TECHNICAL DEVELOPMENT REPORT NO. 371

Some Methods for Inspecting Adhesive-Bonded Joints in Helicopter Rotor Blades

FOR LIMITED DISTRIBUTION

by

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September 1958

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TECHNICAL DEVELOPMENT CENTER
INDIANAPOLIS, INDIANA

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SOME METHODS FOR INSPECTING
ADHESIVE-BONDED JOINTS IN
HELICOPTER ROTOR BLADES

SUMMARY

A study of seven types of nondestructive methods for inspecting adhesive-bonded joints was made to determine if any of these showed promise for application to field inspection of adhesive-bonded metal helicopter rotor blades. A review of research reported by other agencies on the problem of adhesive-joint inspection showed that lap joints and core-to-facing joints in sandwich construction could be inspected.

Seven inspection methods were tested on samples representing the various types of adhesive joints used in metal helicopter blades. No single device could detect all voids in all types of blades encountered. Further, the variety and complexity of structure of metal blades reduces the probability of developing a single relatively simple inspection device which will detect all voids in all types of blades.

The STUB-meter, at present, can be used to detect voids, as well as other defects, in the upper three to five adhesive layers, but is best suited for inspecting single lap-joints and sandwich construction. The STUB-meter still is a laboratory instrument.

The tapping test is the simplest test available and, under favorable conditions, can be used successfully to detect many of the voids in the uppermost adhesive layers. Tapping tests are, at present, limited to interpretation by the human ear.

INTRODUCTION

With the advent of adhesive-bonded metal helicopter rotor blades, inspection of the completed bonds became a difficult problem for the manufacturer and user. Uncertainty about the airworthiness of blades which develop voids in service has prompted periodic inspection to eliminate blades after the voids have developed to a certain size. Prior to 1955, no satisfactory method had been devised for the nondestructive inspection of the complicated joints found in rotor blades.

Three programs for developing or applying instruments for nondestructive testing of bonds have resulted in the use of ultrasonic flaw-detection equipment. Final inspection and, in particular, field maintenance inspection, rely on surface evidence and simple tapping tests.

A review was made of the work done by other agencies in developing methods for inspecting adhesive-bonded joints for voids. Portions of several rotor blades representing the principal types in current use were examined by present nondestructive inspection methods The limitations of these methods for inspecting laminated and sandwich construction are discussed.

Under contract with the Department of the Army, the CAA Technical Development Center (TDC) is undertaking a three-phase program to develop a nondestructive field-maintenance-type device or devices which can detect voids in helicopter blade bonding. The first phase of this program was to determine the degree of feasibility of developing such a device; during the second phase, specifications will be written, while the third phase will involve development of a prototype. This report covers the results obtained in the first phase of the program.

TYPES OF BONDED JOINTS

Four manufacturers have developed metal blades for use on particular helicopters. While the various blades produced by a single blade manufacturer may be constructed similarly, the blades from other manufacturers usually differ in construction details. To show these details, oblique views of sections of six rotor blades are shown in Figs. 1 to 6, inclusive. While several other blades have been made, these views illustrate the principal types of bonded joints used in constructing rotor blades.

The success of a nondestructive inspection method may depend on the physical dimensions and details of construction of the particular joint inspected. Since one blade may utilize several types of joints, a list of the various types follows.

1. Bilaminate Joints.

   a. Bilaminate sheets of the same material and thickness - two-layer skins.

   b. Bilaminate joints of different materials or alloys and different thicknesses - skin to spar, skin to ribs or trailing-edge inserts or strips, cuff attachment plate to spar.

2. Multiple Laminate Joints.

   a. Multiple laminates of similar metals or alloys of the same order of thickness - built-up spar sections and doublers.

   b. Bonded contoured plate used internally and plate bonded to a stack of external doublers.

3. Sandwich Construction.

   a. Skins of sheet or contoured plate bonded to honeycomb sandwich.

Thickness of material:

1. Minimum thickness of sheets used as skins or facings in metal rotor blade aft sections is 0.012-inch aluminum, Type 2024 or 6061, or 0.009-inch stainless steel.

2. Minimum thickness of sheets used in doublers and multiple layer facings is 0.015-inch aluminum, Type 2024 or 6061, or 0.009-inch stainless steel.

Three representative adhesives used in the production of metal rotor blades are:

1. Vinyl-phenolic resin, such as FM 47, Bloomingdale Rubber Co.
2. Nitrile rubber-phenolic resin, such as Plastilock 601, B. F. Goodrich Co.
3. Phenolic-acrylonitrile blend, such as Metabond 4021, Narmco, Inc.

The external plates used to adapt the root end of the blade to the blade fork, blade grip, or cuff have thicknesses up to 0.75-inch or 1.0-inch. Up to 15 Type 2024 aluminum doublers 0.032-inch thick are used to strengthen the root end and adapt the thickness to fit the blade attachment. One manufacturer utilizes 0.0088-inch stainless steel sheet to construct the nose section, facing sheets, and doubler pads. Up to 19 stainless steel sheets may be used to construct these built-up blades.

VOIDS IN ROTOR BLADES - LOCATION AND FORMATION

Adhesive joints vary widely in strength The manufacturers of aircraft components have attempted to limit the strength variation by quality control programs. From these programs and from the work of research organizations, a nomenclature describing the types of joint defects has been developed Defects in adhesive joints may be caused by contamination, starvation, porosity, overcuring, undercuring, thick glue lines, lack of pressure during bonding, or improper venting of the volatile ingredients of the adhesive.

The term "void" refers to areas between adjacent metal surfaces wherein there is no bond of the metal surfaces, one to the other. The problem of eliminating all detectable blisters and voids from large bonded assemblies such as helicopter rotor blades has not been solved. Therefore, certain voids are tolerated in the production of rotor blades. The size, number, and location of voids in an acceptable blade are limited by agreement between the manufacturer and the certifying agency.

Each type of metal blade may have characteristic locations where voids may be anticipated during the service life of the blade. These locations are the result of concentrated operational stresses, particularly where sheets or plates are bonded to the outside of the main airfoil section of the blade. In other cases where the airfoil section consists of cells whose walls are bonded to a nose spar (see Fig. 1), voids have developed in the bond between the cell walls and the spar as at point 1B of Fig. 1, particularly for those cells which are not interconnected by means of a strip insert at the trailing edge of the blade. Facing or skin sheets occasionally separate from supporting ribs. All joints, splices, and changes in section are viewed with suspicion. Manufacturers look upon sandwich construction with some favor because of the continuity of the facing support provided in the aft section of the blade.

PRESENT METHODS OF NONDESTRUCTIVE BOND INSPECTION

Several organizations have worked on methods of bonded joint inspection. While most of the methods have been used for inspecting sandwich construction, several have been used for inspecting other types of bonded joints also. Among the final production and field-maintenance inspection methods in present-day use are:

1. Tapping.
2. Visual inspection.
3. Use of a feeler gage.
4. STUB-meter.

Other methods using ultrasonic techniques which have been used experimentally are:

5. Reflected pulse method.
6. Through-transmission method.

In addition to the foregoing, X-ray and dye-penetrant methods have been considered for bond inspection.

Description of Methods.

The first three methods are used for field inspection of rotor blades. Tapping or otherwise vibrating the surface of the part being inspected with coins, small light hammers, or by means of electrically operated tappers or buzzers has been found to be the most satisfactory of the simple methods for finding voids. See bibliography.[1]

Tapping, the most widely used of the simpler inspection methods, relies upon the changes in the quality of the sound produced by lightly tapping the surface of the part being inspected. The sound produced by tapping over voids is a hollow, dead sound compared with the sound produced by tapping a well-bonded area.

As stated previously, the structural details of the part directly affect the results of the test. In tapping, the type of construction must be considered. Unsupported facings will display the same sound quality as a void. Voids along chordwise and spanwise ribs under a single facing sheet can be detected by tapping. A definite ring will be heard over the major structural elements of the blade where the facing is well bonded.

Careful visual inspection of the rotor blade is made to detect paint cracks over the free edge of joints, loose facings and blisters, or other signs of bond failure. The paint over the free edge of an adhesive joint usually cracks when the joint beneath the paint fails. A suction cup or soft pencil is used occasionally to assist detection of loose facings and blisters. As the point of a soft lead pencil is rubbed over loose areas, a slight deflection of the facing may be noticed. The maximum extent of the void is difficult to determine by this method and it applies only to thin facings. A suction cup may be used to detect blisters by moving the facing under the attached cup. As with the pencil-rubbing method, only relatively thin facings and large blisters can be inspected successfully by the suction-cup method. Occasionally, a special construction feature will assist visual inspection. In the case of one blade with a tape-supported adhesive, the impression of the Fiberglas tape showing through the 0.009-inch stainless steel facing could be seen over the supporting stiffeners in the aft section of the blade. Where there was no adhesion, this impression disappeared. See Fig. 7.

A feeler gage or short length of shim stock has been used to probe the free edge of bonds. Voids extending to, or originating at, the free edge of a joint may be detected, but at least two manufacturers report that overly enthusiastic use of the feeler gage can enlarge the void

A more successful method of bond inspection equipment might be classed loosely as "sonic." It depends on vibration mechanics or sonic wave propagation for the detection of defects in the adhesive. Stanford Research Institute, under contract with the Materials Laboratory, Wright Air Development Center, has developed a method of bond inspection based on the use of their Model 3 Stanford Ultrasonic Bond Meter,[2] or STUB-meter

Briefly, the STUB-meter employs an electrically driven, vibrating crystal approximately 1 inch in diameter by 3/8-inch in thickness which, when coupled mechanically by a film of oil to a surface, will vibrate that surface in a manner similar to a high-speed hammer applied with a very short stroke. The length of stroke or amplitude of the crystal vibrations, although much less than 0.001-inch, is greatest in free air and much less when the crystal is pressed against a firm surface. A surface well bonded to another will give a lower amplitude of crystal vibration than a poorly bonded surface. The crystal vibration is displayed on a cathode-ray oscilloscope (CRO) for interpretation.

The small power and short stroke of vibration of the crystal are compensated for in part by continuously sweeping the frequency of vibration from a low to a higher value and back to the lower value, over a selectable range, between the values of 100,000 and 1,000,000 cps. The STUB-meter has been found to give results on as many as three to five thin bonded layers. A greater number of bonded surfaces or thicker material destroy the reflected pattern by presenting too great a load on the crystal. This effect is referred to as the limit of range of the crystal.

Another type of ultrasonic device, known commercially as the Reflectoscope or Immerscope, also has been used. This equipment, which utilizes pulsed high-frequency sound, has been applied experimentally to the inspection of sandwich construction by Sperry Products, Inc ,[3] and North American Aviation, Inc.[4] Varying success in the detection of voids in sandwich construction has been reported by these organizations. Reflection, refraction, and dispersion of the pulsed sound occur, depending on the acoustic properties of the specimen In reflected-pulse testing, a single search unit is used for transmitting and receiving the pulse. In through-transmission testing, two search units are used, one for transmitting, the other for receiving the pulse.

X-ray photographs have been used to inspect brazed or welded sandwich construction. However, the success of X-ray photographs for inspecting adhesive-bonded construction depends on variations in the appearance of the adhesive layer to indicate defects

Dye penetrants have been used for detecting cracks which extend to the surface of metal castings, forgings, and extrusions. This method can detect voids extending to the free edge of a joint and may be used as an aid to visual inspection.

EVALUATION OF SOME EXISTING METHODS OF BOND INSPECTION

Details of the construction of several currently manufactured rotor blades were studied to determine the possibility of inspecting each type of bond used in the fabrication. Inspection equipments that appeared to show promise were obtained and tested to determine their usefulness in detecting voids in sample rotor blade sections and test panels.

Test Specimens.

Four helicopter blade manufacturers furnished sections of rotor blades with voids. The blade sections were of the types shown in Figs. 1, 2, 3, and 4. Photographs of the blade sections are shown in Figs. 8 and 9. A large multi-laminate spar, Fig. 10, which had been built up of 0 009-inch stainless steel sheets bonded with FM-47 tape, also was supplied. While these samples represented several types of bonded joints in current use, additional samples were needed to have a complete representation of the adhesives and joints used.

Seven square test panels, Figs. 11 to 16, inclusive, simulating the types of bonds and adhesives used in rotor blade construction, were obtained from a local metal fabricating shop. Voids were secured by omitting the prime coat over areas of intended voids and coating the area with a thin film of heavy grease.

X-Ray Tests.

X-ray photographs of the test panels were made. In these photographs, the metallic parts of the panels were sharply defined, but the adhesive is transparent to X rays, therefore, there is no indication of the presence or absence of voids.

Mechanical Tappers and Vibrators

A tapper obtained from Convair, San Diego, Calif., which consisted of a 1-inch length of 0.250-inch round brass rod attached to a brass handle by a 4-inch length of 0.030-inch piano wire was used to examine both the blade sections and the test panels. In the test panels, most of the intended voids and several unintentional voids in the uppermost adhesive layer were detected. Voids beneath two or more sheets and voids which were located beneath a 0.250-inch aluminum channel and a 0.075 inch steel channel could not, however, be identified positively. See Figs. 11 to 16, inclusive, and Table I for the results of these tests. In examining the rotor blade sections, the voids which had been identified previously and marked by the manufacturer's inspection department were identified readily.

Single adhesive joints with thin facings, as for example in the blades shown in Figs. 8 and 9, were tested readily by the tapping method The large void areas in the outer facing of the large multilaminate spar section shown in Fig. 10 were detected easily.

