radiation intensities.

The monochromatic emissive power plotted in figure 6 can be expressed in equation form as follows:

$$q(\lambda) = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT}-1)}$$

where: h = Planck's constant

c = Speed of light

k = Boltzmann's constant

λ = Wavelength of radiation

T = Absolute temperature

This is called the Planck distribution function or Planck's Law. $q(\lambda)$ is the monochromatic emissive power or the rate of energy emission per unit area per unit wavelength at wavelength λ. Another way of defining $q(\lambda)$ is

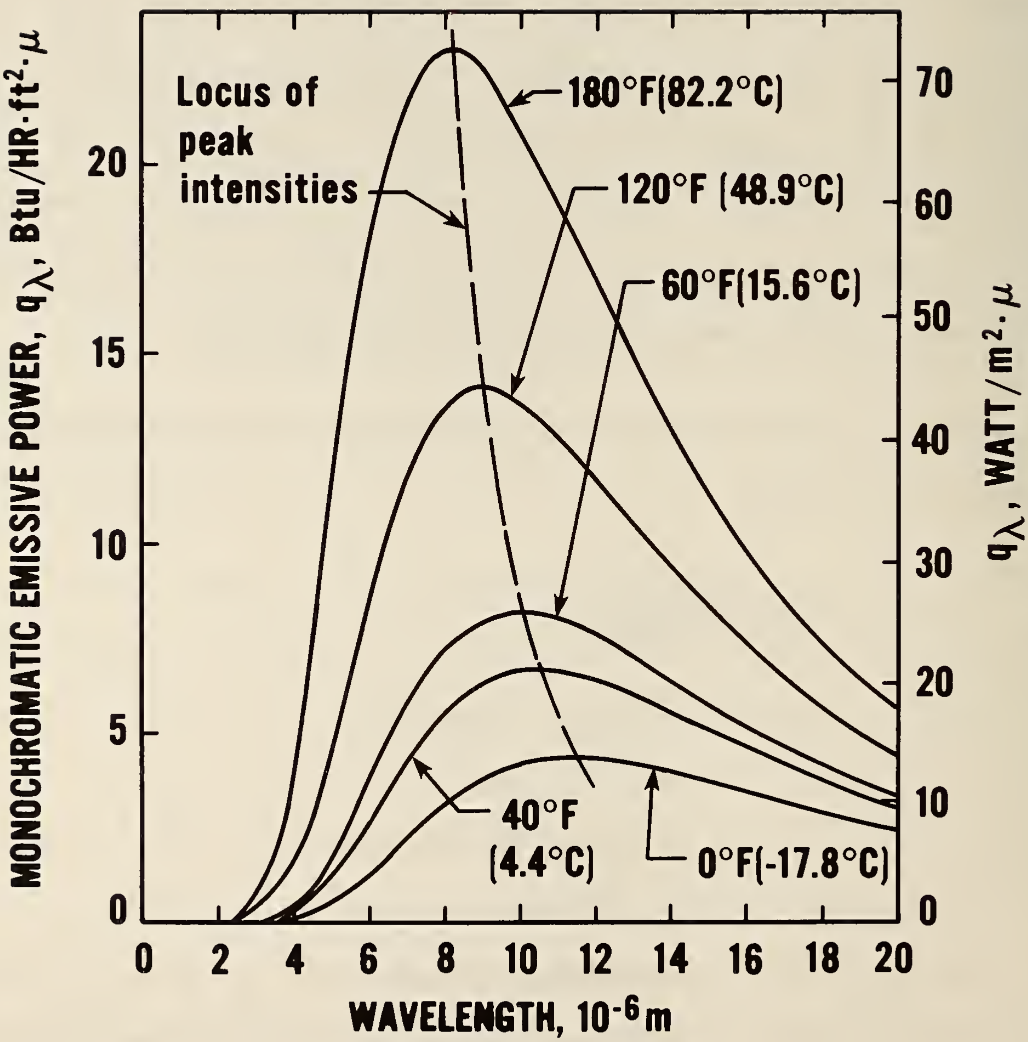

Figure 6. Monochromatic Emissive Power of a Black Body Radiator

$$q(\lambda) = \frac{dQ}{d\lambda}$$

where: Q = Total emissive power

The above implies that Q represents the area under one of the curves in figure 6, or

$$Q = \int_0^\infty q(\lambda)\, d\lambda$$

If the formal integration over all wavelengths is carried out, we obtain Stefan's Law for a black body,

$$Q = \sigma T_1{}^4$$

where: σ = Stefan-Boltzmann constant

T_1 = Absolute temperature of black body radiator

The monochromatic emissive power curves in figure 6 are calculated for temperatures which may be encountered in roofing moisture analysis. Note that the peak occurs at a wavelength which decreases as the surface temperature increases. For example, the peak occurs at $\lambda = 8.2 \times 10^{-6}$ m at 180°F while the peak occurs at $\lambda = 11.4 \times 10^{-6}$ m at 0°F. The image intensity in the infrared scanner would be equal to the area under the curve in the interval of wavelengths to which the instrumentation was sensitive. For some scanners this would be 2×10^{-6} to 5.6×10^{-6} m.

It should be noted that infrared photographic emulsions, which are used in aerial photography or in conventional photography, are not suitable for recording thermal infrared radiation from objects in the 0°F to 180°F temperature range [34]. The longest wavelength to which this film is sensitive is 1×10^{-6} m and it is clear from figure 6 that observed intensities would be negligible at that wavelength.

To aid the reader in converting from wavelength to frequency, which was used in earlier sections, figure 7 presents a plot of the two parameters. This might be thought of as a frequency-wavelength conversion chart for electromagnetic radiation. The frequency-wavelength of the various types of phenomena which have been discussed are also plotted.

5.3 FACTORS WHICH AFFECT SURFACE TEMPERATURE

As noted earlier, thermal infrared scanners can only be effective for moisture detection in the roof system if the presence of the moisture produces a change in surface temperature. Since the moisture will primarily be located in the insulation, it would be expected that a change in heat flow through the roof must occur if moisture is to affect the surface temperature. Moisture will influence two heat transfer parameters, the thermal conductance and the heat capacity. By definition, heat capacity is the product of density and specific heat. Laboratory test results indicate that thermal conductance of insulation increases with moisture content. Heat capacity of insulation also increases with the moisture content. Because wet insulation has a higher conductance and a higher heat capacity than does dry insulation, the roof surface over wet areas will exhibit different temperatures than the surface over dry areas. Further, moisture in the insulation will influence the roof surface temperature under both steady-state (where conductance governs) and transient conditions (where both conductance and heat capacity are involved).

