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INFRARED NONDESTRUCTIVE TESTING OF LAMINATED STRUCTURES AND ELECTRICAL CIRCUITS



TECHNICAL REPORT

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and

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June 1972

RESEARCH DIRECTORATE

WEAPONS LABORATORY AT ROCK ISLAND

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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ABSTRACT

Infrared nondestructive testing (IRNDT) techniques and instrumentation, developed under In-House Laboratory Independent Research funding in the Research Directorate of the Weapons Laboratory at Rock Island, were used successfully to detect unbonded areas in laminated structures. A high-speed infrared camera was used to monitor the thermal signature of the samples while they were being heated. Two methods of external sample heating were used in the IRNDT investigations, a 35 watt, continuous wave, CO₂ laser and a 250 watt infrared lamp. The results obtained with each heat source were compared to determine the relative merits of each, and results are presented. The infrared camera was also utilized to detect an incipient failure in the electrical circuit board of a digital voltmeter.

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OBJECTIVE

The objective of this investigation was to develop new infrared nondestructive testing (IRNDT) techniques for the detection of surface and subsurface flaws in metallic and organic materials with a high-speed infrared camera.

INTRODUCTION

Infrared techniques have been used by many investigators for the nondestructive testing of various types of structures. For example, Kutzscher and Zimmerman used IRNDT techniques to evaluate bonds in aerospace structures;¹ while Vogel used these techniques to evaluate bonds in armor plate, rubber coatings, and missile motor cases;² and Kubiak used IRNDT to detect fatigue cracks and other near-surface defects in aircraft and missile structures.³ In each of the investigations mentioned, a regular heat lamp or a high intensity xenon lamp was used to heat the samples being tested while an infrared camera was used to detect any thermal anomalies that developed. In addition, during FY70 and FY71, the Research Directorate of the Weapons Laboratory at Rock Island submitted reports on new active and passive IRNDT techniques that relied on the use of a CO₂ laser heat source and an infrared radiometer to detect thermal anomalies resulting from programmed flaws in metallic specimens.

In the Research Directorate investigations, laboratory constructed CO₂ lasers were used to inject heat into specimens containing programmed flaws. During FY70, a laser was used having an output of 30 watts that was 100 per cent modulated at 120 hertz. Since this modulation caused detectable variations in the heat flux incident on the surface of the specimen a continuous wave (CW) CO₂ laser with a constant 35 watt output was constructed in the laboratory for the FY71 effort.⁴ In conjunction with the laser heat source, an infrared radiometer was used in active IRNDT investigations to detect surface temperature irregularities resulting from flaws.

For passive IRNDT investigations, a miniaturized infrared radiometer was constructed during FY71 and utilized to detect surface and near surface defects in metallic samples.

The current effort was focused on the development of improved IRNDT techniques with the use of an infrared camera to detect thermal anomalies. In the current work, a high speed double-detector infrared camera was used to view samples while these samples were being heated by radiation from a CO₂ laser and by radiation from a standard 250-watt infrared lamp. In addition,

the infrared camera was used to inspect the electronic circuit board of a digital voltmeter since the operation of this device was unreliable.

THEORY AND TECHNIQUES

All materials with a temperature above absolute zero continuously emit and absorb infrared radiation. The infrared portion of the electromagnetic spectrum extends from 0.75 to 1000 micrometers (μm) and can be divided into four regions. These regions are the near infrared (0.75 to 3.0 μm), the middle infrared (3.0 to 6.0 μm), the far infrared (6.0 to 15.0 μm), and the extreme infrared (15.0 to 1000.0 μm).⁶

The intensity of the emitted infrared radiation is proportional to the fourth power of the absolute temperature; in accordance with the Stefan-Boltzmann law:

$$W = \epsilon\sigma T^4$$

where

W is the radiant emittance in watts per unit area,

σ is the Stefan-Boltzmann constant (5.67×10^{-12} $\text{cm}^{-2} \text{ } ^\circ\text{K}^{-4}$),

T is the absolute temperature in degrees Kelvin, and

ϵ is the emissivity of the surface of the object.

Consequently, a small change in the temperature of an object will result in a relatively large change in the radiant emittance.

In the IRNDT method utilized, an external source is used to heat the surface of an object under inspection. If no flaws are present, the heat will flow evenly away from the heated surface until equilibrium is reached. However, if a flaw is present, this uniform flow of heat is interrupted and a thermal anomaly (hot or cold spot) will develop in the proximity of the flaw. To detect these thermal anomalies, an infrared radiometer or an infrared camera can be used. The conventional external source of thermal energy is a heat lamp. In an investigation (FY70) conducted in the Research Directorate, Weapons Laboratory at Rock Island, the use of a CO₂ laser heat source was introduced; this work was continued during FY71.^{4,5} In the previous

investigations, an infrared radiometer and line scanning system were used to inspect a single line of the sample. In the present investigation, a high-speed double-detector infrared camera was used to inspect an area of the sample. The use of the infrared camera for this application facilitated the detection and the location of flaws since the data were presented in a form more readily interpretable than that of the linear oscilloscope traces previously obtained. The infrared camera method also yielded much more information because of the x-y format, than the single-line scan method.

Objects that actively emit infrared radiation such as electrical circuits, transformers, motors, nuclear reactors, and radiators can be inspected without the use of an external heat source. For inspection of these objects, determination of the characteristic thermal signature of the object or of the component during normal operation is necessary. Then, the thermal signature of a "suspect" or faulty system can be used to identify the faulty components in that system by comparison of the thermal signature obtained during normal operation of the system. If a standard is unavailable, faulty components can sometimes be located by comparison of the thermal signatures of similar components in the system that may be functioning properly. This method is particularly useful for location of problems such as faulty components in electrical circuits, electrical shorts in transformers, and defects in radiators.

INSTRUMENTATION AND PROCEDURE

An in-house constructed CO₂ laser and a standard 250 watt infrared lamp were used to heat the samples. The laser used was a longitudinally excited, split discharge, flowing gas type with a continuous wave output variable to 35 watts. A complete description of this laser can be found in Reference 5. A schematic diagram and a photograph of the laboratory constructed CO₂ laser are shown respectively in Figures 1 and 2.

