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The Feasibility of Using Thermography to Detect Subsurface Voids in Painted Wooden Panels

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THE FEASIBILITY OF USING THERMOGRAPHY TO DETECT SUBSURFACE VOIDS IN PAINTED WOODEN PANELS

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PREFACE

Thermography is a technique whereby the structure or condition of an object is studied by means of precisely measuring temperature variations over the surfaces of the object. The research which is described in this thesis was undertaken to determine whether thermographic techniques could be applied to the field of art conservation to detect subsurface voids within painted wooden panels. It must be stressed, however, that this research was carried out as a feasibility study with no attempt being made to establish or refine a technique that could be immediately applied to the examination of works of art.

The text of this thesis is divided into four sections. The first of these sections, the "Introduction," is an attempt to establish a need for a technique capable of detecting subsurface voids within panel paintings. The second section entitled "The Theoretical Basis for Thermographic Analyses of Subsurface Voids" explains why voids can be detected through the measurement of surface temperatures, and the equipment necessary to make these temperature measurements is explained. The section entitled "Experimental Procedures and Results" describes the research carried out for this thesis and contains a number of photographs which illustrate the effectiveness of thermography in detecting subsurface voids. The final section of the text entitled "Conclusions" summarizes the findings of the research and relates these findings to the possible future application of thermography to the analysis of actual works of art.

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ACKNOWLEDGEMENTS

Preliminary studies of the feasibility of using thermography to detect voids in wooden panels were done with an AGA Thermovision(R) 680 radiometer with the kind assistance of Dietrich Beau, President of the AGA Corporation, Secaucus, New Jersey.

Representatives of the Spectrotherm Corporation were very helpful in supplying technical information about their equipment and in assisting the author in the location of a radiometer with which the research could be undertaken.

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INTRODUCTION

Cleavage and worm tunneling are two defects which affect paintings on wood. Cleavage is the lack of bond between any two layers or strata which were intended to adhere to one another. In art conservation, cleavage most often refers to a loss of bond between two paint layers, between a paint layer and the ground layer, or between the ground layer and the support. Worm tunneling is the condition affecting panel paintings in which insects or worms have penetrated the wood panel and have eaten either the wood itself or the glue sizing and the glue in the ground layers. This gastronomic excavation results in tunnels or galleries beneath the paint surface.

Whenever a paint layer becomes separated from its support, either through cleavage or worm tunneling, the security and integrity of that paint layer becomes threatened. The slightest touch with a finger, or even the normal minute expansions and contractions of a wood panel, could cause an unsupported area of paint to flake off. The resultant loss may seriously disfigure the design.

Fortunately, a qualified conservator can usually repair areas of cleavage and worm tunneling before the paint becomes dislodged. To do this, however, the conservator must first detect and locate these voids.

Because cleavage occurs below the paint surface, one cannot always expect to see it. Sometimes cleavage is noticeable because it is accompanied by a visible distortion or buckling of the paint layer. However, this is not always the case. Moreover, there are normal features of soundly supported paint surfaces such as impasto or distortions in the support which may look like the effects of cleavage. Worm tunneling also cannot be seen unless the paint film is collapsing and at this point damage to the paint would already have begun.

Because visual examination is an untrustworthy and limited technique of detecting cleavage and worm tunneling, conservators have sought other methods of detection. Unfortunately these methods are not ideal. They are either ineffective or potentially injurious to the painting.

One technique which conservators may try is x-radiography. Because this technique measures the amount of radiation absorbed by the matter between the x-ray source and the x-ray sensitive film, an area of cleavage in the midst of well bonded layers would not be detectable because the unadhered paint would contain exactly the same amount of x-ray absorbing material as the surrounding well adhered paint film.

In the case of worm tunneling, however, wood or ground would have been removed from the panel. Therefore, x-radiography should theoretically be capable of detecting those areas where x-ray absorbing matter is absent. In practice, however, this may not be the case. Cellulose has a low absorption coefficient for all but very low energy x-rays (produced at low kilovoltage). Therefore only such low energy x-rays will allow the differentiation between cellulose and voids. These same x-rays, however, will not penetrate a ground or paint layer containing highly absorbing components such as lead white which require the use of high energy (high kilovoltage) x-rays for penetration.

Another problem with attempting to use x-radiography to detect worm tunneling is that with this technique it is difficult to determine the exact placement of a worm tunnel within a panel. This is important because if the excavations were deep within the panel rather than on the surface of the wood just beneath the ground layer, they would not directly cause insecurity to the paint layer. However, if the worm tunneling were directly behind the ground or within the ground layer itself, the security of the paint would be severely threatened. With stereo x-ray pairs or other sophisticated radiographic techniques one might be able to establish the exact location of worm tunnels but only if the ground and paint layers contained small amounts of x-ray absorbing pigments.

There is one technique for detecting cleavage which conservators have used with some degree of success. This method is called "sounding." To do this, one simply rubs one's finger lightly over the surface of the painting, or gently taps a suspected area of cleavage with a blunt pointed instrument and listens for a change in pitch.[1] Whereas this technique may be quite capable of detecting large areas of cleavage or worm tunneling, it is not sensitive enough to detect small voids. The most serious disadvantage of this technique is the risk of damaging the object. Paint which is not adhered to its support is extremely fragile. The rubbing of fingers over this paint surface or tapping it with a pointed instrument could easily cause insecure paint to flake off.

In the past, no entirely satisfactory technique for detecting cleavage and worm tunneling has existed. However, there has always been a need for such a technique because protective measures cannot be taken unless the conservator can locate these voids.

An ideal method for detecting cleavage and worm tunneling should have the following characteristics, listed in order of importance:

1. Harmlessness. (There should be no possibility of damage to the object and ideally there should be no contact with the paint surface.)
2. Sensitivity. (The technique should be capable of detecting small voids and it should be capable of distinguishing between voids just beneath the paint surface and those voids deep within the panel.)
3. Reliability.
4. Simplicity and ease of operation.
5. Low cost.
6. Portability.

X-radiography and the technique of "sounding" do not satisfactorily meet the first three requirements. This being the case, the author feels justified in proposing another technique which has the potential to meet at least the first three requirements, if not all six. The word potential should be stressed, however, since the true worth of any conservation technique can be established only as that technique is applied to a variety of paintings by many conservators.

THE THEORETICAL BASIS FOR THERMOGRAPHIC ANALYSES OF SUBSURFACE VOIDS

The Theory of Heat Flow

The propósed thermographic technique of detecting voids within wooden panels is based on one simple principle. This principle is that the thermal coefficient of air is less than the thermal coefficients of wood and paint.

A basic characteristic of heat, experienced by everyone, is that heat flows from one object to another. The direction of heat flow is invariably from warm objects to cooler objects. The rate at which this flow takes place, however, is dependent on numerous factors. One familiar factor is that some substances, termed thermal insulators, have very low thermal conductivities and when such materials are placed between warm and cool objects, they reduce the rate of heat flow from one to the other.

Gasses such as air are good insulators. The thermal coefficient of air is approximately ten times smaller than the thermal coefficient of a softwood such as pine.[2] Because the voids within wood panels are filled with air, one would expect these voids to locally restrict the flow of heat through those panels. The best way to illustrate the insulating effect of voids within solid substances is through an example. Consider Figure 1 (see p. 7). Depicted is a metal bar with a slot cut near its front surface penetrating from one side of the bar to the other. This slot constitutes a void within the

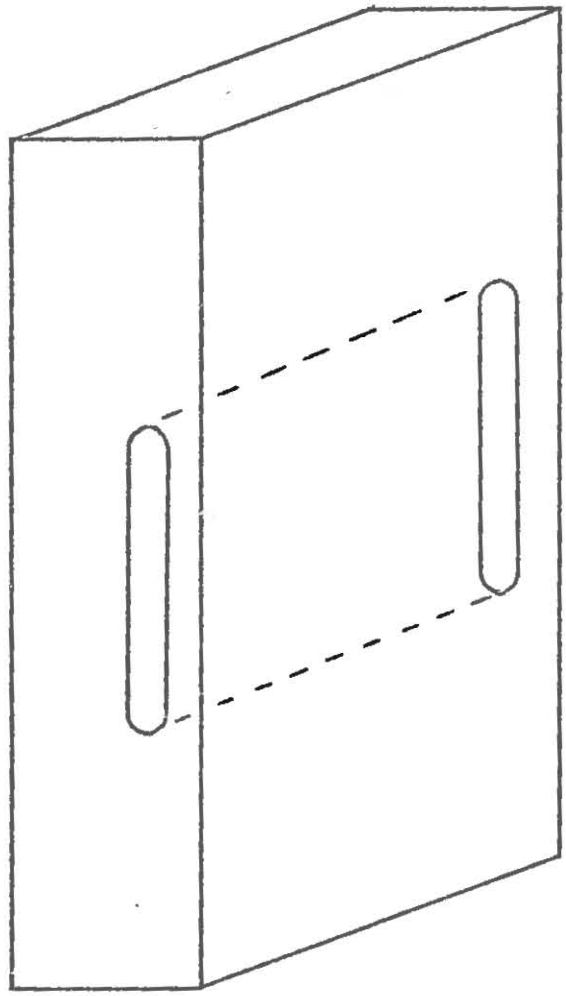

Fig. 1. Diagram of a metalic bar containing a subsurface void.

otherwise solid composition of the bar. If the back surface of the bar were evenly heated, the introduced heat would travel from the back surface toward the front surface. The void, however, would locally slow down the flow of heat. The result would be that when the front surface of the panel begins to become hot, the area over the slot would be cooler than the surrounding area. (To be concise, hereafter the surface above a void will be referred to as a supravoidal surface.)

Whether or not the surface of the bar would achieve a uniform temperature increase or have a cooler area over the void depends on the thermal conductivity of the material composing the bar, the time span during which the thermal response is allowed to take place, and the size of the void.

The fact that subsurface voids restrict the flow of heat within solid structures gives rise to another method of detecting these voids. If the bar in Figure 1 were evenly heated from the front, the supravoidal area on the front surface would be hotter than the surrounding area which is backed by a relatively large mass acting as a heat sink.

If the thermal properties of solid structures can be studied by heating, then the process of cooling these structures should reveal similar structural information. For instance, if the front surface of the bar in Figure 1 were cooled evenly, the supravoidal surface on the front of the bar would loose its heat faster than the surrounding surface. If its back surface were evenly cooled, the supravoidal surface on the front of the bar would retain its heat longer than the surrounding surface.

There are a number of methods by which an object can be heated or cooled. The delicate nature of art works, however, precludes any technique which would drastically change the temperature of the object. Radiation from an infrared lamp is an acceptable source of gentle and even heating. By varying the distance of the lamp from the object, and the time of exposure, one can easily control the temperature change on the surface of a painting. It is also relatively simple to cool a work of art gently. To do this one can lower the temperature of the air surrounding the object, by placing it in an air conditioned room for instance, or one can direct a current of air from a fan on the object and thus increase the amount of heat lost through convection.

Although the thermographic detection of subsurface voids in panel paintings has to the author's knowledge never been tried before, there is considerable industrial literature on the thermographic detection of voids in castings, welds, and laminated structures. A good bibliography of this literature can be found in Riccardo Vanzetti's book, Practical Application of Infrared Techniques.[3] A brief study of some of this industrial literature reveals the fact that it is possible to calculate or predict the differences in surface temperature caused by voids. Such theoretical analyses of heat conduction are found in the works of Dixon,[4] Carnham,[5] and Carslow.[6] The mathematics involved in these computations is complex and beyond the scope of this paper. However, it is doubtful that such computations could be applied to the study of panel paintings because the equations require accurate measurement of thermal conductivities and layer thicknesses. The nature of the materials used in panel paintings such as gesso, paint, and wood, does not permit precise measurement of such variables.

Whether or not the thermal phenomena described above can be applied to the detection of subsurface voids in panel paintings depends on several factors. First, the voids present in paintings must be sufficiently large and near the paint surface to produce thermal gradients. Second, a temperature-sensing device must be available which is capable of detecting fleeting temperature variations. This temperature-sensing device must also be capable of measuring the temperature of many points on the surface of the painting at the same time, in order that the temperature of one area of the panel can be compared to the temperature of surrounding areas. Finally, a method of heating the panel must be found which is not only harmless to the painting, but which also produces absolutely even heating. The purpose of the research conducted for this thesis was to study these factors and thereby determine the feasibility of applying thermographic analysis to panel paintings.

Methods of Measuring Temperature

The fact that voids have the capacity to induce temperature variations on surfaces would be useless if no means for detecting these variations existed. Although there are many instruments capable of measuring heat, few of these devices are suitable for void detection techniques. Temperature-sensing devices can be separated into two groups: contact devices and non-contact or remote devices.

