# FOREWORD

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This report covers work conducted from January 1961 to January 1962.

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## ABSTRACT

The program under Contract AF 33(616)-7725 was a study to determine the feasibility of thermal nondestructive evaluation of materials. From the study, a thermal testing system was conceived and developed with which certain fabricated material inconsistencies have been detected in standard test material samples. The system operation is basically a programmed heating and subsequent temperature measurement over one surface of the test sample. Heat flow from the heated surface into the material is examined through the surface temperature measurement. Temperature is measured with an infrared detection system. A display of the temperature pattern over the surface is then interpreted with respect to internal material inconsistencies. A section of the report entitled "Test Results" summarizes the tests, showing the detection of inconsistencies in the standard material samples. Inconsistencies detected to date include voids, delamination (areas of unbonding), and metallic inclusion.

This report has been reviewed and is approved.

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## SUMMARY

Many intrinsic properties or specific conditions of a material have an effect on the transfer of heat through the material. It would, therefore, seem logical that variations in such parameters could be recorded by investigation of the heat transfer through the material.

In the work effort of this program, under contract AF 33(616)-7725, a thermal test method and the necessary instrumentation have been developed to measure variations in heat transfer in response to a controlled surface heating. The heat transfer variations are subsequently related to variations in test material. Heating is achieved by focused radiation from a tungsten filament or by blowing hot air on test material. Readout of variations in heat transfer is achieved remotely via measurement of the surface temperature of the material with an infrared radiometer. Surface heating varies between ambient and 40°C above ambient. The detector and filter arrangement in the radiometer is designed to work in the 3.8 to 6.5 micron region of the infrared spectrum.

Material samples tested in the program consist of metal plates of thicknesses ranging from 0.010" to 0.375". Known voids, metallic inclusion, or condition of unbond are introduced to the plates, and these irregularities are located by the thermal testing technique.

In this report, theory and details of the test method and instrumentation are given, and test results are compiled. Ultimate aims of a proposed continuation study are given, in which major emphasis is to be placed on evaluation of many material characteristics not yet attempted.

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# I. INTRODUCTION

## 1.0 Objective and Scope of Research

A variety of material conditions and properties have some degree of influence on the transfer and storage of heat within a given material. It is often desirable to determine variations in one of these conditions and properties within a given material configuration.

The purpose of this program is twofold: first, to investigate the feasibility of determining these variations by some measure of the heat transfer within the material; and second, to design, fabricate, test and calibrate a thermal test system for measuring and recording the variations within test material samples.

This program has been essentially a feasibility study. The preliminary study and subsequent work effort produced two definite results, namely

A. A thermal testing method employing a scanning process;

B. A prototype thermal testing system for evaluation of materials.

In the evaluation of material, these three types of material condition have been successfully detected with the prototype thermal testing system:

A. Voids within material,

B. Condition of unbonding or delamination,

C. Inclusion of a metal particle within a different metal.

The material samples tested in the feasibility program have been flat metallic plates ranging in thickness from 0.010" to 0.375", with known conditions, as outlined above, introduced into the material. The reason for the use of flat plates was merely to simplify instrumentation. In this way, it was felt that the major work effort would go into the real purpose

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of the program, that of proving feasibility and developing a prototype test system for thermal testing of materials. It is felt that the approach taken to date can be adapted readily to transition to other test material geometries.

## 2.0 Need for this Program

Nondestructive materials evaluation is a field that is both well-established and very useful. Nearly every known form of energy has been used in nondestructive testing systems. These systems have shown widely divergent and sometimes amazing capabilities for showing an observer information concerning the interior condition of a given material. In spite of the diversification already existing in the field, and in spite of the many marked successes, some problems of materials evaluation remain unsolved.

Due to the interaction between many material parameters (either intrinsic properties or specific conditions) and the rate of heat transfer through the material, it would seem reasonable to expect that a thermal testing system which monitors changes in heat transfer could supply information on internal material parameters. Rather than replacing any presently available nondestructive testing method, thermal testing should complement present equipment, providing correlation of results and, if possible, yielding nondestructive testing evaluation not easily accomplished by other methods.

## 3.0 System Requirements

A thermal test system, as envisioned and developed in this program, must perform the following functions:

A. Heat the surface of a test material sample in some controlled manner;

B. Investigate the variations in heat transfer from the surface after heating;

C. Correlate these variations in heat transfer to variations in internal material parameters.

The test material heating must be at a sufficiently low level so that it does not itself alter the condition of the material. Low level heating is also advantageous from the point of view of material handling, uniformity of heating, and instrumentation. Temperatures slightly above ambient are the most desirable.

Due to the nature of thermal energy, the investigation of heat transfer within the test material must be done by observing the temperature pattern on the surface. It would be preferable to do this remotely, to prevent interaction between test material and temperature sensor. At the temperatures of interest (between ambient and 40° C. above ambient), remote measurement of temperature on a spot on the surface is accomplished by measuring the infrared radiation from that spot. Some radiation-sensitive detector system is thus needed, which is calibrated in terms of surface temperature.

The ultimate usefulness of the thermal test system is dependent on the interpretation of the surface temperature pattern with respect to interior material parameters. This requires a system for recording temperature measurements versus position on the test material, and a display of this information.

## 4.0 Basic Research Approach

The program was conducted in two major phases of effort. The essential nature of the program breakdown is indicated below.

Phase 1: Literature review, formation of thermal testing concepts, survey of available equipment and components.

Phase 2:

A. Instrumentation of the test system.
B. Thermal testing of material samples.

The second phase had two distinct goals as shown above. These two goals, being interdependent, were attacked continuously and concurrently during Phase 2. Progress in one goal usually engendered progress in the other, and vice-versa.

## 5.0 Overall Program Results

### 5.1 Phase 1

During Phase 1 of this program, a concept of thermal testing was formed, in which a heater and temperature sensor combination scan one surface of a plate of test material. The readings of the temperature sensor are interpreted with respect to internal material characteristics.

Another result of Phase 1 was the choice of instrumentation for material heating and temperature sensing. A focused tungsten filament was chosen for a heater unit, primarily because of versatility. For temperature sensing, an infrared radiometer was acquired. Detailed descriptions of these modules are found in the body of the report.

### 5.2 Phase 2

The prototype test system, consisting basically of heater, temperature sensor and recorder, and scanning mechanism, was assembled and tested for operation. This system was purposely left versatile, with scan-speed, heater-sensor separation, and other test parameters widely variable, so that subsequent material testing procedures could be optimized.

After the initial test system was assembled, a series of test plates with known voids, unbonding, or metallic inclusion was prepared. This series and subsequent material samples were tested utilizing the thermal test method envisioned in Phase 1. As testing progressed, improvements were concurrently made in the test system. Eventually all material inconsistencies manufactured in test blocks were detected by thermal testing. The test system now in use is diagrammed and described in detail later in the report. Details of all thermal tests are also catalogued in a later section.

# II. RESEARCH APPROACH

## 1.0 Thermal Test Concept

The impetus for the type of work done in this program is almost solely the following apparent fact: many material parameters (either conditions of the material or intrinsic properties) have a cause-and-effect-relationship with heat transfer through the material. The concept of testing for variations in certain material parameters is based on the above-mentioned dependence of heat transfer on these parameters. A source of heat (radiant or hot air convection) is impressed upon a small spot on the material surface. This heat spot is moved in a path at constant speed in a programmed scan over the surface. The heat transferred away from the surface into the material is governed partly by the material parameters and their variations internal to the material sample. A quantitative measure of the heat transfer is obtained by continuously measuring surface temperature variations at a "detector spot" a fixed distance away from the heat spot. The continuous temperature evaluation is obtained by slaving the scan path of the heat spot, at a fixed separation from the heat spot, with the focal spot of a focused infrared radiometer. Thus by surface temperature evaluation, internal variations in material parameters are inspected.

## 2.0 Application of the Thermal Test Concept

After the thermal testing system was instrumented in its initial form, a series of tests was initiated on material plates with known inconsistencies, utilizing the test procedure outlined above.

### 2.1 Test Parameters

The first objective was to discover which conditions or parameters of the test equipment and procedure were important in determining the success of a test plate evaluation. It was found that the following seven test parameters were of primary importance:

A. Heat spot size,
B. Detector spot size,
C. Heater-detector spot separation,
D. Scan speed,
E. Uniformity of heat spot,
F. Heat spot intensity,
G. Condition of test material surface.

Considerable effort was expended in optimizing these parameters for given test samples in an attempt to establish criteria for setting the parameters for any given material and material configuration. Section IV of this report summarizes this work.

## 2.2 Material Parameters

The first test plates were fabricated with voids machined in the back surface (the surface not scanned by heater and detector). As the program progressed, depth and transverse dimensions of voids were gradually decreased, in an effort to establish the minimum size of such a void detectable with the present system. In general, the introduction of a void of any depth whatever in the back surface of a test plate causes an increase in resistance to heat flow from front to back surface. If test scans can be made both before and after the fabrication of such a void, a comparison of the two scans will reveal the presence of extremely shallow voids (that is, voids obtained as a result of removing very little material from the surface furthest from the scanning spots). Any temperature - determining feature of the test which remains the same for both scans, such as unavoidable surface emissivity variations or surface waviness, can be "subtracted out" in the comparison. The only major parameters left to affect radiometer measurement of surface temperature are random electronic and mechanical noise from the radiometer. In these circumstances, the lower limit on detectable void depth is that depth which causes a surface temperature variation yielding a radiometer signal variation equal to the noise of the radiometer. In proper operation, the radiometer used in this program has a maximum noise level equivalent to about 0.03°C (specifications from the manufacturer give this figure as no more than 0.05°C).

This magnitude of temperature variation is caused by a void depth of approximately 1% of total material thickness, in a range of material thickness from 1/32" to 1/8" and with the present heating system. Thus a 1% variation in material thickness (i.e., a 1% void depth) is theoretically the minimum detectable variation with the present testing system, without recourse to noise suppression or correlation procedures.

The above testing procedure and the derived detectable void depth are, of course, impractical. The goal of the test is to locate voids of unknown position. Thus it is necessary to reliably detect voids on the basis of a test scan performed after the void is fabricated in the test plate, with no reference or comparison to scans made before the void is cut in the material. This implies that a detectable void must be clearly distinguishable over such parameters as surface emissivity variations, etc. On this basis, progress to date has shown voids of depth 3% of total material thickness to be detectable over a range in material thickness from 1/32" to 1/8". Voids of this depth in thicker test plates are not reliably detectable, possibly because of insufficient heating intensity or inadequate heat spot size. Difficulties in fabrication and measurement have delayed the testing of voids of this percentage depth in plates thinner than 1/32". An example is shown of the 3% void depth and its detection in Figure 19.

In transverse dimensions (dimensions parallel to plate surfaces), a detectable void must be either (1) as large as the detector spot size, or (2) twice the plate thickness, whichever is larger. These limitations are believed due largely to the method of heating, which does no selective heating near material anomalies and allows heat to diffuse easily in transverse dimensions. In testing for integrity of bond, it was found that an area of unbond between two brass plates soldered face-to-face is detectable even if the plates are touching in the unbonded area.

For further detail regarding either test parameters or material parameters in a thermal test, refer to Section IV of this report.

## III. THEORETICAL CONSIDERATIONS

### 1.0 Introduction

The purpose of the theoretical discussion is to afford the basis for the discussion of the scan-heating and detecting thermal test method previously described. It is thus necessary to analyze a heat flow pattern in some test material configuration resulting from a moving heat source. The current feasibility and prototype instrumentation program was performed using flat test material plates of various thicknesses. The moving heat source has been a focused heat spot directed to one test material surface. The investigation of heat transfer through the test material has been accomplished by the measurement of the temperature pattern on the heated surface. For these reasons, the analysis carried out in the theoretical discussion will result in expressions for the temperature on the surface of a flat plate heated with a moving point source of heat. (The point source is merely a theoretical simplification to avoid discussing an area source or "spot".)

## 2.0 Formulation of the Basic Equation for Moving Heat Source

Consider a heat source of constant intensity moving at a constant velocity along a path on the surface of a homogeneous material plate of uniform thickness. Bornefeld[1] has shown experimentally that soon a quasi-steady state in the surface temperature occurs; a detector moved with the heat source measures a surface temperature distribution relative to the heat source. The surface temperature distribution is constant with time. In other words, a constant temperature "pattern" moves along the material surface with the moving heat source. Any variation in the pattern as seen by a detector synchronized with the heat source may be interpreted as a variation in some material property or condition if all test parameters are held constant.

Rosenthal[2] developed a theoretical analysis of moving heat sources to substantiate Bornefeld's experimental work. The analysis given here is derived from a presentation by Jakob[3] of some of Rosenthal's effort. Considered here are two extreme cases of heat flow in flat plates with a moving point heat source, namely

A. Heat flow in a thin plate,

B. Heat flow in a thick plate.

The criterion for judging the thickness of a plate is based on the scan-heating and detecting concept. Compare the time required for a thermal transient to travel the material thickness with the time lapse between heating and detecting in the test. If the transient is shorter than the time lapse, the plate is thin. If the transient is longer, the plate is thick.

Consider a Cartesian coordinate system (x, y, z) as shown in Figure 1, filled with a conducting medium, with a point 0' moving at uniform velocity $\underline{v}$ along the x-axis. After time $\underline{t}$, the point has moved from the (x, y, z) origin 0 a distance vt along the x-axis. An observer (i.e. a detector) moving with point 0' would be fixed with respect to a coordinate system ($\xi$, y, z). Any heat source may now be moved with point 0', and it will appear fixed in coordinate system ($\xi$, y, z).

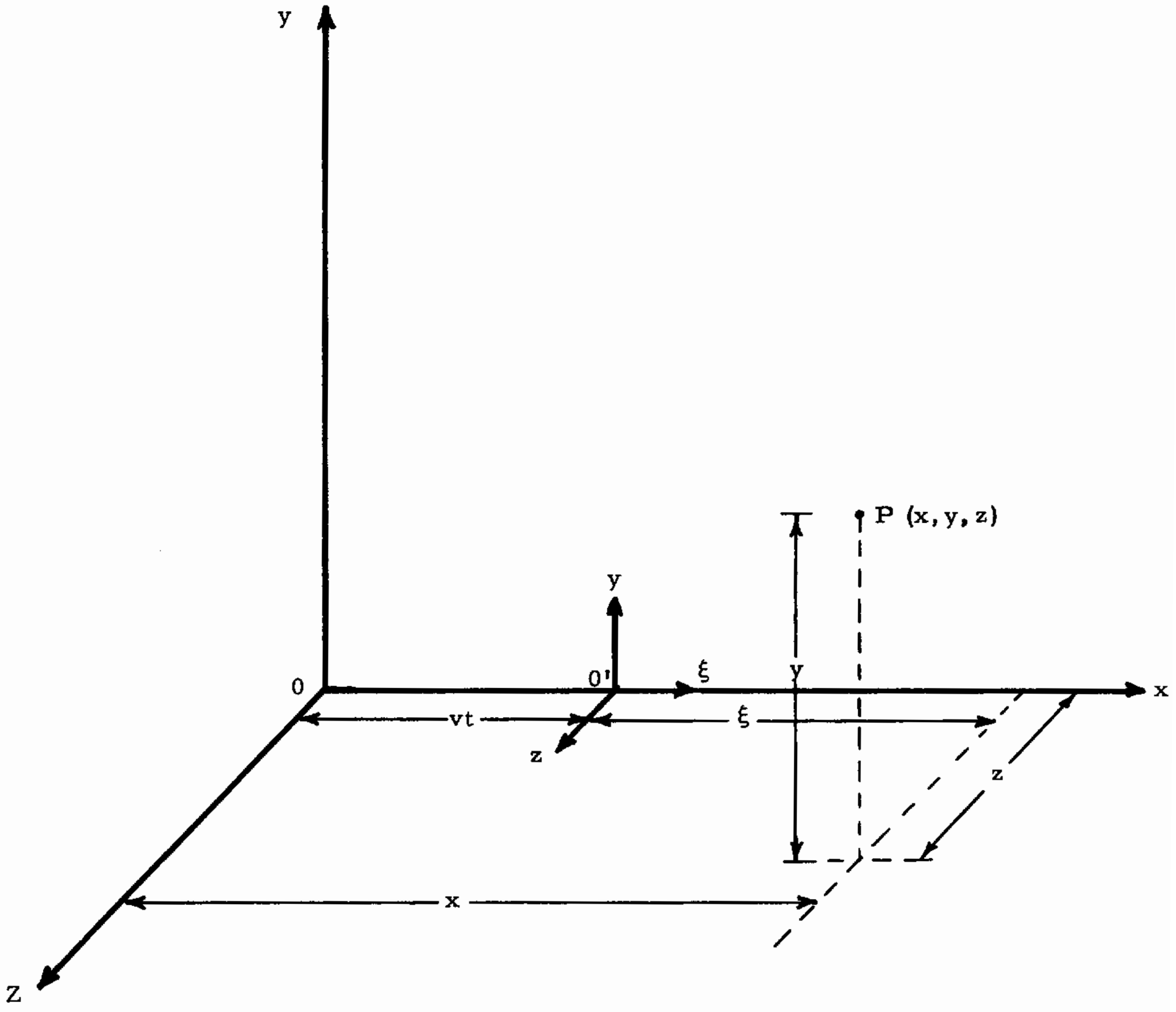


Figure 1. Stationary and Moving Coordinate Systems

The heat conduction equation for a system fixed in the (x, y, z) coordinate system is

$$a \left( \frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} \right) = \frac{\delta T}{\delta t} , \qquad (1)$$

where $\underline{a}$ is the diffusivity of the conducting medium, $\underline{T}$ is temperature and $\underline{t}$ is time. Now if the material is considered fixed in the (x, y, z) system and the heat source fixed in the ($\xi$, y, z) system, the condition of a moving heat source is realized. Thus, in (1) let $\xi = x - vt$.

Then

$$a \left( \frac{\delta^2 T}{\delta \xi^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} \right) = \frac{\delta T}{\delta t} - v \frac{\delta T}{\delta \xi} . \qquad (2)$$

Since the quasi steady-state for $\underline{T}$ exists in the ($\xi$ , y, z) coordinate system, $\frac{\delta T}{\delta t} = 0$ and (2) becomes

$$\frac{\delta^2 T}{\delta \xi^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} = - \frac{v}{a} \frac{\delta T}{\delta \xi} . \qquad (3)$$

It may be noted here that if the observer is fixed in (x, y, z), (3) indicates that a temperature variation with time will be observed through $\xi = x - vt$. On the other hand, if the observer moves with the source, $\underline{\xi}$ is seen as constant and no temperature variation with time is noted.

If it is assumed that $\underline{T}$ is of the form

$$T = T_i + e^{-\frac{v}{2a}\xi} G (\xi, y, z), \qquad (4)$$

where $\underline{T_i}$ is the initial temperature of the conducting medium and $\underline{G}$ is a function dependent only on the geometry of the medium, (3) becomes

$$\frac{\delta^2 G}{\delta \xi^2} + \frac{\delta^2 G}{\delta y^2} + \frac{\delta^2 G}{\delta z^2} = \left( \frac{v}{2a} \right)^2 G. \qquad (5)$$

To make (5) more useful for various geometries, the left hand side may be replaced by the generalized laplacian operator, where it is understood that the operator is to be used in the <u>moving</u> coordinate system. Thus

$$\nabla^2 G - \left( \frac{v}{2a} \right)^2 G = 0. \qquad (6)$$

## 3.0 Heat Flow in Thin Plate

In Figure (2a) is shown a moving line heat source extending infinitely along a z-axis through 0'. The output of heat per unit time interval and unit length is taken as a constant value q. The configuration is essentially two-dimensional since $\frac{\delta T}{\delta z} = 0$.

