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AN INVESTIGATION OF USING
AERIAL INFRARED THERMOGRAPHY
FOR LOCATING SUBSURFACE
MOISTURE IN BUILT-UP ROOFING

THESIS

Christopher L. Claunch, Captain, USAF

AFIT/GEM/DEM/90S-4

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AN INVESTIGATION OF USING AERIAL INFRARED THERMOGRAPHY FOR
LOCATING SUBSURFACE MOISTURE IN BUILT-UP ROOFING

THESIS

Presented to the Faculty of the School of Systems and
Logistics of the Air Force Institute of Technology
Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Engineering Management

Christopher L. Claunch, B.S.

Captain, USAF

September 1990

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Preface

The purpose of my research was to examine the use of aerial infrared thermography to see if it would be a useful and worthwhile tool to help improve the existing Air Force Built-Up Roof Management Program.

Several case studies were analyzed, comparing cost per square foot, quality of information obtained from each survey, and each location's use of the infrared information to see if it helped improve the roofing program there. Interviews with experts in infrared thermography helped immensely in my understanding of how infrared works and the possibilities of its use for locating moisture in low-sloped roofing.

In creating this thesis, I am especially grateful for the assistance and information provided by Thomas Hurley of ISS Thermographic Testing. This thesis topic was inspired by him and much of the information presented within was made possible by his genuine interest and the generous sharing of his time and knowledge. Thanks also are due to my advisor, Major Larry Lawrence, and my reader, Captain Mary Kay Eisert for being incredibly patient during the many weeks that they did not hear from me. I'm thankful as well to the many roofing engineers throughout the Air Force who gave their valuable time to send me information on case studies and who gave me their frank opinions about infrared thermography.

Christopher L. Claunch

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Abstract

thesis
This ~~study~~ investigated the use of aerial infrared (IR) thermography for locating subsurface moisture in built-up roofing. A case study approach was used where several aerial infrared surveys were examined to determine the capabilities of an aerial survey compared to several other non-destructive test methods. The relative cost, the quality of data possible, and the limitations and shortcomings of using infrared from the air were also studied. Several experts in thermography were consulted for further information and recommendations. Overall, the high-resolution infrared cameras and techniques used in the selected surveys demonstrated an outstanding ability to locate moisture in built-up roofing from as high as 1500 feet. The cost of aerial IR is usually the least expensive non-destructive technique for finding moisture in large areas (1 million square feet or more), and an aerial IR survey can rapidly examine an entire base in one night. Infrared can accurately locate areas of moisture damage that cannot be seen from a visual roof survey. The information from IR makes early identification of roof problems possible so repairs can be performed, thus extending the life of built-up roofs and reducing the number of costly roof replacements.

case studies, flat roofs, aerial photography, (KR)

AN INVESTIGATION OF USING AERIAL INFRARED THERMOGRAPHY FOR LOCATING SUBSURFACE MOISTURE IN BUILT-UP ROOFING

I. Introduction

Background

A built-up roof (BUR) is the most commonly used type of roofing on buildings with almost flat roofs. "Approximately one-half of all Air Force roofs are built-up roofs" (7:6) with a surface area totaling approximately 300,000,000 square feet (28). These low-sloped roofs, often called "flat" roofs, are usually designed with a slight slope so water will flow toward the roof drains, preventing standing water. Low-sloped roofs are often used because a "flat" roof has less surface area than a pitched roof which means less material is used and a reduction in overall construction costs is achieved. Built-up roofs are still constructed today in much the same manner as they were over 100 years ago. The general concept has not significantly changed over the years because the built-up roof has been a successful roofing method with a favorable performance history. Failure stories of newer roofing methods for low-sloped roofs, such as the single-ply membranes advertised in popular construction magazines, and the lack of a proven performance record have prompted the Air Force to promote the continued use of the reliable built-up roof membrane (11).

Definition of Terms

Generally, a built-up roof consists of, from the bottom up, a layer (or two) of rigid insulation (approximately 2-6 inches thick) which is attached to the "flat" roof deck and covered with multiple layers of asphalt-coated felt (commonly called "tar paper") which are bonded together during installation with hot asphalt or coal-tar bitumen. A layer of gravel embedded in the bitumen layer on the top surface protects the waterproof membrane from the degrading affects of ultraviolet rays from the sun. Built-up roofs are designed to last 20 years before removal and replacement is necessary (7:6; 31:62; 37).

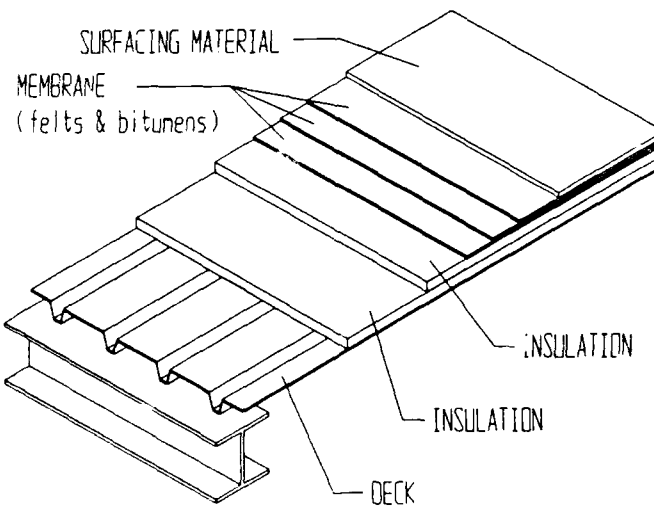


Figure 1. Built-Up Roof Cross Section

Specific Problem

Recent history shows that the Air Force has been replacing its built-up roofs on average about 5 to 8 years after installation (9). The majority of most premature roof failures is due to water damaged insulation caused by an untreated small leak. An untreated pin-hole size leak (which is often undetectable using currently prescribed investigative techniques) may cause localized insulation saturation. Over time, sometimes several years before the occupants ever experience any drips inside, the moisture damaged spot will have eventually grown into a large area which is difficult and expensive to repair. Often, when occupants first start reporting roof leaks, the roof is already beyond repair capability and must be completely replaced (12). After leaks are reported, repair teams attempt to patch the suspected problem area but often to no avail.

Too often, roofing maintenance repairs are unsuccessful. Water leaks persist while repair budgets are expended. Lack of adequate information . . . leads to ineffective repair. (31:62)

Some problems that wet insulation can cause are:

1. Higher energy costs due to reduced thermal efficiency of the insulation.
2. Additional weight on roof leading to possible structural overload.
3. Blisters (pockets of humid air trapped beneath the membrane plies which expand when heated and may eventually rupture the membrane).

4. Expansion stress (wet insulation expands and contracts at a different rate than dry insulation causing membrane splitting, buckling, and wrinkling which can let in more water if a penetration forms).
5. Possible decreased wind resistance. Moisture may cause loss of adhesive strength or may corrode mechanical fasteners which secure the roof in heavy winds.
6. Freeze-thaw damage. This can damage any part of the roof system.
7. Deck deterioration. Corrosion and possible weakening of metal, wood, and even steel reinforced concrete roof decks can occur.

Wet insulation is defined in AFR 91-36 as insulation "that has lost at least 20 percent of its original insulating ability because of moisture in the insulation core" (6:4). A rule of thumb also used is that if insulation is 20 percent moisture saturated, then it is considered wet.

The solution to increasing roof life and decreasing a roof's life-cycle cost is simple according to Dr. Edward Feit, a specialist in non-destructive roof testing.

Intelligent roof management requires periodic inspections. The aim is to remedy problems while they are small and can be easily repaired, thus breaking the cycle by which a roof is replaced every eight years — the national average. (11:24)

In agreement is a quote from the April 1990 issue of Building Operating Management:

[I]f ignored, most roofs will need replacement in less than one-half of their rated life. With a thorough preventive maintenance program, a roof can last for the design life or beyond. Preventive maintenance can reduce reroofing costs by 50 percent or more. . . . A preventive maintenance program can double the life of a roof for 10 to 20 percent of its replacement cost. (33:25)

Premature roof failures, which cost the Air Force hundreds of thousands of dollars each year in replacement costs, have generally been attributed to either poor materials and installation, or lack of adequate maintenance (25).

In an attempt to correct this situation, the Air Force published the Air Force Built-Up Roofing Manual (AFM 91-36) in September 1980. This manual provided guidance on how to organize an effective base roofing program. AFM 91-36 provided detailed procedures on how to inspect a built-up roof visually, and provided formulas to predict when the roof would most likely fail. It also contained recommended repair procedures once problem areas were discovered during the inspection and included guide specifications which prescribed minimum standards of materials and installation procedures for constructing new built-up roofs. According to Mr. Julian "Oz" Ius, current head of the Air Force roofing program at the Air Force Engineering and Services Center, AFM 91-36 was exactly what the Air Force needed to help standardize the roofing program. Although great in theory, the program was not a resounding success because it did not noticeably extend the average lifetime of built-up roofs (13).

According to a telephone survey of 25 base and MAJCOM roofing engineers performed by the researcher between August and December 1989, the reason most often given for the program's lack of success was insufficient interest from upper level management in mobilizing the roofing team per the manual's guidance. This results in a shortage of

assigned manpower to perform the required inspections. Most Air Force bases today have the designated base roofing engineer's job listed as an additional duty (13). Because of this, especially at larger bases, many inspections have not been completed on time according to the schedule in AFM 91-36. The old motto of "out of sight, out of mind" is quite applicable to the built-up roofing program. If commanders don't see or hear of a problem, everything is assumed okay and required maintenance is often neglected. In this case, built-up roofs rarely receive necessary inspection and maintenance because supervisors who budget the inspector's time do not see a problem. In summary, although an excellent method of organizing the roofing program was available, AFM 91-36 failed to extend the life of Air Force built-up roofs significantly.

