WADC TECHNICAL REPORT 54-231
PART 1

DEVELOPMENT OF NONDESTRUCTIVE TESTS FOR STRUCTURAL ADHESIVE BONDS

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STANFORD RESEARCH INSTITUTE

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MATERIALS LABORATORY
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

This report was prepared by Stanford Research Institute, under USAF Contract No. AF 33(616)-2035. The contract was initiated under Research and Development Order No. R614-11 SR7j, "Structural Adhesives," and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Major T. J. Martin and S/Sgt. J. C. Ingram Jr. acting as project engineers.

ABSTRACT

Research has been done on the use of sonic methods for the non-destructive evaluation of metal-to-metal adhesive bonds. No aspect of the low frequency behavior (less than 15,000 cps) has been found to be indicative of joint strength. Techniques utilizing high frequency impedance measurements as provided by mechanical driving systems, and steady displacements produced by the application of vacuum cups, have been developed. These techniques show sufficient correlation between bond strength and measurable parameters to justify further investigation, and one or more of them may ultimately provide a satisfactory solution to the non-destructive test problem for adhesive bonds.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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INTRODUCTION

Air Force Contract No. AF33(616)-2035 with Stanford Research Institute contains in Exhibit A the following statements:

"The objective of this research program is the investigation and evaluation of sonic phenomena as a means for non-destructive and non-damaging inspection of metal-to-metal adhesive bonds used in aircraft structures. The immediate objective of this program is to find out whether or not a non-destructive test for cemented bonds can be accomplished in a practical manner."

Subsequent modifications of the contract extend its duration and permit the consideration of physical methods other than sonic for the development of a test technique. This report describes the work done during the initial year of the contract. The present termination date of the contract is 31 December 1954.

The use of adhesives for joining metal parts sometimes offers advantages over other fastening methods. Less weight, the absence of projections, and the distribution of stresses over larger areas are some of the advantages.

One of the major disadvantages in the use of adhesives is the difficulty of evaluating the quality of the joint. This disadvantage is one factor that deters designers from a more extensive utilization of the adhesive joint, in which it might contribute additionally to aircraft performance. Current practice in the construction of adhesive joints tends toward extremes in process control and in the destructive testing of selected assemblies, partly because no completely satisfactory non-destructive testing technique for finished joints exists.

Two general types of adhesive joint are in use. One is a lap joint in which the metal members overlap and are held together by an adhesive film between them. The second type is used in what is called "sandwich construction." A sandwich panel consists generally of a light central member (for example aluminum foil honeycomb) to which have been cemented outer skins of sheet aluminum. This type of joint, instead of fastening parallel members, fastens an end to a flat in what might be termed a perpendicular joint. Other materials, such as cloth impregnated with adhesive, may be placed in the joint to augment its strength. Figure 1 shows typical examples of these joints. Most of the experiments on this project have been concerned with the sandwich construction, because the size of readily available panels and their smooth surfaces make them

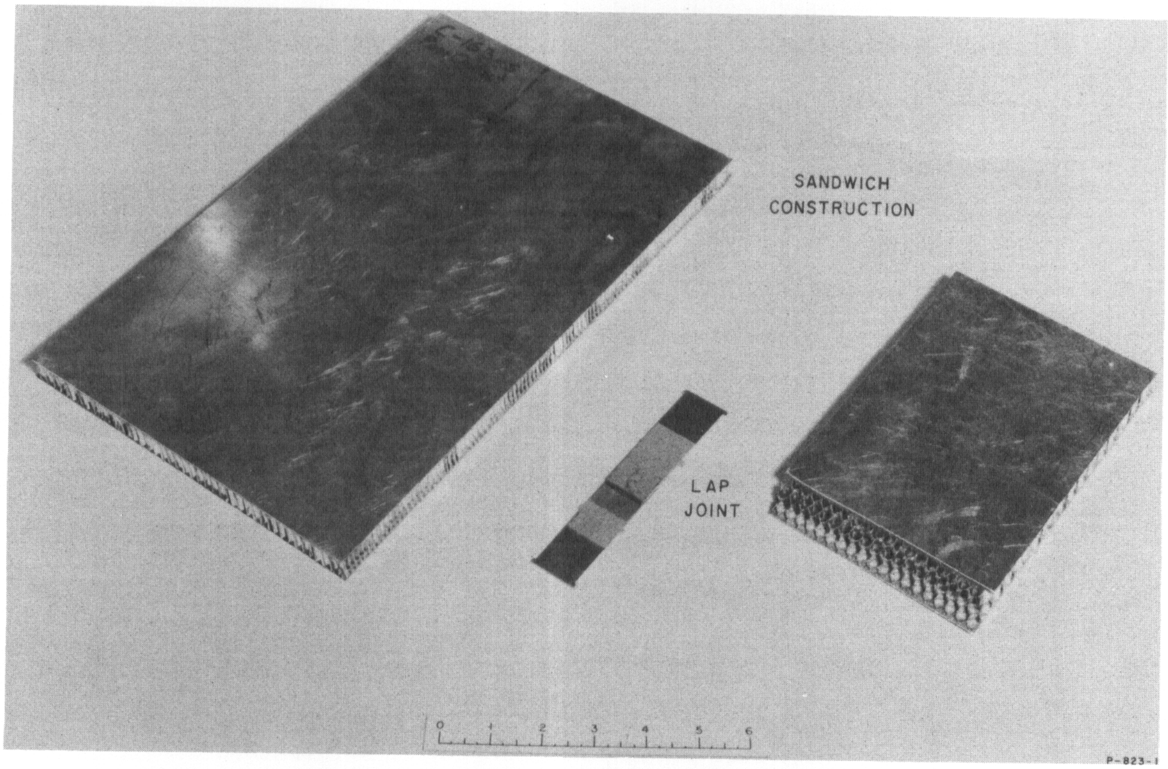


FIG. I

TYPICAL ADHESIVE BONDED METAL PARTS

somewhat easier to work with than are lap joint samples. The specialized area (overlap) and geometry (single lap, scarf, butt, etc.) of lap joints seems to direct the exploratory experiments toward sandwich panels; if a useful non-destructive test method is found, it can then be tailored to fit the requirements of lap joint testing.

SECTION I. EXPERIMENT DESIGN

1.1 Preliminary Discussion

A literature search was undertaken as the first phase of the investigation. About 150 seemingly pertinent abstracts in texts and journals were noted. Of the papers they represented, very few contained information or ideas that might be exploited, and none suggested a clear-cut solution to the problem. This search revealed the work that has taken place and is in progress on this problem in other laboratories, thus preventing possible duplication of effort. The work at other laboratories with heat transmission, acoustical behavior of panels, and behavior under proof loading was studied, and some organizations were visited in order to obtain a more complete knowledge of their approaches to the problem.

The publications of Dietz et al.[1,2]* indicate that the elastic coefficients of the adhesive in a joint can be measured by ultrasonic techniques if the geometry of the joint is known. Further, their work indicates that the probability of future failure under at least one set of environmental conditions can be predicted from a knowledge of the elastic constants. The existence of a relationship between elastic behavior and strength in the one case offers some hope that a similarly useful relationship can be found for application to the adhesive joints with which this project is concerned. Although the configuration of adhesive and metal surfaces cannot be known in detail, the possibility exists that some measurable parameter of the system may provide an indication of the strength of the joint.

The application of "sonic phenomena" to the problem is interpreted as the effort to establish a relationship between the mechanical parameters of the system and the strength of the system. This is attempted by applying forces to the joint and measuring its response. "Sonic" implies that the forces must be alternating in character; the frequency range of the alternations is not specified, and is assumed to cover the entire vibration spectrum from zero to frequencies as high as can be utilized practically.

To supply alternating forces to the test specimen, some sort of driver is necessary. This may apply force over small areas of the test specimen or over large areas. Observations must be made on the effects of the force; a pickup

* For numbered references, see list of References at the end of this report.

device of some sort is applied to the specimen and made to produce a measurable indication. The pickup device may sample the effects over large or small areas. In order to be useful, such a system must have a sufficient degree of resolution to locate faults in the test specimens. If excitation takes place over a large area, observations of response must be made on small areas to provide the desired resolution. If excitation of a small area is used, the response of the sample as a whole may perhaps be correlated with conditions at the point of excitation.

The magnitudes of forces used must be small to be sure that the non-destructive requirement of the problem statement is fulfilled. This requirement does not place a precise limit on forces that may be used, but does provide an order of magnitude indication. Destructive tests on samples of sandwich panels indicate that failures occur when forces of the order of hundreds of pounds per square inch are applied. It has been assumed in the present work that forces in the tens of pounds per square inch range may be applied to the adhesive joints without damage. The question of the criterion that should be established for non-destructive tests is one that may require further discussion.

In the investigation of sonic methods for testing adhesive bonds, the following experimental requirements exist. A driver for applying the energy must be provided. This device must transfer energy from a source to the test specimen. A pickup device must be applied to the specimen so that its response to the driving force can be measured. The applicability of the method to the problem can be proved only by the determination of some parameter of the system that differs in response according to the quality of the bonds in the specimen. Resonant frequencies, phase relationships, impedance, power absorption, transmission velocity, attenuation, and reflectivity at interfaces, are some of the parameters that may exhibit sensitivity to the quality of the bonds and thus be used for their evaluation. The first year of work on this problem has been concerned with design, construction, and measurements with drivers and pickup systems, and with efforts to correlate the results with the bonds in the specimen.

The present destructive tests for sandwich construction are of several types, peel tests, flatwise tensile tests, flexure tests, plate shear tests, edgewise compression, etc. The drum peel test and flatwise tensile tests were used in this investigation to check the results obtained from the non-destructive tests. The peel tests record the force necessary to peel a skin from a panel, the skin being wound around a roller.[3] The tensile test records the force necessary to produce failure in a 1 square inch sample of the material when it is pulled apart. When these tests are applied to a sample, the agreement is usually good, although discrepancies sometimes are recorded. A successful non-destructive testing technique should produce indications that are compatible with the destructive test measurements, at least for cases in which the destructive test techniques produce consistent evaluations of the bonds.

Questions exist regarding the optimum size of test areas and the extent of permissible faults in the samples. General answers to these questions cannot presently be established because of variations in part cost, ultimate use, part geometry, and the like. An applicable non-destructive test technique must be found before they can be answered.

1.2 Test Panels

About 30 panels were purchased and used as typical examples in the experiments. These panels are of aluminum honeycomb construction with aluminum skins and adhesive impregnated fiberglass tape between the core and skins. Appendix 1 gives a description of these panels. The panels were made by the California Reinforced Plastics Company at their factory in Oakland, California. They are approximately 10 in. x 15 in. x 5/8 in. in size, and are equally divided between 1/4 in. and 1/8 in. cell sizes. The standard curing operation for the adhesive, which was performed on all except the undercured panels, consisted of heating the panels while in a rigid steel platen press with pressure equalizing pads of blotting paper. The initial pressure applied to the panels was 4 psi for a period of 5 minutes at 345° F. This was followed by a period of 1 hour at 30 psi and 345° F. The panels may be grouped in the following classifications.

Control Panels. These panels contain no known defects, and were made according to the best manufacturing processes available.

Starved Panels. (1) These panels contain an area in the form of a central strip on one side of the panel that has a sub-standard quantity of adhesive. The core priming operation was not performed on this strip, all other procedures being carried out.

Starved Panels. (2) These panels have an area in the form of a "V" on one side of the panel in which the fiberglass tape was omitted, all other procedures being standard.

Undercured Panels. The construction of these panels was standard, but the recommended curing time for the adhesive was not observed. In this case the curing time and temperature were altered to 35 minutes at 180° F.

Poor Contact. Before these panels were assembled, a strip down the center of one side of the core was sanded, removing the core to a depth of approximately .015-.020 inch. The panels were then assembled, using the standard materials and sequence of operations, including the steel platen press and pressure pads.

Contaminated (1) Panels. These panels were constructed in the standard manner except that the cleaning operation on the skins was omitted.

Contaminated (2) Panels. These panels were constructed in the standard manner except that after cleaning, the skins were allowed to hang exposed in the factory for a period of 100 days before assembly.

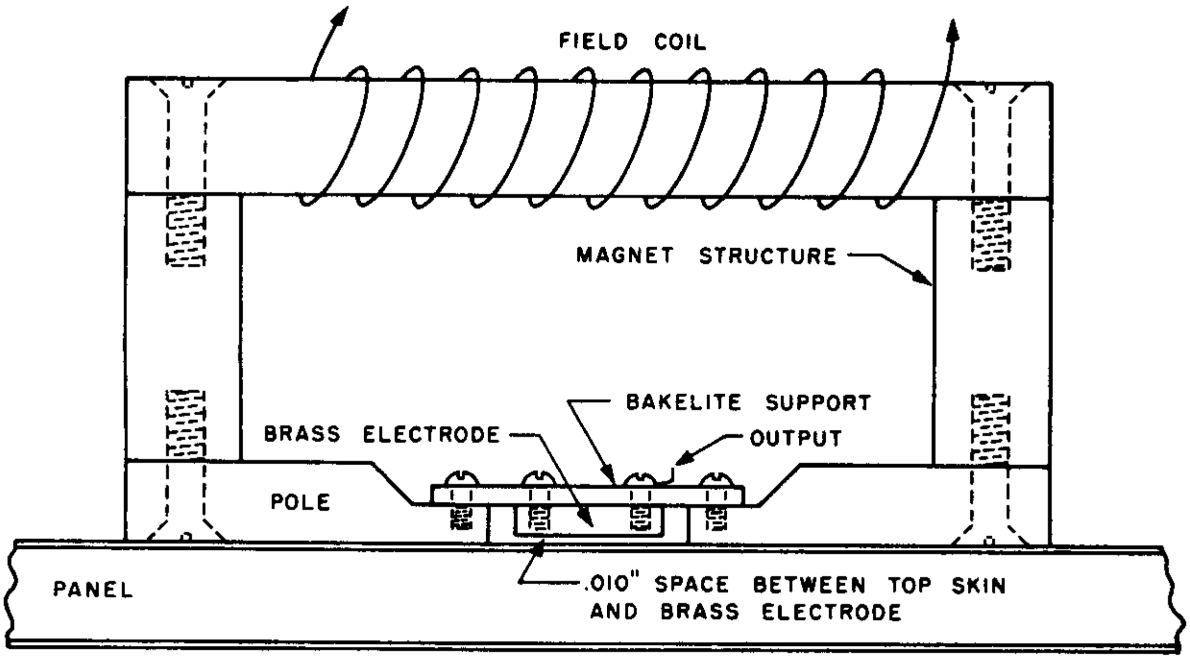
After assembly and curing of these panels, strips were cut from their edges in two directions. These strips were subjected to flatwise tensile and peel tests to evaluate the bonds. These data are included in Appendix 1.

SECTION II. EXPERIMENTAL RESULTS

2.1 Electromagnetic Driver

An electromagnetic driver was constructed as a device to impart a vibratory force to a panel. The force is produced by the interaction of an electric current with a magnetic field: the Faraday Effect. Figure 2 is a diagram of a part of the driving apparatus. A magnetic field is produced between the pole pieces of the electromagnet, having a component in the plane of the top skin of the panel. An alternating current is conducted through the skin at right angles to the direction of the magnetic field. The interaction of the current and magnetic field produces a force that is perpendicular to the directions of the field and the current, i.e. perpendicular to the plane of the panel skin. Figure 3 is a photograph of the apparatus on a test panel.