In the moving coordinate system, the only variation in G is with distance $r = (\xi^2 + y^2)^{1/2}$ because of symmetry in Equation 5 and the infinite extent of the material boundaries in x and y directions. The use of cylindrical polar coordinates (r, θ, z) is thereby suggested. In these coordinates and with r-variation only, (6) becomes

$$\frac{d^2G}{dr^2} + \frac{1}{r}\frac{dG}{dr} - \left(\frac{v}{2a}\right)^2 G = 0. \tag{7}$$

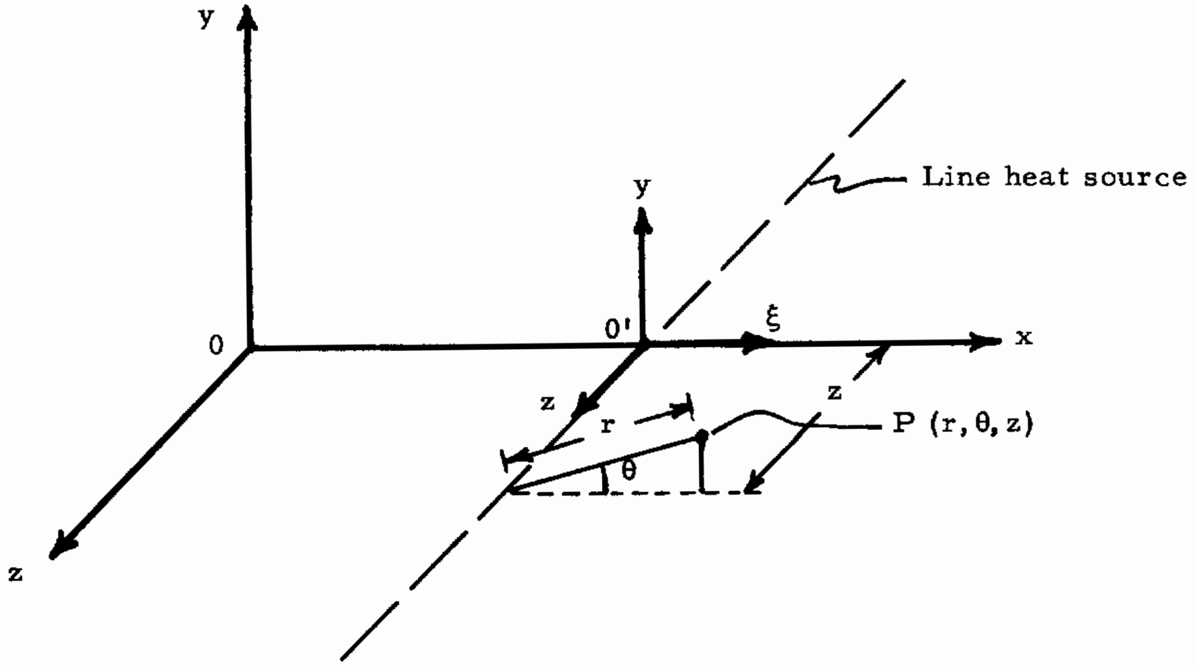
(7) is the modified Bessel equation.

The problem may be changed slightly to implement the solution of a practical geometry. Figure (2b) shows a thin plate of thickness s in the z-dimension, and extending infinitely in the x-y plane. Assuming s sufficiently small such that $\frac{\delta T}{\delta z} \simeq 0$, the line source becomes effectively a point source at 0' in the moving coordinate system. The problem is now the same two-dimensional problem as in Figure (2a), with the exception of heat losses from the surfaces of the thin plate. If the heat transfer coefficient from each surface is h, and the conductivity of the thin plate material is k, then it can be shown that the heat loss from the surface is given by $\frac{2h}{ks}(T-T_i)$.

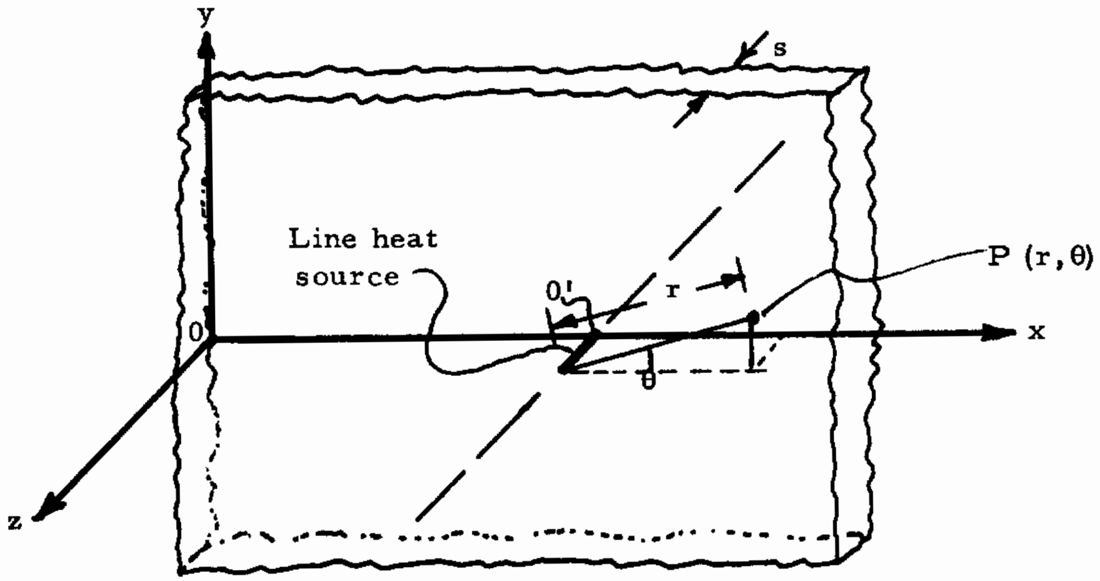
Equation (7) may then be written

$$\frac{d^2G}{dr^2} + \frac{1}{r}\frac{dG}{dr} - \left[\left(\frac{v}{2a}\right)^2 + \frac{2h}{ks}\right] G = 0 \tag{8}$$

for the thin plate with surface heat losses.



(a) Moving line heat source in conducting space



(b) Moving line heat source in thin plate

Figure 2. Line Heat Sources

This equation is of form identical with (7), and the solution is written

$$G = A\mathrm{Io}\ \{[(\frac{v}{2\alpha})^2 + \frac{2h}{ks}]^{1/2} r\} + B\mathrm{Ko}\{[(\frac{v}{2\alpha})^2 + \frac{2h}{ks}]^{1/2} r\}, \quad (9)$$

where Io and Ko are zero-order modified Bessel functions of the first and second kinds, respectively. Boundary conditions are

$$T - T_i \rightarrow 0, \text{ therefore } G \rightarrow 0 \text{ as } r \rightarrow \infty$$

and

$$-2\pi kr \frac{dG}{dr} = q \text{ at } r = 0.$$

Imposing the boundary conditions on (9) yields

$$G = \frac{q}{2\pi k} \mathrm{Ko}\ \{[(\frac{v}{2\alpha})^2 + \frac{2h}{ks}]^{1/2} r\} \quad (10)$$

and from (4)

$$T = T_i + e^{-\frac{v}{2\alpha}\xi} \frac{q}{2\pi k} \mathrm{Ko}\ \{[(\frac{v}{2\alpha})^2 + \frac{2h}{ks}]^{1/2} r\}. \quad (11)$$

From (11) it is seen that, as required, temperature undergoes no change with time if the observation point is moving with the source, because $\underline{\xi}$ and $\underline{r}$ do not then vary. On the other hand, at an observation point fixed in the $(x, y, z)$ coordinate system, $\underline{\xi}$ and $\underline{r}$ both vary with time, and thereby T as given in (11) varies.

A practical investigation of the parameters in equation (11) shows some simplification of the equation to be possible. The following test conditions are assumed:

Test material: aluminum, 1/16" thick;

Ambient temperature: $T_i = 27° C$;

Scanning speed: in excess of 0.5 cm/sec

Material heating: no more than 150°C. above ambient.

Under these conditions, the quantity $\frac{2h}{ks}$ in the argument of the modified Bessel function is about

$$\frac{2h}{ks} = 0.0057 \text{ cm}^{-2}.$$

On the other hand,

$$\left(\frac{v}{2\alpha}\right)^2 = 0.084.$$

Thus with velocities over 0.5 cm/sec, $\frac{2h}{ks}$ is less than $\left(\frac{v}{2\alpha}\right)^2$ by more than an order of magnitude, and (11) may be simplified to

$$T = T_i + e^{-\frac{v}{2\alpha}\xi} \frac{q}{2\pi k} K_o\left(\frac{v}{2\alpha} r\right). \qquad (11a)$$

The essential meaning of this is that surface convection losses under a wide range of test conditions may be neglected. All tests thus far performed in the program fall in this range.

## 4.0 Heat Flow in a Thick Plate

To consider a thick plate, another approach is required. Assume all of space in Figure 1 once again to be filled with a homogeneous conducting medium of conductivity k, and let a point source of constant thermal power input, Q be at 0' in the moving coordinate system. Now there is temperature variation in every direction. From symmetry of equation (5) and from the infinite material extent, G has spherical symmetry. With $r = (\xi^2 + y^2 + z^2)^{1/2}$ and r-variation only, (6) becomes

$$\frac{d^2G}{dr^2} + \frac{2}{r}\frac{dG}{dr} - \left(\frac{v}{2\alpha}\right)^2 G = 0. \tag{12}$$

Rewriting (12) in another form yields

$$\frac{d^2(rG)}{dr^2} - \left(\frac{v}{2\alpha}\right)^2 rG = 0, \tag{13}$$

for which the solution is

$$rG = Ce^{-\frac{v}{2\alpha}r} + De^{\frac{v}{2\alpha}r}. \tag{14}$$

By equation (4),

$$T = T_i + \frac{e^{-\frac{v}{2\alpha}\xi}}{r}\left(Ce^{-\frac{v}{2\alpha}r} + De^{\frac{v}{2\alpha}r}\right). \tag{15}$$

Boundary conditions are

$$T \rightarrow T_i \quad \text{or} \quad G \rightarrow 0 \quad \text{as } r \rightarrow \infty,$$

and

$$-4\pi k r^2 \frac{dG}{dr} = Q \text{ at } r = 0.$$

Imposing the boundary conditions on (15) gives

$$T = T_i + \frac{Q}{4\pi k} e^{-\frac{v}{2\alpha}\xi} \frac{e^{-\frac{vr}{2\alpha}}}{r}. \tag{16}$$

To consider the practical geometry of a thick plate with large transverse dimensions, assume that only the bottom half of the coordinate space in Figure 1 is filled. Then if the plate is thick enough that the effect of heating the top surface at y = 0 does not reach the bottom surface in the time of observation, the "half-space" geometry is representative of the thick plate. Percentage surface loss for a thick plate is less than that for a thin plate, because of its ability to conduct heat from the surface into the material more rapidly and to store more heat. Since it has been shown that surface losses from a thin plate may be disregarded under the test conditions contemplated, certainly they may be disregarded for the thick plate. Thus all that need be done to utilize (16) for the thick plate is to realize that only half as much heat is needed to raise the temperature of the material in the bottom half of the space as would be needed for the entire space. Therefore, the effective temperature rise for a given $Q$ is twice as great as that given in (16), and

$$T = T_i + \frac{Q}{2\pi k} e^{-\frac{v}{2\alpha}\xi} \frac{e^{-\frac{vr}{2\alpha}}}{r} \qquad (17)$$

for the "half-space" approximation of the thick plate. Again note that, in the moving coordinate system, $\xi$ and $r$ do not vary with time and the temperature is not dependent upon time.

## 5.0 Significance of the Analysis

Equations (11a) and (17) are analytic expressions for scan-heated flat plates at opposite extremes of material thickness. In each case, the expression derived indicated that, for plates of uniform thickness with homogeneous material throughout, the process of scan-heating brings about a constant surface temperature as seen by any detector moving with the scan-heater. Ideally, any variation in temperature measured by the detector indicates an inhomogeneity of some kind or a change in thickness of the test material plate.

Some remarks on the physical significance of the equations are pertinent at this point.

Equation (11a) is applicable only in the case of thin plates. The basic assumption in the development of (11a) is that there are no temperature variations with depth into the plate (for a uniform plate). This is a reasonable approximation for plates thin enough that the thermal transient from heating has passed completely through the plate before the surface temperature is measured. It is therefore quite clear that $r$ in (11a) indicates only transverse distance (some direction along the surface) from the heat spot. In (17), derived with spherical symmetry in *G*, *r* could indicate distance in any direction in the material (even normal to the surface) from the heat spot. However, since only the surface temperatures can be remotely evaluated, it is appropriate to consider *r* in (17) as also meaning only transverse distance on the surface from the heat spot.

In (11a), *q* represents thermal power (time rate of energy) input per unit plate thickness. Hence in a test system with a heating unit of fixed power output, *q* decreases with increasing plate thickness. On the other hand, *Q* in (17) is the total power input at the heat spot on the thick plate, and does not vary with thickness. This is necessary, because (17) represents plates sufficiently thick that the back surface (the unheated surface) has not yet affected the flow of heat at the time of temperature measurement. Hence, all plates for which (17) is applicable appear infinitely thick to the heater-detector array, even though they are not. To sum up, *q* and *Q* must be interpreted differently in the two equations for surface temperature.

The "form factors" of the two expressions for surface temperature, i. e. those parts of (11a) and (17) which show the *manner* in which the temperature varies over the surface (as opposed to the magnitude of heating) are shown below:

(11a) form factor: $e^{-\frac{v}{2\alpha}\xi} K_o\left(\frac{v}{2\alpha} r\right)$;

(17) form factor: $e^{-\frac{v}{2\alpha}\xi} \dfrac{e^{-\frac{v}{2\alpha} r}}{r}$ .

These form factors are quite similar, and give close correlation in the thermal patterns for thin plates and thick plates. The extent of similarity between the thin plate and thick plate expressions may be seen in Figure 3. Here the calculated temperature variations along the scan path for a thick plate (1/2" or thicker) and a thin plate (1/16") are shown graphed together. The following hypothetical test conditions are assumed:

Test material: aluminum;

Ambient temperature: 27° C;

Scanning speed: 2 cm/sec;

Heat input: 25 watts
Therefore in (11a): $q = 157$ watts/cm
(17): $\mathcal{Q} = 25$ watts;

Thickness: 1/16" and 1/2" or thicker.

The similarity in curve shapes on Figure 3 suggests that the pattern (not the magnitude) of heating changes very little as test material thickness varies. This is a desirable system characteristic, as it allows the testing of plates of widely varying thicknesses with the same heater-detector configuration.

An inspection of equations (11a) and (17) shows several dependencies upon the test material and its parameters. The following symbols from these equations all have some relation to the parameters of the material:

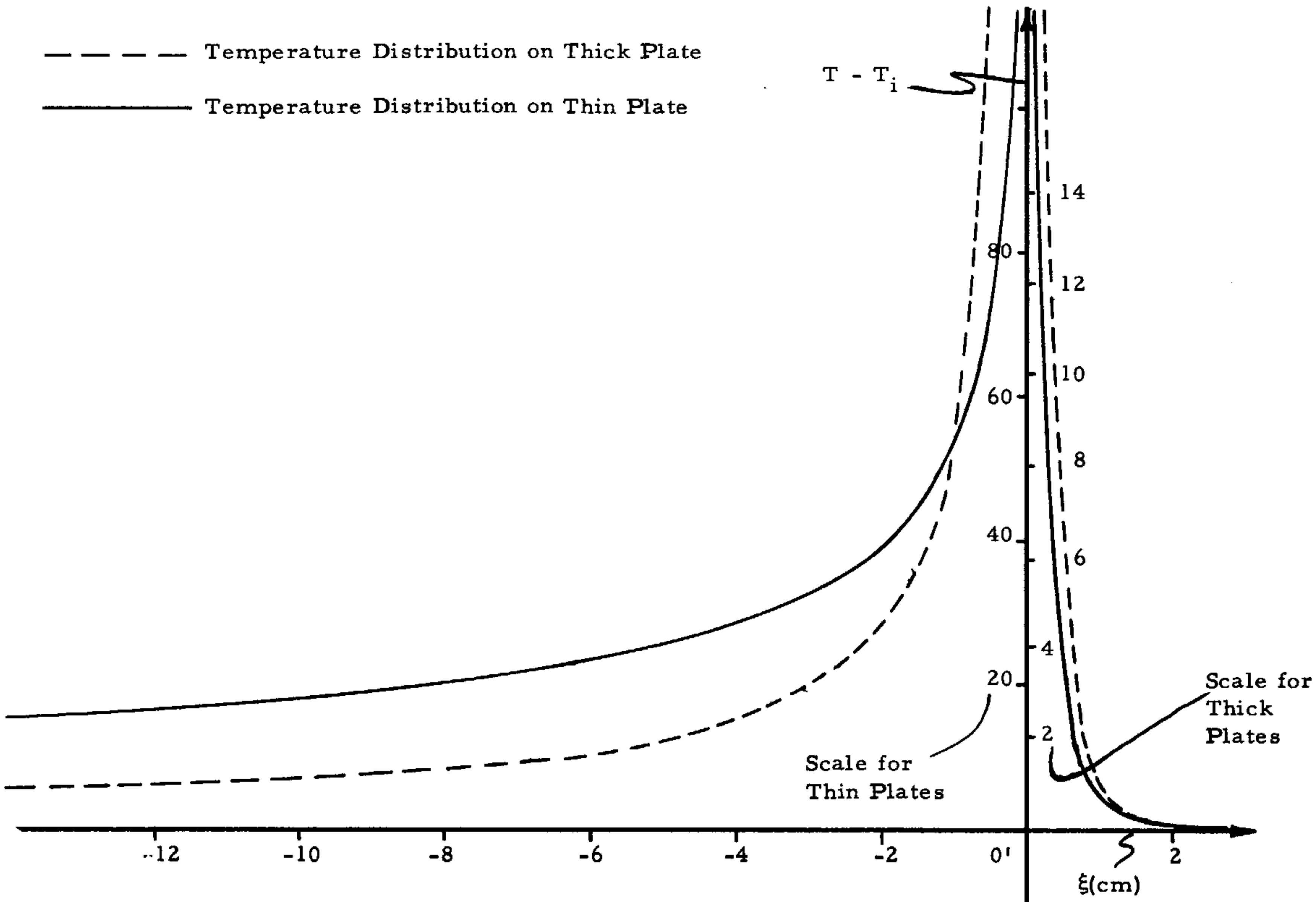


Figure 3. Temperature in °C above ambient along scan path. Moving Heat Source is at 0'.

q [ in (11a)] : input thermal power per unit plate thickness;

k: thermal conductivity;

$\alpha$: thermal diffusivity ( $\alpha = \frac{k}{\rho c}$ , where $\underline{\rho}$ is material density and $\underline{c}$ is specific heat capacity).

First it is seen that the surface temperature measured in a thermal test is dependent on plate thickness. Such parameters as voids, lack of bond, variation in coating thickness, surface waviness, etc., can affect the real or apparent test plate thickness.

A dependence also exists upon thermal conductivity, $\underline{k}$. Some conditions affecting thermal conductivity could be material voids, cracks, corrosion, lattice structure defects, impurities, porosity, inclusion, and alloy. Thermal testing could possibly determine variations in electrical conductivity, since it is directly related to thermal conductivity. However, electrical conductivity is a quantity rather easily measured directly.

A direct dependence of thermal diffusivity $\underline{\alpha}$ on density $\underline{\rho}$ is noted. It appears that density variation could be found by thermal testing. Similar arguments to those above could be applied to specific heat capacity and the effect of material parameters on its value. Certainly voids and cracks change the effective heat capacity of a test plate.

In conclusion, it appears that many internal material parameters will have some obvious effect on the surface temperature of a scan-heated test plate. This group is equally certain that other material conditions and properties can be examined by thermal testing. The next major effort on the program will be a renewal of theoretical investigation, in conjunction with an expanded consultant staff, to attempt to determine the material characteristics most likely to be evaluated in future efforts. Metallurgical and mechanical properties are objects of major interest in the upcoming theoretical investigation.

## IV. INSTRUMENTATION AND TESTING

### 1.0 Test Procedure and Overall System Description

### 1.1 Description of the Test

The scan-heating and detecting test includes three basic operations:

A. Scan-heating one entire surface of a test plate with a series of constant velocity straight-line scans, setting up the quasi-steady state temperature condition on each linear scan of the heater;

B. Slaving the focus of a remote temperature sensor to the heater's linear scans at a fixed separation from the heater, to detect any variation in the quasi-steady state which would indicate material anomolies;

C. Recording of the continuous temperature measurement as seen by the sensor, with information regarding the position on the material surface, for the purpose of material testing.

### 1.2 Thermal Test System

The actual prototype testing system is shown in Figure 4 with an explanatory diagram in Figure 5.

The test material, as identified in Figure 5, is placed in a horizontal plane on a platform, with heater and detector equipment mounted above the material. The scanning is accomplished by holding the heater and detector in fixed positions and moving the platform on which the test material rests.

