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NONDESTRUCTIVE TESTING TECHNIQUES
FOR
MULTILAYER PRINTED WIRING BOARDS

George C. Marshall Space Flight Center

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FOR
MULTILAYER PRINTED WIRING BOARDS

30 June 1964 through 30 September 1965

Contract No. NAS8-11288
IITRI Project E6024

Prepared by

Harlan G. Hamre
Robert B. Moler
Raymond A. Zalewski

of

IIT Research Institute
Technology Center
Chicago, Illinois 60616

N66 11764

for

George C. Marshall Space Flight Center
Huntsville, Alabama

Copy No. _____

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FOREWORD

This is Report No. IITRI - E6024-15 (Final Report) of IITRI Project E6024, Contract No. NAS8-11288, entitled, "Nondestructive Testing Techniques for Multilayer Printed Wiring Boards." This report covers the period from 30 June 1964 to 30 September 1965.

Personnel making principal contributions to this investigation include the following:

Robert B. Moler, Associate Physicist - Laminography
Raymond A. Zalewski, Assistant Engineer - Mutual Coupling Probe
Stuart Howkins, Associate Physicist - Combination Acoustical
J. E. Bridges, Senior Engineer, Consultation

Guidance and counsel by the George C. Marshall Space Flight Center in the persons of James F. Blanche, Josef Boehm, and Adolf Herrmann is gratefully acknowledged.

Respectfully submitted,
IIT RESEARCH INSTITUTE

HG Hamre
H. G. Hamre
Research Engineer
Reliability and Components

Approved:

J. L. Radnik
J. L. Radnik
Assistant Manager
Reliability and Components

JA Granath
J. A. Granath
Director of
Electronics Research Division

ABSTRACT

NONDESTRUCTIVE TESTING TECHNIQUES FOR MULTILAYER PRINTED WIRING BOARDS

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A number of candidate nondestructive testing techniques have been examined for applicability to the inspection of multilayer printed wiring boards. The techniques of axial transverse laminography and the mutual coupling probe were selected for more thorough study. Theoretical and experimental results have shown that laminography shows great promise as a practical inspection method capable of being used in 100 per cent inspection since the technique affords adequate layer and defect resolution. The mutual coupling probe also showed promise, but in a more limited sense, since it would be used to inspect each through-hole individually. Application of the probe is envisioned only as an adjunct to laminography in inspecting multilayer boards.

Author

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NONDESTRUCTIVE TESTING TECHNIQUES FOR MULTILAYER PRINTED WIRING BOARDS

I. INTRODUCTION

The rapid advances in the technology of integrated circuit elements have intensified the demand for corresponding improvements in the performance and reliability of interconnection methods. The achievement of high quality interconnections is essential to fully realize the basic advantages of packaging and reliability that are inherent in multilayer printed circuit boards. Although many methods of interconnection are possible, the most common is the plated through-hole, primarily because its method of fabrication is compatible with the general construction techniques utilized for printed wiring boards and because it is adaptable to the small dimensions involved. In the multilayer systems, the layers are usually laminated together and holes are drilled through the layers exposing the conductor metal in cross-section in the holes. Deposition and plating of copper or other metals results in plated holes which connect the various printed conductor layers together.

The quality of the plated through-hole interconnection depends primarily on surface coverage and the nature of the bond between the hole plating and the printed conductors. The thickness of the hole plating is also important to insure low resistance of the interconnection. Because of the small dimensions and the general inaccessibility, conventional inspection techniques do not permit simple evaluation of the interconnection. Furthermore, conventional resistance tests do not readily establish surface coverage, and thickness effects because the resistance of the plated through-hole is generally masked by the resistance of the printed conductors themselves.

II. THE PROBLEM

The goal of this investigation was the development of a nondestructive test which could be applied to 100 per cent inspection of interconnections in multilayer printed wiring boards. This goal has been accomplished. In pursuit of this goal, it was necessary to examine a number of candidate techniques each having certain attributes and shortcomings when applied to this particular problem.

The inspection of a multilayer board can be approached in two basic ways. These are: 1) Inspection of one through-hole at a time; or 2) Examination of the entire board as an entity. Certain techniques lend themselves more to one type of inspection than the other.

Defects in multilayer boards can also be generally categorized. One type of defect is the geometric deviation of an interconnection from the intended configuration. These result in something less than 360° of contact between the conductor pad and the through-hole. The second type of defect is one which is due to poor bond at the interface or oxidation resulting in resistance change not due to geometric deviations. A successful candidate technique is one capable of detecting both of these types of effects.

III. FEASIBILITY STUDY - ALTERNATE SOLUTIONS

A. Candidate Techniques

A number of candidate techniques were examined initially for relative promise in fulfilling the objective of this program. Among those considered were magnetic field sensing, infrared detection, dynamic resistance measurements, double frequency intermodulation, electric field sensing, a combination electrical resistance - acoustical technique, mutual coupling probe, and axial transverse laminography. From this initial study, the laminography and mutual coupling were selected as most promising and given further consideration. A discussion of each of the rejected methods is contained in Appendix I. The results of the laminography investigation and the mutual coupling probe development will be discussed in detail in succeeding paragraphs.

B. Test Board Configuration

A standardized test board configuration was prepared to allow comparison of alternate methods. The boards (obtained commercially) consisted of one set in which geometric deviations from an ideal interconnection were purposely introduced, with a second identical set having no defects. Each board contained four layers with interconnections between each layer and every other layer.

The standard board was established at a 4" x 4" size having a 5 x 5 matrix of through-holes. The optimum interconnection has been defined as that of 360° of the cylindrical hole making contact with 360° of the land to which it is joined. Some joints were deliberately reduced to 180°, the width of the connecting line, a point contact, and an open circuit as produced by a hairline fracture. Drawings of the test board configuration showing the defects are shown in Appendix II.

IV. AXIAL TRANSVERSE LAMINOGRAPHY

The primary purpose of this portion of the research effort was to explore radiography as a nondestructive method for the testing of the integrity of through-hole interconnections in multilayer printed wiring boards. Any technique, to be of value, should be able to inspect through-holes for integrity in a simple yet rapid manner. Early in the program it was determined that ordinary radiography fell short of the requirements for a good testing technique in this application and some other method would be required. Ordinary radiography was not capable of inspecting the critical through-hole area in any detail as a result of the interference from all other layers of the boards. Laminography was considered and preliminary calculations indicated that it held great promise although the problems involved in the practical application were not trivial. During the course of this investigation, it was shown, using a laboratory model with which high resolution laminographs of printed wiring boards were made, that laminography is entirely feasible as a nondestructive testing technique for multilayer printed wiring boards. It is also clear from these results that development in accordance with suggested recommendations will result in a wholly practical method for the nondestructive testing of multilayer printed wiring boards.

A. Technical Discussion

1. Theory

Laminography [1,2,3] is a technique of radiography which allows one to radiograph a thin section of a thick sample without physically sectioning the sample. Thus, it is a powerful nondestructive testing technique.

Laminography and the allied techniques of tomography and solidography depend on the averaging of the unwanted image over a large area with the image of interest remaining sharp throughout the exposure. In laminography this result is achieved by synchronously rotating both the film and the sample during the exposure. How this process achieves such a result will become clear on examination of Figure 1 The figure shows the sample and its image being produced on the film at a single instant in time. One now has a latent image on the film. A second exposure is to be made after a rotation of 180 degrees. It is observed that the new latent image does not coincide with the old image except at the head of the arrow. Only this point has

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1. W. Watson, Radiography 5, (1939).
2. A. Vallebona, Radiography 55, (1950).
3. Takahashi and T. Matsude, Radiography 74, 61 (1960).

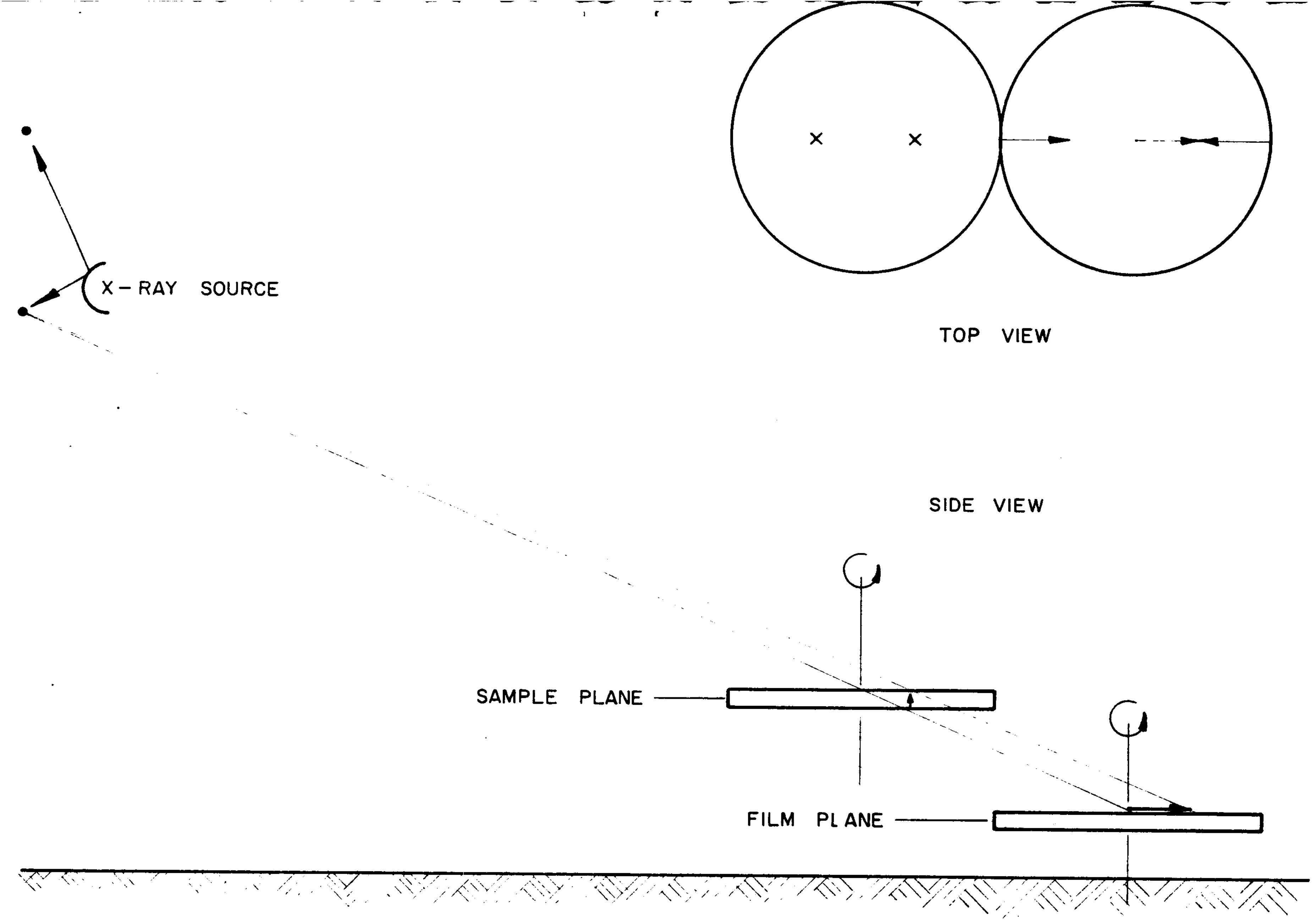

FIGURE I GEOMETRY OF LAMINOGRAPH

produced a reinforced latent image. If one were to expose continuously for the full 360 degree rotation this reinforcement would be much greater. Thus, while the details in the layer of interest are continuously reinforced in the image, details in other layers produce an image smeared over a large area in the film. The subject layer, a sharp image of which is to be recorded, is determined by the geometry of the arrangement and will be a plane parallel to the film passing through the point of intersection of the axis of rotation of the sample and a line joining the source and the axis of rotation of the film.

A number of calculations can be made which indicate the resolution theoretically obtainable and the angle of incidence for best vertical resolution. Since the vertical or layering resolution is of prime importance it will be considered first.

With reference to Figure 2, points outside the subject plane should distribute their image throughout as large an area as possible to achieve good vertical resolution. Thus, a shallow angle of incidence is desirable. The arrow h will result in an image of length ℓ on the film at one instant in time. Since only the top of h is in the subject plane, the lower part of h will result in a smeared image of radius ℓ on the film centered around the image of the top of h. It is easy to show that to a very good approximation, for small h

$$\ell = \cot \theta \frac{d_1 + d_2}{d_1} \tag{1}$$

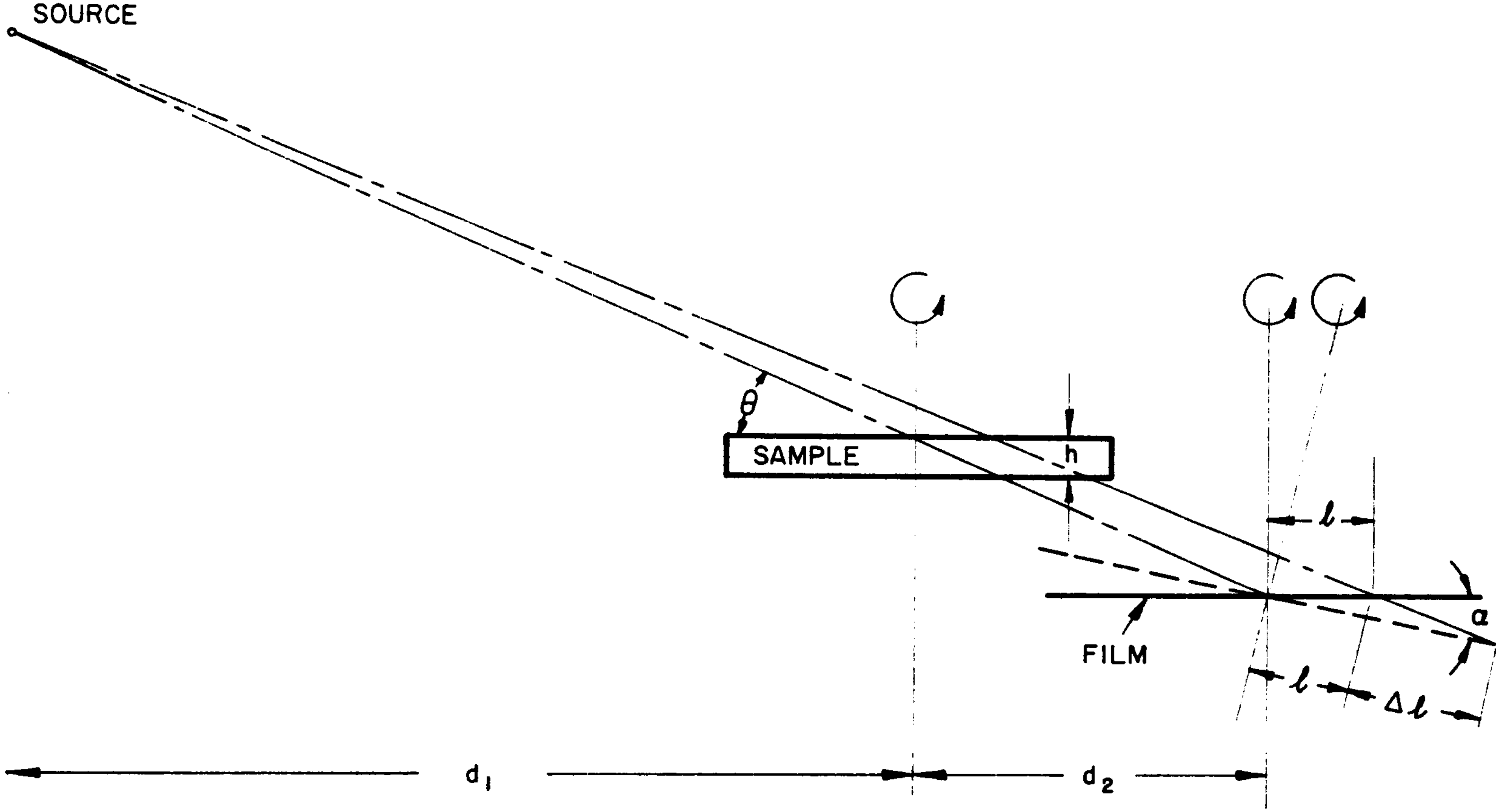

FIGURE 2 GEOMETRY OF LAMINOGRAPH AS IT EFFECTS RESOLUTION

Thus maximum smearing occurs for minimum Θ. Therefore the maximum layer resolution is achieved for minimum angle Θ barring other effects.

The angle Θ may be limited by several factors, among the most significant of which are: (a) the lack of image resolution resulting from the sample and film planes not being parallel, (b) the increased distance the x-ray beam must travel through the sample, and (c) the mechanical problem of supporting and rotating the sample without obstructing the x-ray beam.

Although factor (a) has a theoretical effect on the angle Θ, it is not important in practice and is more significant as a limit on the sharpness of the image formed. Similarily, factor (b) would be important for thick samples and very shallow angles since the exposures would be much longer and scattering would lead to a reduction in image quality; however, such shallow angles cannot be approached due to factor (c) which limits the minimum angle to approximately 20°. This arises from the necessity of having an unobstructed view of the sample and film from the position of the x-ray source. Since the support of the sample is a rim, driven and supported at its periphery, some minimum thickness is required for rigidity. At angles less than 20°, the diameter to thickness ratio becomes very large, and maintaining stability in the rim is difficult. The choice of 20° appears to be a good compromise since it allows adequate planar resolution to be obtained while permitting the system to have a solid mechanical design.

On the question of detail resolution the following points need to be considered to evaluate the image sharpness or resolution that may be achieved: (a) lack of parallelism of the sample and film planes, (b) non-zero size of the source, (c) mis-alignment of the x-ray source with respect to the plane defined by the axes of rotation of the sample and the film, and (d) asynchronous rotation of the sample and film.

The effect of non-parallelism will be considered first. From the figure the top of the arrow h forms an image in the film plane, but if the film plane is tilted, the top of the arrow will generate an image line of length $\Delta\ell$,

where

$$\Delta\ell = \left[\frac{\sin \theta}{\sin (\theta - \alpha)} - 1\right] \cdot \frac{d_1 + d_2}{d_1} , \qquad (2)$$

α being the angle between the sample and film planes, θ the angle of incidence of the x-ray beam on the sample, and d_1 and d_2 being the horizontal displacement of source and sample, and sample and film, respectively. Assuming that θ is small so that $\sin \theta \approx \theta$, the expression for $\Delta\ell$ reduces to

$$\Delta\ell = \frac{\alpha}{\theta - \alpha} \cdot \frac{d_1 + d_2}{d_1} . \qquad (3)$$

This shows that for small values of θ, $\Delta\ell$ is quite sensitive to α due to the occurence of $\theta - \alpha$ in the denominator of this expression. In order to keep $\Delta\ell$ less than 0.001 inches, then α must be less than approximately 1 minute if θ is 20 degrees. We consider that the degree of parallelism implied by $\alpha < 1'$ is readily obtainable and that an error less than 0.5' is possible with care.

Factor (b) above, the non-zero source size, proves to have a small effect in our case. The source size is approximately .0015 inch diameter. The image of this source as viewed on the film plane through a point in the sample plane is a horizontal ellipse whose major axis has a length, I_s, given by

$$I_s = \frac{S_s}{\sin \theta} \quad \frac{d_2}{d_1 + d_2} \qquad (4)$$

where S_s is the source size. Since sin 22° = 0.375 and $d_2/(d_1 + d_2)$ is 0.20, I_s is 0.0008 inch. This causes each point to have a diffuse penumbra whose width is equal to I_s.

Factor (c) results in points on the sample describing a horizontal elliptical path on the film. The major axis of this ellipse will have a length equal to twice the distance of the axis of rotation of the film from the plane formed by the source and the axis of rotation of the sample. This makes it clear that horizontal alignment is rather critical and should be no worse than about 0.0005 inch.

Finally, factor (d) can be readily evaluated by considering the variation in diameters of the rotating sample and film holders. If one wheel were simply larger in diameter by the amount Δd, a point at the distance r from the axis would lead or lag its initial image point by the amount ΔS given by

$$\Delta S = \pi \frac{r}{d} \Delta d \ , \tag{5}$$

after one revolution.

In our case $\frac{r}{d} < 0.5$ and $\Delta d < 0.0005$ inch, so that $\Delta S < .0008$ inch. In any case, the relative speeds of the two wheels may be varied to bring them into synchronous motion except for a small phase effect due to the wheels not being perfectly circular. Considering the worst case, the one in which each wheel is an ellipse whose major and minor axes, a and b, have the ratio $a/b = 1.0002$, resulting from the tolerance of ± 0.005 inch in the diameter of the wheels, one observes that the length of the arc S along the circumference of the ellipse is given by

$$S = a \cdot E\,(k, \phi) \ , \tag{6}$$

where $E\,(k, \phi)$ is the elliptic integral of the second kind. The length s' along the circumference of a circle is given by

$$s' = r\,\phi \ . \tag{7}$$

The difference $\Delta s = s - s'$ as a function of ϕ gives the total linear displacement error as a function of rotation. Setting $d(\Delta s)/d\phi$ equal to 0 and solving for ϕ one finds that angle of maximum displacement to be $\pi/8$ approximately. The maximum displacement Δs_{max} is then found to be 0.0003 inch.