An electrostatic pickup is used to measure the motion of the skin. It is a condenser, formed by the top surface of the skin and the lower surface of an electrode that is supported by the pole pieces a few thousandths of an inch above the skin. Motion of the skin produces changes in the capacitance of the condenser; when used with a suitable polarizing potential, this condenser furnishes



CURRENT PRODUCED PERPENDICULAR TO MAGNETIC FIELD IN SKIN BY CONTACTS NOT SHOWN

FIG. 2
ELECTROMAGNETIC DRIVER

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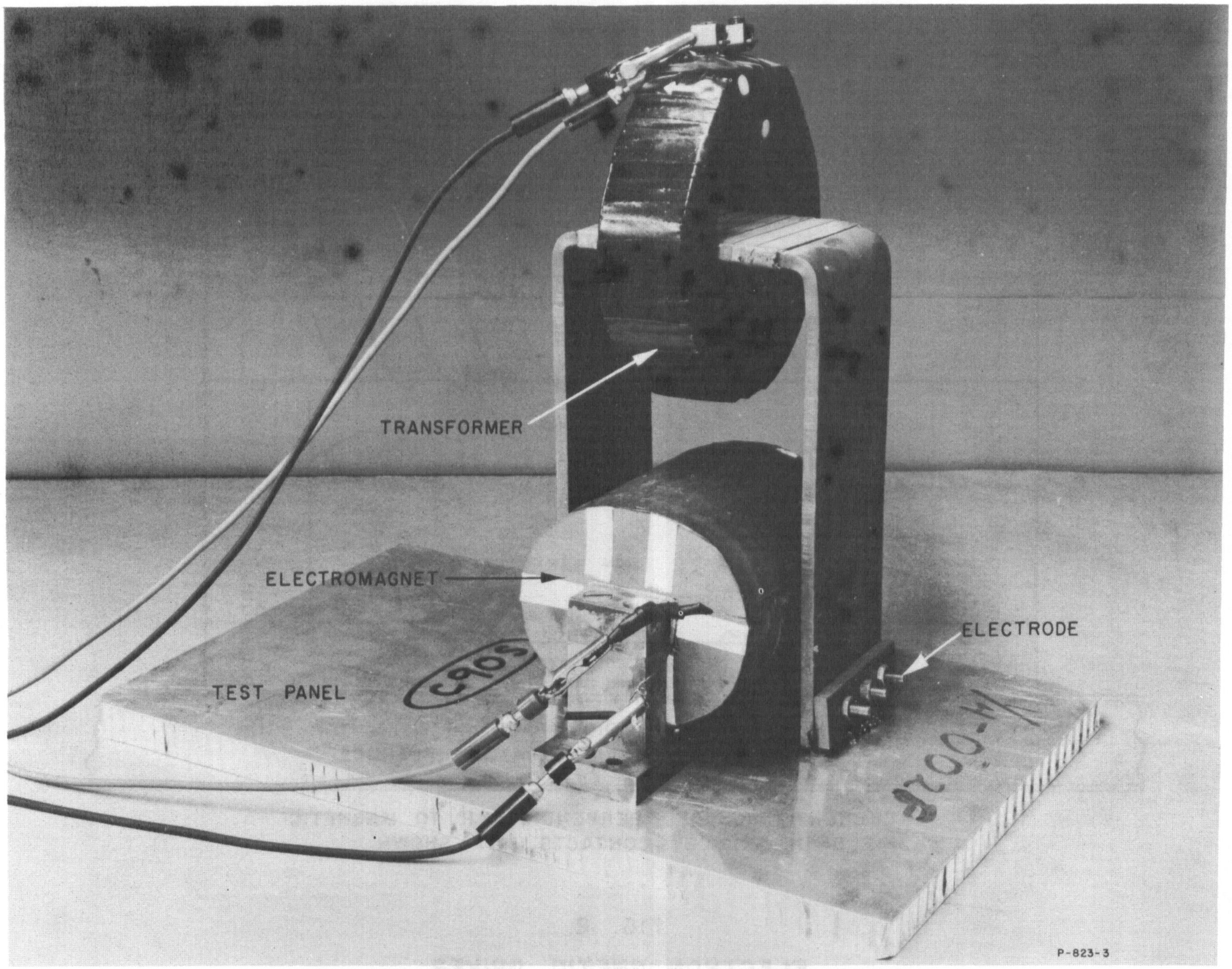

FIG. 3

ELECTROMAGNETIC DRIVER

an electrical output signal directly proportional to the movement of the skin.

The current carried by the skin is produced by a transformer with a one turn secondary; contact with the skin is made by multiple pressure contacts so oriented that the current flow is perpendicular to the magnetic field. A current metering transformer is used in this application, its normal connection reversed to secure the proper impedance match (low voltage, high current). Power to feed to the transformer is obtained from a variable frequency oscillator and power amplifier. The useful frequency range of the circuitry is 25-15,000 cps; the limits are imposed by the characteristics of the amplifier and transformer.

The output of the pickup condenser was connected to an oscilloscope for visual observation or to a Vibralyzer for recording and analysis. The Vibralyzer is an instrument manufactured by the Kay Electric Company for the analysis of audio-frequency signals. Figure 4 is a reproduction of one of the typical Vibralyzer records.

The use of this driver and pickup system makes it possible to establish vibration in the panel and record its presence. This was done at several locations on a number of panels; a total of approximately 100 records was made, while visual observation with the oscilloscope extended the number of observations to approximately 250.

No characteristics of the panels were found that could be attributed to the quality of the bonds. The response of a panel when vibrated and surveyed in this manner seems to be dictated by the geometry of the panel as a unit, not by the bonds at the point of excitation. The panel seems to behave as a rigid plate and to have possible modes of vibration corresponding to those of a plate; they depend upon geometry, method of support, and the imposed frequency. No aspect of the response was found to be related to the known faults in the panels. It should be pointed out that none of these experiments involved the response of an area in which there was no bond between the skin and the rest of the panel. This case (unbonded area) can be detected by tapping and other means, and is not considered to be a case of primary importance in the present program. Test panels with this particular fault were not available when the above tests were made, and if the method is considered further such tests will be performed.

One of the disadvantages of this driving method is the heating that occurs in the panel skin as a result of the large currents necessary to produce a useful

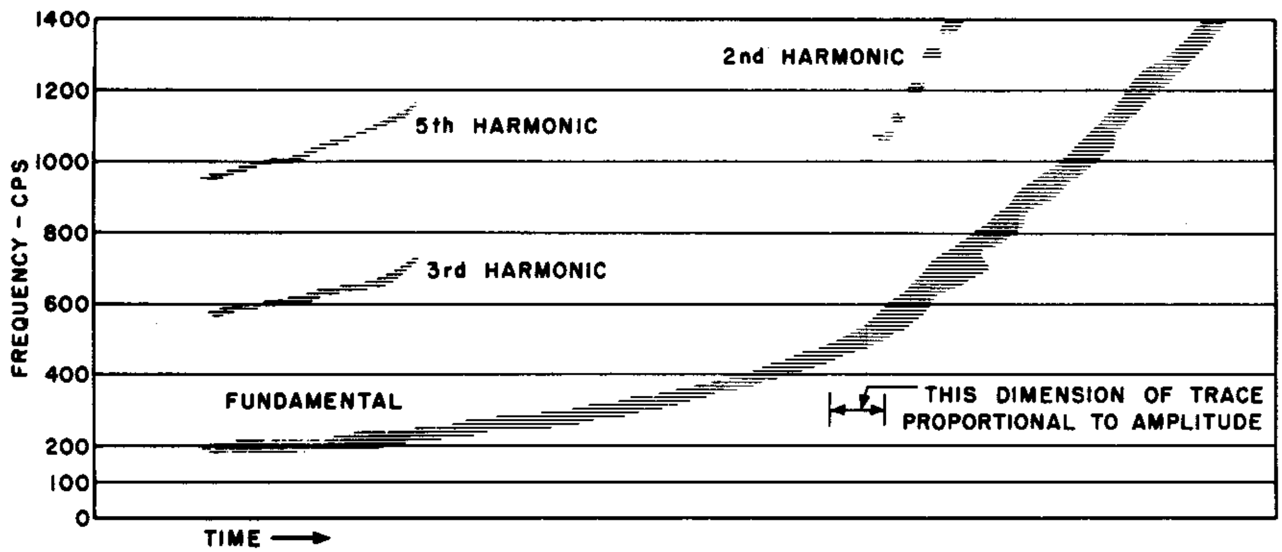

FIG. 4

TYPICAL VIBRALYZER RECORD OF FREQUENCY - TIME SWEEP RESPONSE - SANDWICH PANEL. CAPACITY PICKUP.

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magnitude of vibration. Current densities of the order of thousands of amperes per square inch of skin cross section would be desirable from the force standpoint, and the introduction of these currents into the skin is hardly possible without the development of heat concentrations at the contact areas. An eddy current driver was designed to eliminate the contact heating, but it soon became evident that losses in the skin itself would appear as heat and that with the eddy current driver the current distribution in the skin could not be controlled. This case corresponds to the induction heating of metals by alternating magnetic fields. The temperatures that might be reached in these situations are limited only by the abilities of the systems to dissipate the heat. This advantage, along with the greater apparent success of a mechanical driver that had been developed concurrently, led to the concentration of effort on the mechanical driver.

2.2 Mechanical Driver

A mechanical driver furnishes vibratory force to a test panel by direct transmission. A source of energy, usually electrical, is connected to a transducer. This converts the electrical energy into mechanical energy, which is imparted to the test panel by direct contact. Several types of electro-mechanical transducer are possible; the ones that have been used most successfully in this project are loudspeaker drivers. Such a driver is illustrated in Figure 5. The cone and cone support assembly have been removed from a loudspeaker, leaving the voice coil and its suspension in place. A metal cone has been made, fastened rigidly to the loudspeaker frame. A flexible membrane connects this cone to the voice coil, forming a conical cavity, one end of which is closed by the voice coil, which is free to move.

The cavity is filled with a fluid or semi-fluid coupling medium, the function of which is to transmit the energy from the vibrating voice coil to the test specimen located at the open end of the cone. This end can be sealed with a membrane to prevent loss of the coupling medium. Cellophane and thin rubber have been used as membranes. "Bouncing putty," a silicone compound made by the General Electric Company, has been used most successfully as a coupling medium. Its behavior as a liquid for steady forces makes it easy to flow into place and to remove air inclusions. For vibratory forces it behaves as an elastic solid with very little energy loss, at least in the audio-frequency range. It conforms readily to the surface irregularities of the test panel.

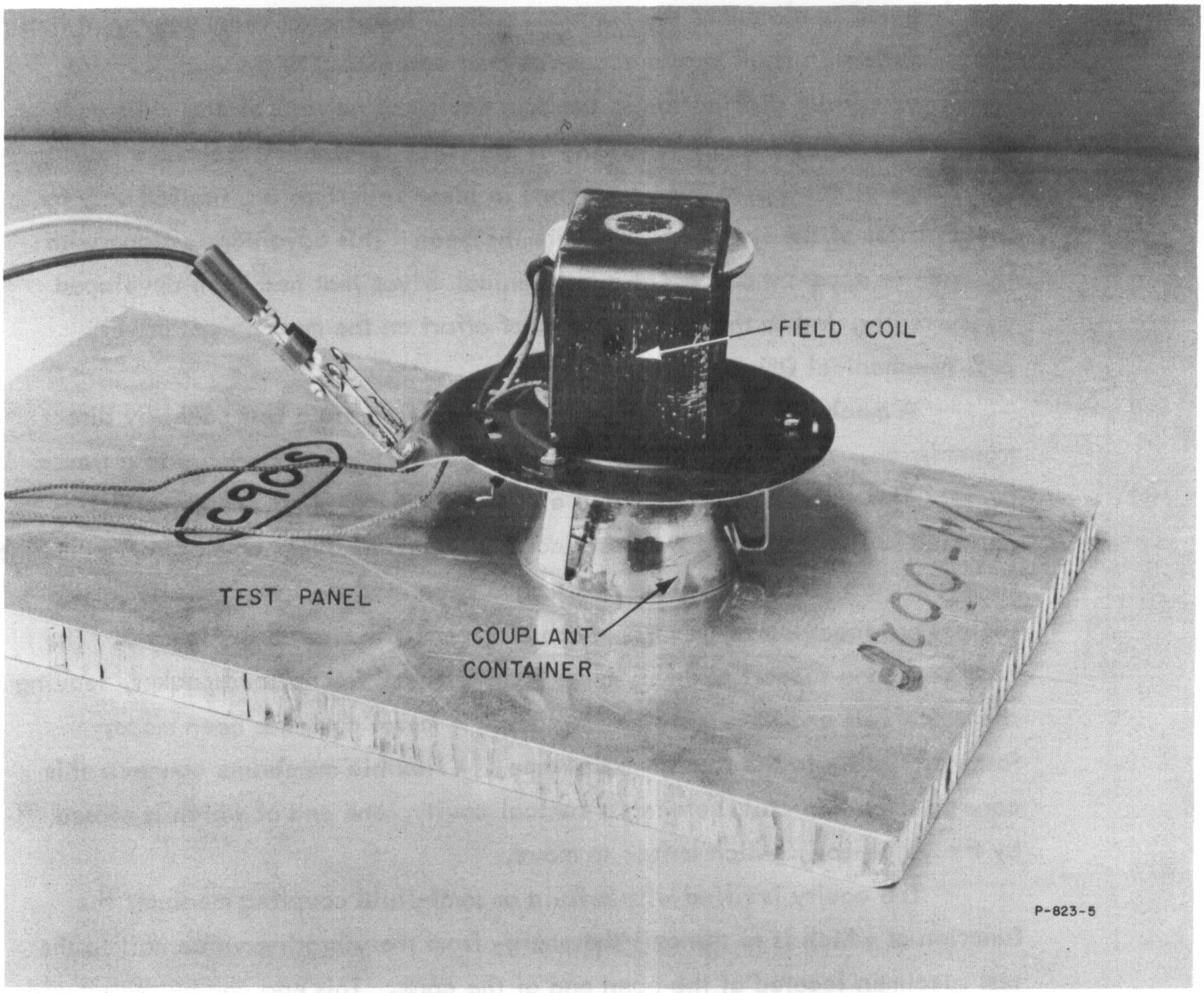

FIG. 5
ACOUSTIC DRIVER

A piezoelectric vibration pickup was used for surveying panels when excited by the mechanical driver. This is a standard commercial device that is held in contact with the vibrating object manually. The output of the vibration pickup was observed on an oscilloscope. In the use of the mechanical driver, the response of the panel at the driven point cannot be measured directly because of the presence of the driver. In the case of the electromagnetic driver this could be done, as the existence of the current and magnetic field did not interfere with the presence of the pickup device.

The observations made with the mechanical driver and vibration pickup led to the same conclusions that had been reached previously, that the response of the sample is determined predominantly by its geometry rather than by the adhesive bonds in the panel. No aspect of its behavior that was measured by a pickup device could be related to the presence of defects in the panel. As in the case of the experiments with the electromagnetic driver, unbonded areas were not tested.

One type of measurement was made with the mechanical driver that did seem to distinguish between good and defective areas on a panel. This measurement did not employ a separate pickup device; it was a mechanical impedance measurement, in which the effect of the test sample upon the driver was determined. The measurement was made by recording the voltage and current in the voice coil circuit, as shown by Figure 6. The vector diagram shows typical voltage relationships, with E_R in phase with E_3, thus proportional to the square root of the power in the circuit. Measurements at a single frequency on good and defective areas cannot be compared directly because of the effects of panel geometry, but when measurements are made over a range of frequencies, a difference in behavior appears. This is illustrated by Figure 7. The peaks and valleys on these curves are related to the panel geometry. If the voltages are averaged over the frequency range, defective areas give values differing from those measured at good areas. The panel from which Figure 7 was measured shows that the voltages remain roughly parallel over the frequency range of the measurements. Other panels exhibited crossing of the voltage curves at frequencies below 8000 cps, and the defective areas became easier to distinguish as the frequency was increased.

Measurements of this type are felt to be marginal in their significance under the conditions which existed. The effect measured corresponds to a change in average power transmitted by a fixed driving force (E_3 constant) through an area of panel. The average power in the driver circuit is affected by electrical losses

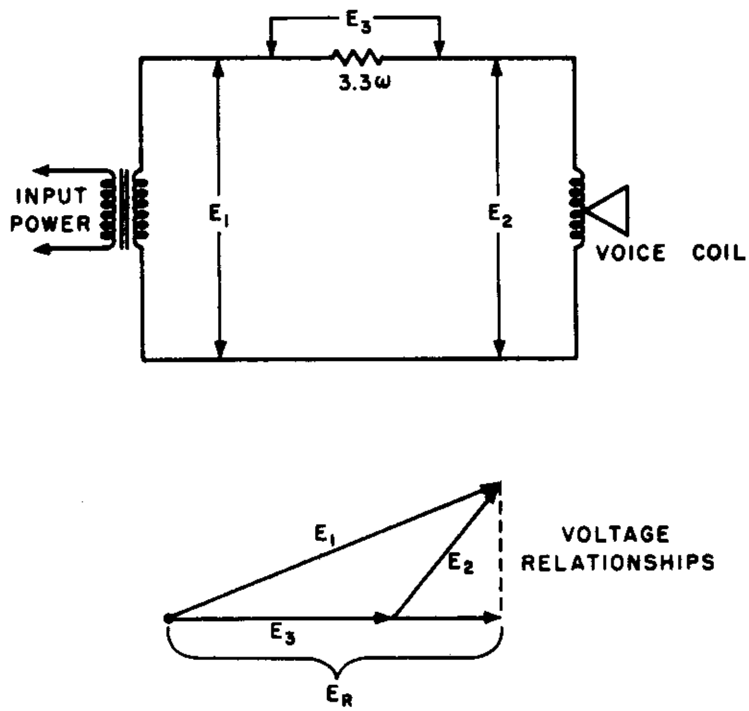

FIG. 6

DRIVER CIRCUIT FOR IMPEDANCE MEASUREMENTS

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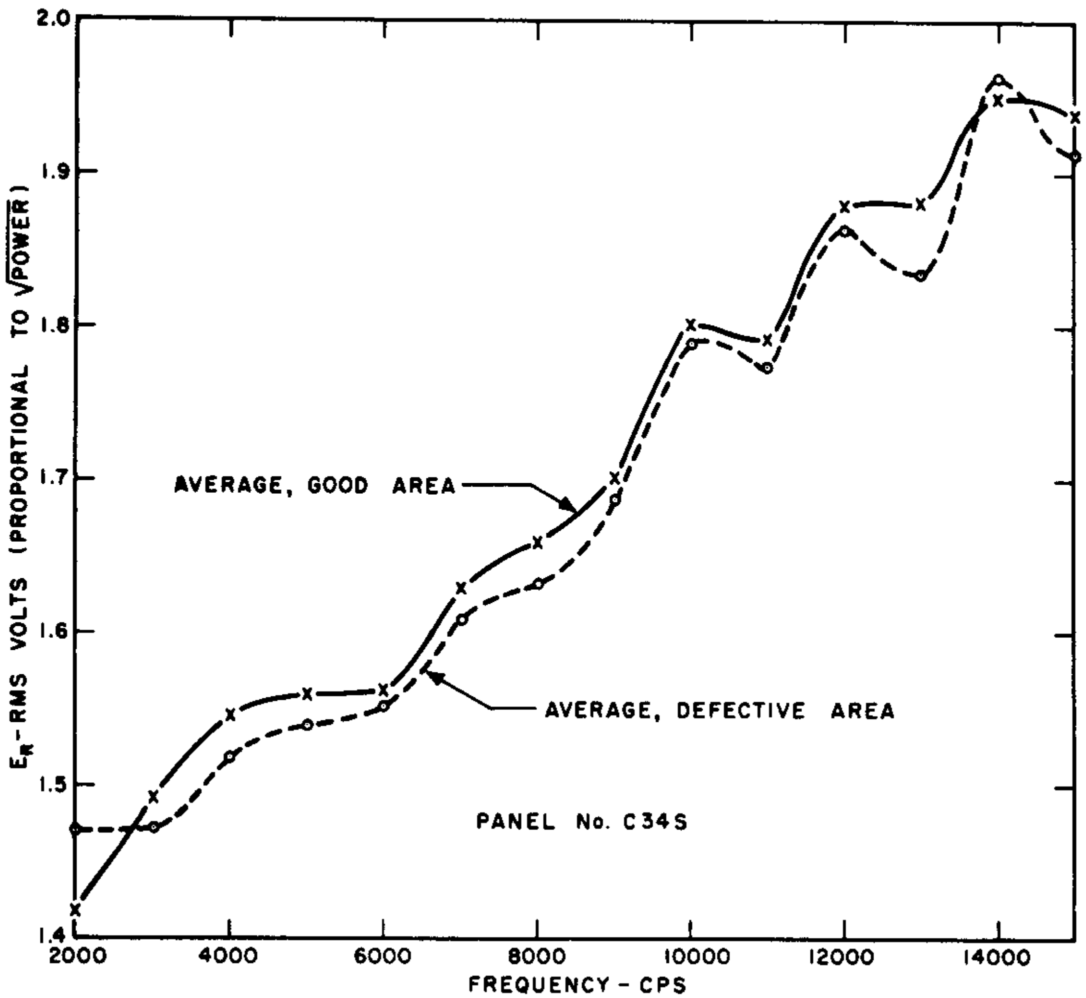