The test samples fabricated to date have been 4" x 6" rectangular plates of varying thicknesses. To scan an entire test plate surface a series of straight-line scans are made parallel to the long edge of the rectangle. Each scan is displaced from the previous one by a

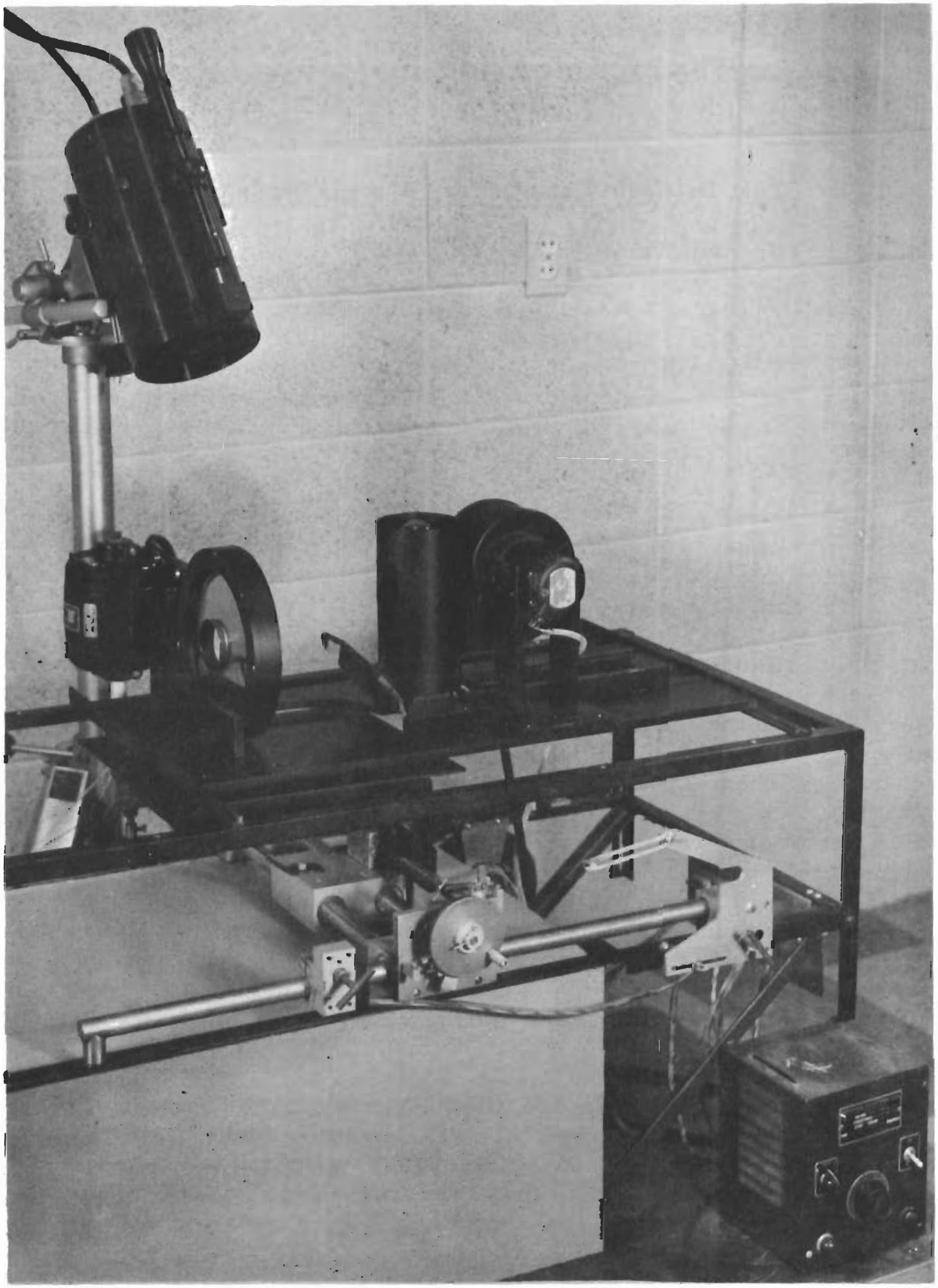


Figure 4. Prototype Thermal Testing System

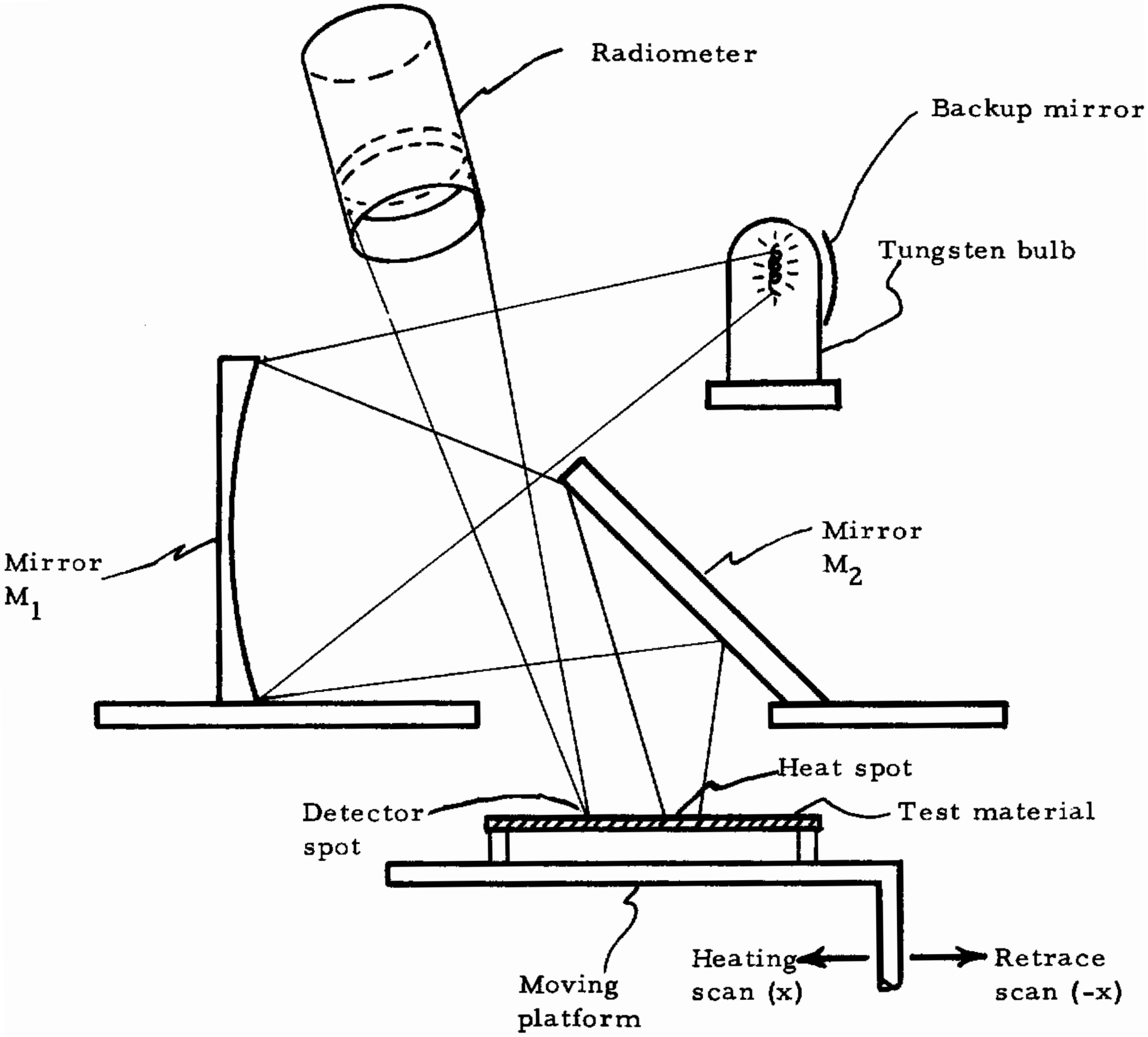


Figure 5. Diagram of Prototype Thermal Testing System

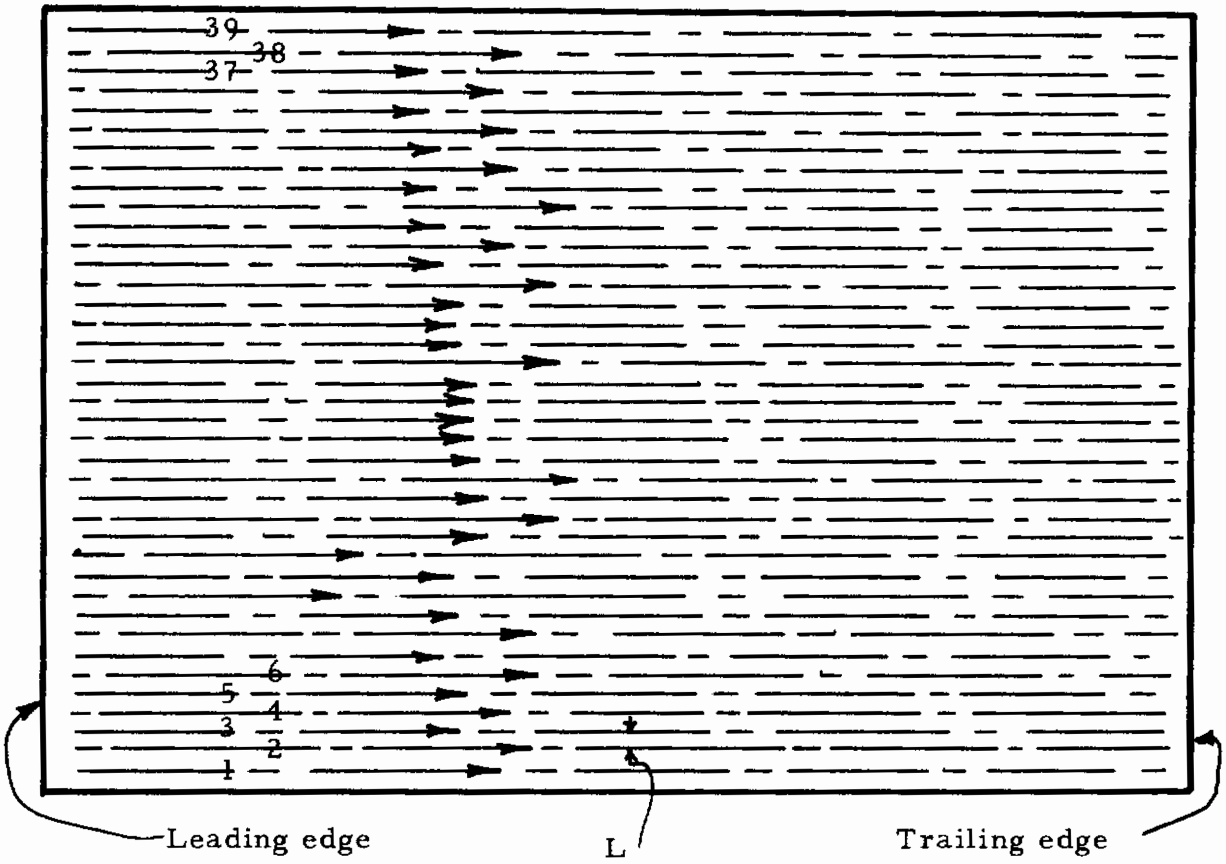
distance adjustable within the 0.05" to 0.2" range. Heating scans are always made with the test sample moving the same direction. To reposition the plate after each heating scan, the scan path is retraced with the heater off. After the retrace, a ratchet wheel moves the sample a preset distance parallel to the short edge of the rectangle; then the heater is turned on and another heating scan parallel to the long edge is initiated. Figure 6 shows a diagram of a complete scan pattern of a test plate. Dimensions x and y are shown in the horizontal plane of the test plate for future reference.

## 2.0 Heating

The radiant heating assembly is pictured in Figure 4 and diagrammed in Figure 5.

Radiation from a tungsten filament is gathered and focused by concave front-surface mirror $M_1$ (reference to Figure 5), and reflected to the test material by plane front-surface mirror $M_2$. The optical system is off-axis to prevent blocking of the effective aperture by $M_2$. (The effective system aperture is the outline of $M_1$ as seen from the radiant source.) The resulting aberration is small and unimportant for this particular application. The image of the tungsten filament on the material surface forms the "heat spot" referred to previously. In size, this heat spot is magnified by a factor of about 1.2 by the optics. In addition, aberration distorts the image shape, lengthening it slightly in the scanning direction (the x-direction in Figure 6).

The heating source used is a tungsten filament in a 1000-watt Sylvania DFD projection lamp with a color temperature of approximately 3325°K. The filament array is about 0.4" x 0.4" in dimensions. With a backup mirror to fill in the open portions (spaces between filament wires), a fairly uniform square of radiation is obtained from this filament. With the magnification and aberration introduced by the optics, the imaged "heat spot" has dimensions of approximately 0.4" x 0.5".



Test plate - 4" x 6"
Scan separation - L = 0.1"
(L adjustable between 0.01" and 0.2")
Scans numbered in time sequence.
Direction of scans shown by arrows;
retrace is in opposite direction.

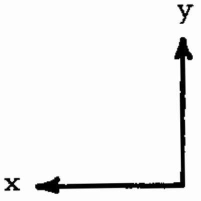


Figure 6. Complete Scan Pattern of Test Plate

With optical surface losses, filtering by the projection lamp envelope, aberration losses, and percentage capture by the optics, an estimated 5% of the power output, or 50 watts is available at the heat spot for material heating. With the heat spot area of 0.2 square inches, a power intensity of approximately 240 watts/square inch is present at the test material surface. At this time it appears desirable to have a higher power intensity at the heat spot, perhaps by a factor of from 4 to 10. This would enable faster scan speeds and, probably, detection of more subtle material variations.

## 3.0 Temperature Measurement

To make the remote temperature evaluation of the heated test material a variable-focus infrared radiometer is employed. This instrument, the Radiation Electronics Company Thermodot TD-5, has Cassegrain collecting optics and employs a photoconductive indium antimonide detector operating at liquid nitrogen temperature.

In test operation, an indium arsenide filter is used in front of the detector to prevent visible reflected radiation fron affecting the temperature measurement. The focus is set at 18" (the closest possible focus), to obtain the smallest possible detector spot (projection of the detector element on the test material).

Full specifications covering the radiometer and the detector element are tabulated below:

### Radiometer Specifications

Operating temperature range: 60° to 3000°F

Chopping rate: 2000 cps

System time constants: 1000, 100, 10, 1 millisecond, and 40 db/octave lowpass 1 KC filter.

Resolution: 5 x 5 milliradians

Focus: 18" to 60" and 4 ft. to infinity

Detector: PC-02 (0.5 x 0.6 mm) cooled InSb

Detector operating temperature: -195°C

Detector D* (500, 500, 1): $1.7 \times 10^{9}$ $w^{-1}$-cm - $cps^{1/2}$

Detector NEI (500, 500, 1): $1.1 \times 10^{-8}$ w-$cm^{-2}$

System NEI (500, 500, 1): $1.5 \times 10^{-12}$ w-$cm^{-2}$

System NET (300°K): 0.05°C

Temperature offset control

Filters available as needed

InSb Infrared Detector Data

| | |
|---|---|
| Type............................ | Photoconductive |
| Model .......................... | PC-02 |
| Serial No....................... | 51 |
| Window ......................... | Sapphire |
| Sensitive Area .................. | 0.5 mm x 0.6mm |
| Operating Temperature............ | -195°C |

| | |
|---|---|
| Resistance...................... | 25 ohms |
| Dynamic Impedance............... | ----- ohms |
| Optimum Bias.................... | 20 ma |
| NEI (Noise Equivalent Input) (500°K, 500, 1)‡................ | $1.1 \times 10^{-8}$ watts/cm$^2$ |
| NEP(Noise Equivalent Power) (500°K, 500, 1)‡................ | $3.3 \times 10^{-11}$ watts |
| NEI (5μ, 500, 1)‡................. | $2.8 \times 10^{-9}$ watts/cm$^2$ |
| Responsitivity at Optimum Bias, 500 cps Operation................. | 0.14 v/w/cm$^2$ |
| D* (Detectivity) (500°K, 500, 1)‡... | $1.7 \times 10^{9}$ cm/watt |
| Spectral Response................ | Quantum |
| Spectral Cutoff (50% down)......... | 6.1 microns |
| Time Constant.................... | Less than 1μsec |

‡500 CPS Chopping frequency, 1 CPS bandpass

At 18" focus, the detector spot on the test material is 0.15" x 0.18" in dimensions. It would be desirable to decrease these dimensions, in order to obtain smaller resolution of transverse dimensions of temperature pattern anomolies. Advance plans are to have a deeper Cassegrain optical system fabricated, with a fixed-focus ellipsoidal primary mirror. This system should focus the image of the detector element at about 8" and give a detector spot size around 0.07" x 0.08". The smaller detector spot should result in greater resolution of transverse dimensions of material variations.

## 4.0 Mechanical Scanning

To implement the test scan, the horizontal test material platform is driven in two degrees of freedom (the x- and y- directions shown in Figure 6) in a horizontal plane beneath the heating and temperature measurement equipment. The photograph in Figure 4 shows the platform and related equipment below the superstructure holding the heating system. The mechanism holding the platform is bearing-mounted on guide rails on either side of the test bench, and the entire scanning mechanism slides along these rails to give the heating and retrace scan motion, in the positive or negative x- direction as shown in Figures 5 and 6. This motion is powered by a d-c motor which is pinion geared to a rack on the back side of the test bench. To vary heater scan and retrace scan speeds separately, a system of speed control is used on the d-c motor. Limit switches reverse the direction of scanning at the ends of the scans.

After each heater scan, the mechanism automatically retraces that scan path with the heater extinguished. Then the ratchet wheel turns a lead screw which moves the test platform in the y-direction (as indicated in Figure 6) a fixed distance between 0.05" and 0.2". The turning of the ratchet wheel is powered by the last small portion of retrace scan motion. The platform is then ready for another heater scan.

## 5.0 Readout and Display

The temperature-sensing infrared radiometer has a signal voltage output proportional (to a good approximation) to the temperature variations at the detector spot on the test material. For this program, the radiometer signal has been displayed on the screen of a cathode-ray oscilloscope. External horizontal deflection of the oscilloscope is used, with a battery and datapot combination providing information on the x-coordinate of position of the detector spot on the test material surface.

The vertical deflection is obtained from the radiometer signal. Thus a plot of surface temperature versus position along the scan path is obtained. A Polaroid camera focused on the scope screen yields permanent records of the scans. If it is desired to record all the scans covering a test block surface on one photograph, the position of the image of the scan pattern on the photograph is altered slightly for each scan. The result is a photograph showing all scans, lined in proper sequence across the plate (in the y- direction), with temperature information as usual obtained from each scan pattern shape.

A C - scan presentation of the sample tests is still in preparation. A memory tube will be employed, with the two dimensions on the screen representing the two dimensions of the test material surface. Datapots on the scanning mechanism of the test system will provide the horizontal and vertical deflections to position the spot trace continuously. The spot will be intensity modulated by the radiometer signal. Thus a two dimensional representation of the test material surface will be present on the memory tube screen; the intensity of illumination will be proportional to temperature as seen during the scan-heating operation at each point scanned on the test material surface.

Automation Industries, Incorporated has a recording instrument with a memory tube display. Scheduling difficulties have rendered impossible its procurement for this program in time for C-scan results to be included in this report. C-scan records of material sample tests are forthcoming in the initial report of the next year's work.

## 6.0 Test Parameters

### 6.1 Heat Spot Size

It was originally believed that the smallest possible heat spot size for any given wattage of heating power would be a desirable objective. However the results of testing for actual material variations have shown three criteria for heat spot size:

Heat Spot Size should be:

A. Large compared to detector spot size,

B. Large in dimensions compared to test material thickness,

C. Small compared to overall plate dimensions.

It is not easy to justify conditions A and B. Condition C is to be expected. A short discussion of these conditions follows.

Regarding A, it is suspected that having a large heat spot compared to detector spot size causes the heat near the center of the heat spot to flow mostly normal to the material surface. Transverse flow is limited. With the smaller detector spot placed in this center location, the temperature pattern as seen by the radiometer is related in large measure to conditions within the material, rather than being affected by any appreciable transverse heat flow. Increased contrast in temperature pattern should result between homogeneous and non-homogeneous internal material conditions.

Criterion B can probably be argued in much the same way. If the material is thin in comparison to heat spot dimensions, then heat flow through the entire plate thickness should be largely normal to the surface near the center of the heat spot.

Criterion C is a result of the scan-heating and detecting method itself. If the heat spot nearly covers the plate, the process of scanning to obtain transient heating with respect to the material and a quasi-steady state in temperature as seen by the sensor, is never accomplished. The overall plate heating achieved by this overly large heat spot tends to cause a "washout" or fading of the temperature pattern seen on the surface of the test material.

In conclusion, it appears that there is an optimum heat spot size for given material test plate thickness and overall dimensions, and a given detector spot size. For the plates tested in this program, with dimensions 4" x 6" and thicknesses from 0.010" to 0.375", and for the presently available detector spot size of 0.15" x 0.18", the optimum heat spot size seems to be about 0.4" x 0.4".

### 6.2 Detector Spot Size

Experimental work to date indicates that the best thermal tests are obtained with the smallest possible detector spot size. Present instrumentation allows a minimum detector spot size of 0.15" x 0.18". Plans for future incorporation of a fixed close-focus deep Cassegrain optical system on the radiometer have been discussed earlier in the report. This will reduce detector spot size by a factor of about 2. Further reduction may be effected by obtaining a smaller detector element for the radiometer.

### 6.3 Heater-Detector Spot Separation

In the thermal test method as applied in this program, the heat spot and detector spot are aligned in tandem on the scan path in the direction of a heating scan. As originally conceived, the detector spot trails the heat spot, i.e., the test material sample passes first beneath the heat spot and then beneath the the detector spot during a heating scan. The optimum separation between heat spot and detector spot would be the distance at which, for a given sample material and thickness, the greatest percentage change in surface temperature occurs from homogeneous to non-homogeneous material.

