# AIR BORNE THERMAL INFRARED AND NUCLEAR METER SYSTEMS FOR DETECTING ROOF MOISTURE

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## INTRODUCTION

Roof maintenance and repair is a multimillion dollar item for both government and industry. Leaks are often associated with moisture entrapped within the roof system. Entrapped moisture in built-up roofs can cause deterioration of roof materials and destroy the effectiveness of insulation, resulting in excessive energy loss through the roof. Early detection of entrapped moisture may prevent costly replacement of deteriorated materials and at times allow localized repair or replacement, instead of replacement of an entire roof system. The ability to nondestrucitvely detect and delineate roof areas with entrapped mositure would be valuable for monitoring roof conditions and planning roof maintenance and repair, and for quality assurance on new roof construction.

The U.S. Army Corps of Engineers has been evaluating a number of techniques for rapidly surveying roof moisture conditions. The techniques of primary interest have been (a) hand-held thermal infrared (IR), (b) airborne thermal IR, and (c) nuclear moisture meter systems. Hand-held thermal IR sensor systems have been investigated by the U.S. Army Engineer Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, and the Facilities Engineering Support Agency, Fort Belvoir, Virginia.

This paper describes a companion effort conducted at the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, to evaluate airborne thermal IR and nuclear moisture meter systems for use as roof moisture survey tools. The WES effort deals not only with evaluating the potential of these systems for operational use, but also with formulating methodologies for their efficient application. The following sections present and discuss (a) the basic principles of the airborne IR and nuclear meter systems and (b) recommended methodologies for their application and examples of results.

## PRINCIPLES OF ROOF SURVEY DEVICES

### Thermal IR sensor systems

Airborne thermal IR sensors differ radically from aerial photographic systems in that they respond to energy radiated by terrain features (as opposed to energy reflected). The source of the radiated energy is normally the energy stored within the terrain features themselves. Any material body at a temperature above absolute zero (0°K) radiates energy; the higher the temperature the greater is the amount of energy radiated. As the body gets hotter, the predominant wavelength of the electromagnetic (EM) energy radiated becomes shorter. Thus, a body that is "red hot" radiates energy in the red portion of the visible spectrum (approximately 0.6 to 0.7 $\mu$m). Most terrain materials at ambient temperatures (say between 0 and 30°C) radiate energy with a predominant wavelength in the neighborhood of 10 $\mu$m. The amount of energy radiated is quite small, and very special detectors are needed to measure it; semiconductor crystals, such as mercury doped germanium or indium antimonide, are normally used. The detectors have to be cryogenically cooled at times to temperatures as low as − 245°C to obtain the necessary sensitivity. Liquid nitrogen is one common coolant used for this purpose.

Figure 1 shows a schema of a typical airborne thermal IR scanner system.
The rotating mirror reflects the impinging energy from the terrain to the detector. As the mirror rotates, the detector receives energy from a path on the terrain perpendicular to the flight of the aircraft. Successive scan lines are produced by repetition of this cycle. The detector transforms the impinging energy into an amplified electrical analog signal and can be recorded directly on film or on magnetic tape. The information recorded is normally displayed on a cathode-ray-tube (CRT) screen for real-time evaluation of the sensor output.

Moisture trapped within a roof cross section can drastically alter the thermal properties of the roof. The most significant difference between "dry" and "wet" cross sections is the presence of water in the insulation. Since water has a heat capacity that may be as much as 5000 times that of insulation materials, such as fiberglass, the effective heat capacity of the wet cross section can be significantly higher than that of the dry cross section and produce a significant temperature difference between them.

Specifically, when the two roof conditions are subjected to a constant energy source, such as the sun, they both absorb (all other things being equal) the same amount of energy. Dry areas gradually become warmer than wet areas, since the temperature rises more rapidly for the same energy input (owing to a lower heat capacity). Thus, during the day when the roofs are heated by solar radiation, the wet roof areas will be cooler than the dry areas. This is illustrated in Figure 2. At night the opposite will occur (Figure 3); the dry areas will decrease in temperature faster than the wet areas, and eventually the wet areas will be warmer than the dry. Winter heating tends to amplify the nighttime temperature differential between wet and dry roof areas. In summary, the feasibility of using thermal IR techniques as a reconnaissance tool for detecting entrapped moisture depends on the magnitude of temperature variations associated with wet versus dry conditions, the magnitude of temperature variations caused by other factors (which can be considered background noise), and the ability to seperate moisture-related temperature variations from others.