An electrically operated tapper, consisting of a solenoid controlled by a relay, was constructed. A photograph of the apparatus in use and a schematic wiring diagram are shown in Figs. 17A and 17B. The sound produced by the tapper was picked up by a crystal microphone. The output of the microphone was read directly on a Ballantine Model 300 vacuum tube voltmeter. Headphones connected to the output of the meter amplifier were used to listen to the sounds produced. The tapping frequency of this system could be varied between 100 and 650 taps per minute by changing the capacitor. The frequency and the force with which the tapper struck the surface varied. These variations were traced to heating of the coils, variations in power-supply voltage, and variations in the mechanical action of the tapper. Consequently, pickup microphone voltage was irregular and could not be correlated positively with the presence or absence of voids The use of the microphone, amplifier, and headphone were less satisfactory than simple listening Results of the tests with this tapper are shown in Figs. 11 to 16, inclusive.

A 12-volt electrical vibrator, a telephone buzzer, and an electrical bell tapper were tested for use as vibration sources. The approximate frequencies of these were 120, 250, and 60 cps, respectively The microphone, meter, and earphones were used with these vibration sources and the voltage output of the microphone also was observed on the meter. When held on the specimen by hand, the quality of the sound produced by the buzzer changed as mechanical pressure was exerted on its case. This change in sound quality was verified by placing the microphone near the buzzer on the test panel and observing changes in the microphone voltage on a CRO. The buzzer produced an oscilloscope trace best described as noise. Voltage amplitude changes occurred when lateral or horizontal pressure or vertical contact pressure was exerted on the buzzer case.

Similar tests with the electrical bell tapper and the electrical vibrator indicated that both units also were subject to vibration changes caused by changes in the manner in which they were held and by the pressure used to contact the surface of the specimen

Of the three units, the electrical vibrator seemed the least disturbed by manual positioning as evidenced by the relatively constant amplitude and the regular recurrence of the vibrations produced as observed on the CRO The vibrator produced less surface vibration than the buzzer, consequently, most of the testing was done with the buzzer even though the irregularity of the vibration produced prevented the possibility of correlating void location with the voltage output of the microphone.

The use of the electrical bell tapper was discontinued after a few trials because the stroke of the tapping rod could not be adjusted easily and the electromagnet brought the rod toward the surface rather than away from the surface of the test specimen.

Another method of finding voids by means of a vibrating device is to clamp the vibrator to the specimen and search the panel with the pickup microphone to detect changes in the sound produced by the resulting vibration. A mounting was made for the electrical vibrator and the vibrator was operated while clamped to the edge of the panel. As before, the microphone, amplifier, and earphone were used to detect sound changes. Similar tests with the buzzer indicated that the buzzer produced more vibration of the surface of the test panel than did the electrical vibrator, consequently, the buzzer was used for clamped tests. Results of the tests with the buzzer are shown in Figs. 10 to 17, inclusive. No separate tests were made with the buzzer using only manual positioning or fixed-position operation because neither method was more successful than simple tapping in locating voids.

The testing of the electrical vibrator, buzzer, and electrical bell tapper indicated the following.

1. A driver or vibration source which produces a vibration of uniform frequency and amplitude and is not affected materially by contact pressure is necessary for finding voids by sound changes or by means of a pickup microphone amplifier and oscilloscope or voltmeter

2. The tapping test is most successful in detecting voids in the uppermost adhesive layer under facing sheets 0.050-inch thick or less, or on thicker sheets and plates where the void extends beyond one side of the plate.

A portable audio amplifier, shown in Fig. 18, was constructed to aid in the inspection of blades by the tapping method. An Ampex PC201 printed circuit amplifier requiring a 6-volt A battery and a 22.5-volt B battery was used. Two microphones, one of the crystal contact type and the other of the dynamic type, were used with the amplifier. Three operators used the device for inspection with mixed results. Two operators received material assistance, the third received none.

Ultrasonic Bond Analyzer.

This equipment, the DuMont Type 2631 Ultrasonic Bond Analyzer, is similar to the Model 3 Stanford Ultrasonic Bond Meter described previously. A DuMont Type 2615 oscillograph record camera was used to record the oscilloscope traces. A peak reading voltmeter and a probe for curved surfaces were constructed from data contained in Stanford Research Institute reports.[5] A photograph of the equipment is shown in Fig. 19

In using the bond analyzer for finding voids, the following steps are taken·

1. A crystal size is selected which is suitable for the outer facing thickness of the specimen examined.

2. The instrument is adjusted to display on the oscilloscope the resonant trace pattern of the probe which has been found to be most sensitive to changes in bond quality.

3. A film of oil or glycerine with a wetting agent is applied to the specimen to couple the probe to the outer facing of the specimen.

4. The pattern of the oscilloscope trace is compared with a similar pattern for a known bond quality. The peak-to-peak voltage amplitude of the signal may be measured directly on the peak-reading voltmeter. A photograph may be made for future reference

For facing sheet thicknesses which are within the total thickness range of the crystal, the apparatus is quite successful in locating voids. This would include Type 1A and 1B joints shown in Fig. 1, and some sandwich shown as "3" in Fig 2.

In addition to the test panels and helicopter blade sections, 4- by 4-inch sheets and plates of aluminum and stainless steel were utilized for studying the response of the bond analyzer to facing sheets of varying thickness. Sheets of 0.020-inch, No. 2024 aluminum alloy and 0.010-inch stainless steel were coupled together with oil to study the inspection of multilaminate structure Figure 20 shows a decrease in amplitude with an increase in the number of sheets in the lamination. These traces were obtained with the oscilloscope record camera using a roll-film back. The oscilloscope patterns were traced directly from the developed-roll film.

The 1- by 3/8-inch crystal probe was used in all tests. Although this crystal was not the optimum size for inspecting all facing thicknesses, the range of this probe, a maximum thickness of about 0.20-inch aluminum or 0.050-inch steel, permits the examination of samples with different facing thickness without the necessity of changing crystals. Within the range of the probe, the equipment performed satisfactorily. Voids in test panels which were identified by the use of the bond analyzer are shown in Figs. 11 to 16, inclusive, and are listed in Table I. Bond analyzer traces from the test panels are shown in Fig. 21. The circled numbers correspond to the number of the test panel. The patterns were photographed as the probe was placed over an area intended to be satisfactory or intended to be void. The last four traces from Panel 7 show no apparent difference because the thickness of the panel sections was outside of the range of the 1- by 3/8-inch crystal.

Figures 22 and 23 show bond analyzer traces from the rotor blade sections. The voids detected in the test panels are marked in Figs. 11 to 16, inclusive. On panel No. 2, a stepped, multilaminate panel, trace amplitude variation was noted between adjacent areas on the various steps. Areas displaying large amplitude patterns were marked on the top step. Later, this top sheet or step was removed with a hammer and chisel. While no large voids existed at this step, a weak adhesive bond corresponded to the indicated void. On the rotor blade section, Fig. 8, the voids, with the exception of A, which had been previously marked, were identified.

Dye Penetrant Inspection.

Dye penetrant inspection was used on test panels Nos 1, 2, and 3 and on two helicopter rotor blade samples. Conventional methods and materials were used for dye penetrant inspection. A cleaner first was applied to remove oil and grime from the surface and cracks of the parts to be inspected. The colored dye penetrant was applied to the part and allowed to remain for approximately 3 to 10 minutes at room temperature. The excess dye was treated with a remover and wiped clean with a dry rag. A white powder, dry or in suspension in a quick-drying liquid known as the developer, then was applied. The white developer was stained by the dye that remained in the cracks and crevices of the part being inspected, thereby showing a void open to the surface.

A void beneath the thin end of the cuff plate, which had been detected previously by tapping, was detected also by the dye penetrant inspection method. See Fig. 24. In a multilaminate leading edge section, several voids were noted at either end of the sample in the thin glue line of FM-47 tape. Sample panel No. 3, a bilaminate panel, showed evidence of bond failure at several places along the exposed edge of the joint. Two additional panels, Nos. 1 and 2, demonstrated similar results as shown in Figs. 25A, 25B, and 25C.

The voids under two exposed outer facings of a multilaminate test panel had gone undetected in a previous tapping test. All of the voids in the other samples had been detected previously by tapping. This method shows some usefulness for inspecting the free edges of bonded joints, such as the joints along rotor blade trailing edges and the joints between doublers, however, the effect of the chemicals in the dye penetrant on the adhesive used in the rotor blade is not known at present.

CONCLUSIONS

1. Tapping tests are successful for locating many voids which are beneath the upper facing sheets of 0.01-inch to 0.02-inch thickness used in helicopter blades. The joints beneath heavier sheets and plates also may be inspected for voids if the voids extend to an edge where tapping can be done on the surface of the blade.

2. An audio frequency amplifier with pickup microphone and earphone, used with a tapper, does assist operators in detecting the changes in sound which are caused by voids.

3. The DuMont Type 2631 Ultrasonic Bond Analyzer was used successfully in detecting voids as well as other bond weaknesses in the uppermost adhesive layers of laminar constructions when the facing sheet was not too thick for the range of the crystal. Multiple joints consisting of 3 to 5 sheets of 0 009-inch stainless steel or 0.020-inch aluminum alloy also may be inspected in some cases, if the surface can be coupled to the crystal mechanically

4. Voids which extend to the free edge of a joint may be inspected by the dye penetrant method. In this limited case, some voids may be detected which otherwise would escape detection by other methods. The effect of the dye penetrant chemicals on the adhesive has not been determined.

5. The tests conducted indicate the possibility of developing a tapper-type field maintenance inspection device that will locate most voids in helicopter blades. Further investigation of electrical tappers and electronic interpreting means should lead to a satisfactory device.

TABLE I

RESULT OF INSPECTION OF TEST PANELS AND HELICOPTER BLADE SECTIONS

	Sample Type	Character of Defect	I Tapping	II Mechanical Tapper	III Buzzer	IV Bond Analyzer	V Dye Penetrant
Blade Section	No. 1 (Fig 8)	Bonding Separation	A,B,C	A,B,C	B	A,B,C	A
	No 2 (Fig 9)	Bonding Separation	A,B,C	B	B	A,B,C	Not Tested
	No 3 (Fig 10)	Blisters and Voids	Void Areas Located Shown in Fig 10				Voids in Several Layers at Ends See Fig 24
Bonded Test Panel	No. 1	No Adhesive	B	None	None	B,C,D	
	No 2	No Adhesive	B	C,D,E,F	None	B,C,D,E,F,G	
	No. 3	No Adhesive	A,B,C,D,F	A,B,C,D,F	A,C,D	A,B,C,D,F	
	No. 4	No Adhesive	A,B,C,D,E	A,B,C,D,E	A,B,C,D	A,B,C,D,E	
	No 5	No Adhesive	A,B,C,D	A,B,C,D	B,C	A,B,C,D	
	No 6	No Adhesive	A,B,C,D,E	A,B,C,D,E,F	A,B,C,D,E,F	A,B,C,D,F	
	No. 7	No Adhesive	B,C,D	B,C,D	None	B,C,D	