To examine the entire thickness of a test plate for inhomogenieties, it is necessary to delay the continuous temperature measurement from the continuous scan heating by at least the amount of time required for heat to travel from the heated front surface to the back surface. After this time delay any inhomogeniety within the material which affects heat transfer should have had an effect on the surface temperature above the inhomogeneity. The purpose of the heater-detector spot separation is to provide this time delay necessary to allow the heat to diffuse through the material before a temperature measurement is made.

The times required for heat transfer through the thin metallic plates tested in this program range from thousandths to tenths of a second. With a typical scan speed of 1 inch per second, the physical separation required to obtain such a separation in time as 1/10 second or less between heating and detecting is almost negligible. The best test results to date have been obtained with heat and detector spots essentially superimposed, that is, with the heater optics and the radiometer optics focusing at the same point on the material (within 0.1").

The fact that heater and detector spots are areas rather than mathematical points tends to eliminate the need for fine heater-detector separation adjustments.

It would appear, then, that heater-detector separation is not a limiting problem in the thermal test procedure. However, conditions of material sample in future tests could make the spot separation a problem. Two conditions which would almost certainly increase the necessary separation by increasing the heat transfer time are

A. Lower thermal conductivity,

B. Appreciably thicker test samples.

### 6.4 Scan Speed

Scan speed is governed by two opposing factors in the thermal test. The test sample must be scanned slowly enough by the heater so that the material is heated sufficiently to show inhomogeneities clearly above system noise.

On the other hand, the scan speed must be fast enough that excessive "spreading" or transverse heat flow does not occur and cause the temperature pattern to show the voids much larger in transverse dimensions than they are.

The experimental results show that the spreading effect mentioned above does exist, even with optimized test parameters, with the present system. However, if the scan speed is increased to alleviate this problem, insufficient material heating results. It appears, from this and other considerations, that a more powerful heating unit is needed to improve system performance. With it, faster scans should be possible, resulting in less spreading.

At present, optimum scan speed has been found to decrease with increasing test material thickness and to increase with increasing thermal conductivity. Optimum scan speeds found empirically show only these trends, and nothing very accurate can yet be said for prediction of optimum scan speeds for given material configurations. Figure 7 shows empirically determined scan speeds versus material thickness for aluminum samples.

### 6.5 Uniformity of Heat Spot

The accuracy with which material inhomogeneities are located has been found by actual thermal testing to be dependent on the uniformity of heat spot intensity. The heat spot uniformity is in turn determined by the uniformity of intensity of the heat source's tungsten filament array.

Several tungsten filament lamps were investigated for usefulness in optically forming a heat spot. Most had a rather non-uniform intensity over the filament array. The lamp presently being used (a Sylvania DFD projection lamp described earlier in the report) presents a fairly uniform filament intensity if a backup mirror is used (see Figure 5).

The resulting heat spot, which is the image of the filament array projected through the heater optics onto the test material, is also satisfactorily uniform.

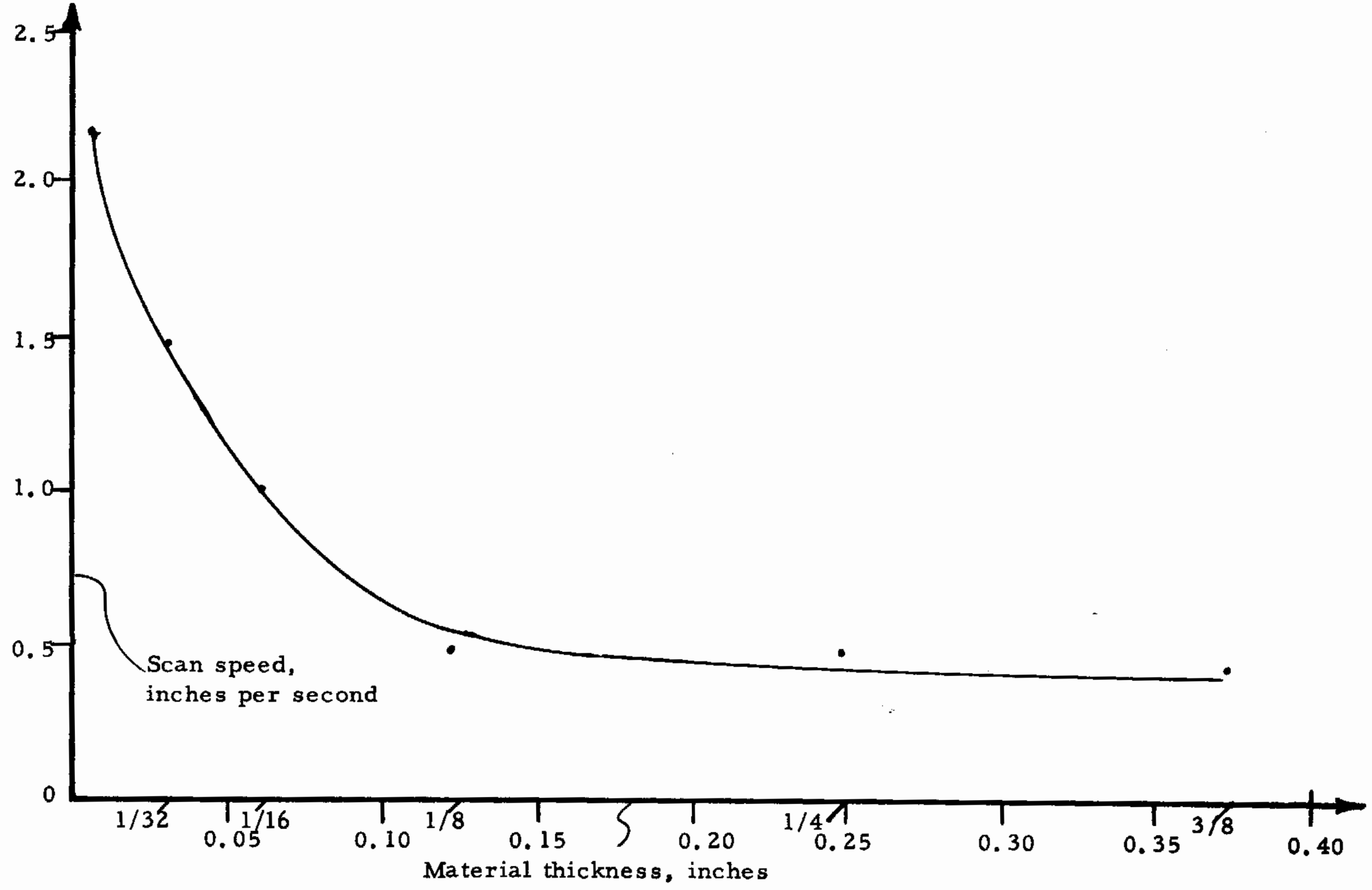


Figure 7. Experimentally Determined Optimum Scan Speed Versus Material Thickness in Aluminum Test Plates

## 6.6 Heat Spot Intensity

Heating intensity has been mentioned above as a possible weak link in the thermal testing system. The present power intensity at the material surface in the heat spot is approximately 240 watts/square inch. An increase in intensity of from 4 to 10 times could result in three important areas of improvement:

A. Faster scan speeds,

B. Finer resolution of transverse dimensions of material variations,

C. Detection of material variations with smaller overall dimensions, or of subtler variations.

A hot-air heating system was attempted at one point, with very promising results. More power intensity apparently can be delivered to the heat spot in this fashion than with a focused tungsten filament. However the system was noisy and inadequate for a thermal test at that time. Components for an improved hot-air heater system are on order. It is probable that hot-air heating, if employed properly, will afford a significant improvement in the heat spot intensity.

## 6.7 Condition of Test Material Surface

A flat metallic plate, such as those tested in this program, has an emissivity which in general varies over the surface. The emissivity of these plates is low,in the range 0.1 to 0.4. Emissivity may be considered a measure of the efficiency with which the material emits or absorbs electromagnetic energy (such as infrared or visible) at its surface. Specifically, the radiation from a surface is determined by emissivity and temperature according to the Stefan-Boltzmann law:

$$W = e \sigma T^4,$$

where

$W$ = radiant power per unit area,

$e$ = emissivity,

$\sigma$ = a universal constant,

$T$ = absolute temperature.

In general, the blacker a surface, the higher the emissivity. For two distinct reasons, emissivity of the test material surface is very significant to the thermal test as it is presently instrumented. These reasons will now be discussed.

Of the energy from the radiant heat source incident on the heat spot, the percentage which is absorbed by the material is directly proportional to emissivity. It is thus apparent that in order to have efficient and uniform heating of the test material surface, its emissivity must be high and uniform. In other words, the surface must be made uniformly black.

The second effect on the thermal test by emissivity is in the remote surface temperature measurement by the infrared radiometer. The radiometer measures the amount of radiation from the detector spot on the test material surface. For a constant surface temperature, as emissivity varies, the radiation from the surface varies. To obtain equal radiometer outputs for equal temperatures at various locations on the test material, emissivity must therefore be uniform over the plate. Otherwise a non-uniform emissivity introduces difficulty in interpretation of radiometer output data.

In this program, to obtain high and uniform emissivity on a test plate, a black coating is applied to the front (heated) surface. The coating, a fast drying paint with carbon black coloring, is sprayed on the material surface uniformly.

From the point of view of eventual practical thermal testing of large metallic and ceramic structures, it is desirable to eliminate the need for surface blackening. First, consider the problem of scan-heating an unblackened surface uniformly and efficiently. It is clear that a heat source is needed which transports its energy to the test material in some way other than by electromagnetic radiation. (In the case of this program, the radiation is from a tungsten filament.) Such a source is the hot-air heater discussed previously in this report. It is felt that the hot-air heater will operate satisfactorily on unblackened test plates, yielding uniform heating.

The next problem is the temperature pattern readout. The difficulty of remote temperature evaluation of a surface with varying emissivity (i.e., an unblackened test plate surface) is essentially a problem of identification. The variation in emissivity over the surface must be identified in some manner. Then the results of the scan-heating and detecting test may be altered to display only the variations in radiometer output due to surface temperature variation.

One method of determination of emissivity variations would be to scan the test plate with the detector assembly under a condition of no heating, and with the test plate at uniform temperature. In this scan, radiometer output variations would necessarily be caused by emissivity variation, as the temperature is uniform over the plate. The information on emissivity variation would be combined with the record of the continuous radiometer output during a heating scan. The combination would then be expected to yield information regarding only temperature variations.

Another approach for obtaining emissivity information might be to evaluate temperature at two detector spots during each heat scan. One detector spot, far ahead of the heat spot, would yield information on emissivity, since the plate along the scan is essentially uniform in temperature ahead of the heat spot. The other detector spot would be in the conventional position for a scan test. The signals arising from the two detector spots could then be combined and processed in such a way that emissivity effects are eliminated in a final signal for display of the temperature pattern during a heating scan.

The average magnitude of the emissivity on an unblackened metallic surface is much lower than that of a well blackened surface. The decrease in emissivity by not blackening is normally a factor of from 2 to 10. In measuring the temperatures over the unblackened surface, then, the radiometer will suffer a loss of sensitivity. In essence, minimum temperature variation detectable with a given detector is not as small when the radiometer is focused on a low emissivity (unblackened) surface as when it sees a high emissivity (blackened) surface. To combat this loss of sensitivity, a detector more sensitive in the range near room temperature may be obtained.

## 7.0 Test Results

### 7.1 General Remarks

Results of the thermal tests on test plates with fabricated voids, area of unbond, or metallic inclusion are compiled in this section. For each test plate, an explanatory diagram is shown. Useful information on the diagram includes:

A. Plate material and dimensions,

B. Position, type, and size of fabricated inhomogeneities,

C. Scan speed,

D. Location and direction of key heating scans.

The arrow on each key heating scan indicates the direction of motion of the heater-detector array relative to the test material. The actual scan motion is achieved by the test material moving in the opposite direction.

Continuous temperature measurements taken during the key scans are shown in photographs of oscilloscope traces representing the radiometer output signal. In each photographic record, the ordinate is proportional to plate surface temperature at the detector spot, and the abscissa represents position of the detector spot along the scan path. The sharp rise 3 centimeters left of the center of the trace indicates the leading edge of the plate, which is heated and detected first in the scan. The trailing edge is shown as a sharp drop off 3 centimeters to the right of center. In the 6 centimeter trace (representing the 6-inch scan path on the test sample), any changes in ordinate ideally represent a material inhomogeneity beneath the detector spot. Edge effects, imperfect surface blackening, and non-optimized test parameters also show as ordinate variations. If the ordinate change is caused by an inhomogeneity in the test sample, the amplitude of change indicates the inhomogeneity's normal extent (for instance the depth of a void in the back of a test plate). Transverse extent of the inhomogeneity (in x- or y- direction) is indicated by the duration of the amplitude change. The transverse extent is enlarged somewhat on present test results, because of heat spreading and finite detector spot size.

For two reasons, the majority of test plates are aluminum or steel. Primarily, these metals differ widely in thermal properties, particularly thermal conductivity. In addition, each is an important structural material. Very little difference was found between results with the two materials.

It should be noted here that some of the test recordings shown were made early in the testing program, some later. Generally, those recordings of voids 10% of material thickness or less in depth, plus the unbonding and inclusion tests, were made late in the program and show present system capabilities. No attempt has been made to include all data taken in the course of the investigation. The purpose in this section on test results is to show representative results to adequately describe the capabilities of the test method and system.

### 7.2 Test Plates with Voids

Figures 8 through 22 pertain to test plates with voids machined in the back (unscanned) surface. Test materials are copper, aluminum, steel, and brass. Plate thicknesses vary from 0.010" to 0.375" and void depths range upward from 3% of plate thickness. In this series of figures, the following significant factors in the scan-heating and detecting thermal test method are shown:

A. Effect of void depth,

B. Effect of transverse dimensions of a void,

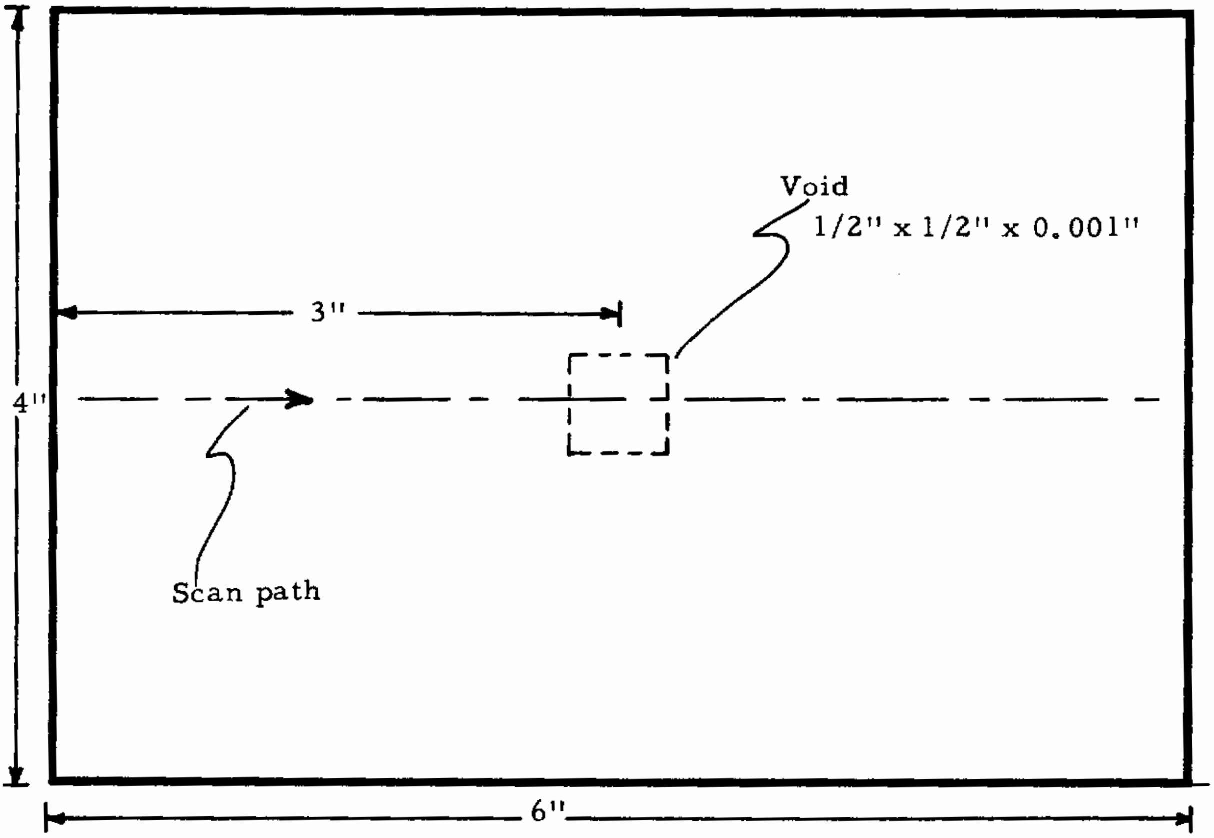
C. Edge effects,

D. Effect of scan-speed variation.

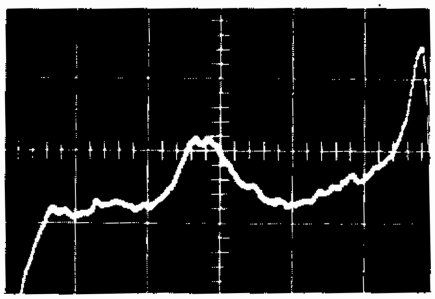
Most of the tests show a fairly level oscilloscope trace over homogeneous material, illustrating the quasi-steady state temperature condition discussed in Section III. Edge effects, surface blackening (emissivity) irregularities, and other causes of variations in the trace level are discussed for particular tests.

## Discussion of Figure 8

This figure illustrates the scan test of a sheet of 0.010" copper with a 0.001" void machined in the unscanned surface. The signal from the void is clearly distinguishable. The temperature rise on the trailing edge (the right hand edge) of the scan path is due to accumulation of heat which cannot flow to the right when the "temperature pattern" readies the right hand edge. Most test plates show much less of this "trailing edge effect" than does this plate. This is believed due to the fact that this test plate is much thinner than others used, and the majority of the heat flow is transverse, of necessity. A smaller heat spot diameter with equal intensity (i.e., less total thermal energy input) might be of benefit in eliminating trailing edge effect.



Copper - 0.010" thick
Scan speed - 2.2 inches per second

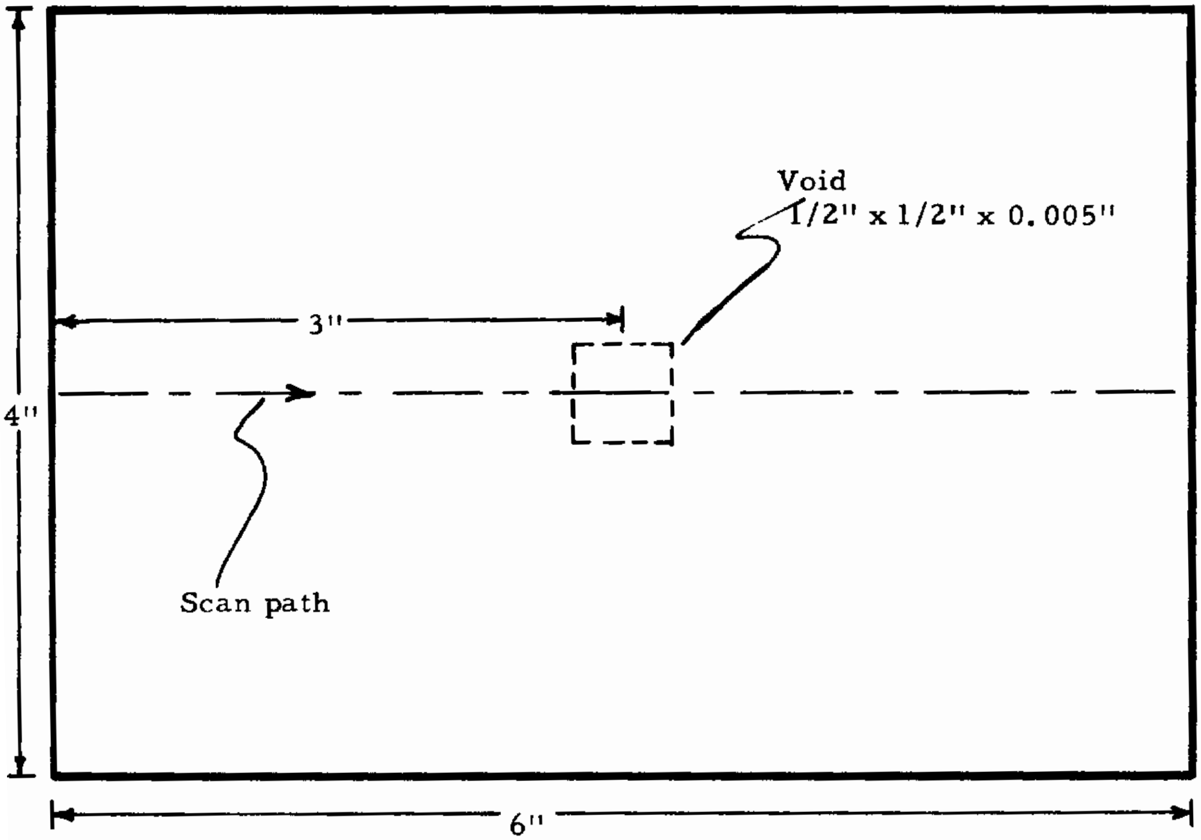


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 2.7°C

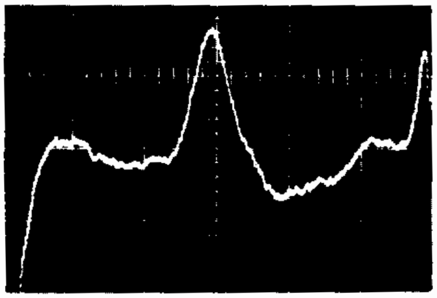
Figure 8. Copper Plate 0.010" Thick With Void

## Discussion of Figure 9

Figure 9 shows the scan test of an aluminum test plate 0.020" thick. The dc level, corresponding to the quasi-steady state condition, is of poor quality in this recording. It is suspected that there are internal inhomogeneities which were unknown at the time of fabrication of the test plate. Destructive examination may later reveal these inhomogeneities.