### Nuclear moisture meter

A nuclear moisture meter, such as those commonly used to measure in situ soil moisture, emits fast neutrons from a by-product radioactive source and counts backscattered slow neutrons. The number of backscattered slow neutrons received (compared with a reference standard) is directly related to the number of hydrogen atoms present in the sample being tested. In soils, the hydrogen atoms present come predominantly from water. The situation is slightly more complex on a roof. Hydrogen atoms abound in roofing materials (especially in bitumens, which are hydrocarbons. Thus, slow neutrons (converted from fast neutrons by collisions with hydrogen atoms) can be produced from the roof material as well as from the presence of water, and a wide range in slow neutron counts is normally observed on any roof area. If a fairly uniform material cross section exists throughout the roof area and there are sufficient insulating or water-absorbing materials in the cross section, the nuclear meter readings representing "wet" roof areas will be consistently higher than readings representing "dry" roof areas. Figure 4 shows a nuclear meter measurement in progress.

Although there are other possible nondestructive means of detecting entrapped moisture in roofs, thermal IR imaging devices and nuclear moisture meters have existed for many years and, therefore, their use requires no instrumentation development. Their effective use for roof moisture surveys does require systematic methodologies that optimize their strengths and minimize their weaknesses.

## METHODOLOGIES AND EXAMPLES OF RESULTS

### Application of airborne thermal IR sensor systems

Airborne thermal IR sensor systems are best applied as reconnaissance tools to rapidly survey roofs over large areas of terrain, such as an entire town, industrial-commercial complex, or military installation. Their greatest single advantage is the ability to acquire for a large number of roofs a photo-like image that can be quickly interpreted to delineate roof areas suspected of having entrapped moisture. Successful application of airborne thermal IR devices requires execution of the following steps.

a. Assemble available data on roofs, including locations of major roof features (vents, air-conditioning units, etc.), presence or absence of insulation, nature of membrane (builtup or not).
b. Plan thermal IR imagery mission, including when to conduct the mission, who will conduct the mission, and technical details of the flight (altitude, etc.).
c. Acquire imagery.
d. Interpret imagery to identify roof areas suspected of containing moisture.

Of these steps data assembly, mission planning, and imagery interpretation warrant additional discussion.

**Data assembly.** Roof areas with entrapped moisture will normally (at night) be warmer than dry roof areas and, therefore, will appear as lighter tones on thermal IR imagery. However, there are other things, such as physical features on the roof (vents, towers, etc.) that can cause warm (light tones) anomalies on the imagery and it is helpful to determine these things prior to the survey. Also, buildings that do not have built-up roofs and those that have built-up roofs with insulation (and thus the ability to trap and hold moisture) need not be included in the survey.

**Mission planning.** Planning is paramount. Start with these questions:

a. **When** should the mission be flown?
b. **What** sensor system should be used?
c. **How high** should the aircraft fly?

For roof moisture surveys, it is most advantageous to **obtain thermal IR imagery at the time of maximum temperature contrast during nighttime hours.** Imagery obtained during the daytime is much more difficult to interpret for roof moisture because of added complexities in the roof's thermal behavior, plus reflection of solar energy. Experience indicates that the **maximum nighttime temperature difference between wet and dry roof areas occurs between 2000 and 2300 hr.** The exact time of the maximum difference depends on the season, the weather, and the roof insulation types. The amount of solar energy striking the roofs decreases in the winter, but many buildings are heated. For unheated buildings, roof areas with entrapped moisture would be best detected during warmer months. Heated buildings, however, can be successfully surveyed in the cold months, because internal heating provides an additional source of energy to create temperature differences between wet and dry roof areas.

Thermal IR imagery should not be obtained during or immediately after a rainfall or snowfall. Roof surfaces must be dry and free of standing water or accumulated snow. Water or snow on a roof will mask the temperature differences needed to detect wet areas. **A cool, clear night after a clear, sunny day is the best time for obtaining thermal-IR imagery for a roof moisture survey.**

Under favorable conditions almost all of the airborne thermal IR sensor systems currently used by military, civil government agencies, and commercial firms have sufficient sensitivity to detect temperature differences between wet and dry roof areas. Propeller-driven aircraft can fly quietly, low and slowly, distinct advantages for imagery acquisition. The low altitude produces easily interpreted thermal IR imagery, because the roofs appear larger on the imagery than on imagery obtained at higher altitudes.

The IR sensors in jet aircraft, such as the U.S. Air Force RF-4C Phantom reconnaissance aircraft, have been shown to be capable of conducting roof moisture surveys. Disadvantages of the jet aircraft are their higher noise level and need to fly at higher altitudes for safety.

