DIFFUSION BONDING AND ITS APPLICATION TO MANUFACTURING

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One of the most important problems in manufacturing is how to join metal parts. In this presentation we discuss a joining process, diffusion bonding, that is receiving increasing attention from design and manufacturing engineers because of its advantages over more traditional joining methods. These advantages and its relatively few disadvantages will be outlined, along with some applications and the theory behind the process.

Let's start with the definition of diffusion bonding and the principles involved. The joining methods for metals can be classified as mechanical fastening, chemical or adhesive joining, and metallurgical joining, which in turn can be subdivided under the headings of soldering, brazing, welding and diffusion bonding. We define diffusion bonding as the unit operation of joining two pieces of the same or different alloys by making clean smooth surfaces on the metal parts, bringing them together in an inert or reducing atmosphere at a pressure and temperature high enough to exceed the yield point of the metal at the surface asperities, and holding them under these conditions until a bond of the desired strength is formed.

A bonding aid may or may not be used. If a solid bonding aid is used its functions are to increase the contact areas at the faying surfaces, to prevent oxidation of the surfaces to be joined, to provide a driving force for diffusion, and in some cases to prevent formation of intermetallic compounds. If a liquid bonding aid is used, its functions are to fill voids at the interface, to displace oxide films, to provide a driving force for diffusion and to accelerate diffusion.

Figure 1 illustrates coalescence by diffusion. Consider the problem of bonding two dissimilar alloys. In the surface of each alloy we have grains or small crystals in which the atoms are arranged in a regular fashion. When the surfaces of these grains are brought together under pressure and are heated, the atoms from one grain diffuse into the lattice of the other grain, and vice versa. We then have a situation as shown on the right side of the figure.

Figure 2 shows the pressure-temperature-time relationship for diffusion bonding. The upper limit on the temperature axis is, of course, the melting point of the lower melting of the two alloys. We can obtain sound joints so long as our pressure-temperature-time conditions are such that we are on or above the curved plane shown in this diagram.

Three stages can be discerned in diffusion bonding. Figure 3 shows the three stages for aluminum alloy 5052. In all three cases the workpiece has been heated at 1080°F. The photomicrograph on the left shows Stage 1, after heating for half an hour. Here we see that diffusion bonding has occurred only at the asperities. In Stage 2, obtained after heating for an hour, we see that half of the apparent surface area has become bonded. In Stage 3, after heating for two hours, the two parts are completely bonded.

Figure 4 shows six laminates of aluminum alloy diffusion bonded together, approaching Stage 3. The arrows indicate the original bond line.

Figure 5, taken from the literature on the subject, shows what happens when titanium parts are heated in contact under a pressure of 1000 pounds per square inch. On heating at 1400°F, only 75 percent of the contact area is bonded after 30 minutes. At 1500°F we reach 75 percent bonded condition in about 8 minutes but have not yet reached complete bonding after 30 minutes. On heating at 1600°F we obtain complete bonding after only 15 minutes. Here again, we see the relationship among time, temperature, and pressure, as they affect bond formation.

Many terms have been used to describe diffusion bonding. These include solid state bonding, cold welding, deformation bonding, thermocompression bonding, gas pressure welding, explosive bonding, extrusion bonding, friction welding, ultrasonic welding, crimping, and roll bonding.

Let's consider some typical applications of diffusion bonding. Figure 6 shows various types of hardware that have been made in our Laboratories by diffusion bonding. In some cases we bond below the yield point of the metal and in other cases above the yield point. We bond below the yield point in cases where we want to maintain accurate dimensions and tolerances, e.g., in making flueric elements and integrated circuits, miniature heaters, gas handling devices for space experiments, hydraulic devices, and heat exchangers. We can bond above the yield point in such cases as connecting cable wires to connectors, or in making shells for transpiration-cooled turbine blades.

In most cases, diffusion bonding is used as one unit operation of a multi-step manufacturing process. We have used one such process in making the various kinds of hardware described earlier. We call it the photoetched bonded laminate process and at this point I would like to describe the steps involved in it. We start by cutting an artmaster on a mechanized drafting machine. The artmaster is prepared from the engineering drawing of the part to be made and is cut on a two-part laminated plastic sheet. One part of the sheet is clear and water-white, the other part being clear and red in color. The artmaster is inspected for dimensional accuracy and then is reduced photographically on an engineering camera. If many images of the same pattern are desired they can be made on a special step and repeat machine. The end product of these operations is the tooling of the work, called an envelope transparency. It consists of two photographic films bearing the image of the pattern to be made, fastened together in registry.

While the tooling is being prepared, sheet metal strips are also being made ready. In fact, they are made into photographic plates by applying a photosensitive lacquer. Application may be by spraying, roller coating, or dip coating. The lacquer is dried, the metal sheets are sandwiched between two parts of the envelope transparency, and the assembly is exposed on both sides to ultraviolet light. The light passing through the transparent parts of the envelope cause the lacquer to harden and become insoluble. The lacquer under the opaque parts of the transparency remains soluble in organic solvents. After exposure, therefore, the plate is developed by immersion in an organic solvent. After a period of time, parts of the metal sheet will be bare and other parts will be coated with lacquer in the desired pattern. The coated sheet is now placed in a spray etcher. The bare metal is attacked and removed by the etchant and the metal under the lacquer remains in place. The etched sheets come through a rinse chamber and proceed out the other end of the spray etcher. The lacquer is then removed with a stripping agent. Figure 7 shows a metal sheet after etching. It contains the pattern for a signal processing network of flueric elements.

In the next step the laminates are stacked and aligned in a laminar flow hood, using reasonable precautions to keep the parts clean. The assembly is then fastened together in a thermal expansion press. Finally, it is placed in a vacuum furnace or in a furnace with a hydrogen atmosphere and diffusion bonded. After removal from the furnace the parts are then tested.

The photoetched bonded laminate process has a number of advantages. First, we can make intricate, close-tolerance passages in single blocks of metal. Second, we can make structures with this process which can not be made in any other way. Third, we can use alloys selected for resistance to service environments rather than for ease of fabrication. Fourth, we can use low cost tooling. Fifth, we can provide quick delivery, since the tooling is relatively easy to make. Sixth, the process is capable of high quantity production. Seventh, it requires only a low capital equipment investment.