FIG. 7

VOLTAGE - FREQUENCY CHARACTERISTIC DEFECTIVE PANEL

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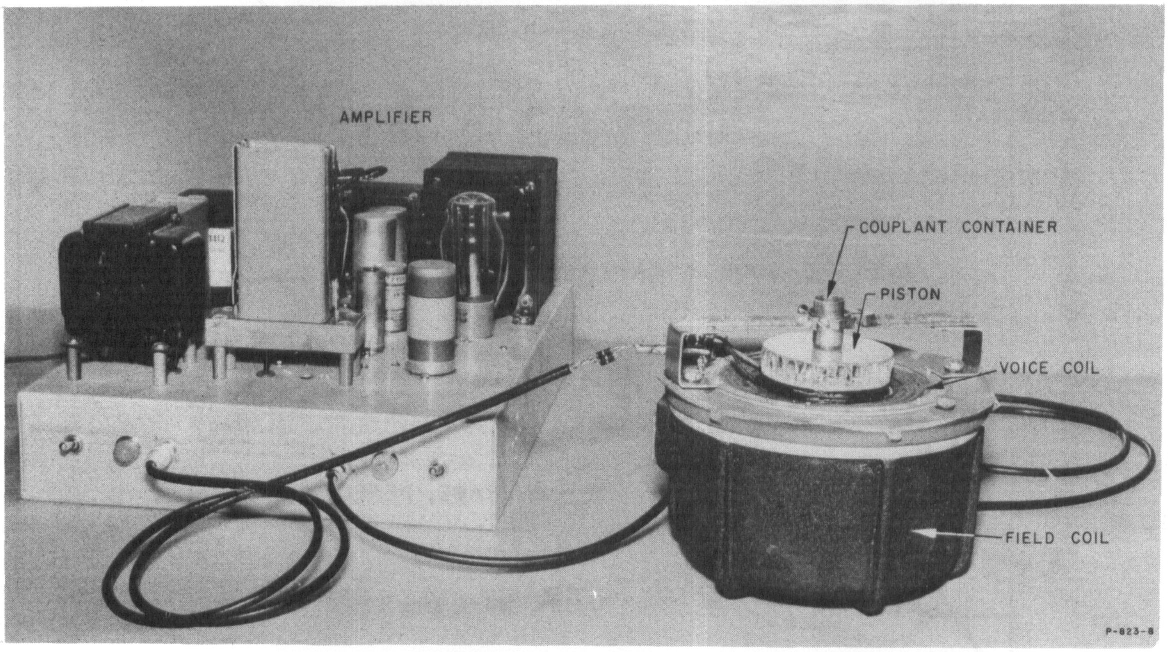

FIG. 8

AMPLIFIER AND SECOND ACOUSTIC DRIVER

in the circuit and mechanical losses in the driver itself. These are frequency dependent variables, and they are large compared to the power transmitted to the panel.

A power amplifier with greater output and an extended frequency range has been constructed so that the power measurements may be extended. Another mechanical driver w built (Figure 8) that had greater power handling capacity than the first. Its losses are too large to make it useful at frequencies greater than 12,000 cps, however. The driver problem for frequencies in the range above 15,000 cps is made more difficult by the requirement of broad band response so that power over a range of frequencies can be measured. Piezoelectric and magnetostrictive devices are commonly used as transducers in this frequency range, but their sharp resonance characteristics made them difficult to use in this application. If a suitable driver can be found, the applicability of this approach to the problem can be evaluated. Work is continuing in this direction.

2.3 Sperry Reflectoscope

A commercial instrument for non-destructive testing, the Sperry Reflectoscope, has been studied for possible application to the present problem. It is a mechanical driver and pickup system, employing a piezoelectric crystal (quartz) as the driver. This crystal is excited by an electrical pulse of high frequency power that is of short duration. The crystal vibrates and some of the energy is transmitted into the test specimen (Figure 9). At the time the pulse actuates the crystal (t_0) the indicating spot on the cathode ray tube leaves its rest position at the side of the cathode ray tube face. The pulse of high frequency sound energy travels through the specimen, away from the crystal. If this pulse encounters a flaw in the sample, part of the energy is reflected back toward the crystal. When this reflected energy strikes the crystal it generates a voltage that is amplified by the receiver and made to produce a visible indication (pip) on the cathode ray trace. The distance along the trace to the reflected pip is thus a measure of the distance from the crystal to the flaw in the specimen. By proper interpretation of the size and shape of the reflected pip, an experienced operator can tell something about the size and shape of the flaw.

In the present commercial instrument the electrical pulse of high frequency power is produced by shock excitation of a resonant circuit that is tuned to the natural frequency of the crystal. Such a circuit produces a power pulse that has a reasonably short rise time and a longer exponential decay, the rate of decay

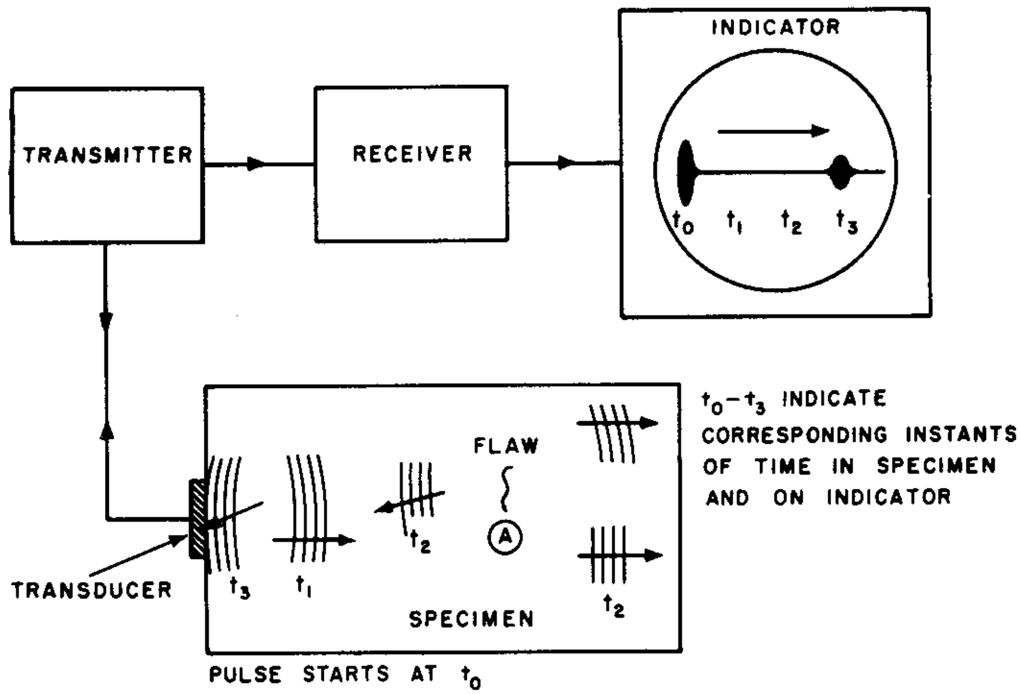

FIG. 9

PRINCIPLE OF REFLECTOSCOPE

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being determined by the losses in the circuit. The minimum pulse length that can be produced will include a few tens of cycles. The velocity of sound waves in aluminum is about 0.2 inch per microsecond. With an operating frequency of 10 megacycles per second and a pulse length of perhaps 10 cycles the detection of reflections from locations as close as about .05 inch from the outside seems to be a possibility. This could be useful for lap joint evaluation if a relationship between the quality of the joint and character of the reflection can be demonstrated.

The commercial instrument has been tried on sandwich panels with negative results in all cases except one. In this case, the 5 mc crystal and shortest pulse length were used and the presence of an unbonded area was shown by an extension of the transmitted pulse on the oscilloscope face. The transmitted pulse is too long to allow the instrument to resolve the leading edge of the pulse reflected from the inside skin surface, but apparently the loose section of skin vibrated mechanically after the electric excitation of the crystal had terminated, thus effectively extending the duration of the oscillation. When the skin was bonded to the core, this pulse extension did not occur.

Additional reflections of energy between the members of sandwich panels continue for tens or hundreds of microseconds after the transmitted pulse. The reflections produce a multitude of pips on the oscilloscope face. Attempts to correlate these reflections with known faults in the panels have not been successful.

If the principle of the reflectoscope is to be applied to sandwich construction, the geometry dictates some of the requirements that the instrument must meet. Assuming that a nominal skin thickness is 0.020 inch and that the pulse duration should be short in comparison with the time of travel to the first possible reflection, the pulse duration should be 0.1 microsecond or less. The desired resolution of reflections from the adhesive layer and core would be more readily obtainable with 0.01 microsecond pulses although the uncertainty of the velocity and character of reflection from the adhesive and its interfaces makes the 0.01 microsecond pulse requirement uncertain. The operating frequency should then be in the range 50-100 megacycles per second. The circuitry for producing such electrical pulses is rather elaborate, but the techniques have been established. Transducers for these frequencies would probably require considerable development work.

An effort will be made to modify a standard reflectoscope, raising its frequency and shortening its pulse length. While it will not be possible to attain the ranges described above, it is possible that smaller changes in operating frequency and pulse length may permit a more accurate estimate of the potential capability of the instrument.

2.4 Vacuum Cup - Capacitance Pickup

A small bell jar or vacuum cup may be used to apply force to a panel skin. When the vacuum is produced inside the cup, the ambient air pressure on the reverse side stresses the skin; the force is directed toward the inside of the cup. This provides a convenient way to impose steady forces on the bonds that exist between the skin and core of a panel. This force could be made an alternating one by providing an alternating pressure superimposed on a continuous vacuum inside the cup. The greatest force that can be obtained in this manner is equal to the ambient absolute air pressure, except in the case in which the force is concentrated by means of pressure pads.

The use of steady rather than alternating forces in attempts to evaluate the bonds has the disadvantage that parameters related to power absorption in the bonds (viscosity, hysteresis) are no longer measurable. It also has an advantage in the fact that forces are not propagated to all regions of the specimen as they are when acoustic waves are employed, thus restricting the effects of the force to the immediate area in which it is applied.

One of the effects of applying force to the bond should be an elongation of the bond, permitting the skin to flex toward the inside of the vacuum cup. The basic knowledge of the stress and strain configuration within the bonds is lacking, but order of magnitude calculations (Appendix II), based on what are believed to be reasonable assumptions, indicate that measurable elongations in a good bond are to be expected. Other elongations in the skin and in the core, as well as bending deformation of the panel as a whole under the vacuum-induced load, will contribute to the total deflection of the top skin. If some of these contributary elastic displacements are related to the strength of the panel bonds, it may be possible to relate deflection measurements in a general way to the bond quality, even in the absence of a specific knowledge of the mechanics of the situation.

Figure 10 illustrates the construction of the vacuum cup employed in the experiments. The earlier experiments were conducted with glass cups, as shown in Figure 11. The condenser pickup system was used, the capacitance between the fixed electrode and the top of the panel skin being the deflection-sensitive element of the circuit. No serious problem has been encountered in obtaining an adequate seal between the cup and the panel skin. The skins are usually smooth

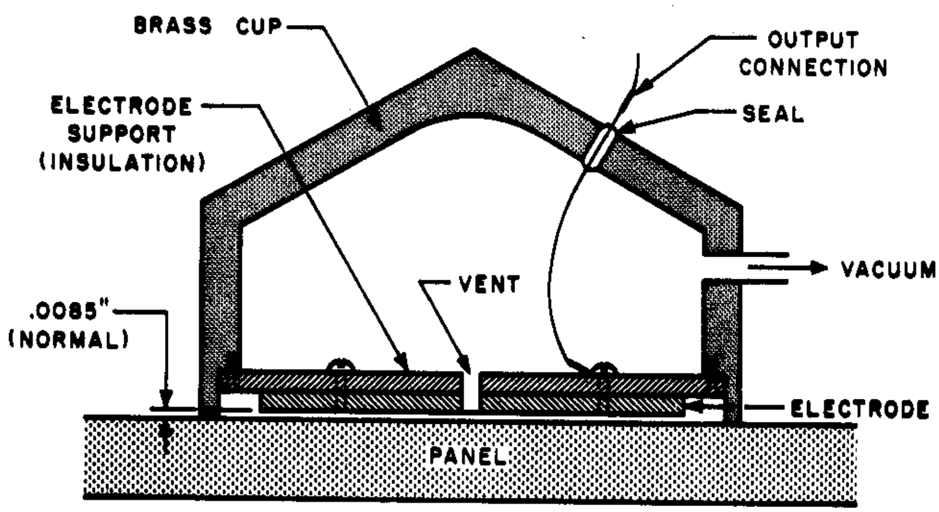

FIG. 10
SECTION THROUGH METAL VACUUM CUP-CAPACITANCE GAUGE

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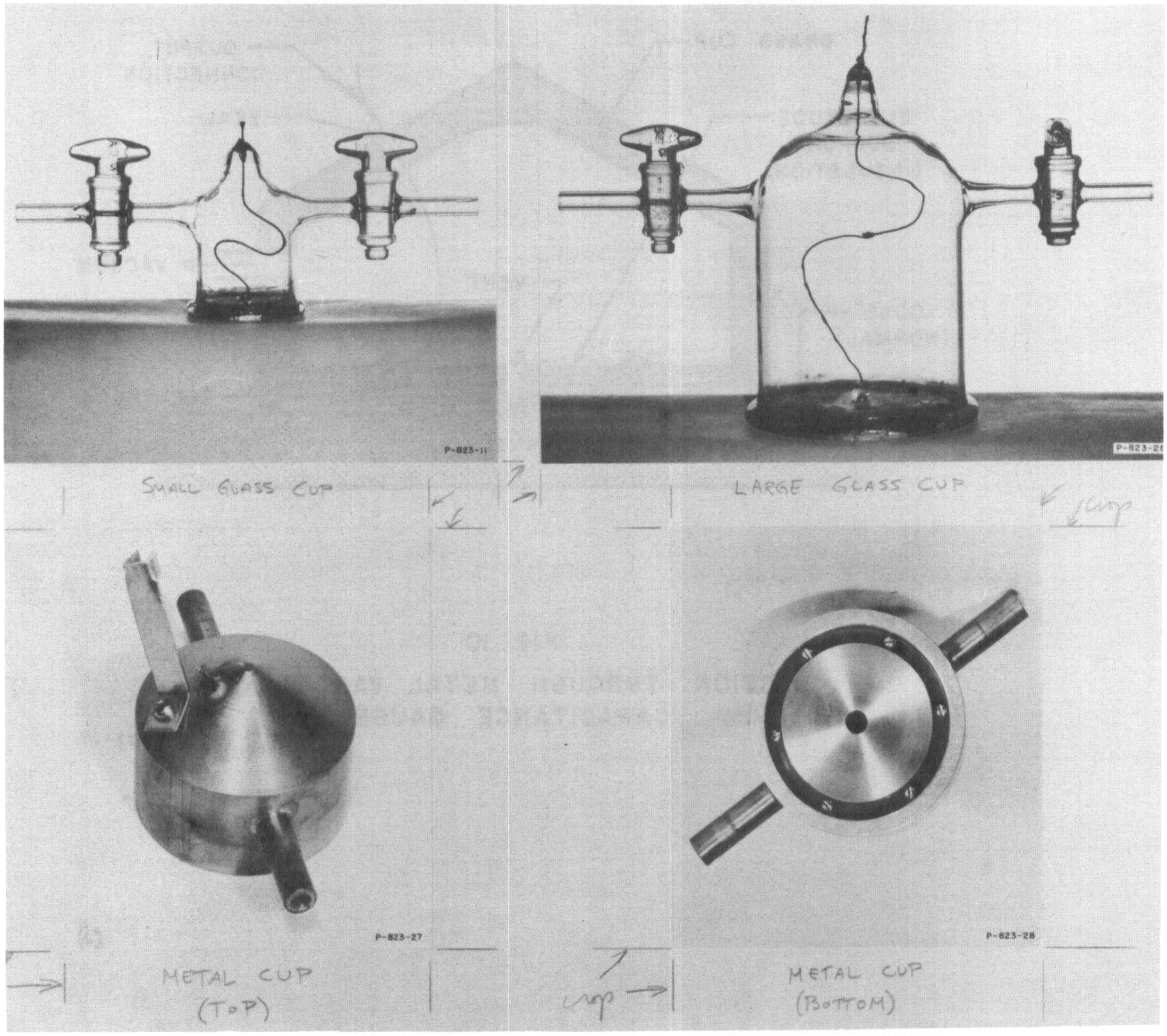


FIG. 11

VACUUM CUP-CAPITANCE GAUGES

enough to seal with the metal-to-metal contact. In cases where panel roughness has prevented this, a thin L-shaped rubber membrane on the outside of the cup at its junction with the panel has sealed it satisfactorily, maintaining the metal-to-metal contact. The metal cup in direct contact with the panel provides electrical shielding for the capacitor, which is isolated from external electric fields.