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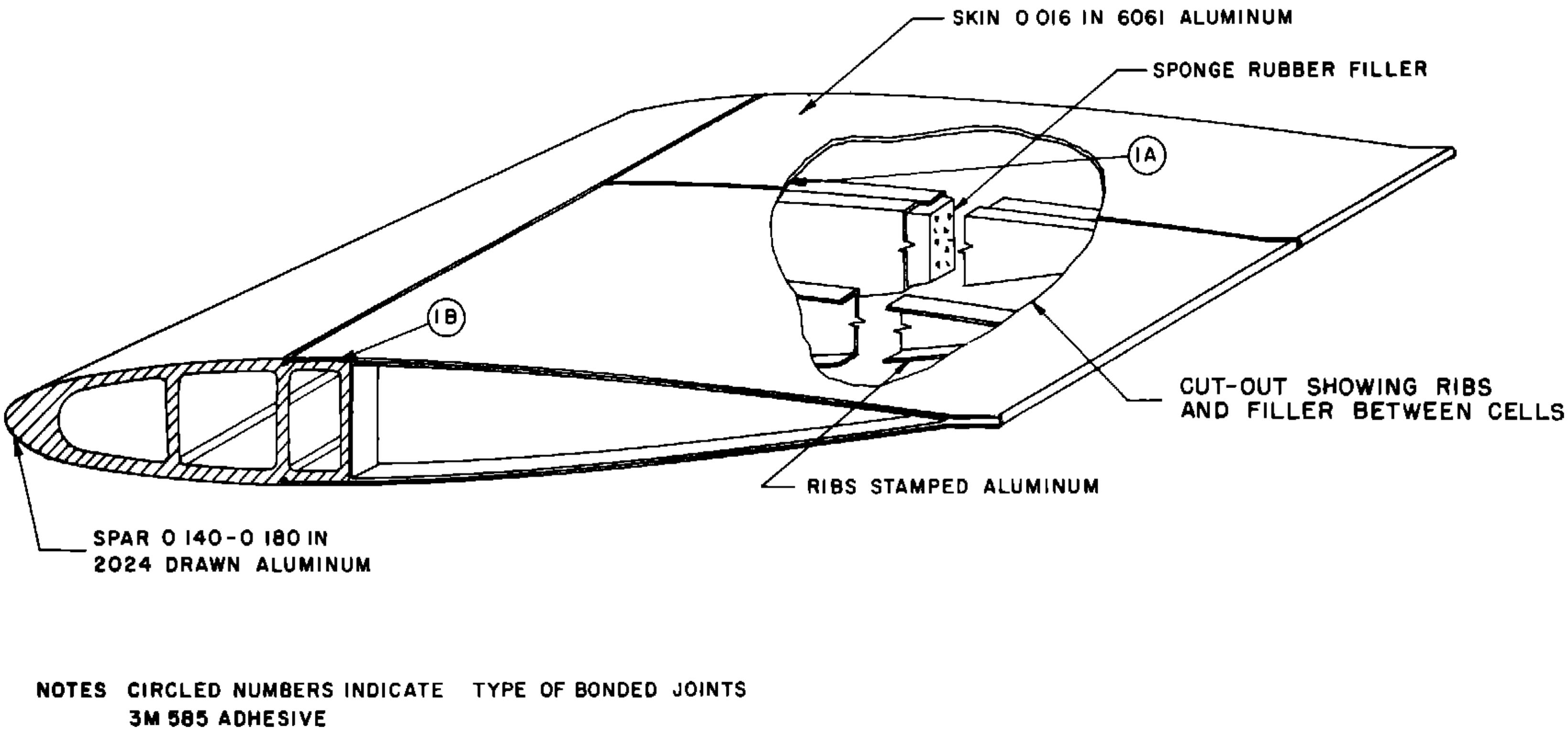
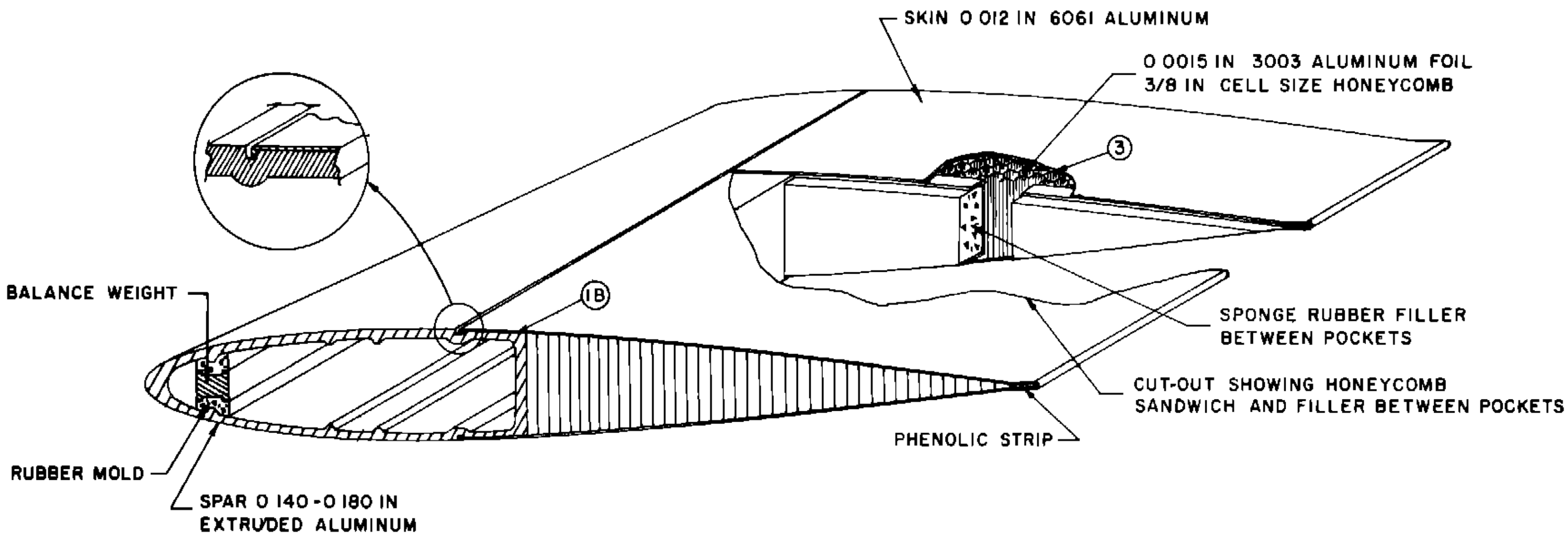


SECTION A

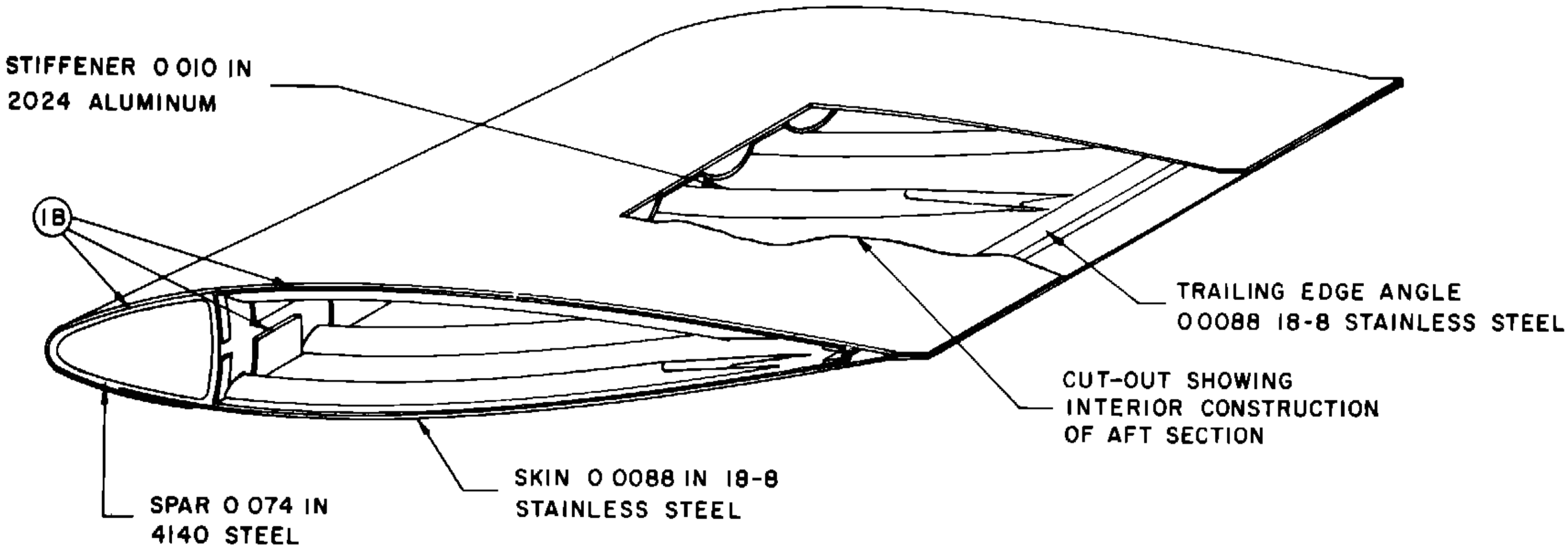
FIG. 1 RIB-SUPPORTED CELLS BONDED TO A SPAR



NOTES CIRCLED NUMBERS INDICATE TYPES OF BONDED JOINTS
SCOTCHWELD 585 FILM ADHESIVE FACINGS TO HONEYCOMB
POCKET TO SPAR
3M AF6

SECTION B

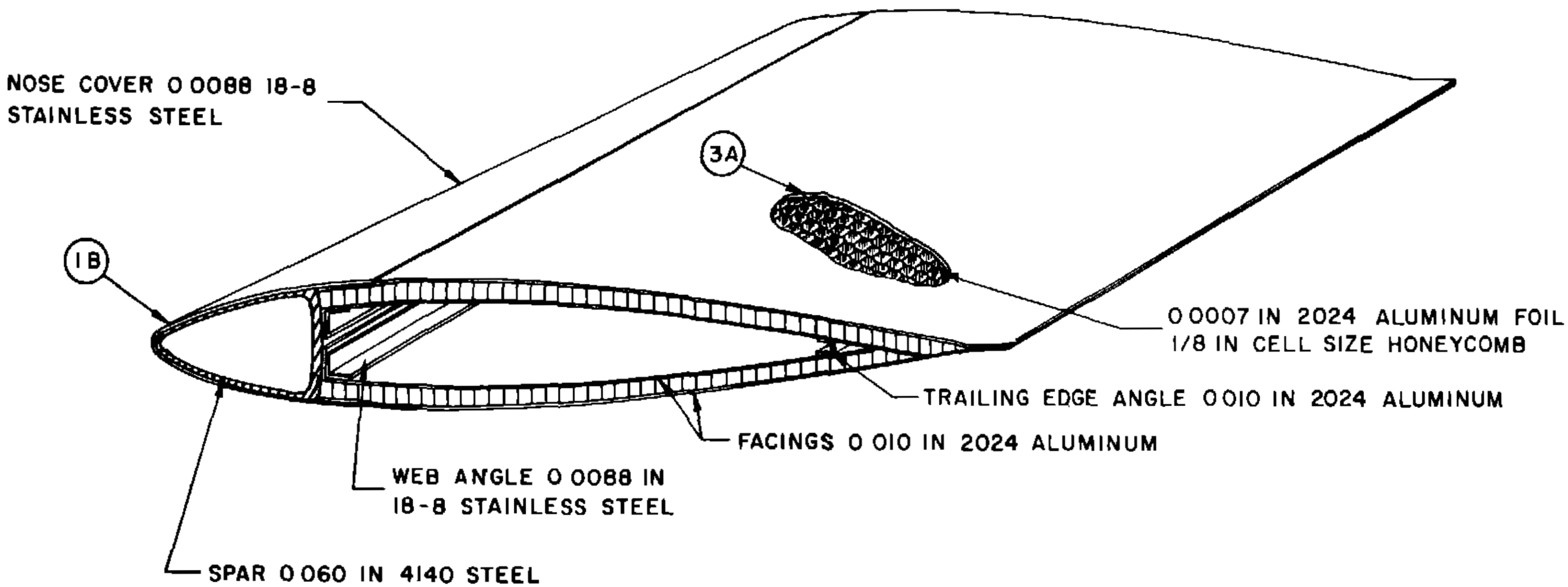
FIG. 2 CELLS SUPPORTED BY EXPANDED HEXAGONAL CELL CORE BONDED TO A SPAR



NOTES CIRCLED NUMBERS INDICATE TYPES OF BONDED JOINTS
FM-47-TAPE ADHESIVE

SECTION C

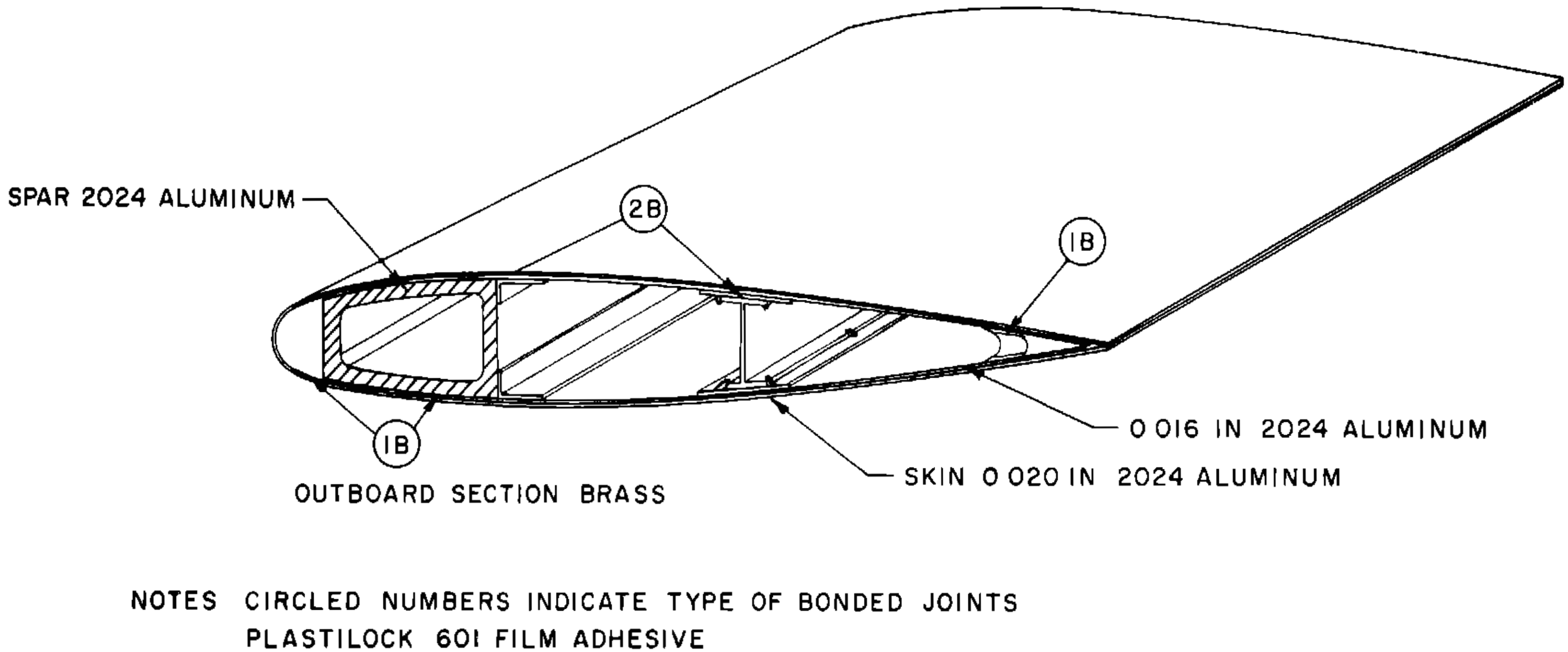
FIG. 3 AFT SECTION SUPPORTED BY RIBBED STIFFENERS