On 31 March 1989 the Air Force changed the prescribed built-up roofing guidelines from an Air Force Manual (AFM 91-36) to an Air Force Regulation (AFR 91-36). Oz Ius notes that the new regulation is less stringent than the manual it superseded because the regulation allows each base greater flexibility than before to make its own decisions regarding its roofing program (26). This flexibility may be an effective approach assuming that each base roofing engineer is adequately trained and is knowledgeable in the different roofing techniques available, but many base roofing engineers lack expertise and experience. Another change in AFR 91-36 worth noting is that the manual stipulated that BURs

were to be inspected only every three years. The new regulation requires at least annual inspection of all BURs, as well as other low-sloped roofs, and requires that all BURs in good shape but no longer under warranty be inspected twice per year. Recounting the previously referenced lack of assigned manpower and time allocated to perform the surveys once every three years, the more aggressive schedule is likely to cause further non-compliance in meeting required inspections.

Problems with the Existing Roof Program

Although the new regulation 91-36 together with its attachments and supplements adequately specifies minimum acceptable materials quality and installation procedures (as was previously included in the manual), it lacks a comprehensive inspection procedure. The currently prescribed inspection method requires only a visual, walk-on-the-roof survey of each built-up roof at least once per year. Even a roofing expert often cannot locate wet insulation using only visual inspection methods (3:11). Since there are now several commercially available non-destructive measurement devices which are useful at detecting otherwise invisible subsurface moisture, a logical decision would be to include mandatory use of at least one of these methods to supplement the required visual inspections on a regular basis. Recognizing the potential benefits of these new moisture sensing devices, Wayne Tobiasson of the US Army Corps of Engineers

published a report in 1983 in which he stated:

It is generally agreed that it is technically unwise and fiscally irresponsible to develop plans for the maintenance, repair and/or replacement of a roof without first conducting a roof moisture survey. (40:30)

New Technology

Over the past five to ten years, many new ideas and improvements to existing technology have enhanced the capabilities of the built-up roof inspection process. Some of the new technology methods currently used to help locate subsurface moisture in the insulation layer of built-up roofs without penetrating the membrane are electronic impedance or capacitance measurement, nuclear measurement, and infrared imagery (13:1-6).

Impedance and Capacitance Tests. These electronic devices create an alternating current electrical field which senses moisture by detecting changes in the dielectric properties of the roofing material. This type of instrument is placed in contact with the roof, and when it senses moisture, the reading on the meter increases. A disadvantage of the capacitance meter is that the roof surface must be completely dry for the test. If the roof surface is damp, a high reading may lead to the incorrect conclusion that there is moisture in the insulation when in reality the moisture is only on the surface.

Nuclear Tests. The nuclear meter is a device that must also be in contact with the roof surface to operate. Similar to a Geiger counter, it measures the amount of hydrogen

in the roof below it. Because water is composed mostly of hydrogen, the nuclear meter readings increase in the presence of moisture (29:1). A difficulty with the nuclear meter, other than its tight control by the Nuclear Regulatory Commission, is that since bitumen also contains hydrogen, a high reading may lead the investigator to incorrectly conclude that there is subsurface moisture present when the same reading may also be caused by an increase in bitumen thickness.

The major limitation of these two non-destructive moisture sensing devices is that they can only sense the area contacted by the instrument. In practice, a grid area is set up on the roof and only several grid locations on the roof are actually tested (about 10 percent of the total roof area). Not being able to test the entire roof area quickly and easily is the primary disadvantage of both the nuclear and electronic devices. When several roofs are involved, the procedure becomes quite time consuming.

Infrared. The basic principle of infrared (IR) thermography is to discern differences in temperature between objects or different areas of the same object. For finding moisture in built-up roofs, the infrared survey is usually conducted at night. For optimal conditions, there should be plenty of sunshine on the roof during the day to heat the membrane, and a cool clear night, allowing the roof to cool rapidly. Effective, dry insulation should "reflect" the membrane's heat upward into the cool night atmosphere so an

entire "good" roof should cool off quickly. If a built-up roof has an area of insulation that is wet, however, this wet area is much slower to react to temperature changes. The water retains heat much longer than dry insulation so a damp area would show up on a thermogram as a hot spot (lighter color or white) contrasted with the dark, cool remainder of the dry roof (29:1; 36:63-66).

The infrared method of searching for subsurface moisture has improved dramatically in the past few years. Newer, commercially available high-resolution cameras are capable of distinguishing warm spots as small as 6 inches across from as far away as 1000 feet (39). A significant advantage over the other non-destructive test methods can be realized by using a high-resolution infrared device from either a plane or helicopter. From the air, all the roofs at one base can be examined within a few hours. Because of this capability to cover the entire roof surface area of each building and to survey a large number of roofs in a short time (often all the built-up roofs on a base in a single night) using a small inspection team of two or three people, the aerial infrared method holds the most promise for improving the existing Air Force roof management program without requiring additional Air Force manpower. The other moisture sensing methods (including walk-on-the-roof infrared) are labor intensive. A complete base survey using non-aerial methods would depend primarily on manpower (which has already been indicated as a significant problem at most

bases). The advantage of being able to survey all the built-up roofs on a base at once gives the roofing engineer a much better "snapshot" of the existing conditions which allows a more accurate roof repair/replacement priority list to be prepared.

Some disadvantages of aerial IR include the need for the surface of the roof to be dry, the need to perform the survey at night (usually), and the need for more favorable weather conditions than the walk-on-the-roof inspection methods require.

Wayne Tobiasson and Charles Korhonen, both pioneers in the use of infrared for roof moisture surveys state:

We see great promise in the expanded use of straight-down thermal imagery using pointable infrared scanners in helicopters. . . . [W]e believe that infrared systems will prove to be best at detecting small moisture problems in new roofs. (29:7)

Because of favorable expert opinions and the potential for monetary and manpower time savings for the Air Force, the aerial infrared method for detecting moisture in roofs has been selected as the focus for this research.

Purpose of Research

The existing Air Force Roofing regulation requires only a visual method of inspection even though it mentions several non-destructive techniques as having merit to aid in moisture detection. This research will compare the present "visual" inspection method required to an aerial infrared thermography inspection method to determine if thermography

should be included in the Air Force roofing program as a required inspection method to aid in subsurface moisture detection. Using aerial infrared photographs to detect thermal patterns caused by moisture in built-up roofs has been used successfully for several years in commercial applications. The premise is that the aerial infrared method of searching for insulation moisture will aid in rapidly detecting the overall condition of an entire roof, and the information provided will also help locate leak sources so that repairs can be made to the roof before a more costly replacement must be performed. Lack of maintenance is known to be a major factor in decreasing the life of built-up roofs (37). Unlike before, when some roofing problems could not be visually identified, the infrared technique promises to provide the roofing engineer with the timely information needed to ensure that minor problems can be repaired before costly major damage develops. If the infrared technique proves to be effective at identifying problems early, the potential for monetary savings to the Air Force (and other military branches as well) is enormous. "Replacement cost for [all Air Force] built-up roofs alone is approximately 1.2 billion dollars" (7:6).

Investigative Questions

To help guide the focus of the research, the following investigative questions were posed.

1. Will aerial thermography provide more valuable information about base roofs (than would otherwise be known from visual inspections) to more accurately develop a valid roofing repair/replacement priority list (required by the regulation)?
2. Can aerial thermography save the government money by decreasing the life-cycle cost of Air Force built-up roofs? (ie. can it pay for itself?)
3. What limitations does the aerial infrared method have for Air Force use?
4. Will the aerial infrared inspection method work at all CONUS Air Force Bases?
5. How often should an aerial infrared survey be performed?
6. What qualifications should be required of the aerial IR surveyor?
7. What type of infrared equipment should be used to produce the resolution necessary to locate subsurface moisture accurately?

Scope of Research

The scope of this research will be limited to CONUS installations. The intent of this research is to examine the aerial infrared survey method to determine if it can improve the Air Force BUR program by providing knowledge that can help extend the life of existing Air Force BURs and save the Air Force money.

II. Review of the Literature

History

Searching for moisture in built-up roofing using infrared (IR) techniques began in the mid 1970s when the Army's Cold Region Research and Engineering Laboratory (CRREL) performed many tests using several different techniques in search of the best method to find wet insulation. Much of the following information is from a special report from CRREL entitled Summary of Corps of Engineers Research on Roof Moisture Detection and the Thermal Resistance of Wet Insulation, dated December 1978.

The U.S. Army spends millions of dollars annually on the maintenance, repair and replacement of built-up roof membranes and insulation. . . . Millions of square feet of sound membrane and dry insulation have been removed during the course of efforts to eliminate leaks. (41:1)

The report continues:

The ability to find wet areas when they are small is . . . considered quite important. When these "cancers" are small they can be removed at minimal cost. If they are not detected they can enlarge and generate major problems which are extremely expensive to resolve. (41:3)

Among the methods investigated at CRREL were:

1. On-the-roof surveys
 - A. Hand-held infrared
 - B. Nuclear moisture meters
 - C. Capacitance meters
 - D. Microwave system (developed by CRREL)
 - E. Impulse-radar system (developed by CRREL)
2. Airborne surveys (all infrared)
 - A. Fixed-wing aircraft
 - B. Helicopters

The non-infrared techniques examined were all grid survey techniques which are time consuming (to set up the grid) and see only the portions of the roof actually tested (usually about 10 percent of the total roof surface). Nuclear and capacitance equipment worked adequately, although both were affected by changes in either bitumen or gravel thickness. The microwave and impulse radar systems were too large and complex, so they were considered inappropriate for conducting routine roof moisture surveys. The CRREL report states:

Comparison surveys have shown that where large wet areas exist, nuclear and infrared surveys generally give similar results. However, grid surveys conducted with a nuclear meter tend to miss small wet areas, which are detected by the infrared camera. The ability of an infrared camera to examine every square inch of a roof makes it quite valuable for the purpose of detecting wet roof insulation. (41:3)

The CRREL study concludes:

After examining numerous roofs with various nondestructive moisture detection systems we have concluded that the most accurate results can be obtained using infrared systems. (41:3)

Although the IR method was selected as the best, it still requires special knowledge and experience to be operated effectively. The following list from a United Scanning Technologies (UST) brochure indicates some common reasons why a warm location on a roof will show on an IR thermogram.

1. Hot air from a roof exhaust fan or vent.
2. A heat source beneath a roof with minimal insulation.
3. Differences in the amount and type of roof insulation.