In the first experiments, a commerical instrument, the Boonton Q-Meter, was used to measure the capacitance directly. Later experiments have utilized a discriminator circuit for the measurements because of its greater sensitivity. The change of capacitance can be related to the average displacement of the skin under the fixed electrode; the over-all sensitivity of the system (capacitor, discriminator, and voltmeter) is approximately 0.02 volt per micro-inch (Appendix III). The effects of irregularities of the panel skin and of differential movement of areas under the electrode have not yet been evaluated. The effective change in capacitance caused by the change in dielectric constant of the air at reduced pressure has been calculated; it is smaller by a factor of 100 than the effects that have been measured due to displacement. No change in measurements has been observed that can be attributed to the leakage of air under the cup. The electrode is rigidly mounted in the cup, and the vent keeps the pressures on the two sides of the electrode structure equal. It is believed that any forces on the electrode which might result from the impact of leaking air are negligible.

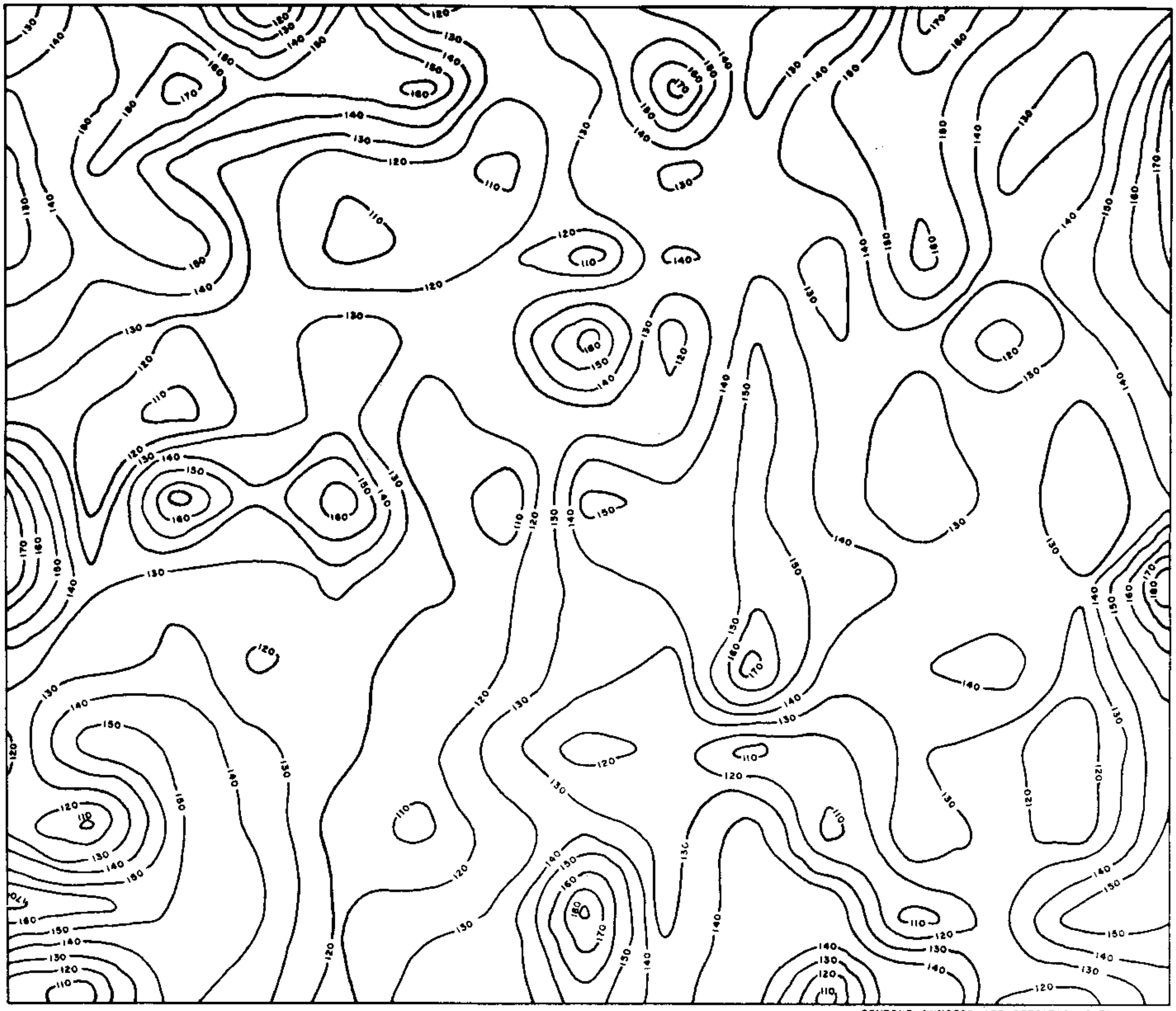
The electrical circuitry utilizes the capacitance of the vacuum cup pickup as part of the frequency control capacitance for a high frequency oscillator. The discriminator chassis (Appendix IV) contains the oscillator, a buffer amplifier, and the discriminator circuit. This circuit effectively measures the frequency of the oscillator as changes are produced by the vacuum cup. The discriminator delivers a DC output voltage that is proportional to the frequency shift. This voltage is in the range 0-5 volts, and is read from a standard high resistance (20,000 ohms per volt) voltmeter. The smallest scale divisions are 0.05 volt, and readings are estimated to 0.01 volt.

The method of making measurements with this apparatus has evolved to a standard procedure. The cup is placed in the desired position and a vacuum of 16 in. Hg is applied, reducing the pressure inside the cup to about 7 psia. The oscillator frequency is then adjusted for zero output from the discriminator. The vacuum is next reduced to 3 in. Hg, the pressure in the cup returning to about 13.5 psia. The voltage developed at the discriminator output is recorded. The 16 in. Hg reduction in pressure was chosen arbitrarily, as a value that could be readily reproduced in the presence of a slight variable leakage under the vacuum cup. Curves were plotted of output voltage as a function of pressure down to 1 psia (28 in. Hg vacuum); these indicated no obvious reason for going beyond a vacuum of 16 inches. The other limit, 3 in. Hg, was chosen because of difficulty in obtaining satisfactory readings at zero vacuum (ambient pressure). These difficulties were caused by the cable and vacuum connections to the cup which have a tendency to tilt the cup slightly when it is not held in place by the external air pressure, thus making the readings erratic. The output voltages measured at fixed locations on a panel show considerable variation, and are quite consistent in their repeatability. Appendix V(a) is a table of voltages obtained for a series of stations on a panel with time intervals between the sets of measurements. The remaining inconsistency, shown by the T+24 column, Appendix V(a), was a result of not allowing sufficient time for temperature stabilization to take place in the discriminator circuit. This can be corrected in a more refined instrument.

The application of this vacuum cup to a panel produced voltage readings that vary considerably over the face of the panel. A survey plan for moving the cup over the face of the panel was chosen in order to examine and try to correlate these variations with the strength of the bonds. As small changes in cup position sometimes produced rather large changes in voltage, it seemed wise to let the cup positions overlap. The standard experimental procedure was to start at one corner and make readings as the cup was moved horizontally (X direction) across the panel in half-inch steps. At the end of this column of readings the cup was returned to the starting side, moved upward 1/2-inch (Y direction), and the second column of readings made. This process was repeated until the desired area had been surveyed. Appendices V(b) and V(c) are typical deflection voltage tables obtained in this way.

The tabulated data for some of the panels tested was used in the construction of deflection contour maps, as in Figures 12 and 13. Such maps were made for 14 panels. The differences in the contour density and configuration between the control and undercured panels are typical. Voids in the tested panels were quite obvious from these maps, and indications were found that were believed to be characteristic of starved and contaminated areas.

Portions of the panels that had been mapped were cut into strips and coupons for peel and tensile tests. The peel strips were 1 inch wide because with 3-inch wide specimens, much of the detail exhibited by the maps would be destroyed by



CONTOUR NUMBERS ARE DETECTOR VOLTAGES X 100

FIG. 12

DEFLECTION CONTOUR MAP, PANEL C48S, CONTROL PANEL

C-823-12

FIG. 13

DEFLECTION CONTOUR MAP, PANEL C91S, UNDERCURED PANEL

C-823-13

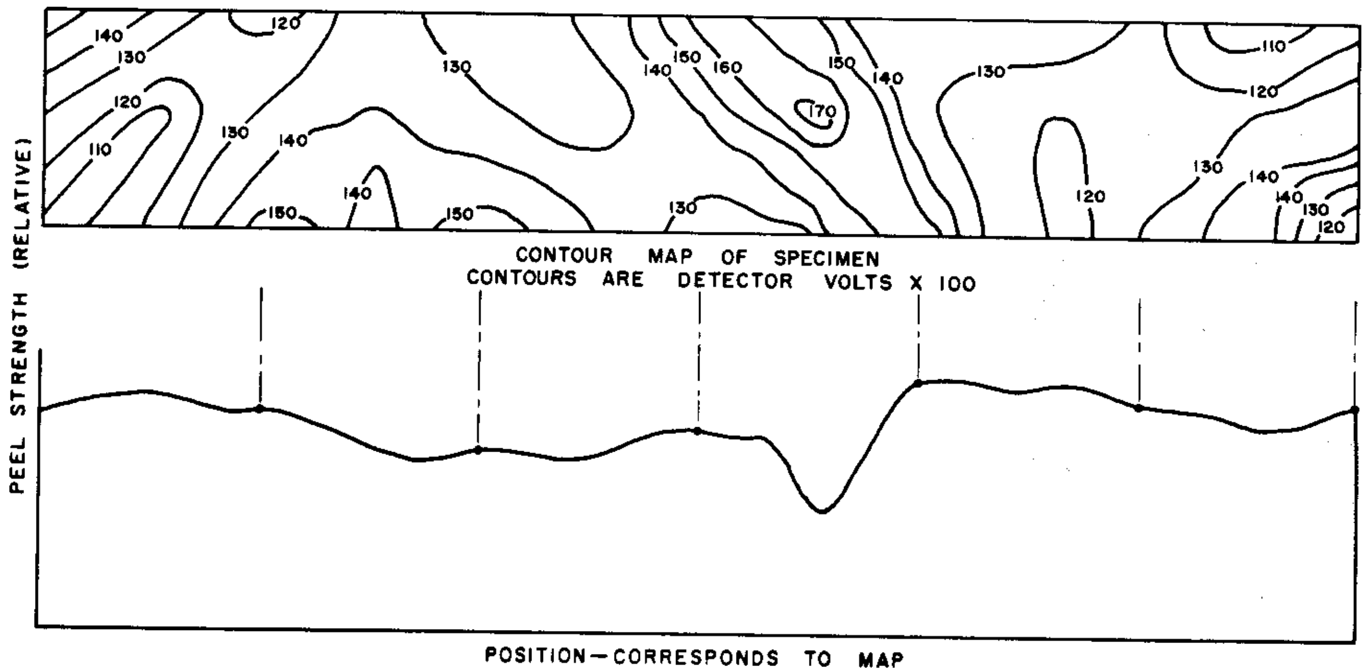


FIG. 14

PEEL SPECIMEN, PANEL C57S

A-823-14

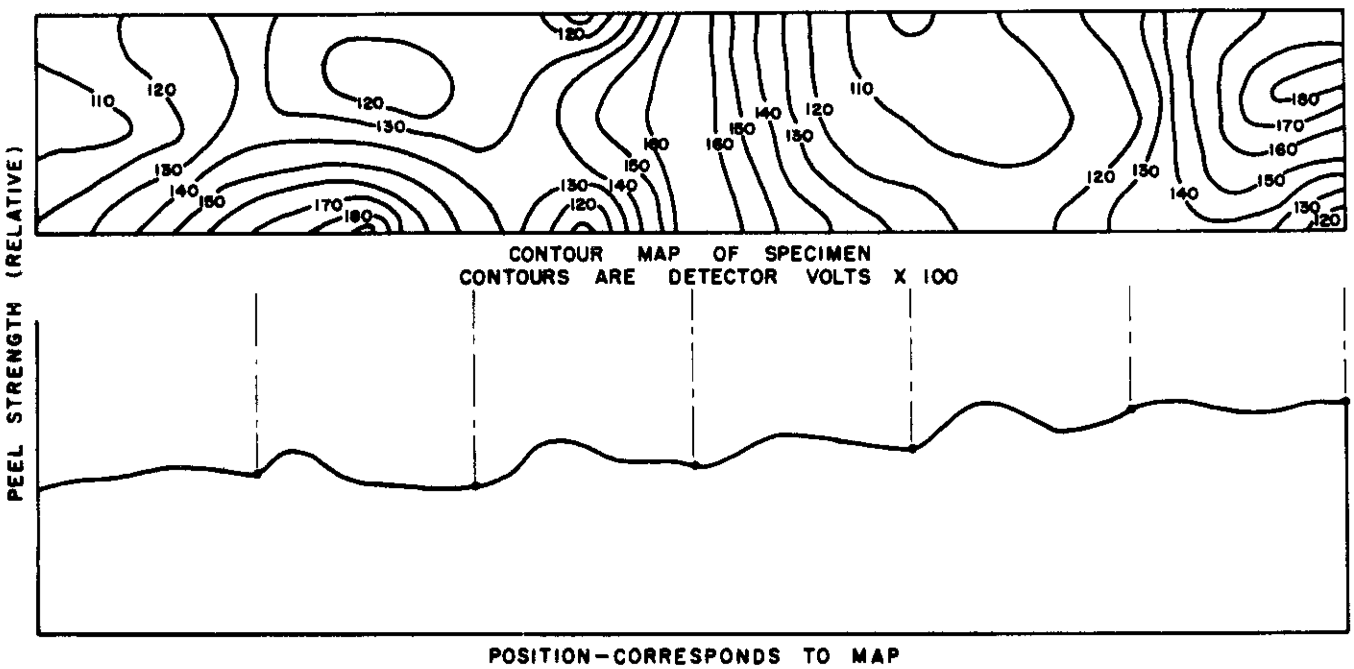


FIG. 15

PEEL SPECIMEN, PANEL C52S

A-823-15

the averaging of the force along the line of the peel. The destructive tests were made at the California Reinforced Plastics Company's factory in Oakland, California. The graphs indicating peel strength were compared with the panel maps, as shown in Figures 14 and 15. The regions of lower voltage do seem to be associated with higher peel strength. In order to evaluate these tests, the specimen maps and the peel strength graphs were divided into inch sections, and corresponding sections were examined qualitatively for consistency. If increasing or decreasing peel strengths corresponded to decreasing or increasing detector voltages respectively, the inch was judged consistent. If the opposite occurred, the inch was judged inconsistent. If uniform peel strength corresponded to uniform detector voltage the inch was consistent, otherwise inconsistent. A total of 350 linear inches of data were compared, of which 73 percent of the comparisons were consistent, 27 percent inconsistent. Comparison of tensile tests with the contour map data exhibited about the same consistency ratio. Appendix VI is a tabulation of the tensile data.

It is pointed out that the measurements, calculations, and mapping described above are time-consuming to a degree that would make them entirely unsuitable for production testing. In the event that the method is shown to be a possible solution for the technical problem, it seems likely that the data accumulating, processing, and evaluation could be done electromechanically with sufficient speed to be a practical solution to the problem.

2.5 Reduction of Deflection Data

The absence of more complete agreement of destructive tests with the contour maps suggests that the simple criterion for agreement that had been assumed is not a proper one. At least two other phenomena provide the same indication. The scale of the variation in contour density is finer than the detail shown on the peel strength graphs. Also, panels with starved areas exhibited sub-standard deflections at those locations, which seems to be "normal" behavior for a starved area. On the other hand, the repeatability of the deflection measurements and the 73 percent consistency value that was obtained seem to point to the conclusion that the vacuum cup capacitance technique does measure something that is related to the bonds in the samples. The tabulated data obtained from the panels has been re-examined for a clue to its proper utilization.