A Dynarad, Inc., Model 210, infrared camera was used in this investigation. This unit has an instantaneous field of view of 10 x 10 degrees and a minimum detectable temperature difference of 0.3°C at 30°C. Two liquid nitrogen cooled infrared detectors are used in the camera system, a mercury cadmium telluride (HgCdTe) detector (which is most sensitive to radiation in the 8 to 14 μm wavelength band) and an indium antimonide (InSb) detector (which is most sensitive to radiation in the 2-5.6 μm wavelength band). The two detectors can be

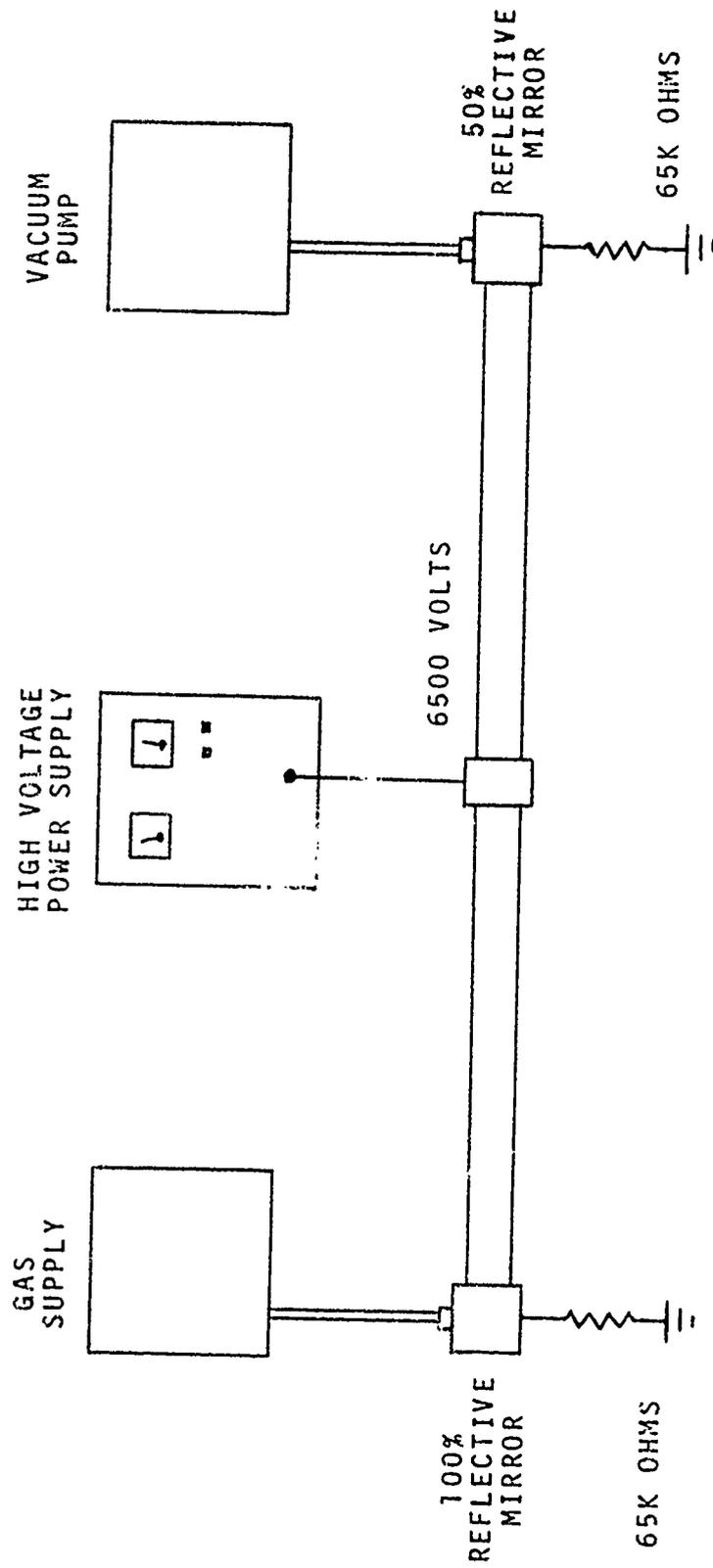


FIGURE 1 SCHEMATIC DIAGRAM OF LABORATORY-CONSTRUCTED CO₂ LASER

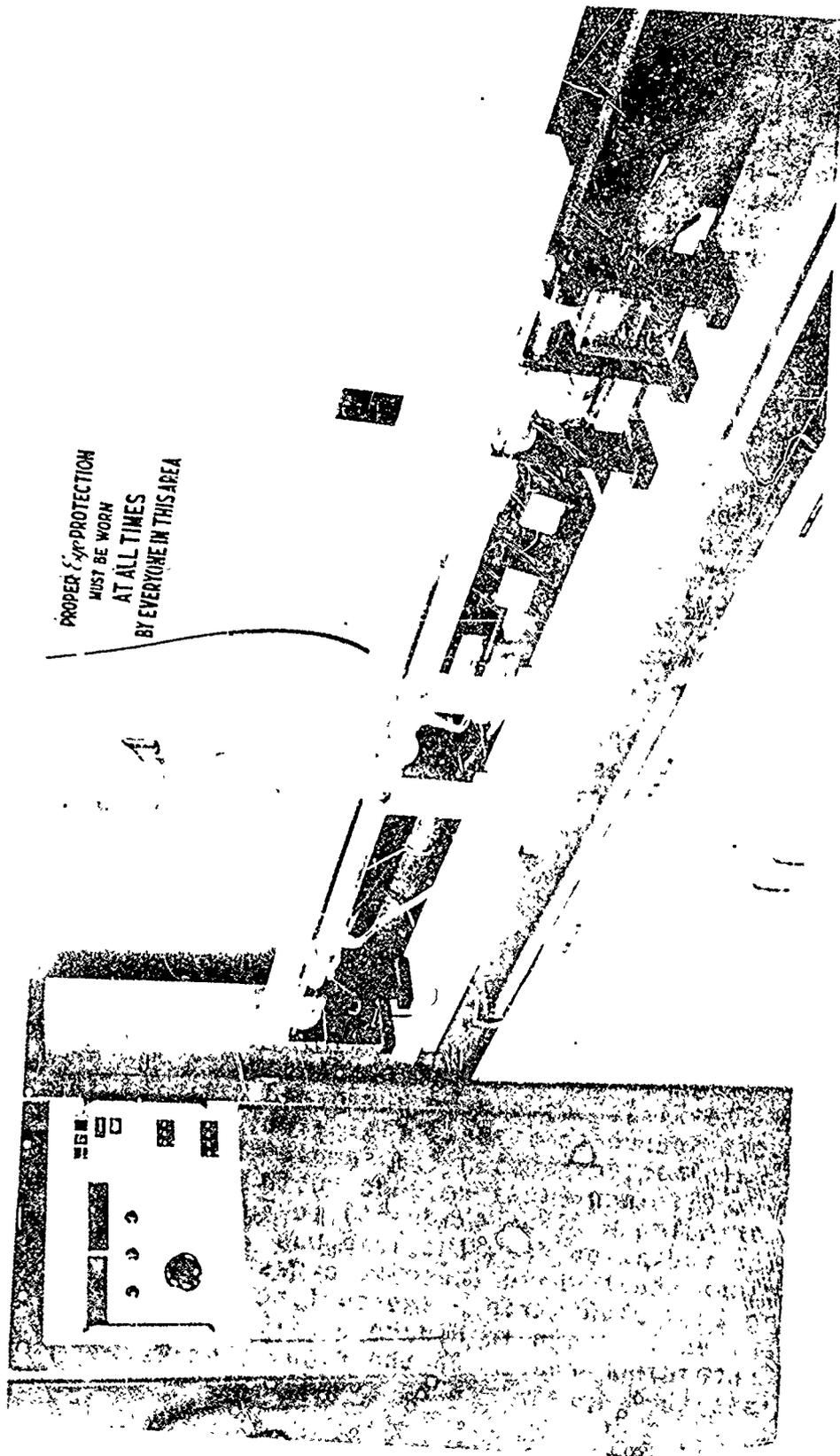


FIGURE 2

LABORATORY-CONSTRUCTED CO₂ LASER

operated individually or with their outputs added or subtracted. Because of the higher sensitivity of the HgCdTe detector, it was used solely in the tests reported.