4. Wind patterns or radiated (reflected) heat from walls higher than the roof.
5. Significant differences in the thickness of the built-up roof membrane.
6. Wet insulation.

How Infrared Works

Infrared radiation is the invisible part of the electromagnetic spectrum that we commonly refer to as heat. Using special sensors, infrared radiation can be detected and reproduced as a visible image. For roof moisture surveys, this visible image is usually recorded on videotape and later examined to determine if each roof has suspected areas of wet insulation. It should be noted that experienced thermographers will rarely identify a roof as having wet insulation without first conducting a secondary test. Secondary tests are walk-on-the-roof tests performed either with non-destructive (nuclear or capacitance) or destructive (core sample or moisture probe) tests.

Daytime vs Nighttime. During the early stages of development, IR was tested using a hand-held device while walking on the roof in the daytime. Several studies have confirmed that a nighttime approach usually produces better results (41:4). The two primary ways that wet insulation becomes warm so that the IR camera can detect it are by solar loading in the daytime, and by interior heat conduction at night (or when there is a significant thermal difference between warm inside and cool outside air). If there has been

sufficient sunshine on the roof during the day to heat the roof, and a great enough temperature drop at night, the thermal image recorded can be very helpful at locating suspected moist areas of insulation. However, if the weather conditions are less than ideal, the results may not be as conclusive. Even if there has been no sun on the roof during the day, the heat loss through the wet insulation can be spotted with the IR camera if there is a great enough temperature difference between the inside and outside of the building. The generally accepted minimum temperature difference to see a thermal pattern formed by conduction is 10 to 15 degrees Celsius (32:28). The conduction method is limited almost exclusively to buildings in colder climates.

Scanning Window. The scanning window, sometimes called the thermal window, is the term attributed to the time when the thermal images from an IR scan produce useful information. When the scanning window is open, conditions are acceptable for generating meaningful images. The length of time that the scanning window remains open is dependent on many factors. The greater the temperature difference between the moist and dry areas of the roof, the longer the scanning window will remain open. This heat difference can be caused by both solar load (in the daytime) and heat loss (usually at night). Sometimes the two methods can complement each other, thus extending the scanning window.

Solar load can be affected by clouds and by the inclination of the sun (which changes with the latitude and season).

A weak solar load reduces the heat gain and shortens the scanning window. At night, cloud cover can have either a negative or positive influence on the scanning window. If the night air is cool enough, the clouds tend to inhibit the speed at which wet insulation dissipates its heat, extending the scanning window. But if the night sky is clear, the thermal image is usually more pronounced though it does not last as long (more useful when the temperature difference is less).

Wind near 15 miles per hour can shorten or even close the thermal window so that no useful images can be seen. Relative humidity, degree of insulation saturation, and roofing material also can affect the scanning window. Some types of insulation do not readily absorb moisture and so do not emit as much heat energy which can cause a significant adverse affect on the length of the scanning window. High relative humidity, around 80 percent, filters the radiated heat so that the thermal contrast suffers.

The scanning window is an important concept to understand since it affects the value of an IR scan. Any one or a combination of negative factors can significantly affect the usefulness of the thermal image (32:28-32). The scanning window must be considered for each survey performed.

20 Band Colorization of IR Images. Infrared information is normally recorded as a black and white or gray image with brighter images corresponding to increasingly warmer areas. For over 10 years the technology has existed to computer

enhance gray-scale images converting certain temperatures or brightness levels to different colors. Although at first this may seem to be the next generation of improved imaging, there are inherent advantages in using standard gray images instead of color enhanced thermograms for roof moisture surveys. The several hundred levels of gray tones produced with black and white thermography present much more information than that of 20 band color thermography (17:188; 22:8). When the image does not have many significant thermal differences, the gray tones are much more useful because 20 band colorization can wash out the thermal image thus rendering much of the valuable information unobtainable (22:8). For this reason, most IR thermography of built-up roofing is performed using shades of gray instead of color.

Aerial Thermography. Aerial thermography was first attempted using a hand-held IR scanner from a helicopter. This method produced less than desirable results primarily due to the low resolution of the commercially available equipment then. Also the handheld IR cameras were cooled with liquid nitrogen which would spill if the camera was pointed straight down, thus further limiting the usefulness of the aerial survey results. Since the 1978 CRREL study, there have been significant improvements in both the resolution and cooling methods used in commercially available IR cameras. The specification sheets of some of the newest IR cameras (early 1990) show gimbal mounted IR cameras that are intended for either helicopter or fixed-wing aircraft

attachment, and can rotate freely in almost any direction, including straight down. These later generation IR cameras use compressed gas coolant such as argon instead of liquid nitrogen, thus freeing them from the previous limitation of being unable to point the camera straight down (38:51). A few of the more expensive cameras even have electrically powered closed-cycle cooling, similar to a refrigerator, eliminating the need to be periodically recharged with compressed coolant gas (14).

The more recent IR cameras, from about 1984 to the present, are capable of very high resolution, and many are intended for aerial use. Several of the aerial IR cameras also have a built-in telephoto lens for multiplying the image (or zooming in) from 2 to 4 times the original size (14; 38:51). This capability gives the thermographer much greater detail of the roof while maintaining a safe distance (14). At 500 feet altitude for example, Wayne Tobiasson reported that the FLIR[™] 2000A aerial camera could spot an image 3 inches across from directly above a roof. At this height using the telephoto (4X) lens, the field of view is 61 feet wide by 28 feet across.

The thermal resolution capability of most aerial IR cameras since about 1984 has been such that temperature differences of less than one degree Fahrenheit are distinguishable (14). The sensitivity is adjustable from inside the aircraft during the IR nighttime survey (21).

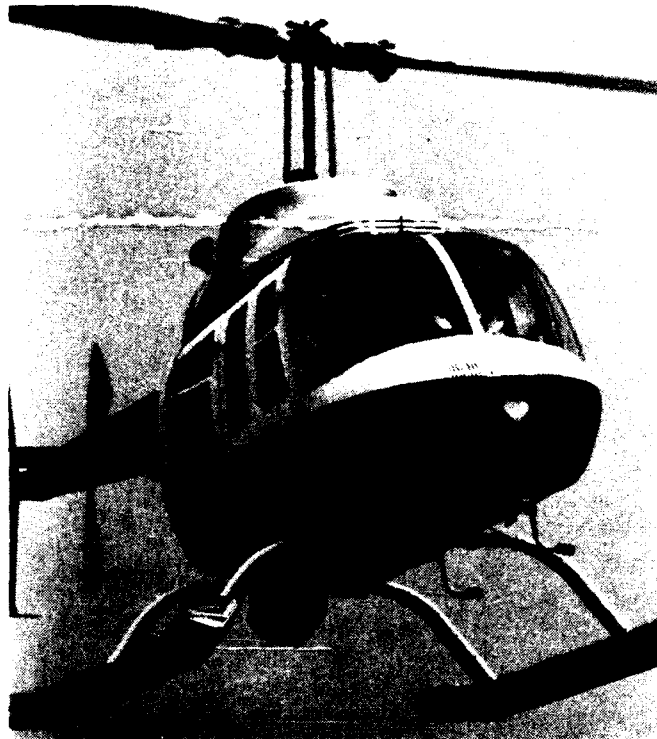


Figure 2. Helicopter with Gimbal Mounted Aerial IR Camera. (Courtesy of ISS Thermographic).

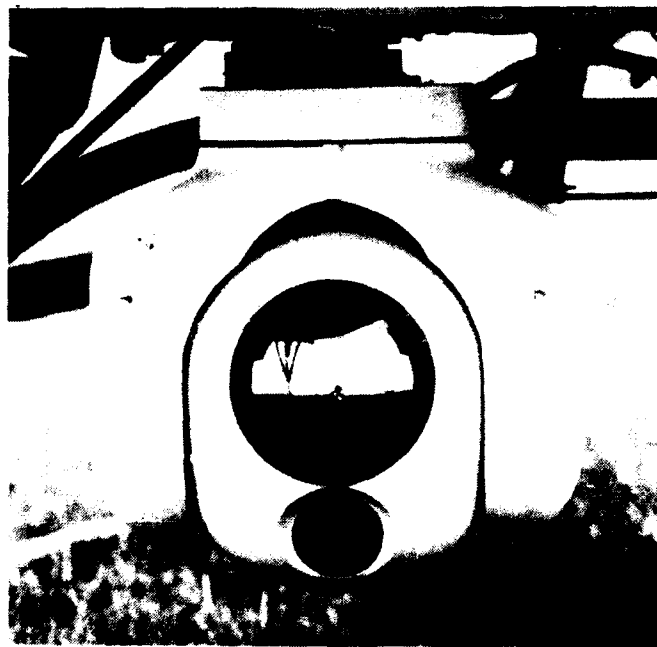


Figure 3. FLIR[™] 2000 A/B High-Resolution IR Camera with 4 Power Telephoto Lens. (Courtesy of ISS Thermographic).

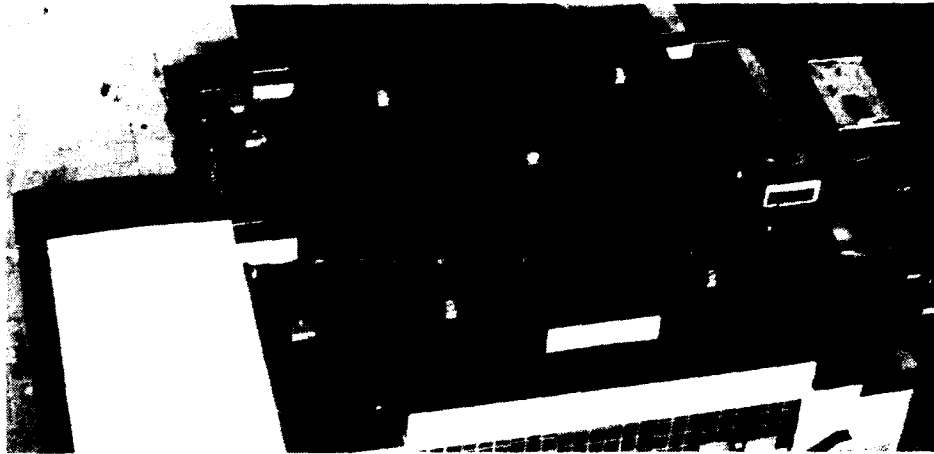


Figure 4. Photograph of Built-Up Roof from 500 Feet Altitude. (Courtesy of ISS Thermographic).