It is difficult to say exactly how factors (a) through (d) above will combine, but assuming a summing of errors, the worst image detail resolution will be 0.0025 inch, a figure which might be bettered if a more elaborate system were constructed in which each of the factors mentioned were limited to minimum effects on image quality.

2. The Laminograph

a. Construction Details

The laminograph was constructed around a microfocus x-ray machine using a Hilgar and Watts* x-ray tube. This tube has a source size of approximately 1.5 mil diameter. The low power of the high-voltage unit for this machine severely limits the x-ray beam intensity, making long exposures necessary.

The rotating tables for the sample and film are supported at three points on their rims by precision bearings in contact with a 45 degree bevel, machined and ground into the rim. The tables themselves were precision machined and ground from low distortion vega steel. The drive mechanism is by a ground rubber rim contacting the rims of the two tables. Changing the compression of the rubber rim causes a variation in the driving ratio allowing precise synchronism to be achieved. The rate of revolution as set by the small motor was approximately one revolution per minute. This was later changed to 0.5 revolutions per minute to permit twice the exposure time with no increase in distortion due to asynchronous rotation of sample and film. The upper wheel has a recessed surface to accomodate a sample

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* Hilgar and Watts Lmd., London, England.

while, to achieve the necessary flatness of the film, a simple vacuum hold-down is incorporated into the lower table.

The vertical motion required to produce an image of a given layer is achieved by having the x-ray tube mounted on an optical micrometer slide mechanism. Plate I is a photograph of the completed apparatus.

b. Operation

When first evacuated and operated at voltage, considerable high voltage arcing was encountered. This was traced to inadequate grounding of the x-ray tube itself resulting from the relocation of the tube from its original position on the high voltage supply cabinet, to the laminograph table. No adequate means had been provided to ground the tube since the vacuum connection had been deemed adequate. A heavy ground cable between the tube and power supply cabinet solved the problem.

During the alignment, as discussed in succeeding paragraphs, a faint image of the vacuum hold down grid could be observed on several negatives. Investigation showed that this image was apparent only in the emulsion in contact with the film table. This indicates that it is produced by photoelectrons from the table, but that these photoelectrons are largely absorbed in passing through the x-ray film base and do not produce an appreciable exposure of the upper emulsion. In all subsequent work only the upper emulsion of a film was developed, the emulsion in contact with the table being stripped with fixer.

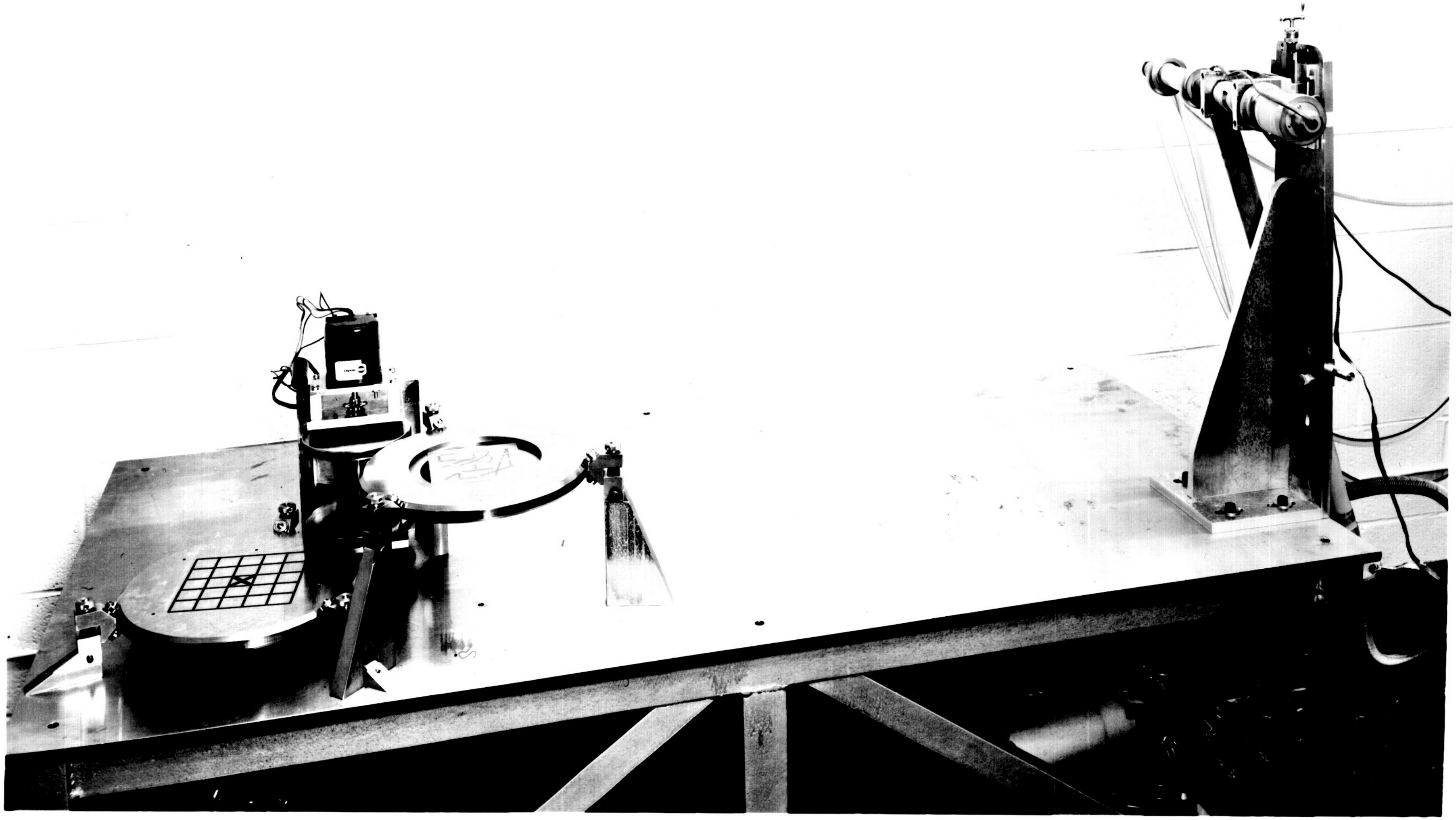


PLATE I EXPERIMENTAL LAMINOGRAPH

A much more serious effect encountered when both emulsions are developed is the substantial lowering of image quality. This is a consequence of the 8 mil separation between the two emulsions producing distinct images of similarly separated layers in the sample. When one emulsion only is developed, the improvement is quite evident.

This result is not unexpected in light of the previous discussion on resolution and layering sensitivity. From Eq. (1) it can be seen that a layer separation of 8 mils will result in two readily distinguishable images. It is not surprising that the images formed on the top and bottom emulsions of a film of this thickness are sufficiently different to give the appearance of degraded resolution. Since to develop only one emulsion is a somewhat cumbersome process, single coated film is obviously a considerable advantage. Eastman Kodak can provide such film, but none was immediately available. Double coated film was used for all the laminographs made during this work, with only one emulsion being developed.

One additional concern has to do with any possible nonuniformity in film thickness which also would lead to a decrease in image quality. On examination of typical film from Kodak the base material was found to have a uniform thickness within ± 0.00005 inch, the emulsion thickness having an even lower tolerance. Any variation in height, and consequent resolution loss, due to the film certainly would be no greater than 0.0001 inch, a value which is much smaller than other sources of resolution loss.

c. Alignment

The alignment of the instrument is rather critical as noted in the previous discussion on resolution. Rotation synchronism was achieved by adjusting the differential compression on the two wheels. Measuring the relative displacment after a number of revolutions gives a measure of the degree of asynchronism. This alignment could be made as precise as 0.0003 inch per revolution, for a short period of time. It was observed that a very small accumulation of dirt on any bearing surface would destroy this synchronism resulting in a tedius realignment. In general, the synchronism observed while most of the laminographs were being made was much worse than the above figure although it rarely exceeded 0.001 inch per revolution.

The parallelism of the two tables was readily measured using a height gauge so that the axes of rotation were made parallel to within 0.0005 inch in 10 inches or approximately 1.5 minutes. This value is larger than anticipated and is due principally to the lack of flatness of the tables which proved to be approximately ± 0.0005 inch, a figure somewhat larger than originally specified.

Horizontal alignment was obtained by exposing an off-center cross-hair twice, the second time after a 180 degree rotation. The separation of the two images of the wire parallel to the x-ray beam direction is twice the horizontal misalignment of the two tables with respect to the x-ray source. This alignment could be made as close as 0.0002 inch. It was found initially that vertical movement of the x-ray source was a source of horizontal misalignment. By using a guide to hold the slide mechanism at a fixed 90 degrees from the horizontal, this effect was eliminated.

Vertical calibration of the x-ray source was effected by using the cross-wires to find the level of the shelf used for sample support. In agreement with calculations it was found that the ratio of change in source height to change in sample height was 4.8 so that a change of 0.1 inch in the source will change the image layer in the sample by 0.021 inch.

3. High Resolution Laminography

After acceptable alignment had been achieved, a number of laminographs were taken of the sample defective multilayer and single-layer printed wiring boards containing known defects. Plate II shows a single-layer board in which a series of cuts have been made in one conductor. The smallest cut, which is 0.003 inch, is clearly apparent. Plate III shows the bottom layer of a four-layer board achieved by developing one side of a standard 5 x 7 Kodak type KK industrial x-ray film. It should be observed that not all of the layer appears in focus. The resolution of the technique is such that if for any reason, such as board warpage, all of a layer is not in a given plane

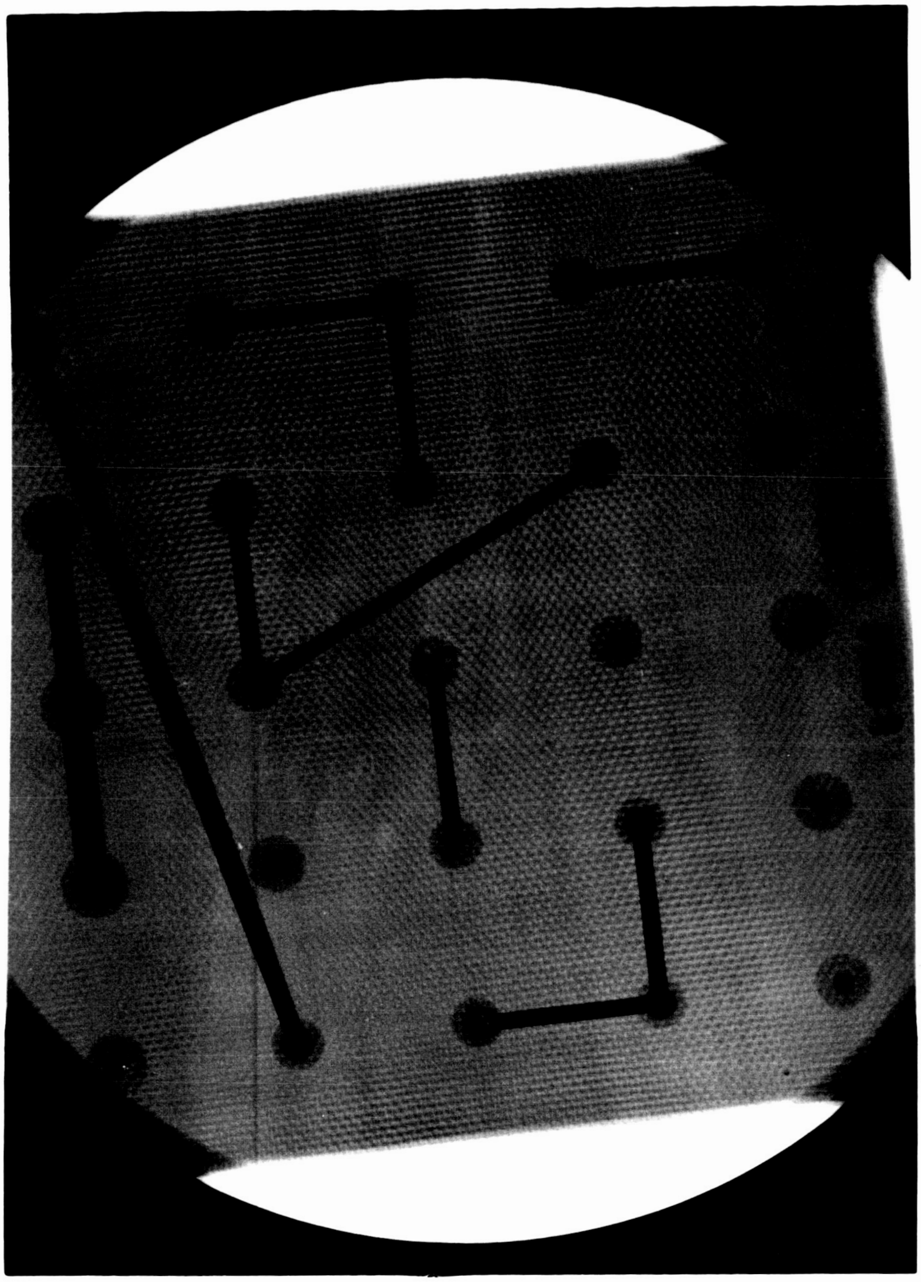


PLATE II. LAMINOGRAPH - SINGLE LAYER BOARD - CUT CONDUCTORS

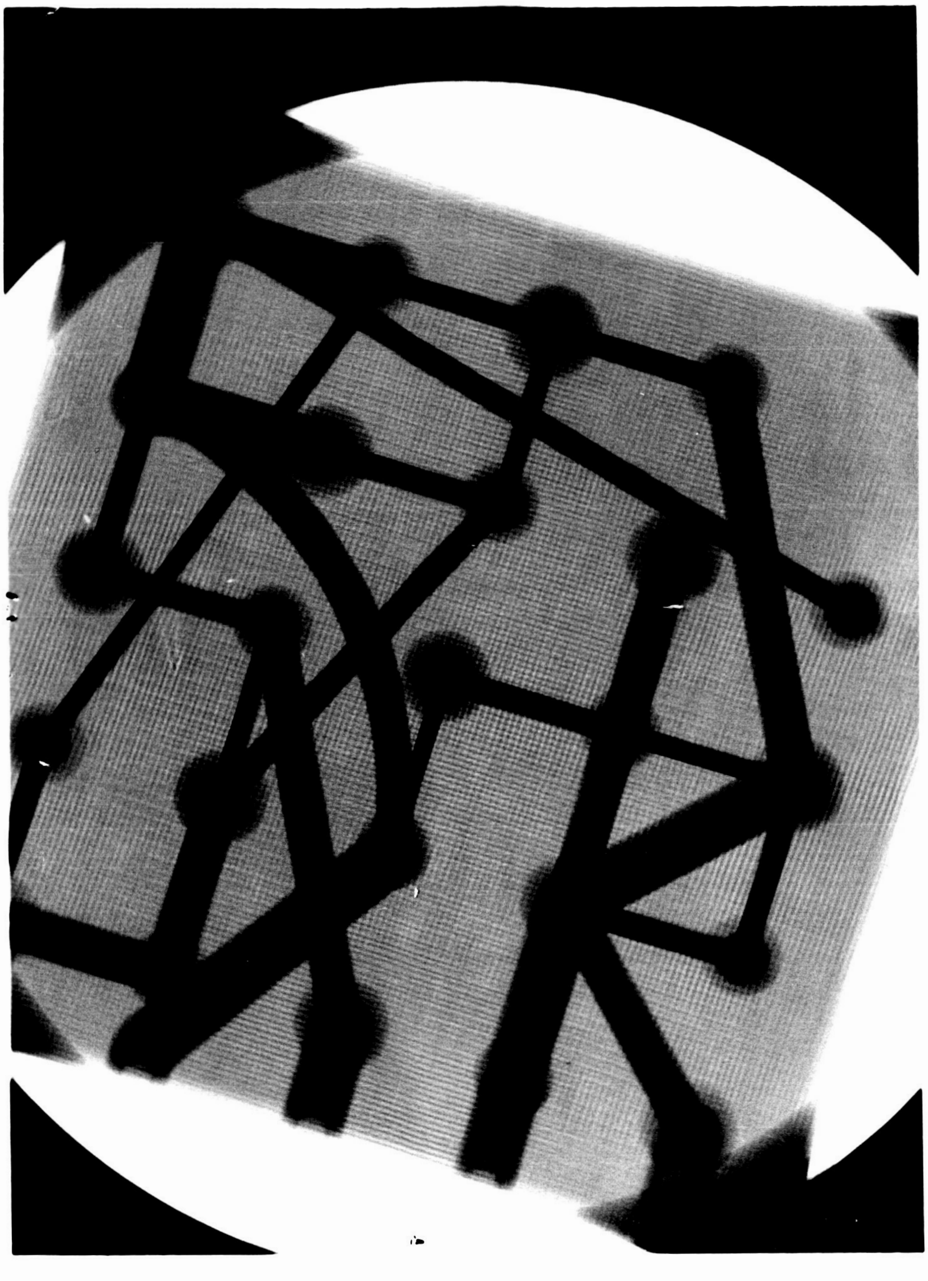


PLATE III. LAMINOGRAPH - LAYER FOUR OF THE FOUR LAYER DEFECT BOARD within about 0.005 inch, some parts will be out of focus. This necessitates that more than one picture per layer be made.

In Plate II of the single-layer board, one can clearly see the area of contact between off-center through-holes and the ring pad. Since the through-holes in this board have thinner walls and have less material on the surface they register much better than do the four-layer boards with thick-walled plated or eyeleted through-holes.

It must be pointed out that detail in the immediate neighborhood of an eyeleted through-hole is not good. This is due principally to the amount of material through which the x-rays must pass. At the energy (25 keV silver K x-ray), and intensity available, these eyeleted and plated through-holes are essentially opaque. Use of a somewhat higher energy and a higher beam intensity should improve this situation considerably, since it would make the material appear more transparent.

In Plates IV, V, and VI, one sees the successive layers of the board with somewhat less contrast than that observed in Plate II. Detail in these plates is quite good, essentially equal to that observed in Plates II and III. As in these plates a single exposure is inadequate to look at a complete layer due to the lack of flatness of the board.