The optical unit of the camera is shown by a schematic diagram in Figure 3. The display unit can be utilized to display the 2-dimensional temperature-map of the object being tested at three different frame rates: 15, 30, or 60 frames per second. Each frame contains 400, 200, or 100 lines for the respective frame rate, and each line contains 100 elements.

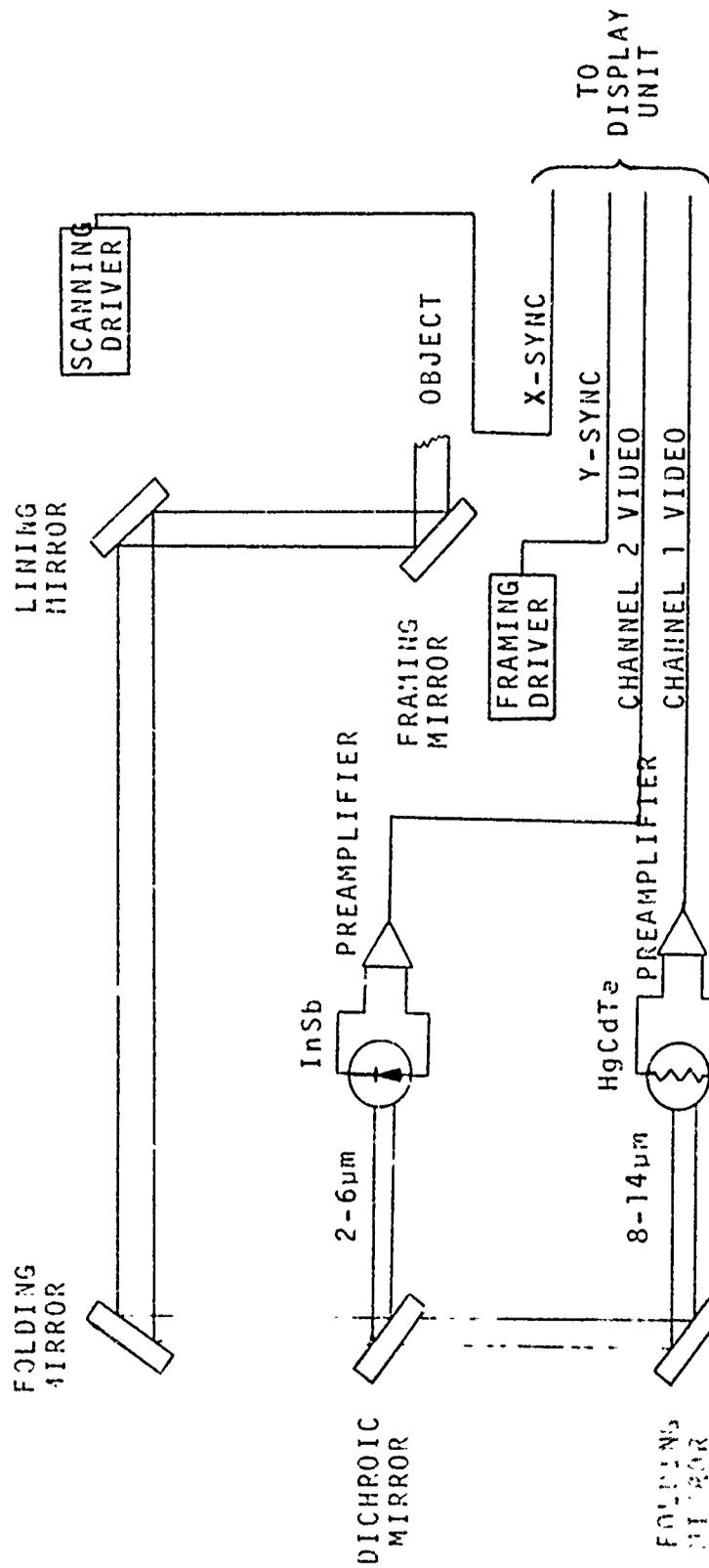
When the lamp was used as a heat source, the camera was focused on the front surface of the sample while the thermal energy was incident on the rear surface (Figure 4). When the laser was used as a heat source, two configurations were utilized. In the first configuration, the laser was focused on the front surface of the sample, but was out of the field of view of the camera (Figure 5, View a). While this configuration was used, the heat flow across the surface of the sample was observed. Unfortunately, the high power radiation incident upon the surface caused the surface under inspection to become rapidly heated; this condition, in turn, masked any minute temperature changes that could occur because of a subsurface flaw.