The oldest type of contact device is the liquid in glass thermometer. Although these can be made to be extremely sensitive and accurate, they are slow to react and difficult to read. It is also difficult to obtain an accurate temperature measurement of a small object with contact thermometers because their mass may be much greater than the mass of the object being measured. The effect of this is that the temperature of the object comes to equilibrium with the temperature of the thermometer rather than the temperature of the thermometer coming into equilibrium with the temperature of the object being measured. Also, because the sensing of voids requires comparative rather than absolute measurements, in order to measure the temperature of many points on a two dimensional surface, one would require many thermometers placed on that surface. This would be inconvenient at best.[7]

Thermocouples are contact thermometers which have fewer disadvantages than liquid in glass thermometers. Thermocouples measure temperature electrically and thus they are easier to read and record. They can be made extremely small and therefore their response time is short and their small mass is less likely to induce large errors into the measurements of small objects.[8] Thermocouples still have the disadvantage that one would require many of them to simultaneously measure the temperature of many points on a two dimensional surface. Tabulation of the resulting information from both liquid in glass thermometers and thermocouples would be difficult and if touching the surface of a suspected area of cleavage or worm tunneling with one's fingers is undesirable, touching an unsupported area of paint with a thermometer would be equally undesirable.

A third means of contact measurement which in some ways is promising for use in the field of art conservation, is the use of liquid crystals. These are fluid organic compounds which exhibit the anisotropic optical properties of crystalline solids. The materials used in liquid crystals are usually esters of cholesterol. Cholesterol esters polarize the light incident upon them and reflect a portion of this polarized light, the color of which is dependent on the temperature of the liquid crystal. In the detection of subsurface voids, liquid crystals are promising because they have the ability to easily measure the temperature gradients over two dimensional surfaces. They are also inexpensive and easy to read. To work best, however, they must be used over a black surface.[9] One would also be justifiably concerned about spreading liquid crystals over the surface of a painting. To avoid this, one can obtain liquid crystals as laminates between pieces of black paper and clear plastic. This sheet of liquid crystals can then be placed on the object to be studied. However, the contact between the paper and the surface to be measured must be perfect, and this would be impossible with most paintings.

Although temperature measuring devices of the contact type are inexpensive and readily available, they are either unsuitable for measuring the temperature of many points on two dimensional surface or they are unsuitable for use on paintings.

There are three basic types of non-contact or remote temperature sensing devices.[10] These are pneumatic cells, evaporative devices, and bolometers. All three devices measure temperature indirectly by sensing the infrared radiation emitted by the object being measured. Because these devices measure radiation, they are all called radiometers. For a description of pneumatic cell and evaporative devices the reader should consult Vanzetti, Chapters 2 and 3. The operation of bolometers will be explained when the type of radiometer used for this research is described, however, some explanation is required of how temperature is determined through the measurement of infrared radiation.

Infrared radiation is that portion of the electromagnetic spectrum ranging in wavelength from 0.76 microns (μ) to 1,000 μ . This band of radiation is bounded by microwaves on the long wavelength end of the spectrum and by visible light on the short wavelength end of the spectrum. (See Figure 2, p. 14.)[11] Infrared radiation is produced by the perpetual movement of molecular, atomic, and subatomic particles.[12] Any piece of matter whose temperature is above 0°K (-273°C) produces infrared radiation through the vibration of the particles which compose that matter. (See Figure 2.) The vibration

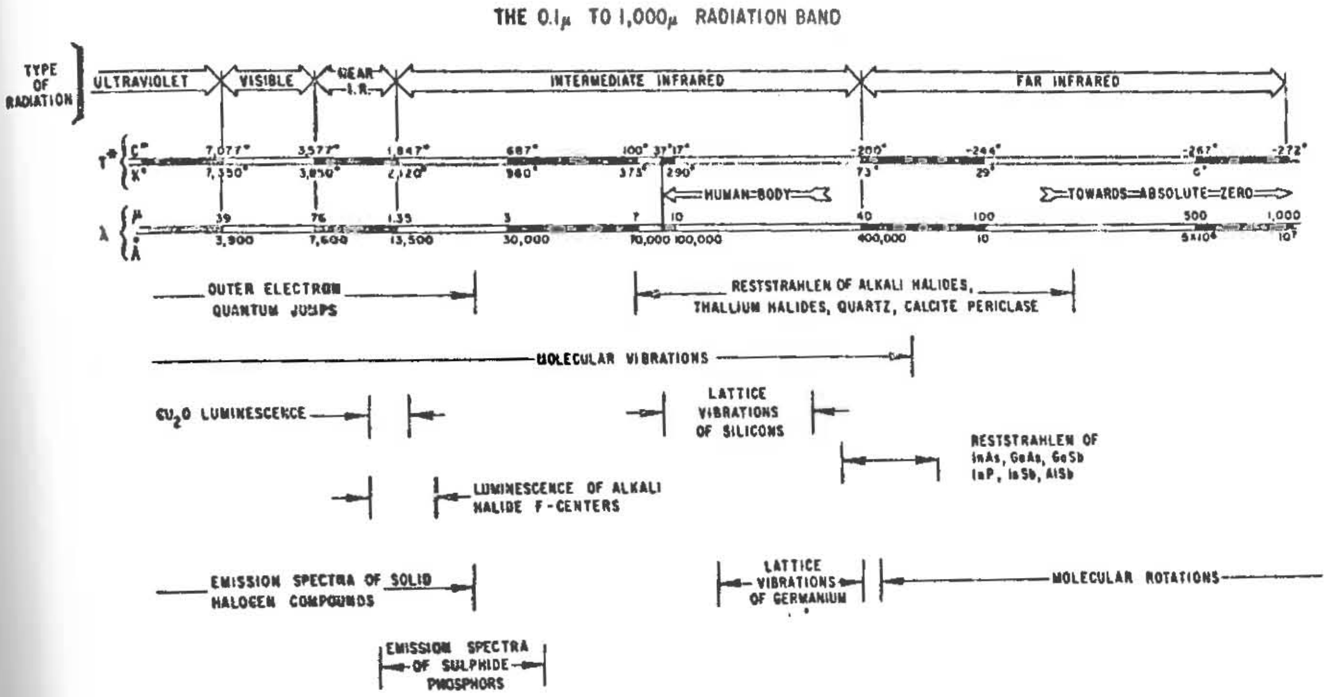

Fig. 2. The infrared spectrum.

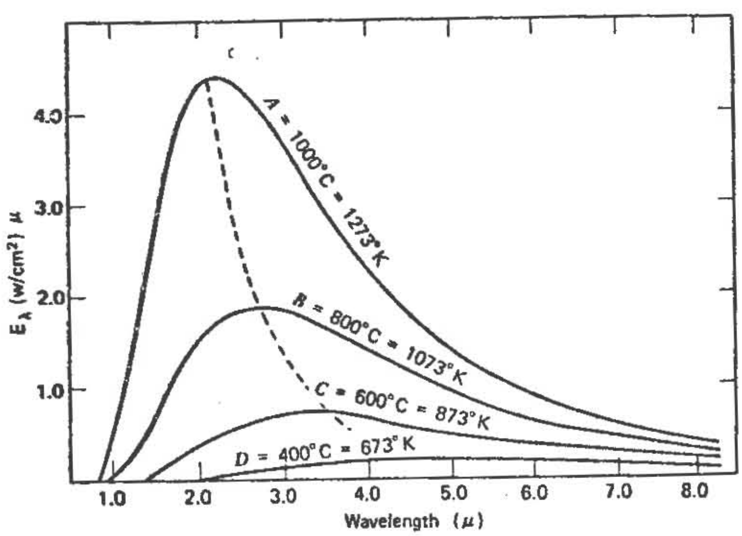

Fig. 3. Infrared emission curves of a blackbody at four temperatures.

within a molecule is directly related to the temperature of that molecule; the higher the temperature, the higher the agitation. Temperature can be defined as the level of agitation of these particles.[13]

At a specific temperature the molecular and sub-molecular particles that compose a substance will emit a band of infrared radiation, rather than a single wavelength. Figure 3[14] (see page 14) shows the theoretical relationship between temperature and the wavelength of infrared radiation emitted by a blackbody. (A blackbody is a perfect emitter of radiation.) The data illustrated in Figure 3 gives rise to the following laws which govern the radiation emitted by blackbodies:

"1. The radiation amplitude is different for every frequency and its envelope (the radiation curve) shows smooth continuity, with one single peak where the intensity is maximum.
2. For every temperature of the emitting blackbody, there is a single emission curve corresponding to it.
3. No curve ever intersects any other curve, but for increasing temperatures, every curve runs above all the curves corresponding to lower temperatures.
4. As temperature increases, the peak of the radiation curve moves toward the shorter wavelengths.
5. As temperature increases, the amplitude of the emitted radiation increases according to an exponential law."[15]

The key to measuring the temperature of an object through the analysis of the infrared radiation emitted by that object lies in these five laws. The essence of these laws is that for every temperature there exists a unique pattern to the amplitude and wavelength of infrared radiation emitted. If the infrared radiation emitted by an object could be measured, the temperature of that object could be calculated.

There is, however, one difficulty in determining temperature through the analysis of infrared radiation. The five aforementioned radiation laws are true only for blackbodies. Unfortunately, no existing object is a perfect emitter and there is considerable variation in the emission characteristics of various materials.

It is possible to manufacture an object that approximates the emission response of blackbodies. The emission curves of these objects are only slightly lower in amplitude than the curves of ideal blackbodies and this discrepancy is constant at all wavelengths. Most materials, however, do not exhibit such an even spectral response. At one wavelength their infrared emission may closely approximate the emission of a blackbody, but at another wavelength their emission may be close to zero, far different from the blackbody emission at this wavelength.[16] A substance's infrared emission over the infrared spectrum is termed the substance's emissivity.

There are numerous causes for variations in emissivity. Chemical composition, impurities, surface characteristics, physical state, and other factors can affect emissivity. However, the emissivity of a substance can only be determined experimentally. There is no theory to correlate emissivity with physical or chemical properties.[17]

The issue of emissivity variations is important to the technique of remote temperature sensing because an object with a high emissivity would emit more infrared radiation than an object with a lower emissivity, even though both objects were at exactly the same temperature. If one were not aware of this emissivity variation between the two objects, and one were using the infrared emission to determine the temperature of the two objects, an error in temperature measurement would result. The ramifications of this in regard to the thermographic technique of void detection are serious. If one cannot determine whether a variation in infrared emission is due to a void or to a variation in the emission characteristics of the source, the technique is obviously useless.

For materials opaque to infrared radiation, emissivity is strictly a surface phenomenon unrelated to the material beneath the opaque surface.[18] Thus if two objects of greatly different emissivities were coated with a substance which is opaque to infrared radiation, the infrared radiation then emitted by the two objects would be solely dependent on the coating, and thus an accurate temperature measurement could be made.[19] Because of the number of pigments used on paintings, one would expect the infrared emission characteristics of a paint surface to be varied. Whether this variation in emissivity is significant can only be determined empirically. However, if the variation in infrared emissions of artist's pigments is found to be significant, the effect that these variations might have on the accuracy of thermographic tests may be reduced by the application of a surface coating to the paint layer. It is possible that the surface coatings normally found on paintings have the ability to equalize infrared emission. This too must be determined empirically.

Raster Scanning Infrared Radiometers

The temperature sensing equipment used for this research was of the raster scanning infrared radiometer type. These instruments produce accurate measurement of a wide range of temperatures and they are designed to measure the temperature of either two dimensional or three dimensional surfaces. The instrument used in the well known work of J.R.J. van Asperen de Boer in which he studied underdrawings in painting was a slightly modified raster scanning radiometer.[20,21]

An infrared radiometer is simply a device that measures infrared radiation. Raster scanning refers to the method by which the radiometer records and displays the information it produces. Raster scanning is the method by which television images are produced. A television camera translates the three dimensional view in front of the camera into an electronic signal and projects this signal in the form of horizontal lines or rasters onto the two dimensional phosphorescent screen of the cathode ray tube (CRT). The raster scanning radiometer does the same thing except that instead of translating visible light into an electronic signal, it translates infrared radiation into an electronic signal. This signal is amplified and finally projected onto a CRT, which produces a visual image of the infrared radiation emitted by the object in the view of the radiometer's optics. The intensity of the image on the CRT is directly proportional to the wavelength and intensity of infrared radiation incident on the radiometer's infrared detector. Thus objects which appear light on the CRT are hotter than objects which appear darker. By adding a constant temperature reference within the instrument, the radiation emitted by an object can be compared to this internal temperature standard, thereby permitting quantitative temperature measurement.

The optics used in infrared radiometers are different from optics designed for visible light applications. Normal optical glasses do not transmit infrared radiation in those wavelengths necessary for heat measurement. Therefore, the lenses used in these radiometers are manufactured out of materials other than optical glass such as germanium, α-alumina (sapphire), and arsenic trisulphide. Mirror optics are also used, either alone or in conjunction with lenses. Mirrors have the advantage of being able to reflect all wavelengths uniformly and thus they are affected by fewer aberrations than refractive lenses.[22]

The infrared detector is the most important component within a radiometer. The detector is what converts the infrared radiation into an electrical impulse. There are many types of detectors. The detectors used in the radiometers which were used to carry out the research for this thesis were of the bolometer or quantum detector variety. Bolometers are made of semiconducting materials. When these materials are irradiated with photons, electrons are freed. The "free electrons" produced by this radiation can then be amplified and measured. There are numerous semiconductive devices and each one is sensitive to a restricted band of the infrared spectrum; for every portion of the infrared spectrum there is at least one detector capable of measuring that region.[23] The two most common detectors used in infrared radiometers are composed of indium antimonide (InSb) and mercury cadmium telluride (HgCdTe). According to Vanzetti, "the HgCdTe detector is exceptionally well suited to the measurement of infrared radiation emitted by targets whose temperature is in the vicinity of 25°C."[24] This is near room temperature where most studies of art objects would by necessity take place. Most of the research for this paper was conducted with a radiometer containing a mercury cadmium telluride detector. The radiometer used by van Asperen de Boer contained a lead sulfide detector which had a peak sensitivity in the 2.0 μ region which de Boer found to be the optimum wavelength for the study of underdrawings.[25] Although the HgCdTe detector is sensitive to infrared in the 8 μ to 14 μ range and would thus be unsuitable for use in underdrawing studies, the InSb detector is sensitive to infrared radiation in the 2 μ to 5.6 μ range and thus <u>may</u> be capable of application to both thermographic and underdrawing studies.