During the time these laminographs were made, the x-ray beam intensity steadily deteriorated requiring longer and longer exposures to achieve good contrast. The tube was opened to air

PLATE IV. LAMINOGRAPH - LAYER THREE OF THE FOUR-LAYER DEFECT BOARD

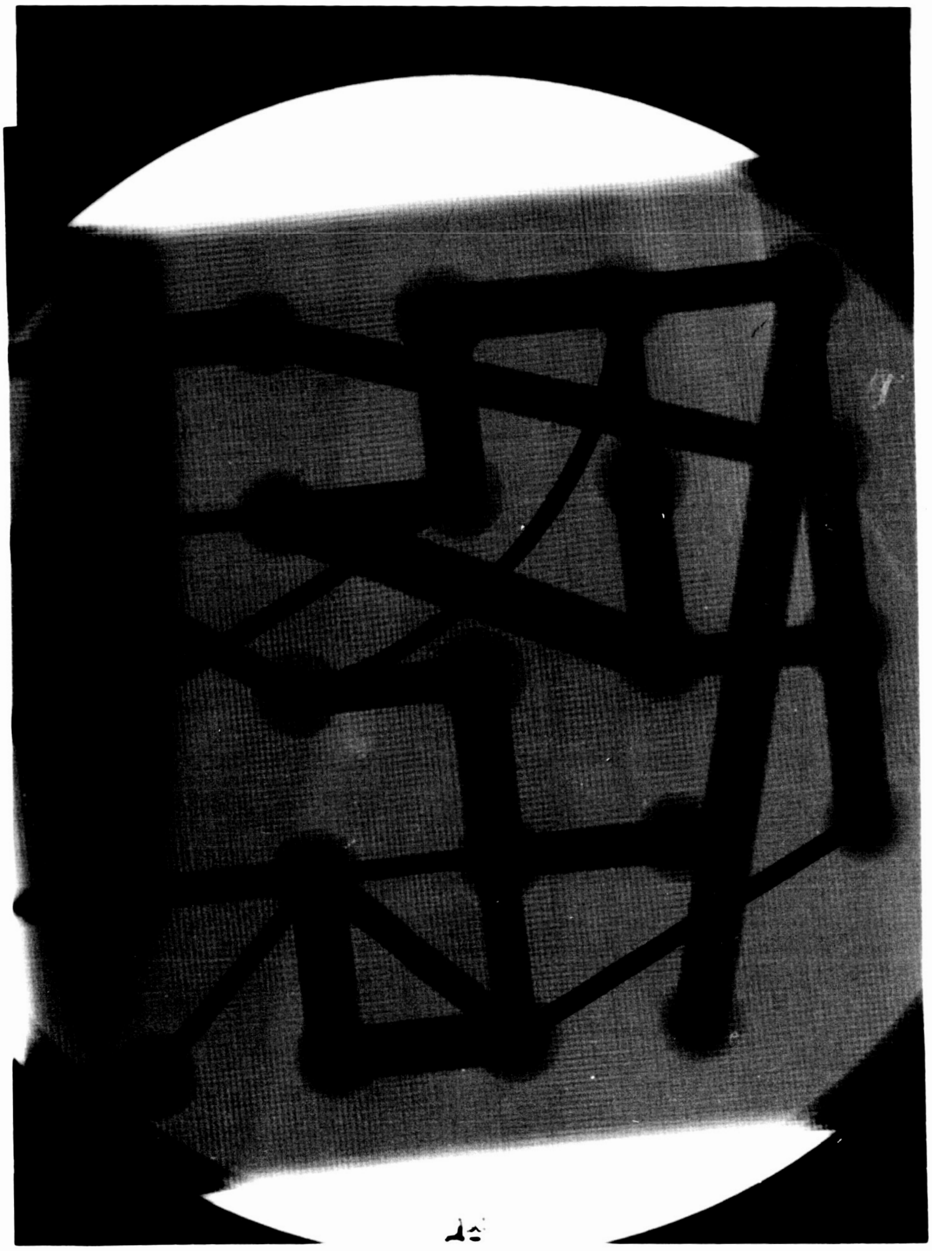


PLATE V. LAMINOGRAPH - LAYER TWO OF THE FOUR-LAYER DEFECT BOARD

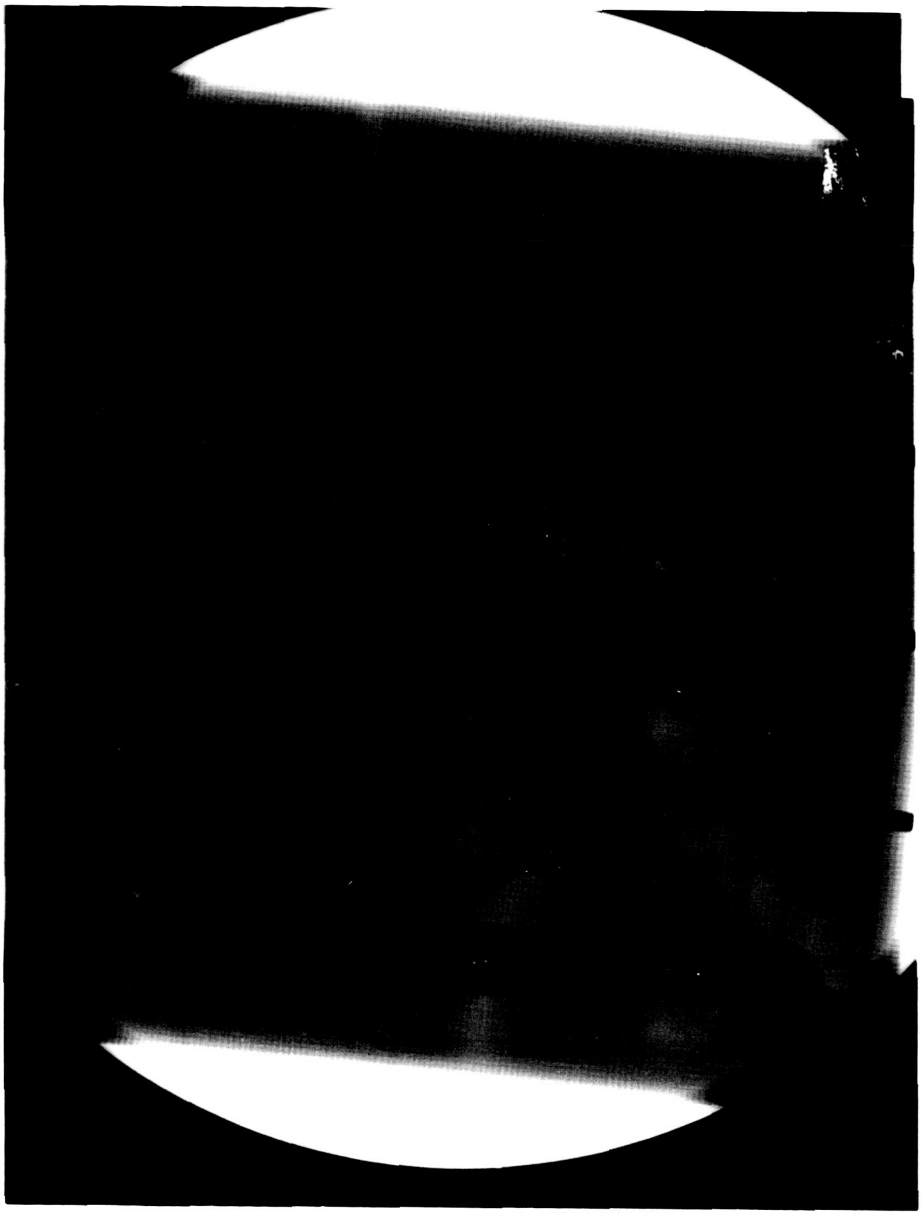


PLATE VI. LAMINOGRAPH - LAYER ONE OF THE FOUR LAYER DEFECT BOARD and the anode was cleaned, but on reassembly, difficulties with the high voltage supply prevented further laminographs from being taken before the project terminated.

Close examination of these plates reveal that detail is limited by the graininess of the film. Originally it had been expected that a fine grain type AA would be used. The low intensity of the x-ray beam made this unfeasible and Kodak type KK was the only film that it was practical to use if a laminograph was to be made in a reasonable time. Even using this film, exposure times as long as eight minutes became necessary. A higher intensity would improve this situation greatly.

A significant point concerning the lack of intensity is that the synchronism of the table becomes very critical as the exposure time is increased to 5 minutes and longer. Plates III-VI were exposed for eight minutes each and suffer from resolution loss due to asynchronism, which at the time these laminographs were made, amounted to 1.0 mil/resolution.

Even in view of these limitations, the results as seen in Plates II through VI show that good detail can be observed throughout a multilayer board and that with minor improvements, substantially greater detail is certainly possible.

B. Comparison of Experimental Results With Theoretical Expectations

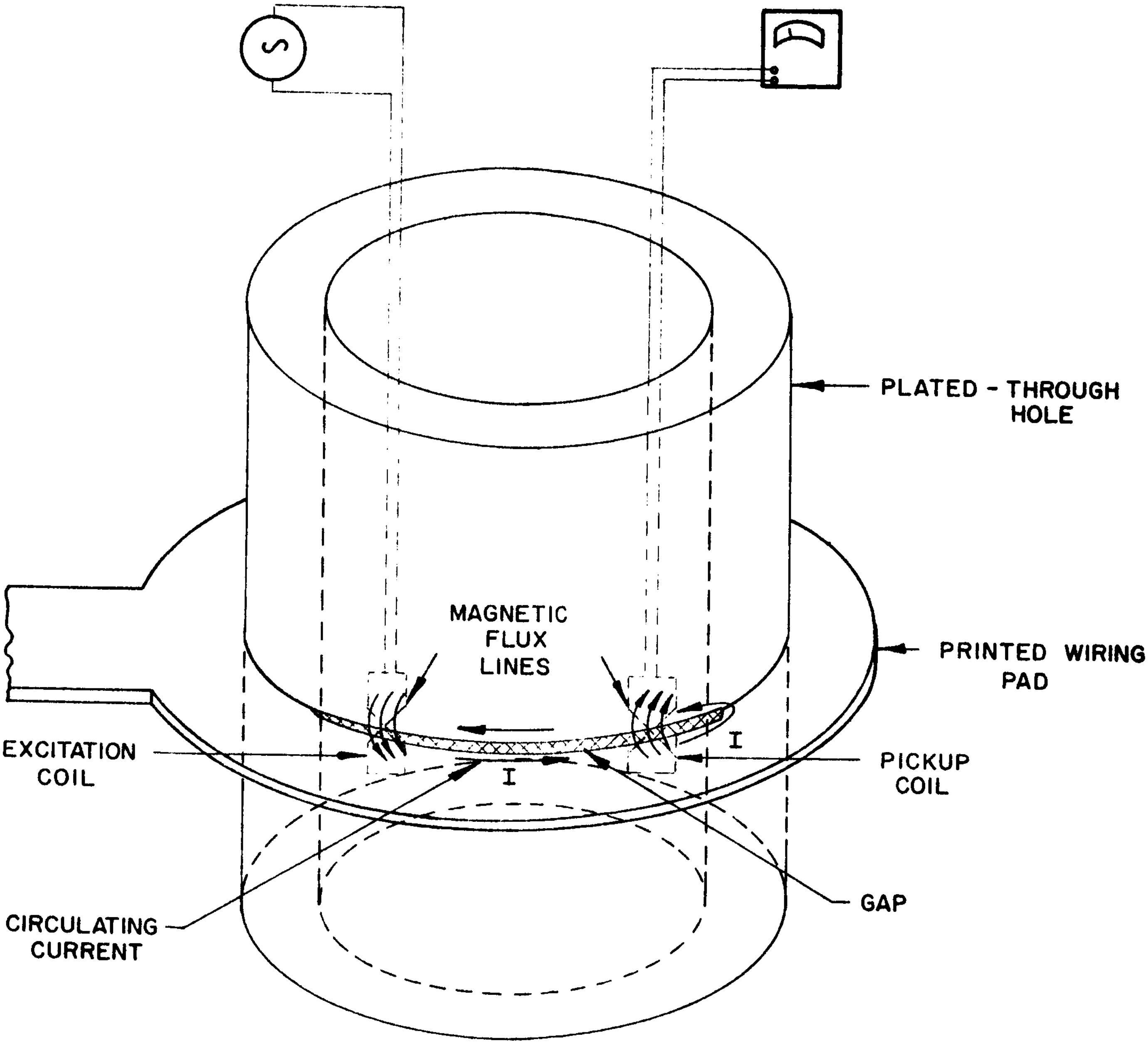
Comparison of the results shown in the plates indicate that the theoretical expectations have been largely borne out by experiment. In Plate II the observation of the five cuts clearly demonstrates the detail resolution which is certainly no worse than 0.002 inch. This compares very favorably with the expected detail resolution of 0.0015 inch.

The layering sensitivity is illustrated by Plates III through VI. The board layers shown in these plates are separated by approximately 0.015 inch. The ability of the laminograph to clearly separate adjacent layers is evident. Examination of one plate indicates that one can even observe the slight variations from planeness of a single layer. Furthermore, the results obtained from developing the top emulsion of one film and the bottom of a second showed that this 0.008 inch separation was sufficient to cause complete misregistration of the subject plane. This is evidence that layer sensitivity is no worse than 0.008 inch compared to an expected 0.004 inch. It is thus clear that within the limitation of the present instrument the theoretical expectations have been verified.

V. MUTUAL COUPLING PROBE

A. Probe Operation

The problem of detecting a gap or poor electrical connection between the metal cylinder of a plated hole and a printed wire, especially when part of this connection is sound, is a difficult one. One method which has shown promise is the method of mutual coupling. This method uses the presence of the gap or high resistance area of the connection to develop an output signal. The application of this technique to the inspection of a plated through-hole connection is shown in Figure 3. Two coils, wound in the form of a figure "8", are magnetically shielded from each other and formed into a probe which is inserted into the through-hole. A signal generator is connected to one of the coils, called the excitation coil, and when this coil is brought near a gap between the plated hole and the printed wiring, the magnetic field from the coil induces a current in the loop formed by the edge of the gap. The magnetic field from this current, which circulates around the gap, in turn, induces a voltage in a second coil, the pickup coil, which is shielded from the direct field of the exciting coil. The pickup coil is then connected to a tuned voltmeter which indicates the presence of the induced voltage. When there is no gap between the plated hole and the pad, the currents that are induced in the pad circulate in the region of the pad near the exciting coil and hence induce little voltage in the pickup coil.



IGURE 3 PRINCIPLE OF OPERATION OF MUTUAL COUPLING PROBE

B. Results of Experiments

Preliminary experiments were made using flat sheets of brass and copper which had metal strips soldered to them with varying degrees of completeness to simulate defective connections. Output voltage ratios of 25-to-1 were obtained in comparing signals obtained from bad connections to those obtained from good connections. A diagram of this experiment is shown in Figure 4.

A large mutual coupling probe, Figure 5, was constructed based on these preliminary results. The pickup and excitation coils were wound with four turns of wire in the form of figure eights and were mounted on the circumference of the probe. To simulate the plated hole, a brass cylinder with an inside diameter of 0.91 inches and an average wall thickness of 0.027 inches was used. Defective and non-defective electrical connections were made to this cylinder by wrapping a 0.027 inch diameter wire once around the cylinder and soldering it to the cylinder along 180 degrees of circumference. This left the 0.0015 inch wire insulation as the gap in the remaining 180 degrees of circumference. Measurements were made with the probe inserted in the cylinder using a current of 100 mA at a frequency of 50 kc passed through the excitation coil. When the probe coils were under the cylinder wall alone, a pickup coil output voltage of 0.39 microvolts was measured. When the coils were moved under the soldered connection, a pickup coil voltage

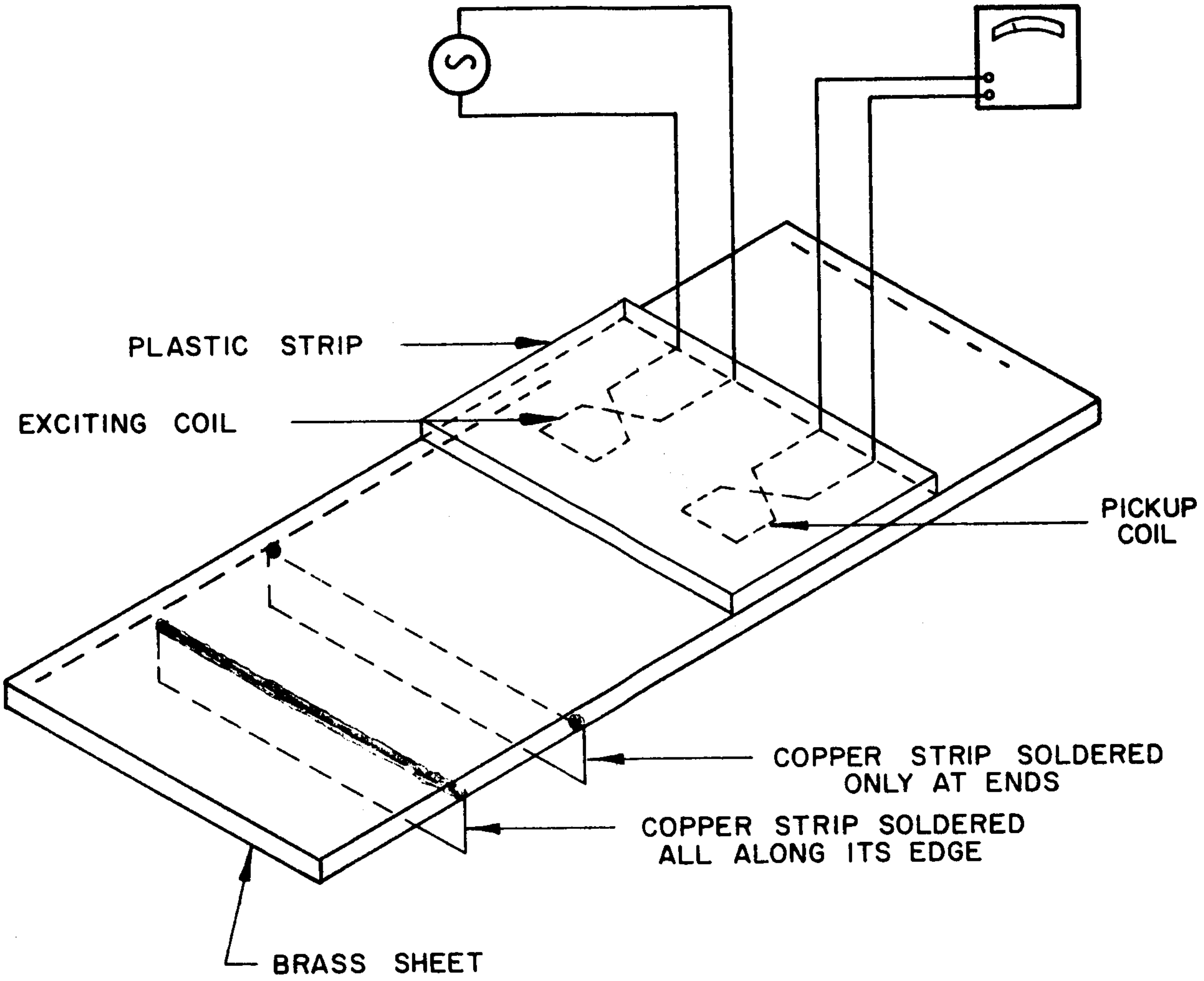


FIGURE 4 PRELIMINARY EXPERIMENTAL CHECK OF MUTUAL COUPLING PRINCIPLE

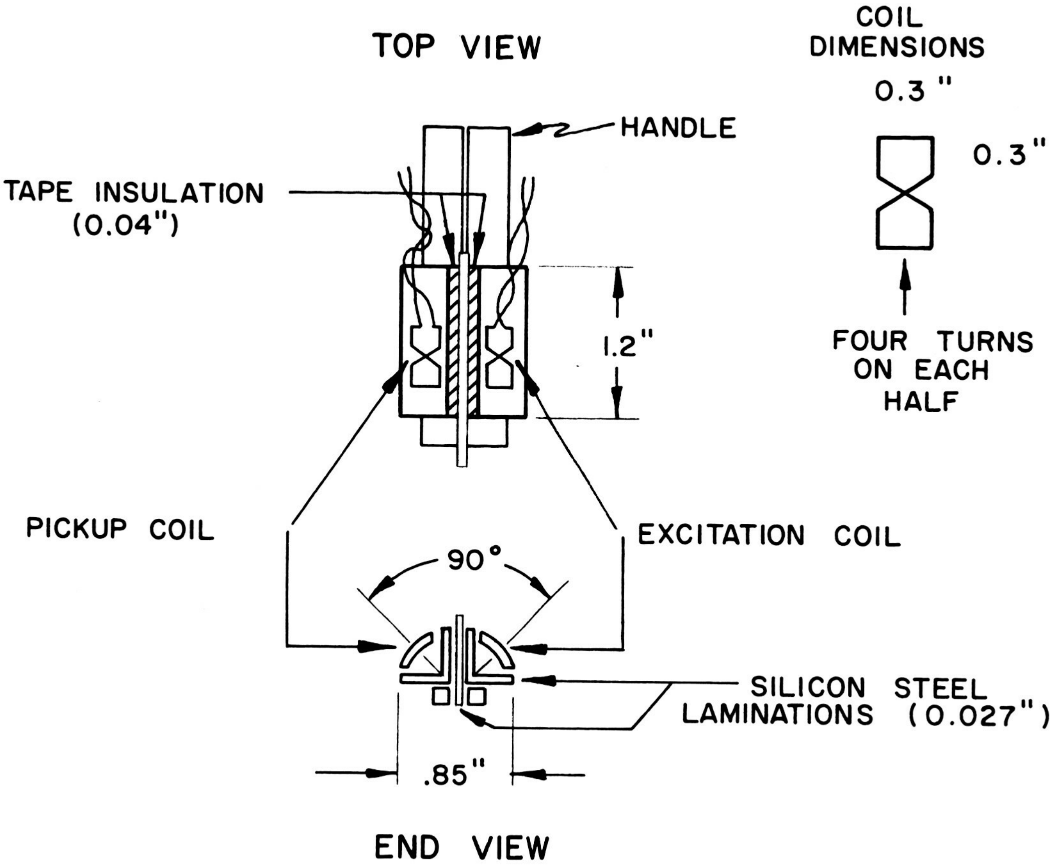


FIGURE 5 LARGE MUTUAL COUPLING PROBE

of 0.57 microvolts was obtained. As the cylinder was rotated so that the coils moved under the unsoldered gap, the pickup coil output voltage increased to 15.6 microvolts. This gave a ratio of gap voltage to soldered connection voltage of about 2 7, (Table I). This served to demonstrate the sensitivity of this method in detecting geometric deviations in the interconnection.

In order to simulate the type of defect which might occur where the interconnection is a rivet rather than a plated hole, an experiment was also made in which a bare copper wire was wrapped around a conducting cylinder. By varying the tension on the wire, a connection having low resistance, but mechanically unstable, characteristics is formed. It was found that the probe could adequately detect this type of connection, and that the output voltage ratio decreased as the tension in the wire was increased.

To facilitate measurement of the very small voltages obtained at the pickup coil, a step-up (10 to 1) transformer was used between the pickup coil and a radio receiver. This resulted in system noise levels of only about 0.01 microvolt.

Results from the preliminary experiments performed on the flat brass and copper sheets indicate that if a copper instead of brass cylinder had been used to simulate the plated hole, the pickup coil output voltages would have been reduced to 1/2 or 1/3 the values measured. However, the voltage ratio should remain unchanged.