In the second configuration with the laser heat source the infrared camera was again focused on the front of the sample, but the laser radiation was incident on the back of the sample (Figure 5, View b). In this configuration, four sample heating techniques were used, a stationary focused and unfocused beam and a scanning focused and unfocused beam.

RESULTS AND DISCUSSIONS

LAMINATED STRUCTURE INSPECTION

Laminated flat samples containing programmed unbonded areas were tested by the external heating technique previously described. The first tests were performed with the infrared lamp as a heat source to inspect flat aluminum/Rulon and aluminum/Plexiglas laminates. The sample used in Test 1 was a 6.0 x 6.5 x 0.1-inch aluminum sheet with a 5.5 x 1.0 x 0.006-inch strip of Rulon A (iron oxide-filled Teflon) bonded to the surface. The radiation from the lamp was incident on the rear of the aluminum sheet while the camera was focused on the other side, facing the Rulon strip. The surface temperature profile of this specimen is shown in Figure 6 with the dark (cool) spots indicating unbonding areas. On the right side of the photograph, an area exists that appears to be a gross discontinuity. This is



OPTICAL UNIT OF CAMERA

FIGURE 3

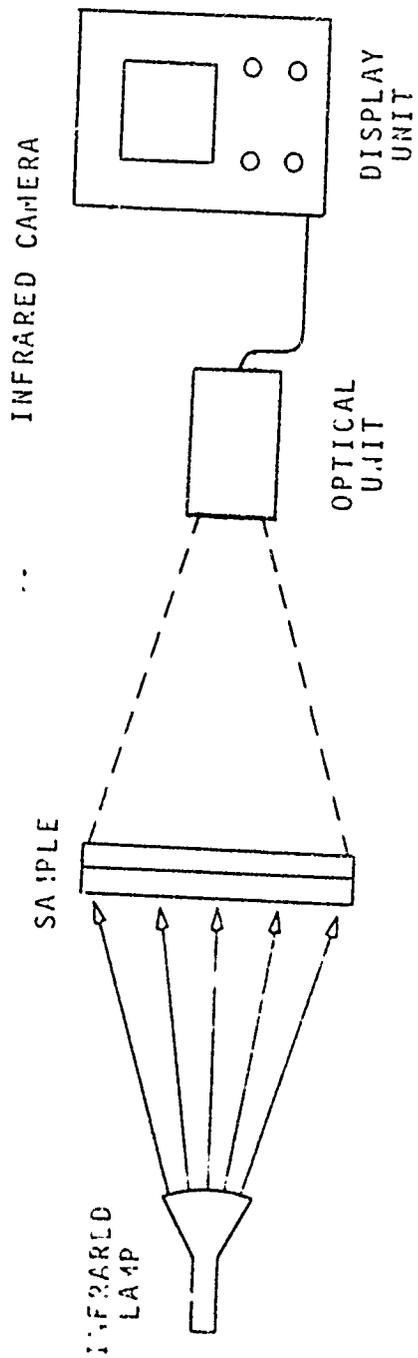


FIGURE 4 INFRARED LAMP HEAT SOURCE TECHNIQUE

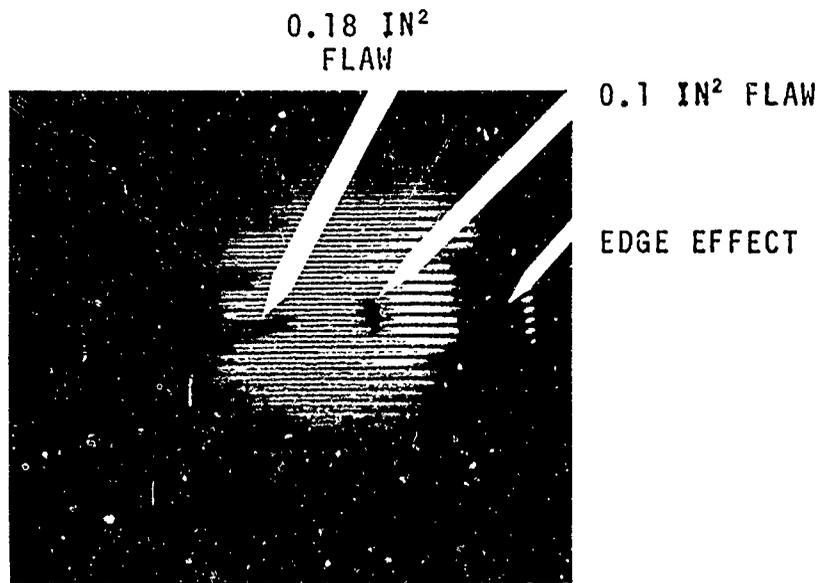


FIGURE 6

THERMAL IMAGE OF ALUMINUM/
RULON A LAMINATE

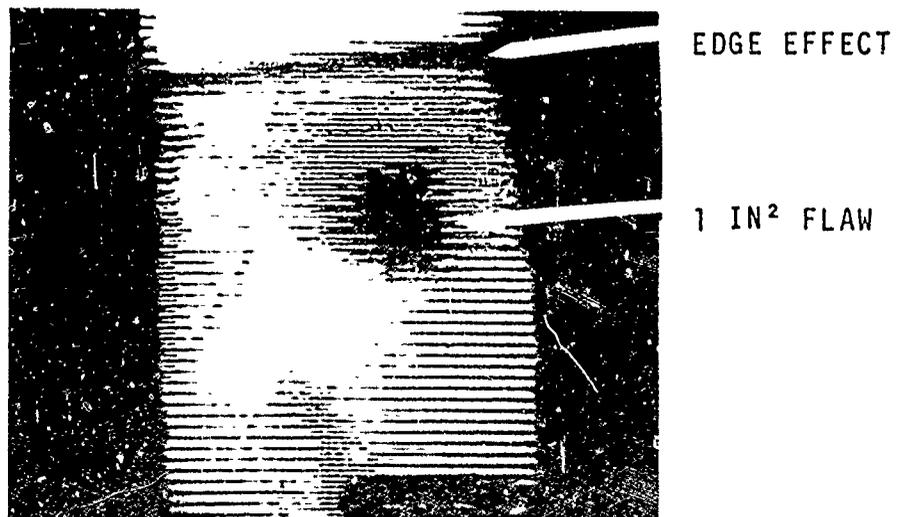


FIGURE 7

THERMAL IMAGE OF ALUMINUM/
0.25-INCH PLASTIC LAMINATE

caused because the Rulon strip does not extend to the edge of the aluminum sheet. Since the surface of the aluminum sheet is hotter than the surface of the Rulon, a discontinuity appears along the edge.

The sample used in Test 2 was a 5.75 x 4.375 x 0.03125-inch aluminum sheet with a 5.0 x 4.0 x 0.25-inch plastic sheet bonded to the surface. The camera was focused on the plastic sheet with the heat incident on the rear of the aluminum sheet. The resulting surface temperature profile is shown in Figure 7 with the dark spot indicative of an unbonded area. An edge effect is also shown in this figure.