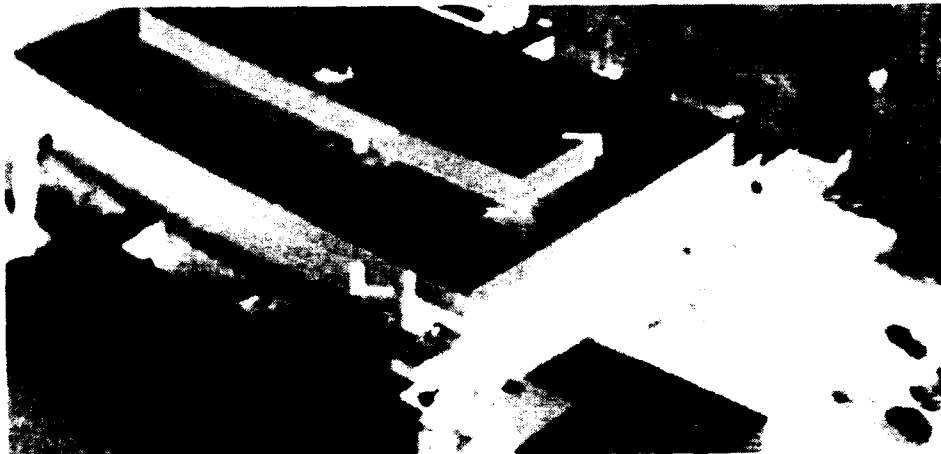


Figure 5. Infrared Thermogram of Same Roof Showing Areas of Insulation Moisture (white areas). (ISS photo).



Figure 6. Telephoto Thermogram Showing Close-Up of Same Area From 500 Feet Altitude. (ISS photo).

Helicopter vs Fixed-Wing. Some commercial companies use a helicopter for their aerial IR surveys and others use fixed-wing aircraft. The significant advantage of a helicopter is its ability to maneuver closer to a building and thus provide improved resolution. However, its primary disadvantage is its substantially higher cost. Fixed wing aircraft travel faster and are therefore more suitable for surveys located great distances from the IR company's location. According to Jay Vanier of UST, his IR equipment which is mounted on a fixed-wing aircraft has pinpointed moisture spots as small as 6 inches square from 1500 feet above roof level. This resolution is accurate enough for the researcher to conclude that there is not a significant enough difference to limit the focus of this research to helicopter surveys. Since overall cost is a significant element, fixed-wing surveys may be cheaper and in the best interest of the government if the results obtained are adequate.

A Method for Conducting an Airborne IR Survey

The following method of performing an aerial IR survey is an excerpt from an article by Wayne Tobiasson presented in 1988 at the International Conference on Thermal Infrared Sensing for Diagnostics and Control (Thermosense X) at Orlando, Florida.

Maps showing the location of buildings to be surveyed are studied and permission for the flights must be obtained.

A daytime flyover is first performed to take color photographs of the buildings to be surveyed and to familiarize the survey team with the location of the buildings prior to the nighttime IR flight. Each member of the flying team should have an area map with the proper buildings circled or highlighted. A designated spotter, with the help of a clear plastic overlay, marks off each building as it is photographed. After the daytime fly-over, the color negatives are submitted to an overnight print processor and the spotter is provided with a clean plastic overlay for the night flight. During the nighttime survey, the IR images are recorded on videotape along with the conversations of the survey team. In the morning, the IR videotape is viewed using a 4-head VCR for clear individual frame images, and preliminary findings are marked onto clear plastic overlays which have been attached to the recently developed color photos. Locations are also marked on the overlays indicating places where core samples will be taken for moisture verification. Each roof is then visually inspected, the core samples are taken, and spray paint is used to mark all located roof defects. The core samples are put into plastic zip-lock bags and sent to a lab for moisture content analysis. Each core in the roof must then be patched.

Afterwards, a fresh overlay is marked with both the visual and core verified findings and is included along with the recommended repair actions in the final report (38:50).

Certain conditions should be fulfilled to ensure that optimum results are obtained during the IR survey. First, there should be no water, snow or ice on each roof and the wind should be less than 15 mph. The difference between indoor and outdoor temperature should be at least 27 degrees Fahrenheit (15°C) for typical built-up roofs. The evening survey can usually commence about one hour after sunset, but on warm and cloudy nights it is best to wait an additional hour. Unless there are unusual circumstances, the survey can continue until sunrise. As a rule of thumb, it takes more than twice as long to complete the nighttime infrared thermography as it does the daytime photography. One hundred roofs will take over 2 hours (38:57).

Cost of IR

In 1978, Wayne Tobiasson reported that most commercial roof moisture surveys, both IR and non-IR, cost about the same; between 5 and 12 cents per square foot. In 1986, the average cost of an aerial IR survey was between 2 and 10 cents per square foot (42:10). Compare these prices to the average cost of a built-up roof replacement (between \$4.00 and \$4.50 per square foot) and the potential savings, when the IR survey can help extend the life of the roof, become apparent (28). Several factors that affect the cost of moisture surveys include: total number of square feet to survey, distance the crew must travel, number of buildings, and distance between them. Airborne IR surveys are not

generally competitive unless several large roofs located close together are surveyed concurrently (41:4-5). In an article published in Roofer magazine, Jay Vanier, head of a commercial aerial IR firm, pointed out that aerial IR surveys are typically one-fourth the cost of hand-held IR surveys (4:50; 42:11).

Life-Cycle Roof Costs. An article published by Dr. Edward Feit in the April 1987 edition of Materials Evaluation magazine reported dramatic life-cycle cost savings from using infrared technology to examine and recommend repairs for a school's built-up roof. In the referenced case study, a handheld IR scan was contracted in 1982 because the roof had leaked in many places since 1980 and normal repairs were unsuccessful at stopping the leaks. After the initial survey, the identified problem areas were successfully repaired. A follow-up survey was performed in 1984 even though there were no reported leaks, and a third was accomplished in 1986. Each time the survey indicated new areas that needed to be repaired. If the roof had been replaced in 1980, it would have cost \$255,000. Amortizing this over 20 years at 10 percent would have cost the school \$28,920 per year. When compared to the total cost of the surveys and roof repairs, which averaged approximately \$5200 per year, the cost savings become readily apparent (11:401).

According to a 1989 article by Dennis Firman, the cost of tearing off and replacing a built-up roof can range from \$2.60 to \$6.97 per square foot. If left alone after

installation, a new roof usually will be leaking after a couple of freeze/thaw cycles and will need to be replaced at about half its expected life.

This no-maintenance approach costs about 15 cents per square foot each year, figuring \$3 per square foot replacement cost, a 20-year design life for the roofing system and money discounted at 10 percent per year. The alternative, proper roof inspection and maintenance, costs about 3 cents per square foot each year. The choice of annual roof inspection and maintenance compared to no maintenance may offer as much as a 5-to-1 payback ratio. (13:15)

The maintenance option clearly is preferable to the no-maintenance option when compared on the basis of life-cycle cost. Maintaining the roof extends the life of a roof and reduces its overall life-cycle cost.

Another viewpoint on costs of an IR roof inspection is presented in an article by Carlton Dawson, published in the Thermosense XI proceedings, March 1989.

There is an order of magnitude of difference between a good predictive maintenance inspection and a poor one. . . . The well done inspection will provide a payback of greater than 20:1 on the inspection cost. (5:134)

This draws attention to the necessity of having a quality IR inspection team perform the aerial IR survey.

Number of Commercial Organizations Using Aerial IR

According to Christopher French of the Infrasppection Institute, there are only three commercial organizations that currently perform predominantly aerial infrared surveys to locate moisture in built-up roofs. The Infrasppection Institute conducts both beginning and advanced training courses

in infrared thermography (15). The author, during the research, has located two additional commercial companies as well as one military team that also perform aerial roof moisture surveys. All six of these organizations use a high-resolution camera designed for aerial use. The names and addresses of the five companies are listed in appendix A.

The 1990 Annual Infrasppection Institute Directory of Thermographers lists 128 certified thermographers in the United States who indicate that they perform roof moisture surveys (primarily hand-held IR) with seven indicating aerial capability (8). The specific question of what type of camera is used during an aerial survey must be asked to ensure that a high-resolution camera is used. Some companies still perform aerial IR surveys with hand-held IR cameras which limits the quality of the information obtainable.

III. Methodology

Overview

To determine whether the Air Force roofing program was a worthwhile candidate to perform investigative research, personal and telephone interviews with Air Force roofing engineers were performed. The results indicated at least a perceived problem with performing the required inspections. A literature review search including the Defense Technical Information Center (DTIC) and CompuServe's IQUEST database revealed few recent articles about roof moisture inspections. The single best source of literature was from the Army's Cold Region Research and Engineering Laboratory (CRREL). CRREL has published many pamphlets describing several promising tools that could help the roof inspection process. After reviewing the literature and discussing the different methods with roofing experts, the aerial infrared method was selected for this research as it seemed the most promising to help in Air Force roofing inspections.

To determine whether the aerial infrared method of searching for roof moisture was effective, several IR case studies were examined. The results from these case studies, together with knowledge from infrared experts and information from the roofing engineers at the case study locations, were combined to form an assessment of the capabilities and suitability of using the aerial infrared method at Air Force bases.

Methodology Issues

Interviews. Telephone and personal interviews played an important role in obtaining data for this research topic. Interviewing was the primary method used to confirm that a problem still exists with the Air Force built-up roofing program, and interviewing was also the method used to collect information on the most current techniques available to improve the roof inspection process. The interview method was chosen because of the speed with which the data could be collected from many different locations. Interviewing was determined necessary for researching the aerial infrared topic due to the lack of current, published material and due to the difficulty in obtaining copies of some of the completed aerial IR case study reports.