Aircraft altitude (height above the ground) determines the scale of the imagery obtained with any given sensor system. For example, the sensor system in the RF-4C Phantom aircraft produces imagery at a scale of 1:10,000 (1 in. = 833 ft.) when the aircraft is flown at an altitude of 1000 ft. above the ground. If the same system is flown at 2000 ft., the imagery scale would be 1:20,000 (1 in. = 1667 ft.). The imagery at 1:10,000 scale would obviously be easier to interpret. With jet aircraft, minimum flight altitude recommended is 1000 ft. For slower propeller-driven aircraft, minimum recommended altitude is 500 ft.

In a mission it is essential that flight paths be positioned parallel to one another and close enough together to provide 50 percent overlap for the imagery from adjacent flight paths. The overlap is important for two reasons. First, 50 percent overlap provides the interpreter with two views of each building. Because of the mechanics of the scanning process, buildings on the edge of the imagery may have some roof areas that are not visible on imagery taken on a given flight line. Secondly, the overlap allows stereo viewing, which is valuable for imagery interpretation.

**Imagery interpretation.** Interpretation of imagery to identify roof areas suspected of entrapping moisture is fairly simple and straightforward. The interpreter must keep in mind that the tonal changes on the imagery are related to temperature changes on the features imaged.

The recommended steps for interpreting imagery are:

a. Identify buildings having insulated built-up roofs.
b. Examine roofs to identify warm anomalies.
c. Compare warm anomalies to known internal heat sources and roof features.
d. Isolate and record anomalies suspected to be caused by entrapped moisture.

Imagery interpretation need only concern these buildings with insulated roofs. Prior marking of these buildings on a reference site map speeds this process.

Examination of buildings on the imagery is perhaps the most important step in the process. The image of each roof should be carefully examined with a magnifying glass, or, if possible, a stereoscope to identify any warm anomalies. Warm anomalies will appear as light tones against a dark background on positives (transparencies or prints) and dark tones on a light background on negatives. When a number of buildings have similar roof plans, the anomalies common to all of the buildings are usually due to some common structure on the roof.

Entrapped moisture does not account for all warm anomalies, or even a majority. Thus, it is important to identify, with reasonable accuracy, anomalies due to internal heat sources in buildings and physical features on the roofs as well as those due to entrapped moisture.

Warm anomalies that cannot be attributed to such things as internal heat sources or physical features on the roof are suspected of entrapped moisture. These anomalies should be recorded on a scale drawing of the roof to facilitate easy checking in the field.

**Example of results.** Figure 5 presents a thermal IR image of building number 5020 at Dyees Air Force Base, Texas. The image was obtained at approximately 2100 hr on 28 February, 1976, by the 155th Tactical Reconnaissance Group of the Nebraska Air National Guard, Lincoln, Nebraska. Examination of the image reveals several regular or systematic image tone anomalies and one widely distributed nonsystematic anomaly. The regular patterns were caused by air vents and expansion joints. The irregular pattern of light (warm) tones comprises areas having entrapped moisture.

The image shown in Figure 5, obtained under favorable weather conditions and at the appropriate time of day, demonstrates the potential of this technique. Under less favorable conditions, such as cloudy skies, immediately following a rainfall that causes standing water on the roofs, or at the wrong time of day, the tonal anomalies that allow delineation of entrapped moisture may not be present at all; hence, the need for rational mission planning.

**Application of nuclear moisture meters**

**Validation of anomalies interpreted from IR imagery.** Not all "suspect" areas actually have entrapped moisture. Interpretation of the thermal IR imagery as suggested in the previous portion of this paper will minimize erroneous inferences about entrapped moisture. But it is essential to conduct on-the-roof surveys to verify the presence of entrapped moisture in each suspected area before starting maintenance and repair.

The detailed on-the-roof survey can be conducted effectively with a nuclear moisture meter. The nuclear meter's relatively low cost ($3000 to $4000), its simple and reliable design, its utility during daylight hours, and its different physical principle from thermal IR imagery (providing independent evaluation) make it an excellent complementary moisture-detecting technique.

The nuclear meter narrows down the search for extra entrapped mositure. It takes readings adjacent to and within the area suspected to have entrapped moisture. If the nuclear meter readings inside and outside of the suspect area are essentially the same, the suspect area can be considered to be dry. If the nuclear meter readings obtained within the suspect area are significantly greater (by at least 50 percent) than those obtained in adjacent areas, entrapped moisture is present. For nuclear meter reading increases slightly less than 50 percent it is advisable to obtain a core sample of the roof for verification of the presence or absence of moisture.

Furthermore, because of the possibility of obtaining high-nuclear meter readings over patched areas or other abnormal occurrences of excess bituminous material, it is useful to obtain a roof core sample to verify the presence of entrapped moisture. This step is advisable when a patch or other area is within the area suspected to have entrapped moisture.