Summarizing the steps for the diffusion bonding operation in this process: we have only to smooth the faying surfaces, clean them, apply the bonding aid (if one is used), clean the sheets again, assemble the piece parts, and heat under pressure.

Figure 8 shows an array of identical patterns used in making flueric elements. With a stack-up of such laminations we can make forty-five or more elements at a time.

Figure 9 shows a radiograph of a flueric integrated circuit, an adder for an air data computer. This is a single block of metal measuring about 4 by 5 inches and about 1/8 of an inch in thickness, made from stainless steel sheets. It contains extremely intricate passages in which close tolerances must be maintained. It is difficult to think of any other process by which this device can be made from metal.

Figure 10 shows a cross-section through the adder, which was made of diffusion bonded stainless steel. The arrows indicate the original bond lines. Note how the grain boundaries have crossed these original lines.

Figure 11 shows an integrated circuit for a bleed control used as part of an aircraft engine fuel control. It shows the various types of laminates used and what the final stack-up looks like. Figure 12 shows the bleed control or fluidic computer in place.

Figures 13, 14, and 15 show photomicrographs of some other alloys which have been diffusion bonded in our Laboratories. They include Inconel 600, diffusion-bonded TD-Nichrome, and diffusion-bonded chromium. In the case of diffusion-bonded TD-Nichrome we see one of the advantages of diffusion bonding, namely, that we do not destroy the dispersed oxide structure in making the bond. In the case of diffusion-bonded chromium, the black spots are particles of magnesium oxide added to the alloy to enhance its ductility.

We have also made heaters and heat exchangers by this process. Figure 16 shows on the right side how we make heater elements by etching Nichrome sheets. The arrow on the left illustrates how the elements are coated with aluminum oxide insulation, sandwiched into a frame, and then covered with base and cover plates which are bonded together to make the complete heater. Figure 17 shows the reaction bed for an oxygen generator made by essentially the same process. Figure 18 shows six aluminum tubes diffusion bonded together in a heat exchanger configuration.

We have used miniature heaters in making devices for space experiments. Figure 19 shows laminations that have been used for making diffusion bonded gas handling columns. Tracing through the arrow you can see the various steps used in making the final column which is shown in the upper right hand corner. The tabs extending from the sides are the contacts for the heaters built into the column. Figure 20 shows a gas chromatograph designed and built for space experiments. The lower part shows the various laminates used in making it. The first and fourth laminates have spiral half-cylinders etched into them. The second laminate is a frame for one of the heating elements which is the third item shown on the lower part. The complete assembly is shown on the upper part of the figure. Compare the size of this chromatograph with that of a laboratory gas chromatograph (Figure 21). The comparable part is the oven shown in the middle.

Now let us turn to some parts made by diffusion bonding above the yield point. The first example is cable wire-connector joining. In assembling an electrical cable one of the main problems is how to join the wires to the contacts. Normally this is done by soldering or crimping. With the experimental yield point bonder shown in Figure 22 we have demonstrated that these joints can also be made successfully by diffusion bonding. When we operate above the yield point of the metal only half a second is required to make one of these joints. Figure 23 shows a photomicrograph of a joint prepared by yield point bonding of copper wire to a gold-plated brass contact.

We have also made shells for transpiration-cooled turbine blades by diffusion bonding. Figure 24 shows an example of one of our materials called Poroloy^{R}. It is made by winding flattened wire on a mandrel according to a predetermined pattern and then bonding the wires together. The conical or cylindrical structures so obtained can be cut open and made into sheet metal; from this, porous shells, such as are shown on the right in Figure 25, can be made in air foil form, ready for fitting onto the structure shown on the left. Figure 26 shows a photomicrograph of the bonds in Poroloy made from an alloy called GE 1541. These are in the as-fabricated condition and illustrate both the nature of the bond and the nature of the pores. Figure 27 shows bonds in Poroloy made from the same alloy after it has been oxidized in air at 2000°F. As you can see, the pores are still open, the oxide is adherent, the bonds are sound. One of the virtues of the alloy selected is that the oxide film is protective and adherent. It does not spall or flake off and thus plug the pores of the material. Figure 28 shows the air flow in Poroloy before and after oxidation, and as you can see the permeability drops initially to about 80 percent of its initial value and then stays constant for as long as 600 hours of exposure at 1800 to 2000°F. This work has been described in a recent NASA report.

Figure 29 shows some of the alloys that have been bonded in our Laboratories. Note that they include heat-resistant alloys and aluminum alloys, both of which form adherent, refractory, stable, high-melting oxides. The problem in joining these alloys, of course, is to remove the oxide film and to keep it off until the bond is formed.

Now let's consider the advantages of diffusion bonding. First of all there are advantages insofar as mechanical properties are concerned. We can join most types of alloys. The joint is as strong as the parent metal. The final part has uniform response to heat treatment, and in general we can obtain better properties in the joint with active metals such as titanium.

There are also advantages from a chemical standpoint. There are no dissimilar metals introduced into the joint as is done in brazing. The joint is stress-free. Both of these are advantages if the part is exposed to a corrosive environment.

There are advantages for the designer in using diffusion bonding. He can join dissimilar metals. He can make thick sections by building up laminations, or he can join thick sections. The process is ideally suited to joining many thin sheets together and can also be used to join tubes and make various complex shapes. No weight is added as is the case when fasteners are added. Diffusion bonded joints are compatible with coatings, an important consideration particularly when the use of heat-resistant coatings is contemplated. Tolerances, of course, can be readily maintained.

The manufacturing engineer, too, finds many advantages in use of this process. He gets stress-free, ductile joints. He can make many joints at one time. Unlike brazing, he can recycle if he uses diffusion bonding. No finishing operations are required, such as flash removal. The process lends itself to mechanization.