NOTES CIRCLED NUMBERS INDICATE TYPES OF BONDED JOINTS
FM-47-TAPE ADHESIVE

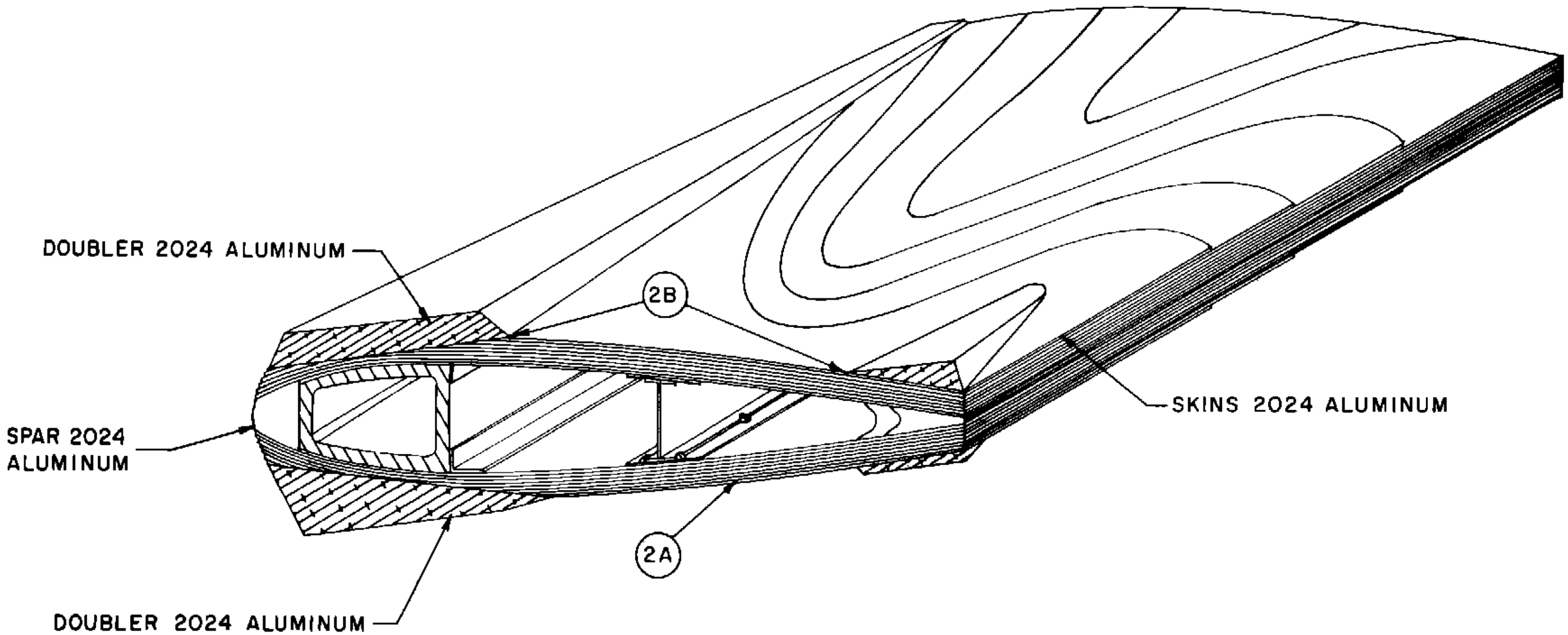
SECTION D

FIG. 4 AFT SECTION COMPOSED OF TWO SANDWICH ELEMENTS



SECTION E

FIG. 5 DOUBLE FACING SHEETS OVER SPANWISE STIFFENER



NOTES CIRCLED NUMBERS INDICATE TYPE OF BONDED JOINTS
PLASTILOCK 601 FILM ADHESIVE
SECTION AT ROOT END SHOWING DOUBLERS

SECTION F

FIG 6 MULTIPLE DOUBLERS

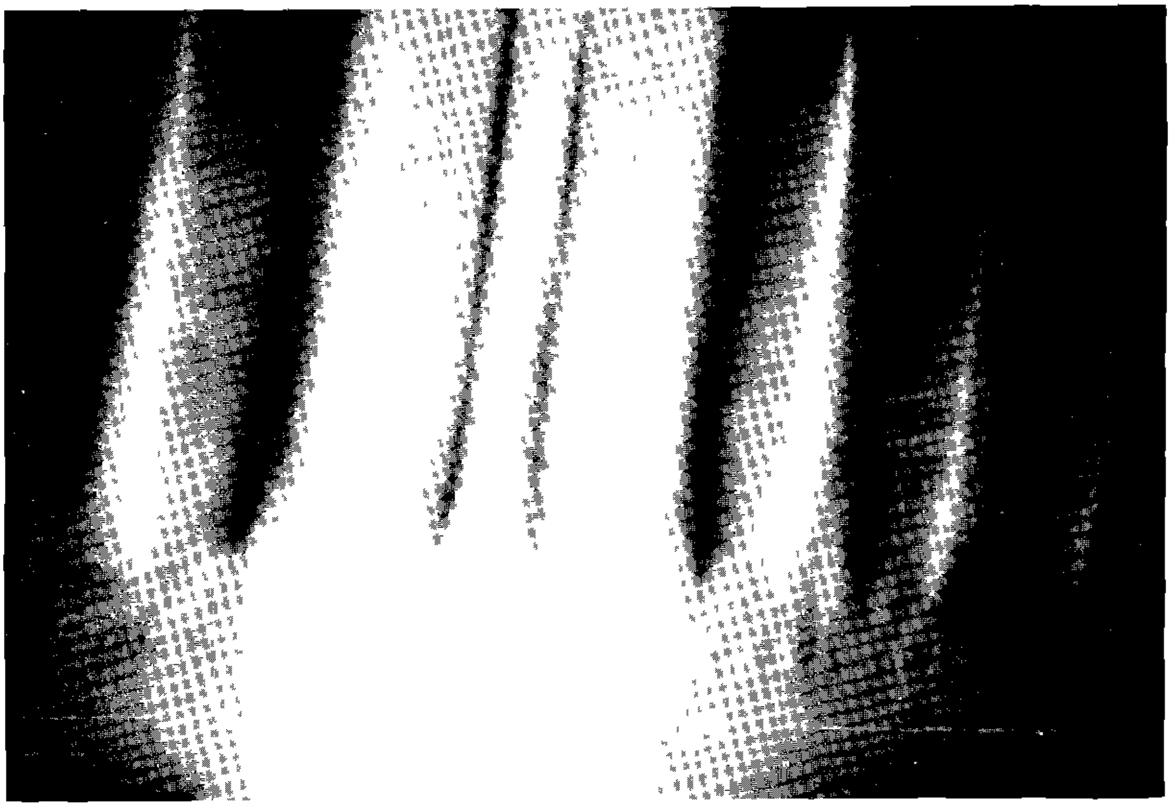


FIG 7 PHOTOGRAPH OF THE IMPRESSION OF FIBERGLAS SUPPORTING TAPE ON THE 0 009 FACING OF THE SECTION OF A ROTOR BLADE

METHOD	VOIDS DETECTED		
TAPPING	A	B	C
MECHANICAL TAPPER	A	B	C
ELECTRICAL VIBRATOR		B	
BOND ANALYZER	A	B	C

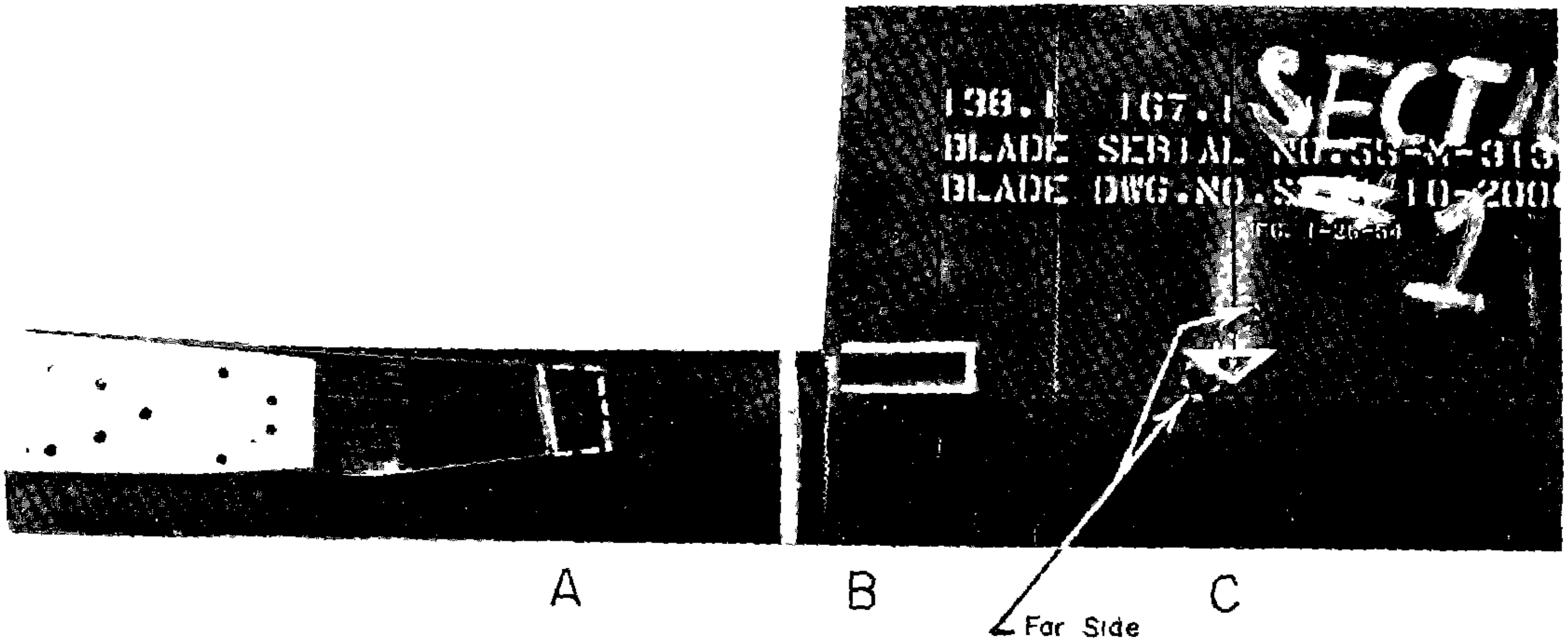


FIG. 8 BLADE SECTION 1 SHOWING RESULTS OF THE TAPPING TESTS

METHOD	VOIDS DETECTED		
TAPPING	A	B	C
MECHANICAL TAPPER		B	
ELECTRICAL TAPPER		B	
BOND ANALYZER	A	B	C

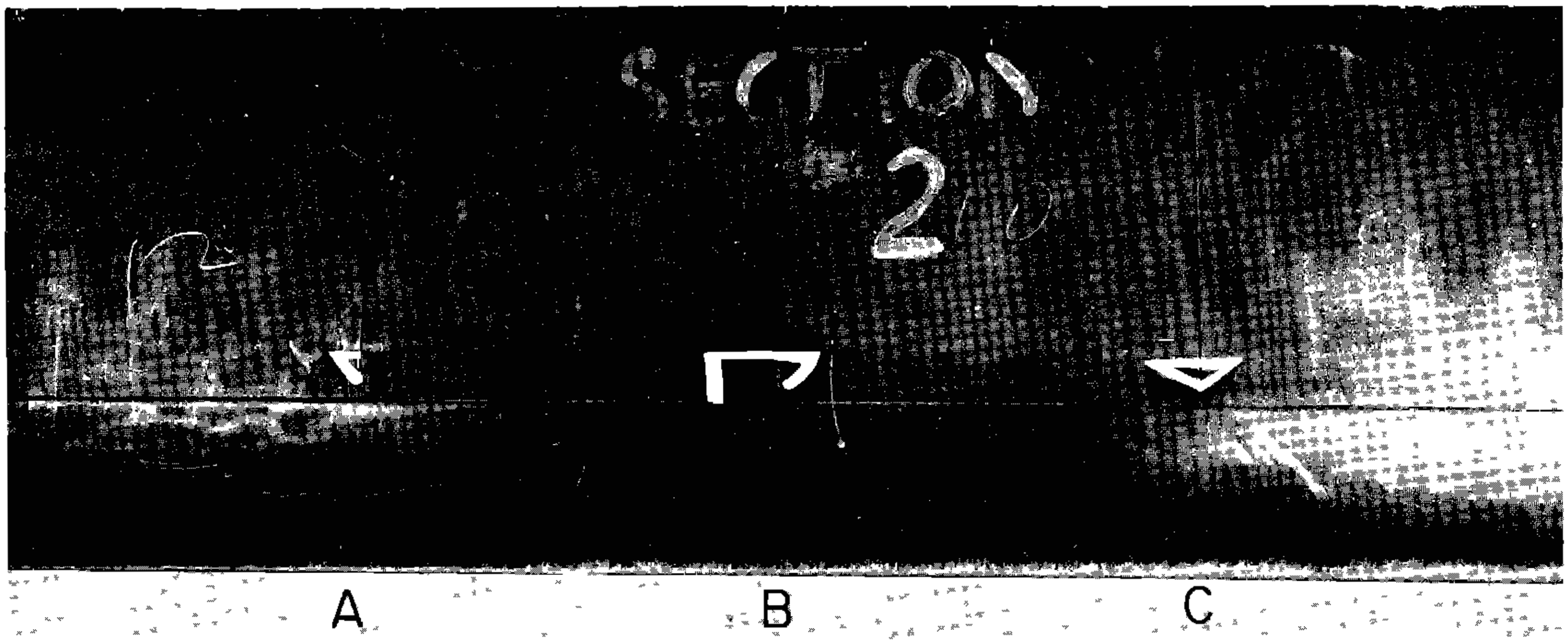


FIG 9 BLADE SECTION 2 SHOWING RESULTS OF TAPPING TESTS

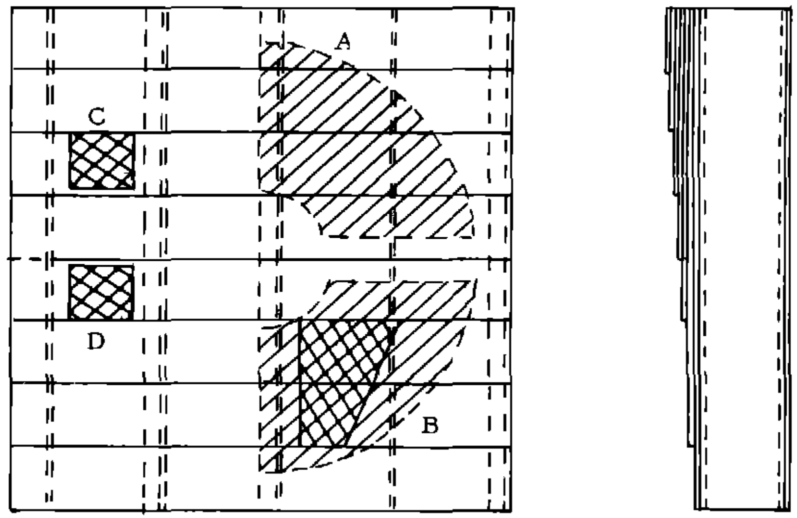
RESULTS OF TESTS

METHOD	VOIDS DETECTED
COIN TAPPING	OUTLINED BY SOLID LINE
MECHANICAL TAPPER	SHOWN BY ▨
BUZZER	SHOWN BY ▧

NOTE ALL VOIDS IN UPPER ADHESIVE LAYER

FIG 10 BLADE SECTION 3 LARGE MULTILAMINATE SPAR SHOWING RESULTS OF TAPPING TESTS

METHOD OF TESTING	VOIDS DETECTED
TAPPING	B
MECHANICAL TAPPING	NONE
BUZZER SYSTEM	NONE
STUB METER	B, C, AND D



NOTE SINGLE-HATCHED AREA INDICATES ACTUAL VOID

DOUBLE-HATCHED AREA INDICATES LOCATED VOID BENEATH UPPERMOST ADHESIVE LAYER

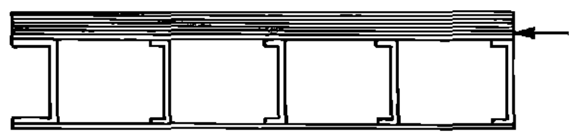