TABLE I

PICKUP COIL VOLTAGES FOR THREE MUTUAL COUPLING PROBES

(Excitation Current = 100 mA)

PROBE PARAMETERS	CYLINDER WALL THICKNESS, INCHES	GAP WIDTH, INCHES	CYLINDER WALL VOLTAGE, V_{cw} MICROVOLTS	SOLDERED CONNECTION VOLTAGE, V_{sc} MICROVOLTS	GAP VOLTAGE, V_g MICROVOLTS	RATIO, V_g/V_{sc}
Probe Dia. ≈ 0.85" freq. = 50 kc cyl mat'l = Brass	0.027	0.0015	0.39	0.57	15.6	27.4
Probe Dia ≈ 0.080" freq. = 500 kc cyl mat'l = copper	0.004	varied	0.41	0.78	4.6	5.9
Probe Dia. ≈ 0.020" freq. = 2 mc. cyl mat'l = copper	0.0015	<0.0001	0.12	--	1.0	8.34*

* $\frac{V_g}{V_{cw}}$

Since usable output voltages were obtained with the large probe, a smaller probe was built as a first step in miniaturization. This probe, which had a diameter of approximately 0.080 inches, was made by mounting two four-turn figure eight coils on two pieces of sheet iron (Figure 6). The sheet iron lamination (the exact composition of the sheet iron is not known) served as magnetic shielding between the coils and had to be bent at 120 degrees to accomodate the figure eight coils, which were a little too large to fit into 90 degree L-sections. To simulate the plated hole, a cylinder whose diameter was approximately 0.080 inches was constructed by bending a section of 0.004 inch thick copper sheet around a rod and then soldering along its edge. This cylinder was then placed through a hole in a second flat section of the 0.004 inch thick copper and the cylinder was then soldered at one point to this flat section, leaving a gap between the cylinder and the flat section for the rest of the circumference of the cylinder. This construction simulates an extreme case of a defective interconnection. A good connection was prepared using a similar copper cylinder but with the flat copper strip soldered completely to the cylinder around its circumference. When the excitation coil of this probe was fed with a 100 ma, 500 kc current, and the probe placed in these cylinders, the following pickup coil voltages were measured: (1) probe coils under cylinder wall, 0.4 microvolts; (2) probe coils under soldered connection, 0.78 microvolts; and (3) probe coils under gap, 4.6 microvolts.

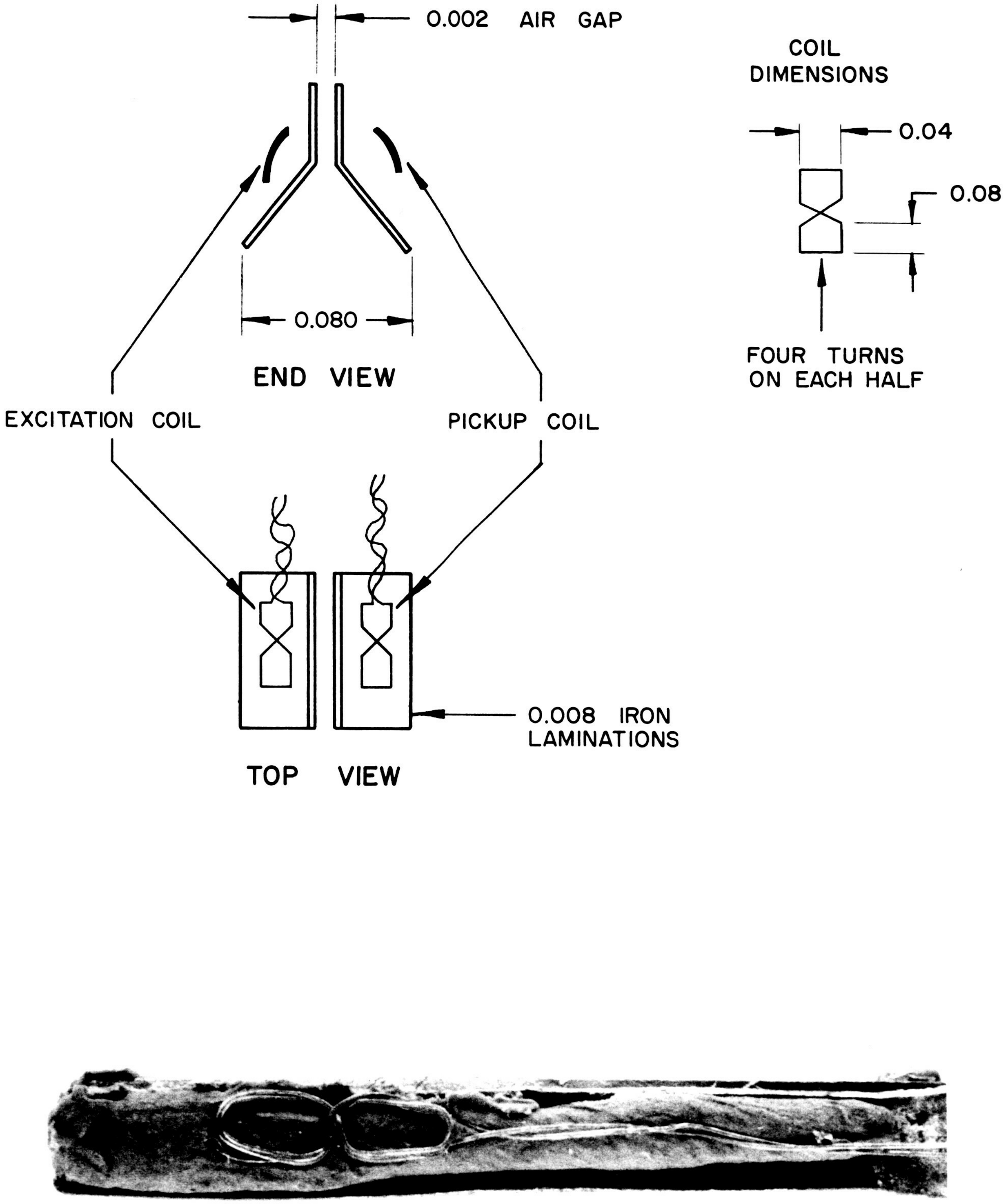


FIGURE 6 80 MIL DIAMETER MUTUAL COUPLING PROBE

These values give a gap-to-soldered connection ratio of about six. Upon comparing the gap voltage (see Table I) of this probe, with 1/2 to 1/3 (estimated amount of reduction that would have occurred if a copper instead of a brass cylinder had been used in the 0.85" D probe) of the 0.85" D probe gap voltage, it is seen that, for a change of a factor of ten in the probe size, only a small change in the gap voltage occurs. It should also be noted that the construction of the 0.080" D probe was not exactly the same as that of the 0.85"D probe. If permalloy or ferrite had been used for the shielding material, the direct pickup would have been reduced, yielding a better voltage ratio. This direct pickup might also have been reduced if a center straight piece of shielding (as in the 0.85" D probe) had been used and kept pressed against the side of the cylinder during the operation of the smaller probe. Also, the back turns of the excitation and pickup coils were partially against the shielding and hence their effectiveness was reduced.

Since results of the 10-to-1 reduction in probe size were encouraging, a further attempt at miniaturization was made. This probe was approximately 0.020 inches in diameter, with the shielding arrangement, using 50 per cent nickel-iron alloy laminations, being a scaled down version of that used on the 0.85" D probe (Figures 7 and 8). The excitation and pickup coils were again wound in the form of figure eights of 0.001 inch diameter copper wire. It proved to be difficult to wind these coils in two layers of two wires each, so that

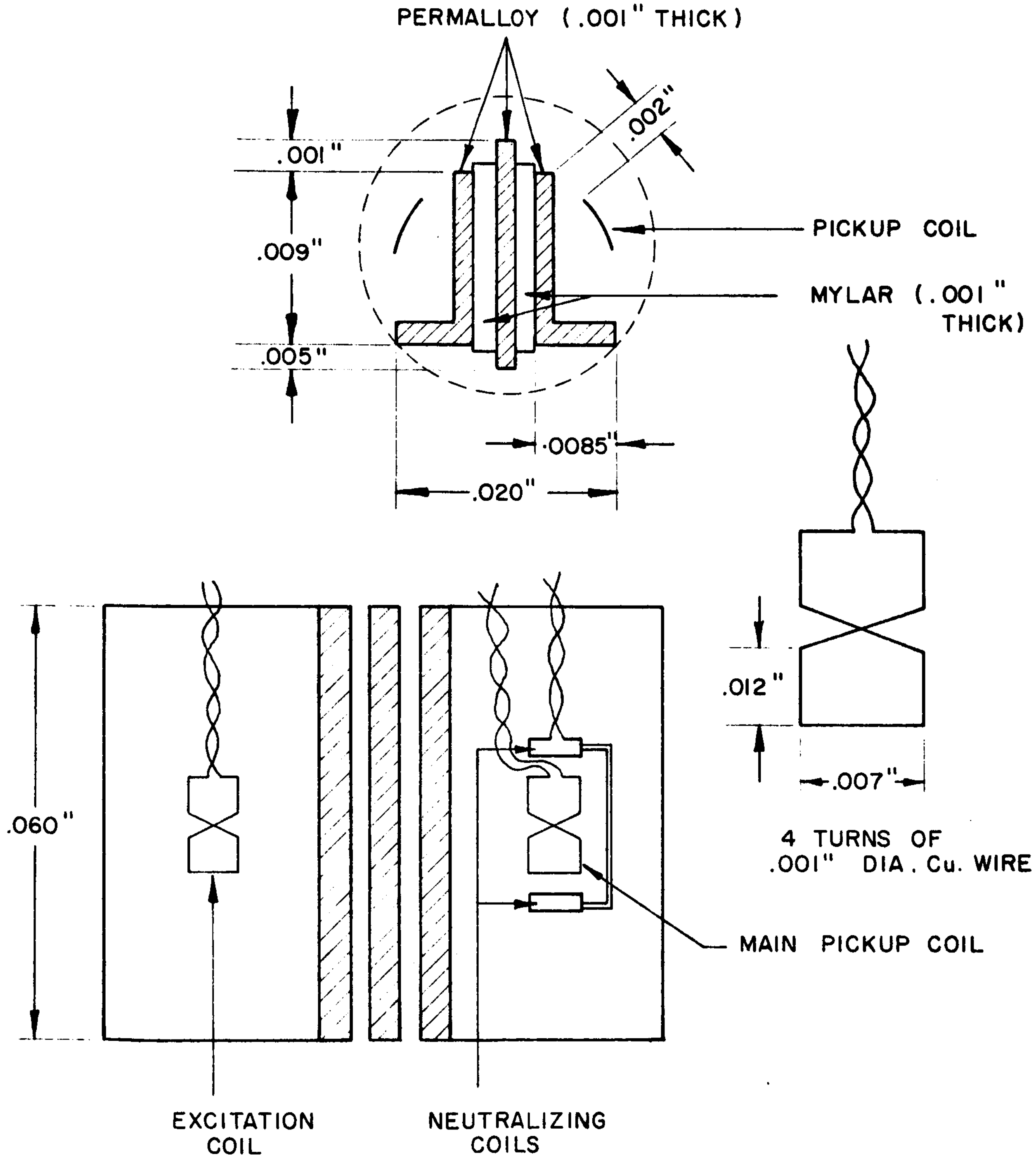


FIGURE 7 MINIATURE MUTUAL COUPLING PROBE AND NEUTRALIZATION ARRANGEMENT

FIGURE 8 20 MIL DIAMETER MUTUAL COUPLING PROBE one layer of four wires had to be used. This required that the coils be placed against the shielding and hence in-line with each other. This arrangement increased the direct pickup from one coil to another and also made the back turn or two of these coils somewhat ineffective as generators or sensors of magnetic flux. It was therefore expected that the gap voltage received would be reduced to 1/3 or 1/4 of the value expected based on the measurements made with the larger probes. A plated through-hole was again simulated using a 0.0015 inch thick strip of copper wrapped around a 0.025 - 0.027 inch diameter rod and then soldering the cylinder along its side.

A gap of approximately 230° in length was formed by soldering ends of a 0.001 inch diameter wire to the cylinder. The wire insulation again constituted the majority of the gap width (<.0001 inch). The excitation coil was driven with 100 ma of current at a frequency of 2 megacycles. This frequency was selected on the basis of the scaling factor, and further voltage gain was achieved by tuning the transformer between the pickup coil and the receiver.

The miniature (0.020" D) probe experiment was conducted in a shielded enclosure since stray signal pickup proved troublesome in the normal laboratory atmosphere. This resulted in cylinder voltages of about 0.12 microvolt and gap voltages of about 1.0 microvolt. Wire breakage prevented soldered connection measurements with this arrangement. However, it is expected that the soldered connection measurements using the 0.020" D probe would be about 25 per cent of those obtained with the 0.080" D probe.

Experiments to more completely characterize the properties of the probe family were conducted with the 0.080" D and 0.85" D probes. This was done for the following reasons:

1. The 0.020" D probe is extremely delicate and difficult to work with in its present state.
2. The scaling factor has been found applicable for frequency change, voltage ratio, and gap width.

These experiments will be discussed in succeeding sections. Table I compares the output characteristics of the three probes while Figure 9 is a comparison of the physical sizes of the probes.

C. Probe Response with Variation in Cylinder Wall Thickness

The effect of cylinder wall thickness was examined using brass cylinders of wall thicknesses measuring 0.027, 0.040, and 0.067 inches, respectively. A 0.027 inch diameter copper wire was soldered to each cylinder along 180° of circumference as previously described to achieve representation of "good" and "bad" connections. Output voltages versus frequency using a constant excitation current of 100 ma were measured and are shown in Figures 10, 11, and 12.