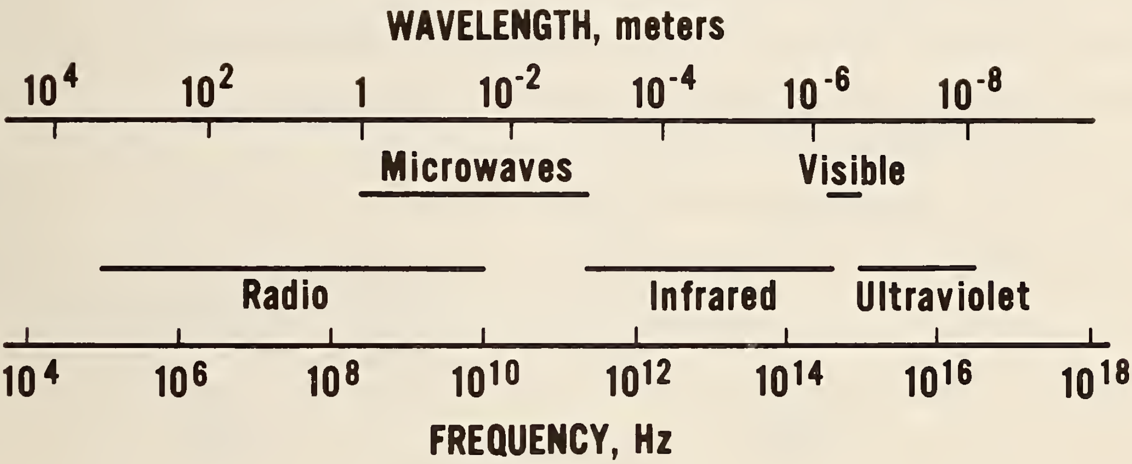

Figure 7. Electromagnetic Spectrum

To illustrate the effect of moisture on the surface temperature, consider two relatively common cases. In the first case, shown on the left side of figure 8, heat flows outward through the roof since the interior temperature, T_i, is higher than the exterior temperature, T_o, and the membrane surface radiates energy to the night sky. In the second case, shown on the right side of figure 8, heat flows inward through the roof because of the higher external temperature and solar radiation impinging on the membrane surface. Roughly, the first case corresponds to nighttime conditions particularly during the winter while the second case corresponds to daytime conditions in the summer.

Using an exact mathematical solution [35], a theoretical analysis was performed for one-dimensional heat flow through a slab of thickness, ℓ, which is bounded by air at temperature, T_o, on the exterior and by air at temperature, T_i, on the interior. This roughly simulates a roofing system like that shown in figure 8. From this analysis, it was predicted that the temperature of the exterior surface of the slab should be:

$$T_{so} = \sum_{n=1}^{\infty} \left[A_n X_n e^{-KB_n^2 t} \right] + T_o + (T_i - T_o) \frac{R_o}{R_{total}}$$

$$+ R_o \left(1 - \frac{R_o}{R_{total}}\right)(\alpha I_{in} - \varepsilon I_{out})$$

In the above equation, B_n depends on the total thermal resistance of the slab, on the resistance of air layers at the exterior and interior surfaces, and on the slab thickness, ℓ. Also, A_n and X_n depend in turn on B_n, on the initial temperature distribution through the slab, and on the steady-state temperature distribution in the slab. The steady-state temperature is discussed below. Other factors are defined as follows:

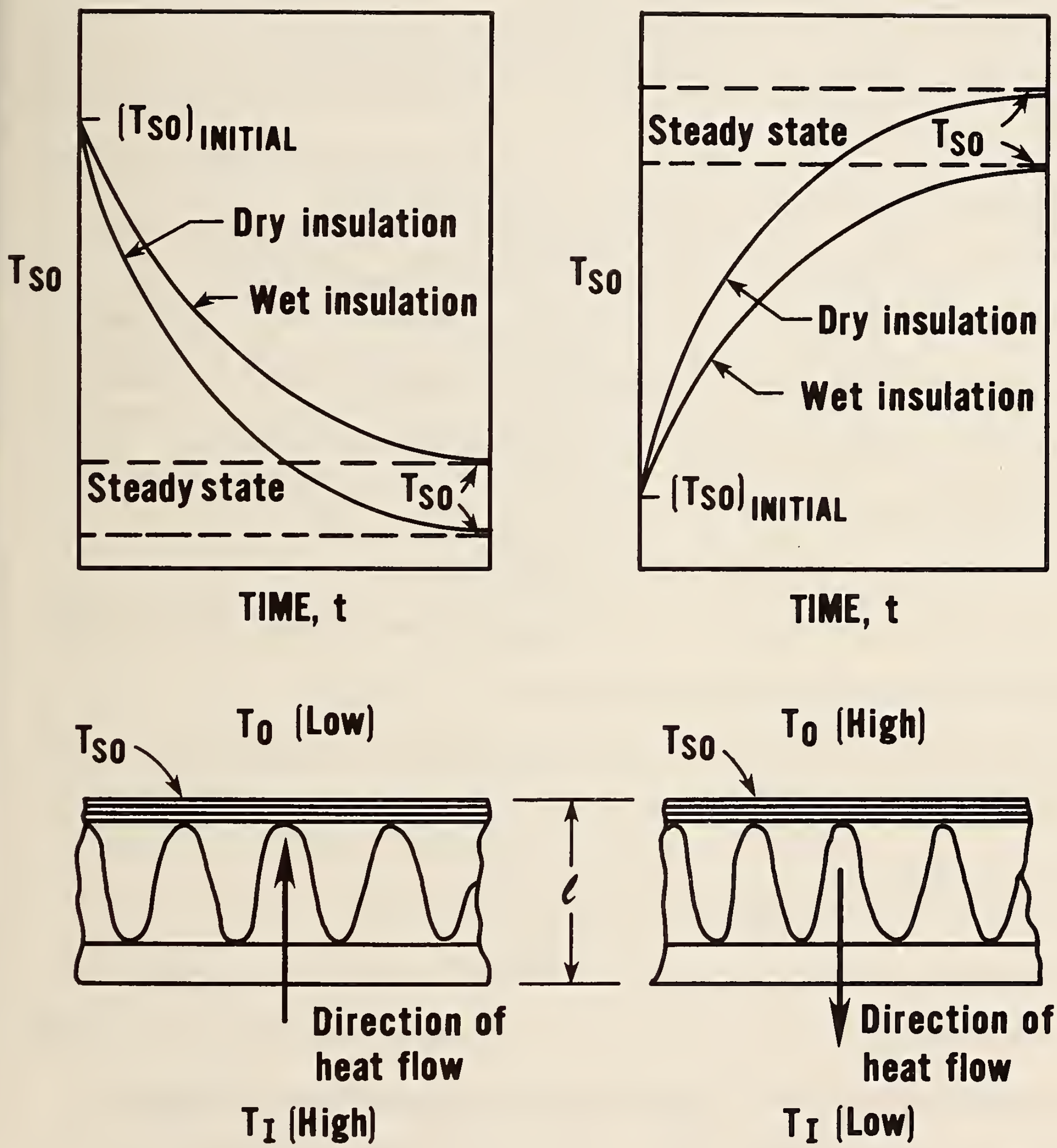

Figure 8. Roof Surface Temperature, T_{so}, for Dry and Wet Insulation

t = Time (h)

T_{so} = Exterior surface temperature (°F)