**Individual roof surveys.** A nuclear meter survey of a rooftop is a simple operation. The first step is to lay out a grid pattern (Figure 6) on the roof; normally a 10 by 10-ft. (approximately 3-meter) grid. Slow neutron counts are then made with the nuclear moisture meter at each grid intersection for a specific time period, such as 30 seconds. Core samples of the roof materials are then obtained (about three per building unless the building is very large) so that their moisture content can be measured and compared with nuclear meter readings.

The nuclear meter is most effective when the data analyzed represent a roof or roof area having uniform conditions or characteristics. Thus, an important step in planning a nuclear meter roof survey is to identify roofs and roof areas having similar characteristics (deck, insulation type and thickness, number of felt plys, etc.). For example, if a building has a new wing and an old wing and the roofs on the two wings have different deck materials and different thicknesses of insulation, the nuclear meter data obtained on each wing should be analyzed seperately.

Analysis of the nuclear meter readings obtained in a roof survey involves application of simple statistical procedures. The object of the analysis is to determine a "threshold" value that can be used to delineate roof areas having entrapped moisture. The first step in the analysis is to separate those readings obtained in central roof areas from those obtained along roof edges and expansion joints. The second step is to prepare a frequency histogram of the center roof readings. Since slow neutrons can result from both the roof materials and water, a wide range in slow neutron counts is normally observed on any roof area. If a fairly uniform material cross section exists throughout the roof area and sufficient insulating or water-absorbing materials occur in the cross section, the nuclear meter readings representing wet roof areas will be consistently higher than readings representing dry roof areas, as shown on a typical frequency histogram of the nuclear meter readings (Figure 7). It must be emphasized that a bimodal frequency distribution, such as that shown in Figure 7, could also occur because of a significant change in the roof material cross section; hence, the need for a few core samples and a knowledge of the basic composition of the roof.

At times the nuclear meter data do not have a bimodal distribution (Figure 8), and more sophisticated techniques are required to ferret out the nuclear meter readings that represent wet and dry roof areas. The current procedure consists of examining the frequency histogram of nuclear meter readings with respect to the moisture content values of the roof core samples as determined by laboratory procedures. The first step is to determine the lowest nuclear meter reading corresponding to a wet core sample (i.e. with measured moisture content greater than 10 percent by weight). The nuclear meter readings above this value are considered to represent wet roof areas. The next step consists of determining the highest nuclear meter reading corresponding to a dry core sample. All nuclear meter readings below this value are considered to represent dry roof areas. It should be noted that the wet and dry areas as defined by this criterion may indeed have some overlap.

The next step is to compute normal frequency distribution curves for the nuclear meter readings representing wet and dry roof conditions as defined by the core-sample moisture data. Figure 9 gives an example of the resulting normal distribution curves for a roof area for which all values below 425 were considered "dry" and all values above 425 were considered "wet". The 90 percent confidence limits (one-tailed) are then computed for the normal curves to provide some criterion for selection of a representative nuclear meter threshold value for separating wet and dry roof areas. The threshold values are selected to correspond to a nuclear meter value that lies between the intersection of the normal curves and either the wet or dry 90 percent confidence limit, whichever results in the lower value. For the buildings represented in Figure 9, the threshold value was selected to be 425.

To establish nuclear meter threshold values for roof edges and expansion joints, the following regression equations were developed:

a. Edge threshold = 55 + 0.92 (center threshold)

b. Joint threshold = 22 + 1.09 (center thresold)

If edge and joint conditions are similar, only the first equation need be applied for both edges and joint. The nuclear meter threshold values are used to map roof areas with entrapped moisture. Figure 6 shows a typical product of a nuclear meter survey.

## SUMMARY

Airborne thermal IR imagery has been used to conduct demonstration or phototype surveys at three Strategic Air Command bases and a number of Army installations. The nuclear meter has been used to survey individual roofs on a large number of Strategic Air Command bases and a limited number of Army installations. These experiments have shown that both techniques, if properly applied, can be very effective in detecting entrapped moisture in built-up roofs.

Several private firms offer nuclear moisture survey services and this technique appears to be gaining acceptance, at least within a portion of the roofing industry. Since the military has a need to survey many buildings at many installations, recent emphasis has been given to such procedures as airborne thermal IR system that allow large areal coverage in a short time. The cost effectiveness of the airborne technique has not been determined quantatively in that military aircraft have been used to conduct all surveys to date. Future efforts will involve the use of commercially available thermal IR imaging systems to establish the costs of such services. Results of these and companion studies conducted by the U.S. Army Cold Regions Research and Engineering Laboratory and Facilities Engineering Support Agency will be used to formulate guidance for operational application of the procedures shown to be cost-effective and most beneficial for Department of Defense use.