The sample used in Test 3 was a 6 x 4 x 0.095-inch aluminum sheet with a 6 x 8 x 0.25-inch Plexiglas sheet bonded (with epoxy) to the surface. The aluminum sheet was heated by the lamp, and the camera was focused on the Plexiglas surface. The surface temperature-map is shown in Figure 8 with the four dark spots indicative of the unbonded areas.

The sample used in Test 4 was a 5.75 x 4.5 x 0.04-inch aluminum sheet with a 5 x 4 x 0.025-inch plastic sheet similarly bonded to the surface. As before, the aluminum sheet was heated and the camera was focused on the plastic surface. The surface temperature-map of this specimen with the two dark spots indicative of unbonded areas is shown in Figure 9.

The sample used in Test 5 with the infrared lamp was a 8 x 8 x 0.2-inch aluminum sheet with a 4 x 7 x 0.1-inch Plexiglas sheet bonded to the surface. The same heating and viewing configuration used previously was used in this case, the resulting thermal image is shown in Figure 10. The entire test specimen is not shown in the figure; actual dimensions of the section shown in the image are 5 x 3 inches.

The results shown indicate that IRNDT techniques can be reliably utilized to detect voids in the bonding material of laminated structures. Voids can be detected when the size of the void is small compared with the depth of the void below the surface. In addition to the detection of unbonded areas in laminated materials, the goal of this Laboratory was to determine whether the use of a CO₂ laser heat source would be feasible and whether it would improve the IRNDT technique when an area is being inspected.

In Test 1 with the laser heat source, the same aluminum/Plexiglas laminate that was inspected in the previously mentioned Test 5 with the heat lamp was reinspected

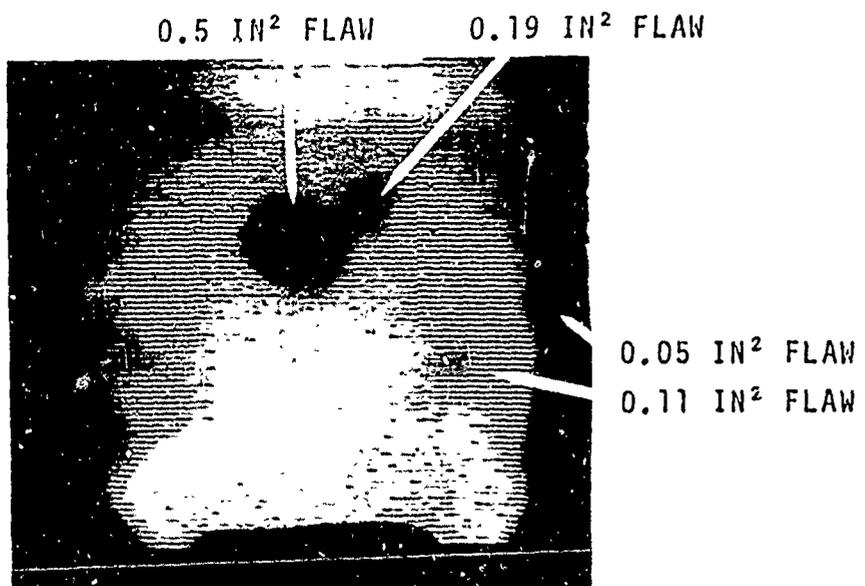


FIGURE 8

THERMAL IMAGE OF ALUMINUM/
0.25-INCH PLEXIGLAS LAMINATE

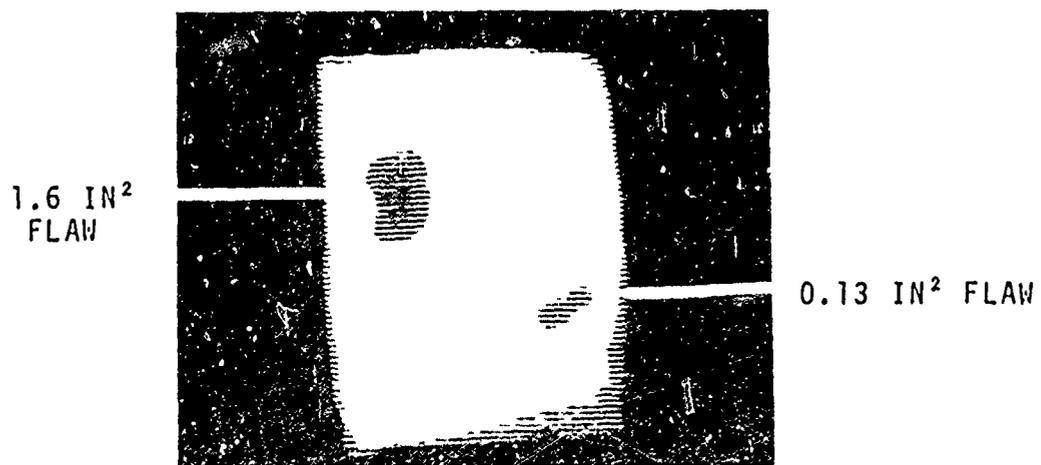
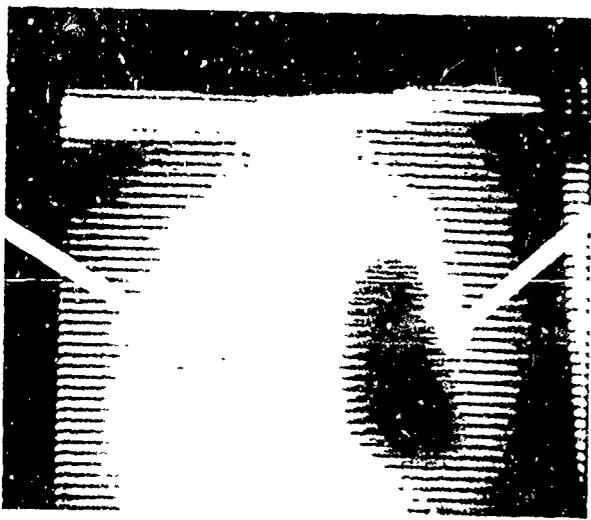