T_o = Exterior air temperature (°F)

T_i = Interior air temperature (°F)

K = Diffusivity (ft^2/h) = $\ell / R_{roof}\ \rho \cdot C_p$

R_{roof} = Thermal resistance of the slab or simulated roof ($h \cdot ft^2 \cdot °F/Btu$)

ρ = Density of the slab or simulated roof (lbm/ft^3)

C_p = Specific heat of the slab or simulated roof (Btu/lbm°F)

R_o = Thermal resistance of the exterior air layer ($h \cdot ft^2 \cdot °F/Btu$)

R_i = Thermal resistance of the interior air layer ($h \cdot ft^2 \cdot °F/Btu$)

$R_{total} = R_o + R_i + R_{roof}$ = Thermal resistance of the slab and the exterior and interior air layers ($h \cdot ft^2 \cdot °F/Btu$)

α = Absorptance of the slab or roof surface

I_{in} = Total radiation incident on the slab or roof surface ($Btu/h \cdot ft^2$)

ε = Emittance of the slab or roof surface

I_{out} = Total radiation emitted from the slab or roof surface ($Btu/h \cdot ft^2$)

In the equation for T_{so}, the first term is the transient term which indicates that T_{so} varies with time according to an exponential law at "short" times. This is represented by the curves plotted in figure 8. As time increases the magnitude of the transient term decreases and at "long" times the last two terms or steady-state terms predominate. The horizontal dashed lines in figure 8 represent the steady-state temperatures. To give some idea of what is meant by "long" time for a roofing system, calculations of the cooling of the Earth's surface at night indicate that the transient period could be as long as 4 hours.

In practice, adequate time must be allowed for steady-state conditions to be established or approached and an allowance of several hours is reasonable.

Curves are plotted in figure 8 for both dry and wet insulation. For outward heat flow as indicated in the left hand portion of figure 8, suppose that the sequence starts with T_{so} relatively large and that T_o drops to a winter night value. In that case, the roof surface over dry insulation cools to a lower steady-state temperature than the roof surface over wet insulation. For inward heat flow as indicated in the right hand portion of figure 8 (the summer day case) the sequence starts with T_{so} at the low night value and T_o rises to a high summer day reading. The roof surface over dry insulation will warm to a higher steady-state temperature than the roof surface over wet insulation under these conditions. The predicted situations of the last two paragraphs have been confirmed by roof temperature measurements and by other calculations [36, 37, 38, 39].

In order to give the reader an idea of numerical values of the roof surface temperatures which could be expected in the situations described above, calculations of steady-state temperature for a typical roofing system have been made and the results summarized in table 1. The steady-state surface temperature is obtained by eliminating the transient terms in the previous equation for T_{so}, resulting in

$$\varepsilon I_{out} + \frac{R_{tot}}{R_o(R_{tot} - R_o)} T_{so} = \frac{T_o}{R_o} + \frac{T_I}{(R_{tot} - R_o)} + \alpha I_{in}$$

Table 1. Steady-State Roof Surface Temperatures

Condition	T_i (°F)	T_o (°F)	Wind Speed (mi/h)	T_{so} dry insul. (°F)	T_{so} wet insul. (°F)	ΔT_{so} (°F)
	72	20	0	1.2	14.5	13.3
Winter	72	20	5	12.4	17.5	5.1
Night	72	20	10	15.2	18.3	3.1
	72	20	15	16.5	18.8	2.3
	72	40	0	22.0	30.9	8.9
Winter	72	40	5	32.4	34.9	2.5
Night	72	40	10	35.2	37.2	2.0
	72	40	15	36.5	37.9	1.4
	78	60	0	43.8	49.6	5.8
Summer	78	60	5	52.7	54.5	1.8
Night	78	60	10	55.7	57.2	1.5
	78	60	15	56.7	57.7	1.0
	78	100	0	159.3	149.1	-10.2
Summer	78	100	5	130.7	126.8	-3.9
Day	78	100	10	120.5	118.3	-2.2
	78	100	15	115.3	113.9	-1.4

Since the emitted radiation, I_{out}, can be represented as

$$I_{out} = \sigma T_{so}^{4},$$

the above equation can be solved for T_{so}. For the results repo

the thermal resistances were:

Component	$(R_{tot} - R_o)_{dry}$	$(R_{tot} - R_o)_{wet}$
3/8 in membrane [5]	0.33	0.33
2 in perlite insulation	5.00 [5]	1.19 [40]
Steel deck [5]	Negligible	Negligible
Interior surface [5]	0.61	0.61
	5.94	2.13

Resistances listed are in $\frac{hr \cdot ft^2 \cdot {}^\circ F}{BTU}$ units. The resistance o

air layer, R_o, is calculated from [41]

$$\frac{1}{R_o} = 0.5 + 0.38W$$

where W is wind speed in mi/h. The incident sky and solar radia depends on the exterior air temperature, T_o, and varies from a v 53.8 Btu/hr $\cdot$ft^2 at T_o = 20°F under night, clear-sky, conditions 300 Btu/hr $\cdot$ft^2 at T_o = 100°F under day, clear-sky, conditions.

The roofing membrane thermal resistance would be typical for fou 15 organic felts with gravel surfacing. A two-inch perlite insu assumed and the wet insulation resistance value which would char rial having 50% moisture by volume is based on recent work at NB that this is extremely wet insulation. The interior temperature conditions is taken to be 72°F (22°C) while for summer condition be 78°F (26°C). Two winter night exterior air temperatures are a rough indication of the effect of the inside to outside temper

The values presented in table 1 for steady-state roof surface temperatures support the general observations already made. For the winter night conditions representing outward heat flow, the roof surface over wet insulation is warmer than the roof surface over dry insulation. The greatest dry-to-wet temperature difference occurs when the external wind speed is zero. Conversely, the least dry-to-wet temperature difference occurs at the maximum convection condition (i.e., 15 mi/h (24 k/h) wind speed). Further, the dry-to-wet temperature difference is greater for an exterior air temperature of 20 °F (-6.7 °C) than for an exterior air temperature of 40 °F (4.4 °C).

For summer night conditions, we have an exterior temperature of 60 °F (16 °C) and, as before, the roof surface over wet insulation is warmer than the roof surface over dry insulation. However, the dry-to-wet temperature difference is less than for either of the winter night cases. In spite of this the temperature differences are thought to be large enough for most infrared scanners to detect the presence of wet insulation.

For summer day conditions, the roof surface over the wet insulation is cooler than the roof surface over the dry insulation. Again the greatest dry-to-wet temperature difference is found when the exterior wind speed is zero. Note that the exterior air temperature, 100 °F (38 °C), is extreme for many parts of the United States. It was selected to provide as large an exterior to interior temperature difference as could be reasonably expected.

Since a large dry-to-wet temperature difference provides greater contrast in the thermogram and thus easier identification of wet areas in the insulation, it is clear that low exterior wind speed and low exterior temperature give better night observation conditions than high wind speed and high exterior temperature.