Detectors used to study objects at room temperature measure infrared radiation in the 5 μ to 15 μ range. Such detectors must be cooled to very low temperatures. If the detector itself were at room temperature, its own thermal energy would produce enough infrared radiation to overpower the radiation incident on the detector from the target. To keep the detectors sufficiently cool, they are housed within Dewar flasks which are filled with liquified gas. The most common gas used is liquid nitrogen, which has a temperature of 77.2°K (-196°C).

The electrical signal produced by the detector is amplified electronically and sent to the display system of the radiometer. There are many types of display systems, ranging from digital readouts to the raster scanning CRT system used for this research. To explain the operating characteristics of raster scanning radiometers, it is useful to compare them again to television cameras. Both TV cameras and raster scanning radiometers are capable of measuring only one small point within the field of view at any one time. The camera scans the field of view, however, collecting information about many small adjacent points, scanning from left to right and from the top of the field to the bottom. This information is projected rapidly, but still point by point, onto the CRT display. The phosphors on the CRT screen retain the image for a short period of time, which gives visual continuity to the image. Television cameras scan the field of view from top to bottom thirty times a second, which is rapid enough to cause the perception of a continuous picture. In infrared radiometers, the scanning rate may be quite different from that of television. Some radiometers produce a number of scans per second while other instruments require several seconds to produce a single scan. With radiometers built around bolometers, the scan rate is determined by the processing electronics rather than the detector itself.[26]

An important aspect of any optical instrument is its spatial resolution. Spatial resolution can be thought of as the machine's ability to distinguish between two small objects placed close to one another. The spatial resolution of radiometers is in part determined by the size of the detector; more important, however, is the nature of the CRT display. The number of horizontal raster lines projected on the CRT and the greater the number of picture elements contained within each line, determine how "sharp" an image the radiometer can produce. The spatial resolution varies for each radiometer model. For the detection of small voids, a radiometer with high spatial resolution is advantageous.

Thermal resolution is the capacity of a radiometer to distinguish between two objects of slightly different temperature. For use in void detection techniques, a radiometer should have the ability to distinguish between two temperatures that vary by only a small amount. A maximum thermal resolution of 0.2°C is common for many radiometers, and this is adequate for void detection applications.

The major difficulty with CRT displays is their limited dynamic range. The cathode ray tube is capable of producing approximately ten gray tones including white and black. The problem is that most radiometers are capable of measuring a wide temperature range which may span hundreds of degrees centigrade. If the black part of the CRT scale were set at the minimum detectible temperature, and the white part of the CRT scale were set at the maximum detectible temperature, there might be a step of 100°C between each discernible gray tone on the CRT. To solve this problem the temperature range depicted by the ten gray tones can be adjusted.

If the radiometer is capable of measuring a wide range of temperatures, and one has the ability to restrict the instrument's sensitivity to a narrow range, one requires the capability of setting that narrow range anywhere within the overall thermal sensitivity of the machine. This is possible and the adjustment is termed the zero level or base level adjustment. Thus if one wished to detect subtle variations in the temperature of the human body, one might set the base level of the radiometer at 37°C and the range at 2°C or 4°C. If, on the other hand, one wished to study temperature variations within a blast furnace, one might set the base level at 1,000°C and the range at 100°C.

There are commercially available a number of radiometers suitable for void detection studies. The manufacturer's literature should be consulted for an exact listing of the specifications of these instruments. Below, some of the more important variations in the working characteristics of the two radiometers used for this research are given.

The Spectrotherm Model 1,000 Medical Imaging System uses a liquid-nitrogen-cooled mercury cadmium telluride detector.[27] Its overall sensitivity range is from 8 μ to 12 μ which gives the instrument the capability to measure temperatures ranging from room temperature (20°C) to body temperature (37°C). Because the instrument was designed for medical applications this temperature range is more limited than that found in industrial radiometers. The sensitivity range of the instrument can be set from 2°C to 8°C. At the 2°C range the maximum thermal resolution is 0.2°C. The CRT produces an image 7.5 cm square and its ability to resolve fine detail is quite good with its 528 horizontal lines and 600 picture elements per horizontal line.

One inconvenient feature of the Model 1,000 is that it requires two seconds to make one complete scan of the image area. Rather than having a single raster travel down the image area every two seconds, the Model 1,000 stores the scanned image in a video recording unit which flashes a complete image on the CRT approximately every three seconds. This intermittent image makes the Model 1,000 difficult to use at times, and impossible to use for studying thermal effects which are of a short duration.

The instrument's components are housed within one unit which is the size of a studio television camera. The radiometer can be focused from 4" to infinity. A very useful feature of the Model 1,000 is that it is capable of producing a graph of the temperature gradient present along any one raster line which can be chosen by the operator. Thus the temperature gradient of the object is represented not only by a series of ten gray tones but also by a graph.

The AGA Thermovision $^{(R)}$ 680 uses a liquid-nitrogen-cooled indium antimonide detector.[28] This detector is sensitive to infrared wavelengths ranging from 2 μ to 5.6 μ which gives the instrument the capability to measure temperatures ranging from -30°C to +850°C. The sensitivity range can be set from 1°C to 1,000°C, and at +30°C object temperature the instrument has a maximum thermal resolution of better than 0.2°C. The CRT display produces a black and white image 90mm x 90mm. The spatial resolution is limited by the CRT which has 210 interlaced horizontal lines per frame and 140 picture elements per horizontal line. The scan time is adequate with 16 pictures per second. This rapid scan time results in the perception of a continuous image.

There are two separate components to the Thermovision 680: the camera and the monitor. In addition to these basic modules, a number of accessories are available. There are several lenses of varying fields of view. There is a color monitor which translates the normal ten gray values of the CRT into ten colors, with each color representing a temperature. There is also a microscope attachment that converts the Thermovision 680 into an infrared microscope. The Thermovision 680 also has an isotherm mode of operation. An isotherm is a line or record of areas having the same temperature. When operating in this mode, the monitor marks all areas of any temperature range set by the operator so that these areas stand out from the rest of the image.

EXPERIMENTAL PROCEDURES AND RESULTS

Introduction

A number of experiments were designed to study the feasibility of using thermography to detect subsurface voids in panel paintings. Each experiment was intended to study one aspect or variable of thermographic technique as it would be applied to panel paintings.

This feasibility study was based on the use of test panels. These panels were designed to simulate various types of voids present in panel paintings. The use of these panels enabled the experimenter to test the accuracy of the thermographic technique by checking the results with the known construction of the panels. The use of test panels also eliminated a number of variables which would have been present had "real" paintings been used.

Experiments were designed to study the following: whether voids simulating worm tunneling in the wood immediately beneath the gesso layer are detectable thermographically and if so, what the minimum size of void that can be resolved might be; whether simulated worm tunnels which are buried within the wood support, rather than on its surface, are detectable; whether voids simulating cleavage between the wood support and the ground layer are detectable; and the degree to which variations in the infrared emissivity of various pigments, media, and surface coatings influence the thermographic results.

Although the use of test panels allowed for the elimination of some variables, the conditions under which the individual thermographic tests were made did not permit the elimination of certain other variables. The thermographic equipment used was situated at the radiology department of St. Vincent's Hospital in Toledo, Ohio. The fact that the equipment was housed within a busy metropolitan hospital, and the fact that Toledo is one hundred miles from the author's place of work and residence, did not provide the conditions necessary for completely controlled experimentation. For instance, in the cramped quarters, the exact positioning of the test panels in relationship to the radiometer could not be standardized, nor could the exact amount of heating of the panels be controlled. The time intervals between the removal of the panels from the source of heat and the first thermograph, or the intervals between consecutive thermographs could not always be precisely recorded. In addition, the radiometer itself may have introduced variables in the research conditions. The instrument used was a Spectrotherm Model 1,000 medical radiometer. The radiology technicians who used this instrument daily felt that because of its state of repair, the radiometer was not producing the quality of image of which it should have been capable.

The experimental panels used were of the "D" series. Several preliminary sets of panels were made prior to the "D" series. These early panels, however, were of various sizes and thicknesses. The voids in these early panels were produced by gouging the surface of the panel and therefore the exact dimensions of the voids were difficult to measure. Whereas the early panel designed to simulate cleavage was produced by blistering a resinous paint with heat and this method produced quite satisfactory cleavage, the paint used was a commercial wall paint. It was decided that the materials used in the panels should be the same as those one might find on an old panel painting. (Therefore the "D" series of panels was made.) All of the "D" series panels had the dimensions H 25 cm, W 16 cm and T 2 cm, and they were all cut from the same softwood board. In each panel the grain of the wood ran with the long dimension. All panels had a layer of gesso on their front surfaces. The gesso was composed of calcium carbonate and 1:10 gelatin size. The gesso was lightly sanded after its application. The exact construction of each panel is explained in conjunction with the descriptions of the individual experiments.

To produce thermal gradients over the voids in the test panels and in studying the emissivities of various artist's materials, the panels were invariably heated and then allowed to cool to the ambient temperature of the room which was kept constant at 68°F (20°C). Thus the experiments measure the relative rate at which supravoidal surfaces and well adhered surfaces radiate and conduct heat. If this rate of heat loss is different for the two types of surface, one would expect the appearance of temperature gradients. Two methods of heating the panels were used and these methods remained constant for all experiments. Method one required that the front surface of the panel be evenly heated. This was accomplished by passing a 250 watt infrared heat lamp back and forth across the surface of the panel at a distance of roughly four inches. This heating was continued for ten seconds. Method two required that the reverse of the panel be heated evenly until the front surface of the panel became warm. Because the heat lamp was not intense enough to carry out this heating method in a reasonable length of time, another source of heat was required. The only other convenient means of heating the reverse of the panel available at the hospital was to place the panel in a stream of hot air. The source of this hot air happened to be the hot air blower of an x-ray film processor operating near the radiometer. The temperature of this hot air was roughly 90°F. This temperature seems rather high to be used to heat actual works of art. It must be stressed that the use of this high temperature was dictated by convenience rather than necessity. With the facilities available no attempt was made to control or determine the maximum temperature attained by the panels after heating. A separate discussion of heating methods and the predicted minimum rise in temperature needed to produce thermal gradients over voids in panel paintings is to be found at the end of this section.

When the reverse side of the panels were heated, it was found that in the time it took to bring the panel from the heat source to the radiometer, the edges of the panels cooled faster than the central portions, producing uneven surface temperatures. To reduce the loss of heat at the edges of the panels, immediately after heating, the panels were placed within a frame constructed of two sheets of styrofoam which fit snugly around the perimeter of the panel. This insulating frame had the added advantage that it blocked from the view of the radiometer any hot objects which might have been behind the panel as it was being thermographed. Any such hot objects would interfere with the radiometer's analysis of the panel.

When a panel was heated from the front, however, this insulating frame could not be used. It too absorbed radiation from the heat lamp and because it was a good insulator, it retained its heat longer than the wood panel and interfered with the results. The reason why a hot object in the field of view of the radiometer caused difficulties is that the Spectrotherm Model 1,000 has an automatic base level adjustment which sets the base level to measure the hottest object in the radiometer's field of view. Thus a hot object near the panel could prevent the radiometer from registering any information at all about the panel. Therefore, when panels were heated from the front, they were suspended in the air from a metal frame at the desired distance from the radiometer. Behind the panels was the wall of the room which was at the same temperature as the room itself.

Between the time that a test panel was removed from the source of heat and the time that the first thermogram was made, there was always a delay of ten seconds or more. There were two reasons for this. When heating the panel from the reverse it took roughly one minute to bring the panel from the heat source to the radiometer and suspend the panel securely in front of the radiometer. When heating the panel from the front, however, it would have been physically possible to make a thermogram within one second after the heat was removed, but the instrument itself would not produce a Polaroid(R) record of the thermographic image on its CRT until at least ten seconds had elapsed. If one tried to make a thermogram during this ten second period the instrument would usually produce a blank print, a print with a thermal image but no graph, or a print with a graph but no thermal image. The cause of this delay appears to have been a malfunction within the radiometer.[29] Whatever the cause, however, it was unfortunate, because thermograms of the panel made immediately after heating may have contained more information about the voids than thermograms made after the panel had cooled for ten seconds. After the initial delay, thermograms could be produced for one to three minutes before the temperature variations on the supravoidal surfaces gradually disappeared or became so minute that they were not detectable by the radiometer. The hotter the panel had been heated, the longer the temperature variations over the voids remained detectable.