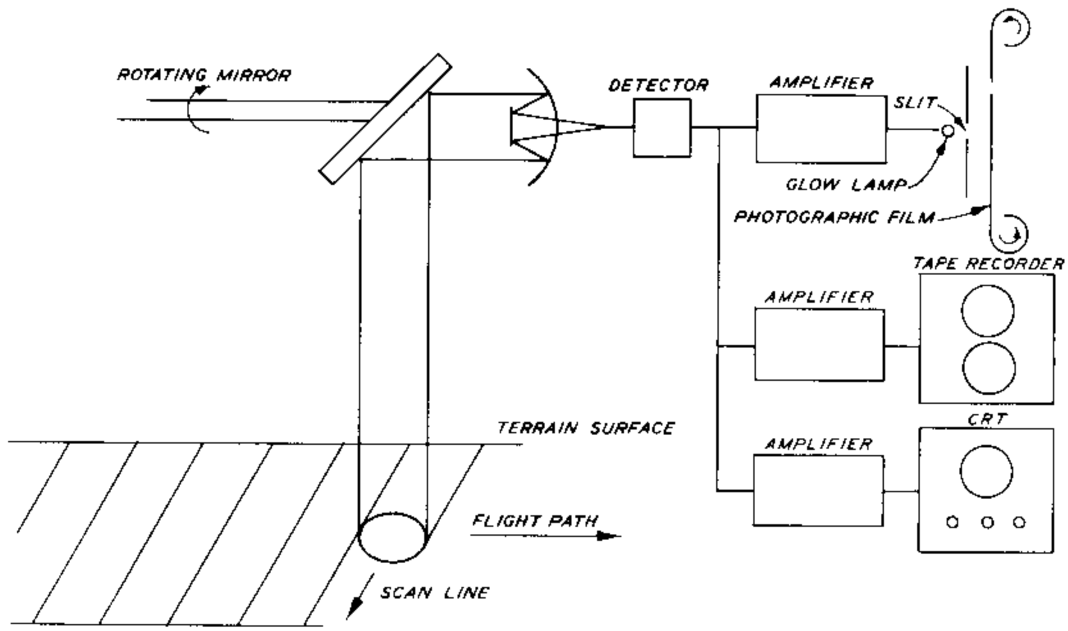


FIGURE 1. SCHEMA OF TYPICAL AIRBORNE THERMAL IR SCANNER SYSTEM

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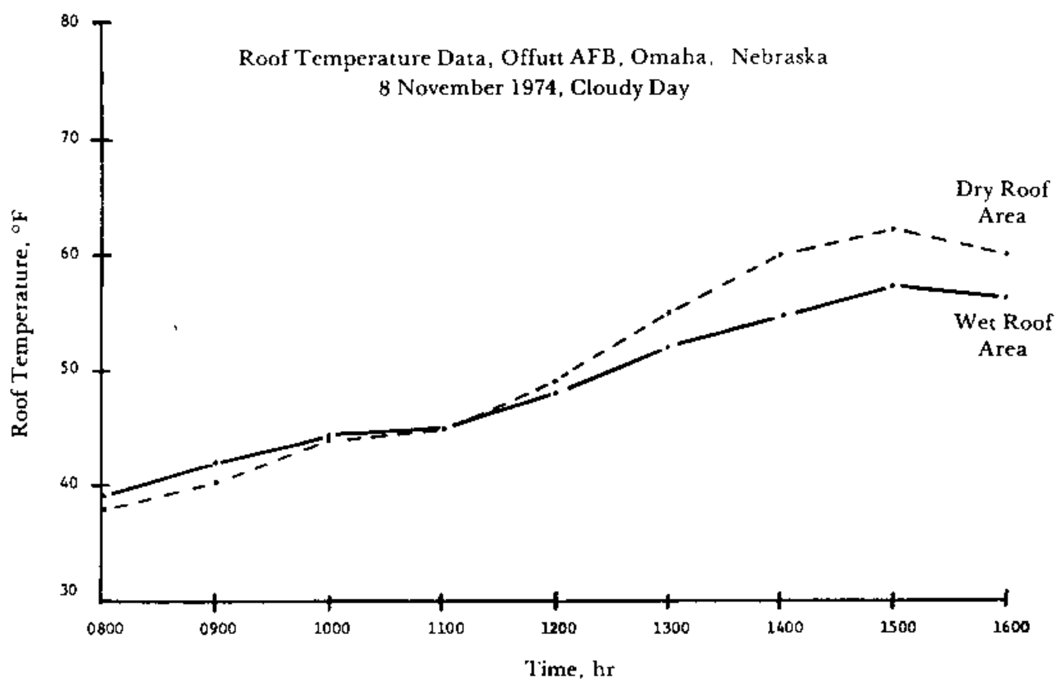