Aluminum - 0.020" thick
Scan speed - 1.8 inches per second



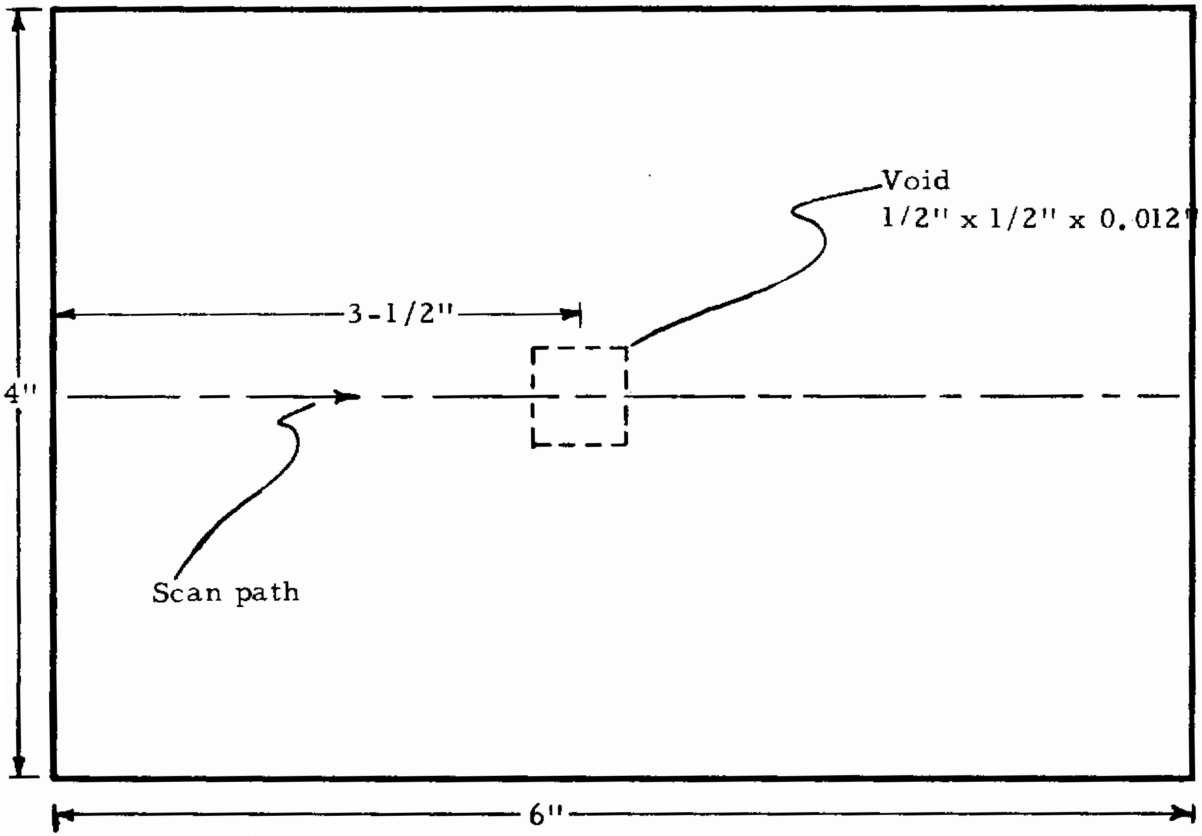
Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 3.0°C

Figure 9. Aluminum Plate 0.020" Thick With Void

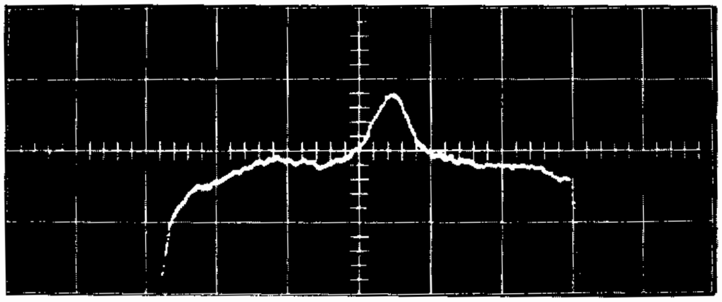
## Discussion of Figure 10

Figure 10 describes the testing of a 1/32" steel test plate. Comparison with tests of aluminum plates of equal thickness shows the scan speed on the steel plate to be relatively slow. It is reasonable to assume that this would be true, in view of steel's much lower diffusivity compared to that of aluminum.

This test was made early in the testing program, and shows the detection of a rather gross void. Because of limitations on time, no later tests were performed on steel plates with shallower voids. (Figure 13. shows the only other test run on a steel test sample; it also contains a rather deep void). However, at the time this test was run, the results with steel plates compared favorably with those of aluminum. Thus, there is reason to believe that void detection in steel comparable to that in aluminum is feasible.



Steel - 1/32" thick
Scan speed - 0.9 inch per second



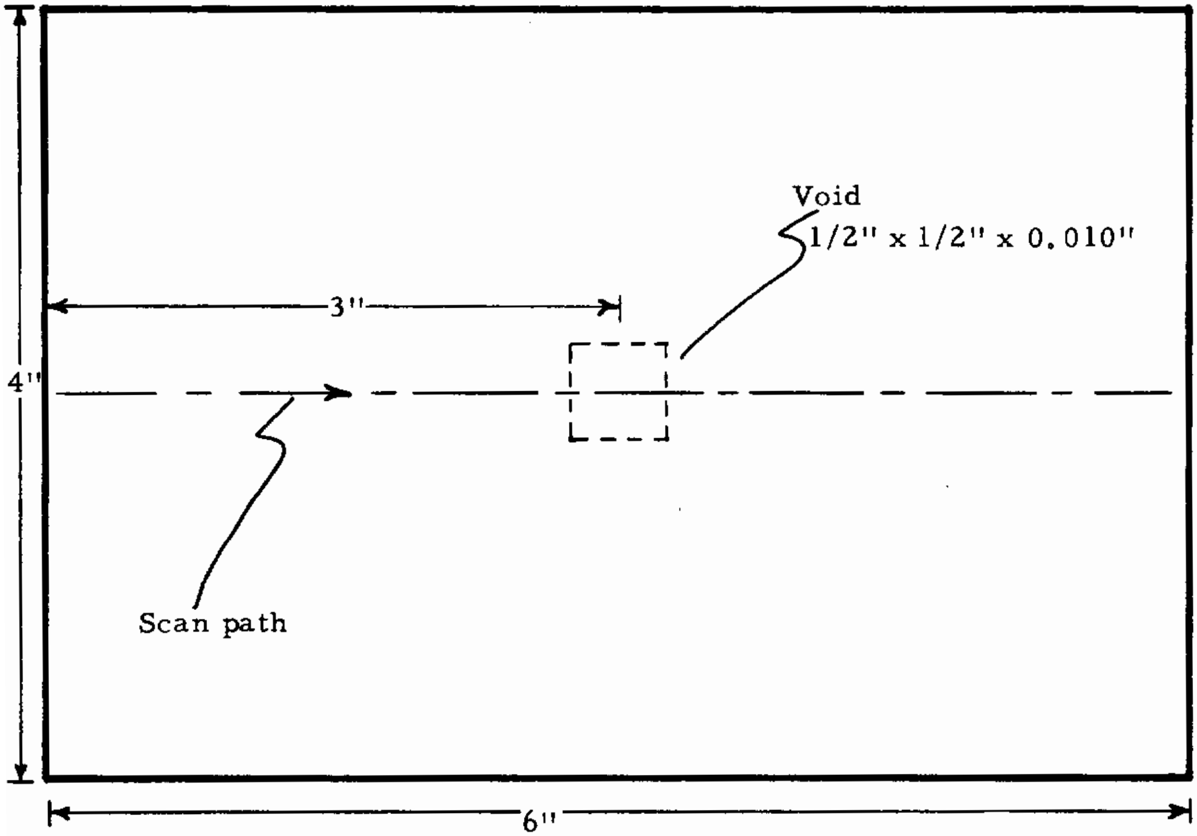
Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 2°C

Figure 10. Steel Plate 1/32" Thick With Void

## Discussion of Figure 11

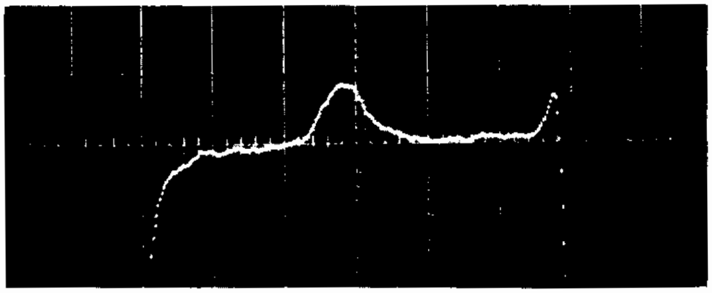
In Figure 11, an aluminum test plate 1/32" thick is scanned. The depth of fabricated void is approximately 30% of material thickness. This is a test conducted early in the testing program.

Comparison of this test with the test summarized in Figure 12 ( a recent test ) shows a marked improvement in system sensitivity during the program.



Aluminum - 1/32" thick
Scan speed - 1.5 inches per second

(Early Test)

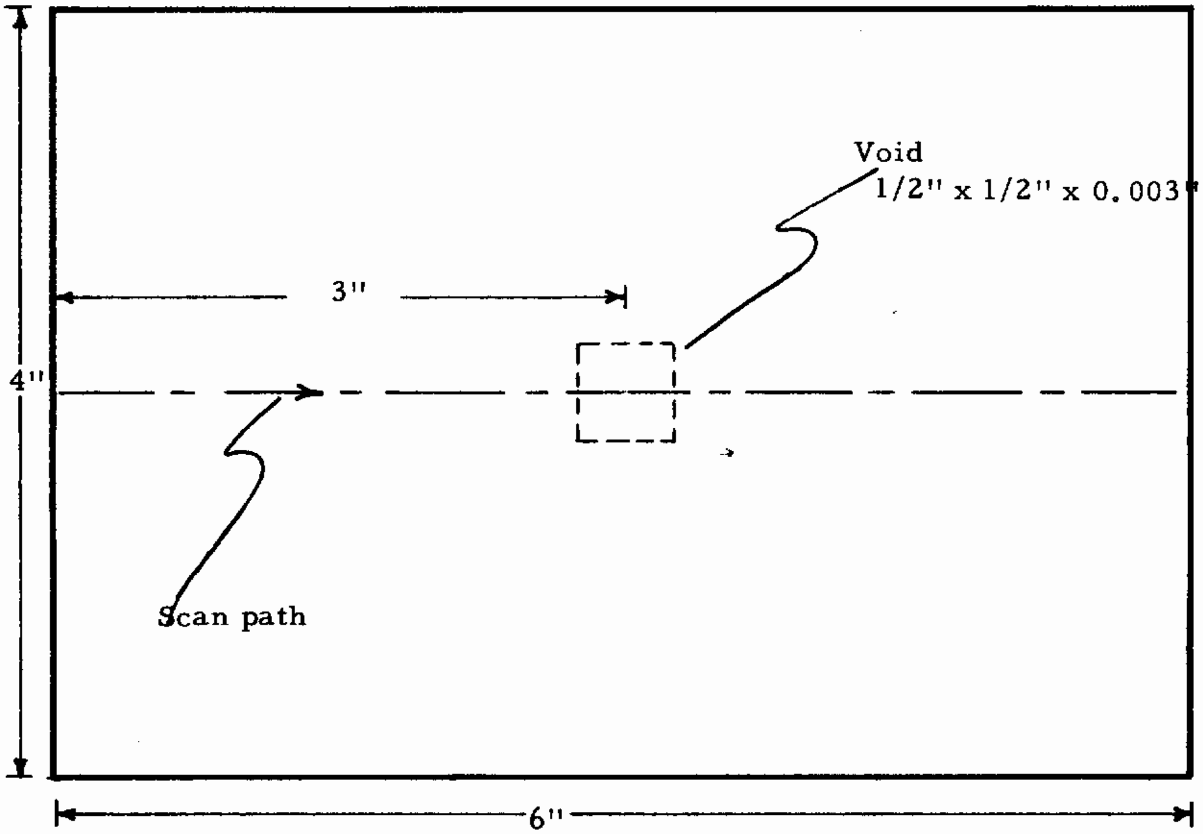


Scales - Abscissa: 1 cm $\propto$ 1 in. along scan path
Ordinate: 1 cm $\propto$ approx. 2.0°C

Figure 11. Aluminum Plate 1/32" Thick With Void

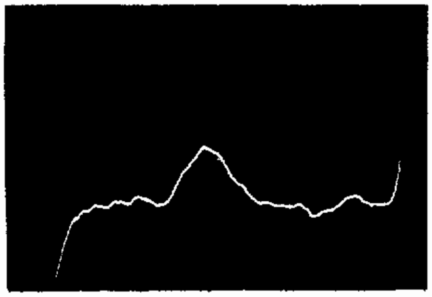
## Discussion of Figure 12

Figure 12 shows the scan test of a 1/32" aluminum test plate similar to that shown in Figure 11, with a considerably shallower void depth (approximately 10% of total material thickness). This test was made recently, about two months after the test shown in Figure 11. Heater system improvements, such as increased intensity of heating and improved heat spot uniformity, have increased the contrast between void and no-void conditions. As a result, the 10% void yields a signal almost identical with the 30% void of the earlier test. Improved radiometer noise level has made the trace cleaner. The increased "waviness" of the trace over void-free material is probably a function of the test plate itself or its black coating. In this particular comparison, trailing edge effect seems to have worsened rather than improved from the old test to the new. This is somewhat perplexing, due to the fact that comparisons of old and new tests of other plate thicknesses do not show this same tendency. A destructive examination of the two 1/32" test plates may indicate a reason for the edge effect behavior.



Aluminum - 1/32" thick
Scan speed - 1.5 inches per second

(Recent Test)

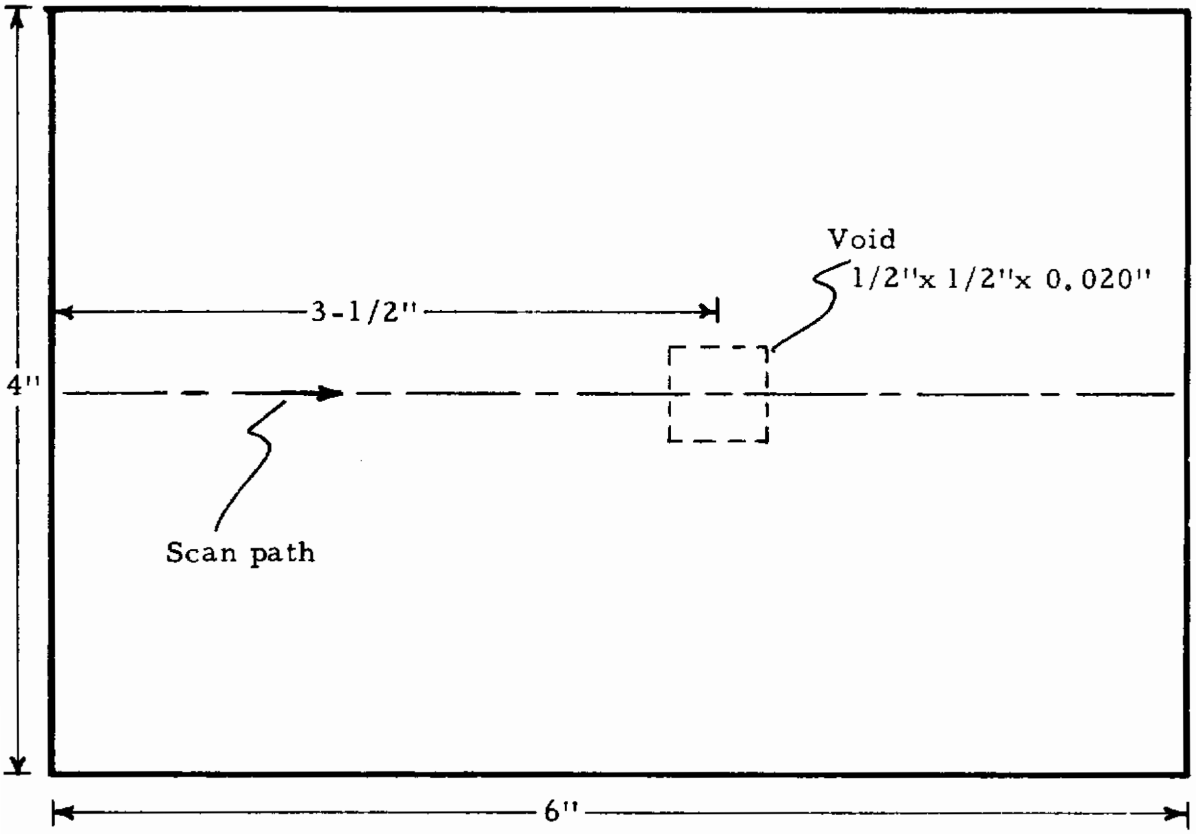


Scales - Abscissa: 1 cm $\propto$ 1 in. along scan path
Ordinate: 1 cm $\propto$ approx. 2.0°C

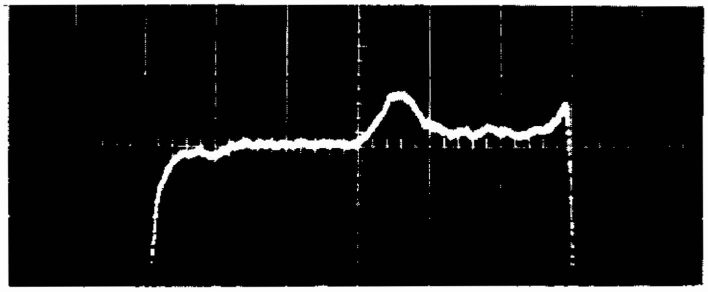
Figure 12. Aluminum Plate 1/32" Thick With Void

# Discussion of Figure 13

This is a recording from a test scan of a 1/16" steel plate made early in the program. Again, it is noted that scan speed is considerably slower than with aluminum test plates.