The thermograms illustrated in this paper require some general explanation. The number in the lower right corner of each thermogram is the range setting at which the thermogram was made. (See Figure 5.) The 2°C setting usually gave more contrast to the temperature variations while the 4°C setting tended to make less apparent any temperature variations caused by uneven heating or cooling. As mentioned above along with the operating characteristics of the Spectrotherm radiometer, the graph in each thermogram is a record of the relative temperature across a narrow strip of the panel corresponding to the fiducial line which runs horizontally across the image area. The temperature scale represented by the graph is determined by the range setting. At the 4°C setting the entire graph represents 4°C. Therefore, each line represents 1°C. At the 2°C range setting each line represents 0.5°C.

The "R" and "L" designations in the upper right corners of the thermograms are unrelated to this research. They are used by the medical technicians who use the instrument to indicate to the doctor who studies a thermogram, which side of the body is depicted by the thermogram.

Experimentation

Worm Tunneling Experiments

Two experiments were designed to determine whether or not thermography can detect the following two types of simulated worm tunneling: (1) voids present in the surface of the wood support immediately beneath the gesso layer and (2) voids present deep within the wood rather than on the panel's surface. The experiments were also designed to determine what the spatial resolution of the instrument is when detecting such voids.

(1) The detection of worm tunnels which affect the surface of the wood immediately beneath the gesso layer

Description of test panel D-4:

On the surface of this panel a number of grooves and holes were produced. The grooves were divided into five groups. Each group contained a different width of groove. Within each group, the depths of the grooves varied. Because the grooves were carved out by hand with a dentist's drill, their widths, depths, and space between grooves varied slightly.

The first group contained six parallel grooves, 1/32" in diameter and 3/32" apart. The depths of the grooves ranged from one to six millimeters.

The second group contained nine grooves, 1/16" in diameter and 1/16" apart. However, the distance between grooves was too narrow to be structurally sound. When the grooves were made, small sections of the walls between the grooves collapsed. The depths of the grooves ranged from 1 to 5 mm.

The third group contained seven grooves, 3/32" in diameter and 1/8" apart. The depths of the grooves ranged from 1 to 6 mm.

The fourth group contained six grooves, 1/8" in diameter and 5/32" apart. The depths ranged from .5 to 6 mm.

Finally, a fifth group contained four grooves, 3/16" in diameter and 3/16" apart. The depths of the grooves ranged from 2 to 4 mm.

Each groove was 5 cm long and ran perpendicular to the wood's grain. Thirteen millimeters to either side of each groove, holes were drilled with diameters and depths corresponding to the depth and diameter of the adjacent groove. Figure 4 is a photograph of this panel after the grooves and holes were produced. The depths of the grooves and holes were measured and recorded on the left side of the panel, while the diameters of the openings are recorded on the right side of the panel.

The next step in the construction of the panel was to adhere a sheet of mulberry tissue to the perforated surface of the panel with the gelatin size. Over the dry mulberry tissue a layer of gesso approximately .5 mm thick was applied. The tissue prevented the gesso from penetrating the grooves and the resulting panel simulated a painting with worm tunneling just beneath the gesso. In two locations on the panel, the bond between the wood and the tissue was faulty. This added an

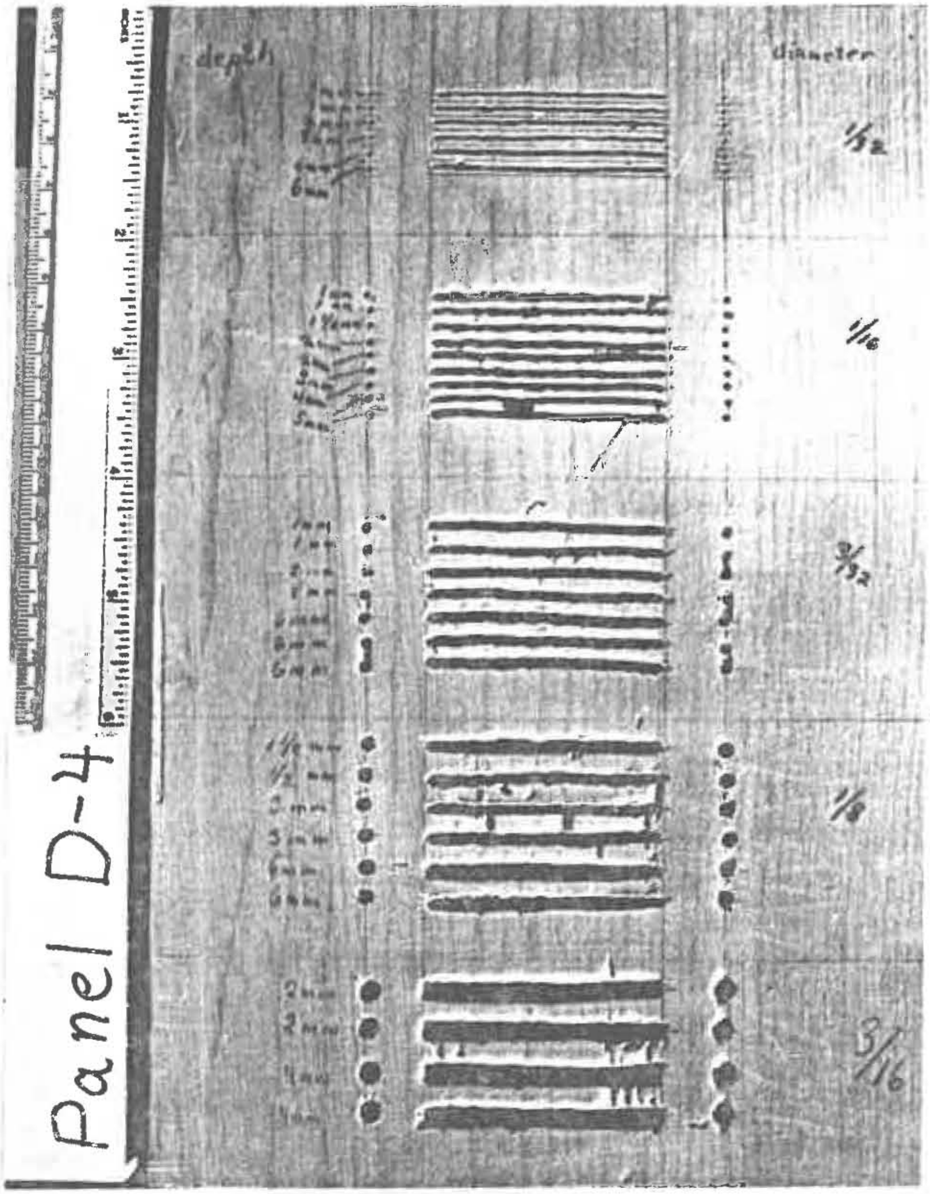

Fig. 4. Panel D-4 during construction, showing areas of simulated worm tunneling.

element of cleavage to the panel, but these areas of cleavage were small, roughly 3/8" (1 cm) in diameter, and they were surrounded by well adhered paper. After the application of the gesso, the location of these areas of cleavage could be located with the sounding technique described earlier. Over the dry gesso a layer of Acryloid(R) B-72 acrylic resin was applied to increase the infrared emission of the panel.

Experimental method:

Both heating methods were used to heat the panel and the distance from the radiometer to the panel was 20".

Results:

Figure 5 is a thermogram of panel D-4 made ten seconds after the surface of the panel was heated for ten seconds with the infrared lamp. The range setting of the radiometer was 4°C. Figure 6 is a thermogram of the same panel made ten seconds after the panel was heated a second time for ten seconds. For this thermogram the range was set at 2°C. In these two thermograms all five groups of voids are visible but poorly differentiated.

Figure 7 is a thermogram of panel D-4 made one minute after the panel was removed from the hot air current which had been directed at the reverse side of the panel. Figure 8 is a thermogram of the panel made three minutes after it was removed from the heat source. All but the first group of voids are visible in these thermograms.

In Figures 5 and 6 one can see that the technique of heating from the front has the capacity to create detectible

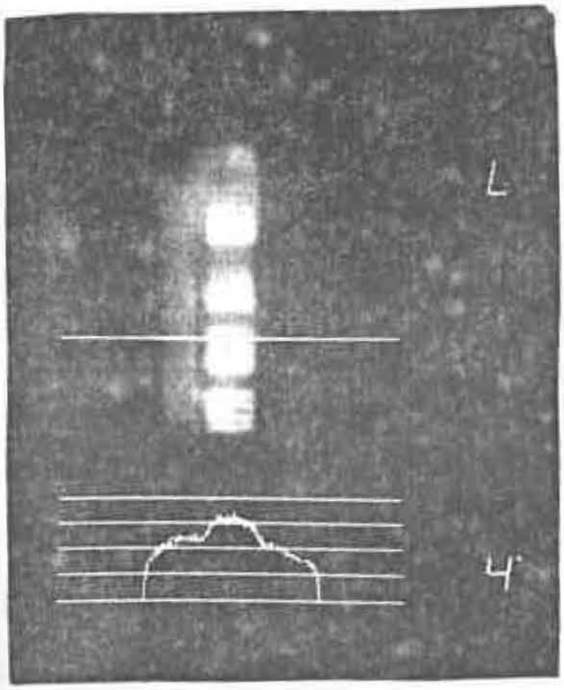

Fig. 5. Thermogram of panel D-4 10 seconds after heating the front surface of the panel.

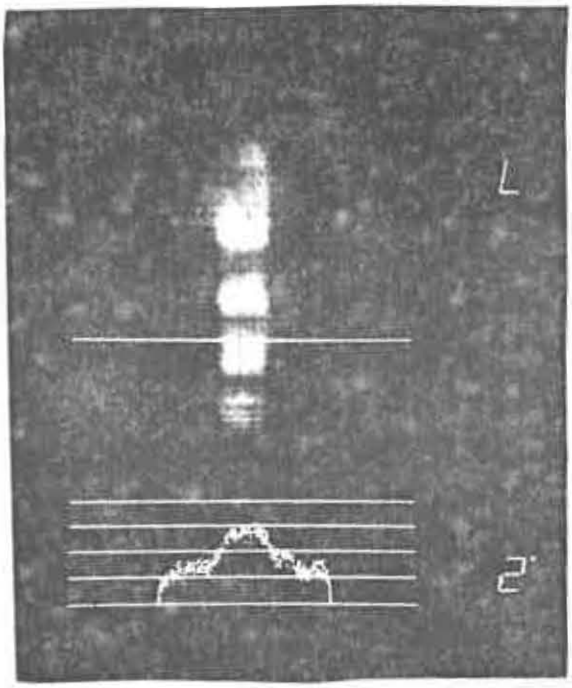

Fig. 6. Thermogram of panel D-4 10 seconds after heating the front surface of the panel.

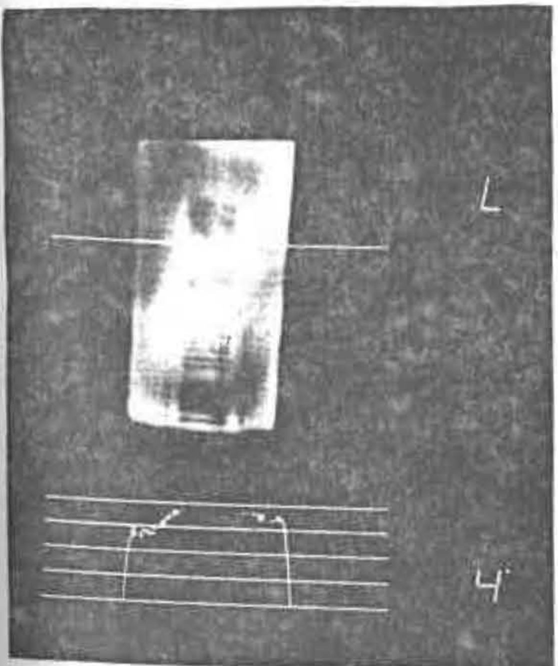

Fig. 7. Thermogram of panel D-4 1 minute after heating the reverse of the panel.

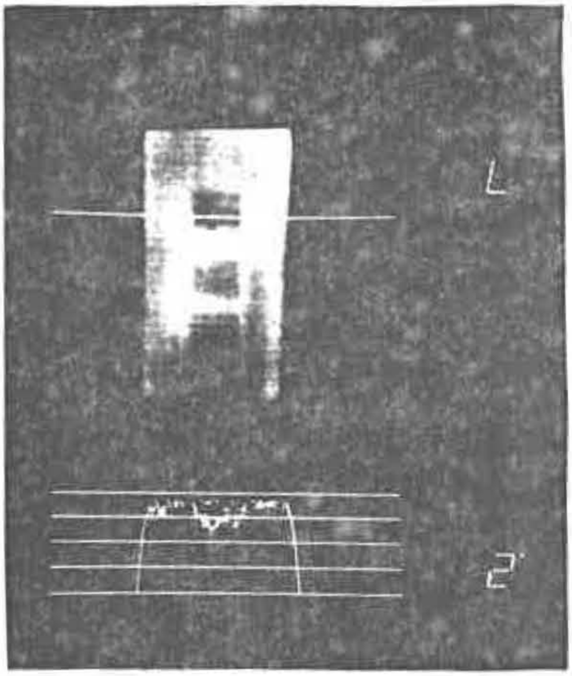

Fig. 8. Thermogram of panel D-4 3 minutes after heating the reverse of the panel.

temperature variations over subsurface voids. Indeed the top area of voids, those 1/32" wide and 3/32" apart, are to some extent visible in Figures 5 and 6 whereas this group of small voids was not at all visible when the panel was heated from the reverse as shown by Figures 7 and 8.