Here we present some guidelines for design and manufacturing engineers. Diffusion bonding should be considered if we have work-hardened, solution-strengthened, precipitation-hardened, dispersion-strengthened, or fiber-strengthened alloys to be joined and the properties of the alloys must be retained. It should be considered when structures with large cross sections must be made, having fine grains throughout, or when active metals such as titanium must be joined, or when dissimilar metals must be joined without forming intermetallic compounds. Diffusion bonding should be used when dissimilar metal combinations such as brazed joints can not be used because of the danger of corrosion, or when the joints must be coated, especially for high temperature service. It should be used when stress-free joints are required, or when reduced assembly weight is desired. Diffusion bonding is a good method to use when many lap joints are required in the assembly, especially laminations, or when structures must be made with intricate, close-tolerance channels or cavities. It should be used when weld structure spatters are not permissible, or when close tolerances must be held in the joint region.

Summarizing then, in its simplest form diffusion bonding is accomplished by placing clean metal surfaces together under a sufficient load and heating. The natural interatomic attractive force between atoms transforms the interface into a natural grain boundary. Therefore, in principle, the properties of the bond area are identical to those of the parent metal. Other advantages of diffusion bonding over conventional methods of bonding include freedom from residual stresses, excessive deformation, foreign metals, or changed crystal structures. Theoretically, any metal or metal combinations can be bonded. In our Laboratories, stainless steels, nickel-base superalloys, and aluminum alloys have all been successfully joined. Complex hardware, including integrated flueric devices, jet engine servovalves, and porous woven structures have been fabricated. The processing involved has been discussed, along with such theoretical considerations as the role of metal surfaces, the formation of metal contact junctions, and the mechanisms of material transport in diffusion bonding. Guidelines for utilizing the theoretical principles in joining operations were also presented.

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COALESCENCE BY DIFFUSION

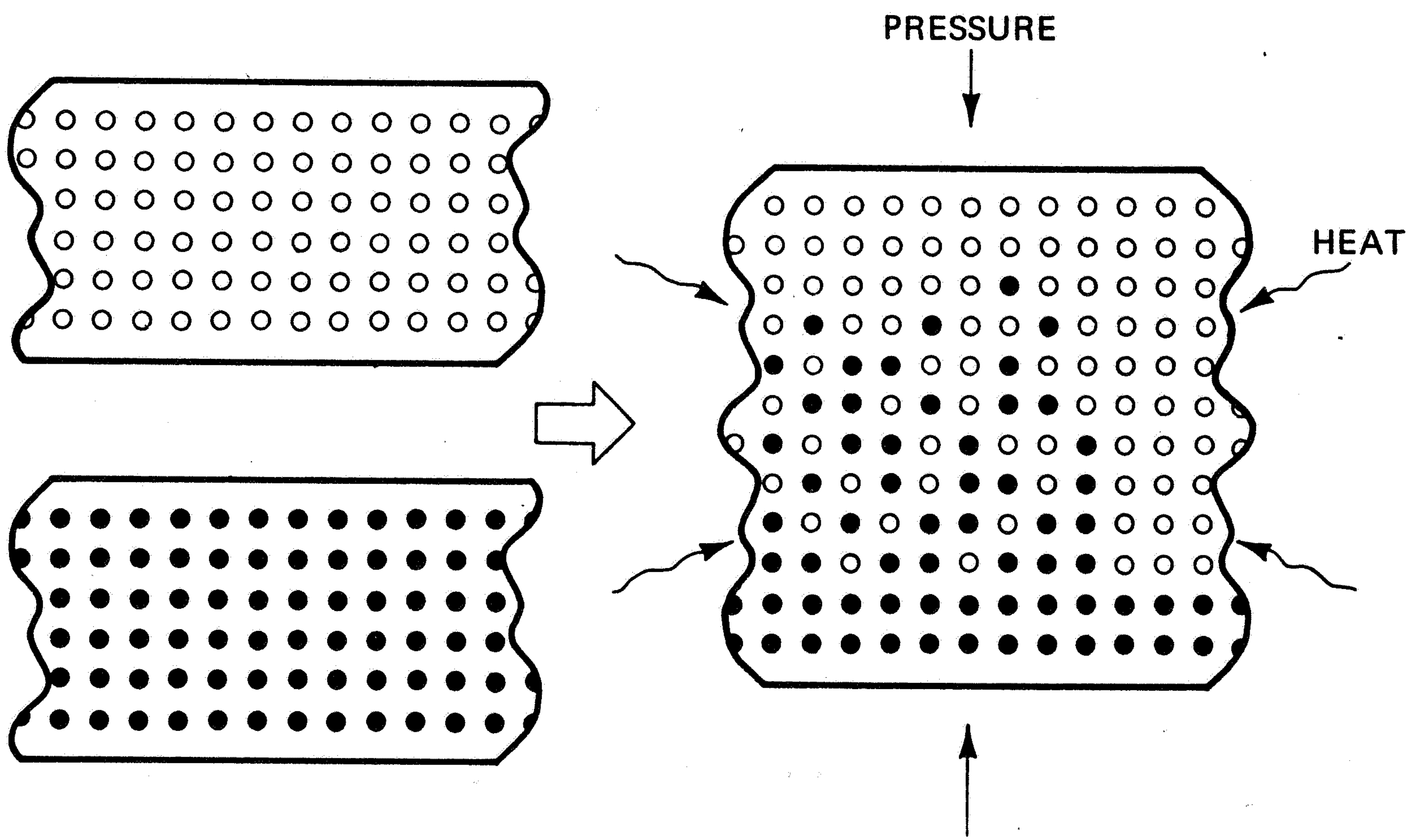


Figure 1.