FIGURE 9

THERMAL IMAGE OF ALUMINUM/
0.025-INCH PLASTIC LAMINATE

0.2 IN²
FLAW



1.25 IN² FLAW

FIGURE 10

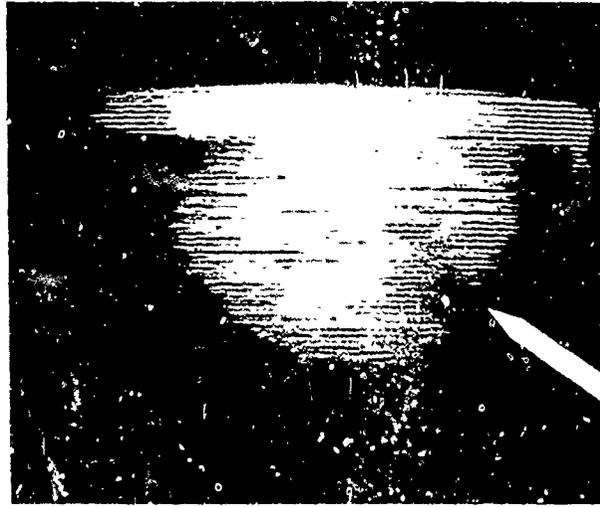
THERMAL IMAGE OF ALUMINUM/
0.1-INCH PLEXIGLAS LAMINATE

In this test, the defocused laser beam was incident on the aluminum sheet while the camera was focused on the Plexiglas surface. Two tests were performed, one with a stationary laser spot and the other with a scanning laser spot. The thermal signature of the sample being irradiated by the stationary laser spot is shown in Figure 11a. (Note the hot center and cool edges.) A situation in which this sample is being heated by the scanning spot is shown in Figure 11b. (Note the more uniform temperature distribution.) In Views a and b of Figure 11, the larger flaw is distinguishable, but the smaller flaw shown in Figure 10 is indistinguishable.

In the next test with the laser heat source, the aluminum/Rulon A composite, previously described, was inspected. As before, the laser energy was incident on the aluminum while the camera was utilized to monitor the thermal signature of this sample. The signature that resulted from the use of a stationary unfocused laser heat source is shown in Figure 12, View a, and the signature of the sample resulting from the use of a scanning laser heat source is shown in Figure 12, View b.

The last sample tested with the laser as a heat source was the aluminum/plastic sheet laminate described previously in Test 2. The laser was again used to heat the aluminum sheet while the thermal profile of the plastic surface was monitored with the infrared camera. The thermal profile that resulted from this sample while the stationary laser was used as a heat source is shown in Figure 13, View a. The thermal signature that resulted when the sample was heated by a scanning laser spot, is shown for comparison in Figure 13, View b.

The results from the tests with the laser as the source of specimen heating clearly indicated that flaws are detectable. However, when these results were compared with those obtained with a heat lamp as a heat source, the use of a relatively low power CO₂ laser did not increase flaw detection capabilities. This is explained by the fact that none of the advantageous properties of the laser (high power density, coherence, and fine focus) were being utilized since the radiation was unfocused and the power density on the surface was low. Therefore, the laser was being utilized essentially to simulate a heat lamp. When a focused beam was utilized to achieve high power densities, the resulting hot spot saturated the thermal image and masked the thermal effects due to flaws. Since in this investigation, a laser was used with an output of only 35 watts when the beam is unfocused, the power density on the sample was low (0.66 watts per square centimeter). With the use of the unfocused beam from a higher power CO₂ laser having an output on the order of hundreds of watts, flaws located further below the surface and flaws in massive components would probably be detected.