Recall that the wet insulation is extremely wet in this example. Thus the predicted roof surface temperatures over wet insulation are higher under night conditions and lower under day conditions than would be the case if the insulation were not as wet.

To this point, predicted surface temperatures have been discussed. However, the infrared scanner actually senses an apparent radiance temperature, T_{APP}. There are two basic reasons for this. First, the roof not only emits radiation because it is at temperature T_{so} but also it reflects radiation from the night sky, the sun, and other sources. For roofs which have an emittance of about 0.9, about 0.1 I_{in} would be reflected. Even at night, this amount of reflected radiation makes a significant contribution to the total radiation from the roof surface. Second, the scanner "sees" only a part of this emitted plus reflected radiation since it is sensitive to a limited range of wavelengths. As noted, detectors operate in the 2×10^{-6} to 5.6×10^{-6} m or in the 8×10^{-6} to 14×10^{-6} m wavelength ranges. Consequently, to calculate the area under one of the curves in figure 6, we do not integrate over all wavelengths but only between the appropriate wavelength limits, or

$$Q = \int_{\lambda_1}^{\lambda_2} q(\lambda)\, d\lambda.$$

This does not result in Stefan's Law but another relationship which can be approximated as

$$Q = CT^n$$

over a limited temperature range. The values of C and n depend on the specific wavelength range, λ_1 to λ_2, which is selected.

After some algebraic manipulation an expression for T_{APP} is obtained:

$$T_{APP} = [\varepsilon \, T_{so}{}^{n} + (1-\varepsilon) \frac{1}{C} I_{in}]^{1/n}$$

Using this equation, apparent radiance temperatures, T_{APP}, were calculated for the various cases listed in table 1. Although they differ from those listed, the apparent radiance temperature differences between points over dry and wet insulation are virtually the same as the corresponding "actual" surface temperature differences.

CRREL [31] has observed that differences between wet and dry areas are obscured when viewing in the daytime with hand-held infrared equipment. A "mottled" or "blotchy" appearance of the thermogram seems to be responsible for this. Thus while there are predicted temperature differences in the roof surface over wet and over dry areas, infrared scanners may not be able to detect these differences.

Reflected radiation may be the cause of the "mottling" seen by CRREL, since local variations in flatness and local changes in reflectance could result in different intensities of radiation sensed by the equipment. Thus T_{APP} could vary from point to point for fixed T_{so}. A similar effect can occur at night when reflected radiation from the night sky is considered but the effect is smaller than the solar effect during daylight.

As noted above, roof surface temperatures different from the dry background temperature or "anomalies" in the roof surface temperature pattern may be caused by moisture. "Anomalies" can also be caused by structural members such as roof joists, by reinforcement in concrete or by subpurlins in insulating concrete decks. They can be caused by variations in the insulation thickness or by abrupt changes in the membrane construction such as changes in the number of felts or thickness of bitumen. Any structural feature which alters heat flow through the roof and heat storage in the roof can influence the surface temperature pattern and thus the thermographic image. In addition, hot air from vents and the like can increase surface temperature which could be interpreted incorrectly. Finally, the roof surface temperature can be altered by surface convection (wind) which may vary from point to point on the roof. Some of these problems and their effect on surface temperature have been discussed by Link [37] and by Goldstein [36]. Careful interpretation of the results from an infrared scanner is certainly necessary, and the interpreter must be familiar with roofing construction and roofing problems. It is recommended that cores must be taken for verification of suspected wet areas.

5.4 AIRBORNE INFRARED SCANNERS

Airborne infrared scanners comprise a particular class of instruments which are used in remote sensing or aerial reconnaissance applications. By definition they are aircraft mounted systems in which the scanner operates in the direction lateral to or normal to the flight path. The forward motion of the aircraft provides scanning of the field along the flight path. In general, precise control of aircraft heading, attitude, and ground speed is necessary for good results. When the aerial mapping mode of operation is used, the data are recorded on film or on magnetic tape. Viewing and interpretation is done on the ground. The Manual of Remote Sensing [42] is a good general source of information on this topic. Infrared surveys of the type just described are available through a number of consultants and aerial mapping firms, including for example [30, 43, 44]. Several different manufacturers produce thermal infrared scanners (see table 8-2 of Reference [42]), and these employ sensors which operate in both the 2×10^{-6} to 5.5×10^{-6} m and the 8×10^{6} to 14×10^{-6} m wavelength ranges.

The thermal and spatial resolving ability of the airborne scanner should be understood if the system is to be used correctly in roofing moisture detection. Basically the problem is one of detecting "small" temperature differences between "points" in an image of a roof, or very likely several roofs, and other terrain features. Thus wet insulation might be present but the temperature difference between points on the roof surface over the wet insulation and dry insulation would be too small to detect. Similarly, wet insulation might be present but the region affected would be too small to be sensed.

Temperature resolution in airborne infrared scanners, and in other infrared scanners, is not a constant value, e.g. 0.5°F (0.3°C). Minimum detectable temperature differences depend on the temperature of the surface viewed [37]. This is demonstrated by applying the following equation

$$Q_1 = \varepsilon\sigma(T_1^4 - T_2^4)$$

for a grey surface and the full spectrum of wavelengths. Q_1 is the total emissive power. If T_1 = 102°F (39°C) and T_2 = 100°F (38°C), there is a 2°F (1°C) temperature difference and Q_1 equals 2.18 Btu/h•ft^2. If T_1 = 22°F

(-5.6°C) and T_2 = 20°F (6.7°C), Q_1 equals 1.37 Btu/h•ft^2. It is seen that for a particular temperature difference (here 2°F), higher temperatures induce a greater total emissive power than lower temperatures. Note that Q_1 represents the total radiation from the surface and that the scanner would respond to only a part of this radiation because it is sensitive to a limited wavelength band.

As discussed to this point, the temperature resolution problem is no different in airborne infrared from that in hand-held infrared. However, some airborne infrared scanners have an automatic gain control feature which creates some unique problems in roofing moisture detection. A large temperature difference between roof and surroundings can pose a particular problem. Because of the automatic gain control, the available range of intensities is adjusted to fit between the observed temperature extremes. Of course, the image will be all black or all white at the ends of the intensity range and might show the roof area as totally white or totally black. In other words, the problem may arise when the roof surface is the "hottest" or the "coldest" object in the field of view. Link [37] discusses this problem in some detail.

Spatial resolution in infrared scanners refers to the size of the "spot" on the ground that is viewed at a given instant of time. The sensitive part of the infrared detector is small (typically 0.35 x 10^{-3} m in diameter) in size. When this region on the detector is projected through the optical system to the field plane (see figure 5), the size of the region on the field plane is magnified and depends on the distance of that plane from the infrared camera. For many infrared systems, the resolution, which is defined as the solid angle subtended by the sensitive part of the detector, ranges from 1.0 to 2.5 milliradians measured from the optical axis [41]. For example, at 1,000 ft (305 m) altitude the radius of the "spot" would be 2 ft (0.6 m) if the angle is 0.002 radian.