A first statistical approach to evaluation of the data was made by plotting the number of deflection voltage readings in 0.1-volt intervals against the

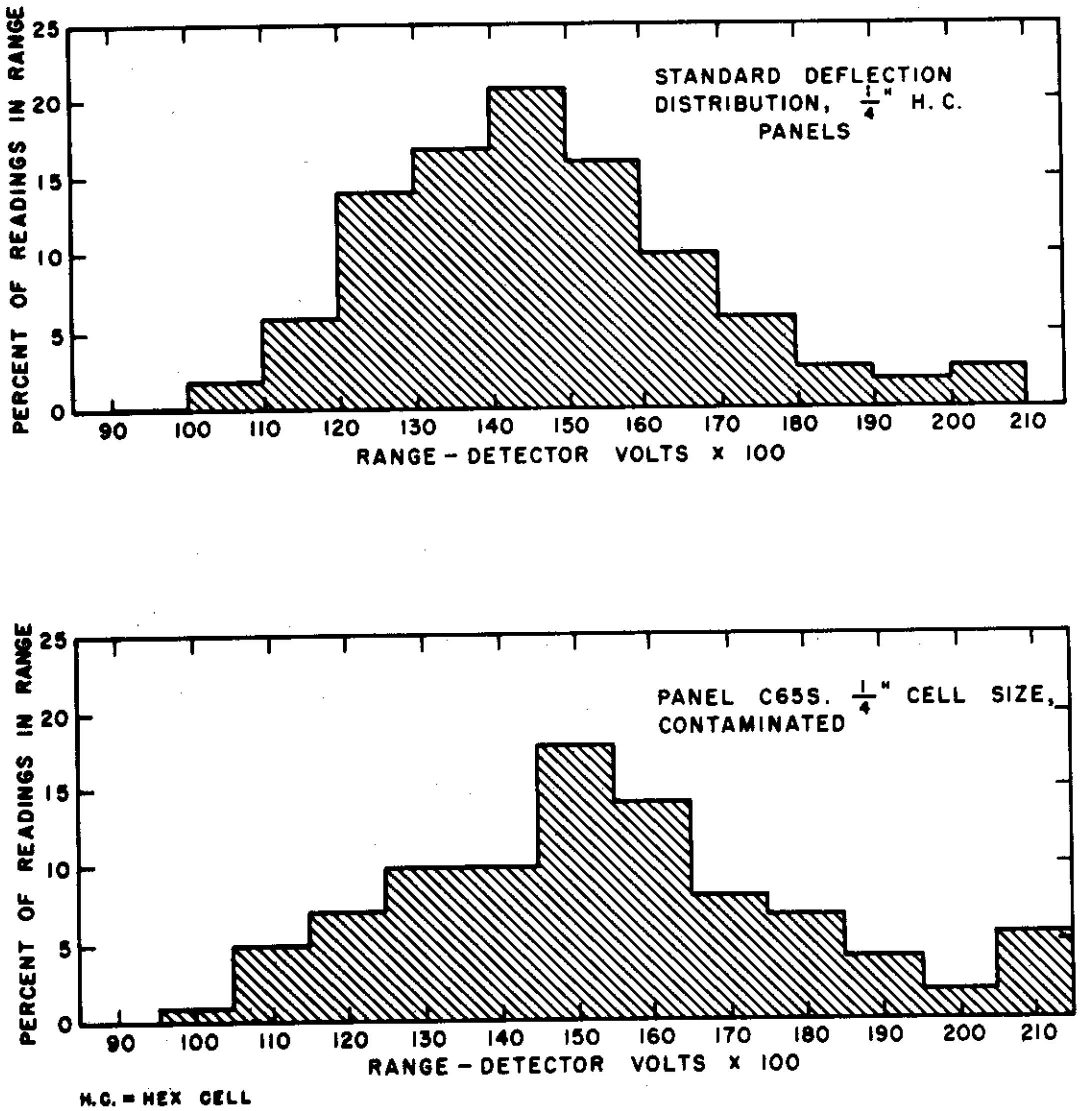
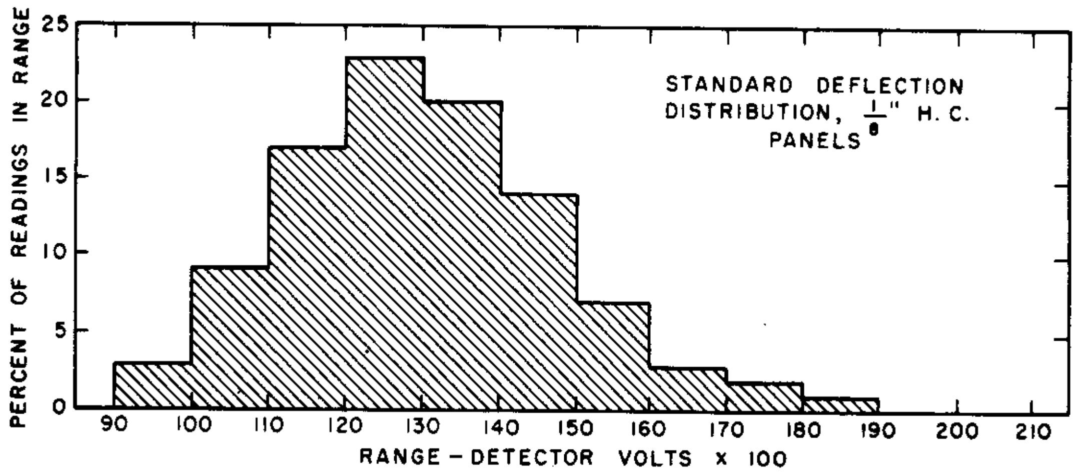


FIG. 16

DEFLECTION DISTRIBUTION, 1/4" H.C. PANELS

A-823-16



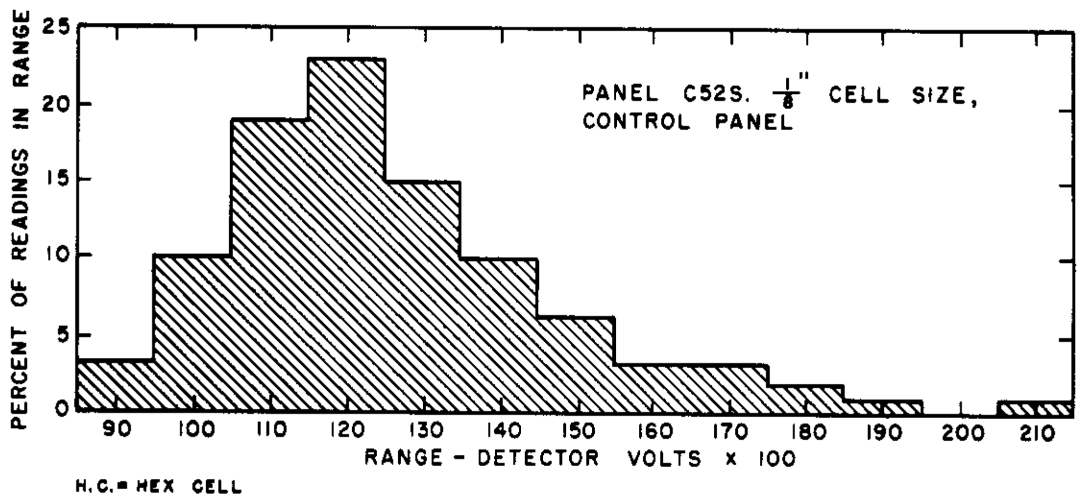


FIG. 17

DEFLECTION DISTRIBUTION, 1/8" H.C. PANELS

A-823-17

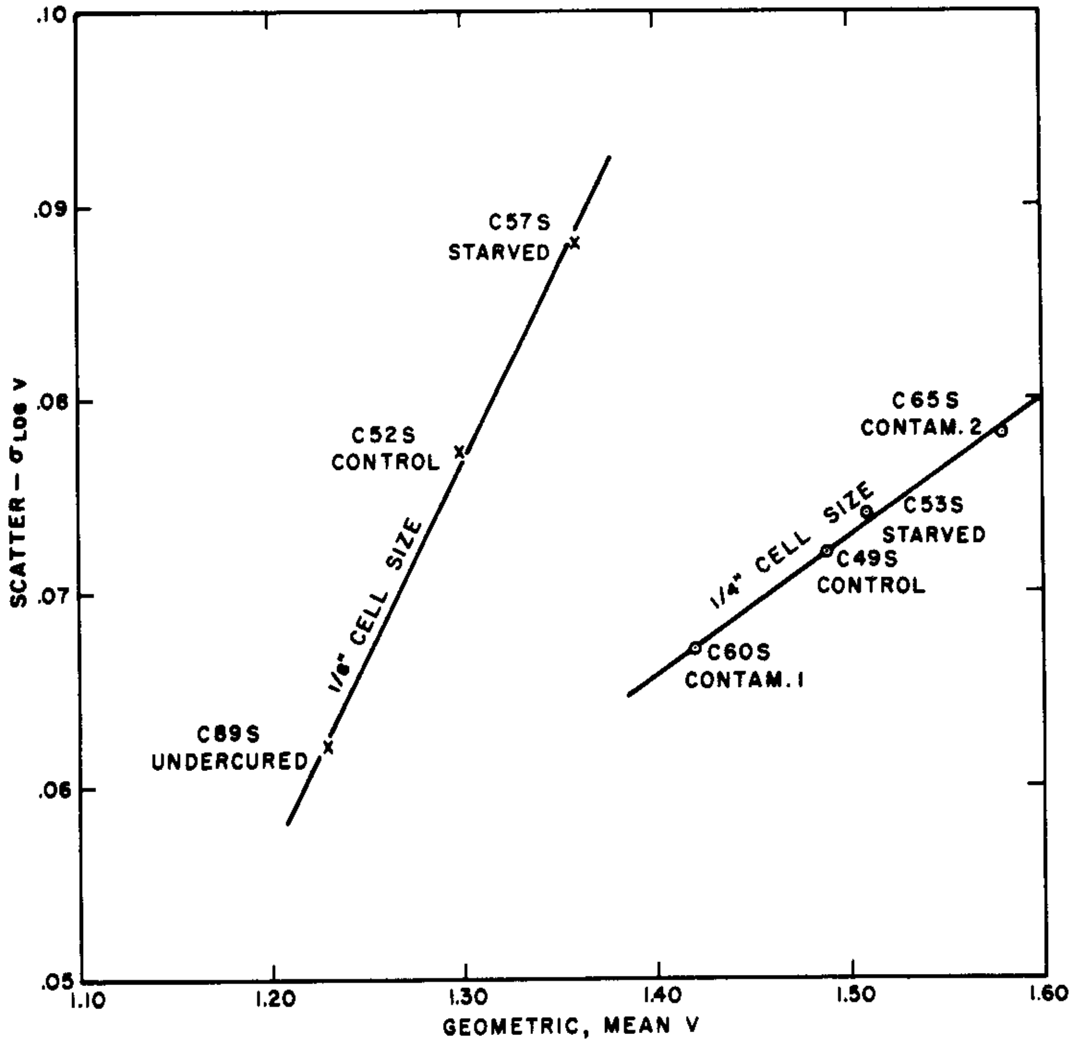


FIG. 18

SCATTER OF PANEL DEFLECTION VOLTAGES

A-823-26

voltages. The curves so obtained have characteristics that can apparently be associated with the quality of the panel, at least to the extent that the voltage distributions obtained from faulty panels are different from those measured on control panels. The distributions for the available control panels were averaged to obtain a "standard" distribution curve for such panels. These curves are different for 1/4-inch and 1/8-inch cell sizes. Figures 16 and 17 show the standard voltage distributions compared with two typical distributions obtained from individual panels.

The average deviations of the deflection voltage distribution curves from the standard distributions were plotted for all the panels that had been surveyed. These were calculated without regard to sign, and provide a sort of figure of merit for the panel. Small values of average deviation indicate good agreement with the standard, large values indicate poor agreement. Table 1 lists the values of average deviation so obtained. The average deviations for the panels, as indicated by this table, fall in the order of panel strength as shown by destructive tests in almost all cases. Appendix VII illustrates the calculations of the average deviation.

TABLE 1

Deflection Voltage Average Deviation

Panel No.	Description	Average Deviation
C48S	.003 - 1/4" h. c. control	1.34
C49S	.003 - 1/4" h. c. control	1.41
C40S	.003 - 1/4" h. c. control side	1.46
C92S	.003 - 1/4" h. c. undercured (all over)	1.59
3	.003 - 1/4" h. c. control (old)	1.67
4	.003 - 1/4" h. c. control (old)	1.85
C58S	.003 - 1/4" h. c. starved (strip)	2.66
C65S	.003 - 1/4" h. c. contaminated (all over)	3.69
C37S	.003 - 1/4" h. c. starved (strip)	4.38
C164S	.003 - 1/4" h. c. poor contact (strip)	8.52
C52S	.0015-1/8" h. c. control	1.15
C59S	.0015-1/8" h. c. contaminated (all over)	1.24
C50S	.0015-1/8" h. c. control	1.31
C64S	.0015-1/8" h. c. contaminated (all over)	1.97
C56S	.0015-1/8" h. c. starved (strip)	2.36
C57S	.0015-1/8" h. c. starved (strip)	2.51
C34S	.0015-1/8" h. c. starved (strip)	2.62
C35S	.0015-1/8" h. c. starved (strip)	3.85
C91S	.0015-1/8" h. c. undercured (all over)	4.26
C163S	.0015-1/8" h. c. poor contact (strip)	9.09

A second statistical approach to the data evaluation has been made by comparing the mean values of the voltage distribution with the scatter of the voltages for the panels. The logarithms of the voltages were used in computing the scatter. When these quantities are plotted (Figure 18) the 1/4-inch and 1/8-inch cell sizes divide themselves into two groups, points for one set of panels falling on one line, points for the other set falling on another line. Data from seven panels have been analyzed in this manner, and the spread of the points on the respective lines seems to be related to the bond strengths. Several methods for computing the mean values and values of scatter for the data have been investigated. Additional data must be analyzed in this manner before the value of this approach to the problem can be determined.

The consideration of this tabulated data leads one to suspect that there are at least two parameters represented by the variations. The surface configuration of the panels was thought to be one of these. These surfaces have many irregularities that may be observed visually by examining images of objects that are reflected from the panels. The patterns are generally random in character, except in instances in which the panel core has been deformed intentionally. The poor contact panels exhibit a depression in the panel skin over the poor contact area, for example. A wavy panel surface would be expected to support the vacuum cup at the high points of the waves. Upon applying the vacuum to the cup, the loading would be concentrated at these points, and if any local elastic deformation of the skin occurred, movement of the cup toward the panel would produce abnormally large changes in capacitance and deflection voltage.

The removal of surface unevenness on some small samples by surface grinding was done so that the effect of surface waviness might be evaluated. Figure 19 shows "before and after" measurements of deflection voltage on these samples. It is seen that grinding removed much of the irregular character of the curves and reduced the average value of the readings, observations that are consistent with the anticipated effects of panel waviness. The remaining pattern of variations is thought to contain information that is related to the panel bonds. The surface grinding was done solely to evaluate the effect of surface irregularities; it is not suggested in any practical application to production testing.

The utilization of vacuum cup information as described above depends upon being able to distinguish and measure the significant variations in deflection voltage in the presence of the (presumably) extraneous ones that result from surface irregularity. The results of the statistical approaches indicate that this might be

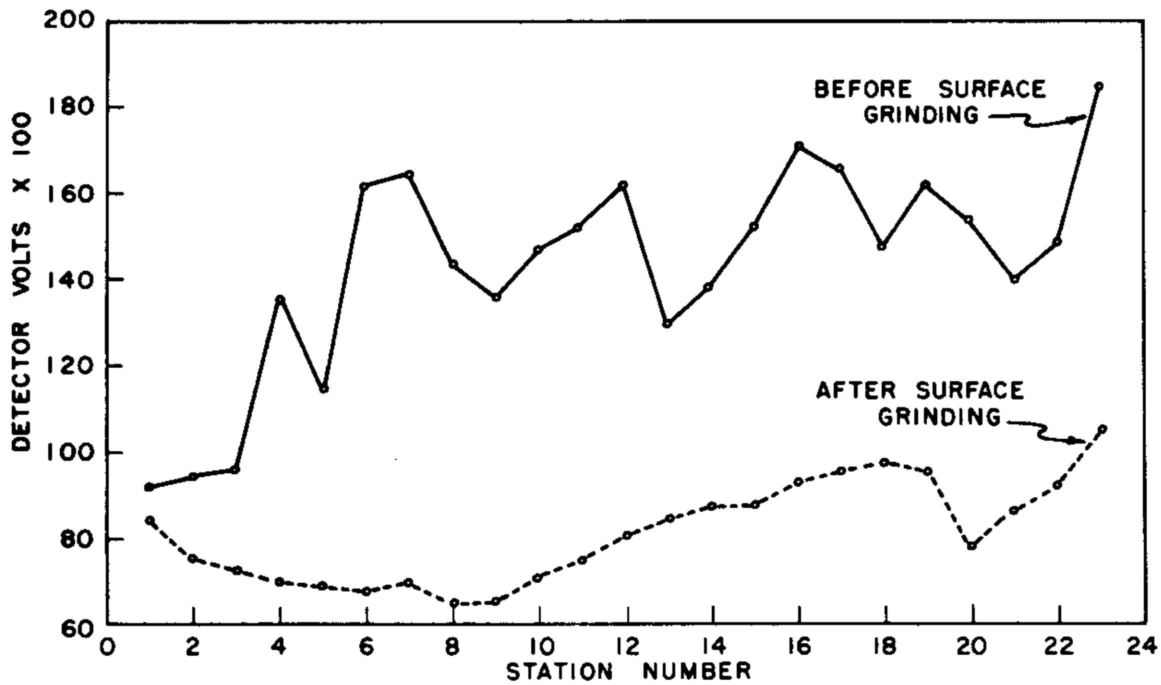


FIG. 19

EFFECT OF SURFACE GRINDING ON COLUMN OF VACUUM CUP MEASUREMENTS. PANEL C91S

A-823-18

accomplished with a reasonable degree of success. Some of the effects of surface unevenness might be eliminated by the use of a vacuum cup in which the inner electrode is supported by the panel skin instead of the cup. When supported in this way, changes in pressure on the cup should not affect the electrode position to the extent that they do in the present model.