FLAW

VIEW a
UTILIZATION OF A STATIONARY LASER BEAM

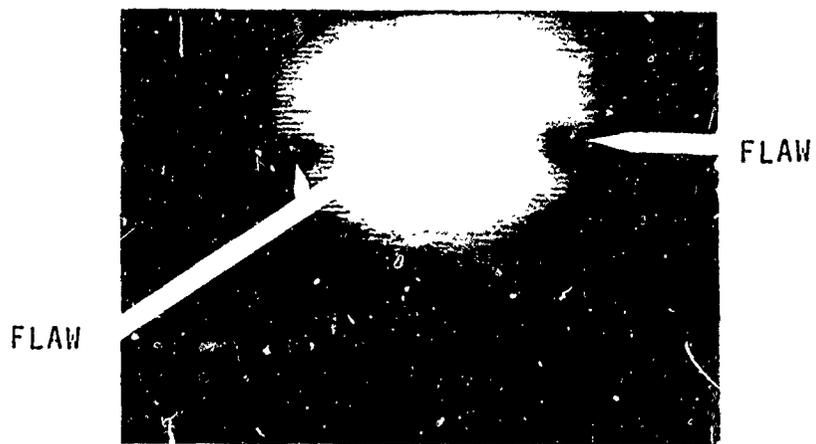


FLAW

VIEW b
UTILIZATION OF A SCANNING LASER BEAM

FIGURE 11

THERMAL IMAGE OF ALUMINUM /
0.1-INCH PLEXIGLAS LAMINATE



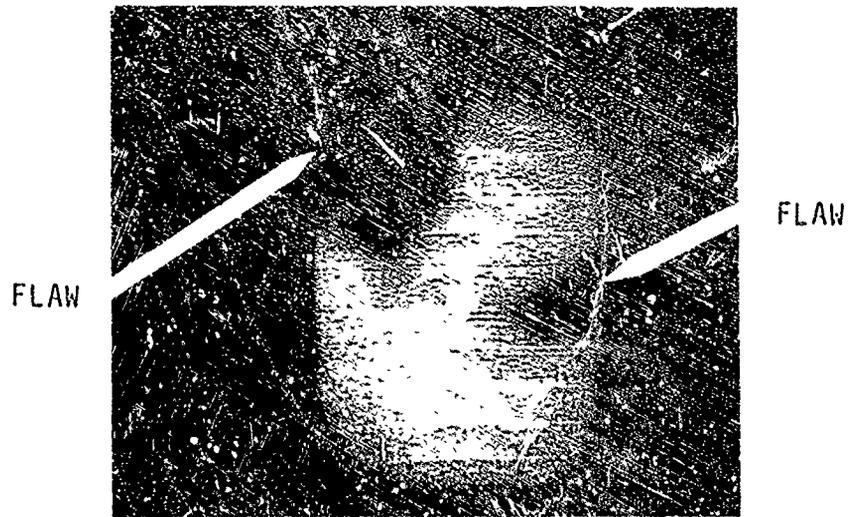
VIEW a
UTILIZATION OF A STATIONARY LASER BEAM



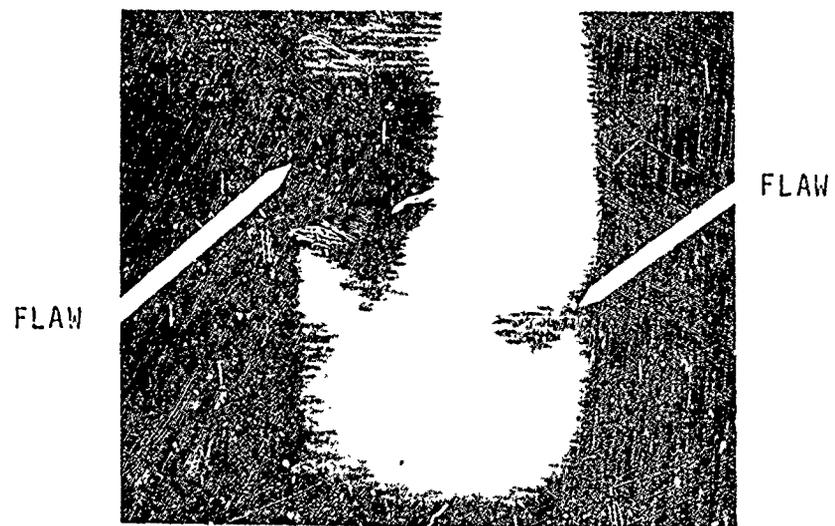
FLAW
VIEW b
UTILIZATION OF A SCANNING LASER SPOT

FIGURE 12

THERMAL IMAGE OF ALUMINUM/
RULON A LAMINATE



VIEW a
UTILIZATION OF A STATIONARY LASER SPOT



VIEW b
UTILIZATION OF A SCANNING LASER SPOT

FIGURE 13

THERMAL PROFILE OF ALUMINUM/
0.025-INCH PLASTIC LAMINATE

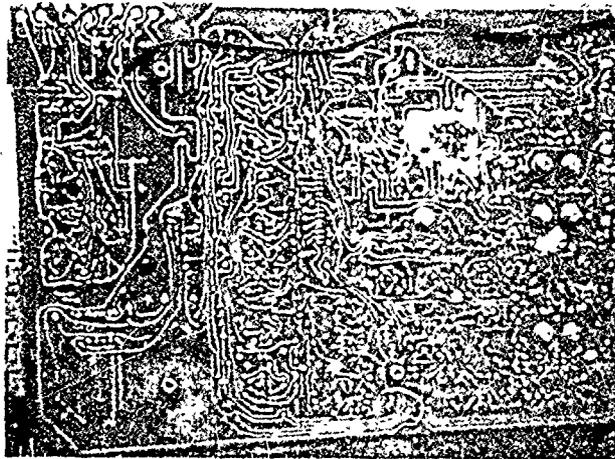
When the results of the FY71 and FY72 investigations are compared, the IRNDT technique which is best, must be determined by physical geometry, material, and mass of the object being tested. A laser heat source and a single-line scanning radiometer are preferred when the surface of interest is narrow and massive. A combination of a heat lamp and an infrared camera is best for testing components with relatively large areas and consisting of materials that are adversely affected by high temperatures. The cost of the instrumentation must also be taken into account. The cost of an infrared radiometer plus a CO₂ laser system would be approximately \$15,000 whereas the price of an infrared camera ranges from \$17,000 to over \$50,000, but the cost of a heat lamp is negligible. Therefore, before an attempt is made to choose the IRNDT technique best for a particular application, the type of component being examined and the type of flaw expected must be studied carefully.

The intelligibility of the data presented should also be considered. Since the thermal image resembles a normal reflected-light, representation of the object, thermal images are much more readily interpreted than single line outputs. In addition, the location of the flaw is easily determined with a thermal imaging-system. However, with a scanning radiometer system, the location of a flaw is difficult to determine

ELECTRICAL CIRCUIT INSPECTION

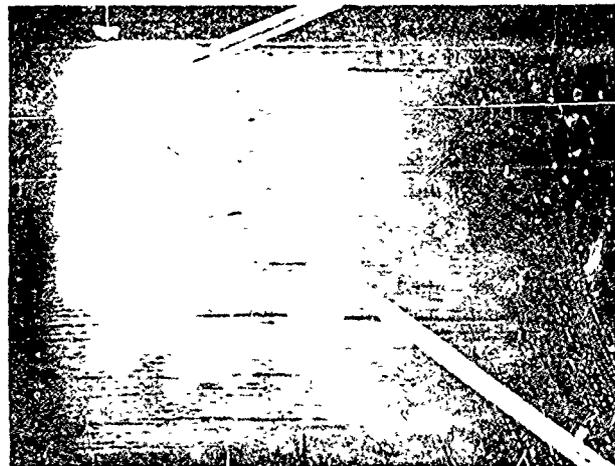
During the FY72 IRNDT investigation, the electrical circuit testing was limited to the inspection of the circuit board of a digital voltmeter. This particular instrument was not operating reliably and had a mean time before failure of approximately 8 hours, with the same two transistors failing in each case.