FIGURE 2. DAYTIME ROOF TEMPERATURE DATA

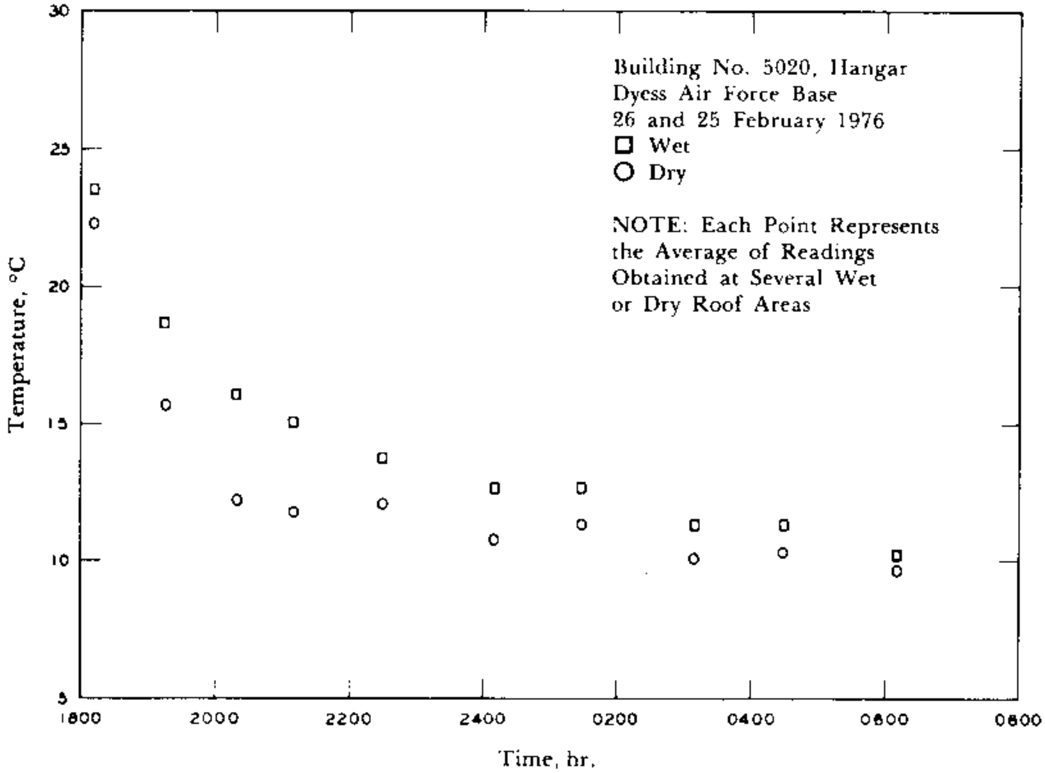


FIGURE 3. NIGHTTIME ROOF TEMPERATURE MEASUREMENTS

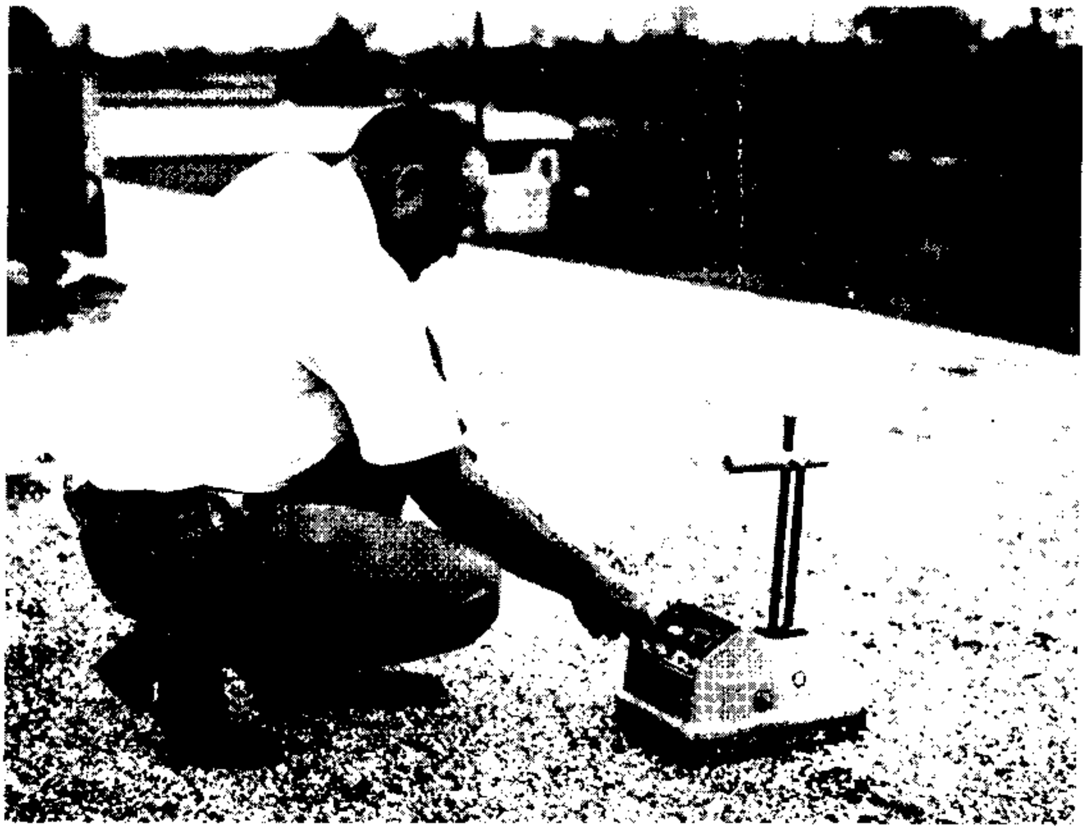

FIGURE 4. NUCLEAR METER MEASUREMENT IN PROGRESS

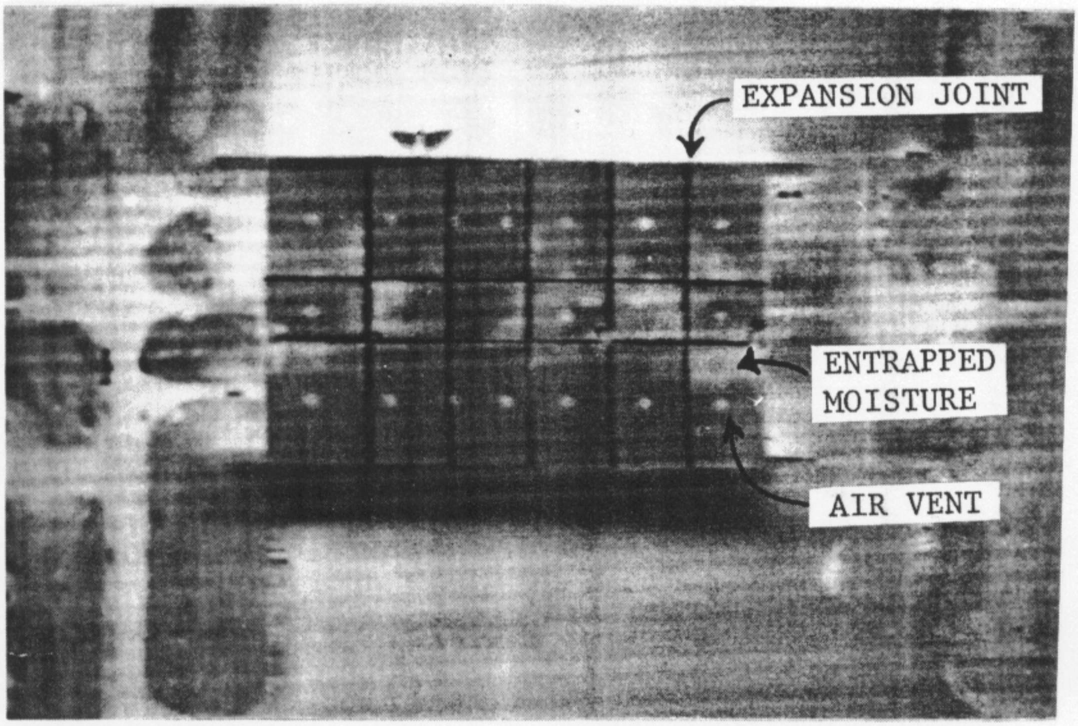