PRESSURE-TEMPERATURE-TIME RELATIONSHIP FOR DIFFUSION BONDING

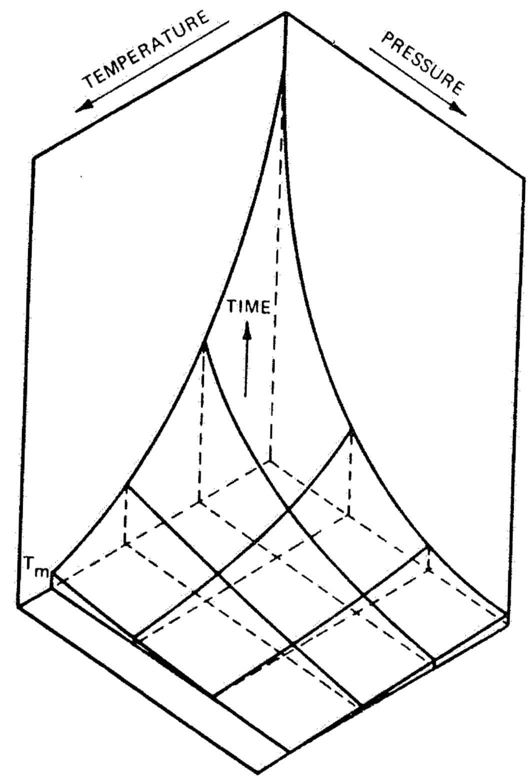
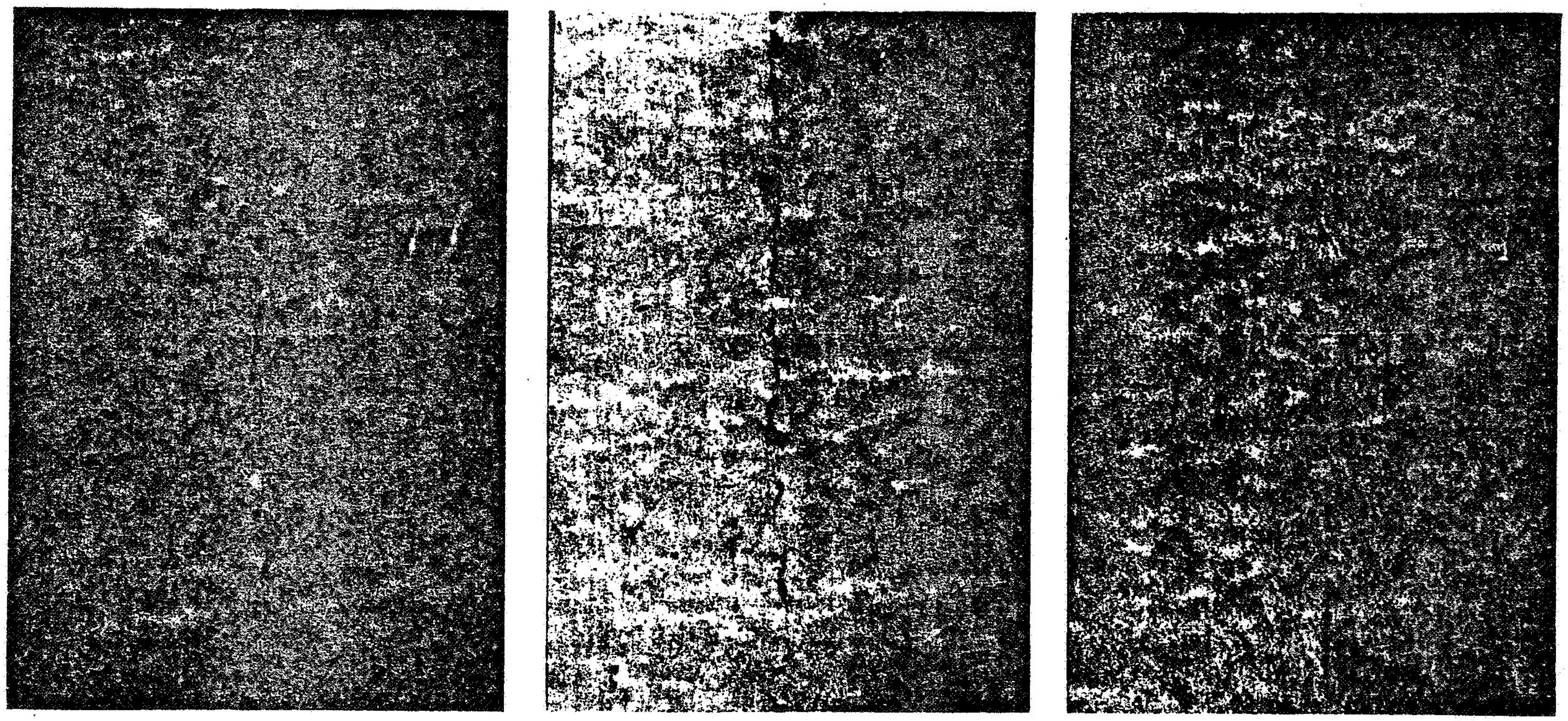


Figure 2.

THREE STAGES OF DIFFUSION BONDING
(Aluminum Alloy 5052)



STAGE I	STAGE II	STAGE III
1/2 HR. AT 1080°F (500 X)	1 HR. AT 1080°F (500 X)	2 HRS. AT 1080°F (500 X)

Figure 3.