In addition to the two types of resolution already discussed, there is an atmospheric resolution or atmospheric attenuation of the radiation intensity to be considered. This is minimized by using the 8×10^{-6} to 14×10^{-6} m wavelength range since there is high atmospheric transmission at these wavelengths. Low flight altitudes have the advantage of shortening the transmission path length which may reduce atmospheric attenuation [41].

The Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers has evaluated airborne infrared from fixed wing military reconnaisance aircraft as a tool for detecting moisture in roofing systems. While military reconnaisance aircraft were used in the WES work, it is thought that their observations may apply in general to the method. Preliminary work was done, under WES guidance, at Offutt Air Force Base in November, 1974. This activity provided the techniques which were used in subsequent work and led to the conclusion that airborne infrared was a valid method for rapid evaluation of roofs of an entire installation [29, 37]. In May, 1976, a program of observation and evaluation was performed at Pease Air Force Base and at Offutt Air Force Base. A total of nearly 250 buildings were surveyed [38]. In each of the locations, measurements were made of roof temperatures over dry areas and over previously identified wet areas. This was done to establish that the maximum temperature difference between wet and dry areas occurred roughly between 10 p.m. and midnight and flights were made within that time period. In all cases the thermal infrared scanners in the reconnaisance aircraft sensed in the 8×10^{-6} to 14×10^{-6} m wavelength band.

A summary of the WES recommendations follows. First, roofs which were identified as having possible moisture problems on the basis of the airborne survey should be further checked with hand-held infrared. Second, all available data on roof characteristics and construction should be assembled to reduce the number of "false alarms", i.e., areas which were warmer due to anomalies other than water in the roofing system. Third, flights should be made on clear nights having low humidity. Fourth, fifty percent, or more, overlap between adjacent flight paths should be enforced. Fifth, for the photographic recording mode, film negative or film positive is preferable to prints. Sixth, slow flying aircraft operated at a low altitude, e.g., 1,000 ft, should be used [30, 39, 45].

A different application of airborne infrared, although one involving the same parameters, is the evaluation of the thermal resistance or insulation performance of residential roofs. The purpose, of course, is to identify roofs with little or no insulation. Recent analyses have shown that the apparent temperature sensed by the equipment can be affected as much by variations in roof emittance, outdoor temperature variations, local wind speed variations, and transmission of the atmosphere as by varying amounts of thermal insulation [36, 41]. Burch [41] reported that for pitched roofs of residential buildings there is little chance that an uninsulated roof could be distinguished from an insulated one since the factors noted above would override. However, he found that in the case of flat built-up roofs of commercial buildings it is possible that uninsulated roofs could be distinguished from those that are insulated.

Among the organizations which have used airborne infrared imagery to evaluate insulation performance are the Remote Sensing Institute of South Dakota State

University [46], the Ontario Centre for Remote Sensing [47], and the Environmental Research Institute of Michigan [48]. Note that the difficulty in identifying roofs with little or no insulation does not stem from the image quality but rather from the multiple factors which can affect local image intensity. Very careful interpretation is necessary as in the case for moisture detection.

5.5 PORTABLE INFRARED SCANNERS

Portable infrared scanners are compact, light-weight instruments which can be hand carried or hand held. As discused in the following, there are a number of available systems of this type which can be moved about a roof by an individual. The sensor or camera-like unit, in particular, is small and portable similar to a home movie camera. The accompanying display or recording unit is also small and can be carried by the same person or be placed on a cart. Because of the small size of the sensor unit, it can easily be handled by an observer in a helicopter. The operating principles were discussed in Section 5.1.

As has been discussed previously, thermal infrared scanners, portable or airborne, measure the apparent radiance temperature pattern on a roof if the emittance of the roof surface is known. Variations in emittance over a roof do not appear to be a problem since both a gravel surface and a smooth bitumen surface have an emittance nearly equal to one [31, 49]. An exception to this is an aluminized bitumen surface which has a markedly different emittance [50]. If the emittance varies from one region to another, an observer might mistakenly interpret this as a temperature change when none actually exists.

The previous discussion (Section 5.3) indicates that it is necessary to sense small temperature differences if the roof survey is to detect areas of wet insulation. As shown by the example summarized in table 1, the temperature contrast between wet and dry areas may be small, e.g., 2 to 3°F (4 to 5°C). Portable scanners used on the roof have an advantage over more remote sensing since they are uninfluenced by atmospheric attenuation and since the temperature range covered on the display unit can be adjusted to conform to ambient conditions. The isotherm feature which is available on some commercial units may be useful here also.

The value of a roof survey is enhanced if wet areas can be detected when small and when litle damage has been done. To assure that small wet regions are not missed, it is important to improve spatial resolution by shortening the distance from the camera to the roof. Using portable scanners on the roof surface shortens the distance to the greatest practical extent. In Section 5.4 spatial resolution was discussed, and it was assumed that the solid angle substended by the sensitive area of the detector was 0.002 radian. This means that, at a distance of 5 ft (1.5 m), the radius of the smallest "spot" which could be detected is 0.01 ft (0.003 m) or 0.12 in. CRREL field experience confirms that smaller anomalies could be detected when observing on the roof than when observing from the air [51].

The field work discussed in this Section of the report was done by Cold Regions Research and Engineering Laboratory (CRREL) in cooperation with Waterways Experiment Station (WES) and Facilities Engineering Support Agency (FESA). All are activities of the U.S. Army Corps of Engineers. The reported field work is the primary effort on the part of the Federal government relative to the use of infrared in moisture detection in built-up roofs and is well documented. There has been parallel activity in the private sector but because of proprietary considerations it has not been widely discussed in the open technical literature. The cooperative activity led by CRREL began in 1975 [31]. Since then, they have surveyed a large number of roofs at many installations, both military and nonmilitary. Many types of building have been involved [32, 49, 52, 53].

CRREL compared the operation of several commercially available systems and two systems developed by the U.S. Army Night Vision Laboratory [30, 32, 51]. Two commercial systems, one operating in the 2×10^{-6} to 5.6×10^{-6} m wavelength range and one operating in the 8×10^{-6} to 14×10^{-6} m wavelength range, successfully detected wet insulation. In addition, one of the Night Vision Laboratory systems, the AN/PAS-10, also was successful in locating wet insulation in roofs [32, 51]. Inability to sense small temperature differences is not necessarily a reflection on instrument quality or sensitivity. Rather it may be a matter of the display capabilities or format of the system which may not allow a small, full scale temperature range to be displayed on the screen of the instrument or to be recorded by the instrument.

Since the radiation detector used in the successful commercial portable infrared scanners must be cooled by liquid nitrogen, provisions must be made by users of such equipment to obtain the relatively small amounts needed. This may pose a minor logistics problem when surveying roofs in remote locations. Further, the liquid nitrogen should be handled carefully by experienced personnel since it can cause frostbite or topical freezing if it contacts the skin.