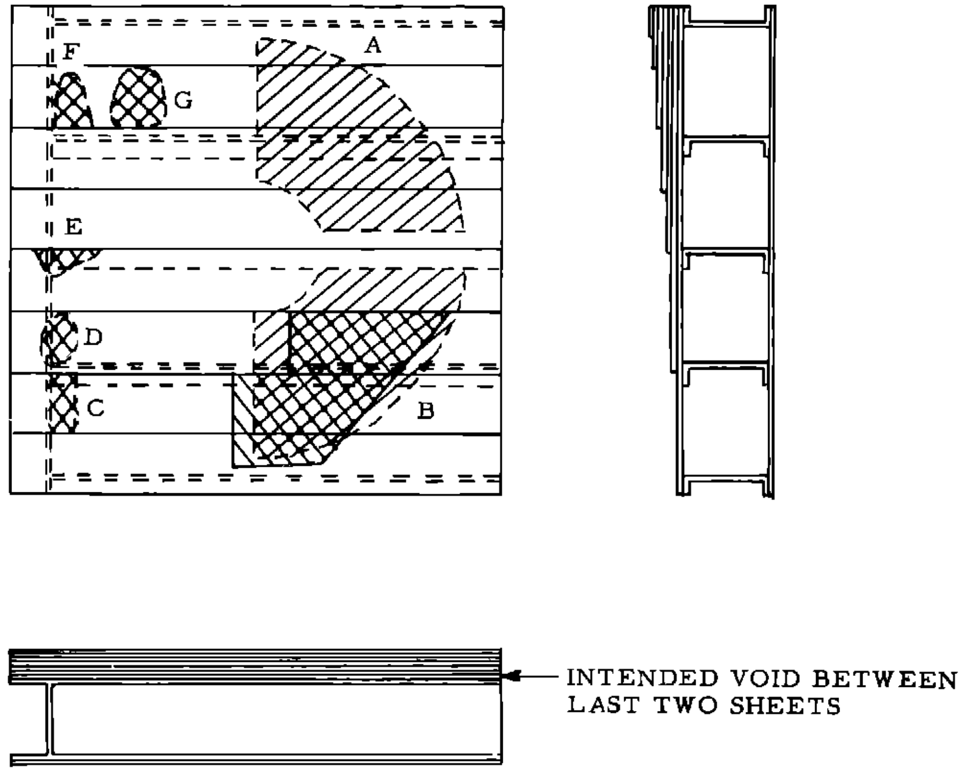


FIG 11 PANEL 1 SHOWING VOIDS DETECTED

METHOD OF TESTING	VOIDS DETECTED
TAPPING	B
MECHANICAL TAPPING	C, D, E, AND F
BUZZER SYSTEM	NONE
STUB METER	B, C, D, E, F, AND G



LOW STRENGTH BONDS

NOTE

SINGLE CROSS HATCHED AREAS A AND B SHOW LOCATION OF ACTUAL VOID

DOUBLE CROSS HATCHED AREAS SHOW LOCATION OF VOIDS FOUND UNDER UPPERMOST SHEET.

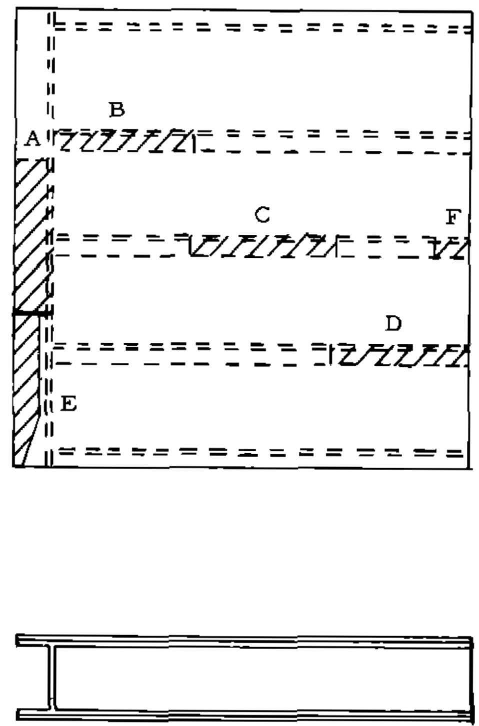
FIG 12 PANEL 2 SHOWING VOIDS DETECTED

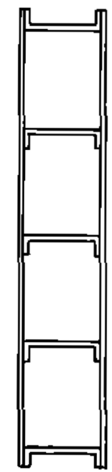
PANEL NO 3

METHOD OF TESTING	VOIDS DETECTED
TAPPING	A, B, C, D, AND F
MECHANICAL TAPPING	A, B, C, D, AND F
BUZZER SYSTEM	A, C, AND D
STUB METER	A, B, C, D AND F

PANEL NO 4

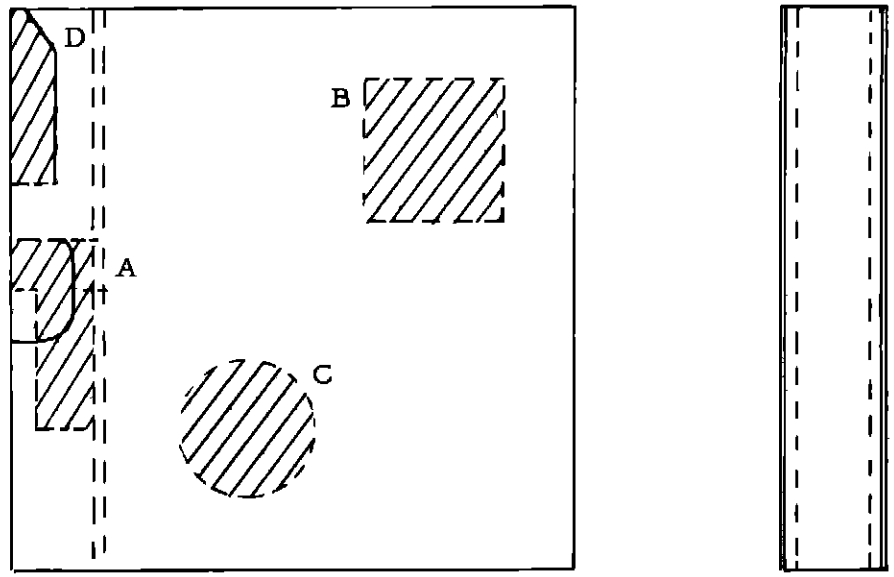
METHOD OF TESTING	VOIDS DETECTED
TAPPING	A, B, C, D, AND E
MECHANICAL TAPPING	A, B, C, D, AND E
BUZZER SYSTEM	A, B, C, AND D
STUB METER	A, B, C, D, AND E





NOTE VOID F IS ON PANEL NO 3
VOID E IS ON PANEL NO 4

FIG 13 PANELS 3 AND 4 SHOWING VOIDS DETECTED



METHOD OF TESTING	VOIDS DETECTED
TAPPING	PART OF A, B, C, AND D
MECHANICAL TAPPING	A, B, C, AND D
BUZZER SYSTEM	B AND C
STUB METER	A, B, C, AND D

FIG. 14 PANEL 5 SHOWING VOIDS DETECTED

METHOD OF TESTING	VOIDS DETECTED
TAPPER (UPPER PART)	A, B, C, D, E, AND F
MECHANICAL TAPPING	A, B, C, D, AND F
BUZZER SYSTEM	B, C, D, E, AND F
STUB METER	A, B, C, D, AND F

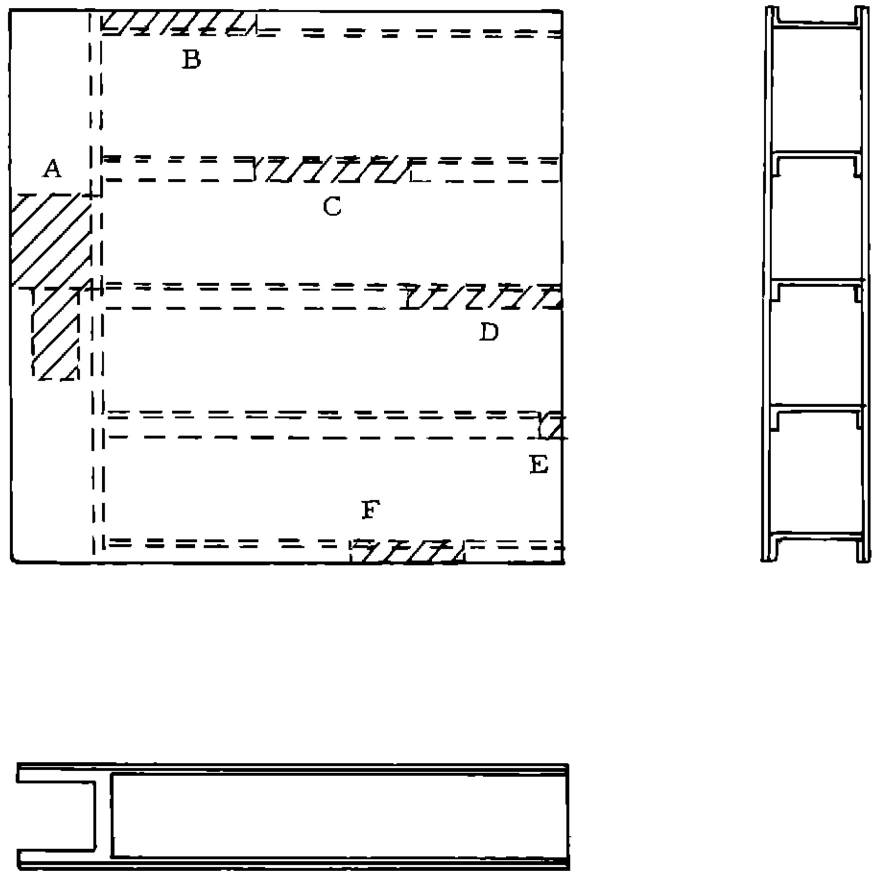


FIG. 15 PANEL 6 SHOWING VOIDS DETECTED

METHOD OF TESTING	VOIDS DETECTED
TAPPING	B, C, AND D
MECHANICAL TAPPING	B, C, AND D
BUZZER SYSTEM	NONE
STUB METER	B, C, AND D