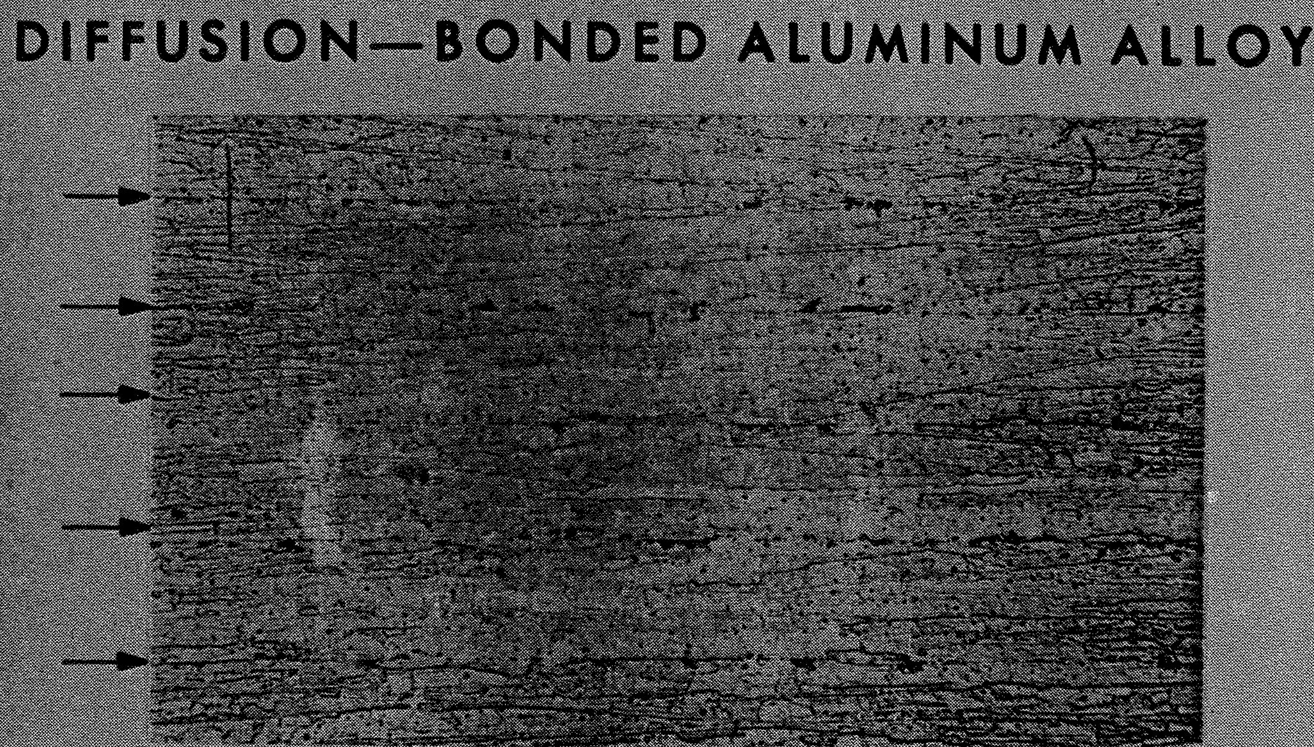


Figure 4. - Diffusion-bonded aluminum alloy (arrows indicate bonding interface).

BONDING TITANIUM

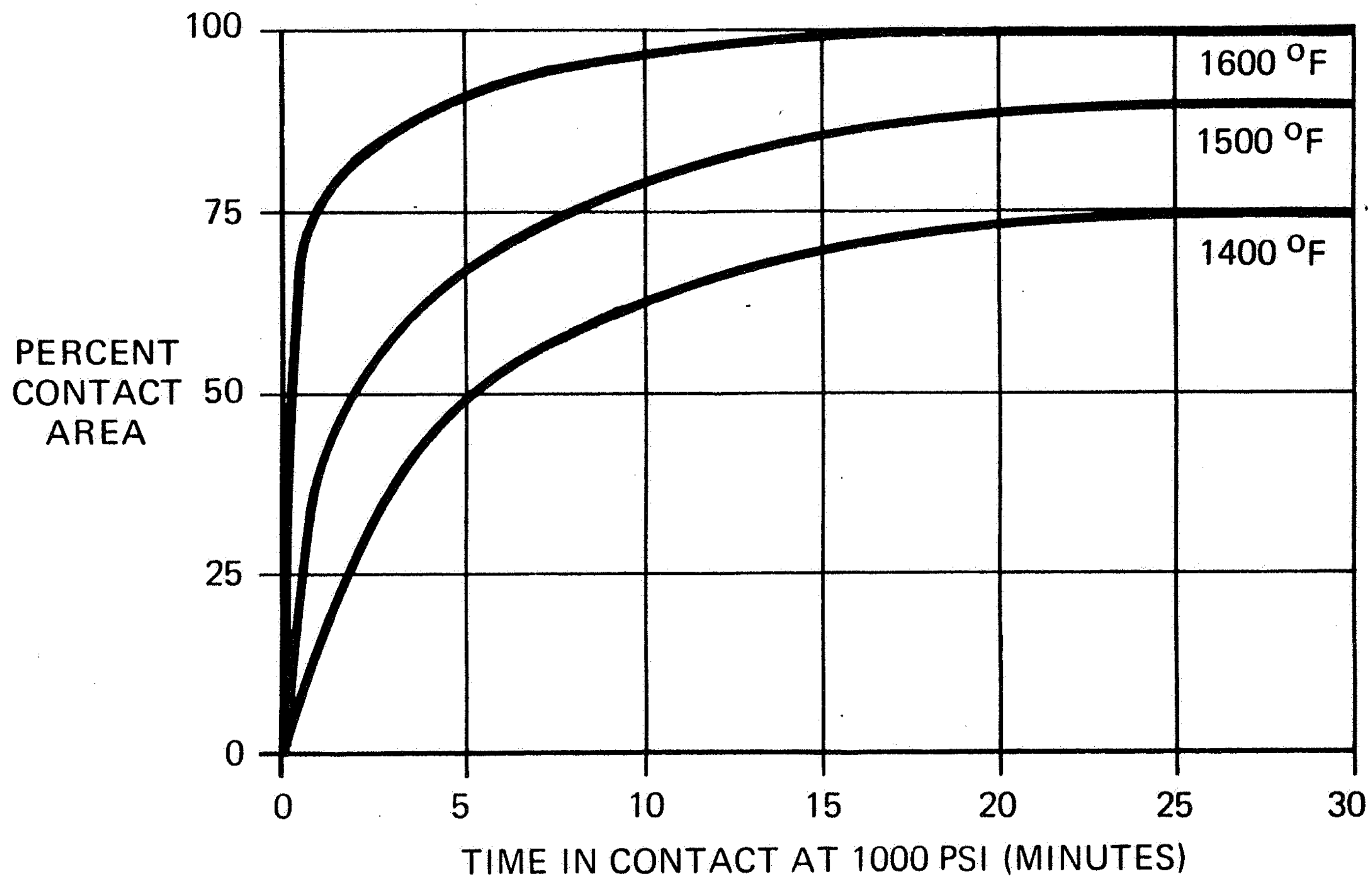


Figure 5.