The consideration of this vacuum cup technique and its application to the problem will continue.

2.6 Vacuum Cup - Mechanical Interferometer

Experiments on a visual pickup in conjunction with the vacuum cup loading have been performed, utilizing a system that has been called "mechanical interferometry" to distinguish it from true optical interferometry.[4/] By this method very small displacements are translated into patterns of fringe shifts (light and dark areas); the fringes are produced by the interaction of small reflecting, transparent, and opaque areas rather than the destructive interference of light waves. Figure 20 shows the operation of the system schematically. A grid of alternate transparent and opaque sections is suspended immediately above a panel skin, illuminated and viewed from the directions indicated. If the distance between the skin and the grid agrees with that shown in Case 1, a minimum of light is reflected to the observer. If it agrees with Case 2, the observer sees a maximum light intensity. The difference between maximum and minimum has been caused by the change in spacing between the grid and the skin. If placed in a vacuum cup so that the grid is fixed in position, the shift of the fringes when the vacuum is applied becomes a measure of the displacement of the skin.

The grids used in the present experiment are contact prints on photographic film of a lithographic half tone screen. The grids resemble checkerboards with alternate opaque and transparent sections. Several spacings are available; the finest screen has 300 lines per inch, and was used in these experiments. A line corresponds to a complete transparent-opaque cycle. The film is stretched by a clamp over a carrying ring, which is screwed into a vacuum cup with a transparent plastic top. The grid-to-panel spacing is adjustable. Figure 21 shows the parts of this vacuum cup.

The best results have been obtained when the cup is illuminated by a collimated light beam, with as little diffuse light as possible. A mercury arc and condensing lens system is presently used (Figure 22). Experiments have been performed with a monochromatic source; no improvement was observed. Troublesome reflections

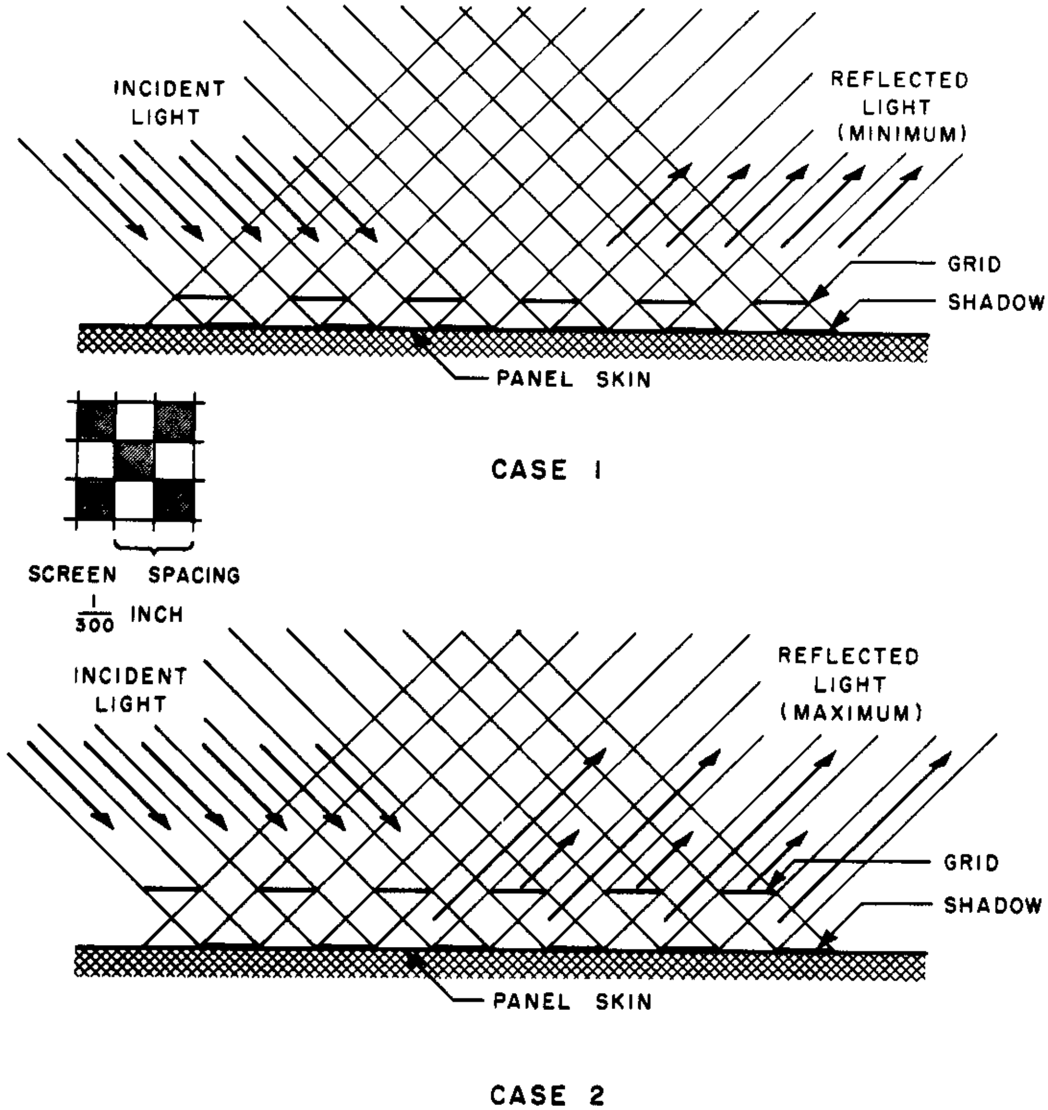


FIG. 20
MECHANICAL INTERFERENCE

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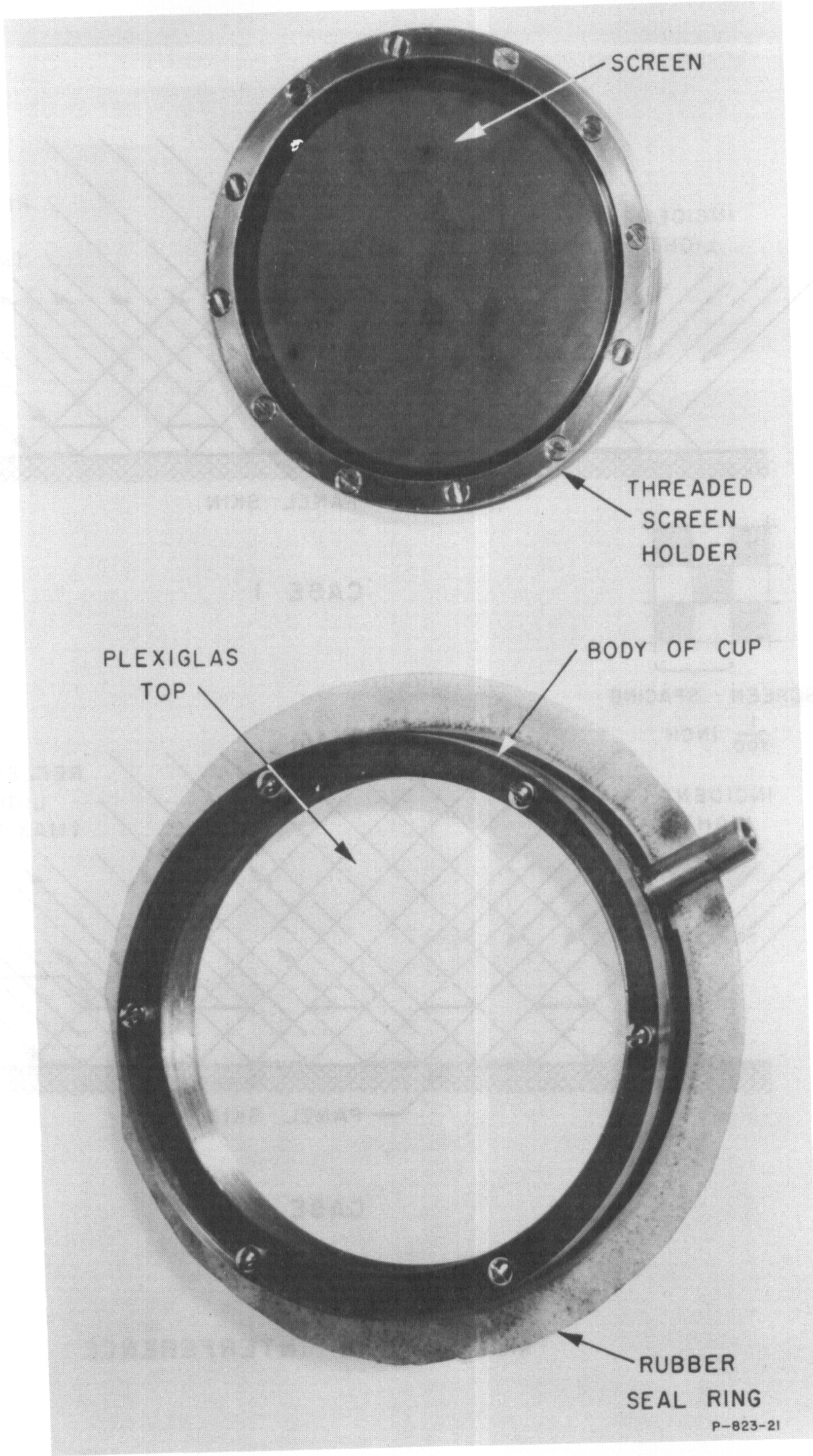


FIG. 21
MECHANICAL INTERFERENCE VACUUM CUP
DISASSEMBLED

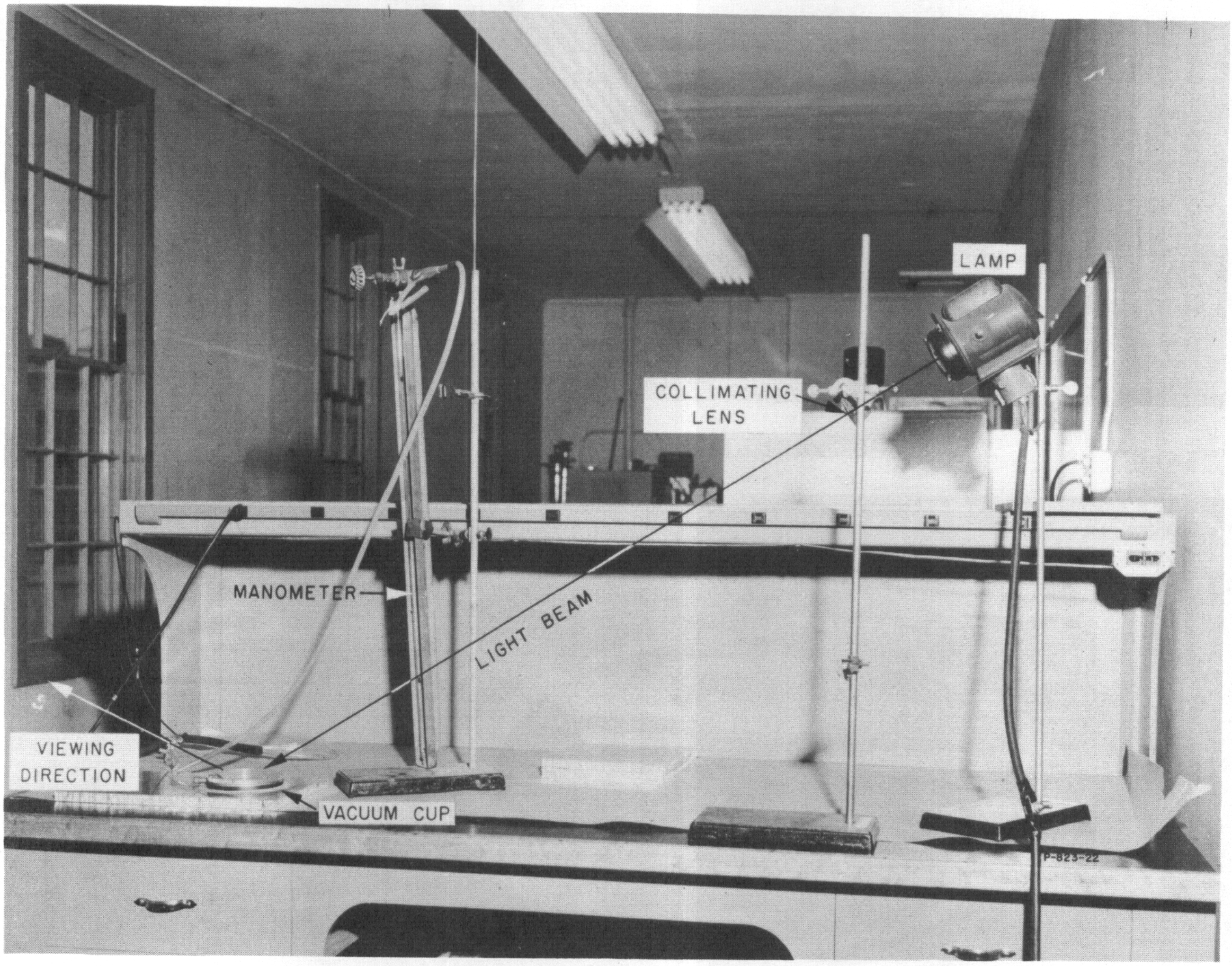
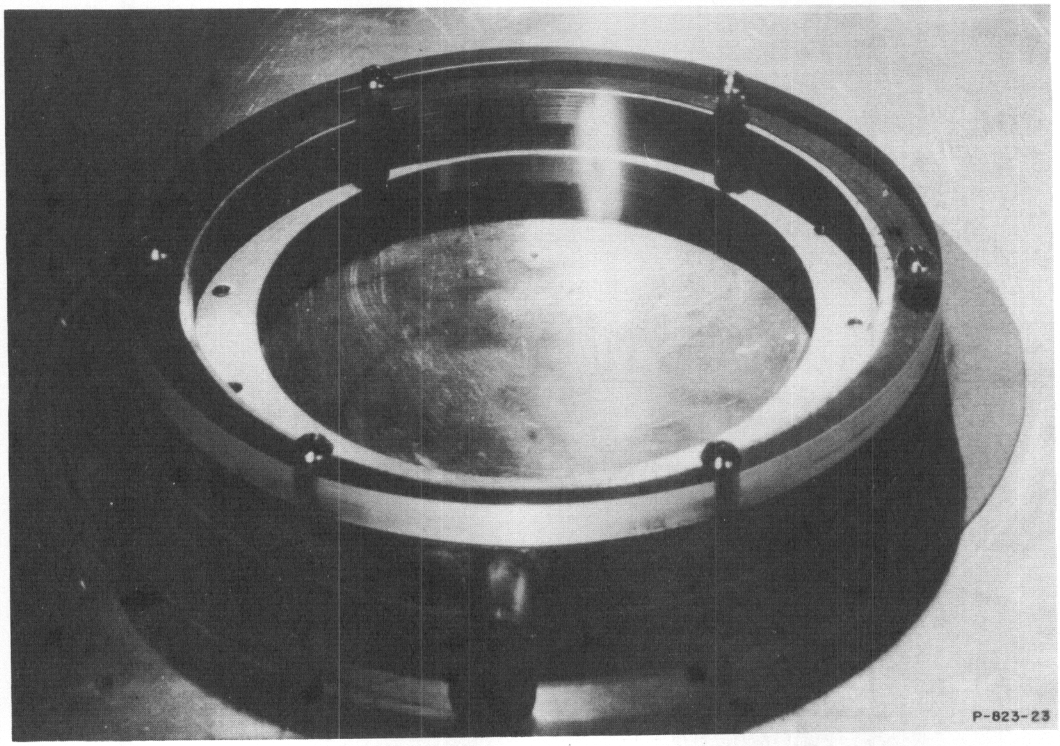
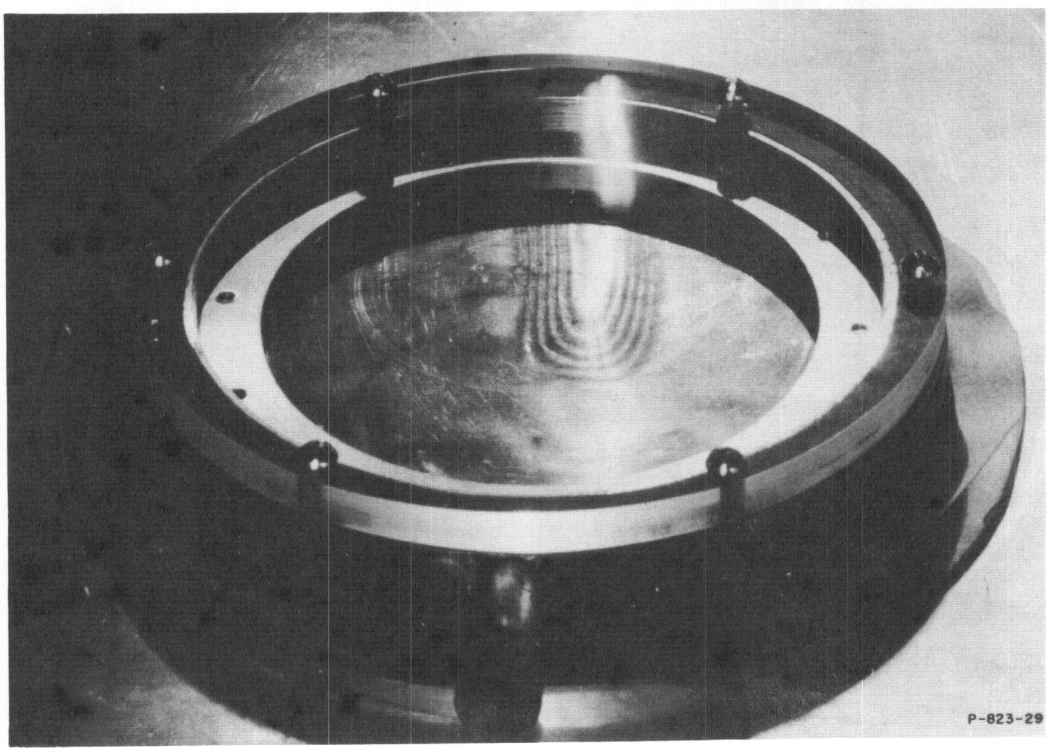