Steel - 1/16" thick
Scan speed - 0.4 inch per second

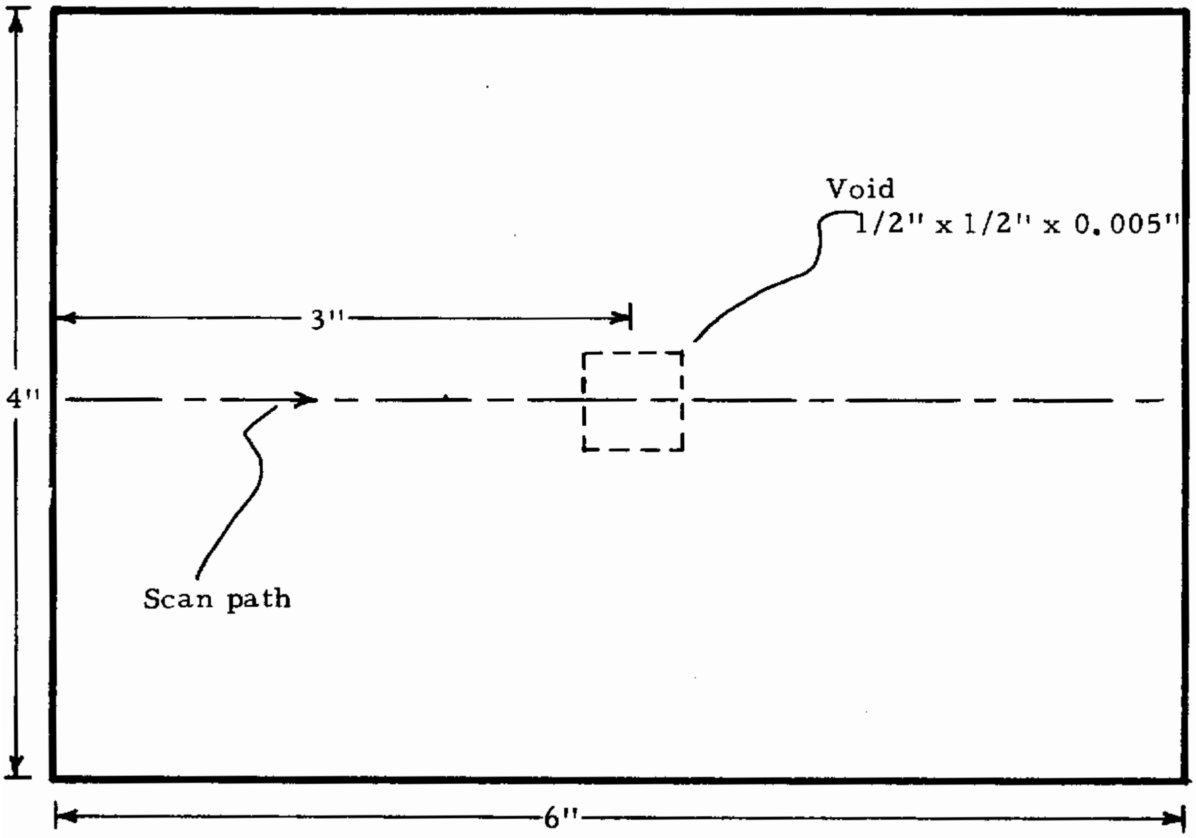


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 2°C

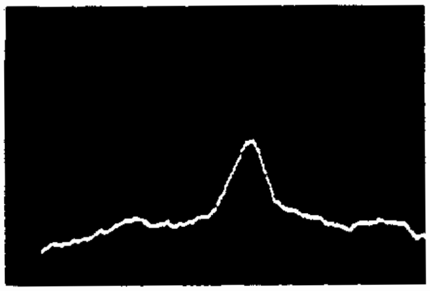
Figure 13. Steel Plate 1/16" Thick With Void

## Discussion of Figure 14

Here a scan is shown of a 1/16" aluminum test plate with a void 8% of material thickness. At this material thickness, it is felt that the presently used heat spot size of 0.4" x 0.5" is nearly optimum. This indicates an optimum spot size between 6 and 8 times the material thickness.



Aluminum - 1/16" thick
Scan speed - 1 inch per second

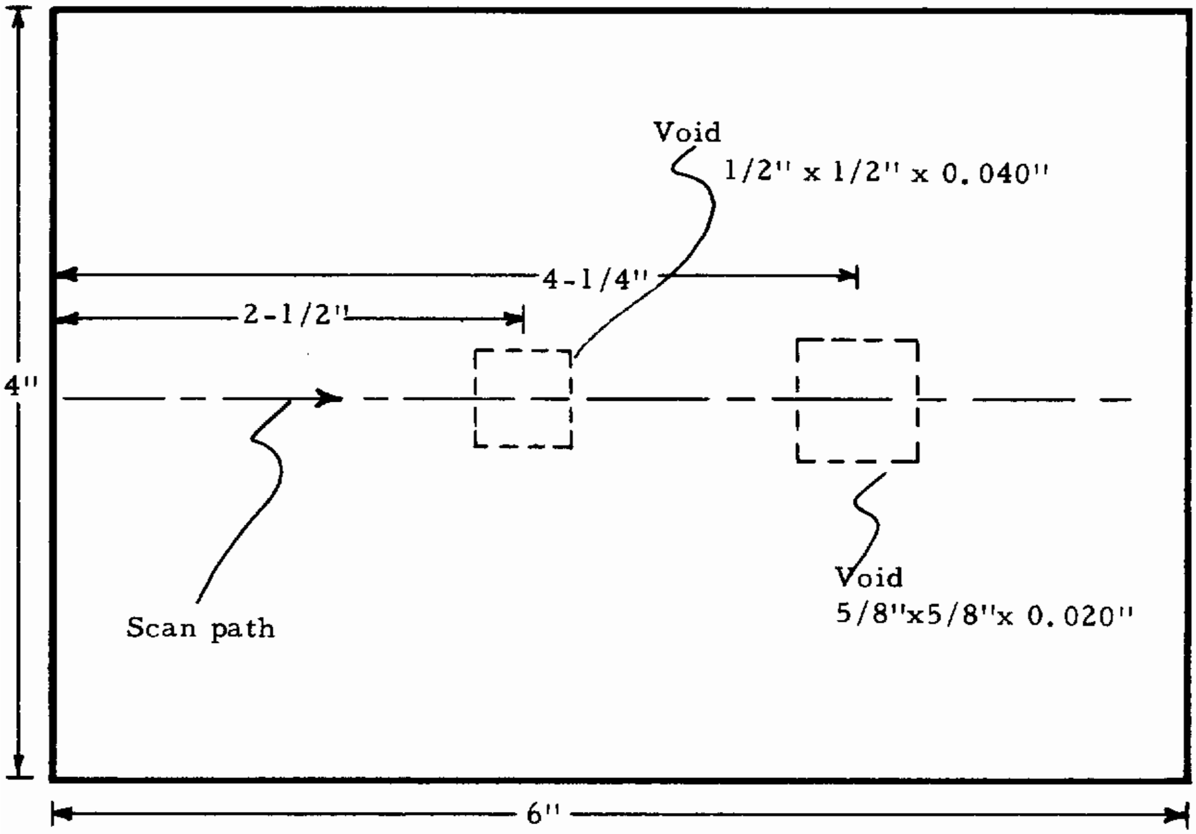


Scales - Abscissa: 1 cm $\propto$ 1 in. along scan path
Ordinate: 1 cm $\propto$ approx. 1.0°C

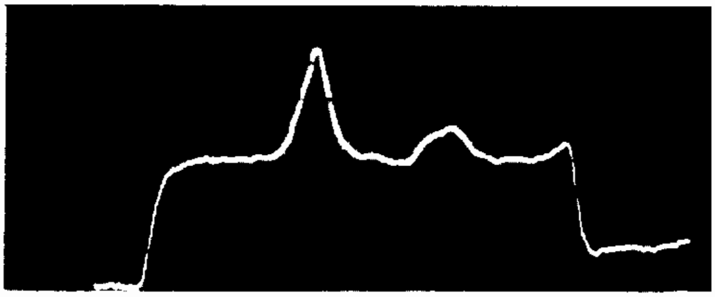
Figure 14. Aluminum Plate 1/16" Thick With Void

## Discussion of Figure 15

This recording was included to demonstrate the detection of two voids along the same scan path, and the manner in which the dc level is maintained over the homogeneous material between voids. Further useful investigations in the future might be to determine the minimum separation between voids for which they are distinguishable.



Aluminum - 1/16" thick
Scan speed - 1 inch per second

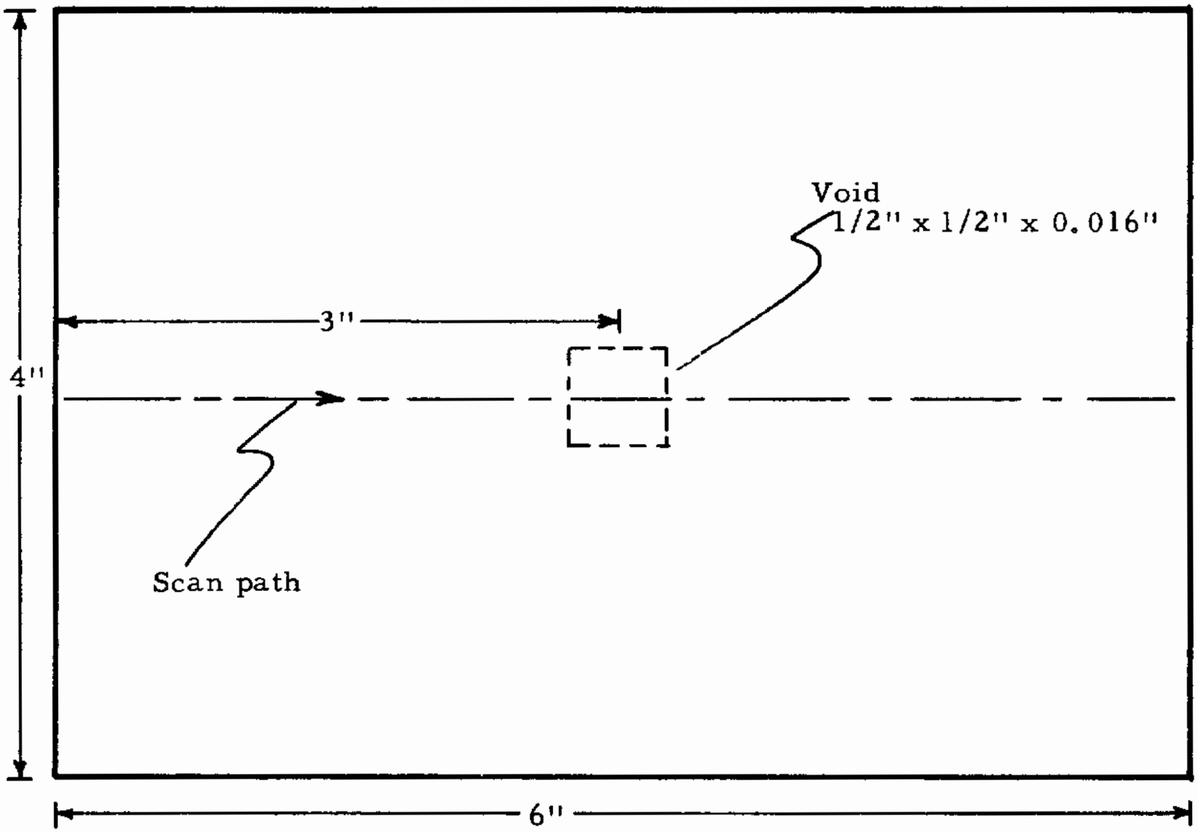


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 4°C

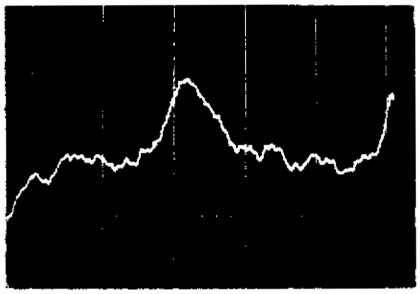
Figure 15. Aluminum Plate 1/16" Thick With Two Voids

## Discussion of Figure 16

Here the effects of thicker test material begin to show, in decreased temperature contrast and higher noise level. More thermal energy, in the form of higher heater intensity or a larger heat spot with equivalent intensity, is needed to improve void detection for all test plates of thickness 1/8" or more.



Aluminum - 1/8" thick
Scan speed - 0.5 inch per second

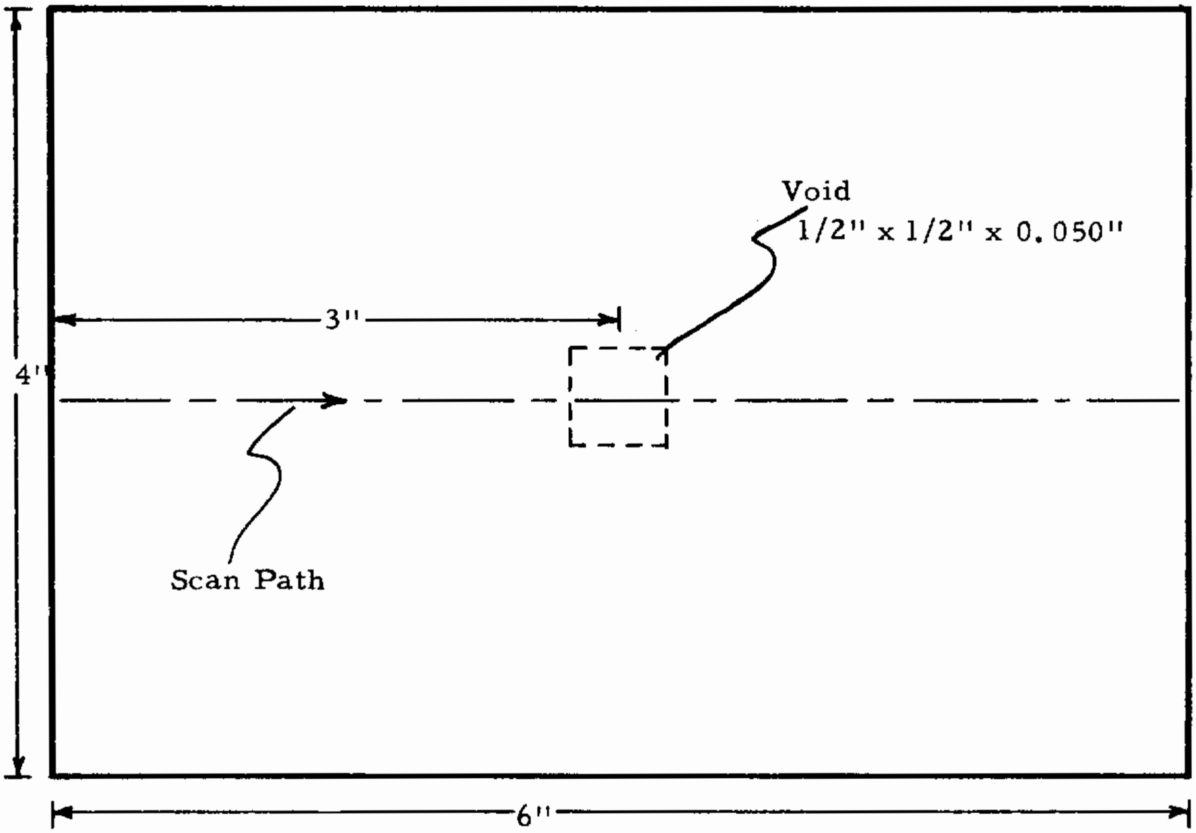


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 0.6°C

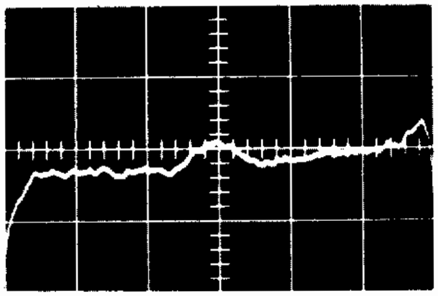
Figure 16. Aluminum Plate 1/8" Thick With Void

## Discussion of Figure 17

In this test, a void of depth 20% of material thickness is detected in a 1/4" thick aluminum test plate. Further loss in temperature contrast is noted as thicker samples are employed.



Aluminum - 1/4" thick
Scan speed - 0.5 inch per second

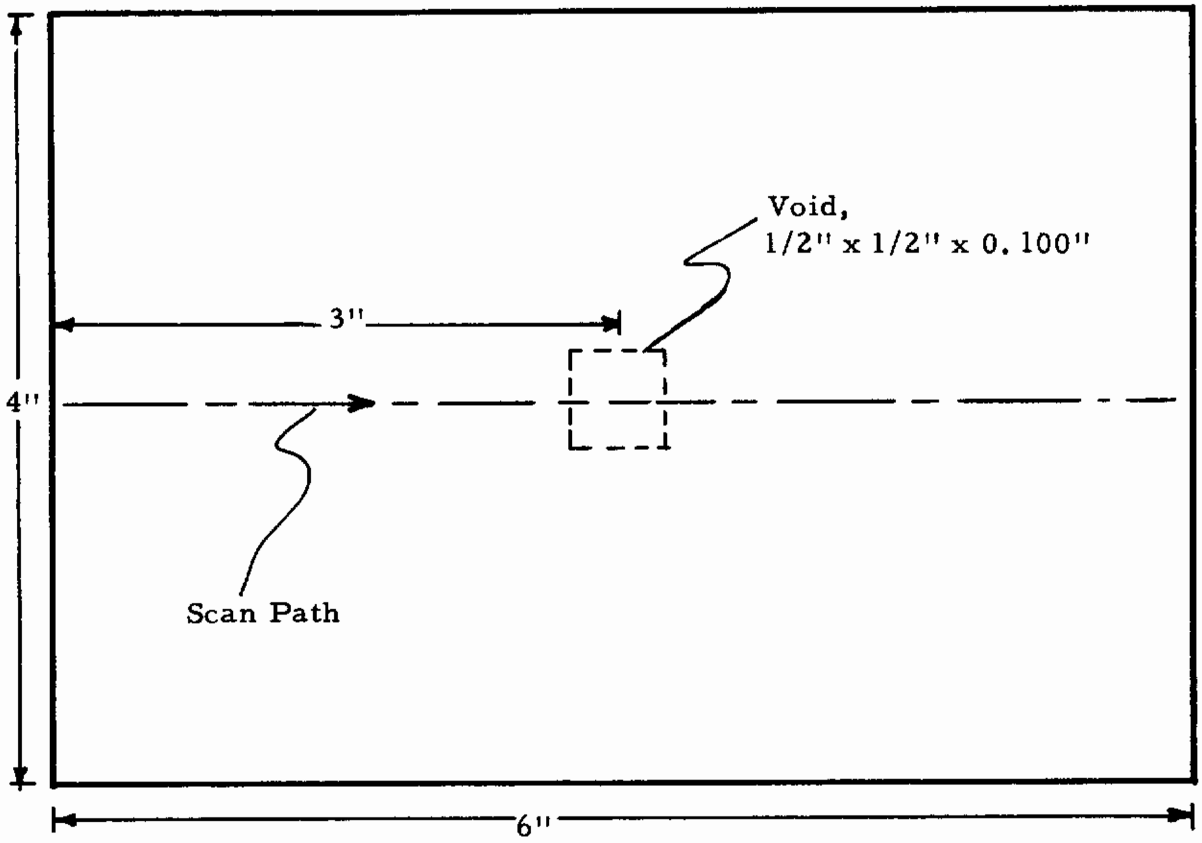


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 0.3°C

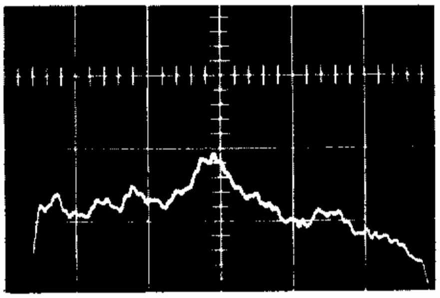
Figure 17. Aluminum Plate 1/4" Thick With Void

## Discussion of Figure 18

This recording illustrates the increasing loss in temperature contrast with increasing material thickness. It is felt that the temperature contrast may be enhanced by employing more thermal energy input. Note that the quasi-steady state temperature condition over non-void areas is quite uniform, varying by approximately 0.05°C over the entire plate.



Aluminum - 3/8" thick
Scan speed - 0.4 inch per second



Scales - Abscissa: 1 cm $\propto$ 1 in. along scan path
Ordinate: 1 cm $\propto$ approx. 0.1°C

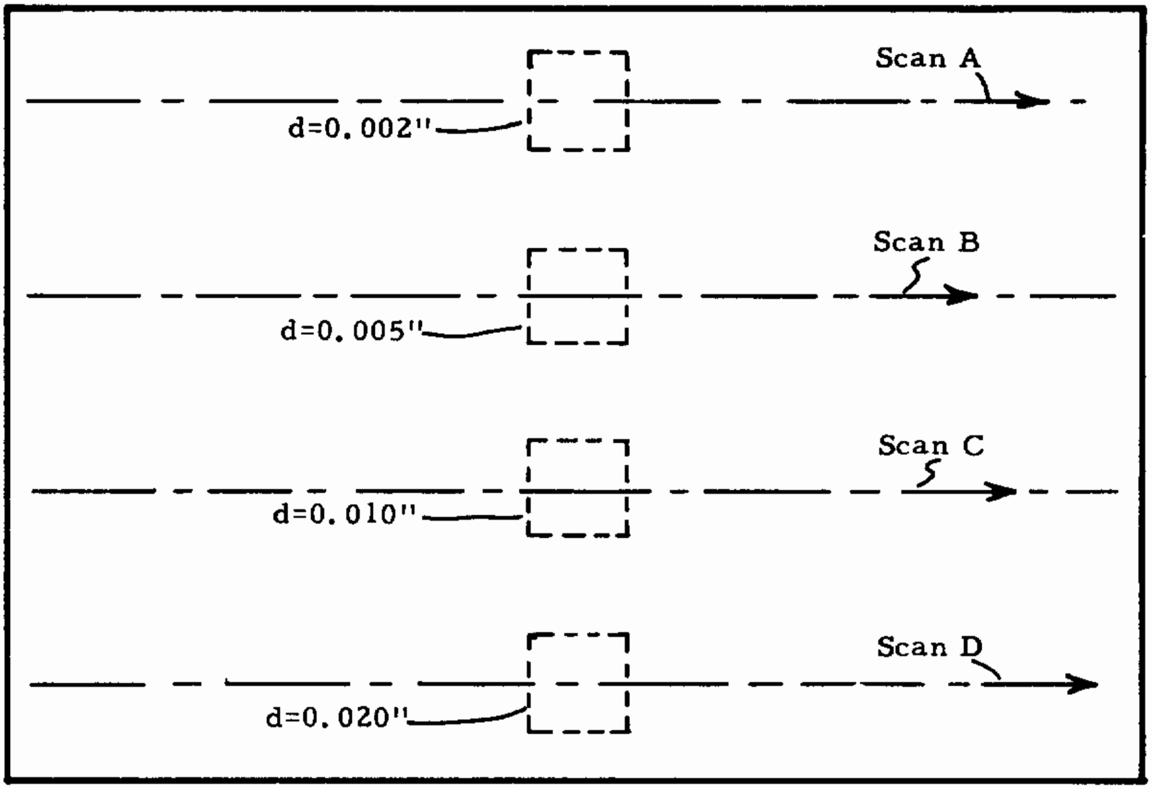
Figure 18. Aluminum Plate 3/8" Thick With Void

## Discussion of Figure 19

In this test series, the recordings show variation in temperature gradient as void depth is changed.