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HARDWARE MADE BY DIFFUSION BONDING

BELOW THE YIELD POINT

- FLUERIC ELEMENTS AND INTEGRATED CIRCUITS
- MINIATURE HEATERS
- GAS HANDLING DEVICES FOR SPACE EXPERIMENTS
- HYDRAULIC DEVICES
- HEAT EXCHANGERS

ABOVE THE YIELD POINT

- CABLE WIRE CONNECTOR JOINING
- SHELLS FOR TRANSPIRATION-COOLED TURBINE BLADES

Figure 6.

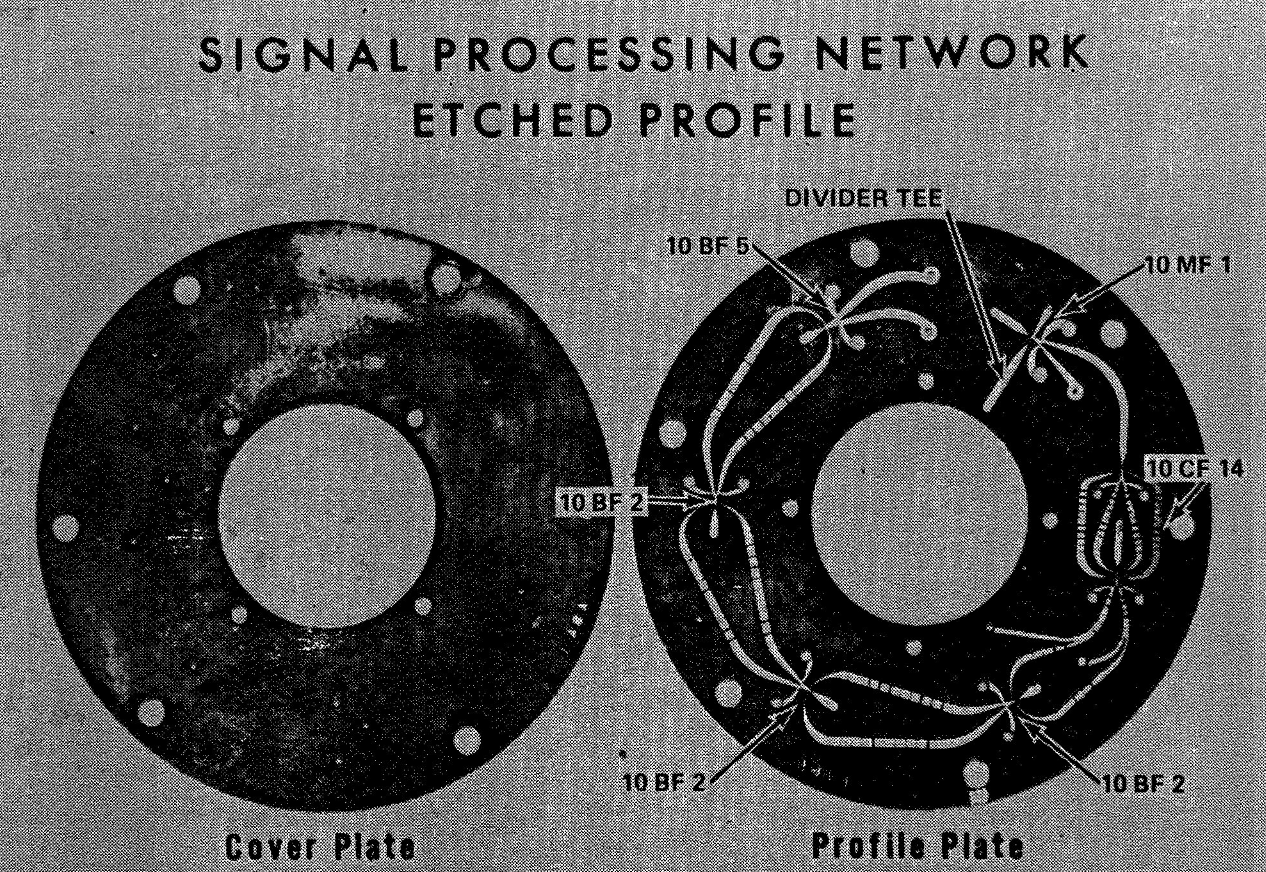

SIGNAL PROCESSING NETWORK
ETCHED PROFILE
DIVIDER TEE
10 BF 5
10 MF 1
10 BF 2
10 CF 14
10 BF 2
10 BF 2
Cover Plate
Profile Plate

Figure 7.