Heating panel D-4 from the front seemed to produce poor spatial resolution in the thermograms. None of the individual grooves in the panel are visible in Figures 5 and 6, whereas thermograms produced after heating the panel from the reverse show much better resolution. In Figures 7 and 8 one can count the grooves and see traces of the adjacent holes in the group of 1/8" diameter voids. Furthermore, the bottom group of voids, that with 3/16" wide grooves, is distinct enough for one to count both the grooves and the adjacent holes. These thermograms were made at an object-radiometer distance of 20" only. Variations of this distance may yield higher resolution, and must be further investigated.

As mentioned above in the description of panel D-4, several small areas of cleavage between the support and the mulberry tissue developed during the construction of the panel. After the gesso was applied, these two areas of cleavage remained and could be detected by the sounding technique. Both of these areas of cleavage appear as cold spots in the thermograph in Figure 7. One area is on the bottom edge of the second group of voids and the other is in the bottom right corner of the last group of voids. This panel was given to a number of experienced conservators who were requested to locate any areas of cleavage or worm tunneling with the sounding technique. Although the two areas of cleavage were consistently detected, none of the grooves or holes were detected by sounding. Thus, at least for this panel, it seems that thermography is a more sensitive technique for void detection than is "sounding."

These experiments also indicate that the degree to which a void penetrates the panel does not greatly affect its detectability as long as the void begins immediately beneath the paint or ground layer.

(2) The detection of worm tunnels which are buried deep within the wood support

Description of test panel D-5:

To fabricate this panel a board similar to the others in the "D" series was sawn in half lengthwise. Holes were drilled with a drill press into the sides of each half of this board. Drill bits of 1/16", 1/8", 3/16", and 1/4" were used. The panel was then glued together so that the holes in each half joined together and became tunnels beneath the surface of the panel. Figure 9 is a photograph of the perforated sides of panel D-5 before the two halves were glued together. The photograph indicates the depth of the tunnels beneath the front surface of the panel, the diameter of each tunnel, and their locations. However, because the two halves of the panel were not always perfectly parallel to the drill bit when the holes were produced, the depths of the tunnels beneath the surface of the panel may vary over the length of the tunnels. Figure 10

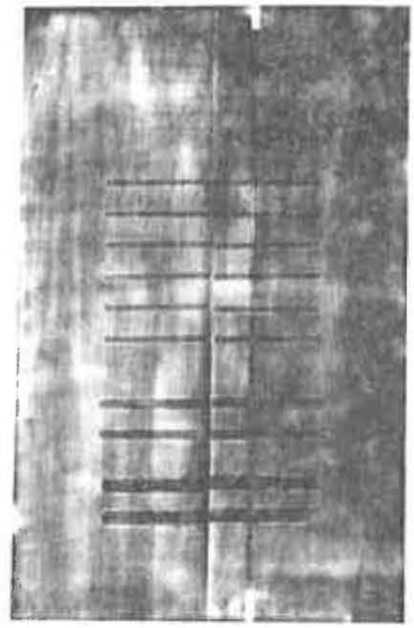

Fig. 10. X-radiograph of panel D-5, showing the placement of tunnels beneath the surface of the panel.

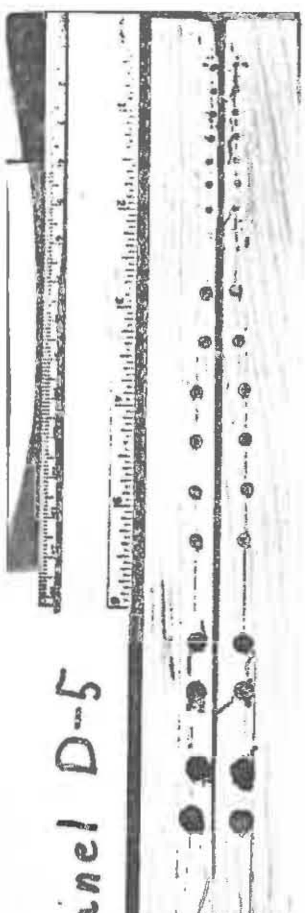

Fig. 9. Photograph of panel D-5 during construction showing the depths of the voids beneath the surface of the panel.

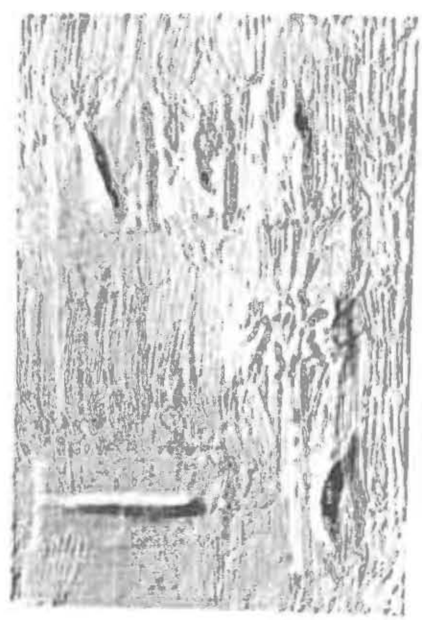

Fig. 11. Raking light photograph of panel D-1, showing the areas of simulated cleavage.

is an x-radiograph of the panel which shows the lengths of the tunnels and their location beneath the surface. In addition to these tunnels, a saw cut 1/16" wide and 1/8" deep was made, running with the wood grain (perpendicular to the tunnels) on the front surface of one of the two halves of the panel. After the two halves were glued together this groove was situated 5/8" from the center of the panel. The groove simulated a worm tunnel in the wood support just beneath the ground layer, while the drilled holes simulated worm tunnels deep within the wood support. The panel was covered with mulberry tissue, gessoed, and coated with Acryloid(R) B-72.

Experimental method:

Two methods of heating the panel were used. It was heated from the reverse and following this it was heated from the front. The panel to radiometer distance was 20".

Results:

Figure 12 is a thermogram of panel D-5 made one minute after the panel was removed from the hot air source. The sensitivity range was 4°C. Figure 13 is a thermogram of the panel made two minutes after the panel was removed from the hot air source and was made with a sensitivity range of 2°C. Although the vertical groove which was just beneath the gesso layer is visible in these thermograms, only one of the tunnels is visible. This void is one of the largest tunnels in the panel (1/14" in diameter) and it was drilled much closer to the surface of the panel than any of the other voids; its depth beneath the surface of the panel is 1 mm (as seen in Figure 9) while the other voids

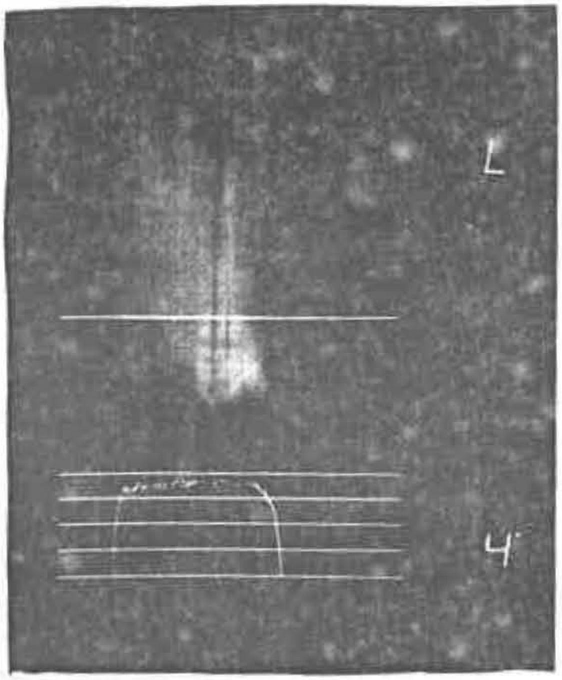

Fig. 12. Thermogram of panel D-5 1 minute after heating the reverse of the panel.

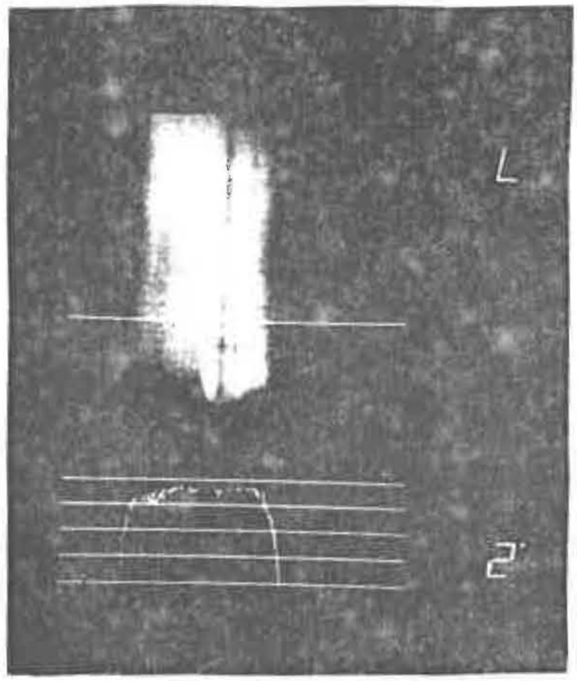

Fig. 13. Thermogram of panel D-5 2 minutes after heating the reverse of the panel.

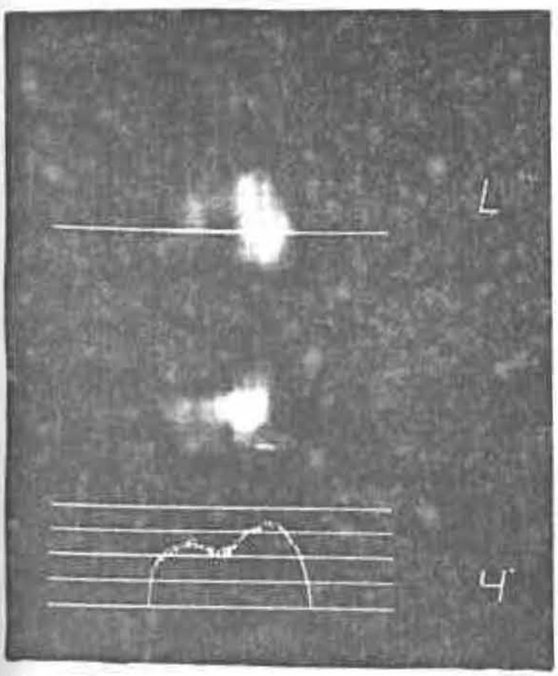

Fig. 14. Thermogram of panel D-5 ten seconds after heating the front surface of the panel.

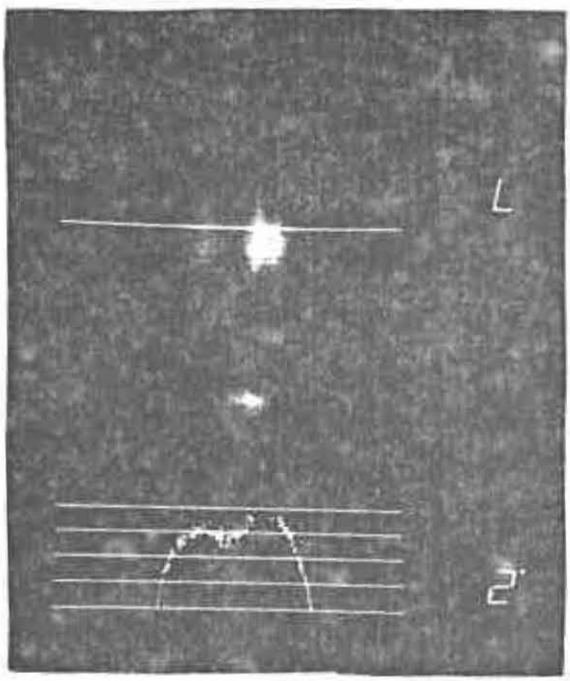

Fig. 15. Thermogram of panel D-5 15 seconds after heating the front surface of the panel.

are all at least 2 mm below the surface. Thus, from this evidence one can conclude that with this heating method only those voids which are extremely close to the surface of the panel are detectable and even then the resolution of such a void, as shown in Figures 12 and 13, is poor.

Figure 14 is a thermogram of panel D-5 made roughly ten seconds after the front surface of the panel was heated with a heat lamp; the sensitivity range was 4°C. Figure 15 is a thermogram of the panel made roughly fifteen seconds after the front of the panel was heated. The sensitivity range for this thermogram was 2°C. For some reason it was difficult to heat this panel evenly from the front. The reason for this may have been that the standardized ten second heating was too short for this panel. However, in Figure 14 the vertical groove is not discernible and in Figure 15 it is poorly resolved. There is a hot spot in the lower right corner of the panel in both thermograms. In Figure 14 this hot spot appears to be caused by both of the 1/4" diameter tunnels on the right half of the panel but in Figure 15 this hot spot is poorly defined. Whereas these two large tunnels seem to have caused the hot spot in the lower right corners of the thermograms, there are also hot spots in the upper right corners of the thermograms which do not seem to be related to underlying voids.