The interviewing technique offers both advantages and disadvantages when compared to other data collection methods. An advantage is that the unstructured interviewing technique does not restrict the researcher to certain questions. Therefore, the course of the interview is free to flow toward the areas of interest and expertise of the interviewee which enhances the depth and quality of information obtained. A disadvantage of the interview method is the possibility of unknowingly inflicting personal bias into the questioning and possibly obtaining other than impartial or truly representative information.

Each interview was conducted in an impartial manner to achieve the most accurate information possible. Additionally,

the three-step guideline in Emory's textbook, Business Research Methods, for increasing a respondent's receptiveness was followed. Every attempt was made by the researcher to ensure that the respondent felt the experience was "pleasant and satisfying", believed that the research survey was "important and worthwhile", and had "any mental reservations satisfied" (10:162).

Case Study Method. The case study methodology differs from a statistical approach in that emphasis is on "the detailed analysis of a limited number of events or conditions" (10:61) for a case study, rather than broad coverage of a topic in which the interest would be focused on "the frequency with which certain characteristics or instances occur" (10:61). The case study approach is appropriate because of the limited number of case studies available and the narrow focus of the research objectives.

The case study methodology in this research application is both valid and reliable. Validity refers to measuring what is meant to be measured and reliability is the repeatability or consistency of a test to provide the same results under identical conditions (10:9). The case study method is valid because the information available from the case studies is the pertinent information necessary to help answer the research objective questions. The case studies selected are enough alike so that the data from each can be combined to reach a valid general conclusion. The case study methodology is reliable because the recorded information is

available for verification by other researchers.

The actual raw data and interpretations provided by thermographers in the written reports of each case study are likely to be unbiased and valid because the infrared companies who perform the surveys have nothing to gain by presenting false interpretations of thermograms. The infrared companies do not perform roof repair work and the roof owner could easily determine if the interpretations were inaccurate by taking his own probe or core test.

Instrument Validity and Reliability. In this research, the moisture content in the insulation layer of built-up roofs is being measured with an infrared camera. Since the IR camera measures heat, other heat sources may confuse the thermographer into predicting a damp area when the roof is actually dry. The validity check is on-the-roof verification testing - either taking destructive cores or using another nondestructive method. The best verification test is taking a core sample from the roof to confirm the actual moisture content. In most of the case studies included, at least one method of verification testing is performed to ensure measurement validity.

The infrared camera testing procedure, although it may not provide the exact same readings at different times under identical situations, is reliable. The infrared camera generally does not attempt to determine the numerical heat content in roof insulation. Rather the IR camera provides visible evidence of a difference in temperature which can be

interpreted as moisture content. This means that the camera may not produce the exact same image at different times under the same conditions, but the difference in temperature will still be detectable. The reliability of the camera is confirmed by pointing it at a known heat source for calibration and by on-the-roof verification testing after an IR survey.

Research Problems. Because of the few Air Force bases that have had an aerial infrared survey performed that meets the guidelines of this research, the author had to seek elsewhere to locate potentially valid case studies pertinent to the research goal. Additional case studies were chosen from recommendations by infrared experts. An effort was made to choose case studies that were representative of a typical Air Force Base (ie. many built-up roofs with differing ages in a relatively small area). Due to the shortage of qualifying case studies, some of the cases used do not fit the typical pattern desired.

The historical nature of the data for this research cannot easily be validated by reaccomplishing the IR surveys because the conditions change over time, so an inherent weakness in this research design is dependence on the accuracy of data collected by others. In this research effort, however, the problem of depending on others for accurate data collection was minimized because most of the pertinent information was recorded on videotape during the actual surveys and thus should be accurate and valid.

Research Methods

The methods used to guide the research effort of determining the usefulness of the aerial infrared technique for locating subsurface moisture in Air Force built-up roofs were a combination of historical case analysis (by analyzing as many appropriate cases as could be located), and extensive interviews with experts in the field of aerial infrared thermography (both military and civilian). Another source of valuable information was the roofing engineer assigned to the base where an aerial infrared survey was conducted. Although the possibility of personal bias in interviews may exist, an effort was made to recognize such impressions and keep all data objective.

An ideal method to compare inspection results would have been an experiment where several roofs were visually inspected by experts and then surveyed using the aerial infrared technique to compare findings. Additionally, to determine if the implementation of a regularly scheduled infrared survey would decrease overall life-cycle costs, a long range (15-20 year) study would be most preferable. Unfortunately, the lack of available resources (primarily time and access to aerial IR equipment) precluded the use of these recognized more stringent (and probably more conclusive) research methods. Instead, the approaches that follow attempt to answer the same questions.

Infrared Experts. Due to the relative newness of this branch of technology, the small number of experienced aerial

thermographers, and the lack of the author's expertise in infrared image interpretation, the following list of experts was invaluable in helping interpret the data collected from case studies. The list of aerial infrared experts and their qualifications begins with Mr. Wayne Tobiasson from the Army's Cold Region Research and Engineering Laboratory (CRREL) located in Hanover, New Hampshire. Wayne Tobiasson pioneered the use of infrared thermography for built-up roof moisture detection in 1975. Since then he has written many published papers on the aerial infrared method of detecting moisture in built-up roofs and is still regarded by others in the field as a leading authority on the infrared technique of detecting moisture in built-up roofs.

Mr. Thomas Hurley, the founder of I.S.S. Thermographic Testing, located in Mt. Airy, Maryland, has performed many built-up roof aerial IR surveys including the Andrews AFB and Langley AFB case study surveys. Mr. Hurley has been using the aerial IR technique for locating moisture in roofing since 1985.

Mr. Al Knehans from the US Army Corps of Engineers is another expert who has performed a number of aerial surveys and heads an Army team that travels to different military installations (mainly Army posts) to survey built-up roofs. He is the promoter of an Army developed program called "Roofer" which is an extensive, improved version of the method used in the old AFM 91-36. The "Roofer" program manipulates the data generated from an infrared and visual

survey to compute a roof condition index. This index is then used to estimate the expected roof life (2:6).

Mr. Jay Vanier, head of United Scanning Technologies of Peoria, Illinois, is also an IR expert who has been using aerial IR for locating roof moisture commercially for several years. He performed an aerial survey at Kelly AFB, a cursory demonstration flyover at Tyndall AFB, and the Michigan State case study survey.

Case Analysis. Since neither adequate time nor funding existed to create a controlled experiment to determine the potential usefulness of infrared thermography compared to an expert roofing technician performing a visual inspection, the historical case analysis method was chosen to obtain the data for comparison.

Each videotaped case study was examined by at least one of the qualified experts listed previously. Although the videotapes of three aerial IR case studies were available for review by the author, it was necessary to leave the interpretation up to the experienced thermographers. A written report usually accompanies each completed videotaped survey. The data for most of the case studies included in this research was obtained primarily from the written reports. The written report typically includes photographs taken from the videotaped footage of suspect areas and describes likely reasons for the thermal patterns identified. A visual walk-on-the-roof survey usually follows the IR portion of the survey to perform secondary tests which

confirm the IR results. A confirmed finding is a suspected IR identified wet area that has been validated as wet by physically taking a core sample, using a moisture probe, or using some other nondestructive test such as a capacitance meter or nuclear moisture meter.

As an additional source of information, the roofing engineer at each of the case study locations was asked for his overall impressions of the IR survey and was asked if any surprising conclusions were discovered from the infrared survey that would otherwise have remained unknown.

The cost of each aerial survey was obtained so that a comparison could be made between the typical costs of aerial IR per square foot and the square foot cost of comparable handheld IR inspection methods.

Case Study Restrictions. The only aerial infrared case studies included in this research were those performed using a high-resolution infrared camera intended for aerial use, comparable to the resolution provided by the FLIRtm 2000A, manufactured by FLIRtm Systems (14). Previous research by Wayne Tobiasson in 1984 used a lower resolution camera with less than desirable results (29:2). In addition, only case studies from locations in the continental United States (CONUS) were examined.

Initial Survey

To confirm that there was a perceived problem regarding the implementation of the inspection guidelines outlined in

AFR 91-36, a telephone survey of 25 different roofing engineers at Air Force bases across the country and representing 6 different Major Commands was conducted. The first question asked was "Do you feel that the roofing program as outlined in AFR 91-36 is being fully implemented at your base in the manner in which it was intended?" The remainder of each interview focused primarily on the topic of roof inspection. Specifically, an attempt was made to ascertain particular problem areas in performing the inspection procedure required by the regulation. Other questions asked were whether the roofing engineer's job at that particular base was a full-time or part-time duty; whether there was perceived adequate upper-level interest to ensure that there was enough time, manpower, and money allotted to correctly implement the AFR 91-36 program; and whether any non-destructive methods of evaluation were either tried or currently used to search for subsurface moisture in built-up roofs. In addition to the telephone interviews, a written questionnaire was completed by six roofing engineers who attended the October 1989 offering of the one-week long Air Force "Roof Design and Management Class" (the majority of students were roof technicians and supervisors) taught at Wright-Patterson AFB. The actual questionnaire is included as appendix B. Anonymity was promised to each of the roofing engineers (both in the telephone and written surveys) in an attempt to extract the true state of the roofing program at each base.

The results showed that 25 out of the 31 surveyed roofing engineers perceived that there were definite problems at their base with the present implementation of the existing roofing program as prescribed in AFR 91-36. All 25 respondents that indicated problems with complying with the inspection requirements in AFR 91-36 complained that there was not enough time allocated for them to accomplish their required duties. The roofing engineer's job was a full time or primary duty at only 2 of the 31 bases contacted. Twenty respondents also perceived the lack of management interest in the built-up roofing program as the cause of both time and manpower shortages. Over half of those surveyed were familiar with at least one of the non-destructive techniques described in chapter 2, but most bases either lacked the equipment, manpower, time, or expertise needed to operate the equipment.