FIG. 22
LABORATORY USE OF MECHANICAL INTERFEROMETER



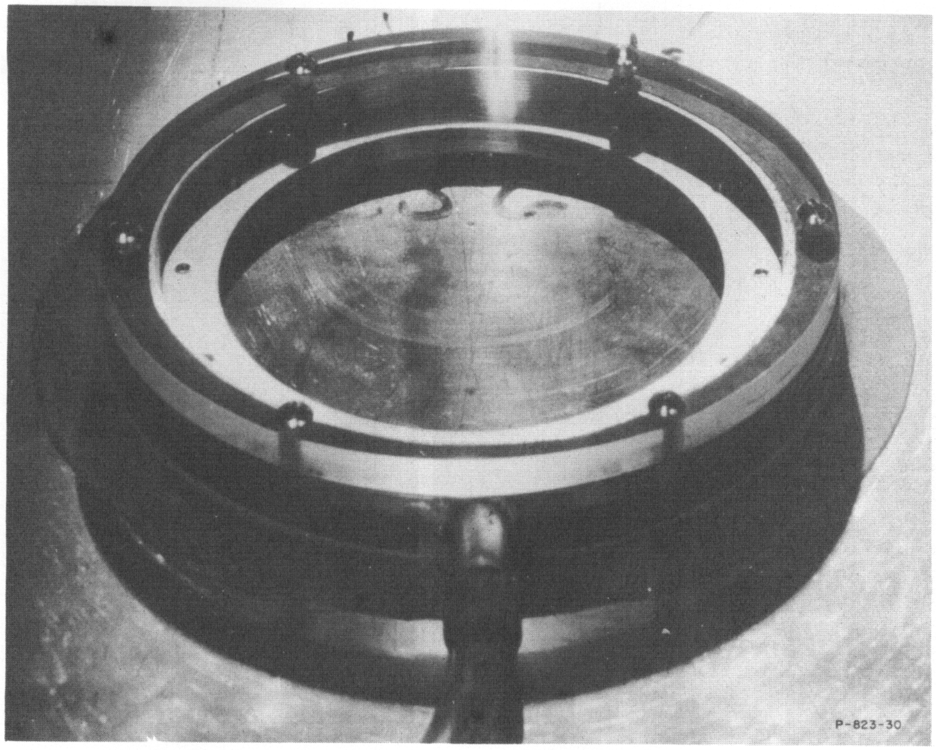
NO VACUUM



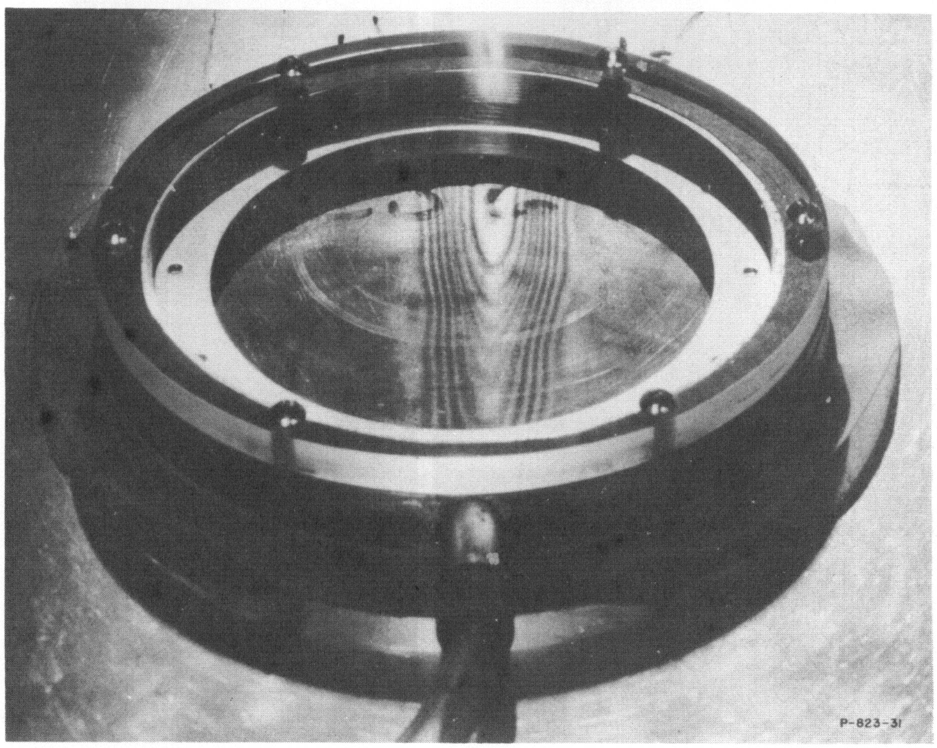
26" Hg

FIG. 23a

INDICATIONS OF UNBONDED AREAS

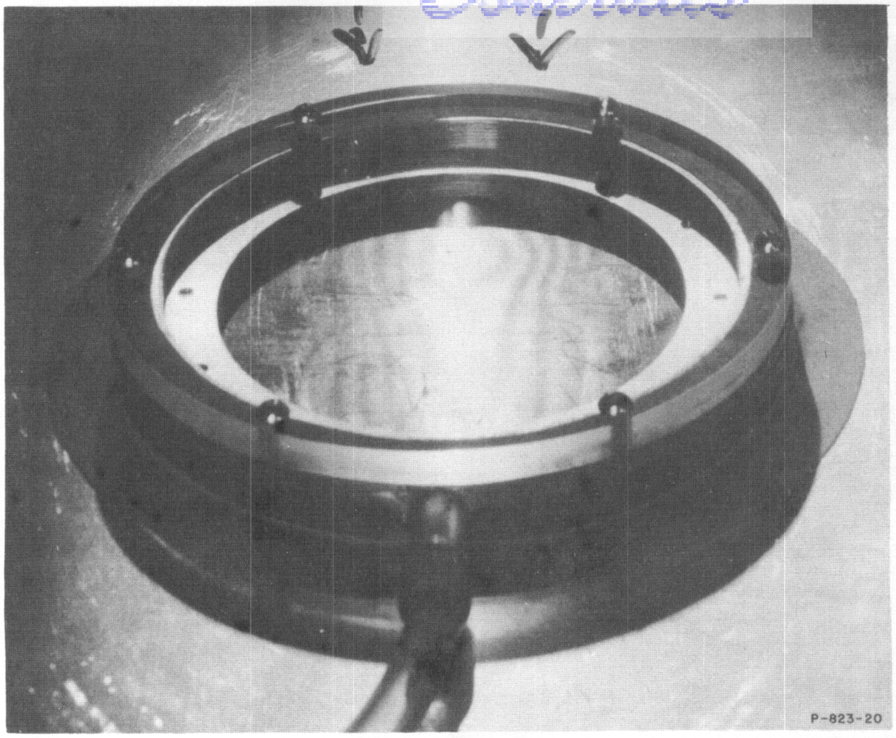


NO VACUUM



26" Hg

FIG. 23b
INDICATIONS OF UNBONDED AREAS



NO VACUUM

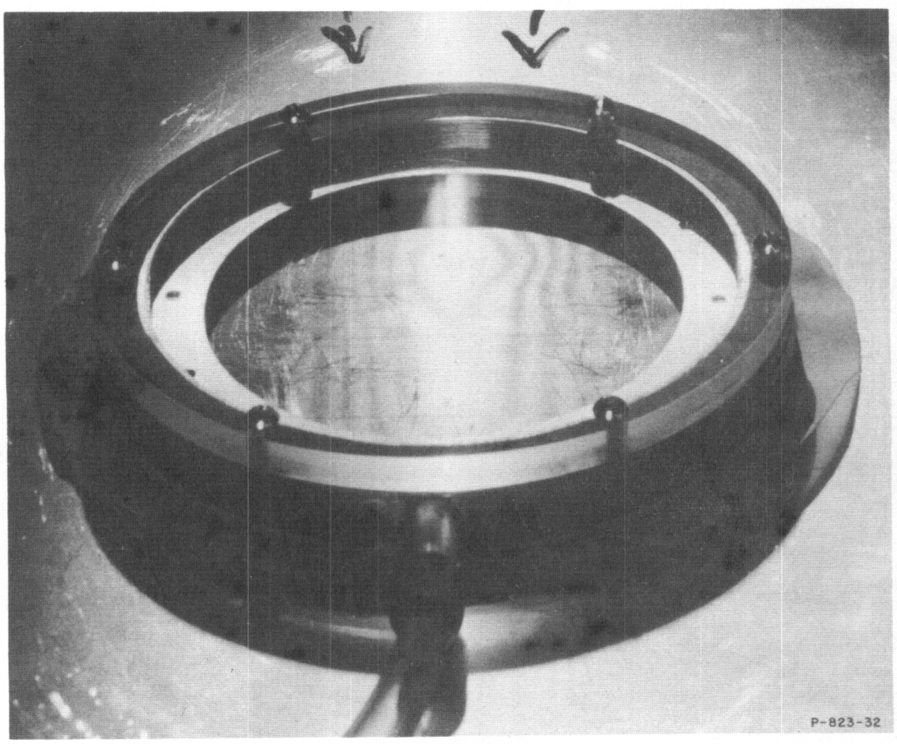


FIG. 24
INDICATIONS OF SURFACE IRREGULARITY

from the top surface of the vacuum cup can be alleviated by the use of a polaroid disc between the observer and vacuum cup, and can be eliminated by a re-design of the vacuum cup.

This system provides a very obvious indication of unbonded areas in sandwich panels. Figure 23 shows typical unbonded areas. In places where the panel is not flat, an indication is provided by this technique. Figure 24 shows the cup over a poor contact area on a panel; the depression of the panel skin is clearly shown by the fringes when no vacuum is applied. This property of the system, the possibility of evaluating surface unevenness, may be useful. Direct quantitative measurements are possible, as the geometry of the skin, grid, and lighting can be accurately known and the sensitivity computed. For the 300 line/inch screen and 30° lighting and observing angles, the formation of the first order fringe requires a skin deflection of .0005 inch. Fractions of a fringe shift are readily discernable.

The extent to which this technique can be exploited is not yet known. Observations made to date indicate that changes in the fringe pattern exist when the vacuum is applied to all the panels tested so far. A systematic study of the changes has not been attempted because efforts have been concentrated on the sensitivity of the system. It seems reasonable to expect that the visual and electrical methods of deflection measurement and interpretation may be used concurrently in the development of test methods. The electrical method has, at present, greater sensitivity; the optical method seems potentially useful because its visual data presentation may be more easily interpreted.

SECTION III

SUMMARY AND CONCLUSIONS

Electromagnetic and mechanical drivers have been used to study the amplitude, phase, attenuation, and mode characteristics of test panels in the audiofrequency range. Although these characteristics can be readily measured, no relationship has been found that could be used to evaluate the bonds in the panel.

The ultrasonic reflection technique for the detection of flaws, as embodied in the Sperry Reflectoscope, has been applied to the test panels. The electrical characteristics of the instrument do not permit it to display reflections from discontinuities at the small distance from the surface that such discontinuities occur in sandwich panels. These electrical characteristics must be altered before the applicability of the method to the problem can be demonstrated.

An impedance measurement technique was used with the mechanical driver that produced a marginal indication of bond quality at frequencies in the range of 10,000-20,000 cps. The measurement is basically a determination of the energy absorbed by the panel when it is subjected to a local vibratory force; this is apparently related to the bond quality. This approach holds sufficient promise to warrant continued investigation, in the direction of finding transducers that will transfer more power at high frequencies to the test panels.

A vacuum cup - capacitance method for steady deflections has been tested extensively. When the experimental data from this device are analyzed on a statistical basis the evaluation of the bonds is consistent with data from destructive tests in about 75 percent of the cases. The problem of data collection and analysis is a major one in connection with this method.

A vacuum cup - mechanical interferometer method of measuring steady deflection has been applied to the problem. This apparatus produces an immediate visual indication of unbonded areas in test panels, with a reliability approaching 100 percent. The applicability of the method to the evaluation of bond strength is not yet established.

Sufficient experimental investigation of the audio-frequency behavior of sandwich panels has been completed to justify the exclusion of such methods from further consideration in the matter of bond strength measurement. The ultrasonic reflectoscope technique in its present form does not seem to be applicable to the problem; the extensive development of the electrical characteristics of the system does not seem warranted at present, because one or more of the following methods may provide a simpler solution to the problem.

The ultrasonic behavior of panels, as embodied in impedance measurements, and the vacuum cup techniques remain as potential techniques for solving the problem. Of these, the vacuum cup-capacitance method is presently the most highly developed. The next immediate objective should be the further development of the impedance and mechanical interference methods, so that a suitable basis for comparison may be reached.

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3. "Curved Sandwich Parts and Curved or Contoured Metal Honeycombs," by R. C. Steele, Air Force Aircraft Industries Associations Conference on Structural Adhesives for Metals and Sandwich Construction, Dayton, Ohio, 1952

4. "Displacement Measurement by Mechanical Interferometry," by R. Weller and B. M. Shepard, Naval Ordnance Laboratory, Washington, D.C.

APPENDIX I. TEST PANEL DESCRIPTION

All panels described in the following list are of sandwich construction. The cores for the 1/4" cell size panels were made of .003" aluminum foil, those for the 1/8" cell size of .0015" aluminum foil. The core thickness is .625" in all cases; the skins are .016" aluminum. The cores were primed with FM47 liquid adhesive, and Bloomingdale FM47 tape was used between the core and skins.

The tensile and peel strength columns list the values of these quantities that were obtained from coupons cut from the panels when they were fabricated. These figures serve as a guide to the panel strength during the non-destructive test development, and are checked against the values obtained when the panel is tested destructively to compare with non-destructive test information. In all cases to date the correlation between the manufacturer's original tests and the final destructive tests of the panel has been excellent.

1/4" Hex. Cell Panels

Number	Description	Tensile(Psi)	Peel(In./Lbs)
C48S	Control	461	45
C49S	Control	435	47
C37S	Starved (1) - Strip	418	26
	Good area	858	63
C40S	Starved (1) - Strip	416	12
	Good area	712	31
C53S	Starved (2) - Strip	144	23*
	Good area	582	66
C58S	Starved (2) - Strip	24	12*
	Good area	582	66
C90S	Undercured	---	11
C92S	Undercured	216	17
C164S	Poor Contact Strip	313	24
	Good area	571	48
C165S	Poor Contact Strip	321	23
	Good area	535	42
C60S	Contaminated (1)	428	23
C65S	Contaminated (1)	696	13
C222S	Contaminated (2)	558	42
C223S	Contaminated (2)	573	41

1/8" Hex. Cell Panels

Number	Description	Tensile(Psi)	Peel(In./Lbs)
C50S	Control	1000	78
C52S	Control	772	69
C34S	Starved (1) - Strip	60	15
	Good area	1045	53
C35S	Starved (1) - Strip	----	18
	Good area	921	65
C56S	Starved (2) - Strip	----	9*
	Good area	965	52
C57S	Starved (2) - Strip	----	19*
	Good area	865	72
C89S	Undercured	435	25
C91S	Undercured	539	19
C162S	Poor Contact Strip	532	29
	Good area	982	63
C163S	Poor Contact Strip	557	32
	Good area	936	60
C59S	Contaminated (1)	1001	20
C64S	Contaminated (1)	981	13
C220S	Contaminated (2)	976	62
C221S	Contaminated (2)	1017	67

* Starved (2) panels exhibit unbonded areas (voids) over part of the regions in which the FM47 tape was omitted; other parts of these regions do have bonds, however.

APPENDIX II. PANEL DEFLECTION CALCULATIONS

It is desired to estimate the deflections of a panel caused by vacuum cup loading. The total deflection is assumed to be the sum of several contributing deflections and elongations, some of which can be estimated; others are not known in sufficient detail to permit a reasonable estimate, although they are present and deserve mention. These components can be described as

D_1 - elongation in skins. With the elastic modulus, the force per unit area, and thickness of skin known, D_1 can be calculated.

D_2 - elongation in the adhesive bonds. Estimates of the effective bond thickness, effective bond area, and elastic modulus can be made. With the force per unit area known, D_2 can be calculated on this basis.

D_3 - elongation in the core. Core thickness, effective area, elastic modulus and force are known. D_3 can be calculated.

D_4 - deflection due to bending of the panel as a whole. The modulus of rigidity for this particular manner of force application is not known.

D_5 - apparent deflection resulting from local deformation of skin as vacuum cup rim applies pressure. This is random in character and cannot be calculated.