It is unfortunate that the heating of the front surface of the panel was uneven, but, nevertheless, from the four thermograms it seems apparent that voids which are buried deep within the panel surface (at depths greater than 1 mm) are less likely to be detected through thermographic analysis than voids which are present immediately beneath the ground layer.

The Detection of Cleavage Between the Support and Ground Layers

This experiment was designed to determine whether or not thermography can detect cleavage between a wood panel and a gesso ground.

Description of test panel D-1:

Because the creation of "real" cleavage is difficult to control, it was decided to simulate cleavage in the manner described below. Rectangles of kraft paper were cut out and permeated with hide glue. The centers of each rectangle were stretched to distort the paper while it was wet. These pieces of paper were then applied to the surface of panel D-1 in such a manner that in the center of each piece of paper there was an air space covered by a small "tent" of glue-saturated paper. The surrounding paper was well adhered to the panel surface with the hide glue. When the glue dried, the "tented" paper shrank slightly and reduced the size of the air space. There is one rectangle of kraft paper that was adhered to the surface of the panel over the entire area of the patch. This patch acted as a control. To simulate a large pocket of cleavage, a piece of waterproof kraft paper coated on one side with polyethylene was placed on the panel with the polyethylene coating next to the panel surface. In order to adhere this paper to the panel, the polyethylene coating around the perimeter of the paper was sanded off; this exposed the kraft paper itself which could then be glued to the panel with hide glue. Because there was no adhesive between the wood and the remaining polyethylene, this paper provided a rectangular patch of unadhered paper approximately 2.5 cm x 3.5 cm in size.

The various pieces of paper were brushed with a synthetic resin dissolved in solvent to make the paper moisture resistant. A layer of gesso was applied to the panel surface and on the dry gesso a coating of Acryloid(R) B-72 was applied to increase the infrared emission of the panel.

The location and approximate shape of the areas of simulated cleavage are visible in the raking light photograph of the finished panel illustrated in Figure 11 on page 40. The height of the air space or tent naturally varied over the dimensions of the void. This elevation would be difficult to describe accurately without a contour map of each area of cleavage. It would also be difficult to measure this dimension accurately. Therefore, only the maximum distance between the panel and the paper was estimated. The two large areas of cleavage on the bottom of the panel reached a maximum height of 1.5 mm. The void in the upper right of the panel had a maximum height of 1 mm. The three other areas of cleavage had maximum heights of less than 1 mm.

Experimental method:

The panel was first heated from the front and thermographed. When the surface of the panel had cooled to room temperature the panel was heated from the reverse and again thermographed. The distance from the panel to the radiometer was 20".

Results:

The thermogram in Figure 16 was made 20 seconds after the panel was heated from the front; the sensitivity range was 4°C. Figure 16 is a thermogram of the panel made 30 seconds after heating the panel from the front; the sensitivity range was 2°C. In these thermograms the areas of simulated cleavage are discernible but poorly defined.

The thermogram in Figure 18 was made one minute after the panel was removed from the hot air source which had heated its reverse surface. The sensitivity range was 4°C. Figure 19 is a thermogram of the panel made two minutes after the panel was removed from the heat source. The sensitivity range of this thermogram was 2°C. In Figure 18 all of the voids are visible; they are well defined and the image exhibits adequate contrast. In Figure 19 the contrast is somewhat greater than in Figure 18 and the square patch of simulated cleavage in the center of the panel near the right edge is much better defined than in the preceding Figure. However, in the two minutes from the time of heating, the bottom edges of the panel had cooled significantly; therefore the voids near the bottom of the panel are poorly defined in Figure 19.

Unfortunately this experiment does not indicate the minimum size of an area of cleavage that can be detected with this technique. However, by estimating the diameter of the smaller areas of cleavage which were detected, a resolution of between 1/4" and 1/8" seems attainable.

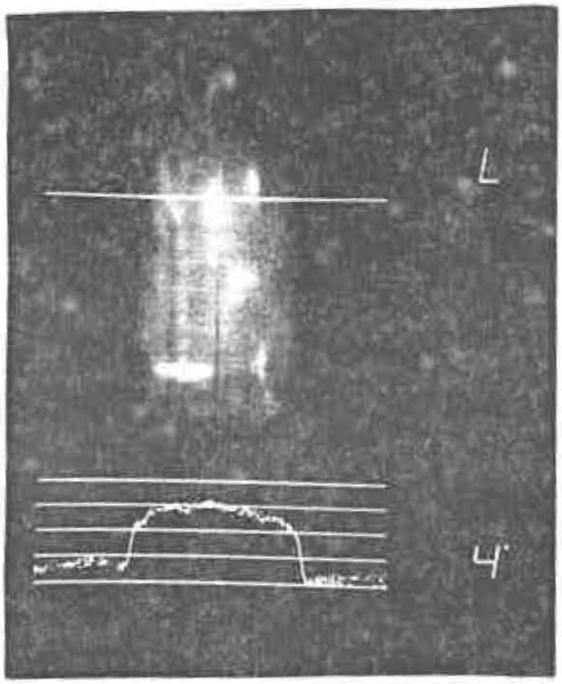

Fig. 16. Thermogram of panel D-1 20 seconds after heating the front surface of the panel.

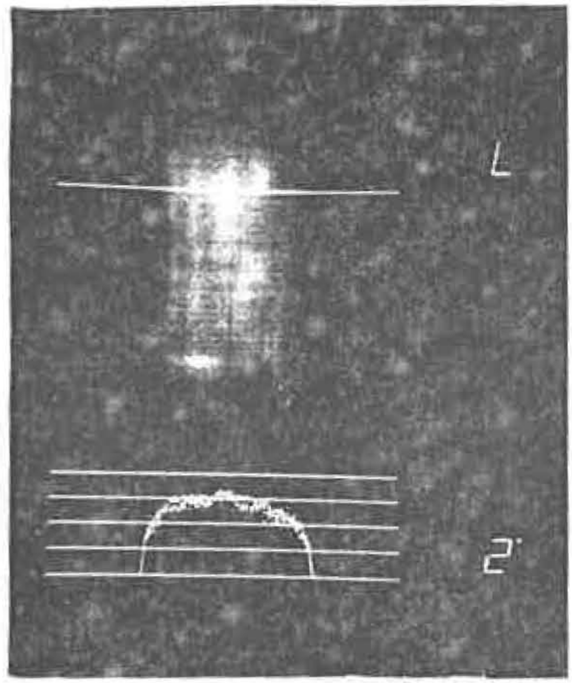

Fig. 17. Thermogram of panel D-1 30 seconds after heating the front surface of the panel.

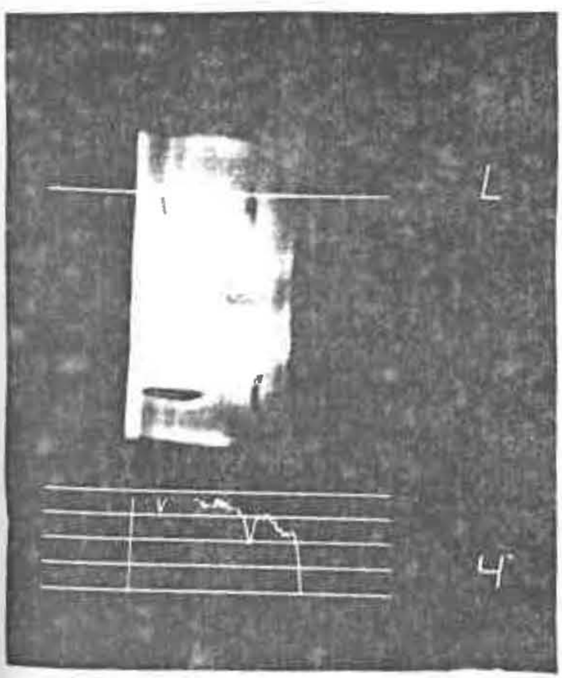

Fig. 18. Thermogram of panel D-1 1 minute after heating the reverse of the panel.

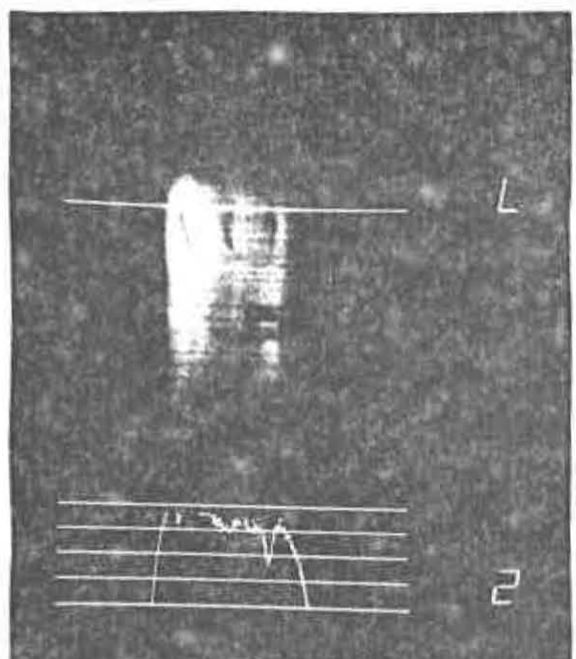

Fig. 19. Thermogram of panel D-1 2 minutes after heating the reverse of the panel.

This experiment indicates that thermography has the capacity to detect simulated cleavage between a wood support and a ground layer. The technique of heating the panel from the front did not produce adequate thermal gradients over the voids although some of the voids are discernible. The technique of heating the reverse of the panel provided good resolution of these voids and excellent contrast.

The effect of emissivity variations on thermographic studies

As previously explained in the sub-section on non-contact temperature sensing devices (pp.16-18), variations in emissivity between one substance and another are possible sources of error in thermographic studies. To determine how great an effect emissivity variations might have on the thermographic analysis of panel paintings, the emission characteristics of common artists' pigments, media, and surface coatings were studied.

The effect of pigments on emissivity variations

Description of test panel D-6:

The surface of this panel was divided into 24 squares each approximately 1 1/2" square. In the center of each square a 1/8" diameter hole was drilled with a drill press to a depth of 1/4". A sheet of thin mulberry tissue was then adhered to the face of the panel with gelatin size. When the size was dry a layer of gesso approximately .5 mm thick was applied over the tissue.

The original squares were again marked off with a pencil. Each square was then painted with an oil paint containing a specific pigment. The paints used were commercial artists' oil colors applied as they came from the tube with a small amount of cobalt linoliate drier added. Most of the paints were manufactured by Grumbacher and conformed to the National Bureau of Standards Commercial Standard CS 98-42 which should assure the purity of the pigment content listed on the tube. Several of the paints were manufactured by Winsor and Newton and Permanent Pigments; the latter also conformed to Commercial Standard CS 98-42. Figure 20 describes the pigments used and their location on the panel. Only one coat of paint was brushed on each square, therefore the thickness of the paint layers should be roughly the same. Naturally some pigments appear more transparent than others in visible light but this does not necessarily coincide with the pigments' transparency or opacity to infrared radiation. All squares of paint except the prussian blue and the stand oil squares dried with mat finishes.

Experimental method:

The validity of this experiment required that all of the squares of paint on the panel be heated evenly so that any variations in the thermographic image could be confidently attributed to variations in the emission characteristics of the pigments rather than to variations in temperature. The panel was therefore heated from the reverse with hot air. The distance from the radiometer to the panel was 20".

Results:

Figure 21 is a thermogram of panel D-6 made approximately one minute after the panel was removed from the heat source. The sensitivity range was 4°C. Figure 22 is a thermogram of panel D-6 made shortly after the thermogram in Figure 21; its sensitivity range was 2°C.

From the thermograms in Figures 21 and 22 it is apparent that the surface temperature of the panel was not completely constant. The edges of the panel are cooler than the central

Orientation of pigment swatches on panel D-6

venetian red (G)	raw sienna (G)	cadmium red medium (G)	cobalt blue light (G)
cadmium yellow (G)	raw umber (G)	zinc oxide (G)	chromium oxide (G)
ultramarine blue (G)	vermilion (WN)	prussian blue (G)	chrome yellow (G)
naples yellow (WN)	ivory black (G)	viridian (G)	burnt umber (G)
terre verte (G)	phthalocyanine blue (G)	alizarin crimson (G)	gesso
rose madder genuine (WN)	lead white (G)	stand oil (F&S)	cerulean blue (G)

key to commercial sources

G = Grumbacher

F&S = Fezandie and Sperrle

PP = Permanent Pigments

WN = Winsor and Newton

Fig. 20

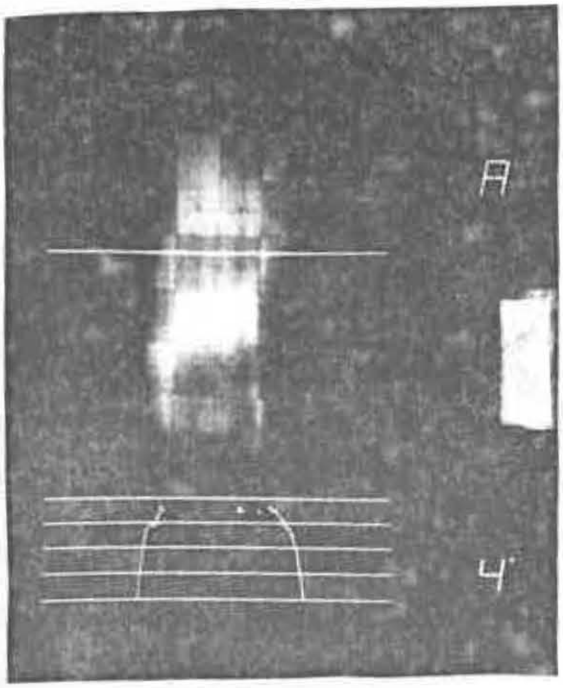

Fig. 21. Thermogram of panel D-6 1 minute after heating the reverse of the panel.