ARRAY OF IDENTICAL PATTERNS

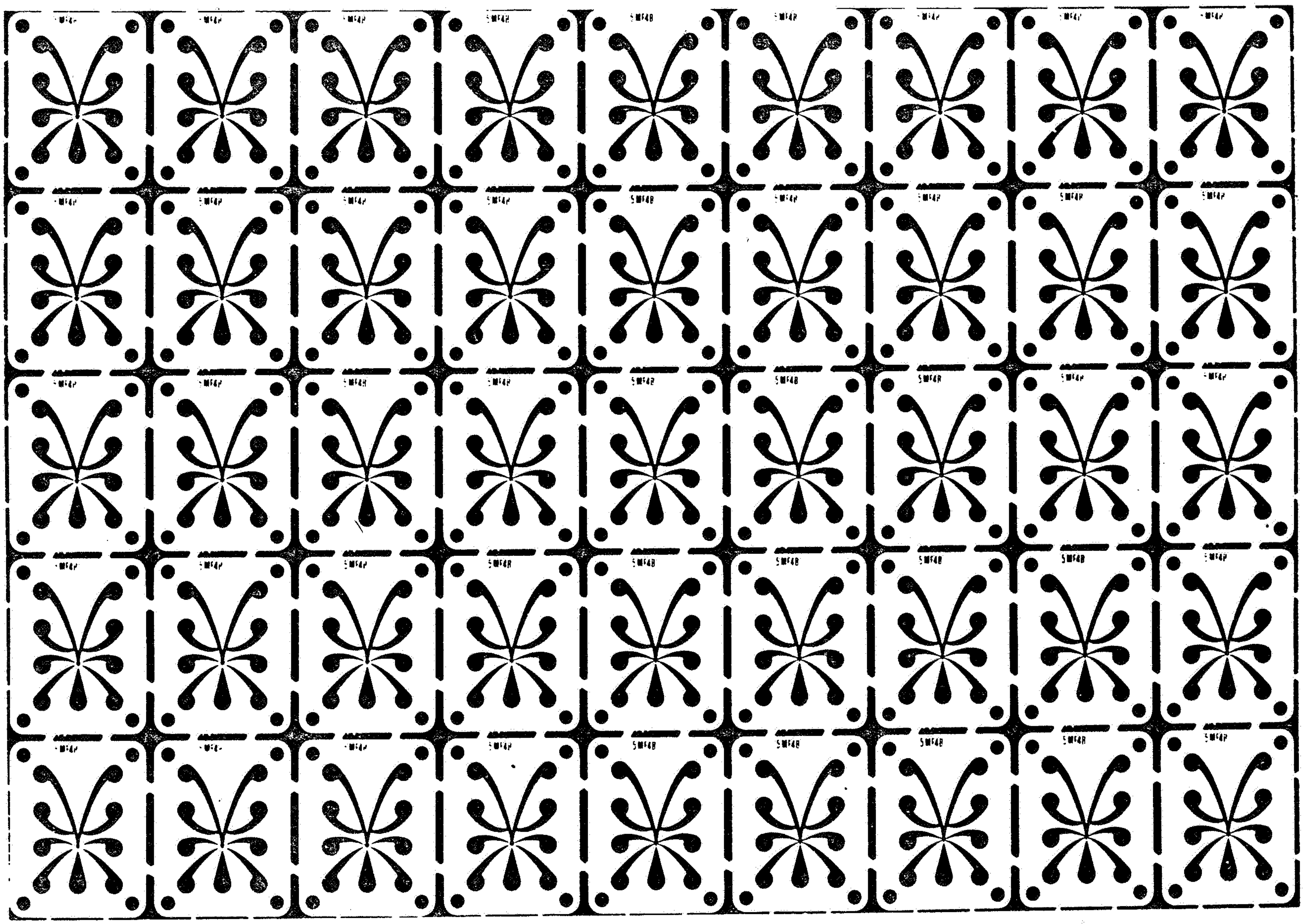


Figure 8.

Figure 9. - Radiograph of Flueric integrated circuit.

DIFFUSION—BONDED STAINLESS STEEL

Figure 10.

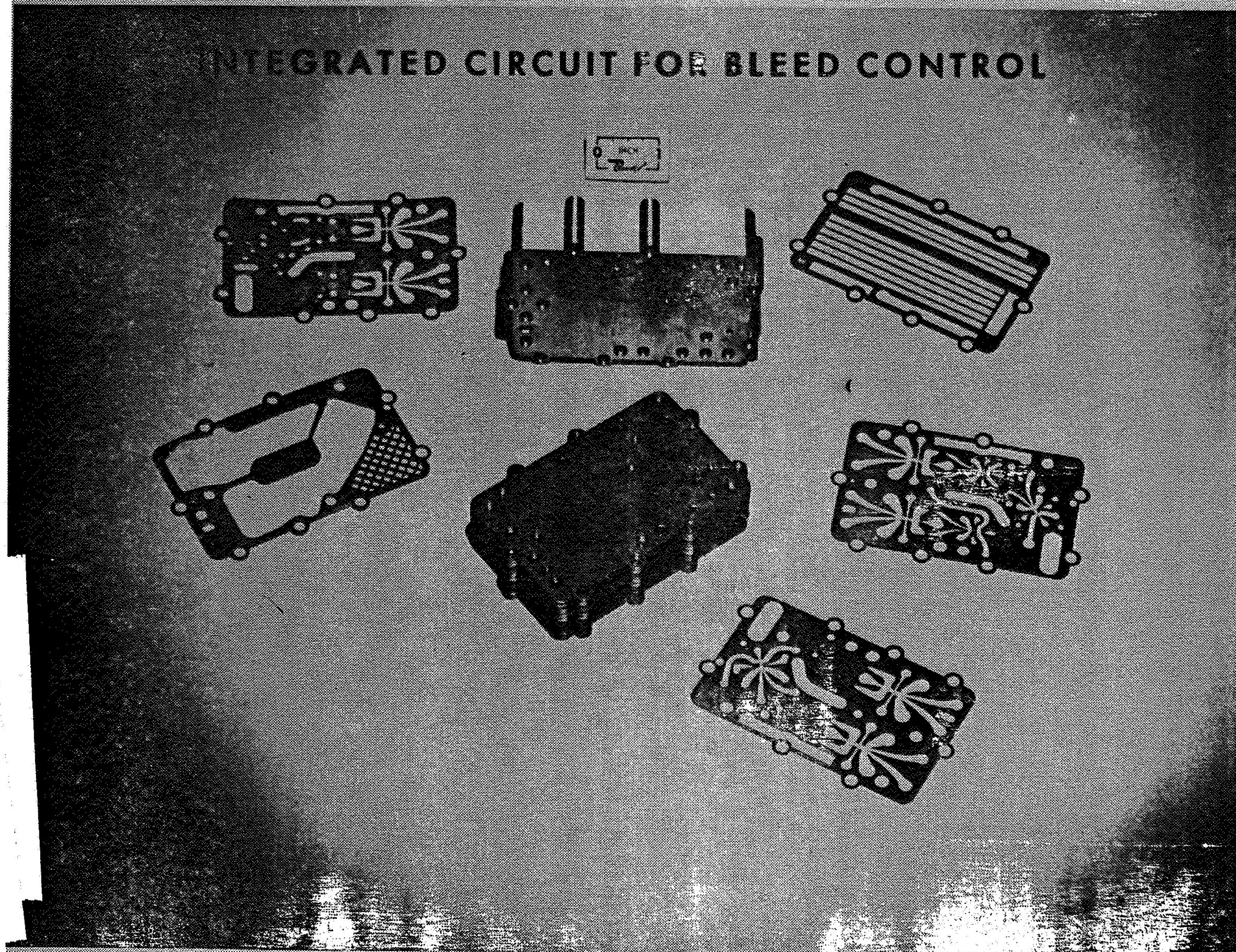


Figure 11.