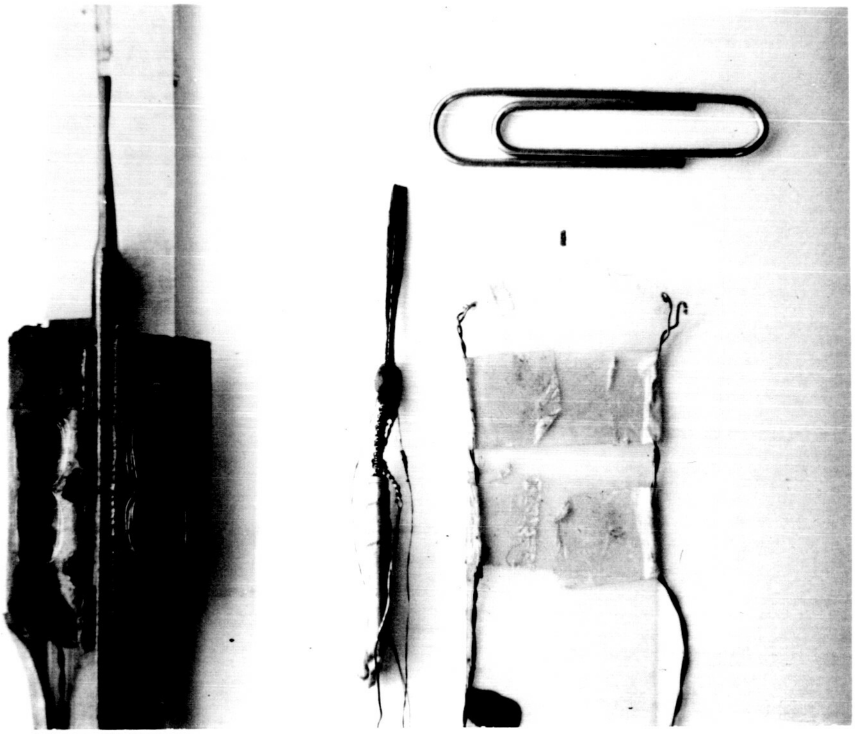


FIGURE 9 COMPARATIVE SIZES OF MUTUAL COUPLING PROBES

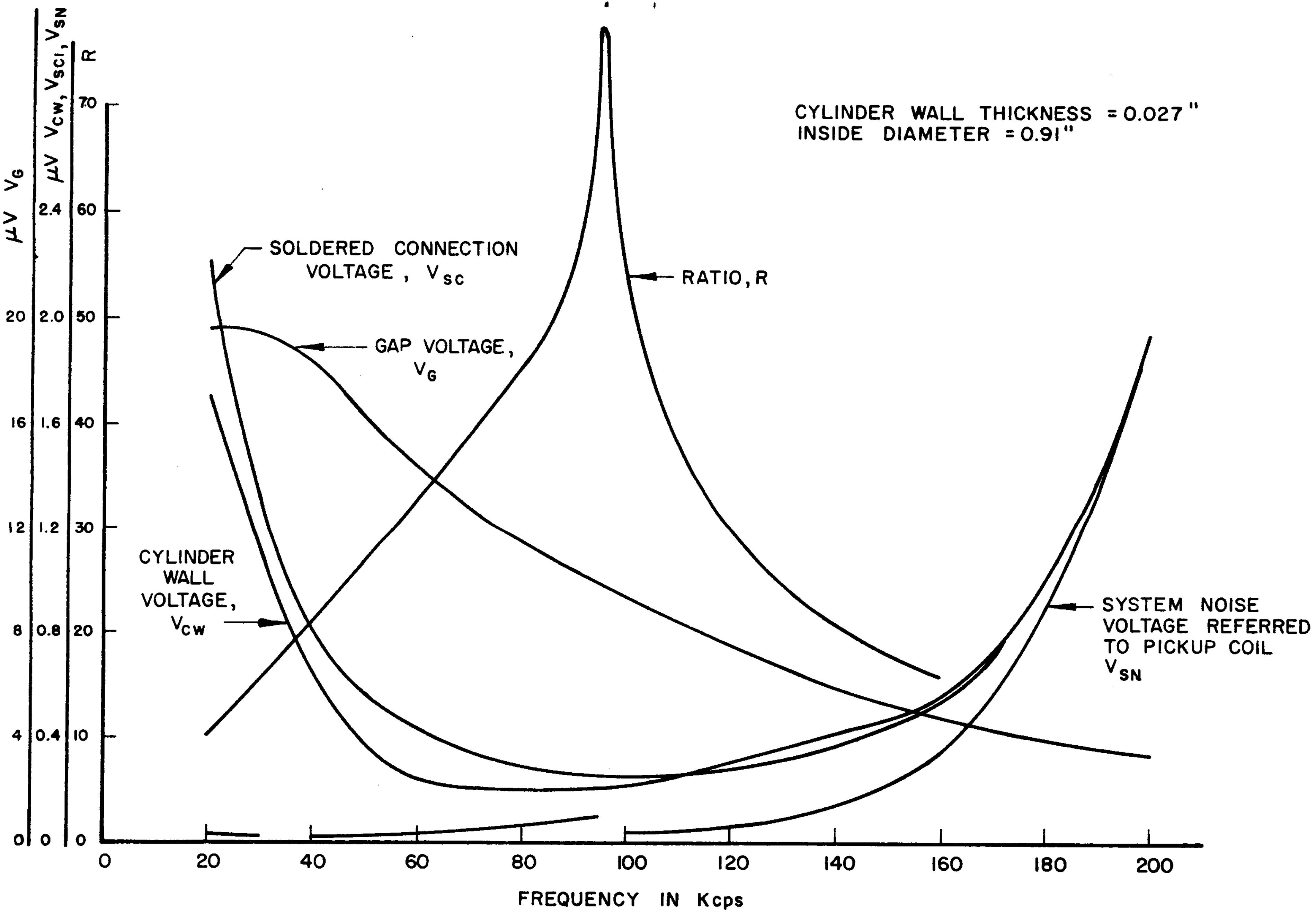


FIGURE 10 PROBE RESPONSE FOR 0.027 INCH CYLINDER WALL

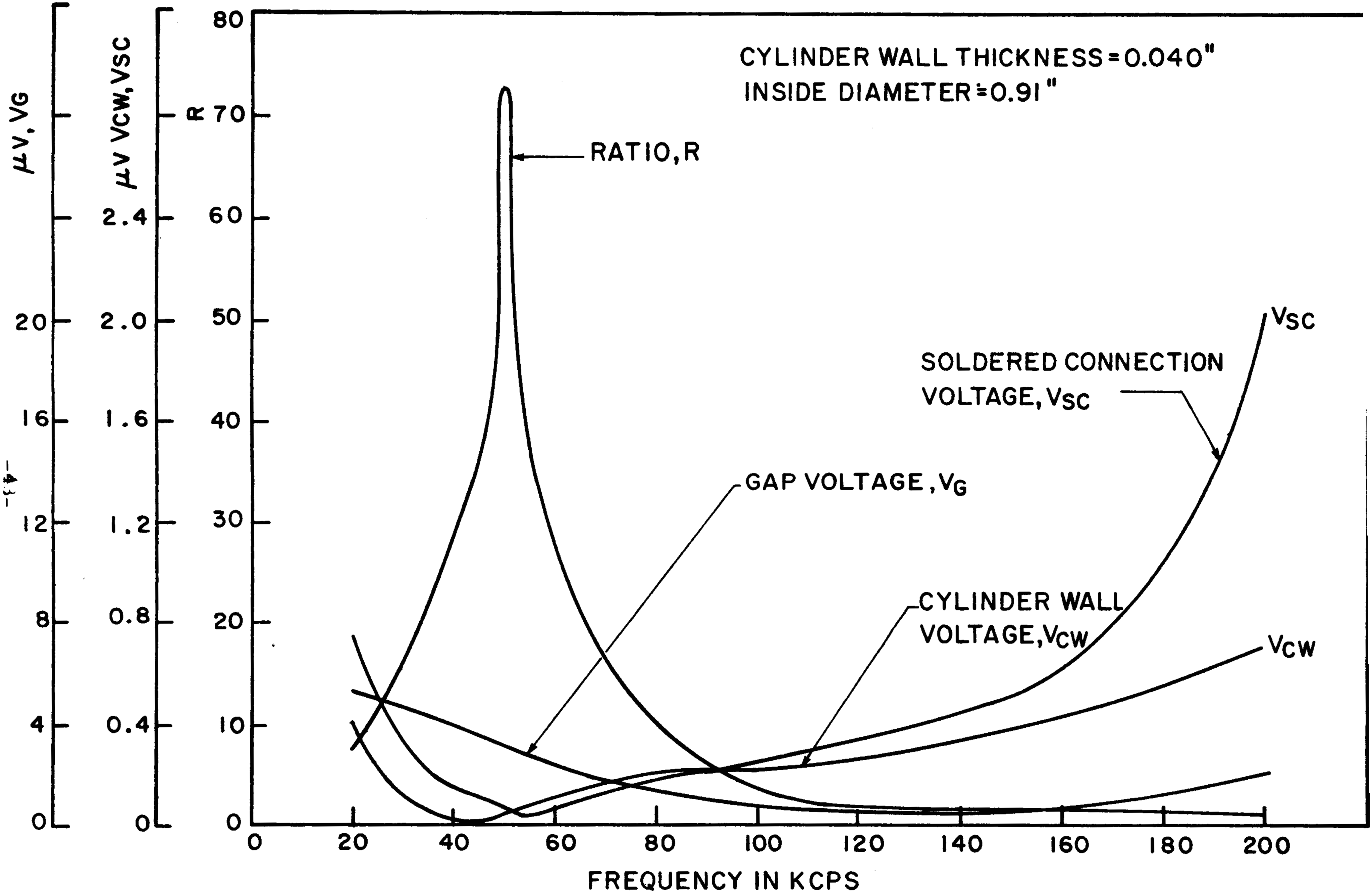


FIGURE 11. PROBE RESPONSE FOR 0.040 INCH CYLINDER WALL

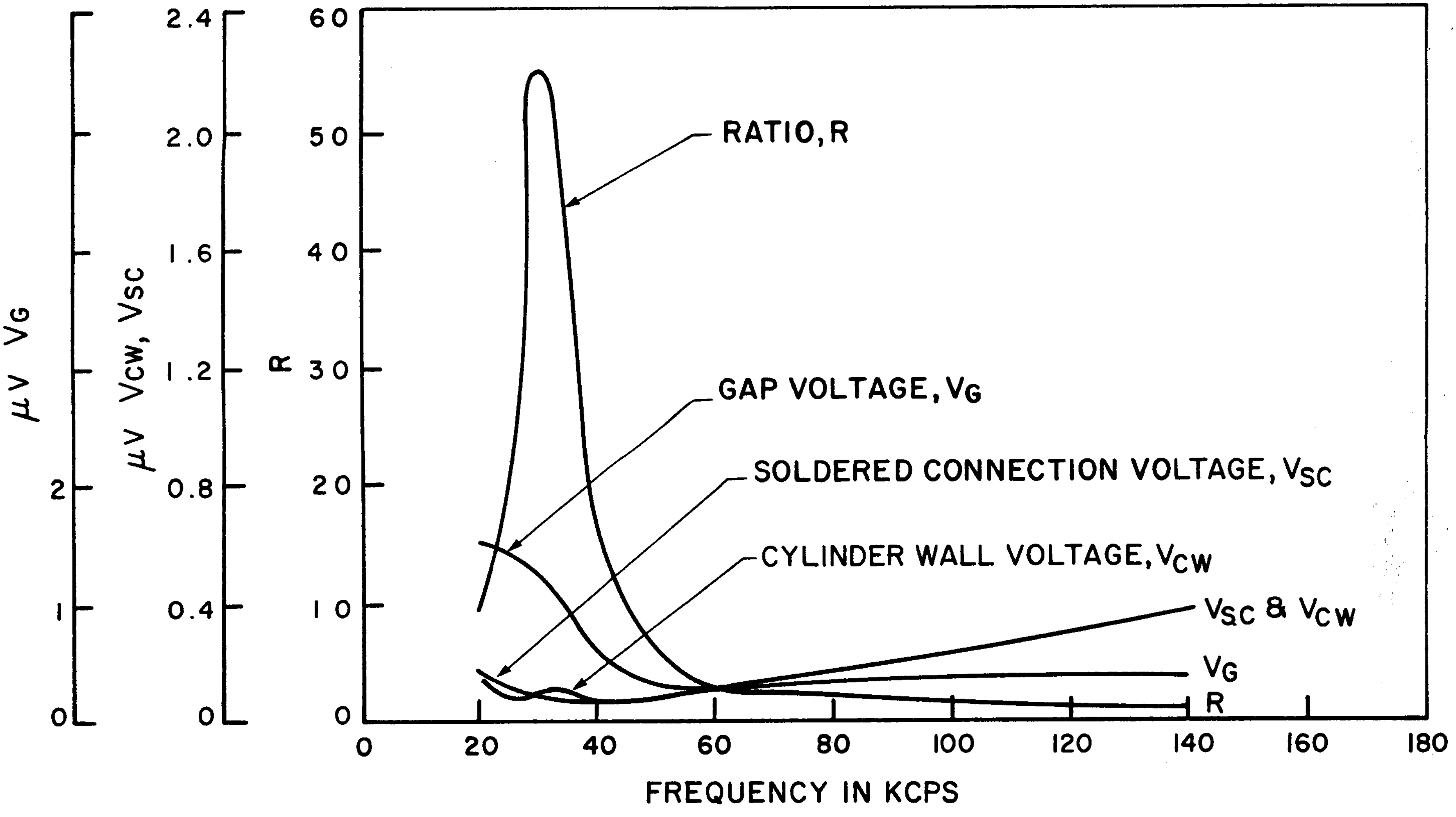


FIGURE 12. PROBE RESPONSE FOR 0.067 INCH CYLINDER WALL

The following definition of quantities will apply to succeeding discussions:

V_c = cylinder wall voltage, or the output of the pickup coil when both probe coils are under a portion of the cylinder wall to which no printed wiring connection is made.

V_{sc} = solder connection voltage, or the output of the pickup coil when both probe coils are under a portion of the cylinder wall to which a good soldered connection is made.

V_g = gap voltage, or the output of the pickup coil when both probe coils are under a portion of the cylinder to which a defective connection is made.

V_{sn} = system noise voltage.

Examination of Figures 10 , 11 , and 12 shows that V_{cw}, the cylinder wall voltage, and V_{sc}, the soldered connection voltage, both vary in a similar manner with frequency. The gap voltage, V_g, is seen to vary inversely with frequency and to decrease rapidly with increasing wall thickness. The decrease with wall thickness is to be expected since the near magnetic field of the excitation coil decreases as $1/r$ and the field of the turn formed by the gap reduces at least by $1/r$ and approaches $1/r^2$ when the distance is large compared to the gap width. It is therefore possible that the gap voltage could decrease as the reciprocal of the square or cube of the wall thickness.

The ratio, R, is an indication of true sensitivity and is given by:

$$R = \frac{(V_g - V_{sn})}{(V_{sc} = V_{sn})} \quad \text{or} \quad \frac{(V_g - V_{sn})}{(V_{cw} - V_{sn})} \quad .$$

The larger of the two quantities V_{sc} or V_{cw} is taken.

As the cylinder wall thickness increases, the ratio R is seen to peak at lower and lower frequencies. This peaking is due to a decrease in the quantities V_{sc} and V_{cw} rather than a peaking of V_g. This decrease may be due to partial neutralization of the excitation coil magnetic field by the magnetic field from the wall currents. This is the part of the excitation coil magnetic field that penetrates the shielding to the pickup coil.

Figure 10 also shows a plot of the system noise level voltage. This noise level is given in terms of the voltage at the output of the pickup coil that would produce the noise voltage observed. The system noise level for Figures 11 and 12 is the same as for Figure 10 except in the 25-35 kc range where pickup problems necessitated screen-room measurements. Breaks in the curves correspond to different ranges on the same receiver.

D. Probe Response for Gaps of Different Angles

Another problem of concern in the use of the 0.020 inch D probe in finding faulty connections to plated holes is the problem of detecting gaps which cover small angles. To obtain information on the small probe response for different gap angles which is difficult to determine directly, advantage can be taken of the previously noted fact that the responses of the largest probe roughly scale down to those of the smallest probe. Hence the response of the largest probe to various gap angles should give an indication of the response of the smallest probe. To measure the response of the largest probe to different gap angles, the 0.91 inch diameter, 0.027 inch wall thickness brass cylinder was used. One end of a 0.010 inch diameter bare copper wire was soldered to the brass cylinder at a fixed position while the other end was soldered to cylinder at various angles to the fixed end. A section of tape, approximately 0.006 inches thick, was used to form the gap between the brass cylinder and the copper wire. The voltage ratios obtained as the angle of the gap, θ, was varied, are shown in Figure 13. The peak of the gap voltage to cylinder wall voltage ratio occurred when the gap extended from the far edge of the excitation coil to the far edge of the pickup coil, about 112 degrees. For smaller angles this ratio drops off rapidly, being about two for a gap that extends between the inner edges of the two coils, approximately 42 degrees in Figure 13. For

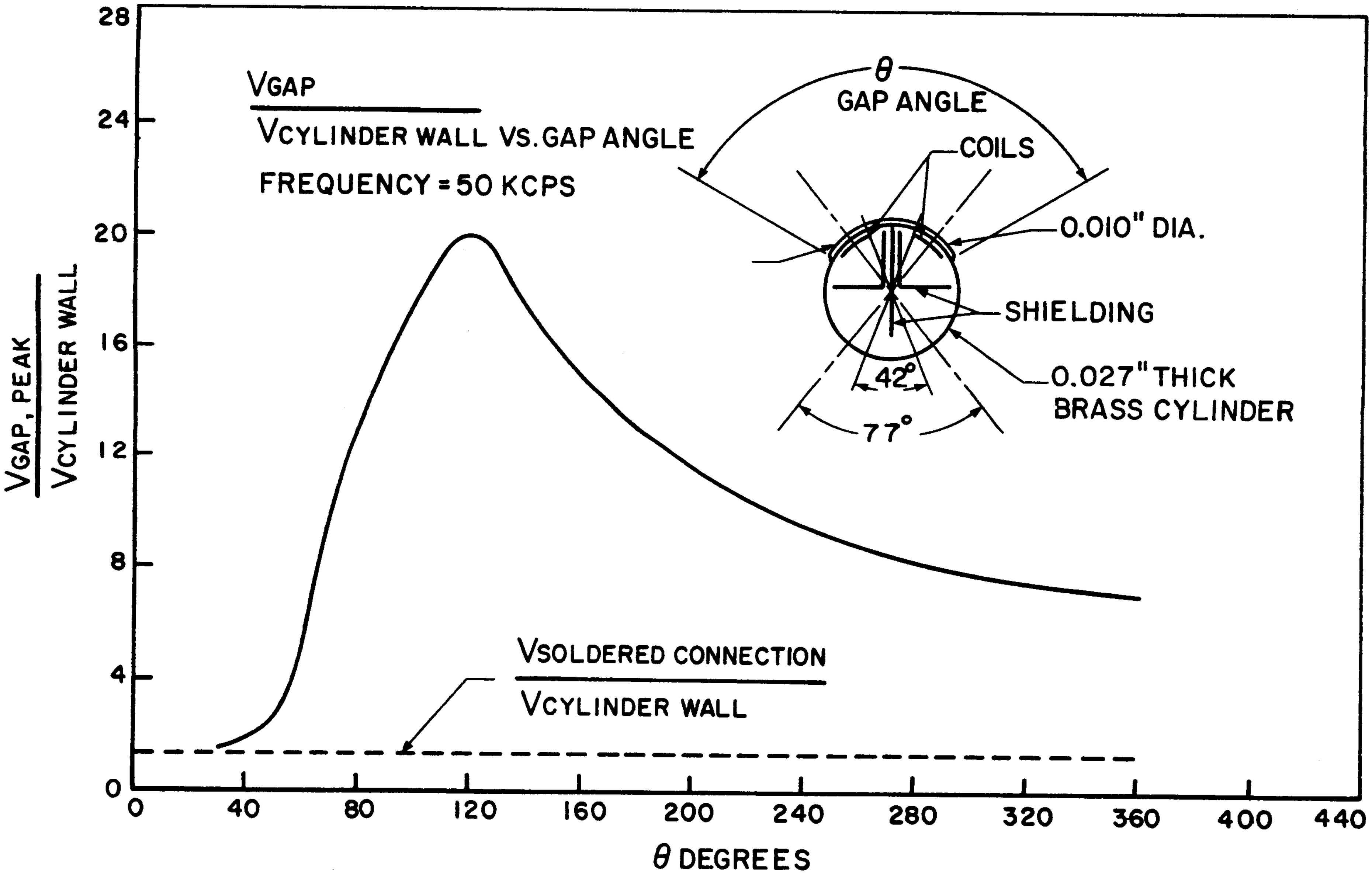


FIGURE 13. PROBE RESPONSE TO VARYING GAP ANGLES

angles of gap which extended beyond the far edges of the probe coils, the voltage ratio decreases very nearly as the reciprocal of the gap angle.

Thus, for the present design of the smallest probe, the minimum detectable gap angles, for a reasonable voltage response ratio of about five, would be the angle corresponding to a gap that extended 25 per cent of the way from the inner coil edges, into both probe coils, or 60 degrees in Figure 13.

E. Problem Areas in Probe Design

The mutual coupling probes, as designed, depend partly on the cylinder wall for direct pickup shielding. It is therefore to be expected that this direct pickup will increase as the probes are used in cylinders whose diameters are much larger than that of the probe. Also, since the probe coils are relatively farther away from the cylinder wall in larger diameter cylinders, the gap voltage pickup decreases. Tests, using both the .85" D and the 0.080" D probes, indicate that reasonable gap voltages and response ratios can be obtained for cylinder diameters 25 per cent larger than the probe diameter. If, as can be done with the 0.080" D probe, the pickup and excitation coils and their shielding L-section compartments are allowed to expand apart from one another, as the probe is placed in larger cylinders, the range of cylinder diameters over which useful probe performances can be obtained may be extended to 50 per cent and more.

When the mutual coupling probes are placed with their coils at the edge of a cylinder, strong currents circulate around this edge, giving pickup coil voltages 10 to 30 times larger than the gap voltages. Thus, with the present design of the mutual coupling probes, faulty electrical connections made to the ends of the cylinder (the top and bottom layers of the printed circuit board) could not be detected readily. However, these connections could probably be easily inspected visually. The increase in pickup coil voltage as the probe coils approach the cylinder edge occurs as soon as the top or bottom edges of the pickup and excitation coils line up with the edge of the cylinder, and when both coils extend above the edge of the cylinder, the pickup coil voltage increases greatly. Thus, to inspect the printed wiring connections one layer above the bottom layer or one layer below the top layer, with the present coil configuration, the distance between the center and top or bottom edges of at least one of the two probe coils must be less than the spacing between the printed wiring layers. This, of course, limits the pickup or radiating area of the probe coils.

The direct pickup between the coils of the mutual coupling probes in free space is normally, but not always, greater than the gap voltage produced when the coils are in a cylinder under a gap. Thus, it is normally necessary for minimum direct pickup, to keep the magnetic shielding between the pickup and excitation coils pressed against the side of the cylinder in which the probe is being operated. This direct pickup then limits the roughness of cylinder which can be inspected to, perhaps, a 10 or 15 per cent variation in diameter, although no specific data in this regard has been generated.

Coils of four turns each, wound in a figure "8" pattern are the excitation and pickup coil on the mutual coupling probes which were constructed and tested during this program. This coil design was used primarily because of ease of construction. For equivalent ampere-turns, a simpler construction of the excitation coil could be achieved by using a one turn figure "8" coil of larger wire and passing four times the current through this coil. In the case of the 0.020" D probe, this coil could be made of one turn of 0.002 inch diameter wire through which a 400 ma current is passed. If needed, this wire could probably carry a current of 600 - 800 ma without over heating thus giving added signal strength. Since the pickup coil is not subjected to high currents or voltages, further increases in signal strength could be obtained by using thinner wire with more turns. For the 0.020" D probe, 0.0005 inch diameter (size 56) wire could be used with 20 to 30 turns while continuing to maintain a low output impedance. This coil could be wound on some soluble coil form, such as wax, and then the form dissolved and the coil glued or fixed in place with epoxy. A second possible way in which a large number of turns can be achieved is through the use of printed wiring. Printed wiring 0.0001 inches wide could be plated in the form of two attached square spirals on a section of mica or some other suitable substrate. Twenty to forty or more turns could be achieved by this method, particularly if more than one layer of printed wiring is used. By these techniques it should be possible to increase the signal strength from the pickup coil by an order to an order and one half of magnitude. The probe could be ruggedized by encapsulating it in epoxy, suspending it from a wire spring and also using a wire spring to press the probe against the side of the cylinder.

There are other mutual coupling probe configurations which could prove useful. Instead of coils in the shape of a figure "8", use single coils; one in the position of the top coil of the excitation figure eight coil, and one in the position of the lower coil of the pickup figure eight coil of the present design. These could be used as excitation and pickup coils. This coil arrangement would allow the probe to be used almost to the edge of the plated hole cylinder on circuit boards where the distance between the printed wiring layers was quite small. As noted previously, mutual coupling probes might be made to operate in plated holes of widely varying diameters by fitting the pickup and excitation coils in scheduled compartments which spring out and rub against the sides of the plated hole. Several sets of pickup and excitation coils could be mounted on the same probe at the same level so that more of the area of the cylinder could be inspected with one probe insertion.

It might be possible to increase the cylinder wall thickness through which the mutual coupling probes can function, and/or decrease the minimum detectable gap angle, by the use of neutralization coils. To accomplish this, two neutralizing coils are placed on the probe in such a position that they pick up the direct coupling signal, but intercept only a small amount of the mutual coupling signal. The voltage induced in these coils is then subtracted from the voltage induced in the main pickup coil to produce a voltage which is more nearly independent of the direct pickup signal. The neutralizing voltage is taken from the neutralizing coils rather than directly from the signal generator because the voltage induced in the neutralizing coils depends, as does the direct pickup from the main coil, on the type of metal, the thickness, and the physical condition of the plated hole.

VI. SUMMARY AND RECOMMENDATIONS

A. Laminography

In the course of this project a theory for this application of laminography has been developed and the theory has been verified experimentally through the construction of a laboratory model laminograph. The lab model was used to make high resolution laminographs of a mock-up multilayer printed wiring board which demonstrated the ultimate practicality of the technique as a nondestructive testing method.

There are, however, a number of limitations which would tend to restrict the present laminograph to that of a specialized laboratory instrument. The most serious of these drawbacks is the use of x-ray film to make individual exposures of each layer of a sample. This involves a series of exploratory exposures to find the layer of interest. In the case of the four-layer board some thirty exposures were made to achieve a complete laminographic sectioning of the board. Such a technique is much too cumbersome to be used on a routine industrial basis. A continuous scanning method would be extremely worthwhile. Other drawbacks of the present device are the lack of intensity, too low an x-ray energy, and the difficulty of maintaining synchronism. The following paragraphs contain suggestions designed to overcome the above limitations.

To achieve continuous scanning it is suggested that a fluorescent screen be used in place of the x-ray film. This screen would be of relatively long persistence and high resolution. The image formed, which is a duplicate of the one observed on film, could be observed visually if it did not rotate at the same rate as the sample. The use of a prism which rotates at one-half the rate of the sample but in the opposite direction, allows one to observe an apparently stationary image. Synchronism between this prism and the sample need not be precise since some rotation of the image can be tolerated.

As an adjunct to the above method of achieving continuous scanning, a closed circuit television system is very attractive. This would allow the operator and inspector to be remotely located from the x-ray source. The television camera could have a zoom-type magnifying lens for detailed inspection of a small region of a sample, which would remove the limitation on resolution imposed by the line resolution of the usual television monitor.

Critical to the above system would be a much higher speed of rotation, probably of the order of 0.5 to 1 revolution per second, since the longest persistence fluorescent screen of appropriate resolution has a persistence of about one second. Maintaining the required degree of synchronism, planeness, and axial parallelism would be difficult but by no means impossible to achieve. Matched gears probably will provide the necessary positive drive to achieve the required degree of synchronism at these rates of rotation.