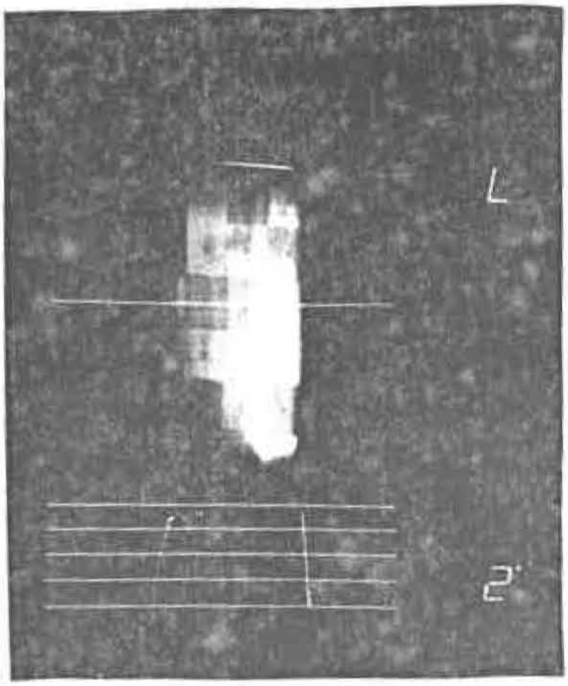

Fig. 22. Thermogram of panel D-6 made shortly after the thermogram in Fig. 21.

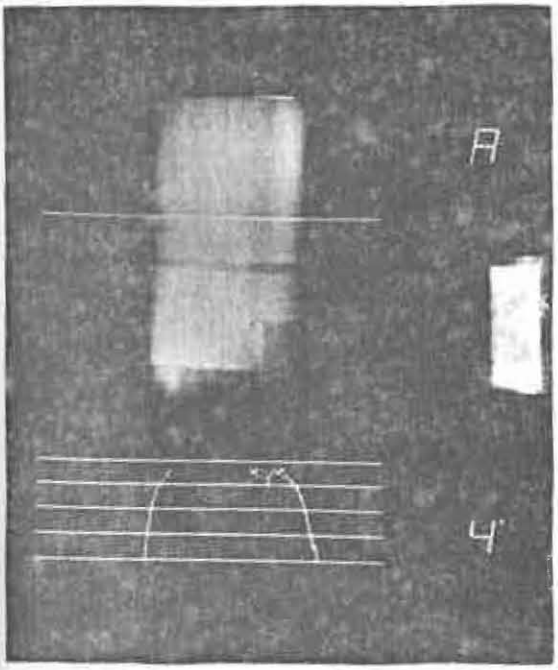

Fig. 23. Thermogram of panel D-7 1 minute after heating the reverse of the panel.

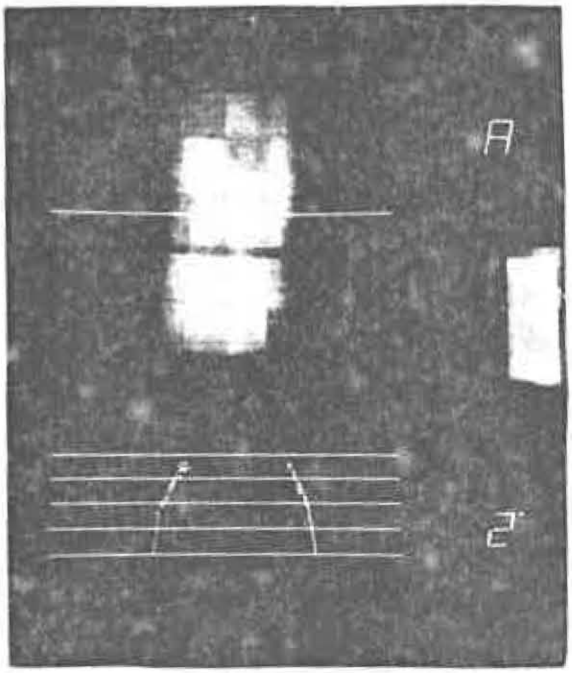

Fig. 24. Thermogram of panel D-7 2 minutes after heating the reverse of the panel.

portion and in the lower right corner of the panel there is a hot spot. However, none of the squares of paint are completely obscured by these temperature variations. Therefore the thermograms do provide the necessary information about the emissivities of these pigments.

These thermograms do not give quantitative data about emissivities but they do indicate that these common artists' pigments do have varying emissivities in the spectral range measured by the radiometer. Visual examination of Figures 21 and 22 allows one to separate the pigments on panel D-6 into high emitters and low emitters. These two groups are given below with the pigments listed in alphabetical order.

High emitters	Low emitters
1. alizarin crimson	1. cadmium red
2. burnt umber	2. cadmium yellow
3. cerulean blue	3. chromium oxide
4. chrome yellow	4. gesso
5. cobalt blue	5. venetian red
6. ivory black	6. naples yellow
7. lead white	7. phthalocyanine blue
8. raw sienna	8. prussian blue
9. raw umber	9. stand oil
10. rose madder	10. vermilion
11. terre verte	
12. ultramarine blue	
13. viridian	
14. zinc oxide	

These two categories are rough estimates. Only a careful quantitative study of the emissivity properties of these pigments would produce accurate data. However, for the technique of void detection, quantitative data on emissivity seems not to be necessary.

Most of the 1/8" diameter voids in the center of each square of paint are visible in one of the two thermograms. This indicates that with this heating technique the temperature gradient caused by even small subsurface voids is greater than the emissivity gradients produced by various pigments. However, if there were a 1/8" diameter spot of a low emitting paint within a field of paint with a high emissivity, one might mistake the resultant dark spot on the thermogram for a small void. Therefore, the issue of emissivity variations remains crucial to the technique of void detection in panel paintings.

The emissivity characteristics of artists' media and varnishes

Description of test panel D-7:

No voids were produced in the surface of this wood panel before the layer of gesso was applied. The surface of the gesso was divided into 24 squares as was panel D-6. In the center of the panel, however, eight squares were made slightly smaller to provide a horizontal strip 8 mm wide running from one side of the panel to the other.

Various transparent media and resins were brushed onto these squares. Figure 25 lists the coatings used and their location on the panel. The horizontal strip in the center of the panel was left free of any coating to serve as a control. Ideally the thickness of each coating should have been constant, but this was difficult to achieve. Some of the coatings were not thick enough to mask the mat texture of the gesso surface. These coatings are designated as being "thin" in Figure 25. All other coatings were sufficiently thick to have a glossy or brush-marked surface.

Experimental method:

Panel D-7 was heated from the reverse with hot air and placed 20" in front of the radiometer.

Results:

The thermogram in Figure 23 (p. 53) was made approximately one minute after the panel was removed from the source of heat; the sensitivity range was 4°C. The thermogram in Figure 24 (p. 53) was made approximately two minutes after the panel was removed from the surface of heat; the sensitivity range was

Orientation of surface coating swatches on Panel D-7

walnut oil thin (F&S)	mastic thin (WN)	Liquitex(R) Gloss Polymer Medium (PP)	oil-copal varnish (WN)
stand oil thin (F&S)	mastic (WN)	Acryloid(R) B-72 (RN)	white shellac (WZ)
PVA AYAA (UC)	Soluvar(R) varnish (PP)	Elvacite(R) 2044 (D)	gum arabic
- - - -	gesso	- - - -	
PVA AYAC (UC)	egg white	dammar in turpentine	gelatin size
PVA emulsion Elmers(R) (B)	egg yolk	AW II (BASF)	dammar in turpentine thin
copaiba balsam (F&S)	beeswax	gesso control	Acryloid(R) B-72 thin (RH)

key to commercial sources

B = Borden

BSAF = Badische Anilin Film and Soda Fabrik

D = duPont

F&S = Fezandie and Sperrle

PP = Permanent Pigments

RH = Rohm and Haas

UC = Union Carbide

WN = Winsor and Newton

WZ = Wm. Zinsser & Co.

Fig. 25

2°C. These thermograms indicate the emissivity characteristics of the resins and media contained on panel D-7. It is apparent that the emissivities of the coatings on the panel are higher than that of gesso. Because the thicknesses of the coatings could not be accurately controlled and because those squares with the lowest emissivities are those with thinly applied coatings, it would be pointless to draw conclusions about the comparative emissivities of the various resins. All of the resins emit more infrared than raw gesso and it is obvious from the dammar and mastic coatings, where both thick and thin layers were applied, that emissivity is dependent to some degree on layer thickness.

The ability of surface coatings to mask emissivity variations caused by pigments

Description of test panel D-8:

In the center of the gessoed panel seven vertical strips each 12 mm wide and 175 mm long were outlined with pencil. Within the outline of each strip a layer of one of seven oil paints or pure media was applied. These seven substances were chosen to provide a wide variation in infrared emission. The seven substances were (from left to right) 1:10 gelatin size, cadmium yellow light in oil, lead white in oil, viridian in oil, prussian blue in oil, alizarin crimson in oil, and a layer of stand oil. Adjacent to the stand oil and gelatin size strips, two more bands were outlined with pencil; these bands were 20 mm wide and no paint or medium was applied to them.

Horizontal strips of nine surface coatings were applied over the strips of media and paint. These strips were 17 mm wide and 135 mm long. The length of each horizontal strip allowed it to cover a portion of each strip of medium and paint and also the 20 mm patch of gesso on either side of the media strips. The surface coatings composing these horizontal strips were (from the top of the panel to the bottom) AW 2, linseed oil, mastic, Acryloid(R) B-72, a control strip with no coating, dammar in turpentine, Elvacite(R) 2044, PVA AYAA, gum arabic, and methyl cellulose. All coatings were sufficiently thick to provide a uniformly glossy or brush-marked finish. Figure 26 illustrates the locations of the various coatings and paint layers. Figure 27 is a photograph of the finished panel.

	gesso	1:10 gelatin size	cadmium yellow	lead white	viridian	prussian blue	alizarin crimson	stand oil	gesso
AW 2									
linseed oil									
mastic (WN)									
Acryloid(R) B-72									
control no coating									
dammar in turpentine									
Elvacite(R) 2044									
PVA AYAA									
gum arabic									
methyl cellulose									

Fig. 26

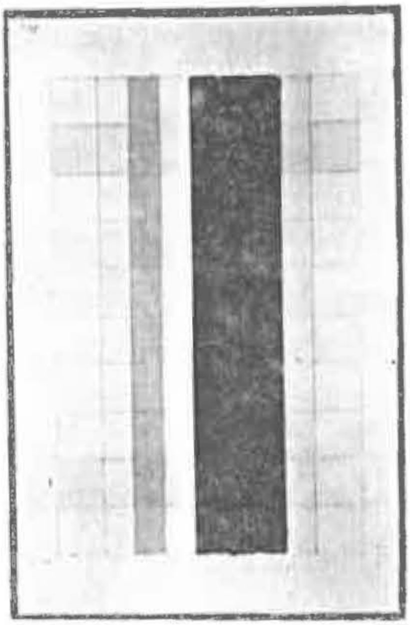

Fig. 27. Photograph of panel D-8.

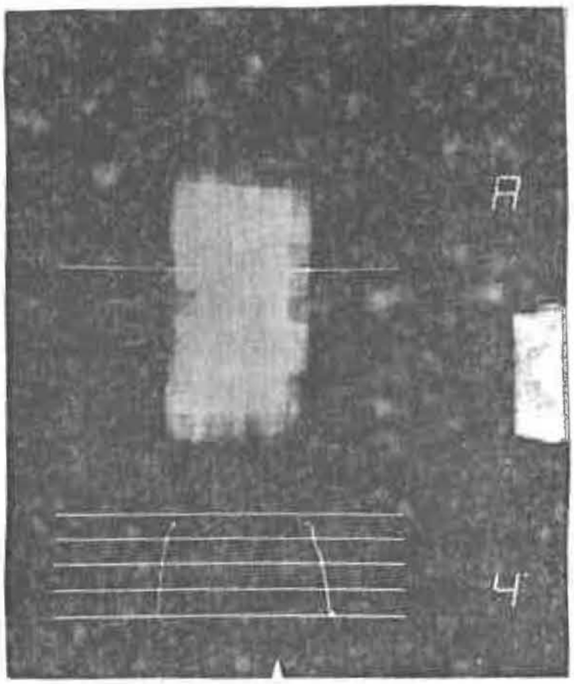

Fig. 28. Thermogram of panel D-8 1 to 3 minutes after heating the reverse of the panel.