As a result of the extensive roof survey experience, Tobiasson and Korhonen of CRREL have developed a number of recommendations to facilitate and enhance portable infrared scanner work. The first of these recommendations is to make a daytime "reconnaissance" of the roof. Usual features can be observed from a helicopter or from the roof surface and conventional photographs made for planning or later identification of anomalies [31, 51, 54]. The second and perhaps the most important recommendation is to make the actual infrared survey at night. As shown by the calculated temperatures presented in table 1, good contrast between roof surface temperatures over wet insulation and over dry insulation can be obtained if time is allowed for steady-state conditions to develop. A substantial steady-state period develops only at night. Another reason for night surveys is the "mottling" or "interference" which appears on thermograms made in daylight hours. This effect probably is due to erratically reflected solar radiation as discussed in Section 5.3 [52, 53]. A photograph illustrating this point is contained in Reference [31]. Night surveys can be made from a helicopter if a large number of roofs are involved but on-the-roof surveys are most reliable because of the greater spatial resolution possible [31, 51, 54, 55]. CRREL experience indicates that there is very little difference between working in warm weather or in cold weather as long as the work is done at night after approximate steady-state conditions develop [31]. Obviously the diurnal atmospheric temperature variation occurs during all sessions. A third recommendation is to outline the wet or "hot" areas with spray paint. These areas can be photographed the next day for a permanent record. If the roof is surveyed at some later time these markings can serve as a check as to whether the area is still wet and whether new wet areas have developed. Further, with the wet areas marked, cores can be taken the next day to check on actual wet or dry status of the insulation [31, 56, 57]. This leads to the fourth recommendation and that is to take as many cores as seems feasible. Although coring is destructive rather than purely nondestructive, it is the only method available to confirm whether wet (or dry) insulation is present. CRREL has developed some coring techniques which involve a unique device to cut 3 in (0.08 m) diameter cores from membrane and insulation [31, 32, 52, 53, 55, 56, 58].

Tobiasson and Korhonen have concluded from the CRREL field work that portable infrared scanners can locate wet areas in roofs even though the wet areas are small. Coring data for the most part confirm this [55, 56]. Since it permits inspection of every square inch of roof surface, infrared is preferred by CRREL over other nondestructive evaluation methods such as nuclear meters, capacitance-radio frequency meters, or capacitance-microwave devices [33]. Another general CRREL observation was that while some roofs contain wet insulation covering large portions of the roof, most roofs surveyed have small wet areas associated with vents, other penetrations, or flashing flaws [31, 49, 58]. Their catalogue of sources of spurious anomalies, that is anomalies or warm areas caused by something other than wet insulation, include: hot air exhaust on the roof, space heaters below the roof, hot rooms such as boiler rooms, variations in the amount or type of insulation, non-uniform convective cooling on the roof surface, radiation from adjacent buildings, extra thick membrane, and variations in thickness of gravel surfacing [31, 57]. Incidentally, blistering did not show up as a thermal anomaly [58].

6.0 SUMMARY AND RECOMMENDATIONS

6.1 ROOFING SYSTEM CHARACTERISTICS

A typical low-slope roof is a layered, multi-component system in which a variety of material choices can be made for each component. The makeup of the roofing system and its supporting structure is not the same at every point of the roof. Therefore, the first step in a roofing moisture survey is to obtain as much information as possible about the roof to be surveyed. This can be done by consulting roof plans, by discussion with owner's representatives, and by visual inspection.

Since the bulk of the moisture is likely to be in either the poured insulation or the rigid board insulation, the roofing moisture survey requires that material below the roofing system surface be examined. Moisture levels in the insulation must be determined and this can be done by coring and by nondestructive evaluation. Coring is destructive, in that it requires a roof repair, but it is the most reliable way of getting quantitative data on insulation moisture contents. Nondestructive evaluation should always be accompanied by some coring to confirm instrument readings. The insulation is not the only roofing component which may be wet, however, since both concrete and plywood decks may contain considerable moisture. Moisture in the deck may not be readily detected by nondestructive evaluation instruments placed on the membrane.

6.2 NONDESTRUCTIVE MOISTURE SURVEYS

The purpose of a nondestructive moisture survey is to locate moisture inside the roofing system. The information is then used to delineate the boundaries of wet areas and, possibly, the amount of moisture present. This is accomplished by measuring some property or parameter of the roofing system which is affected by moisture. That property or parameter may be affected by changes in other characteristics such as roofing geometry, materials, or environment. The ability to identify instrument responses due to factors other than moisture varies from system to system.

Another unknown with nondestructive moisture detection instruments is the volume of material which is sampled. This would be no problem if the roofing systems were homogeneous with a uniform distribution of moisture. However, roofing systems are composed of several materials in a layered configuration with moisture not uniformly distributed even in the insulation. The result is that the instrument readings correspond to average properties in the volume sampled. The interpreter of the reading must assume that the average properties in the sample are "typical" for that location.

Most nondestructive moisture evaluation instruments may not respond correctly if there is standing water, ice, or snow on the roof surface. Reliable readings cannot be made in these areas.

All of the instruments and systems covered in this report are designated to be used on the outside surface of the roof or above this surface in an airborne application. One of two methods of data taking is followed during NDE roof surveys. In one case, a grid is laid out by marking intersection points on the roof surface and readings are taken at those points (see figure 9). Readings may be taken at closer spacings when attempting to identify moisture entry paths. Typical grid dimensions are 5 ft x 5 ft (1.5 m x 1.5 m) or 10 ft x 10 ft (3.0 m x 3.0 m). Obviously, the reading at a grid point is assumed to be characteristic of the neighboring material. In the other case, or the full-field