An alternate system which has some possibilities, involves the use of an image retaining panel[4,5] in place of the x-ray film. These panels are capable of producing an essentially permanent image which may be destroyed at will by removing a bias voltage. This device allows one to employ a much slower rate of rotation, thus by-passing some of the problems inherent in the high speed rotation suggested above. Also lower intensities of x-rays may be used, reducing the radiation hazard. Since the image is essentially permanent the rotation may be stopped for scanning, thus eliminating the need for the optical system and its loss of intensity. The intensity available from the panel is high enough to allow direct scanning of the image with a television camera. There remains one further potential advantage to this method which is the possibility of making an immediate permanent record of the image of one layer of a sample simply by exposing a photographic film to the image on the panel. An important drawback to this system is its inability to perform continuous vertical scanning, the vertical scanning being in discrete steps requiring perhaps 10 to 20 seconds per step. This could very well make the inspection of a sample much too long an operation.

In both the methods suggested the use of a higher x-ray energy has been assumed. It would, in fact, be highly desirable

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4. S. A. Henderson, The New Scientist (Dec. 20, 1962).
5. Radiography 29, 206 (1963).

if the x-ray energy could be varied so that samples of a variety of materials and thicknesses could be effectively laminographed, a result which would immeasurably broaden the usefulness of the technique.

A device built along the lines suggested above would make laminography an eminently practical method for nondestructive testing generally and the testing of multilayer printed wiring boards specifically.

B. Mutual Coupling Probe

The principle of using mutual coupling to detect deficiencies in interconnections of multilayer printed wiring boards has been shown to be feasible. Difficulties experienced in working with subminiature geometries have limited the complete characterization of this concept, but technology underlying probe construction is well within the present state-of-the-art and development of a completely practical arrangement should be possible with the recommendations which have been made. This means of examining each through-hole in detail should complement the laminography technique.

APPENDIX I

FEASIBILITY STUDY - ALTERNATE SOLUTIONS

APPENDIX I

FEASIBILITY STUDY - ALTERNATE SOLUTIONS

I. Techniques Involving Heat. Constrictions in the printed wiring of a circuit may be found by passing current through this wiring and detecting the temperature gradients that occur at these constrictions. The following methods were considered in attempting to sense these constriction "hot spots:"

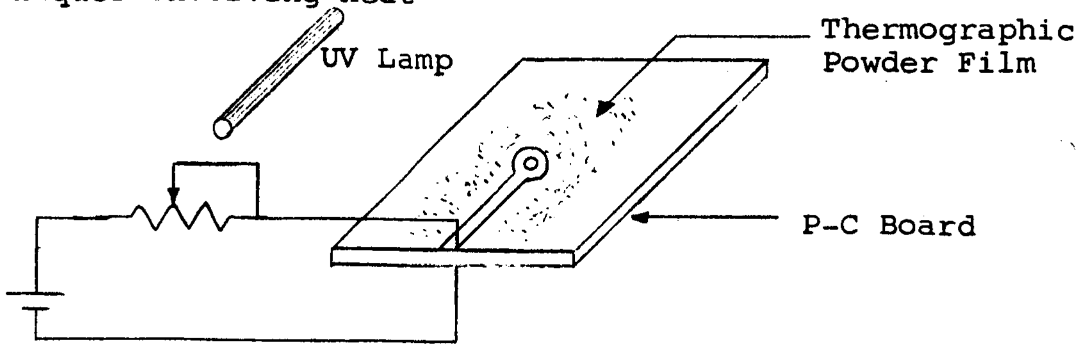
A. Thermographic Powder. Under ultraviolet light, the fluoresence of this powder decreases with increasing temperature. A board to which this material has been applied will show hot spots in the wiring as darkened areas. This method should then detect surface hot spots whether caused by surface defects or by heat reaching the surface from defects within the multilayer structure. (See Sketch I-A).

This method was examined experimentally and was found to be useful in detecting surface defects. However, defects other than those on the surface tended to be obscured and sensitivity is lost rapidly as the number of layers increases.

B. Infrared. Infrared radiation from areas heated by circuit hot spots on the surface or lower layers of circuit boards may be detected by the use of infrared cameras or microscopes.

I. Techniques Involving Heat

A



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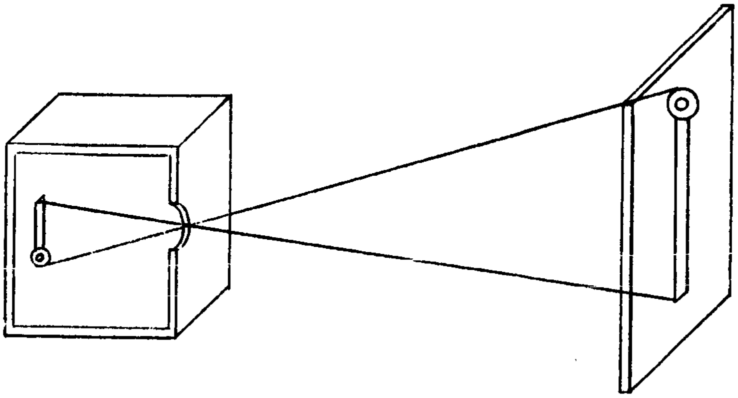

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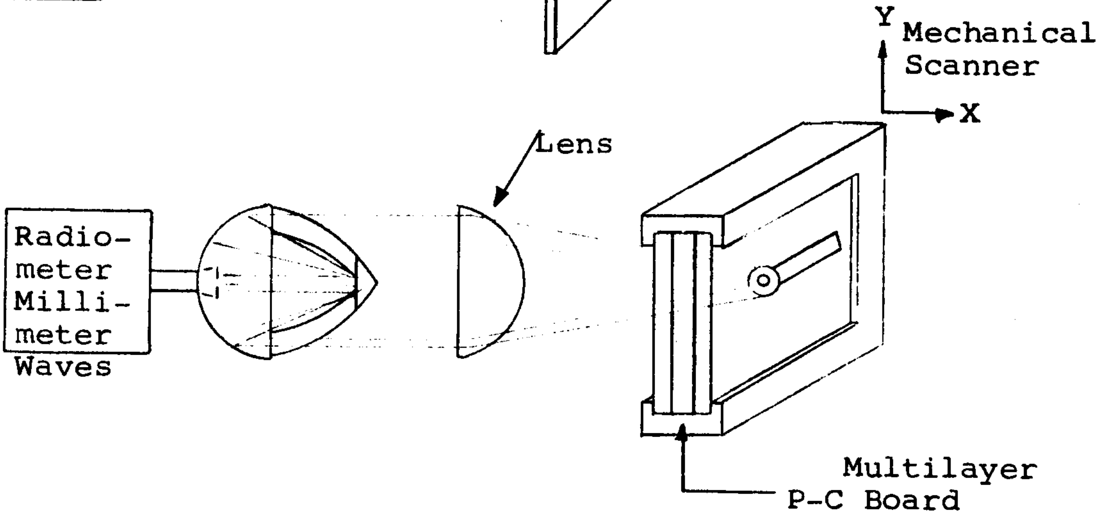

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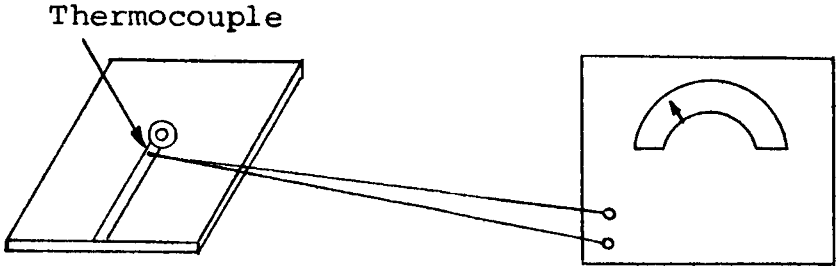


This method would involve comparison of test boards with a reference "good" board. Experience has indicated a great degree of reliance on operator judgement is needed. In addition, non-surface layers tend to be obscured.

C. Millimeter Waves. In addition to giving off infrared, hot spots also give off electromagnetic radiation in the millimeter range. This radiation should easily penetrate the insulating material of a circuit board and thus allow inspection of printed wiring which is deep inside the board. (See Sketch I-C)

This method has decreasing utility as the number of layers is increased from the standpoint of both sensitivity and resolution.

D. Thermocouples. Hot spots inside of plated-through or riveted holes and on the surfaces of circuit boards might be most easily located by the simple method of using a thermocouple. However, a thermocouple has the disadvantage of disturbing the thermal balance of the system being measured, and complexities in adapting this to 100 per cent inspection would be very great. (See Sketch I-D)

II. Eddy Currents. Passing an A.C. current through a coil placed in a plated-through or eyeleted hole in a circuit board will cause eddy currents to flow in the metal of the sides of the hole. The fields of these eddy currents will, in turn, affect the electrical properties of the coil. Varying the frequency of the a.c. current will change the depth of penetration of the eddy currents and, hence, the depth of metal affects coil's electrical properties.

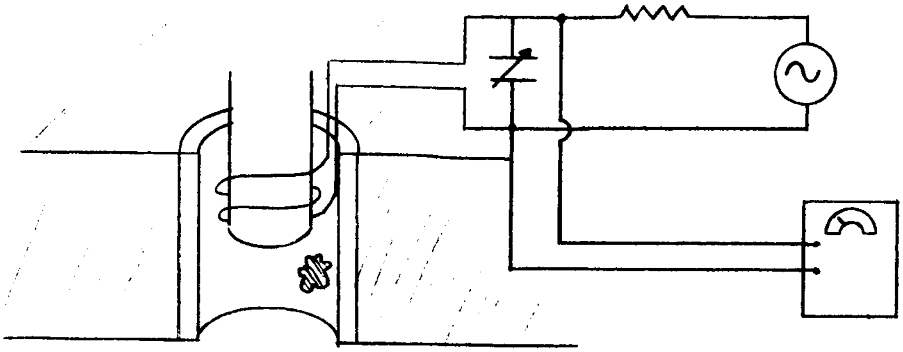
A. Impedance Magnitude. A coil, which is part of a resonant tank circuit, is inserted into the plated hole. When the coil encounters an imperfection, such as a hole, in the plated-through structure, the impedance reflected into the coil changes and the circuit goes off resonance with a corresponding large change in the tank circuit voltage. (Sketch II-A)

B. Differential Method. Two coils connected as two branches of a Wheatstone bridge are inserted into the plated-hole structure. When one of these coils encounters an imperfection, its impedance changes and a differential output voltage appears. (Sketch II-B)

C. Mutual Coupling. Two coils, an exciting coil and a pickup coil, are inserted into the plated hole. When the exciting coil passes over a hole in the plating, the eddy currents which normally flow under the exciting coil are diverted around the hole and in so doing flow under the pickup coil. Magnetic flux from these eddy currents then

II. Eddy Current Techniques

A



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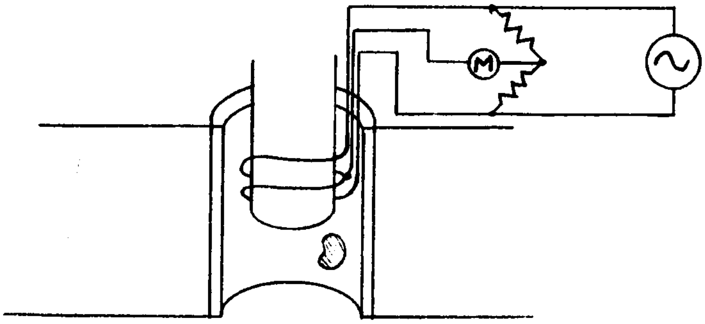

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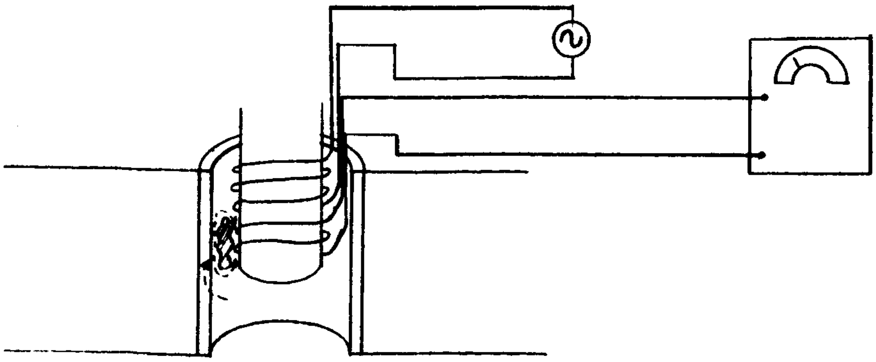


links the pickup coil and induces a voltage in this coil which is read on an output voltmeter connected to the coil. (Sketch II-C)

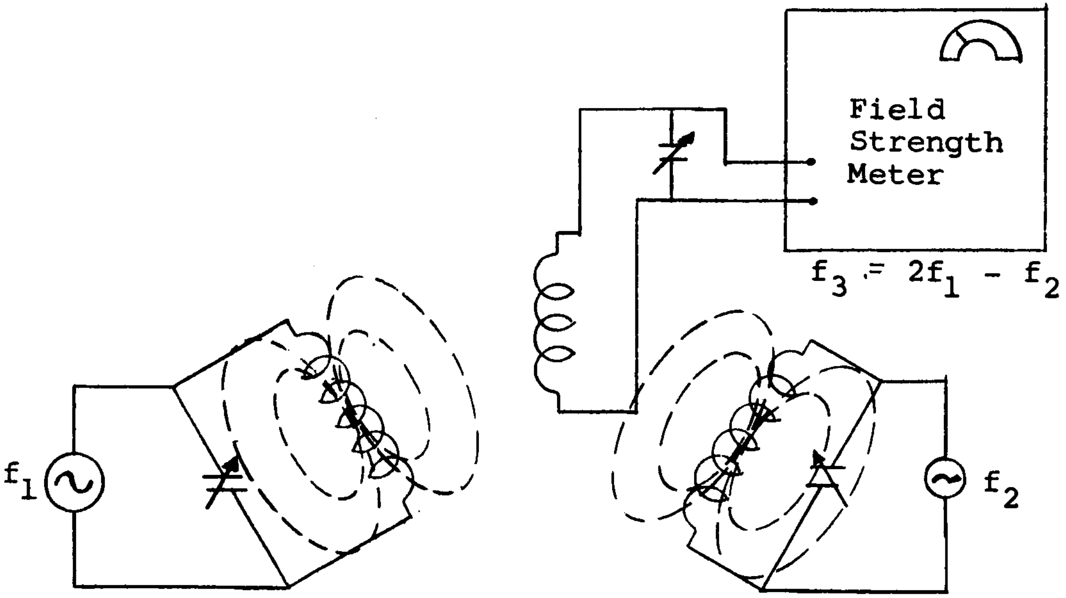
This method showed good initial experimental feasibility and was the subject of more detailed experimental investigation as described in the body of this report.

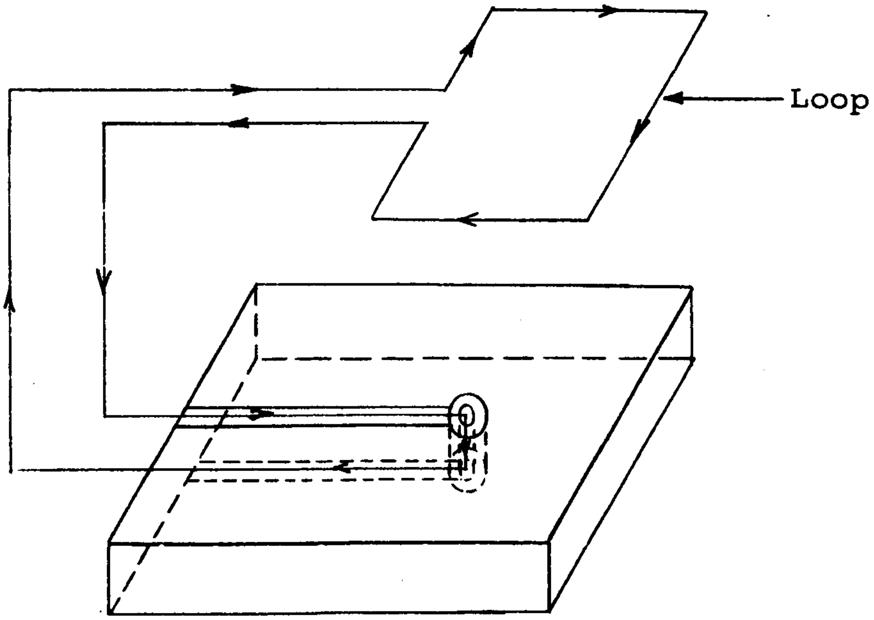
III. Intermodulation. Currents of two different frequencies are passed through printed wiring which contains an electrical nonlinearity. Currents at intermodulation frequencies are then produced. Since the frequencies of the intermodulation products can be appreciably different from those of the two fundamental frequencies, the intermodulation currents can be easily filtered out and detected. Thus, even small non-linearities are easily detected by this method. (Sketch III)

Oxide films are one source of non-linearity. These oxide films could occur, for example, in hair-line cracks in plated wiring or between printed wiring and a plated through-hole.

Preliminary measurements were made on double sided boards having defective interconnections. These interconnections had resistances ranging from 25 ohms to 1000 ohms. The defect was introduced into a board by reducing the cross-section of the electrical conductor at the point where it joins the pad surrounding the through-hole. This junction was then wired in series with several other junctions known to be defect-free. Attempts to detect the defect using an intermodulation technique

III. Intermodulation





were successful. The nonlinear junction locator consists of three tuned coils inside a large shielded enclosure. The first coil is connected to a transmitter operating at a frequency of 2.025 MHz, with an output of twenty watts. The second coil is connected to a similar transmitter tuned to 4.530 MHz at an output power of 20 watts. The third coil is tuned to a third order intermodulation product whose frequency is $2(4.530) - 2.025 = 7.035$ MHz. This third coil is connected to a monitor to determine the relative strength of the third order intermodulation product in the shileded enclosure. When boards containing defects were introduced, the intermodulation level increased by a factor of 30-60. Boards containing no defects produced no change in the intermodulation level. The possibility exists that these changes were due to oxide formation in the area of reduced cross-section and not to the difference in the geometry of the cross-section itself. However, detection of both types of defects is desired, so this would not necessarily be a limitation. Difficulties were experienced in reproducibility of test results, and the ability to pinpoint a defective connection (as compared to a bad board) is seriously questioned.

IV. <u>E-Field Sensors</u>. Faults in printed wiring and plated through-holes may be found by the irregularities they cause in the equipotential surfaces of the currents flowing through the wiring.

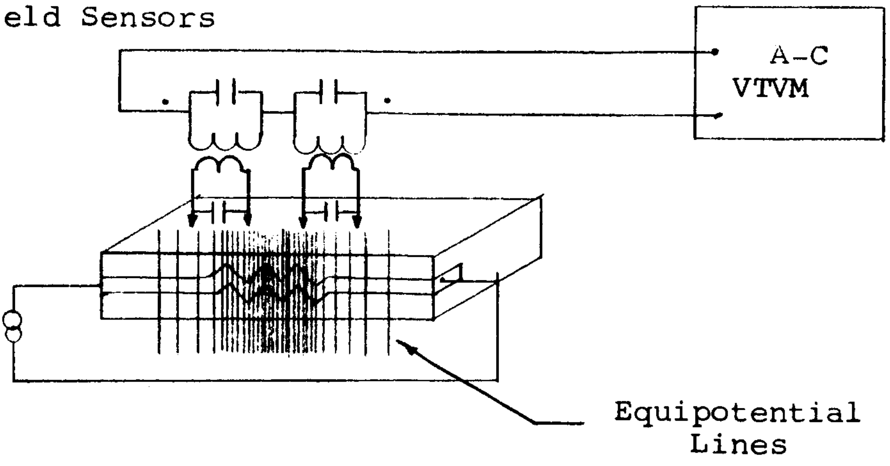
<u>Sketch IV-A</u>. Two identical high impedance probes, which sense potential differences between equipotential surfaces (the probes can be thought of as being capacitively coupled to the wire), are connected in a differential circuit. When one probe encounters a stronger E field (a region where the equipotential surfaces are crowded together) than the other, as would be caused by a higher than average resistance in the printed wiring, an unbalance occurs and a voltage output results.

<u>Sketch IV-B</u>. The outputs of two high impedance capacitance probes are compared differentially. One is inserted in a plated through-hole which is known to be good and one is inserted in the plated hole being tested. An output, above some predetermined level, from the differential circuit indicates a flaw in the plated hole under test.