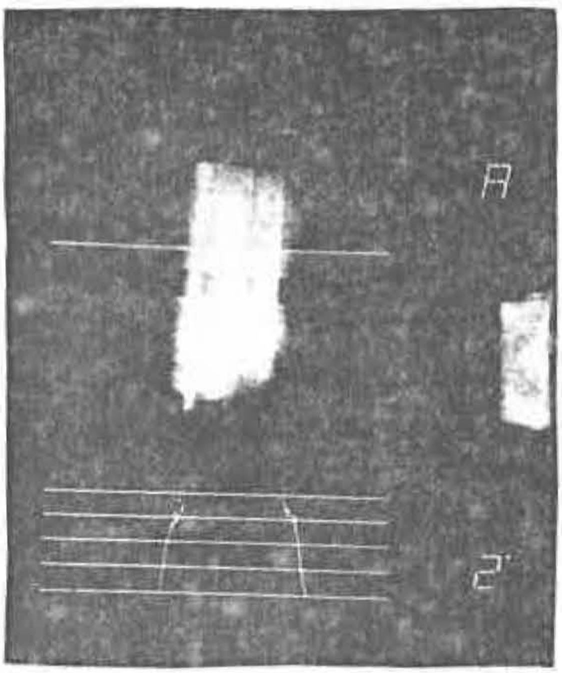

Fig. 29. Thermogram of panel D-8 1 to 3 minutes after heating the reverse of the panel.

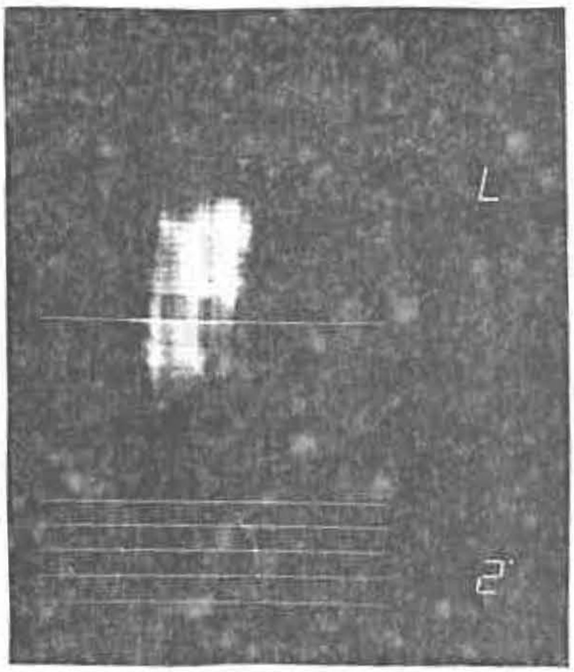

Fig. 30. Thermogram of panel D-8 1 to 3 minutes after heating the reverse of the panel.

Experimental method:

Panel D-8 was heated from the reverse with hot air and placed 20" in front of the radiometer. The thermograms in Figures 28 through 30 were made from one to three minutes after the panel was removed from the source of heat but the exact time interval was not recorded for each thermogram.

Results:

The thermograms in Figures 28 through 30 illustrate the ability of surface coatings to mask the emissivity variations produced by variations in pigment content in an underlying paint layer. From the thermograms it is apparent that the linseed oil, Acryloid(R) B-72, and Elvacite(R) 2044 coatings had the highest emissivities and thus were most effective in masking the emissivity variations produced by the various pigments. Again, however, layer thicknesses might play a large role in the ability of these resins to equalize emissivity variations. All of the coatings except one, methyl cellulose, produced much more even emission than in the uncoated control strip. From this experiment one can conclude that if a painting contains a surface coating of one of the resins usually found on paintings such as dammar or one of the synthetics, it is likely that emissivity variations will not present a large problem in thermographic studies. Indeed, if emissivity variations were present they should conform to the design layer and thus be obvious to the conservator who could then apply a layer of a highly emitting resin to the surface of the panel to eliminate these variations.

The amount of temperature change required for void detection and the effect of this heat on the panels

Two questions must be raised before the thermographic analysis of "real" paintings is attempted. The first question is: how much of a temperature change must the object undergo in order to obtain the required information? The second question is: how much of a temperature change can panel paintings tolerate safely?

The answers to these two questions are not readily available. To the author's knowledge, no data have been published on the sensitivity of panel paintings to small and brief variations in temperature. To be sure, a great deal has been written about relative humidity changes within panels and this is related to temperature, but the relative humidity of panels can be kept constant at high temperatures.[30] To safely raise the temperature of a panel one should insure that the relative humidity of the air surrounding the panel is the same as the relative humidity of the panel itself. One should also consider the temperature and humidity control within museums. Variations of 10 or even 20°F from season to season, from day to night, or even from hour to hour (as sunlight passes over objects) are probably common in some museums. Although it is not known exactly how much of a temperature change a panel painting can tolerate, the temperature change required to reveal subsurface voids through thermographic analysis is probably on the same order of magnitude as the temperature variations to which the object is subjected as it hangs on a museum wall.

The minimum temperature change to which a panel must be subjected in order to reveal subsurface voids is not known. As stated earlier, the conditions in which this research was conducted did not allow for precise measurement or control of the heating of the test panels. However, from the thermograms illustrated, one can extrapolate information about how much heat is required to produce thermographic evidence of voids.

If one studies the graphs of the temperature variations in the thermograms of panels D-4 and D-1, especially Figures 5, 6, and 7, and Figures 18 and 19, it is apparent that subsurface voids are quite detectable when the temperature of the paint over the voids differs from the temperature of the surrounding well adhered paint by only 0.5 to 1°C. If the temperature variation caused by a subsurface void need be only 0.5 to 1°C, is it necessary to raise the temperature of the whole panel by 20°F (11°C) as was done in this research? Could one achieve the same results with a smaller rise in the panel's overall temperature? In one of the author's early experiments with thermography a test panel similar to panel D-4 was taken in the summer to St. Vincent's Hospital. The day was warm and the panel reached a temperature of between 75 and 80°F (23 to 28°C) in transit from Oberlin to Toledo. A thermogram was made of the warm panel without any auxiliary heating and voids as small as 1/8" in diameter were detected. Another indication of this can be seen in Figure 16. The temperature graph in this thermogram records the temperature of the panel in relation to the temperature of the background. The background in this case was the wall of the room which was approximately the same temperature as the air temperature of the room 68°F (20°C). If one assumes that the emissivity of the wall was near that of the panel, the graph of the temperatures in the thermogram would indicate that the temperature of the panel was only three degrees centigrade higher than the temperature of the room which was the initial temperature of the panel before it was heated. Although the voids in the panel do not exhibit the best contrast in this thermograph, they are discernible. Thus although this research does not establish the minimum temperature change required to reveal subsurface voids within a panel, there are suggestions in the accumulated data that thermal variations on the order of 5 to 10°F (3 to 6°C) may be sufficient to reveal subsurface voids.

It is also important to note that the required temperature change in the panel might be significantly reduced by the use of heating or cooling techniques other than those used in this research. For example, the front of the panel could be cooled with a fan as either the front or back surface is heated with infrared radiation. Short pulses of high intensity infrared radiation might produce brief and therefore less dangerous but possibly more detectable temperature variations over voids. Also, the panel could be cooled below room temperature rather than heated. Any combination of these techniques might significantly reduce the amount of temperature variation required for void detection.

CONCLUSIONS

From the experimental evidence the author concludes that thermography is a feasible method for detecting subsurface voids in painted wooden panels. Individual voids beneath the gesso ground as small as 1/8" in diameter were resolved and smaller voids were discernible when grouped together. This resolution is better than the resolution achieved by the technique of sounding. Thermography appears to detect only voids which are immediately beneath the paint or ground layers; this can be considered an advantage because such voids cause the most insecurity to the design layer. Variations in infrared emissivity which are a source of possible error do not appear to cause spurious results if the panels subjected to thermographic analysis have uniform surface coatings.

Although the feasibility of the technique has been established, its true worth can only be determined by conservators who attempt to use the technique to study actual panel paintings. Before the technique is applied to works of art, it would be advantageous to improve the heating technique to maximize detectability and minimize the required temperature change. Another promising area of further study is the effect that different radiometers might have on the detection of subsurface voids.

References

[1]Harold J. Plenderleith, "Notes on Technique in the Examination of Panel Paintings," Technical Studies in the Field of the Fine Arts, I (July, 1932), p. 6.

[2]Robert C. Weast (ed.), Handbook of Chemistry and Physics (49th ed.; Cleveland: The Chemical Rubber Co., 1968-1969), pp. E4-E5.

[3]Riccardo Vanzetti, Practical Applications of Infrared Techniques: A New Tool in a New Dimension for Problem Solving (New York: John Wiley and Sons, 1972), pp. 329-350.

[4]R. D. Dixon, G. D. Lassahn, and A. DiGiallonardo, "Infrared Thermography of Subsurface Defects," Materials Evaluation, XXX, No. 4 (April, 1972), pp. 73-76.

[5]B. Carnham, H. A. Luther, and J. O. Wilkes, Applied Numerical Methods (New York: John Wiley and Sons, 1959), p. 508.

[6]H. S. Carslaw, Introduction to the Mathematical Theory of the Conduction of Heat in Solids (2nd ed.; New York: Dover Publications, 1945).

[7]Vanzetti, pp. 33-35.

[8]Ibid.

[9]Ibid., 71.

[10]Ibid., p. 33.

[11]Ibid., p. 10, after Leo J. Neuringer.

[12]Ibid., pp. 34-39.

[13]Ibid., p. 11.

[14]Ibid., p. 12.

[15]Ibid., p. 14.

[16]Ibid., p. 15.

[17]Ibid.

[18]Ibid.

[19] N. R. Burrowes, "Emissivity Equalization by Thermosetting Coatings," Published paper from the Spring Convention of the Society for Nondestructive Testing, Los Angeles, California (February, 1965), (Evanston, Illinois: distributed by The Society for Nondestructive Testing, Inc.).

[20] J. van Asperen de Boer, "Infrared Reflectography: A Method for the Examination of Paintings," Applied Optics, VII, No. 9 (September, 1968), pp. 1711-1714.

[21] J. van Asperen de Boer, Infrared Reflectography, A Contribution to the Examination of Earlier European Paintings (Amsterdam: Central Research Laboratory for Objects of Art, 1970), p. 49.

[22] Vanzetti, pp. 76-81.

[23] Ibid., p. 47.

[24] Ibid., p. 52.

[25] de Boer, Infrared Reflectography, A Contribution, p. 49.

[26] Vanzetti, p. 115.

[27] Spectrotherm Corporation, 3040 Olcott Street, Santa Clara, California 95051.

[28] AGA Corporation, 550 County Avenue, Secaucus, New Jersey 07094.

[29] Phone conversation with Andy Anderson, Product Manager for Medical Thermography, Spectrotherm Corporation, April 9, 1976.

[30] Buck, Richard D., "A Note on the Effect of Age on the Hygroscopic Behavior of Wood," Studies in Conservation, I, No. 1 (October, 1952), pp. 39-44.

BIBLIOGRAPHY

Asperen de Boer, J.R.J. van. Infrared Reflectography, A Contribution to the Examination of Earlier European Paintings, Amsterdam: Central Research Laboratory for Objects of Art, 1970.

________. "Infrared Reflectography: A Method for the Examination of Paintings," Applied Optics, VII, No. 9 (September, 1968), pp. 1711-1714.

Buck, Richard D. "A Note on the Effect of Age on the Hygroscopic Behavior of Wood," Studies in Conservation, I, No. 1 (October, 1952), pp. 39-44.

Burrowes, N. R. "Emissivity Equalization by Thermosetting Coatings," Published paper from the Spring Convention of the Society for Nondestructive Testing, Los Angeles, California (February, 1965). Evanston: distributed by The Society for Nondestructive Testing, Inc., 1965.

Carnham, B., Luther, H. A., and Wilkes, J. O. Applied Numerical Methods. New York: John Wiley and Sons, 1959.

Carslow, H. S. Introduction to the Mathematical Theory of the Conduction of Heat in Solids. 2nd. ed. New York: Dover Publications, 1945.

Dixon, R. D., Lassahn, G. D., and DiGiallonardo, A. "Infrared Thermography of Subsurface Defects," Materials Evaluation, XXX, No. 4 (April, 1972), pp. 73-76.

Plenderleith, Harold J. "Notes on Technique in the Examination of Panel Paintings," Technical Studies in the Field of the Fine Arts, I (July, 1932), pp. 3-7.

Vanzetti, Riccardo. Practical Applications of Infrared Techniques: A New Tool in a New Dimension for Problem Solving, New York: John Wiley and Sons, 1972.

Weast, Robert C. (ed.). Handbook of Chemistry and Physics, 49th ed. Cleveland: The Chemical Rubber Co., 1968-1969.