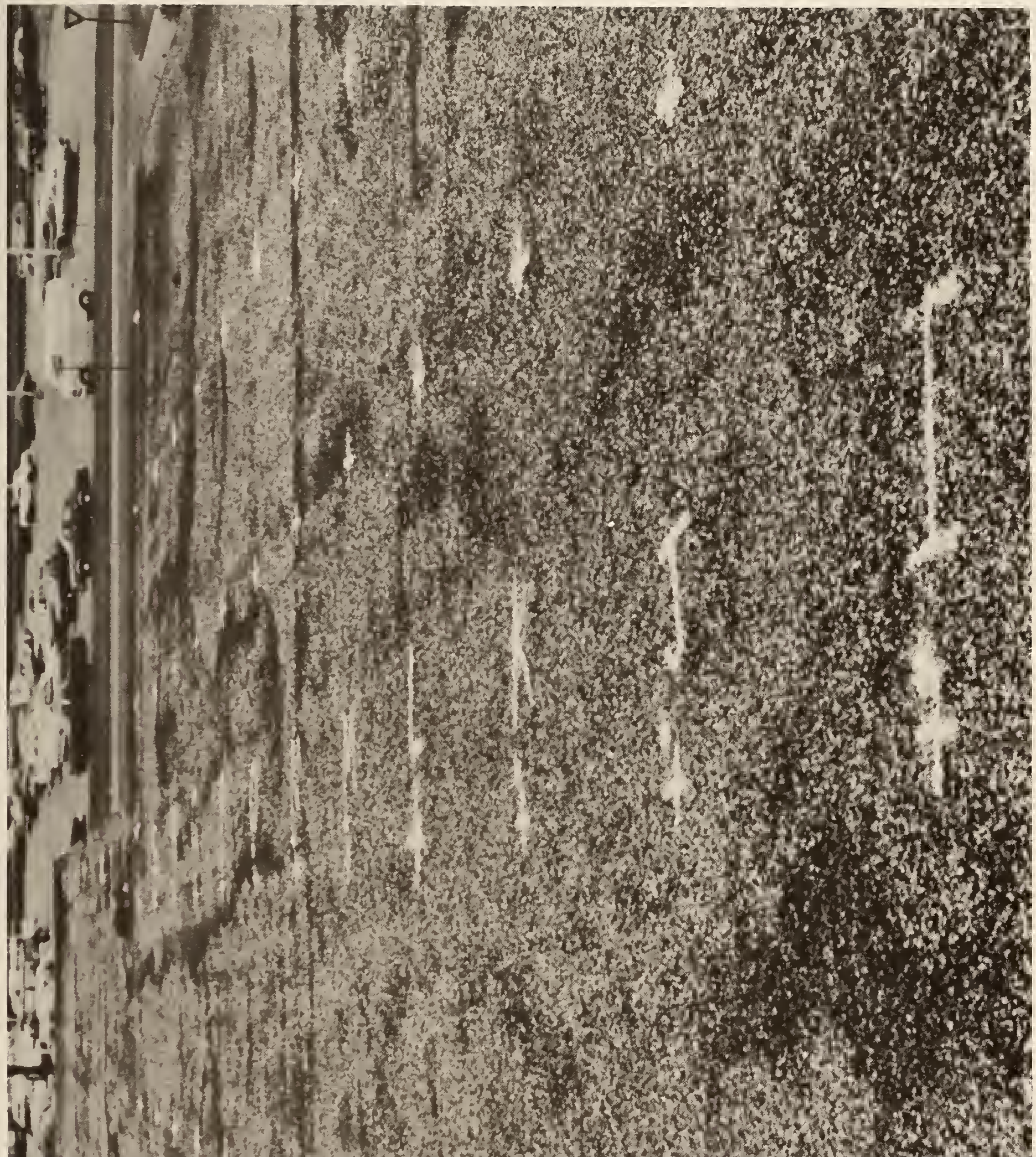

Figure 9. Typical Grid Array for Roof Inspection

case, the instrument sees all points in the field of view in the same way that a photographic camera would see all points in a scene. Since relatively small wet areas would not be missed, more complete information is obtained. For both grid and full-field cases, the final result could be a wetness contour map.

For any nondestructive moisture detection system, the user needs to establish several reference parameters. First, the reading or response for a dry area on the roof being inspected needs to be known. Second, the change in reading or response representing the dry-to-wet threshold should be determined. Third, if at all possible, the relation between change in reading or response and moisture content should be empirically determined. To be realistic, rarely is the third parameter known to any degree of certainty. Very likely the relation depends on the specific construction details of the roofing system and thus cannot be generalized. In any case, a large change in reading or response from the dry value probably means more moisture is present.

Along with visual inspection observations and coring data, the results of the nondestructive moisture survey can be used to evaluate the condition of a roof and to select areas where replacement may be necessary.

6.3 CAPACITANCE-RADIO FREQUENCY

Instrumentation in this category measures the dielectric constant or dielectric loss factor in material which lies in the radio frequency electrical field established by the device. These devices have various electrode configurations which control the shape of the electrical field. Generally, it is possible to control the depth of penetration of the electrical field although the presence of moisture does influence the field configuration. Since water has a dielectric constant and dielectric loss factor which are different from those of other insulators, its presence has a significant effect on the readings. When taking readings on a typical built-up roof however, it is difficult to determine whether the field penetrates deeply enough into the insulation of the roofing system to give a reading which is "typical" of its moisture condition. Since the distance of the electrode from the material surface can affect the results, some problems may be anticipated when working on a gravel-surfaced roof. One moisture detection service recommends that their instrument should not be used on gravel thicknesses greater than 5/8 in.

Meters of this type (figure 10) are quite compact and readings are taken by placing the unit on the roof surface. The grid measuring system is used. Capacitance measuring instruments have been used for over 40 years in paper, textile, and wall board production and thus are highly developed measurement systems. Currently, instruments specifically for roofing moisture detection cannot be purchased but a patented moisture survey service is available.

6.4 CAPACITANCE-MICROWAVE

This class of instruments measures the dielectric constant in a higher frequency alternating field than used in the radio frequency method. For most insulations which would be found in a roofing system, the dielectric constant measured in this microwave frequency range would not be much different from that measured in the radio frequency range. However, the frequency or shorter wavelength radiation has a greater tendency to reflect from interfaces in the system. None of the microwave systems have been sufficiently developed to be used for field moisture surveys but some do appear to be promising. They would be grid measuring instruments.

Figure 10. Typical Capacitance-Radio Frequency Moisture Detection Instrument

6.5 NUCLEAR METER

Nuclear meters contain a radioactive isotope source of fast neutrons. These neutrons enter from the roof surface and are slowed down and scattered by colliding primarily with hydrogen nuclei. The slowed neutrons (thermal neutrons) which are directed back to a nearby point on the roof surface are counted by a sensor also contained in the nuclear meter. Moisture in the portion of the roofing system which is sampled furnishes many hydrogen nuclei. Thus, wet insulation would tend to increase the count or instrument reading. However, hydrocarbons present in the bitumens of the built-up membrane also contain hydrogen so that variations in the bitumen thickness might be interpreted as variations in water content.

Both gravel thickness and deck type may influence the reading level. Similar to the situation for the capacitance-radio freqency method, it is difficult to predict how deeply into the roofing system a fast neutron would penetrate before being scattered back to the detector. There are indications that depth of penetration may depend on the total amount of hydrogen present. In any case, the depth needs to be sufficient to give a reading which is typical of the material in that vicinity. Much field work has been done with nuclear meters on actual roofs. Examples of commercially available instrumentation are shown in figures 11, 12, and 13. Based on surveys of many roofs and roof types, statistical techniques for establishing a dry-to-wet threshold reading have been developed. Results also show that careful calibration of the meter is necessary.

Nuclear meters are small and easily portable. The radioactive isotope in all cases is packaged in such a way that the radiation hazard is minimized. Other

Figure 11. Nuclear Meter

Figure 12. Nuclear Meter

Figure 13. Nuclear Meter

forms of the nuclear meter have been used for many years in soil moisture and soil density determination. In roofing moisture detection, the grid measurement system is employed.