TABLE 1
Results of Initial Interview Survey
Base Level Roofing Engineers

	<u>Number</u>	<u>Percentage</u>
Roof Engineers Contacted:	31	
Roof Engineer's job is an additional duty.	29	94%
Perceived Problems:	25	81%
a) Lack of Money	11	35%
b) Lack of Time/Manpower	21	68%
c) Lack of Equipment	3	10%
d) Inadequate Training	9	29%
e) Inadequate Management Interest	20	65%

From the survey conducted, the dominant problems seemed to be the lack of perceived management interest and its apparent affect of limiting available manpower and time allotted for the proper implementation of the built-up roofing program (AFR 91-36), especially in the most time-consuming area of inspection. In this research, the aerial infrared technique was explored to see if it could help improve roofing knowledge (and thus the roofing program in general) especially when there is not enough time or manpower available to visually inspect all the roofs in accordance with the regulation.

TABLE 2

Roofing People and Organizations Contacted
During the Entire Research Project

<u>Major Command</u>	<u>Number at Base Level</u>	<u>Number at HQ or Other</u>		
MAC	6	1		
SAC	10	1		
TAC	8	1		
ANG	1	1		
AFSC	3	1		
AFLC	7	1		
AFESC		2		
AFDW	1			
Air Force Total	36	8		
Army	2	2		
Nonmilitary		8		
TOTAL	38	18	+	= 56

IV. Case Study Analysis

Overview of Case Studies

The material examined for each case study included in the research was dependent upon the available resources. For three case studies, the author obtained and examined a copy of the VHS videotape including both airborne visual and aerial infrared views. In most cases, the information was obtained from the written report which was prepared from the videotape. In a few cases, the information was obtained through telephone interviews with the most knowledgeable person involved with each IR survey.

Each written report includes photographic prints taken from the master videotape which indicate suspected moisture damaged areas. In the written reports, both visual and IR photos of a particular area were typically presented side by side, together with the most likely explanation for any warm areas indicated by the IR scan. In the following case studies, the source of information and the method used to obtain the information is identified.

Case Studies Considered

There have been very few Air Force installations that have received aerial IR roof moisture surveys using a high-resolution aerial IR camera. The bases that have had such surveys accomplished within the past 5 years are: the Air National Guard portion of Andrews AFB Maryland, Kelly AFB

Texas, Langley AFB Virginia, and Tyndall AFB Florida. The Army's Aberdeen Proving Grounds in Maryland had a qualifying aerial IR survey so it was included as a case study. Also examined was information from hand-held IR surveys performed at Hill AFB Utah, and McClellan AFB California, primarily for price comparison purposes. Several civilian locations were also included due to the lack of qualifying military case studies. The civilian case studies include the Supreme Court Athletic Club, and the University of Michigan. Excerpts from Roof Moisture Survey: A Case History, a published case study from the proceedings of Thermosense X is also presented (31).

Andrews AFB, Maryland. The Air National Guard's 113th Civil Engineering Squadron hired a commercial firm to perform a helicopter IR roof moisture survey on 12 buildings in June 1989 at a cost of \$9,748. Approximately 244,000 square feet (SF) of roofing area were examined from about 500 feet above ground level (AGL). Of the 12 buildings, five were built-up roofs with a total area of 76,850 SF. No follow-up verification was performed on the built-up roofs. One single-ply roof was verified using core cuts and a moisture meter. The average cost of this survey, including the BUR and single-ply roofs, was 4 cents per square foot.

The written report was used to obtain most of the information for this case study (19). Additional information was received from telephone interviews with the roofing engineer.

From a June 1990 phone conversation with the roofing engineer, the IR tests identified several problems that were covered under warranty. The aerial IR results indicated two small wet areas on the Support Center roof which were promptly repaired under warranty. On another building, enough money was saved on one 22,000 SF roof to pay for the entire survey. Because of the information made possible with the IR tests, this entire roof was reprogrammed as a roof repair instead of a total replacement, saving an estimated \$150,000.

The following results are from the built-up roofs included in this survey. The IR pictures of Building 3119 showed probable total roof insulation saturation. Building 3212's IR results indicated extensive moisture damage and total membrane failure. Building 3222's IR indicated a large section that showed no evidence of moisture infiltration and a small section that appeared uniformly wet to a medium degree. Building 3252's IR revealed extensive subsurface moisture damage and some ponding water. An estimated 20 to 30 percent of the entire surface was predicted wet. The survey team's recommendation was for total roof replacement on buildings 3119, 3212 and 3252 and replacement of just the moisture damaged area on building 3222. The IR information from building 3227 showed no insulation saturation but likely moisture infiltration into the felt plies. The recommendation was for quick corrective action (repair). Although no verification testing was performed on any of

these built-up roofs, the IR pictures convinced the proper managers to program for future roof repairs and replacements.

One single-ply membrane roof in this study was worth including in the discussion. Building 3500, a single-ply ballasted roof was only 5 years old but the IR indicated serious water saturation. A follow-up survey was performed in November 1989 when 7 core samples were taken corresponding to the areas identified as most saturated by the IR. The results confirmed that the insulation where the cores were taken ranged from 5 percent to 100 percent saturated. A visual survey revealed that several attempts had been made to patch the roof. What could not be seen was that an estimated 70 percent of the roof area was extensively saturated. The recommendation for this roof was total roof removal and replacement.

Aberdeen Proving Grounds, Maryland. An aerial IR survey was performed in November 1988 by helicopter at an average altitude of 500 feet. The survey included 13 buildings totaling 398,812 square feet of roof area. Six of the 13 buildings were built-up roofs comprising 165,836 square feet. Only the built-up roof results from this case study were examined. The total cost of this survey, including the single-ply roofs, was \$16,000. The average cost was approximately 4 cents per square foot. The information for this case study was obtained from a copy of the final written report submitted to Aberdeen Proving Grounds (18). The report included photos of both visible and IR indicated

suspect areas. The IR results were confirmed using a combination of moisture probe tests and core samples.

Building 315; 74,396 SF. The IR showed extensive subsurface moisture possibly causing the structural integrity of the building to be questioned. Since this was a tectum deck (where the poured tectum material forms both the strength and the insulation of the roof), severe moisture saturation could significantly affect the soundness of the structure.

Building 3147; 14,090 SF. The IR indicated large areas of subsurface moisture not visible in the walk-on survey. This building has a concrete deck with 4 inches of poured perlite insulation. Visual examination did reveal structural damage to a wall due to moisture penetration and resultant freeze thaw cycles. The recommendation was to reroof.

Building 3148; 14,090 SF. IR showed large areas of subsurface moisture similar to 3147. The insulation in this roof was fiber board. The recommendation was for total roof replacement.

Building 3245; 20,391 SF. This multi-sectioned roof incorporated many different materials in different locations. The IR showed several areas of moisture saturation. Some of these areas proved to be quite badly saturated and deteriorated, however this roof appeared feasible to repair. One small hole in the membrane of this roof was discovered by IR from about 500 feet AGL and located visually during the walk-on survey, even though it was only 3 inches long.

The two areas that were tested with a moisture probe confirmed the moisture saturation problem.

Building 4305; 16,904 SF. This roof was less than one year old. Serious workmanship flaws were noticeable in many areas during the visual inspection. The IR results revealed some subsurface moisture patterns. One internal leak had already occurred. Even though the core sample was taken in an area least significant in the thermogram (due to the presence of ponding water, the core sample could not be taken in the area which the IR showed most likely to be wet), the moisture saturation level was still 55 percent. The recommended remedy was to pursue warranty action immediately.

Building E1930; 25,425 SF. The IR tests on this one year old roof revealed several areas believed to be only slightly saturated. Most of the problems were due to visible defects in the metal counter flashing and holes in the felt base flashing. No visible flaws were noticed in the built-up membrane. There was one bright area identified by the IR tests on this roof. The probe verification test revealed 55 percent moisture saturation in this location where a pipe penetrated the roof. Warranty repairs were recommended for this roof as well.

Kelly AFB, Texas. An aerial IR survey of 32 buildings was performed by a commercial firm using a fixed-wing aircraft from approximately 1000 feet AGL in March 1989. Unfortunately the survey results package could not be

located and thus prevented its inclusion in this research. The company that performed the survey provided the only information available about this survey. The total built-up roof area surveyed was approximately 1 million square feet costing \$47,927. There was no follow-up verification provided by the IR survey company, and the present Kelly AFB roofing team has not performed verification testing of their own. The cost per square foot for this survey was 4.8 cents.

Langley AFB, Virginia. In February 1989, Langley AFB contracted a commercial firm to perform a helicopter IR survey for all of its built-up roofs for about 2 cents per square foot. Approximately 1,612,500 square feet of built-up roof area were examined from about 500 feet AGL costing approximately \$31,000 (21). The information for this case study was acquired from a draft copy of the videotape, the written results package, personal interviews with both the current roofing engineer and the IR expert who performed the survey, and the researcher's personal working knowledge from having been the roofing engineer at Langley AFB during the IR survey (16; 22; 23).

With the help of the aerial IR survey, the existing five-year roofing upgrade plan was validated. One roof, which had never been visually inspected, was identified by IR as having completely failed. Due to the building's low priority (a swimming pool house), it was added near the end of the existing repair/replacement priority list.

Building 339 had a new roof installed in July 1986 (almost three years old), yet the IR showed that an entire seam along the edge flashing had leaked. This roof may still be under warranty.

Perhaps the most dramatic finding at Langley AFB was the condition of the new Base Supply Complex roof. This building was constructed in three separate phases about one year apart and is the base's largest building comprising 204,104 square feet of built-up roofing area. The oldest section of roof had been installed about three years prior to the IR survey, with the newest section barely one year old. A comprehensive visual inspection performed by the author approximately 6 months before the IR survey indicated one seam of catastrophic failure on the second bay. At the highest portion of the roof, the roof membrane had slipped, exposing about a 1/2 inch wide strip of insulation approximately 40 feet long. Aside from this major flaw, no other roofing problems were evident. The IR results, however, indicated otherwise. Although this was a "new" roof, the IR videotape showed numerous thermal anomalies intertwining over half the roof area. Many of the skylights in the roof showed "hot spots" around them indicating moisture infiltration. A comprehensive investigation of the second bay, including secondary verification of the roof using destructive core samples and a nuclear moisture meter, confirmed that there was a moisture infiltration problem. A moisture meter reading of 45 percent saturation was taken at a

location near the membrane slippage. Approximately 20 percent of this roof section had greater than 20 percent saturated insulation. The verification team's recommendation was to pursue legal action against the roofing contractor who installed the roof.