In Scan A, a void depth of 3% of material thickness causes a temperature change of approximately 0.1°C. A figure of merit showing temperature change over shallow voids would thus seem to be approximately 0.03°C/% depth of void. For deeper voids (20% of material thickness or more), this figure increases markedly, as high as 0.25°C/% depth of void, as shown in Scan D.

The quasi-steady state level in these recordings is poorly maintained. It is hoped that eventually a destructive examination of the plate will explain this behavior.



Aluminum plate - 4" x 6" x 1/16"
Voids - 1/2" x 1/2" x d, in back of plate
Scan speed = v

Scan A: v=0.6 in/sec
Ordinate: 1 cm ∝ approx. 0.1°C

Scan B: v=0.8 in/sec
Ordinate: 1 cm ∝ approx. 0.3°C

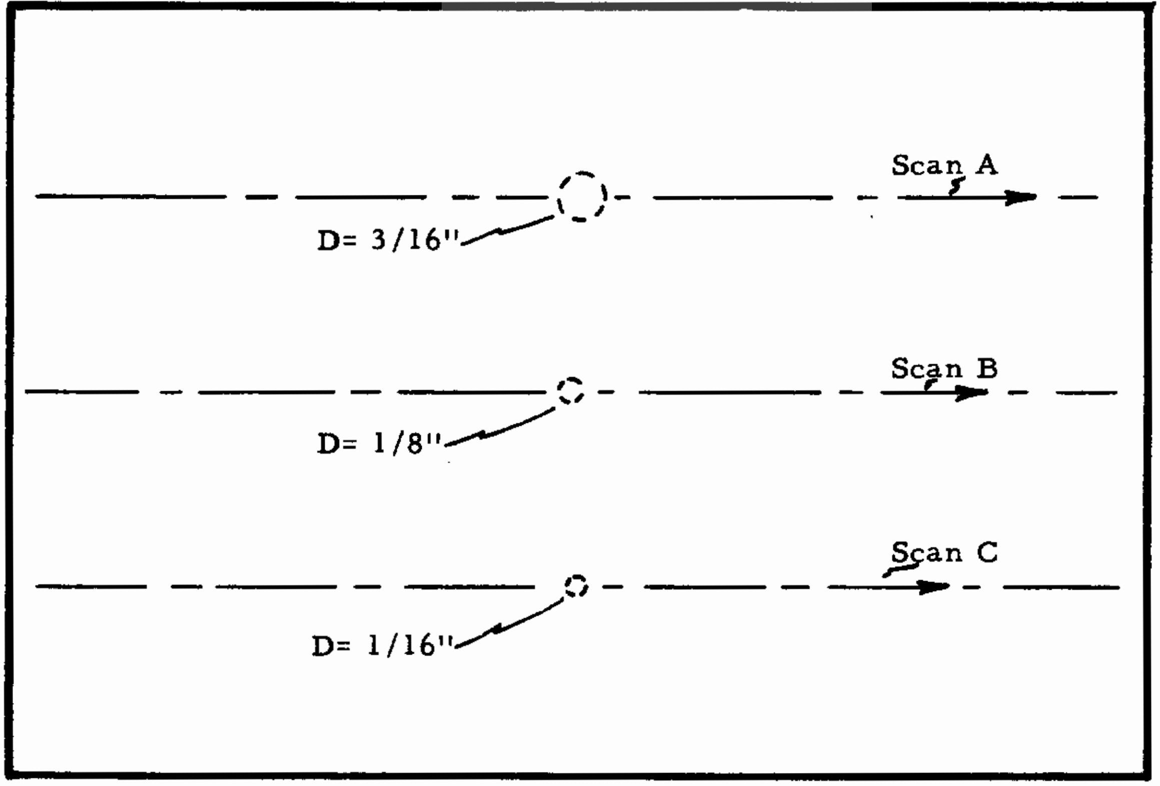
Scan C: v=1.0 in/sec
Ordinate: 1 cm ∝ approx. 0.8°C

Scan D: v=1.0 in/sec
Ordinate: 1 cm ∝ approx. 3.0°C

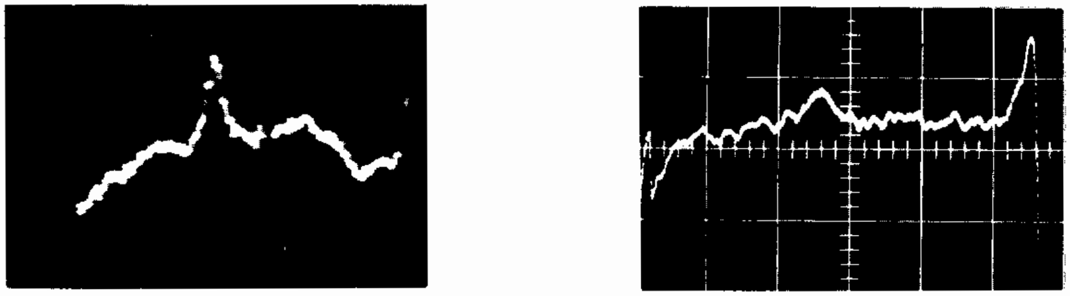
Figure 19. Showing Effect of Void Depth

## Discussion of Figure 20

In this series of recordings, the effect of changing transverse dimension is shown. At a void diameter equal to material thickness, no indication of the void is noted. More efficient heating may improve system response to voids with small transverse dimensions. Certainly a decrease in detector spot size is desirable in this respect.

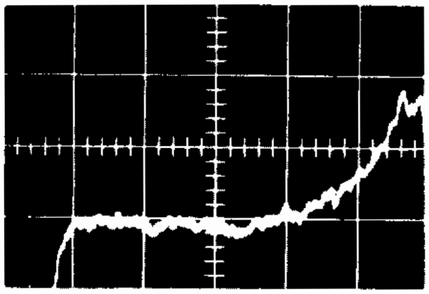


Aluminum plate - 4" x 6" x 1/16"
Voids - D = diameter, .020" deep, in back surface
Scan speed = v



Scan A: v = 1 ips
Ordinate: 1 cm ∝ approx. 0.2°C
Abscissa: 1 cm   1 in. along scan path

Scan B: v = 0.8 ips
Ordinate: 1 cm ∝ approx. 0.2°C
Absicissa: 1 cm   1 in. along scan path

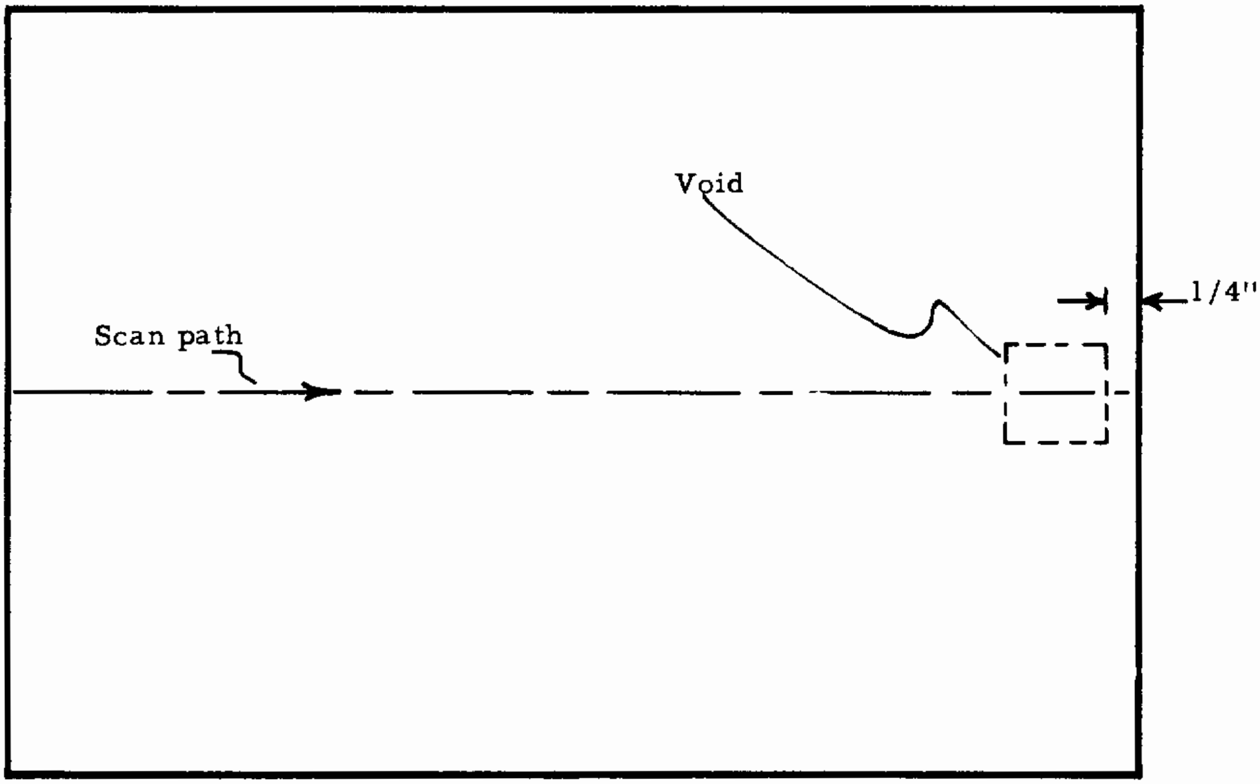


Scan C: v = 0.7 ips
Ordinate: 1 cm ∝ approx. 0.2°C
Abscissa: 1 cm ∝ 1 in. along scan path

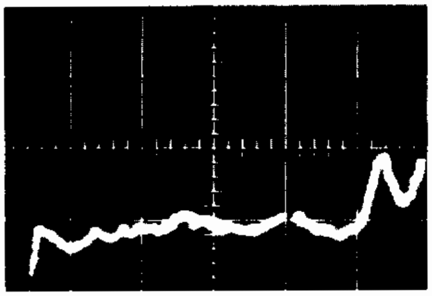
Figure 20. Showing Effect of Transverse Dimension of Void

## Discussion of Figure 21

In this test plate, a void is placed within 1/4" of the trailing edge. Although the surface noise level is particularly poor on this plate, the void is clearly discernible in the recording.



Aluminum plate - 4" x 6" x 1/16"
Void - 1/2" x 1/2" x 0.010", in back of plate
Scan speed = 1.0 in/sec



Scales - Absicissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 2.0°C

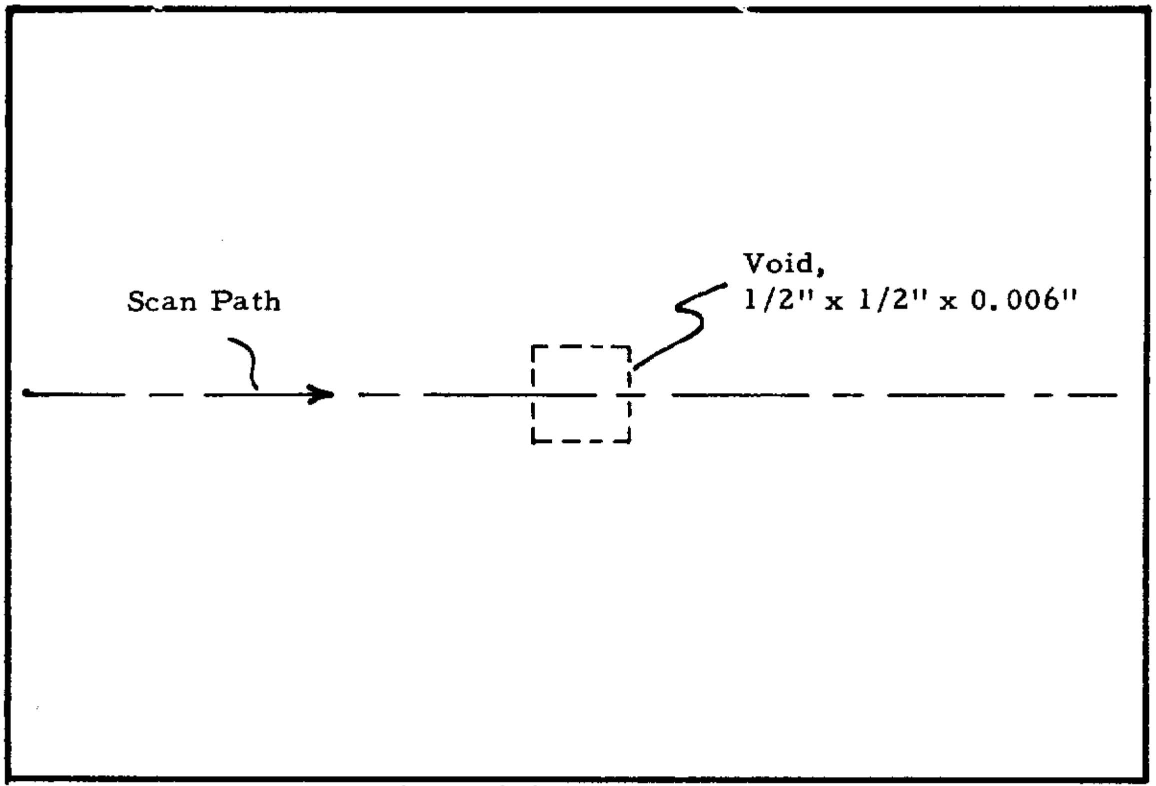
Figure 21. Showing Apparent Present Limit of Edge Effect

## Discussion of Figure 22

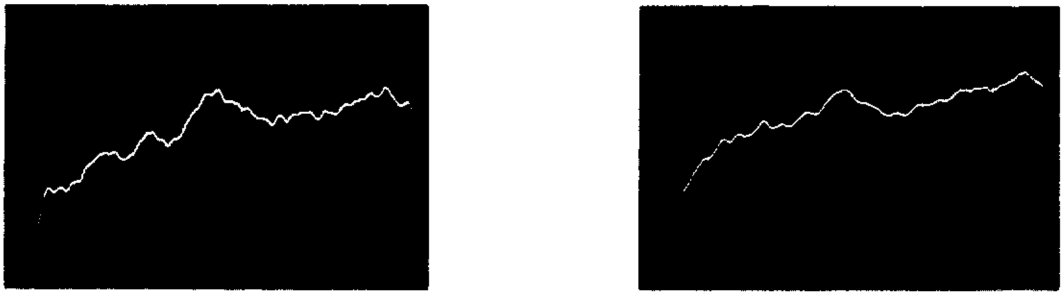
Here the effects of scan speed variation are illustrated. At the experimentally determined optimum scan speed, this particular plate shows a temperature gradient over the void of about 0.8°C. Heat spreading causes the void to appear to be about 0.8" in transverse dimension, rather than 0.5".

At a scan speed slower than optimum, the temperature gradient remains approximately 0.8°C. However, noise due to surface emissivity variations increases in amplitude. Another undesirable effect is the excessive spreading; the void now appears to be 1.4" in transverse dimension.

The effect of faster-than-optimum scan speed is readily apparent: the temperature gradient indicating the void deteriorates.

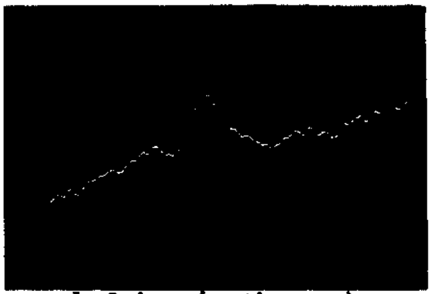


Aluminum plate - 4" x 6" x 1/16"
Tests run at three different scan speeds - at optimum scan speed, below optimum, and above optimum speed.



v = 0.5 ips (below optimum)
Ordinate: 1 cm $\propto$ approx. 1.0°C

v = 1.5 ips (above optimum)
Ordinate: 1 cm $\propto$ approx. 1.0°C

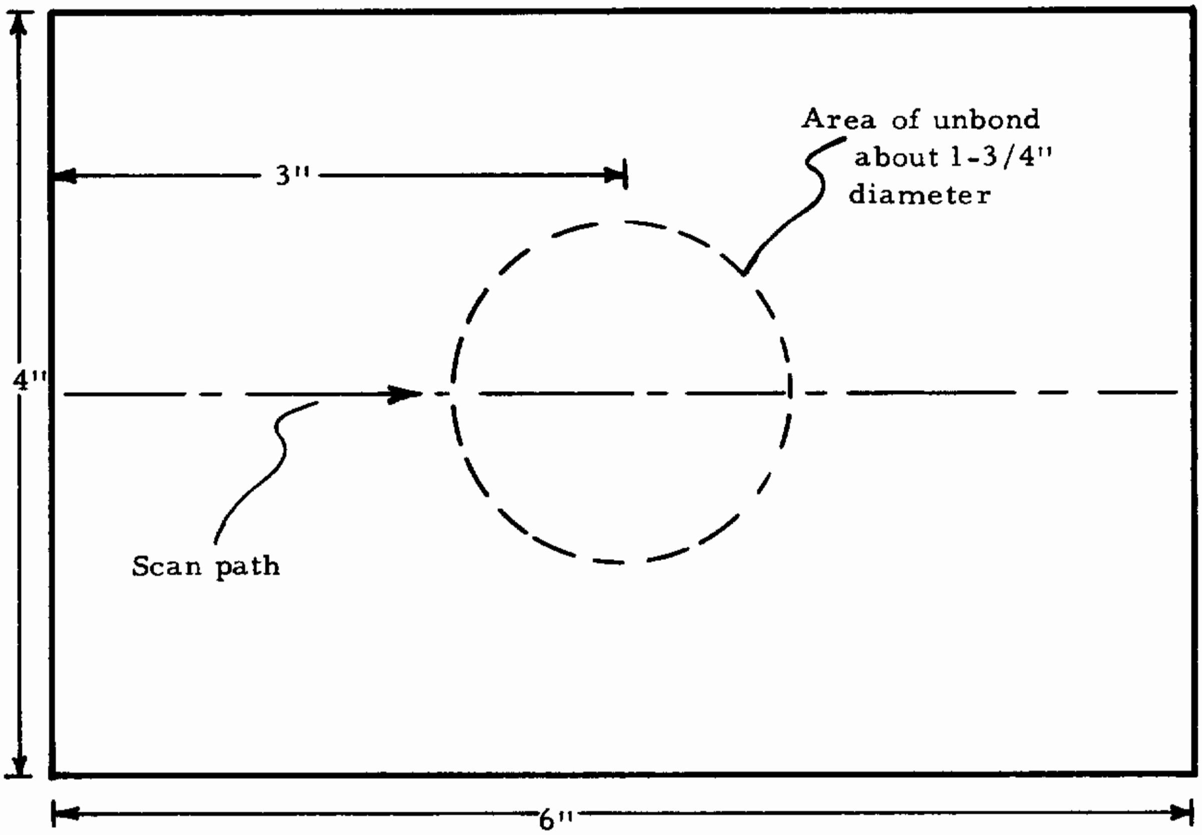


v = 1.0 ips (optimum)
Ordinate: 1 cm $\propto$ approx. 1.0°C

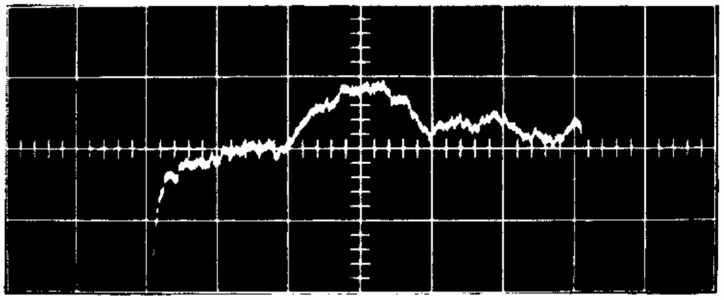
Figure 22. Showing Effect of Scan Speed Variation

## 7.3 Test Plate with Unbonded Area

The 4" x 6" surface of a homogeneous brass plate 1/16" thick was soldered to the 4" x 6" surface of a homogeneous 1/8" brass plate. An area about 1-3/4" in diameter was contaminated on one plate, causing an area in which there is no solder bond between the plates. Figure 23 shows the detection of this unbonding in a thermal test. At the area of unbond, it is believed that there is metal-to-metal contact.