6.6 THERMAL INFRARED SCANNERS

Thermal infrared scanners respond to the infrared radiation which is emitted or reflected from a roof surface. Radiation levels can be interpreted as roof surface temperatures if the emittance is known. The format of the thermal infrared system is much like that of a portable TV camera and monitor as shown in figures 14 and 15. Grey tones displayed on the screen correspond to infrared radiation levels or apparent radiance temperatures. For example, cooler portions in the viewed surface area appear to be dark while warmer portions are light. A large region on the roof can be viewed at one time including an entire roof if the camera is airborne. Within the spatial resolution limit discussed below, all points in the field of view can be "seen" simultaneously. Clearly, this is a full-field method, in contrast to the grid method of measurement.

In order to detect moisture, the surface temperature must be affected differently by dry and by wet insulation. This depends on the heat conduction through the roofing system, convection on the inside and outside roof surfaces, and net radiation into the outside roof surface. Both field experience and calculations for typical roof thermal conditions show that, under most conditions, roof temperatures over dry insulation and over wet insulation are sufficiently different to be detected by the infrared scanners. Since the surface temperature over wet insulation is higher than the surface temperature over dry insulation at night, the observer would look for light or "hot" anomalies in the

Figure 14. Portable Infrared Scanner System

Figure 15. Portable Infrared Scanner System

field of view. This condition applies when the outside temperature is lower than the inside temperature.

Conditions for detection of wet areas are improved by large inside-to-outside temperature gradients and low wind velocities at the outside surface. Since both radiation to the roof surface and reflection of radiation from the roof surface can have a large effect on the temperature sensed by the scanner, it is preferable to work at night when solar radiation is not present. Another advantage of working at night is that steady-state conditions are approached over a relatively long period of time and this allows a large roof to be surveyed under virtually the same thermal conditions. During the day, steady-state conditions are not approached. The season of the year is not, in itself, important provided the inside-to-outside temperature gradient is large enough and ponded water, ice, or snow are not present.

Any roof feature which influences either heat flow through the roof or the roof surface temperature directly may cause an instrument response similar to that caused by moisture. These include: (1) variations in supporting structure, (2) variations in thickness of membrane, insulation, or deck, (3) localized heat sources under or on the roof surface, and (4) variations in surface convection over a large roof.

Airborne thermal infrared scanners which are mounted in fixed wing aircraft are operated in essentially an aerial mapping mode or in an aerial reconnaisance mode. Even for low altitude (i.e., 1,000 ft) flyovers, these systems may not produce the detailed information necessary for all roofing moisture surveys. This occurs primarily because the radiation sensor occupies a solid angle of about 0.002 radian in the optical system. At 1,000 ft altitude, this means that radiant energy variations over a spot 4 ft in diameter or a square 4 ft on an edge would not be detected. A spatial resolution problem then arises because the system could detect wet areas larger than this spot size but might not detect smaller wet areas. The principle advantage of the system is that a large number of roofs can be surveyed in a short period of time.

A variation of the above is the use of a portable or hand-held infrared scanner in a helicopter for a large single-roof or a multiple-roof survey. In this configuration, shown in figure 16, the distance from the roof is reduced so that the spatial resolution problem is less severe. Field experience suggests that this type of airborne system may be effective.

Portable infrared scanners, such as those shown in figures 14 and 15, are sufficiently light-weight to be used on the roof surface. Being able to work on the roof surface gives several advantages over airborne systems. First, the temperature range can be selected for maximum contrast coupled with the greatest sensitivity. Second, the spatial resolution is good since the camera-to-roof distance is short and the area covered by the radiation detector spot is small. Detection of small wet areas is essential since field experience shows that most roofs have small wet areas. Third, areas identified as wet can be outlined on the roof surface as the survey is being done.

A number of portable infrared scanner systems have been compared in field surveys and systems are commercially available which performed well in roof moisture detection.

Figure 16. Portable Infrared Scanner as Used in Helicopter Observation

6.7 CONSIDERATIONS FOR THE SELECTION AND USE OF NDE METHODS

A. The equipment and NDE methods discussed in this survey are intended to locate areas containing moisture in a roof system. Moisture in insulation is of primary interest. Nondestructive methods allow these interior regions to be examined.

B. Several significant features of three commercially available nondestructive moisture detection systems and one laboratory system are compared in table 2. The features compared are depth of penetration or volume sampled, grid versus full-field data taking format, data presentation format, and nonmoisture parameters which affect response.

C. Nondestructive evaluation should always be accompanied by visual inspection of the roof and by core-taking to verify moisture contents.

D. Results of nondestructive roof moisture surveys can be presented in the form of moisture contour maps and all systems discussed are adaptable to this approach.

E. Selection of nondestructive moisture evaluation equipment should be based on:

- Cost of equipment, personnel, and data analysis.
- Skill of personnel required to operate equipment and to collect and analyze data.
- Knowledge of the roofing system and the effects of the construction and environmental variables on the NDE method.
- Purpose of moisture survey (routine maintenance, reroofing evaluation, etc.)
- Reliability and quality required in survey results.

Table 2. Nondestructive Moisture Detection

Method	Measure Property	Depth of Penetration	Data-Taking Format	Data-Presentation Format	Nonmoisture Parameters Which Affect Readings	Unique Features
Capacitance-Radio Frequency	Dielectric constant or dielectric loss factor.	Can be varied. Not fully predictable.	Grid	Numerical meter reading relating to dielectric constant or loss factor.	Thickness of gravel surfacing. Lack of uniformity of electrical field.	Complete service is available but instruments are not available.
Capacitance-Microwave	Dielectric constant at higher frequency.	Through or unpredictable.	Grid	Frequency shift (Hz) or signal attenuation (db).	Interfaces (cause reflection).	Not ready for field surveys.
Nuclear Meter	Frequency of neutron collisions with hydrogen nuclei.	Variable. Not predictable.	Grid	Numerical meter reading relating to count.	Variable bitumen thickness. Concrete deck background.	Uses low-level radioactive source. Licencing is required.
Infrared Scanner	Infrared radiation intensity from surface. Surface temperature.	Through	Full-field	Pictorial or videotape thermogram with isotherms.	Structural features that affect heat flow. Surface convection. Heat sources under or on the roof. Anything that changes surface temperature.	Usually used at night. Must have liquid nitrogen. May be used in an airborne mode.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. 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 survey is presented of nondestructive evaluation (NDE) methods for detection of moisture in roofing systems. The methods discussed include the use of capacitance-radio frequency instruments, capacitance-microwave instruments, nuclear meters, and thermal infrared scanners. For each method, the principles of operation are reviewed and the measured properties which are affected by moisture are identified. Factors other than moisture which may affect the response of the instruments are also described for each method. These factors produce responses which are similar to those due to moisture and include non-uniformities in the roofing system, roof construction details, and building equipment. The use of each NDE method in actual moisture surveys is reviewed.

It is emphasized in the report that the validity of roofing moisture surveys depends on both a knowledge of the factors noted above and a familiarity with roofing practice. Furthermore, cores of the roofing system at selected points are needed to confirm NDE observations.

To define operating conditions for infrared scanners, calculated temperatures of roof surfaces over dry and over wet insulation are presented for representative night and day conditions.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

built-up roofing; moisture; moisture detection; nondestructive evaluation; nondestructive testing; roofing; thermal resistance.

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