FIGURE 5. NIGHTTIME THERMAL IR IMAGE OF BUILDING NO. 5020, DYESS AFB, TEXAS

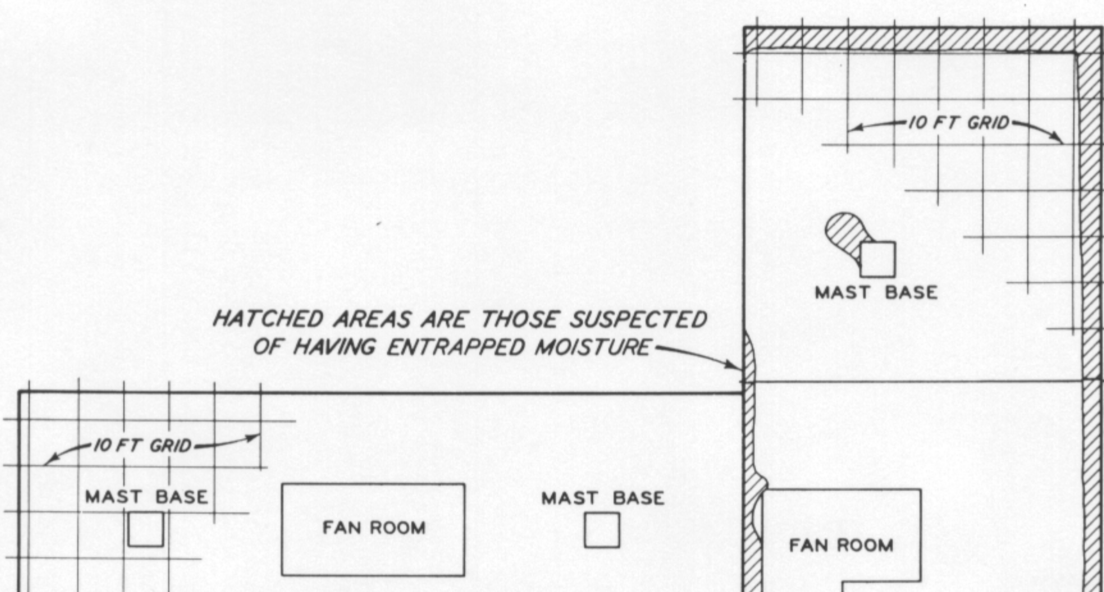


FIGURE 6. TYPICAL PRODUCT OF NUCLEAR METER SURVEY

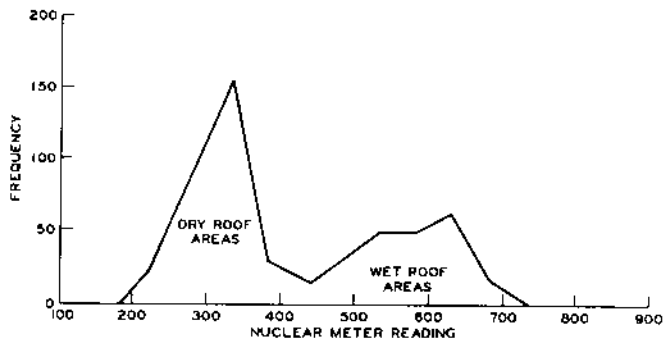


FIGURE 7. FREQUENCY HISTOGRAM OF NUCLEAR METER READINGS SHOWING BIMODAL CHARACTER; BUILDINGS 525, 526, and 527, OFFUTT AFB, NEBRASKA