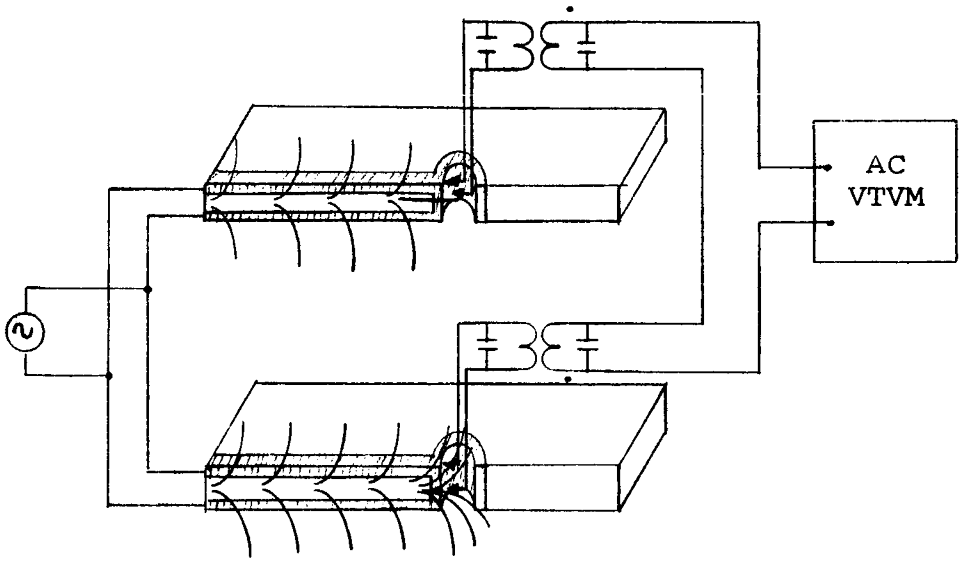
<u>Sketch IV-C</u>. A capacitance probe compares, again in a differential circuit, the capacitance from one side of the probe to the plated hole to a similar capacitance from the other side of the probe to the plated hole. If, as the probe is rotated, one side of the probe crosses a fault in the plating, the capacitance between this side of the probe and the plated hole changes, an unbalance occurs, and a voltage appears at the output of the differential circuit.

IV. E-Field Sensors

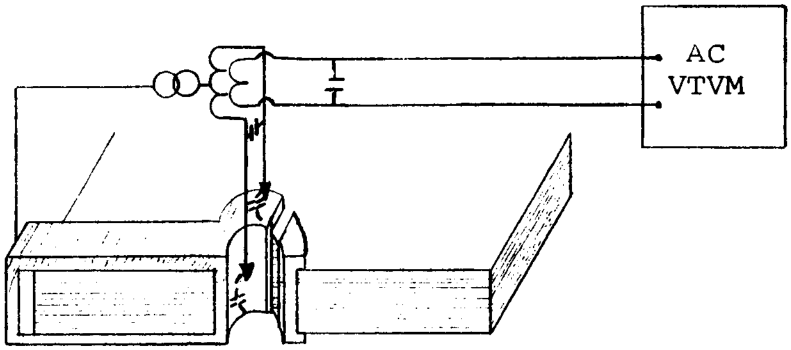
A



B



C



Theoretically, these techniques appear workable. However, further consideration indicated a large number of practical difficulties which would seriously limit the usefulness of these methods. Among these was the inherent geometry limitation of capacitance probes.

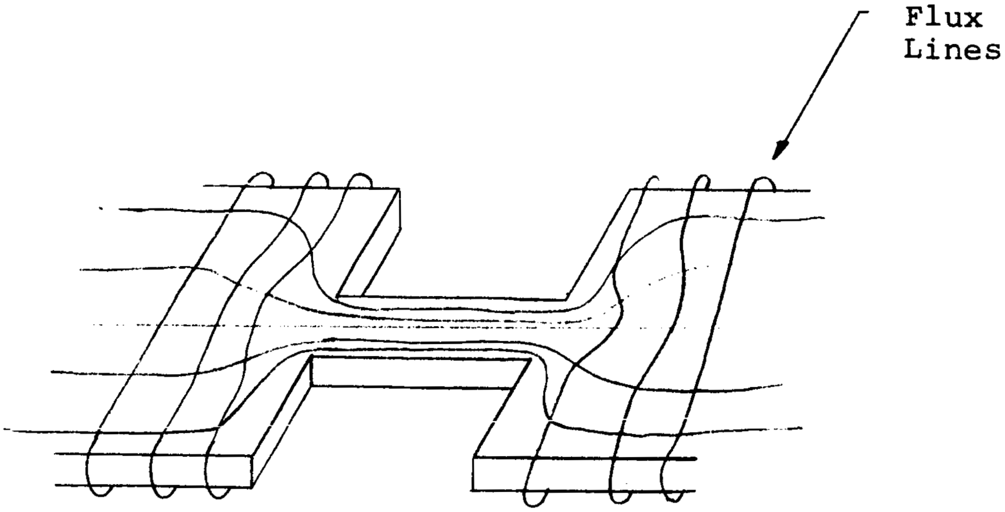
V. Magnetic Field Sensing. It may be possible to find faults in printed wiring by the anomalies they cause in the magnetic field around the wire. These anomalies may be detected, for example, by placing magnetic recording tape on a printed wire, passing a high current pulse through the wire, and then playing back the tape while listening for any unusual sound. (Sketch V)

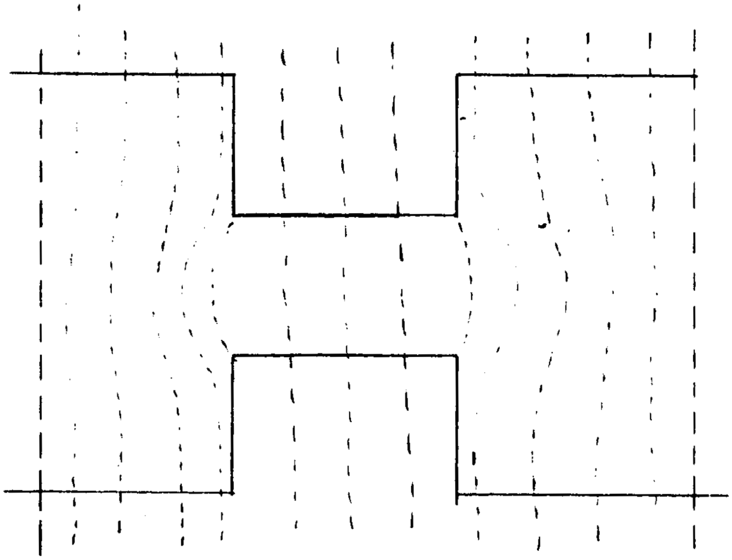
This technique also requires a reference standard and would probably be primarily limited to surface defects.

VI. Borescope. A mirror used in periscope fashion may make it possible to visually inspect the inside of the plated hole. Irregular areas inside the plated holes may also be found by using fiber optic bundles to conduct the light reflected from inside of the hole to a photo-cell. (Sketch VI)

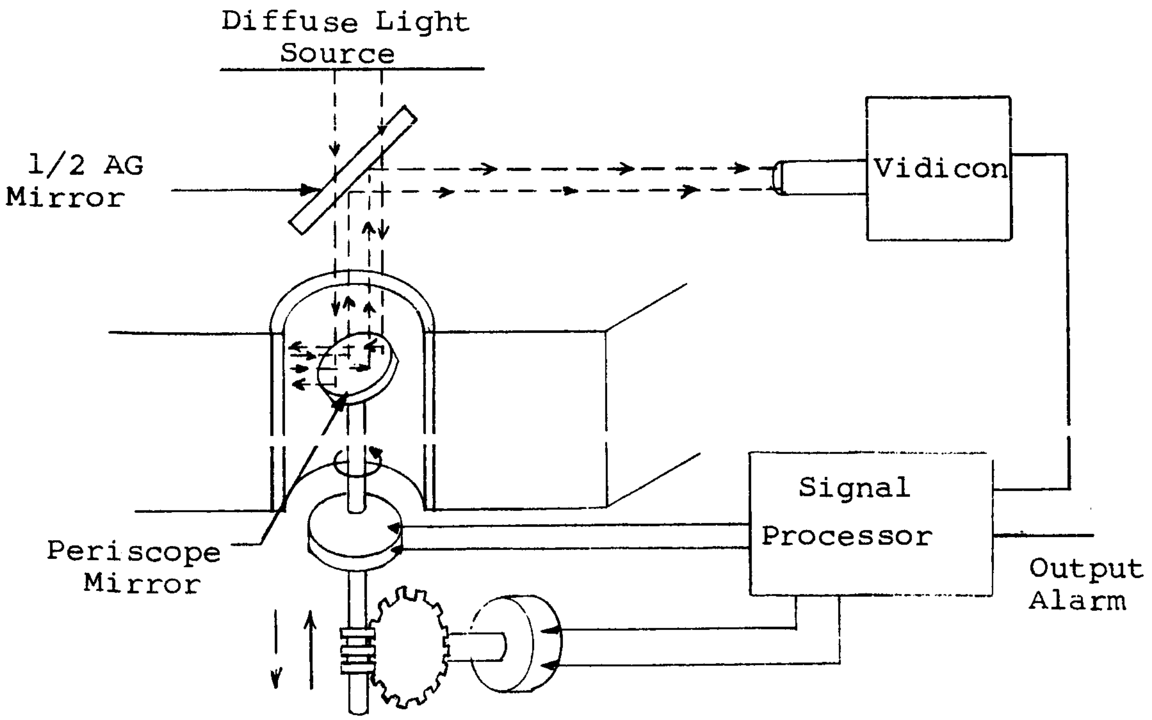
The borescope approach was rejected as too cumbersome and complex for the geometry under consideration, i.e., holes ≈ 0.020 inch in diameter.

V. Magnetic Field Sensing





VI Borescopes



VII. Radiography

A. Neutron. Initial calculations indicated that for silver conductors the cross-section for epi-thermal neutrons (4-5 eV) was large enough that good contrast might be obtainable. Using gold foils of 0.003 inch thickness it was found that radiographs of silver-plated thru-holes could be obtained, but that resolution and contrast were not of sufficient quality to continue this line of inquiry further in view of the significantly better results obtained using x-rays.

B. Autoradiography. Autoradiography seems to hold some promise as a useful technique. If the hole-plating material can be doped with an active isotope or if, as in the case of silver or gold, it can be easily activated, an x-ray film inserted into the hole could produce an image which faithfully reproduces the characteristics of the plated material.

C. Electron Microscopy. Scanning electron microscopy can have a degree of utility, especially for an accurate description of the surface characteristics of individually selected through-holes. This would allow one to make relatively accurate determinations of the ability of the various radiographic techniques to distinguish small defects in the through-hole plating material.

D. X-Ray. Radiographs using the microfocus x-ray tube were made which show good contrast between the copper strips and glass-epoxy base material on the thickest available multilayer boards. Resolution studies showed that details with dimensions somewhat less than 1 mil could be readily discerned. Additionally, the silver in silver-plated through-holes could be readily distinguished from copper and in one case, a faulty plating was apparent. These results were obtained using the K x-rays from silver which are only poorly attenuated by silver itself. Much higher contrasts could be obtained from antimony. If gold were the hole-plating material, a much higher contrast would be achieved using silver x-rays.

An important result of these investigations was the finding that a technique called laminography should be eminently applicable. This technique results in the radiography of cross-sectional areas of any solid object. In effect, it would allow the inspection of each layer of printed wiring board for a close examination of the integrity of the through-holes. The method involves an arrangement of film and test board on rotating tables. The board and film are rotated at the same rate through 360°. Only those points in a very narrow slice produce reinforced images on the film, all other points being averaged throughout the film area. For initially thin samples such as printed circuit boards, this averaging will result in only a small reduction in contrast. Laminography appeared to offer a number of advantages such as the ability to inspect one layer at a time, rather than one hole, and its ready adaption to mass testing. Consequently, it was the principal subject of further investigation as described in the body of this report.

VIII. Combination Acoustical Excitation - Resistance Measurement Method.

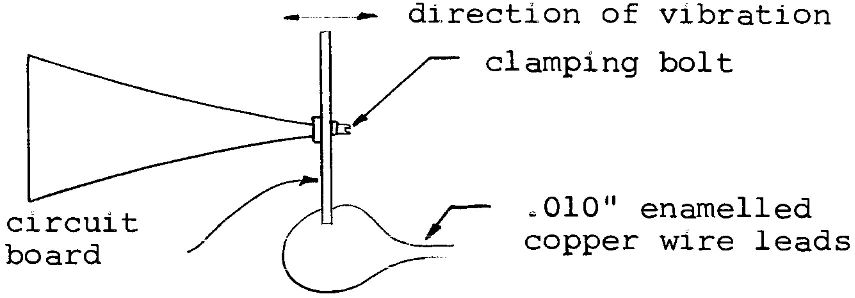
Two possibilities for the detection of very small cracks in the through-joints in multilayer wiring boards were considered, using acoustical methods.

1. Changes in attenuation (or scattering) or velocity of an acoustic wave caused by the defect.

For any appreciable change to occur, the wavelength of the sound would need to be of the same order as the dimensions of the defect. The defects that are of interest in this case are probably very much smaller than say 1/1000"--the frequency of sound waves in copper having this wavelength is 160 MHz. Because losses due to scattering are so great at high frequencies, this method was not pursued further.

2. Changes in electrical resistance in the presence of a sound field.

An experiment to investigate this possibility involved vibrating the board at certain frequencies in such a way that the velocity amplitude would be known at every point on the board and preferably would be maximized at the joint under test. The printed wiring board was attached to the tip of a 14 Kc/s magnetostrictive horn driver as shown in the sketch.



The horn was driven so that the amplitude at the end (as measured with a capacitance ultramicrometer) was 4×10^{-4} inches as the resonant frequency of 14 KHz. At higher amplitudes ($\sim 10^{-3}$ inches) some heating effects at the corners of the board were noticed and at amplitudes $\sim 3 \times 10^{-3}$ inches, the board started to burn at the corners.

The resistance of each joint was measured by passing a direct current which could be varied from 12 mA to about 500 mA by means of a variable resistance (0—500 Ω) in series with the joint. Leads were taken from across the joint to a tunable amplifier and thence to an oscilloscope.

It was found that the output signal was the sum of voltage fluctuations due to the resistance changes and also direct electrical pick-up radiated from the magnetostrictive element. The radiated signal was determined by observing the difference between the voltage on the oscilloscope with and without the current flowing through the joint. Fluctuations in resistance of a joint were always compared with a "good" soldered joint which was situated near (compared with a wavelength) to the joint under test. The wavelength was estimated approximately from the theory for the propogation of flexural waves in thin plates.

$$C_{\text{flexural}} = \left[\frac{Ek^2}{\rho\,(1 - \sigma^2)}\right]^{1/4} \omega^{1/2}$$

where E is Young's modulus of the plate material,

ρ is the density of the plate material,

σ is Poisson's ratio for the plate material,

ω is the angular frequency, and

k is the radius of gyration about the axis of bending and is given by

$$k = a/\sqrt{12}$$

for a plate of thickness a.

This is an example of velocity dispersion, but at 14 KHz, the velocity turns out to be ~10^4 cm/sec, so that the wavelength is ~7 mm. This means that the test joints may not have necessarily experienced the same vibration amplitude as the "good" comparison joints.

The results of the measurements can be summarized as follows. A fluctuation in resistance at the frequency of the sound field and also at some of the harmonics (the first harmonic especially) was noted in all of the joints tested. However, no changes in resistance were seen with the standard "good" joint, provided that the soldering was done carefully.

The fluctuations observed varied rapidly from time to time in a random way and were very responsive to any mechanical shocks such as were caused by lightly tapping the board. This was also noticeable even in the absence of sound. Generally, it was found that the periodic resistance fluctuations and also the non-periodic random changes were greater for joints having a higher resistance (the resistance varied from 0.5 Ω for good joints to 7.5 Ω for one bad joint). Both the periodic and random resistance changes increased very rapidly with D.C. current passing through the joint when the current was increased from 100 to 500 mA.

Two joints, one initially 3.5 Ω and the other initially 1.5 Ω were found to have a permanent decrease in resistance as a result of the combination of passing a heavy current (500 mA) and being vibrated for a period of about two minutes. It is uncertain whether this change was caused by the current alone or whether the vibration played some part in the process. The joint initially having a resistance of 7.5 Ω was found to become open circuited due to the vibration alone, but other joints didn't show any permanent changes in resistance.

Typical resistance changes for a joint having a resistance of 1/2 Ω are shown.

Current Being Passed (mA)	R (10^{-6} Ω)	Vibration Amplitude (10^{-4} inches at junction with horn)
100	--	4
200	25	4
300	30 - 60	4
400	30 - 70	4
500	0 - 500	20

These experiments were carried further using boards having through-hole connections made in a variety of ways: by painting with silver paint, by soldering wire connectors into the hole, and by filling the hole with low-melting-point metals in an oven. In all of these cases, small variations in resistance could be seen very readily when the board was vibrated at the resonant frequency of a magnetostrictive horn driver (14-15 KHz). In the case of these boards the tests were found to be particularly sensitive for evaluating the quality of the various types of joint. The following reasons show why this type of test is suitable for this application.

1. The changes in resistance that occur are periodic at the frequency of the sound field and at its harmonics, and since the mechanical oscillating system has a high "Q", a sharply tuned amplifier can be used with a very high gain to separate small electrical signals caused by the periodic resistance changes from electrical noise. Changes

in resistance of less than $10^{-6}\ \Omega$ can be detected with a direct current of 500 mA flowing through the test joint.

2. Electrical coupling between the magnetostrictive oscillator and the detecting apparatus is difficult to eliminate, but can be very easily compensated for by taking readings with and without the D.C. supply connected. This could be done automatically with a simple electronic switching and difference circuit.

3. The quality of a joint can readily be compared with that of a good standard joint made onto an outside conductor of a comparison test board as a small change in resistance can be detected in even the best soldered joints obtainable. This change was about $1/2 \times 10^{-6}\ \Omega$ for a current of 500 mA and was smaller by a factor of 10 to 100 than the resistance change measured for bad joints, some of which eventually failed at very high vibration amplitudes.

4. Owing to the high sensitivity of this method, it is possible to work with vibration amplitudes well below that at which joints might be damaged.

Additional tests were made with the multilayer boards that had been commercially fabricated in a test pattern, which included a number of purposely introduced defects in the form of geometric deviations from the ideal. The tests that were made on both "good" and "bad" boards were once again very successful in showing a marked difference between good and bad joints, and they enabled an arbitrary standard of maximum acceptable resistance change to be established. In these tests, however, owing to the complicated configuration of the circuit, it was impossible to make tests on the joints individually. By making three connections, circuits including every joint on the board could be tested, and separate tests conducted on individual joints afterwards (made semi-destructively by cutting through conductors) showed that every single bad joint had contributed towards the over-all change in resistance that was measured. It was expected that measurements made across many joints in series would not suffer from any loss of sensitivity to single bad joints, because the method of measuring resistance changes responded to changes in δR absolutely, and not to relative changes $\delta R/R$ for good joints in parallel circuits with a bad joint; however, there will be a decrease in sensitivity by a factor f given by:

$$f = 1/(nB + 1)^2 ,$$

where n is the total number of good joints in parallel with a bad joint and B is the resistance of the bad joint relative to a good joint. (In many cases there is no difference in resistance between good and bad joints so that $B \approx 1$). This value of B would mean that for $n \approx 1$ the sensitivity would be decreased by a factor of 4, for $n \approx 2$ the sensitivity would be decreased by 9 times, and so on.

Some of the measurements of resistance change for various joints are shown in Table II. Connection letters refer to Sketch VII.

The resistance changes, $5 \times 10^{-5}\ \Omega$ at 100 mA, $3 \times 10^{-6}\ \Omega$ at 200 mA, $2 \times 10^{-6}\ \Omega$ at 300 mA, and $1 \times 10^{-6}\ \Omega$ up to 500 mA, were arbitrarily chosen as maximum acceptable standards. Analyzing the above date, it can be seen that the circuit A↔C on the supposedly good board has a resistance change of about 5 times the maximum acceptable value for good joints and the circuit A↔E has a resistance change of about 100 times the acceptable maximum. When the good board was dissected and each joint tested individually, it was found that the points P and Q (see Sketch VII) were the only bad joints in the whole board. It will be noticed that the circuits on the "bad" board vary from a factor of 5 to a factor of 100 times the maximum acceptable resistance change. Some of the lower values being undoubtedly due to "masking" of the measurements by parallel combinations being present.