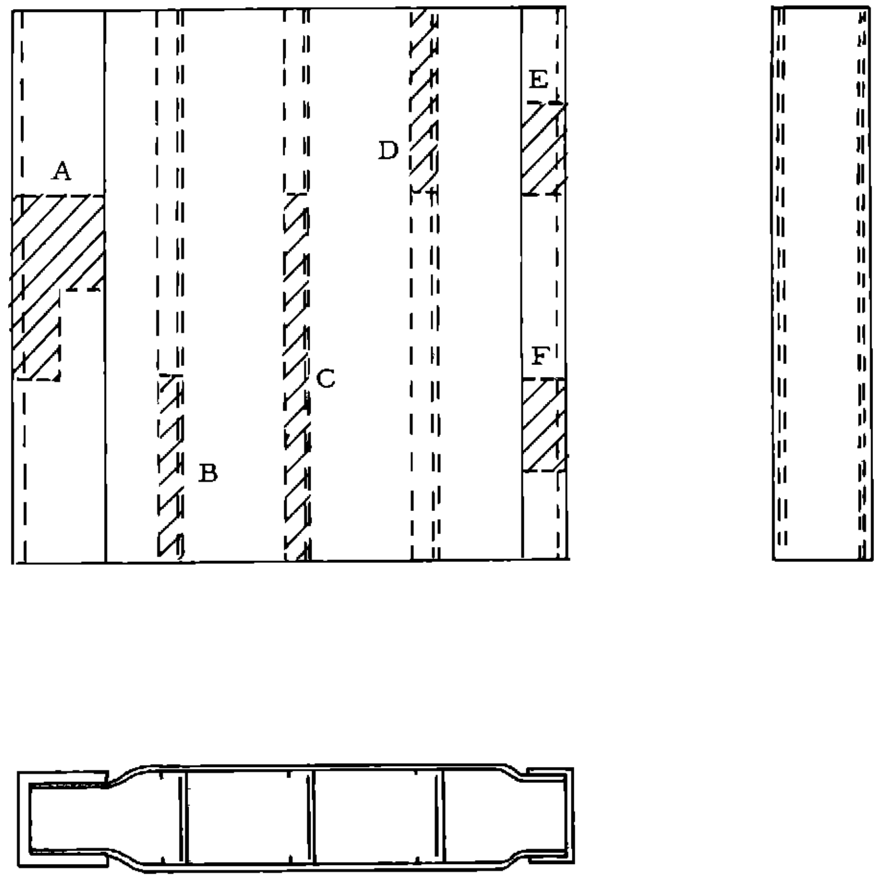


FIG 16 PANEL 7 SHOWING VOIDS DETECTED

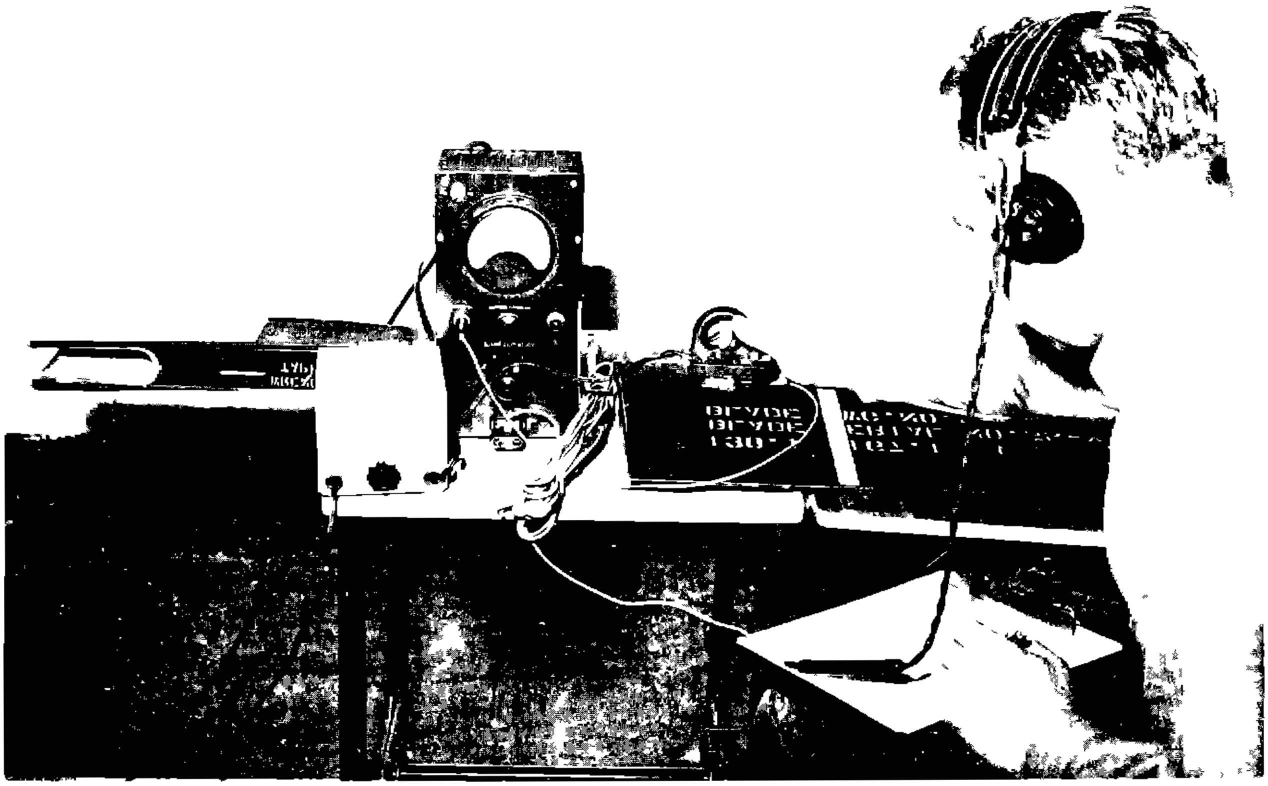


FIG 17A MODEL 1 TAPPER WITH EXPERIMENTAL PICKUP

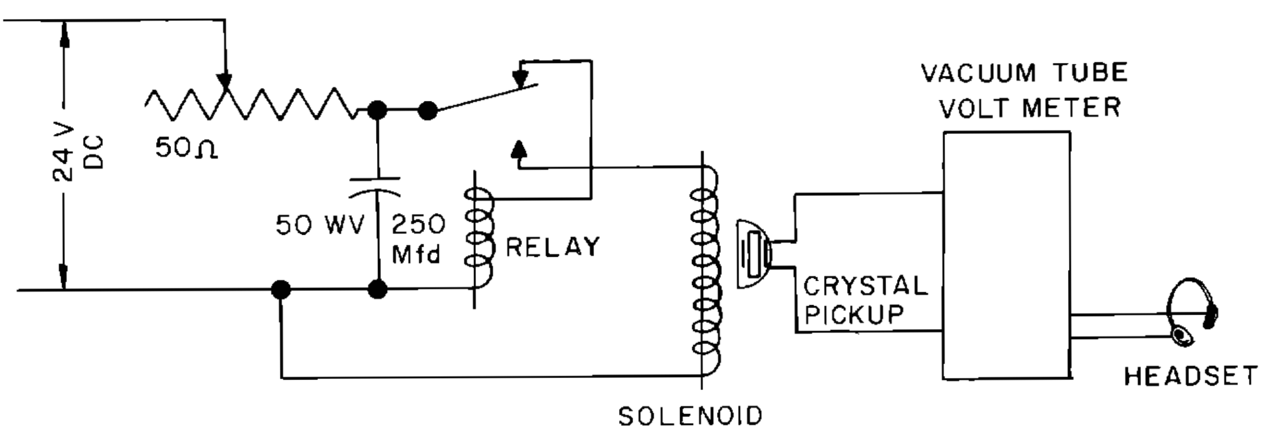


FIG 17B SCHEMATIC WIRING DIAGRAM

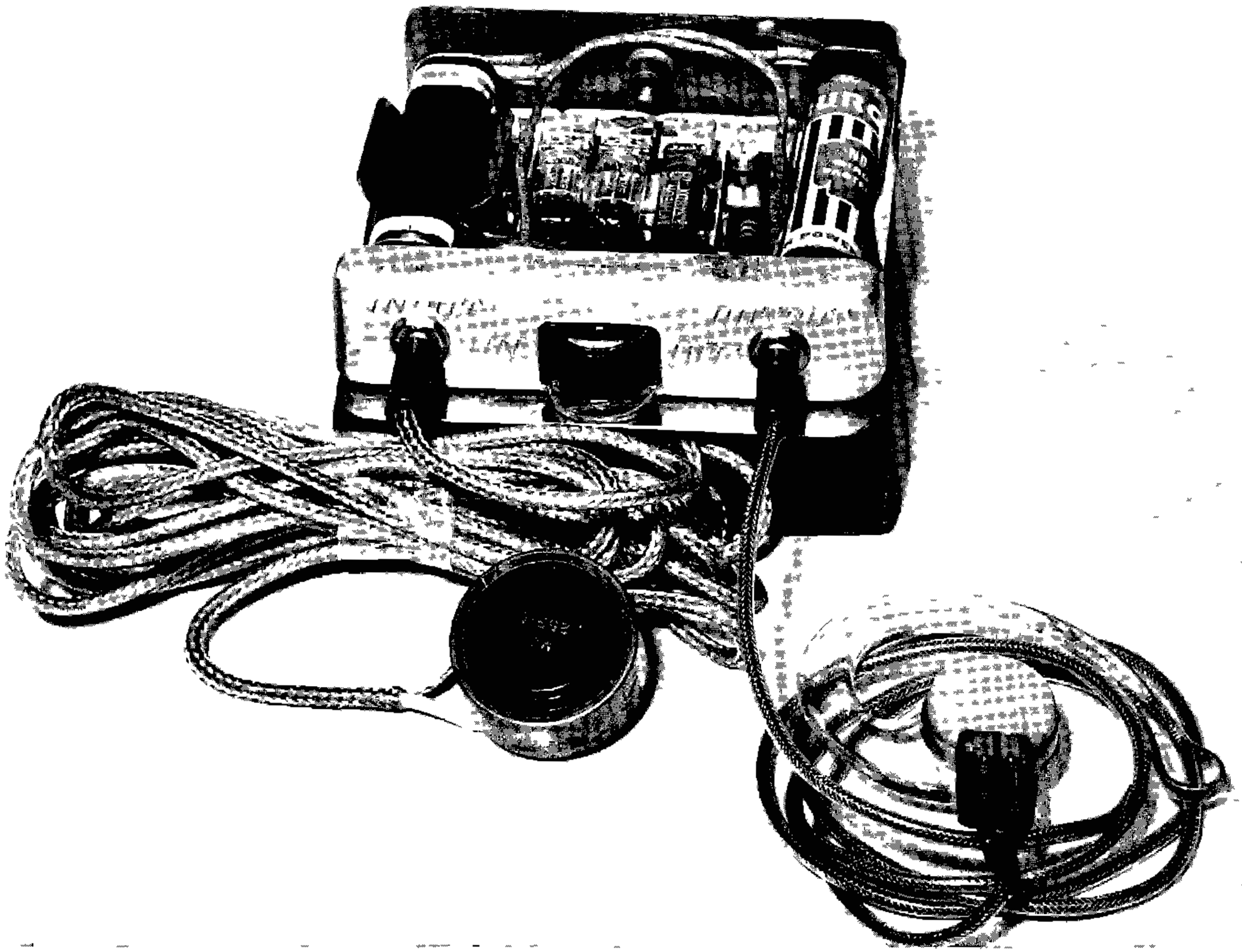


FIG. 18 PORTABLE AMPLIFIER WITH EARPHONE AND DYNAMIC PICKUP MICROPHONE