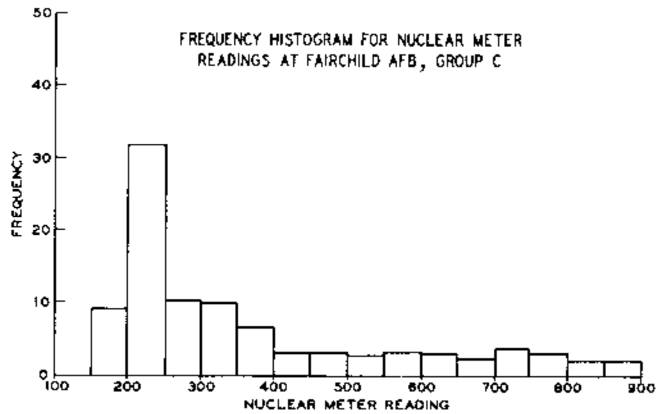


FIGURE 8. FREQUENCY DISTRIBUTION OF NUCLEAR METER READINGS LACKING BIMODAL CHARACTER

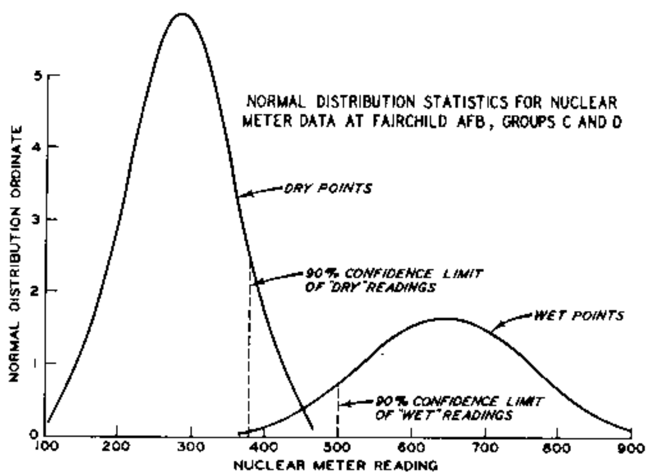


FIGURE 9. COMPUTED NORMAL DISTRIBUTION CURVES FOR WET AND DRY VALUES AS DETERMINED FROM CORE SAMPLES