As the remaining Langley IR survey results have not yet been physically verified, they are not included in this research.

Michigan State University. A fixed-wing aerial IR survey was conducted by a commercial firm in 1989 including over 1 million square feet of BUR area. The results of this survey were obtained from a telephone interview with the roofing engineer, Mr. Bob Smith (35). He has been the Michigan State roofing engineer for 40 years and therefore, has an intimate knowledge of the roofs and roofing practices there. He used a nuclear moisture meter for 5 years doing his own surveys but quit using it in 1983 when hand-held IR equipment became available. He has been renting an IR camera and using IR ever since. From years of hands-on experience, he feels that IR is the best method yet to aid in moisture detection of roofing insulation. To quote him, "IR as been a real lifesaver"(35). Many of his roofing projects have been repairs instead of whole roof replacements because of the information that the IR imagery provided.

The aerial survey in 1989 cost about \$34,000 which equates to about 3.4 cents per square foot. Included in the

survey price were the written results, photos, thermograms, and reproducible mylars. Secondary testing was not included as Mr. Smith has his own team of roofers to assist him in the verification testing. A hand-held IR camera was rented to aid in the secondary verification testing. Mr. Smith was very pleased with the results obtained from his first aerial IR survey and indicated that it was considerably cheaper to hire the aerial survey than to rent a hand-held IR camera to cover the same area. Most of his (primarily coal tar) roofs last between 20 and 30 years before replacement is necessary. This is a strong indicator of how successful a roofing program can be if effectively managed with sights fixed on long term results. Mr. Smith has a crew of nine fully trained and equipped people that is qualified to perform any type of repair. He still says he wishes he had more people. Regular maintenance can extend the life of built-up roofs.

Mr. Smith said one of the more useful aspects of IR is that it produces a visible image that can be shown to the people who make the budgets. He tries to program all major roof repairs or replacements 5 years in advance and finds it much easier to get funding now that he has tangible evidence to show what is wrong with the roofs (35).

Supreme Court Athletic Club. An aerial IR survey of the Supreme Court Athletic club in Maryland was performed in July of 1989 by helicopter at about 500 feet AGL. The information presented here was obtained from a copy of the written survey package (20).

The one built-up roof surveyed had an area of 9,672 square feet. The roof was about 10 years old and only one interior leak had been reported. A follow-up verification survey was performed in September 1989 which included visual walk-on, an electronic non-destructive test, moisture probe tests, and several core samples.

The IR survey indicated many varied and extensive thermal patterns suspected as being moisture related. The fiberboard insulation used for this roof created ideal conditions for infrared moisture detection because of fiberboard's ability to absorb and concentrate moisture near the leak source.

The walk-on visual survey identified various membrane and flashing defects though no obvious leak locations. Nine incorrectly applied superficial patches were identified (a correct repair would have first removed the saturated insulation before recovering the area with a new waterproof membrane).

The nondestructive electronic impedance test results were obtained using a Tramex Dec Scannertm, an instrument with a surface area of about 3 square feet that was rolled over the entire roof by pushing its long handle. The impedance results coincided very closely with the IR results. The Dec Scannertm moisture saturation meter indicated that the entire roof insulation was at least 5 percent saturated.

Both of these non-destructive evaluation techniques were confirmed with a moisture probe and several core samples.

The moisture probe revealed that all the IR identified suspect areas were at least 15 percent water-saturated, including all of the superficially patched areas. Three of the superficially patched areas which showed an extremely pronounced thermographic pattern actually spewed forth water (100 percent saturation) when penetrated with the moisture probe.

The overall roof prognosis was that even though there was only one reported interior leak, the other areas would begin to leak soon. An estimated 1/3 of the roof was at least 30 percent moisture saturated rendering the roof on the verge of being unsalvageable. The recommendation given by the commercial IR survey team was to begin programming a replacement roof for the building. However, the service life of the existing roof could possibly be extended another 3 to 5 years if repairs costing about \$500 were performed to remove the 100 percent saturated insulation areas (about 84 SF) and reseal the membrane. The cost of this aerial IR survey was unavailable.

Tyndall AFB, Florida. A helicopter IR survey was performed by the Army in November 1985 and a courtesy fixed-wing cursory flyover was performed by a commercial company in December 1989. The Tyndall AFB roofing engineer did not have the results package from the Army's study, but the following information was obtained from a copy of an official letter of correspondence.

The total cost of the Army's aerial IR survey was \$4,500. The total area of roofing surveyed was not available. Thermographic conditions were satisfactory the night of the IR flyover and two buildings showed indications of possible wet insulation. Verification information for these two roofs was not available. The letter expressed a desire for Mr. Knehans, the Army IR engineer who performed the survey, to resurvey the base at a later date to validate the findings of the first survey. Another aerial IR survey by the Army at Tyndall AFB, has not yet occurred.

The weather conditions during the commercial cursory flyover in December 1989 were not favorable, so there was no useful information available from this survey. A copy of the videotape from the cursory flyover was viewed, but it contained only a few buildings and there were no appreciable thermal images.

Hand-held IR Case Studies

Hill AFB, Utah. Hill AFB paid about \$72,000 or 2.2 cents per square foot in 1987 for a walk-on IR survey of 3,318,220 square feet of built-up roofing. The contract included the completion of the two forms required for each built-up roof per AFM 91-36: AF forms 1059 and 1060. No verification testing was performed. The information for this case study was obtained from copies of official letters sent from Hill AFB (34) and from telephone interviews with the roofing engineer.

Hill AFB realized remarkable savings when the IR revealed that the 7 bays of building 850 did not need the entire roof insulation replaced. A project had already been designed that included complete replacement of the roof and insulation, but after the IR results revealed that most of the insulation was dry, the project was redesigned, which lowered the cost estimate by approximately \$308,000. No other significant information was discovered.

McClellan AFB, California. McClellan AFB contracted a two-phase walk-on-the-roof survey for its BURs in 1988. The first phase which was performed with IR tests included 298,672 SF and cost about 25 cents per square foot. The second phase did not include an IR survey. Instead, the Tramex Dec Scanner™ was used to locate moisture damaged insulation. The average cost of the second phase was 15 cents per square foot. About 12 percent of the total 8 million SF area of built-up roofing was surveyed in both phases of this project. No specific results about individual roofs or repair work initiated because of the IR test results was obtained (24).

Roof Moisture Survey: A Case History. This case study is from a hand-held infrared survey published in April 1988 (31:62-69). Follow-up verification included visual and nondestructive electronic tests. The information in this case was obtained solely from the published article about the case study.

One 85,000 SF roof surveyed with hand-held IR showed 16 separate wet areas totaling 4950 SF (31:66). An interior visual survey identified 22 interior leaks of which only 6 could be visually located on the roof. Only 8 of the 16 IR identified wet insulation areas could be found from the interior leak locations (31:68). Interior leaks had not yet occurred below many of the wet insulation areas. None of the wet insulation areas were evident during the visual walk-on-the-roof survey.

V. Conclusions

Conclusions From Personal Interviews and Case Studies

From the substantial amount of information received through personal and telephone interviews with roofing experts, and the information obtained from the case studies, the questions posed in chapter one are answered.

- Q1. Will aerial thermography provide more valuable information about base roofs (than would otherwise be known) to more accurately develop a valid roofing repair/replacement priority list (required by the regulation)?
- A1. The answer is an emphatic yes. An aerial IR survey has the ability to provide information that was previously only available to those who had the right equipment, training, and plenty of available time and manpower to perform time consuming walk-on-the-roof surveys. An inexpensive alternative now possible is to hire a commercial firm experienced in providing the necessary information to assist in built-up roof management. A list of organizations that perform aerial IR roof moisture surveys is included in appendix A.
- Q2. Can aerial thermography save the government money by decreasing the life-cycle cost of Air Force built-up roofs? (ie. can it pay for itself?)
- A2. All the roofing experts attest that aerial IR is an effective method to understand the problems of a roof early enough to make effective and inexpensive repairs which will extend the life of a built-up roof. By replacing roofs less often, tremendous savings can be realized - enough to pay for the cost of the IR surveys many times over.
- Q3. What limitations does the aerial infrared method have for Air Force use?
- A3. Aerial IR tests must be performed by a qualified and experienced thermographer in order to obtain the maximum information possible from an IR survey. Weather conditions must be satisfactory for proper results to be achieved. The roofs must be dry and a minimum temperature difference must exist for the IR test to produce a meaningful image.

- Q4. Will the aerial infrared inspection method work at all CONUS Air Force Bases?
- A4. In discussing this question with several IR experts, they all affirm that the IR method can be successfully used at any location in the CONUS. Some special precautions need to be observed in especially cold or especially hot climates but the usefulness of IR tests in all climates has been confirmed in many experiments.
- Q5. How often should an aerial infrared survey be performed?
- A5. The average recommended time is 3 to 5 years. A good plan ensures that newer roofs will be surveyed to help enforce the warranty.
- Q6. What qualifications should be required of the aerial IR surveyor?
- A6. A qualified IR thermographer for investigating moisture in built-up roofs should have experience both in roofing and thermal imagery. Completion of the level-1 course from the Infrasppection Institute is a good indication of adequate training in IR. Completion of the level-2 course is an even better indication. Prior experience as a roofer or proven IR experience on a minimum of 10 built-up roofing surveys should be an adequate rule of thumb.
- Q7. What type of infrared equipment should be used to produce the resolution necessary to accurately locate subsurface moisture?
- A7. To perform a useful aerial IR survey, the camera must be designed and intended for aerial use. The resolution of a hand-held IR camera is usually not adequate to successfully perform an aerial roof moisture survey. Most of the commercial companies (and the Army IR team) use a model FLIR[™] 2000A/B or FLIR[™] 2000F with excellent results. Several other camera manufacturers produce aerial equipment with equal or better resolution.