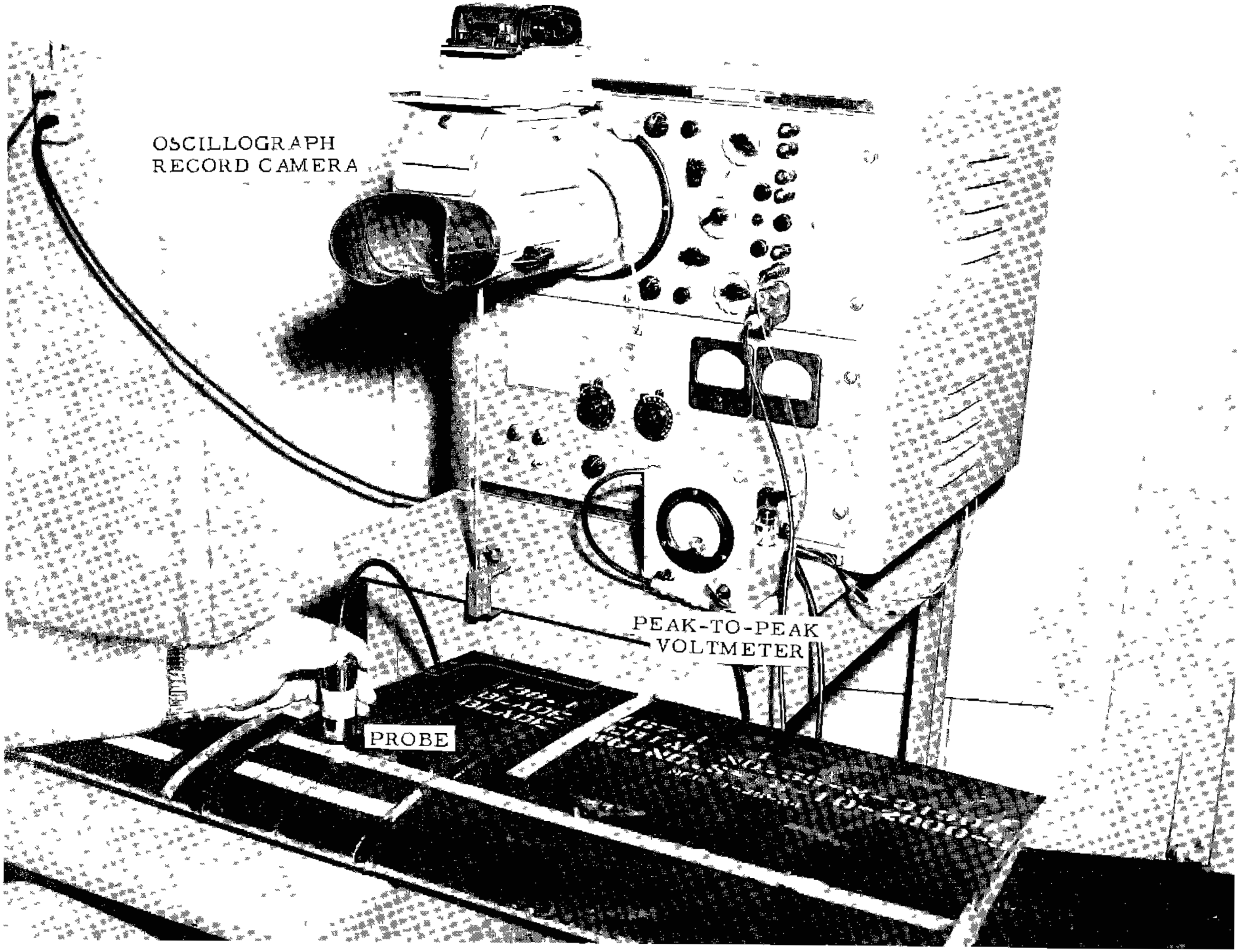


FIG 19 DUMONT ULTRASONIC BOND ANALYZER WITH PEAK-TO-PEAK VOLTMETER

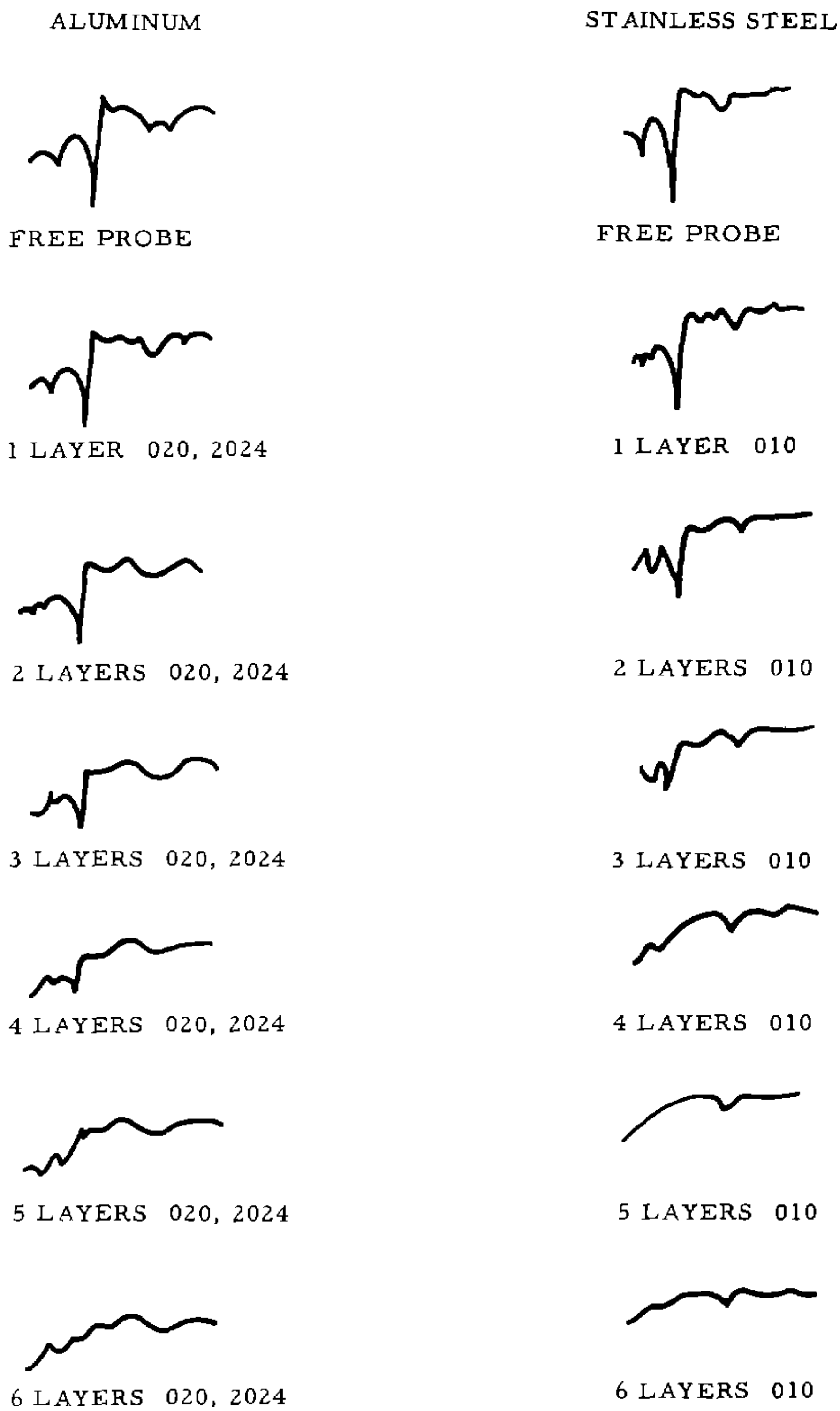
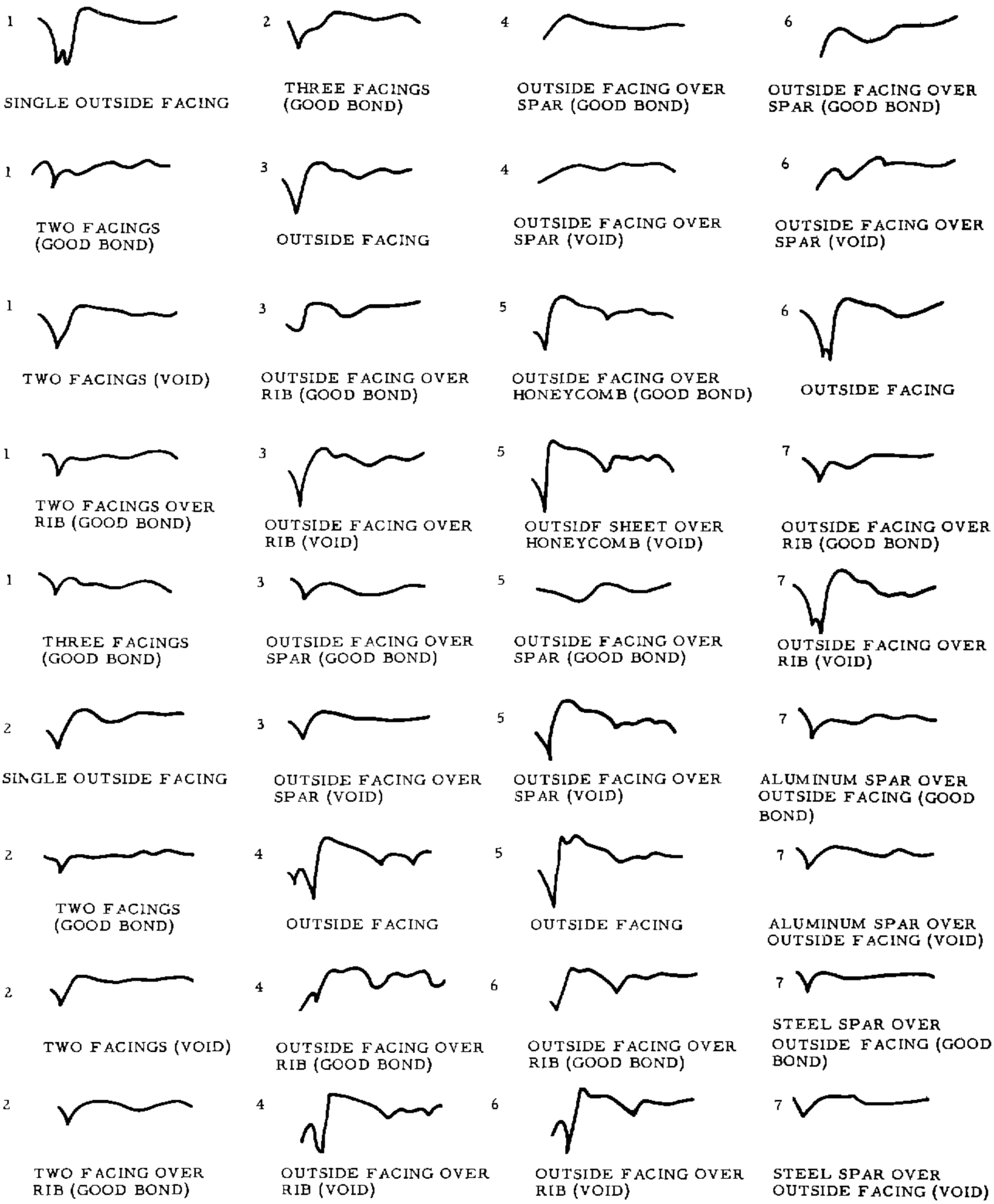


FIG 20 BOND ANALYZER TRACES FROM OIL COUPLED SHEETS SHOWING DECREASE IN AMPLITUDE WITH INCREASE IN MASS DRIVEN, 1 X 3/8 PROBE