The calculations are based on the following assumptions:

Elastic modulus for aluminum,

$$M_a = 10^7 \text{ lbs/sq in.}$$

Elastic modulus for bonds,

$$M_b = 10^5 \text{ lbs/sq in.}$$

(nominal values from Handbook of Chemistry and Physics)

Effective bond thickness

$$L_b = 0.015"$$

This is an estimate that seems to be compatible with the glue line thickness on the panels inspected. At the junction of the core ends with the top skin the adhesive thickness if less than . 015", while in the fillets the adhesive is somewhat thicker. The actual quantity of adhesive that is effective in these bonds could be the subject of a very useful investigation.

Effective bond area

$$A_b = 0.1 \text{ skin area}$$

Estimated subject to same limitations as L_b.

Skin thickness

$$L_s = 0.020" \text{ (nominal)}$$

Core thickness

$$L_c = 0.600" \text{ (nominal)}$$

Core area

$$A_c = 0.01 \text{ skin area (nominal)}$$

Then

$$D_1 = \frac{2L_s}{M_a} = \frac{0.040}{10^7} = 4X10^{-9} = 0.004 \text{ micro-inch/psi}$$

$$D_2 = \frac{2L_b}{A_b\, M_b} = \frac{0.030}{(0.1)(10^5)} = 3X10^{-6} = 3 \text{ micro-inch/psi}$$

$$D_3 = \frac{L_c}{A_c\, M_a} = \frac{0.600}{(0.01)(10^7)} = 6X10^{-6} = 6 \text{ micro-inch/psi}$$

D_4, D_5 - cannot estimate.

On the basis of these estimates and assuming Hooke's Law behavior of the system, it appears that D_2 and D_3 contribute appreciably to deflection measurements. The average deflections obtained experimentally are in the range of 15 micro-inches per psi; the difference between the above and 15 micro-inches per psi is presumably contributed by D_4 and D_5. Of these contributions, one would expect D_2 and D_4 to be directly related to the bond strength, D_1 to be negligible, D_3 to be constant, and D_5 to be random.

APPENDIX III. CALCULATION OF CAPACITANCE - DISCRIMINATOR SENSITIVITY

The capacitance of the vacuum cup pickup condenser can be calculated from the standard parallel plate condenser formula

$$C = \frac{0.0885D(N-1)S}{t} \qquad \text{(Handbook of Chemistry and Physics)}$$

in which C is the capacitance in micromicrofarads, D the dielectric constant, N the number of plates, S the area of one plate, and t the separation of the plates, the dimensions being expressed in centimeters. Applied to the present capacitor, D=1, N=2, S=15.2 cm^2, t=.0085" = 2.16X10^{-2} cm, and

$$C = \frac{(8.85\times10^{-2})(1)(1)(1.52\times10)}{(2.16\times10^{-2})} = \frac{K}{t} = 62.5 \text{ mmf.}$$

The rate of change of C with t,

$$\frac{dC}{dt} = \frac{d}{dt}\frac{K}{t} = \frac{-K}{t^2}$$

$$= 2.9\times10^3 \text{ mmf/cm}$$

$$= 7.36\times10^3 \text{ mmf/inch,}$$

for small variations in thickness of the dielectric.

The discriminator was calibrated with a standard condenser, and was found to deliver 2.8 volts output when the gauge capacitance was changed by 1.0 mmf.

The sensitivity of the system is then:

$$S = \frac{(7.36\times10^3)(2.8)}{(10^6)(1)} \frac{(\text{mmf})}{(\text{micro-inch})} \frac{(\text{volts})}{(\text{mmf})}$$

$$= 0.02 \text{ volt/micro-inch}$$

APPENDIX IV. DISCRIMINATOR

The discriminator circuit used in the vacuum cup capacitance gauge was made from standard electronic components, as shown by the schematic diagram, Figure IV-a. It has a self-contained power supply. The first tube, a 6BE6, is used as the oscillator and amplifier. The RF signal is supplied by this oscillator, the frequency of which is established by the capacitance and inductance in the oscillator tank circuit. The vacuum cup condenser is used as a part of the frequency control capacitance, in parallel with two other variable condensers (one large and one small) for precise adjustment of the oscillator frequency which is nominally 4.5 mc. The oscillator section is resistance coupled to the amplifier section, which feeds the primary of the 4.5 mc IF transformer, T_1.

The second stage, a 6AU6, is used as a conventional IF amplifier, at 4.5 mc. Frequency changes due to the panel skin deflection are small compared with the band width of the amplifier, 1 mc. The output of the 6AU6 feeds the discriminator transformer, T_2. The discriminator circuit is a conventional one, of the type used in many FM and TV receivers. The circuit is so adjusted that when the incoming signal frequency is the same as that for which the discriminator coil is tuned, no rectified voltage appears at the output: the equal and opposite components due to the split secondary cancel. If a frequency deviation occurs, a phase difference exists between the two component voltages; this produces a DC voltage at the output, the polarity of which depends upon the direction of the shift in the incoming frequency. The magnitude and linearity of the DC output voltage depend upon the slope and linearity of the discriminator circuit characteristic. The slope of the discriminator characteristic was found to be a function of temperature, and the unit must be allowed to come to a stable operating temperature in order to obtain repeatable measurements.

The circuit is shielded in an aluminum box, and the RF connection to the vacuum cup is made with coaxial cable (RG55/U) and BNC connectors.

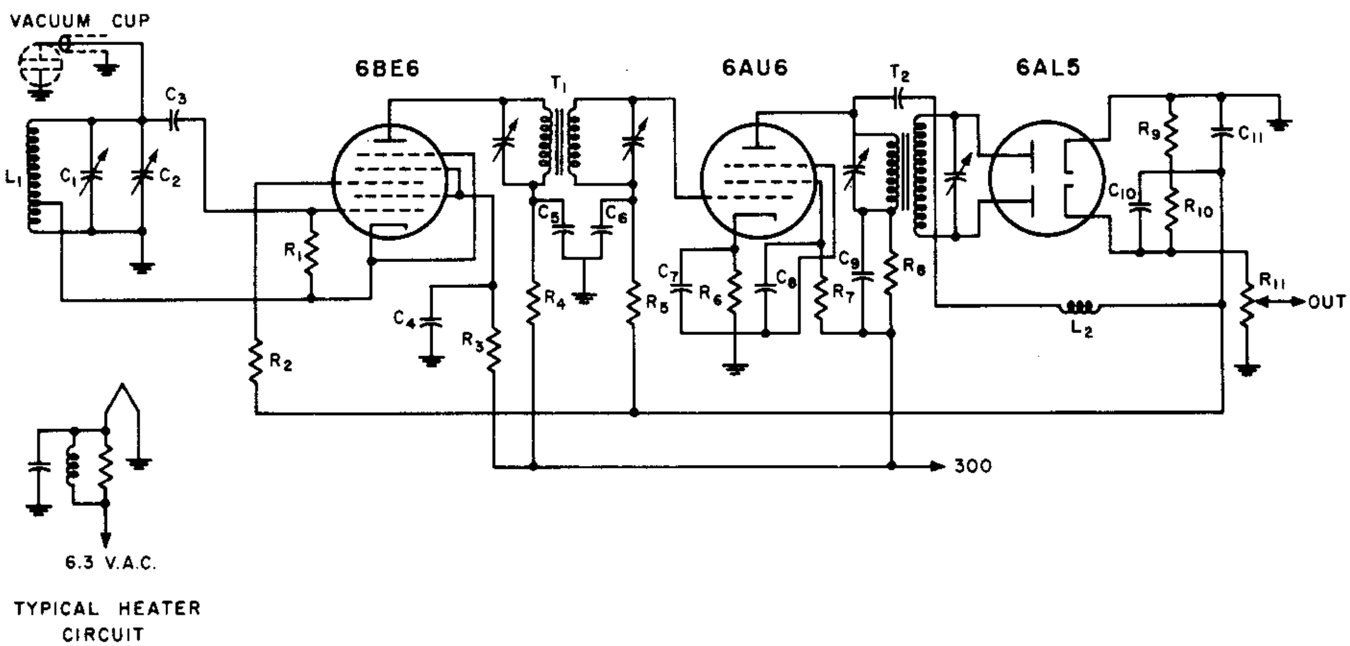

FIG. IVa

DISCRIMINATOR FOR VACUUM CUP-CAPACITANCE MEASUREMENTS

B-823-24

Discriminator Circuit Constants

$C_{1,2}$	3-25 mmf	R_7	150,000 ohms
C_3	200 mmf	R_8	10,000 ohms
$C_{4,5,6,7,8}$	.002 mf	$R_{9, 10}$	100,000 ohms
C_9	500 mmf	R_{11}	250,000 ohms
C_{10}, C_{11}	250 mmf	L_1	Meissner 14-1063 osc. coil
R_1	22,000 ohms	L_2	250 mh
R_2	1 megohm	T_1	Miller 6203 IF trans.
R_3	30,000 ohms	T_2	Miller 6204 IF trans.
R_4	500 ohms		
R_5	200,000 ohms		
R_6	68 ohms		

APPENDIX V. DEFLECTION VOLTAGE MEASUREMENTS

Appendix V(a)

Deflection voltage measurements as function of time to demonstrate repeatability.

	E			
Station	t	t + 2 hrs	t + 6 hrs	t + 24 hrs
1	1.65	1.64	1.66	1.61
2	1.20	1.20	1.22	1.19
3	1.55	1.55	1.58	1.51
4	1.62	1.65	1.63	1.53
5	1.16	1.19	1.17	1.23
6	1.42	1.46	1.47	1.56
7	1.80	1.77	1.77	1.68
8	1.95	1.95	1.93	1.87
9	1.50	1.53	1.54	1.45
10	1.29	1.31	1.32	1.23
11	1.44	1.42	1.41	1.33
12	1.03	1.04	1.05	.99
13	1.15	1.07	1.11	1.07
14	1.30	1.31	1.30	1.32
15	1.35	1.35	1.36	1.29
16	1.35	1.37	1.38	1.37
17	1.77	1.73	1.75	1.75
18	1.15	1.15	1.13	1.13

The above voltages are proportioned to the change in capacitance, and thus to the average skin deflections under the electrode. "Deflection voltage," the voltage measured in this way, has been used in this report as a parameter for the comparison of the test specimens. It is so used because it is the quantity that was measured directly. The data of Appendix III can be used for the conversion of the deflection voltages to change in capacitance or average deflection in inches.

Appendix V(b)

Deflection voltages, Panel C91S, undercured, 1/8" h. c. 1/2" x 1/2" survey

Column	Row 1	2	3	4	5	6	7	8
1	1.56	1.27	1.55	1.15	1.88	1.68	1.50	1.30
2	1.23	1.28	1.31	1.30	1.47	1.70	1.47	1.64
3	1.24	1.16	1.12	1.41	1.32	1.65	1.62	1.14
4	1.53	1.48	1.21	1.37	1.22	1.43	1.39	1.41
5	2.45	1.27	1.31	1.19	2.00	1.65	1.52	1.44
6	1.86	1.51	1.24	1.44	1.92	1.72	1.44	1.71
7	1.24	1.45	1.47	1.51	1.24	1.15	1.60	1.06
8	1.47	1.62	1.31	1.36	1.55	1.40	1.49	.99
9	1.63	1.54	1.54	1.70	1.36	1.45	1.38	1.16
10	1.40	1.73	1.45	1.62	1.12	1.26	1.22	.89
11	2.18	1.43	1.40	1.41	1.28	1.20	1.18	1.75
12	1.44	1.60	1.28	1.22	1.04	1.27	1.16	1.54
13	1.40	1.12	1.31	1.37	1.17	1.25	1.22	1.52
14	1.42	1.36	1.06	1.22	1.42	1.40	1.39	1.34
15	2.22	1.55	1.47	1.45	1.92	1.80	1.41	1.47

Column	Row 9	10	11	12	13
1	1.39	1.24	1.24	1.55	2.15
2	1.20	1.76	1.60	1.35	1.76
3	1.07	1.16	1.02	.88	1.66
4	1.08	1.15	1.08	1.00	.96
5	1.27	1.21	1.24	1.66	1.80
6	1.74	1.36	1.37	1.68	1.83
7	1.26	1.47	1.17	1.35	1.42
8	1.64	1.29	1.53	1.40	1.40
9	1.40	1.33	1.70	1.58	1.78
10	1.03	1.46	1.46	1.44	1.62
11	1.62	1.71	1.39	1.43	1.56
12	1.39	1.33	1.45	1.16	1.44
13	1.51	1.40	1.56	1.36	1.43
14	1.47	1.52	1.64	1.50	1.34
15	1.21	1.26	1.60	1.27	1.15

Appendix V(c)

Deflection voltages, Panel C52S, control, 1/8" h. c., 1/2" x 1/2" survey

	Row							
Column	1	2	3	4	5	6	7	8
1	1.47	1.11	1.14	1.29	1.24	1.31	1.41	1.22
2	1.45	1.04	1.27	1.33	1.18	1.44	1.30	1.19
3	1.46	1.37	1.09	1.16	1.36	1.27	1.08	1.44
4	1.00	1.34	1.31	1.24	1.41	1.19	1.11	1.31
5	1.20	1.05	1.09	1.49	1.54	1.20	1.22	1.27
6	1.25	1.18	1.41	1.33	1.60	1.33	1.34	1.46
7	1.30	1.14	1.00	1.70	1.39	1.47	1.16	1.52
8	1.92	1.18	1.26	1.29	1.28	1.19	1.22	1.11
9	1.67	1.22	1.33	1.08	1.14	1.30	1.09	1.33
10	1.24	1.19	1.09	1.15	1.08	1.33	1.11	1.18
11	1.76	1.47	1.22	1.22	1.27	1.11	1.40	1.09
12	1.71	1.05	1.40	1.30	1.42	1.13	1.47	1.02
13	1.70	.95	1.27	1.11	1.13	1.34	1.39	1.44
14	1.02	1.37	1.18	1.17	1.09	1.47	1.28	1.46
15	1.13	1.62	1.22	1.46	1.37	1.61	1.14	1.33

	Row				
Column	9	10	11	12	13
1	.75	1.30	1.19	1.22	1.30
2	.81	.91	1.22	1.18	1.22
3	1.25	1.39	1.37	1.26	1.47
4	1.12	1.27	1.56	1.33	1.53
5	1.04	1.16	1.42	1.24	1.29
6	1.35	1.07	1.29	1.11	1.18
7	1.07	1.11	1.61	1.09	1.23
8	1.20	1.21	1.32	1.22	1.44
9	1.17	1.04	1.08	1.38	1.31
10	.89	1.19	.99	1.29	1.26
11	1.35	1.22	1.27	1.18	1.29
12	1.22	1.11	1.34	1.27	1.42
13	1.11	1.37	1.31	1.16	1.60
14	1.31	1.41	1.28	1.20	1.44
15	1.29	1.33	1.46	1.31	1.29

APPENDIX VI. TENSILE TEST DATA

The following table lists the force required to produce failure in the 1-inch square coupons that were subjected to flatwise tensile tests. Values with an asterisk indicate that the failure occurred in the core or on the side of the sample that had not been surveyed. The listed values of average deflection voltage were obtained by inspection of the panel contour maps. The successive values of deflection voltage and strain to produce failure are compared for consistency, using the criterion that small values of deflection voltage should be associated with weak bonds.

Panel	Sample	Def. Voltage	Tensile (Psi)
C49S	1	1.70	576
"	2	1.30	576 inconsistent (I)
C52S	1	1.50	956*
"	2	1.20	983* consistent (C)
"	3	1.40	983 C
C92S	1	1.30	283*
"	2	1.60	346* I
C65S	1	1.40	983*
"	2	1.80	673 C
C40S	1	1.40	318*
"	2	1.50	557* I
"	3	1.40	626* C
C35S	1	1.20	575
"	2	1.10	700 C
"	3	1.60	359 C
"	4	1.30	258 I
"	5	1.30	257 C
"	6	1.40	833 I
"	7	1.30	864 C

Panel	Sample	Def. Voltage	Tensile (Psi)
C91S	1	1.50	352
"	2	1.30	604 C
"	3	1.20	644 C
"	4	1.30	608 C
"	5	1.50	558 C
"	6	1.50	688 I
"	7	1.40	645 C
C57S	1	1.40	1042
"	2	1.20	1069* C
"	3	1.40	1014 C
C50S	1	1.40	1105
"	2	1.10	1025 I
"	3	1.30	1100 C
"	4	1.20	1130 C
"	5	1.30	1190 I
"	6	1.50	1090 C
"	7	1.50	1210* I
C48S	1	1.50	290*
"	2	1.40	509 C
"	3	1.40	534 C
"	4	1.30	540 C
"	5	1.40	562 I
"	6	1.50	536 C
"	7	1.40	585 C
C91S	1	1.30	352
"	2	1.30	604 I
"	3	1.40	644 I
"	4	1.40	608 C
"	5	1.50	558 C
"	6	1.20	688 C
"	7	1.30	645 C

Consistent - 70%, Inconsistent - 30%

APPENDIX VII. TYPICAL DEVIATION CALCULATION

Calculation for average deviation, Panel C52S, 1/8" h. c. control panel

Range	No. Readings	% Readings	Standard %	Difference
90	1	0.5	1	.5
90-99	6	3.1	3	.1
100-109	20	10.4	9	1.4
110-119	36	18.8	17	1.8
120-129	45	23.4	23	.4
130-139	30	15.6	20	4.4
140-149	19	9.9	14	4.1
150-159	15	7.8	7	.8
160-169	5	2.6	3	.4
170-179	6	3.1	2	1.1
180-189	4	2.1	1	1.1
190-199	4	2.1	0	2.1
200	1	0.5	0	.5

Total Deviation	18.7
Average Deviation	1.45