1/16" brass plate soldered to 1/8" brass plate
(Scanned on surface of 1/16" plate)
Scan speed - 1 inch per second

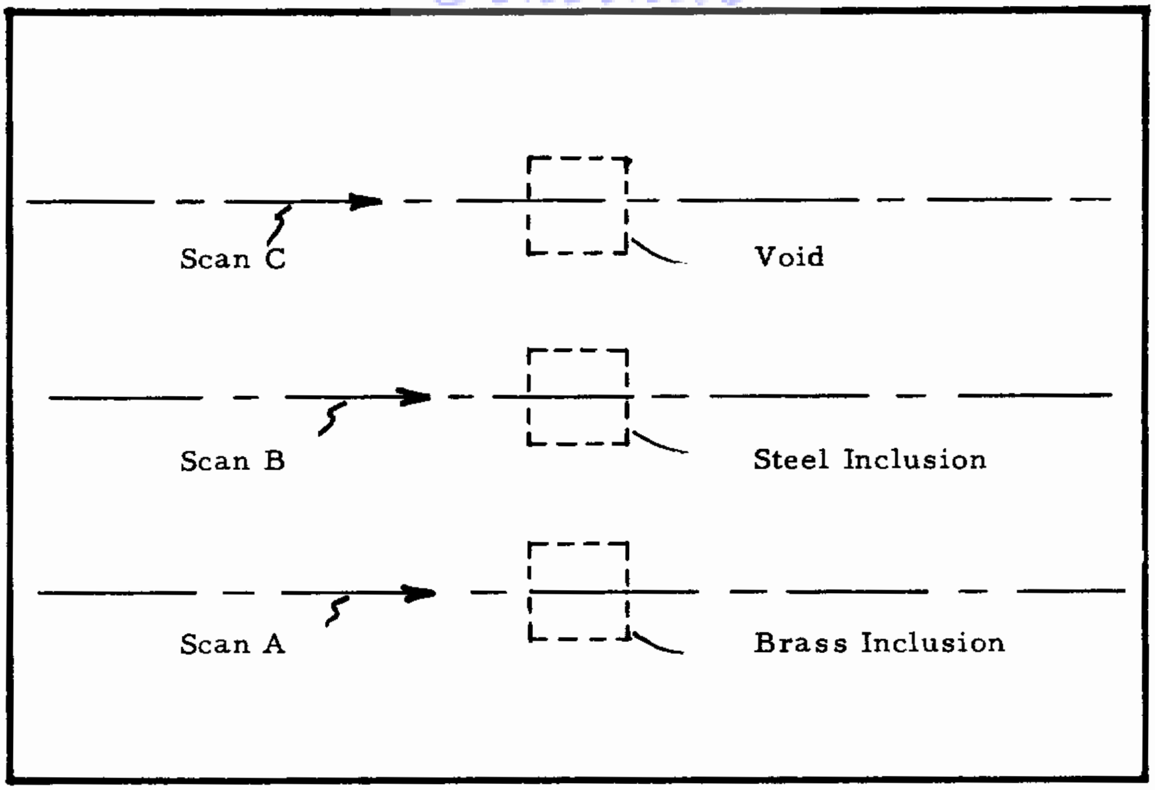


Scales - Abscissa: 1 cm $\propto$ 1 in. along scan path
Ordinate: 1 cm $\propto$ approx. 0.8°C

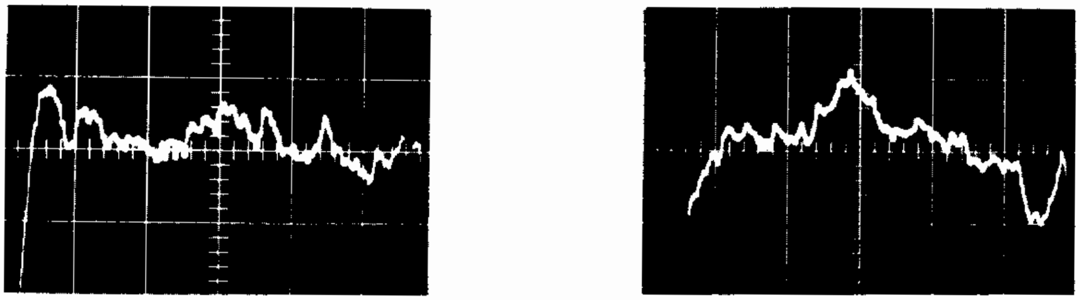
Figure 23. Area of Unbond

## 7.4 Test Plate with Metallic Inclusion

The brass plate shown in Figure 24 is 1/8" thick. Machined in the back surface are three identical voids, 1/2" x 1/2" x 1/16". Two of the voids are filled with close-fitting metal plugs soldered carefully in place (so that all surface contact between plug and void surface is bonded with solder). These two constitute fabricated metallic inclusions. The third void is left empty. Three key scans crossing the surface above these material irregularities are recorded below the sketch of the test plate. There is appreciable response to the soldered steel plug, and virtually none to the soldered brass plug. Thus, it would seem that a soldered interface contributes little surface temperature differential under scan heating, and the detection of the steel plug is due largely to the difference in thermal characteristics between brass and steel. The temperature differential due to the void left empty is shown to illustrate relative magnitudes of effect between void and metallic inclusion.

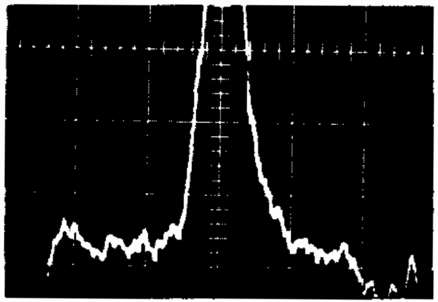


Brass Plate - 4" x 6" x 1/8"
Fabricated Inhomogeneities - 1/2" x 1/2" x 1/16"
Scan Speed - 0.5 inches per second



Scan A
Ordinate: 1 cm ∝ approx. 0.15°C

Scan B
Ordinate: 1 cm ∝ approx. 0.3°C

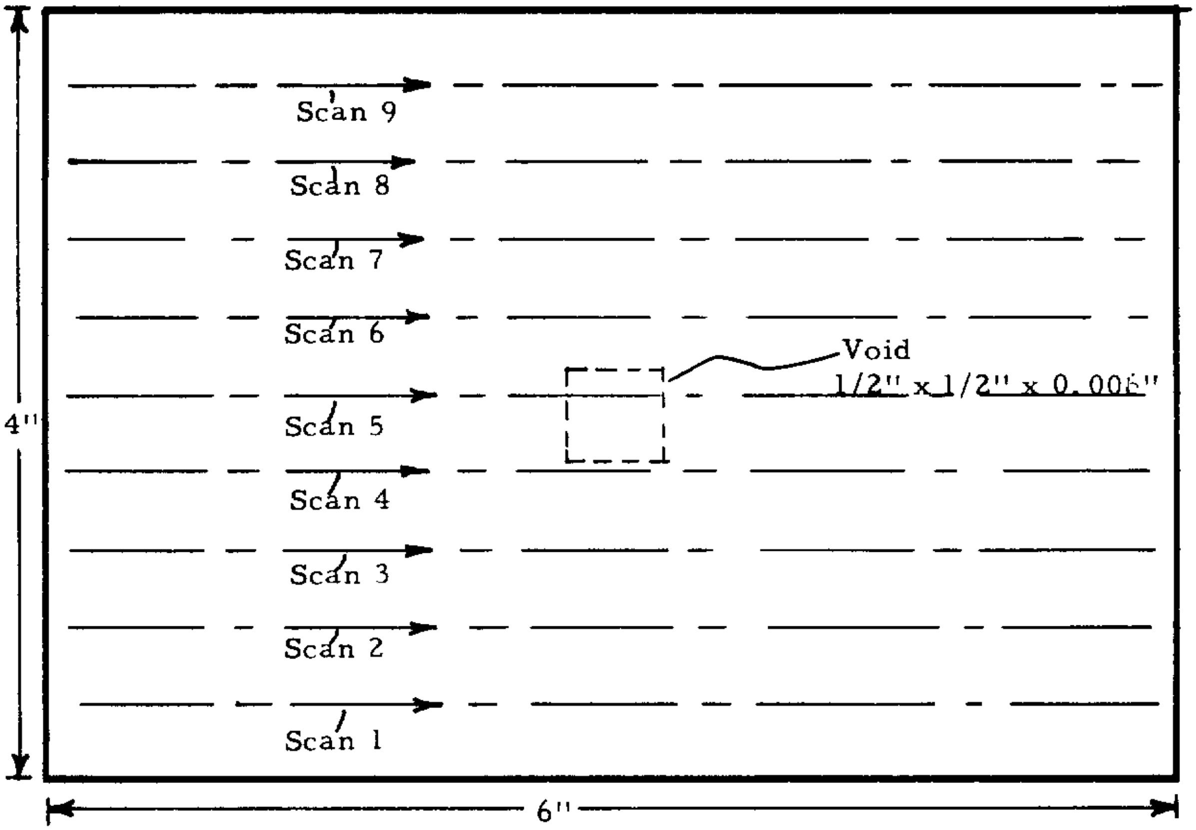


Scan C
Ordinate: 1 cm ∝ approx. 0.3°C
Pulse height: Approx. 10 cm

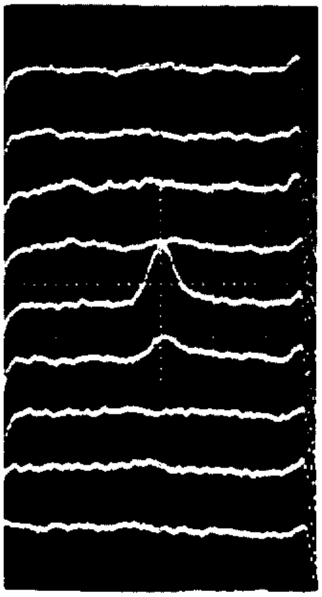
Figure 24. Brass Plate with Metallic Inclusions

## 7. 5 Overall Test Plate Inspections

In Figures 25 and 26, results of entire test plate scans are shown. In each test, distance between heating scans is 0. 1". Every fourth scan is recorded in the photograph below. Figure 25 summarizes the complete thermal test of the 1/16" aluminum test plate also shown in Figure 14. Figure 26 shows the complete scan test of the test plate with an area of unbond; this test plate is also shown in Figure 23 and described in Article 7. 3. The effect of the unbonded area shows quite clearly in scans 4, 5 and 6. Other areas of unintentional unbonding appear to be present near the top and bottom edges. Eventually the plate will be tested destructively in an effort to correlate the thermal test results with the actual condition of bond at the edges.

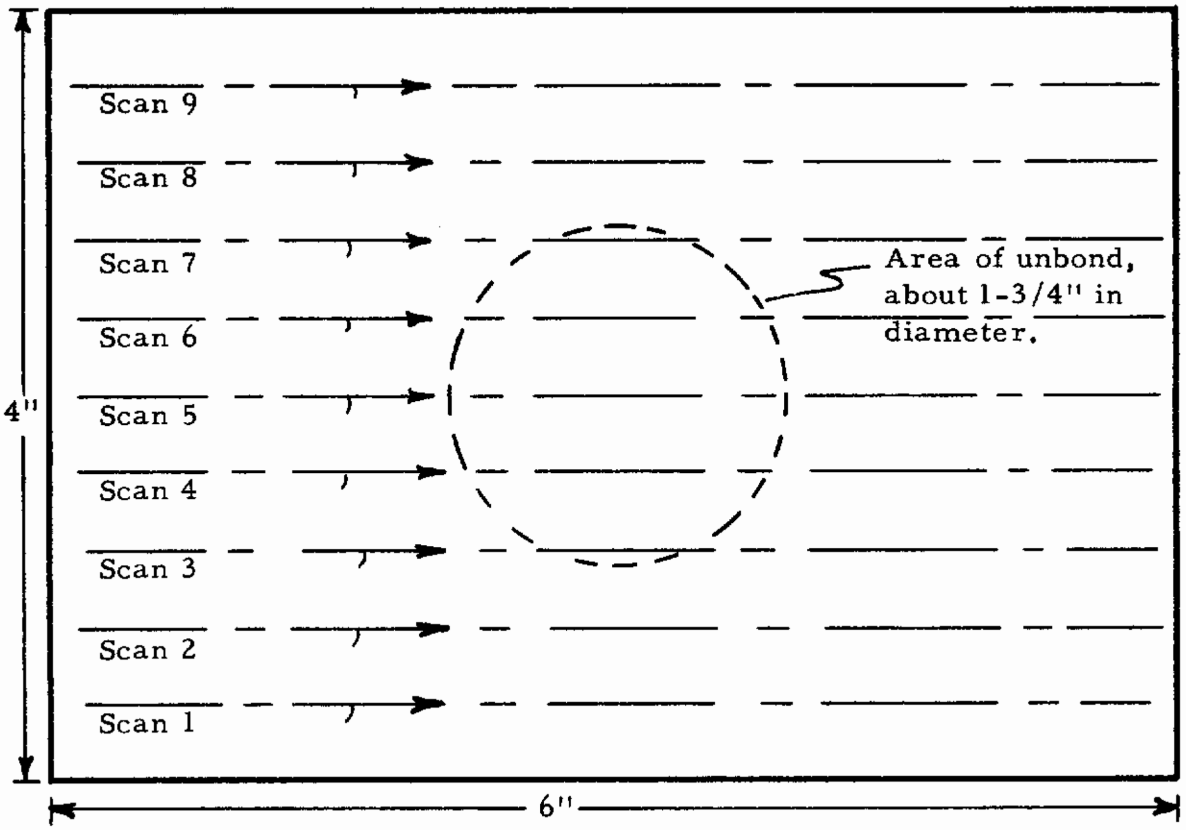


Aluminum - 1/16" thick
Scan speed - 1 ips

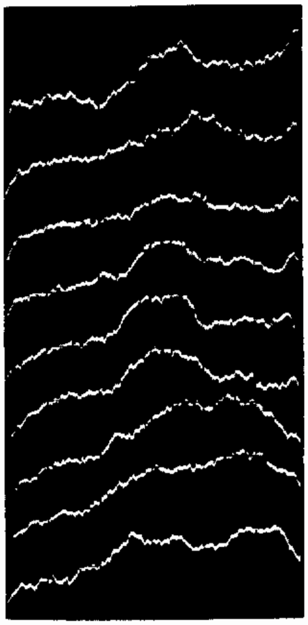


Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 2.5°C

Figure 25. Complete Scan of Aluminum Plate 1/16" Thick With Void



1/16" brass plate soldered to 1/8" brass plate
(Scanned on surface of 1/16" plate)
Scan speed - 1 inch per second



Scales - Abscissa: 1 cm ∝ 1 in. along scan path
Ordinate: 1 cm ∝ approx. 0.8°C

Figure 26. Complete Scan of Test Plate with Area of Unbond

# V. CONCLUSIONS

## 1.0 Program Performance

### 1.1 General Remarks

The scan-heating and detecting method for nondestructive evaluation of materials has been shown feasible for the following three types of material inhomogeneities:

A. Voids in material,

B. Areas of unbonding in a bonded structure,

C. Test Plates with metallic inclusions.

A thermal testing system based on the scan-heating and detecting method has been fabricated and tested. Throughout the program the system has undergone gradual refinement. Present system capabilities are described in the Test Results. Suggested further changes in the system are described in appropriate articles throughout the body of the report. These suggested changes are summarized in Section VI.

### 1.2 Thermal Testing System

The thermal Testing System used in the program performs these three basic operations:

A. Heat a surface of the test material in a programmed scan with a small heat spot:

B. Follow this same programmed scan some fixed time later with a continuous temperature evaluation at a detector spot on the surface;

C. Record the continuous temperature reading with information as to the position of the detector spot as it moves over the surface.

The heat introduced at the surface penetrates the material at a rate dependent on the material parameters beneath the surface. This varying rate of penetration, gauged by the surface temperature evaluation, is then a means of investigation of the internal material parameters.

The programmed scan heating system brings each point on the material surface, in turn, to a maximum temperature from 20°C to 40°C above ambient. The moving rectangular'heat spot'is approximately 0.4" x 0.5" in dimensions. Intensity of power input at the heat spot is about 240 watts/in$^2$.

To measure the surface temperature, an infrared radiometer is employed, being focused at a "detector spot" behind the heat spot. This instrument responds to infrared radiation from the material surface in the 3.8 - 6.5 micron range, and is calibrated in degrees Centigrade. The resolution spot of the radiometer (the "detector spot" described above) on the material surface is approximately 0.15" x 0.18".

Such test parameters as scan speed, heater and detector spot sizes, heater-detector spot separation, and heater intensity have optimum values. The optimizing of test parameters is discussed in this report.

## 1.3 Test Plates and Results

All test plates in this program have been flat metallic plates of aluminum, steel, brass and copper. Plate thicknesses vary from 0.010" to 0.375". Voids, areas of unbonding, or metallic inclusion have been fabricated in the plates as standard inhomogeneities.

Fabricated voids in test plates have been obtained by milling out a part of the material from the back (unscanned) surface. Voids as shallow as 3% of total plate thickness have been detected. Transverse dimensions of a detectable void appear at present to be a minimum of approximately twice the plate thickness. An area of unbond has been found between two plates soldered face-to-face. A steel inclusion soldered in a brass test plate has been located by thermal test procedures.

Surface blackness (emissivity) variation has been found to be somewhat a problem. At present, all test plates are blackened with a fast-drying flat black paint. Effort is under way to eliminate this surface problem.

## 2.0 Program Limitations

The ultimate goal of thermal nondestructive materials evaluation program at this facility has always been to establish feasibility for evaluation of various physical, mechanical, and metallurgical parameters of metals and ceramics by thermal means. No particular set of material parameters has been set forth as a goal. This is primarily because it was not known originally which parameters could be reasonably expected to be evaluated by thermal energy means. Relatively gross material parameter variations have thus far been detected; these are material void, lack of bond and inclusion of a foreign material. Indications are that future efforts with variations in more subtle material parameters should be successful. The extent of possible successes in this line is not easily predictable. More discussion of future efforts in material parameter evaluation is included in Section VI.

It was originally intended to investigate a thermal shock-transient condition believed by some to be present in materials upon pulsed heating. Such a shock-transient, with a velocity of travel far greater than the normal heat diffusion in a solid, would be of great interest in rapid materials evaluation if it exists. No evidence whatever was uncovered in a literature search that such a phenomenon has been measured or even sensibly postulated in a mathematical model. A decision was made during the course of the program that more theoretical investigation was needed to determine answers to two questions, namely

A. Whether a material will support or admit such a high-speed thermal transient;

B. How to instrument to attempt to determine if it does exist.

A portion of future theoretical effort is outlined to attack these two questions. To date, no effort has been expended on the shock transient phenomenon, other than the literature search.

## VI. RECOMMENDATIONS FOR FUTURE INVESTIGATION

As previously reported, many material parameters are suspected of having a relation to heat transfer through the material. Thus it is felt that the investigation of heat transfer through controlled heating should yield information regarding these parameters. Gross changes in parameters such as voids and delamination (unbonding) have already been found by heat transfer investigation in the form of the scan-heating and detecting thermal test. Plans for the immediate future are to fabricate test plates with material parameter variations other than voids, delaminations, and metallic inclusion. Variations in the following parameters look particularly promising for thermal testing methods of evaluation:

A. Density,

B. Porosity,

C. Purity or alloy concentration,

D. Electrical and thermal conductivity,

E. Internal corrosion,

F. Metallic coating thickness.

Other material parameters which might be investigated by thermal testing are:

A. Lattice structure variations,

B. Type and extent of heat treat.

These last two parameters of material condition are strictly speculative at the moment. The theoretical study to be performed at the outset of the continuation program should shed more light on such parameters as these. Key consultant personnel in metallurgy and solid state physics will be utilized in the theoretical study.

The most significant instrumentation problem at this time is to secure a better scan-heating system. Plans are to incorporate a hot-air heating system. This heat source will deliver much more heating power to the test plate. In addition, it will provide for more flexibility in heat spot size. The more intense heating should enable faster scan speeds and detection of smaller material inhomogeneities.

The temperature pattern readout is to be converted to a C-scan type display. The x- and y- dimensions of the test plate surface will be indicated by horizontal and vertical deflections on a storage tube. Radiometer output voltage (representing surface temperature) will intensity modulate the beam of the storage tube, thus showing temperature variations as variations in intensity on the display screen. Permanent records will be obtained by Polaroid photography.

To decrease detector spot size, a new optical focusing system is to be designed for the radiometer. This will be a close focus Cassegrain System with an ellipsoidal collecting mirror.

Investigations are being pursued into methods for eliminating the need for surface blackening of test plates. Some discussion of this problem is given in the body of this report. Further studies will be reported as the coming continuation study progresses.

Finally, serious preliminary thought is being directed toward the ultimate incorporation of larger area transient heating with very rapid temperature scanning. It is felt that this technique, if practical, will provide the most useful device yet contemplated for thermal nondestructive materials evaluation with infrared readout.

## VII. REFERENCES

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