To determine whether any abnormal thermal concentrations were present on the circuit board, the electronics were removed from the case and the unit was allowed to operate while the infrared camera was focused on the circuit board. A conventional photograph of the underside of the circuit board is shown in Figure 14, View a. The thermal image of the circuit board is shown in Figure 14, View b. The hot spot (white) in the upper left of this view was caused by a resistor by which the board was heated. The transistors that were of interest are located below the hot resistor in the locations indicated. An isometric image of the circuit board is shown in Figure 14, View c. In this type of image, amplitude modulation of the horizontal line



VIEW a
PHOTOGRAPH

RESISTOR



VIEW b
THERMAL IMAGE

TRANSISTORS

RESISTOR

VIEW c
ISOMETRIC IMAGE

FIGURE 14

TOP SIDE OF CIRCUIT BOARD

scan is used to present a 3-dimensional temperature-map. The peaks in this view indicate hot spots.

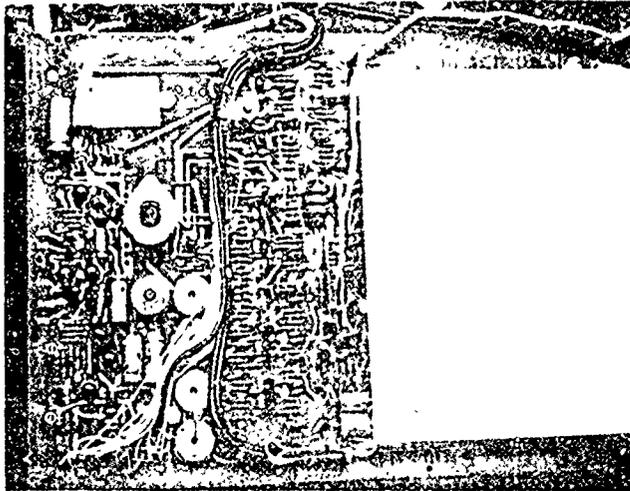
Since the thermal image of the bottom of the printed circuit board did not yield all the necessary information, the board was rotated 180° (top to bottom) and the temperature profiles of this surface were monitored. A photograph of the area under inspection is shown in Figure 15, View a, (Note. What was shown at the top in Figure 20 is now at the bottom). The thermal and the isometric images of this side of the board are shown respectively in Figure 15, Views b and c with the location of the components of interest marked. Since the transistors that had been failing after prolonged use (8 hours) were operating at a higher temperature than the comparable units in the circuit, these transistors were replaced by transistors with comparable electrical characteristics but with a higher power dissipation capability. In addition, the gold cases of these transistors, which have a very low emissivity (typically less than 0.1), were painted with ultra flat black-enamel, which has an emissivity of greater than 0.95, to improve the radiative heat transfer characteristics. After these transistors had been changed, the instrument was operated continuously for three 8-hour periods without malfunctions; the unit has also operated reliably during normal use after the test period. Therefore, the ability to use infrared nondestructive testing techniques for electrical circuit analysis was also shown during this investigation.

CONCLUSIONS

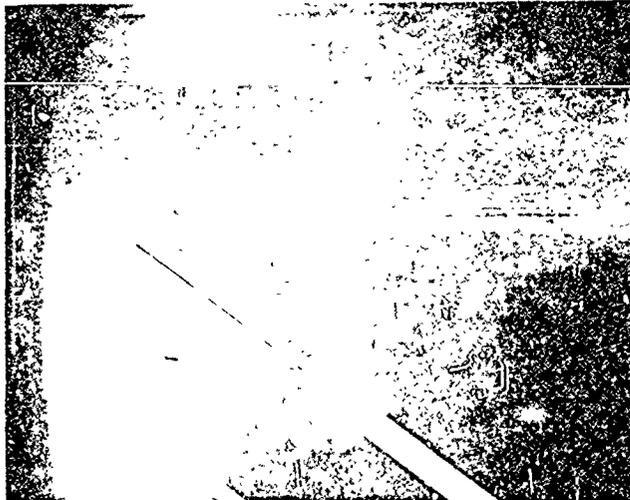
The capability of the IRNDT techniques for the detection of unbonded areas in laminated structures was shown. In addition, the capability of the IRNDT techniques for the detection of faulty electrical components and for the detection of incipient failures in electrical circuits was demonstrated.

From the results of this IRNDT investigation, it can be concluded that the flaw detection capabilities when an infrared lamp or a low-power CO₂ laser heat source is used in conjunction with a thermal imaging device are approximately equal. Since the capabilities are equal, the logical choice of a heat source for most applications, would be the infrared lamp because of the low cost and ease of operation.

In addition, the use of a thermal imaging device for the inspection of electrical circuits is clearly superior to the use of a scanning radiometer because of the more intelligible format of the information presented.



VIEW a
PHOTOGRAPH



VIEW b
THERMAL IMAGE

PLSISTOR TRANSISTORS

VIEW c
ISOMETRIC IMAGE

FIGURE 15 VIEW OF CIRCUIT BOARD

RECOMMENDATIONS

Further research should be directed toward the use of the techniques developed in the Research Directorate of the Weapons Laboratory at Rock Island for the inspection of particular weapon components. In addition, experiments should be performed on a series of identical samples without flaws to determine the characteristic thermal signature of the set of samples. Once the characteristic signature is determined, samples containing programmed flaws should be tested to determine the changes in the characteristic signature resulting from the flaws. This signature information should be employed to determine the feasibility of using pattern recognition techniques for the automatic inspection of components.

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