The two bad joints that were present on the good board were unintentionally bad and probably represent the type of defect that is of the most interest. Before the test, both

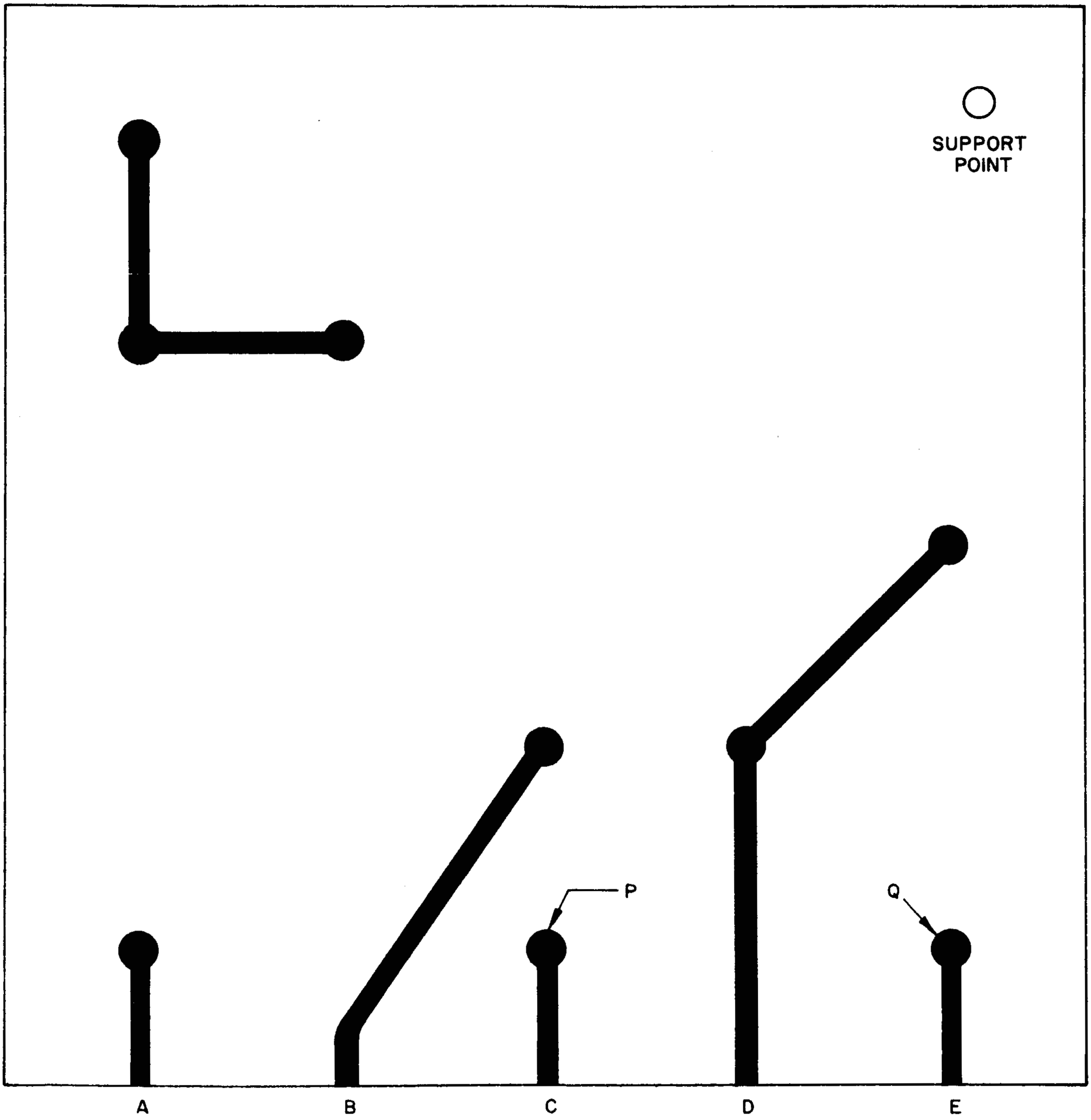
TABLE II

RESISTANCE CHANGE RESULTING FROM ACOUSTIC VIBRATION

Circuit Connection	Circuit Current Milliamperes	Resistance Change in Microhms	
		Good Board	Bad Board
A ↔ B	100	< 5	250
	200	< 3	110
	300	< 2	100
	400	< 1	90
	500	< 1	160
A ↔ C	100	20	50
	200	30	60
	300	10	70
	400	10	70
	500	5	60
A ↔ D	100	< 5	15
	200	< 3	40
	300	< 2	30
	400	< 1	30
	500	< 1	60
A ↔ E	100	105	25
	200	145	30
	300	115	35
	400	100	45
	500	100	70

Vibration amplitude was 3 x 10^{-4} inches at the support point - frequency 14 KHz.

MATERIAL - 2oz. COPPER - EPOXY - GLASS LAMINATE
SCALE = 2x
REDUCE TO 4" x 4" BOARD



SKETCH VIII CIRCUIT CONNECTIONS FOR ACOUSTICAL TEST joints had a resistance which was very low and equal to that of the other joints present; but after the test, the joint Q was made to become an open circuit by vibrating the board more vigorously (vibration amplitude of 10^{-3} inches at the support point). The resistance of joint P was not affected by this treatment, but on repeating the tests for resistance change, a slight increase in resistance change was noted, whereas for all of the other joints the data remained the same, thus showing that P and Q alone had been permanently affected by the vigorous vibration.

Possibilities for Further Development of this Method

So far no measurements have been made of vibration amplitudes over various parts of the board, and, therefore, each joint in the tests was probably not subjected to the same constant vibration amplitude although in one case the tests were repeated for three different support positions. It would be very valuable to make these measurements using an ultramicrometer, so that the best support position could be found to avoid the production of sharp nodes and antinodes in the standing wave system. It may be found necessary to sweep through a certain frequency range continuously or to simultaneously excite the board at different frequencies from different support points. Some research work on the vibration of thin plates in a sound field is already being conducted at IITRI.

It is also believed very strongly that some effort should be made in an attempt to understand the fundamental mechanism whereby resistance changes are caused by vibration. This would be of value from a practical standpoint as well in helping to choose the continuing conditions under which the tests should be conducted. For instance, the way in which the resistance changes depend upon the D.C. current is not understood and does not appear to be a reproducible effect from one bad joint to another. There are many variables in the experiment which could be isolated one by one in order to ascertain their effects upon the resistance changes. The results tend to indicate that the changes are caused by flexural waves in the board producing small changes in dimensions of the joints. Comparison of the data with calculations based on this theory should be made.

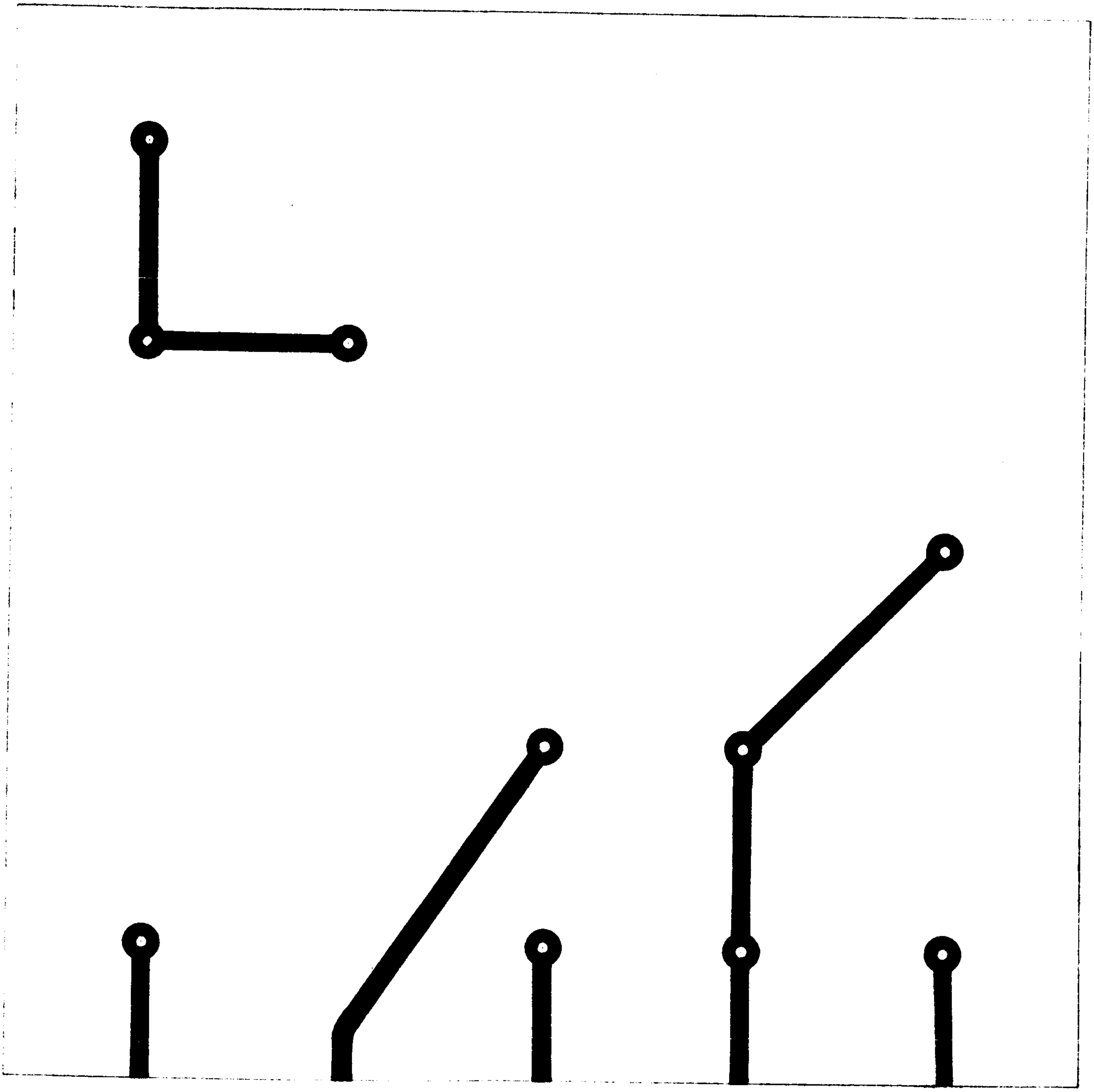
Conclusion

This technique has proven very sensitive to resistance variations, being able to detect changes of 10^{-6} ohm under vibration. Several riveted joints which appeared good under static resistance measurements were shown to be defective under vibration. The very great disadvantage in this method is the need for a multiplicity of electrical connections to the test board and isolation of individual connections for measurement. Because of these disadvantages, a decision was made to concentrate on development of laminography and the mutual coupling probe and to discontinue further effort on the combination acoustical techniques.

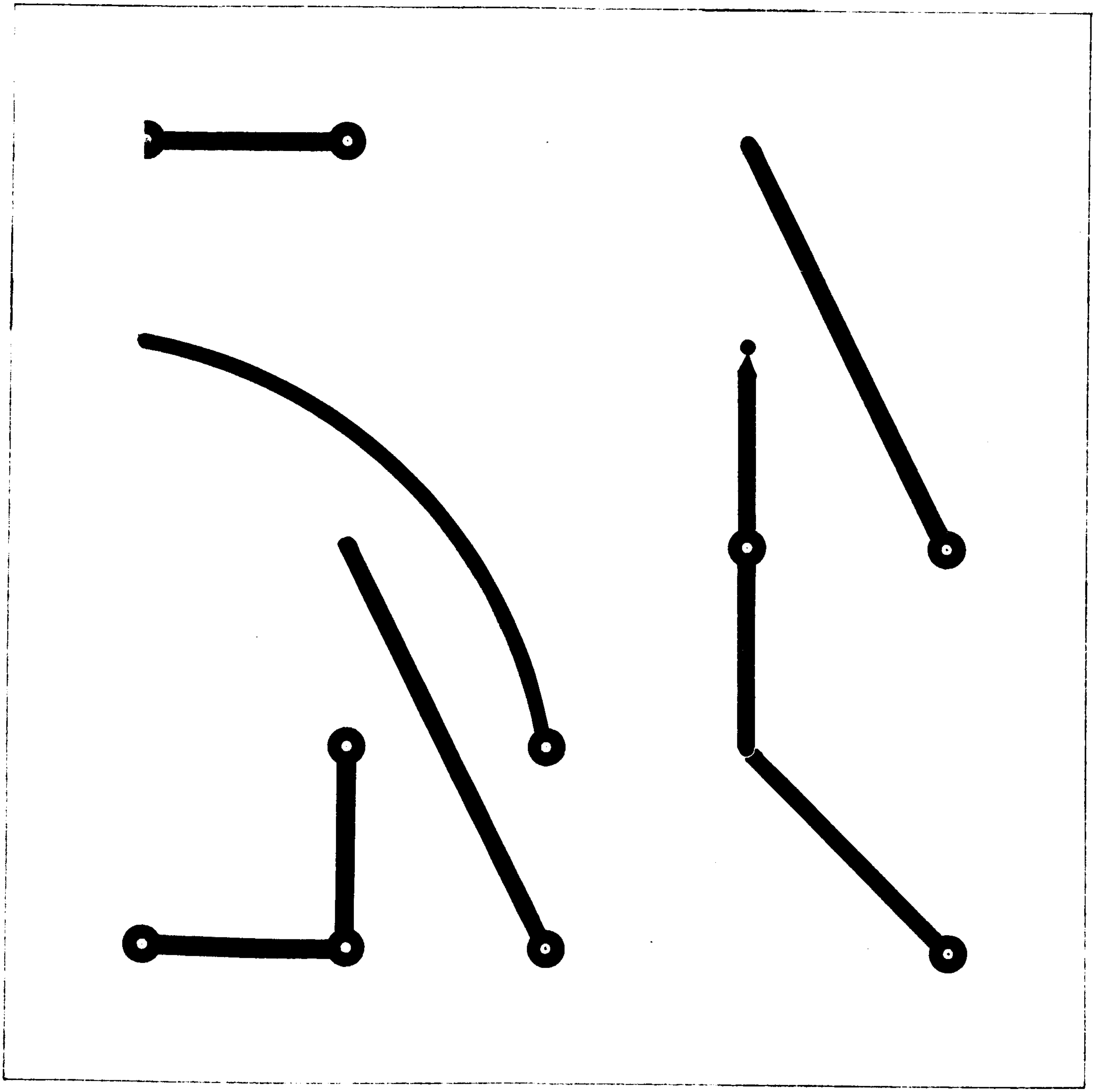
APPENDIX II

TEST BOARD CONFIGURATION

MATERIAL - 2 oz. COPPER-EPOXY-GLASS LAMINATE
SCALE = 2x
REDUCE TO 4"x 4" BOARD

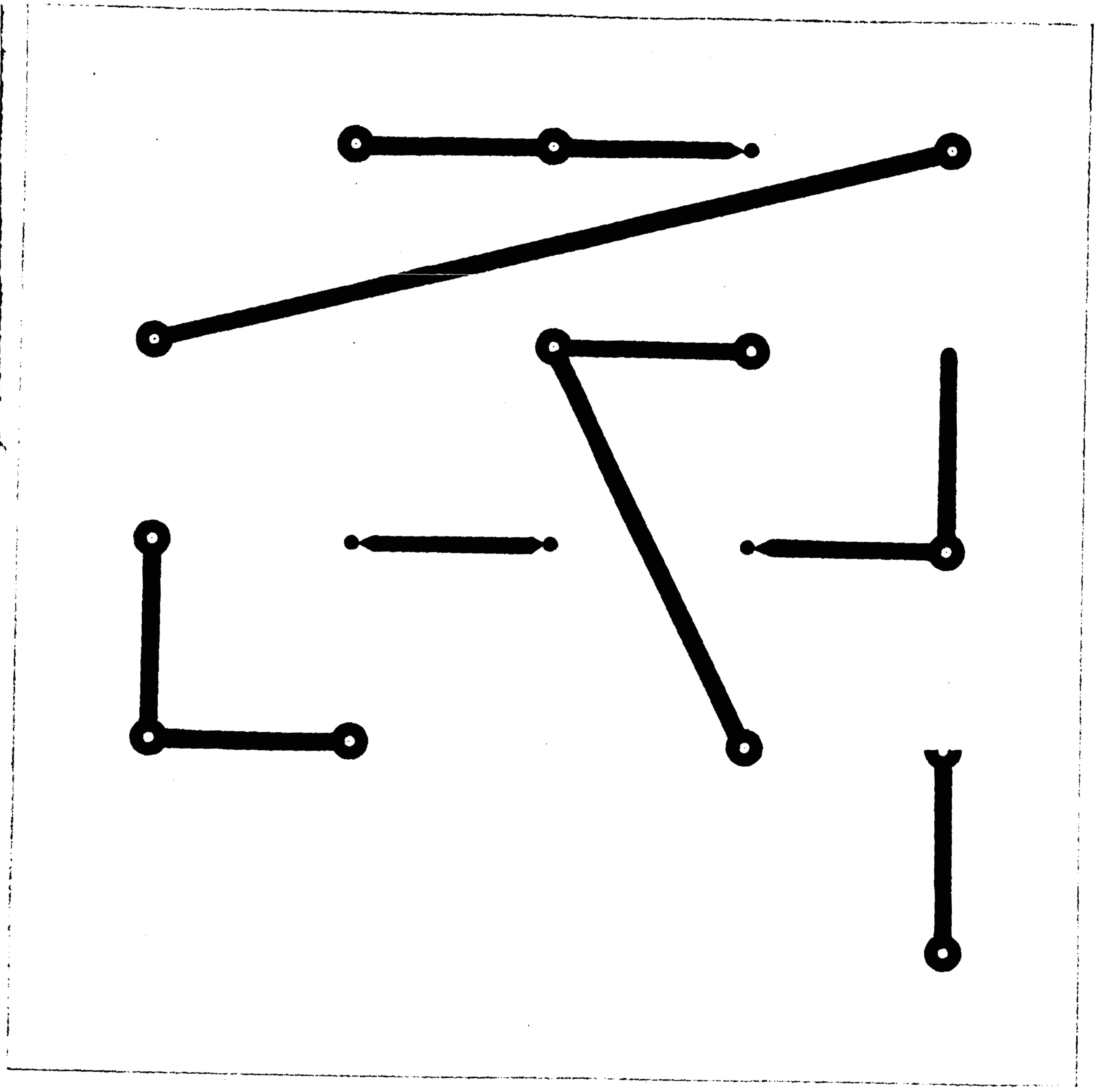


LAYER 1
(TOP)
E6024



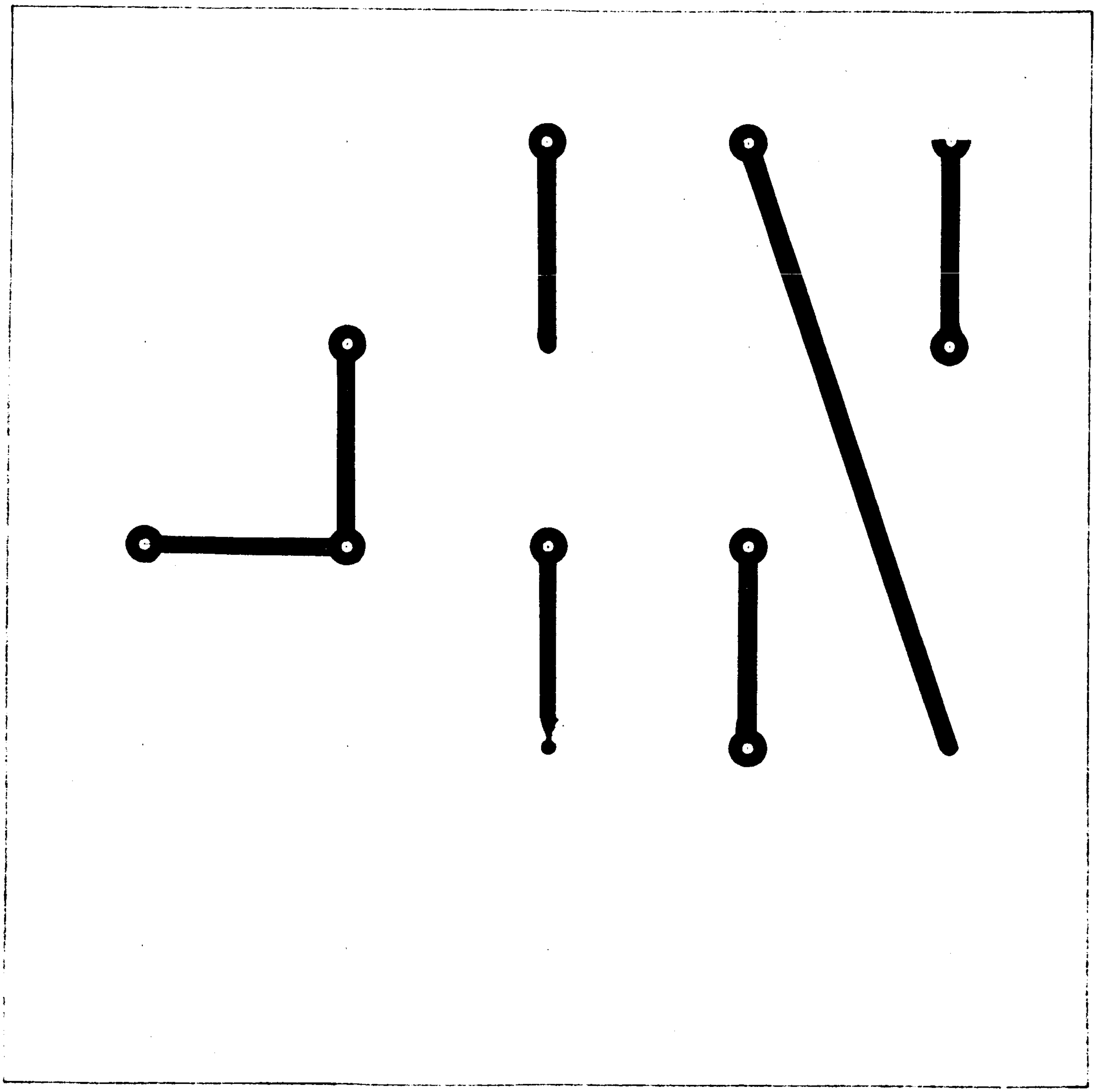
LAYER 2

E 6024



LAYER 3

E 6024



LAYER 4
(BOTTOM)

E6024