One of the best uses of the aerial infrared photographs included in the written survey report is to show them to the managers who make the decisions of where maintenance and repair money gets spent. Before infrared, the manager had to depend on the expertise of the roofing engineer to make

acceptable decisions. Now that visible evidence of roof moisture problems can be provided to the manager, the manager can make a much more informed and confident decision about providing necessary roof maintenance funds.

The results from the case studies reviewed indicate the use of infrared for locating subsurface moisture in built-up roofing is not only feasible but can be highly time and cost effective. Aerial IR can take much of the guesswork out of what is really happening inside a built-up roof so that informed decisions can be made to optimize the time and money spent on maintaining a roof. Identifying the true cause of a problem is often the larger part of fixing it. With aerial IR, a roof problem can be identified, making informed decisions possible for the best course of action to pursue.

Using aerial IR is a very quick way to determine the condition of many roofs at the same time. This capability can help a roofing engineer develop an accurate roof priority list and can help the engineer decide which roofs should receive further examination. Additional scrutiny may reveal roofs that can be maintained or repaired to stop leaks, instead of requiring an expensive, complete roof replacement.

In the case studies where the information from the aerial IR survey was used to diagnose and treat certain ailing roofs, the cost of the IR survey was usually offset by the money saved from repairing a roof rather than

replacing the entire membrane. At Hill AFB, the projected \$308,000 savings was significantly greater than the \$72,000 cost of the IR survey. At Andrews AFB, the \$10,000 survey cost revealed information which saved approximately \$150,000 on one roof repair. At Aberdeen Proving Grounds, the \$16,000 IR survey revealed major problems on two roofs that were still under warranty. These cases demonstrate that the aerial IR roof moisture inspection method does have the ability to save more money than its cost.

A direct comparison between the cost per square foot for the aerial and walk-on-the-roof IR surveys would not be very fair or meaningful considering the case studies researched. There were significant differences in the total roof area and the number of roofs surveyed between the particular case studies. The large area of roofing surveyed with a hand-held IR camera at Hill AFB may lead the reader to conclude that handheld IR is about the same cost as an aerial survey. This is misleading because several other factors have an impact on the cost. The actual work completed at Hill AFB did not include follow-up verification and the written results package included different information than some of the other surveys. Alternatively, the relatively expensive McClellan AFB walk-on-the-roof IR survey was subcontracted and included a more detailed final written report. On average, the aerial surveys were less expensive than the hand-held surveys for large areas of roofing.

The resolution and quality of information obtainable was not significantly different between the hand-held walk-on-the-roof IR surveys and the aerial IR surveys using the aerial cameras. This led to the conclusion that either method is equally acceptable and that other variables, particularly price, time, and manpower, should be used to decide which method is selected.

Although the literature suggested that IR interpretation can lead the thermographer to conclude there is moisture in a particular area of roof when there is not, this type of incorrect interpretation was not mentioned by any of the roofing engineers at any of the case study locations researched. In addition, none of the written survey reports indicated areas that tested wet during the walk-on verification that were not already indicated as suspect areas by the infrared results. The aerial IR camera survey for locating moist areas in built-up roofing seems to be both reliable and valid, even without performing secondary testing; although most thermographers are hesitant to jump to conclusions using only the IR results. The secondary testing performed in the research confirmed that the aerial IR method was accurate in locating moisture without further verification, however, all the experts interviewed agreed that secondary testing should be performed to be absolutely sure of the existing conditions before roof repair/replacement decisions are made.

Concerns

When investigating the aerial IR roof moisture surveys to include in this research, a potential problem was discovered. At three Air Force bases, an aerial IR roof moisture survey was accomplished but the results were not adequately acted upon. Most often the inaction was caused by the person who had asked for the survey or who was interested in the results of the IR survey transferring out of the organization. This practice can be more detrimental than helpful to the Air Force because of the wasted money spent on useful, but time-sensitive information. If the survey results are not acted upon expeditiously, there is great likelihood that the size of the problem areas will have grown to such an extent that when the repair team finally arrives, the wet areas will be much larger than indicated in the thermograms. Once the information on moisture locations is obtained, action should be taken immediately to use this information before it becomes obsolete and of questionable value. One way to ensure that the IR results are acted upon is by gaining steadfast support from senior management.

The perception by most of the roofing engineers surveyed is that existing management support is severely lacking, and since there is little, if any, enforcement of the existing regulation, the roof inspections are not being performed as required. Regularly scheduled aerial IR inspections could help with some of the roofs that don't get visibly inspected, but an infrared survey should not replace the visual

inspection requirements in AFR 91-36. Although the infrared method has demonstrated a remarkable ability to locate moisture beneath the membrane that could not be identified in a visual survey, the visual survey is still necessary to locate obvious potential problems such as deteriorated edge flashing (where close to 80 percent of all roof leaks occur), clogged roof drains, and poor pitch pockets.

Side Benefits

The infrared flyover survey can provide valuable additional information on electrical substations and steam lines. At Langley AFB, an unknown underground steam pipe leak was identified as well as one warm connection at an electrical substation. Both of these findings were not part of the roof survey but were identified in the written survey package received from the IR inspection company. Aerial infrared scans have also been useful at locating some hazardous waste dump sites.

VI. Recommendations

There is much information that the author has acquired during this research that is not specifically mentioned in the text. The combination of all that has been presented and what was learned during the research but not included in the written presentation has had an influence on the final opinion of the author. In concluding this research, the author is extremely optimistic that a built-up roof management program including aerial IR can, if implemented correctly, turn around the present posture of leak management in roofing to true maintenance and repair which will save time and money and achieve fewer customer complaints. The key to initiating an improved and workable roofing program is to ensure top level management commitment toward acknowledging and solving the problem.

The first recommendation is that there be centralized control over the Air Force roofing program at a level including all the MAJCOMs. Lessons learned, both beneficial and detrimental, would be more easily compiled and disseminated from a central roofing control location. This would ensure that all bases receive the most current and cost effective roofing policies available. Each major command should be responsible for maintaining and enforcing the Air Force Roofing Program standards. Centralized control is necessary to enforce the roofing program regulation.

Worth noting, however, is that even if all base civil engineers were to enthusiastically support the roofing program, it is the wing commanders on base that often have the strongest vote in deciding which programs receive funding priority over others. Somehow the necessity of relentlessly pursuing a comprehensive roofing program needs to be impressed upon the "true" decision-makers of the Air Force if significant cost savings are to be realized.

The second recommendation is that each base roofing engineer's job should be a full-time or at least a primary job at most Air Force bases in order to get the roofing program under control. The additional duty status of the roofing engineer at most bases almost guarantees that not all the required work can be accomplished. If full-time status is given to one person at each base, the roofing program should be under control in an estimated 2-5 years. The roofing engineer should be a civilian who plans to remain at that base for several years in order to begin and maintain an effective roofing program. The transient nature of military engineers ruins the information continuity and stability necessary to have an efficient and effective roofing program.

The third recommendation is that a policy or public campaign should be initiated to promote the benefits of maintenance as a way of getting more value from the money spent by the government. The notion of "don't fix it if it ain't broke" needs to be erased from the minds of Air Force

managers. A proper roofing maintenance program alone can at least double the life of Air Force built-up roofs. The money and time saved from fewer roofing replacements could then be used for many other purposes - perhaps to hire a commercial full-time roofing professional so that Air Force people would not have to maintain the roofing program any longer.

The fourth recommendation is that a routine IR inspection of all the roofs on a base should be required as part of the Air Force Roofing Program at all CONUS bases. An infrared survey, either aerial or handheld, should be required at least every 5 years - with special consideration given to schedule surveys that can catch problems that can still be repaired under warranty. Since the information obtainable from both aerial and handheld IR surveys is comparable, the cost and reputation of the company should be the primary selection factors.

This thesis provides convincing evidence to conclude that aerial IR testing, when included as part of a continuing roof maintenance program, can significantly benefit the Air Force.

Appendix A

List of Aerial Infrared Organizations

- | | |
|---|--|
| 1. ISS Thermographic Testing
4757 Buffalo Road
Mt. Airy, Maryland 21771 | Point of Contact:
Mr. Tom Hurley
(301) 875-0234 |
| 2. United Scanning Technologies
1200 W. Pioneer Parkway
Peoria, Illinois 61615 | Point of Contact:
Mr. Jay Vanier
(800) 223-1865 |
| 3. Horizon Helicopters
7443 Muriata Drive
Rancho Muriata, California 95683 | Point of Contact:
Mr. Joe Fernandez
(916) 966-8181 |
| 4. World Aeronautical Infrared Testing (WAIT)
2265 133rd Lane NE
Ham Lake, Minnesota 55304 | Mr. Larry Davis
(612) 754-3193 |
| 5. Photo Science
7840 Airpark Road
Gaithersburg, Maryland 20879 | Point of Contact:
Mr. Jim White
(301) 948-8550 |
| 6. United States Army Engineering
& Housing Support Center
Attn: CEHSC-FB-S
Ft. Belvoir, Virginia 22060-5516 | Point of Contact:
Mr. Al Knehans
(703) 355-2359
AV 345-2359 |

For additional information on thermographers in your area or to attend training courses to learn about infrared thermography, contact:

Infraspection Institute
33 Juniper Ridge
Shelburne, Vermont 05482

(802) 985-2500

Appendix B

Base Roofing Program Questionnaire

1) What is your job title (roof engineer, technician, etc.)?

2) What MAJCOM do you represent? _____

3) What base are you from? _____

4) How long have you been associated with the Air Force
Roofing Program? _____

5) Is the roofing engineer's position at your base a full-
time job or an additional duty? _____

6) In your honest opinion, do you think that your base roof-
ing program is comfortably under control or do you think
it is seriously lacking one of the following?

Circle all that apply
and write any comments
below.

- a. Money
- b. Manpower
- c. Equipment
- d. Adequate Training
- e. Management's
Attention

7) Do you feel that you know enough about your present base
roofing program to answer question #6 adequately? yes or no.

8) For CONUS base level and MAJCOM level roofing engineers
only. Please give your name, rank, and autovon number so
that I may be able to ask you further questions later if
necessary. Names will be held strictly confidential and
will be used for information collection purposes only.

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Vita

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