NOTE NUMBERS INDICATE THE TEST PANEL NUMBER

FIG 21 BOND ANALYZER TRACES FROM TEST PANELS, 1 X 3/8 PROBE

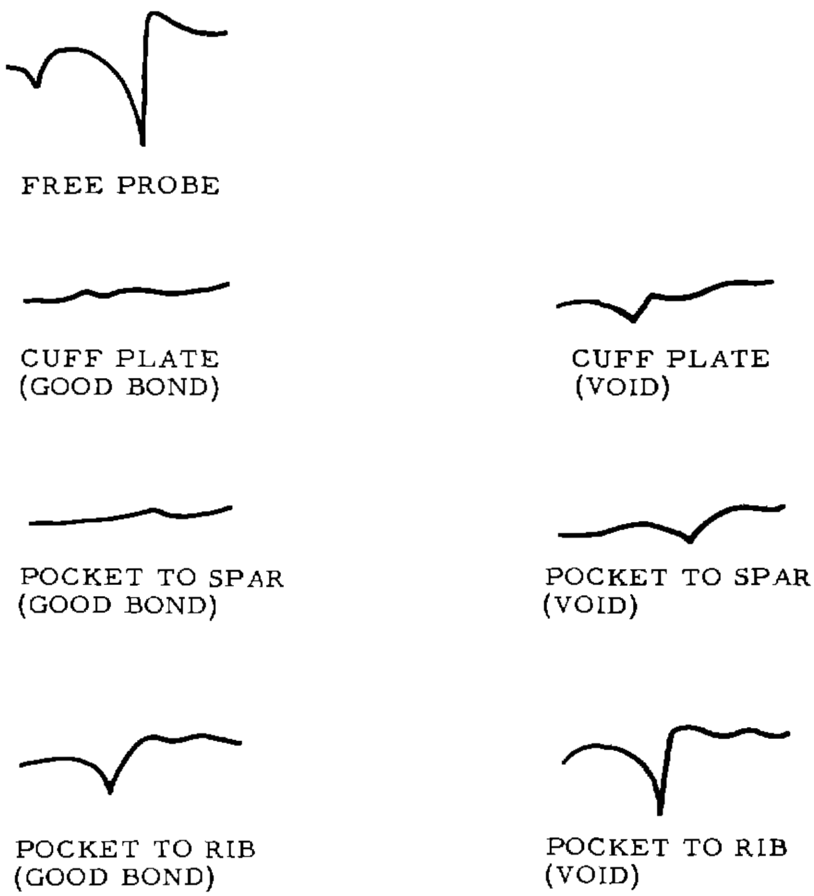


FIG 22 BOND ANALYZER TRACES FROM ROTOR BLADE SAMPLE, 1 X 3/8 PROBE

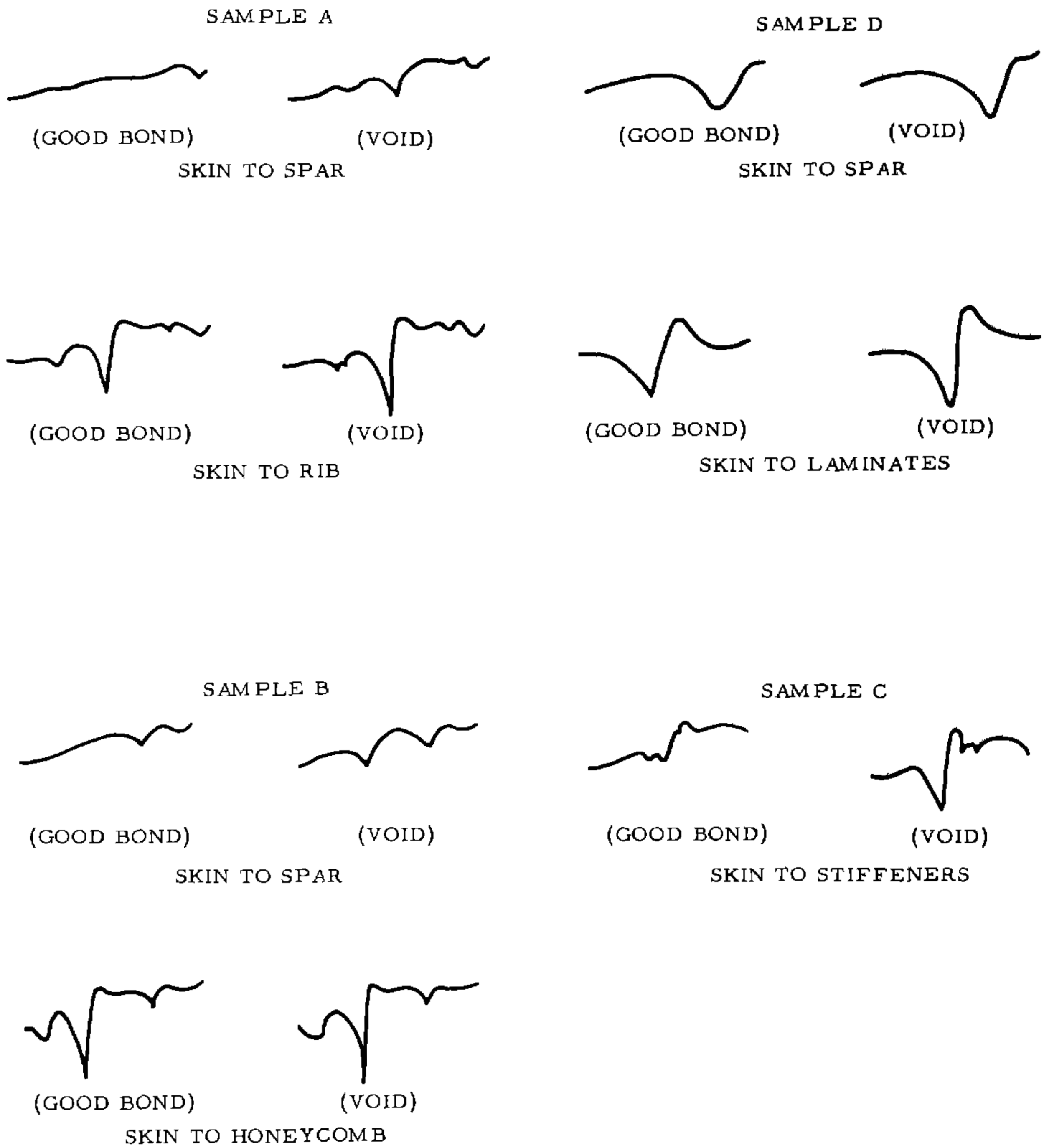


FIG 23 BOND ANALYZER TRACES FROM ROTOR BLADES, 1 X 3/8 PROBE

FIG 24A PHOTOGRAPH OF HELICOPTER BLADE SECTION 1 SHOWING RESULTS OF DYE PENETRANT TEST

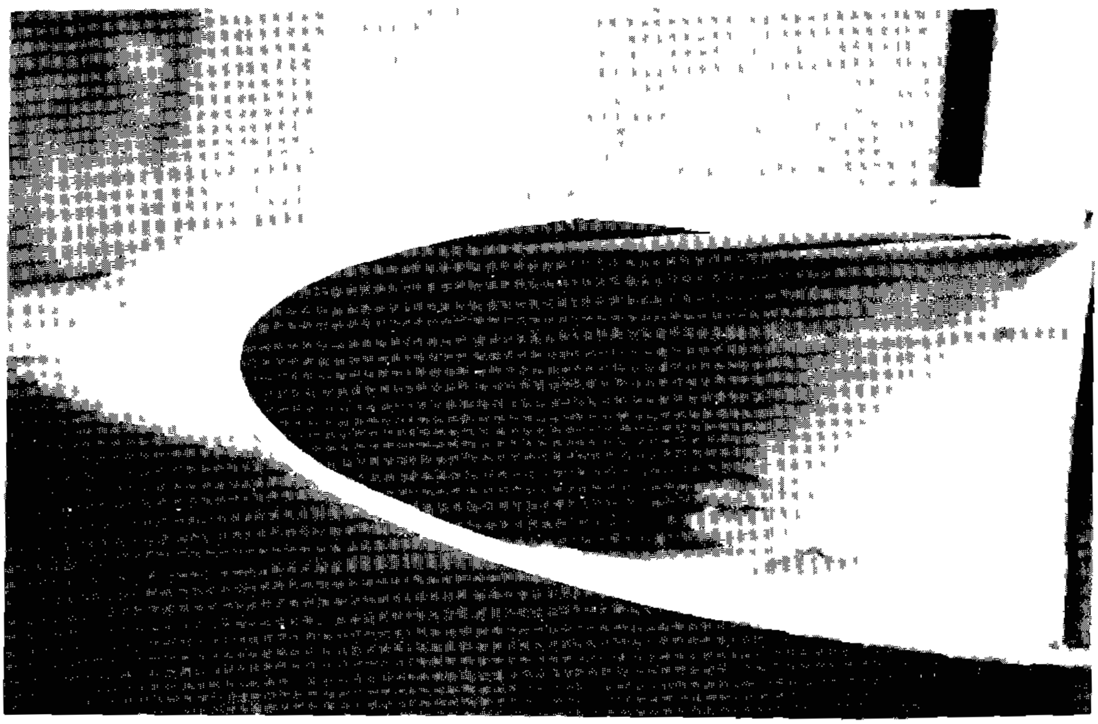


FIG 24B PHOTOGRAPH OF HELICOPTER BLADE SECTION 3 SHOWING RESULTS OF DYE PENETRANT TEST

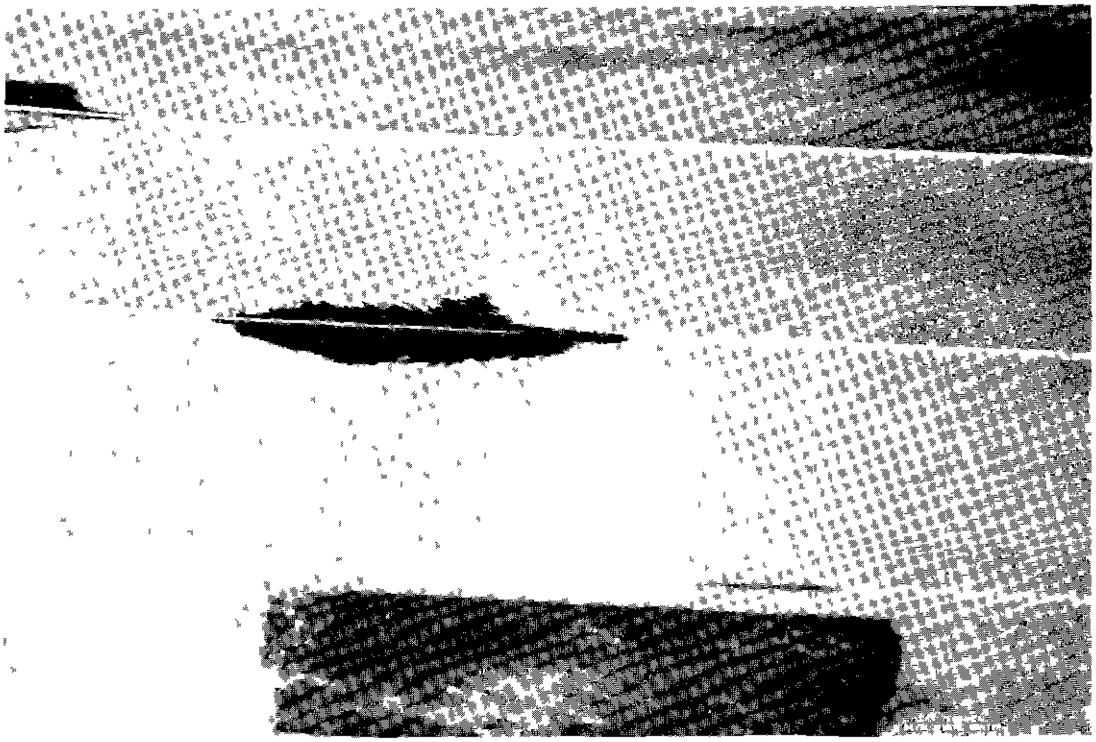


FIG 25A PHOTOGRAPH OF PANELS SHOWING RESULTS OF DYE PENETRANT TEST

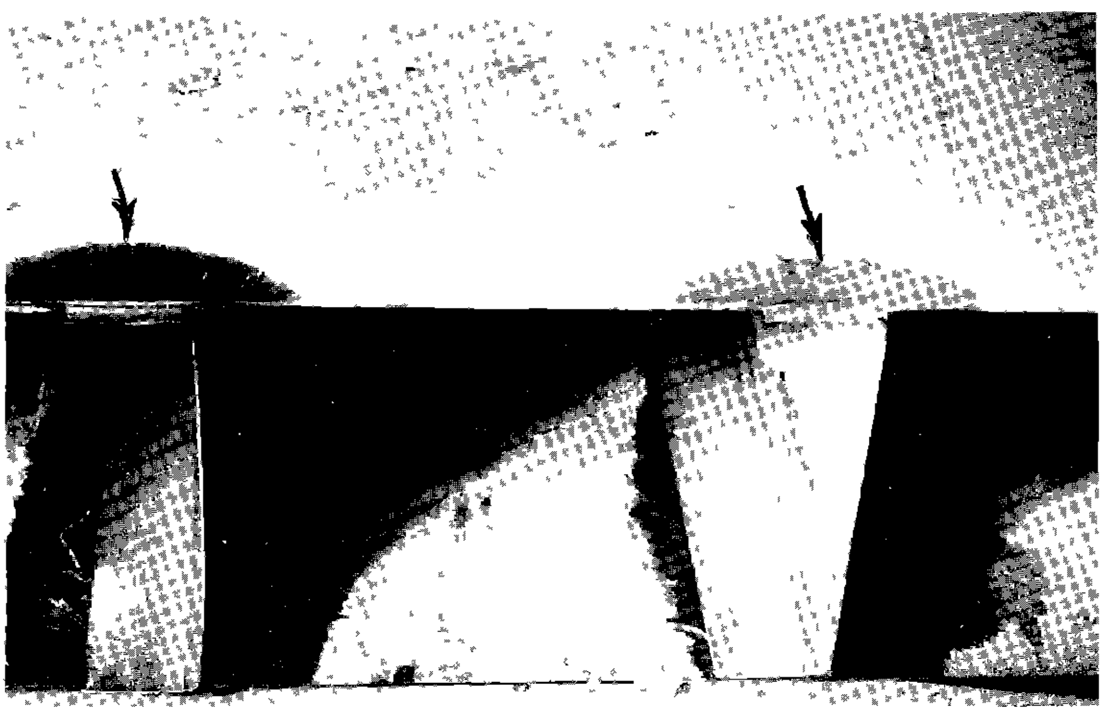


FIG 25B PHOTOGRAPH OF PANELS SHOWING RESULTS OF DYE PENETRANT TEST

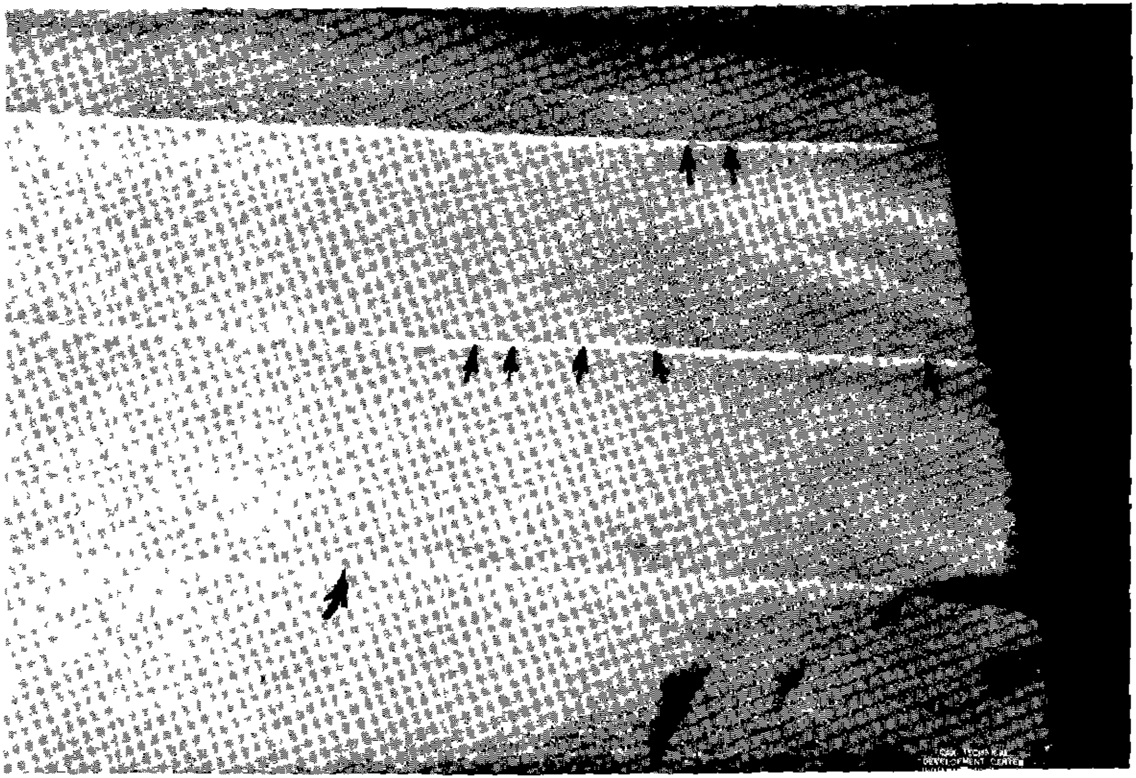


FIG. 25C PHOTOGRAPH OF PANELS SHOWING RESULTS OF DYE PENETRANT TESTS