COMPRESSOR BLEED CONTROL

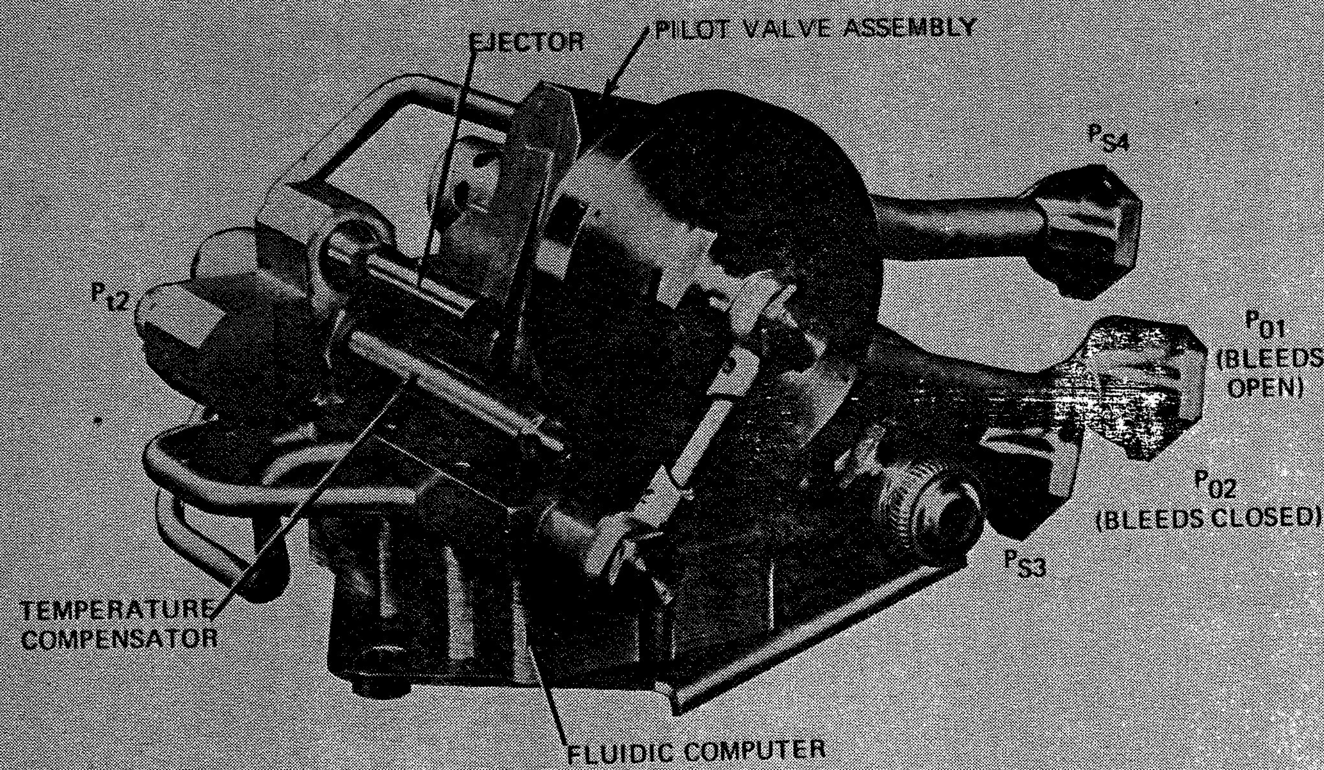


Figure 12.

INCONEL 600

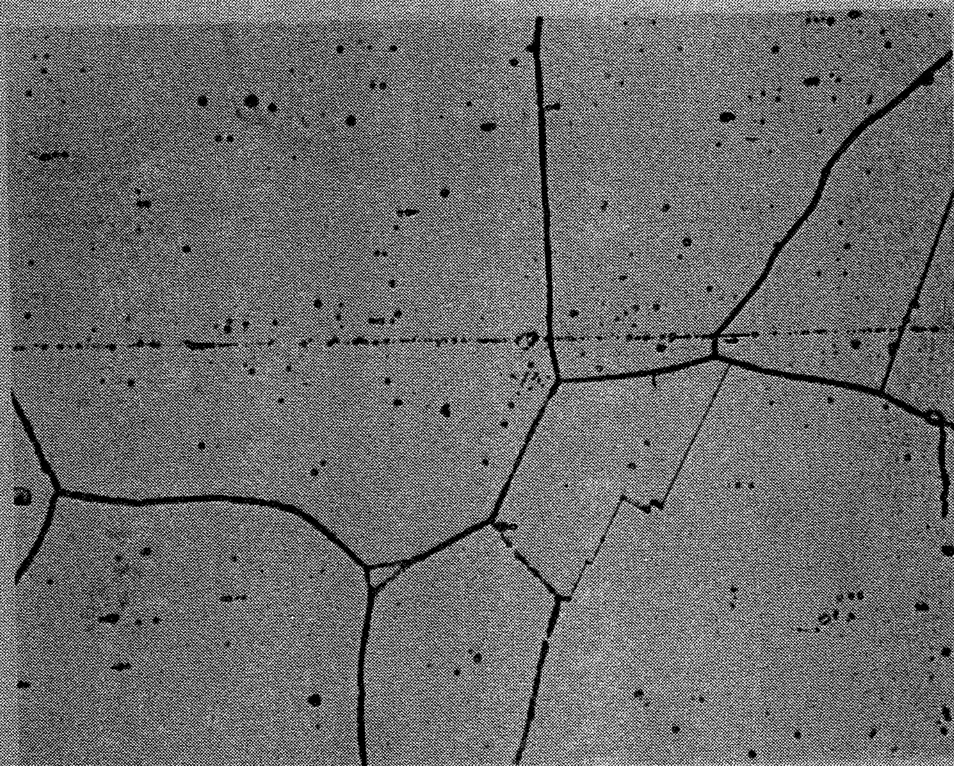


Figure 13. - Diffusion-bonded Inconel 600.

DIFFUSION—BONDED TD NICHROME

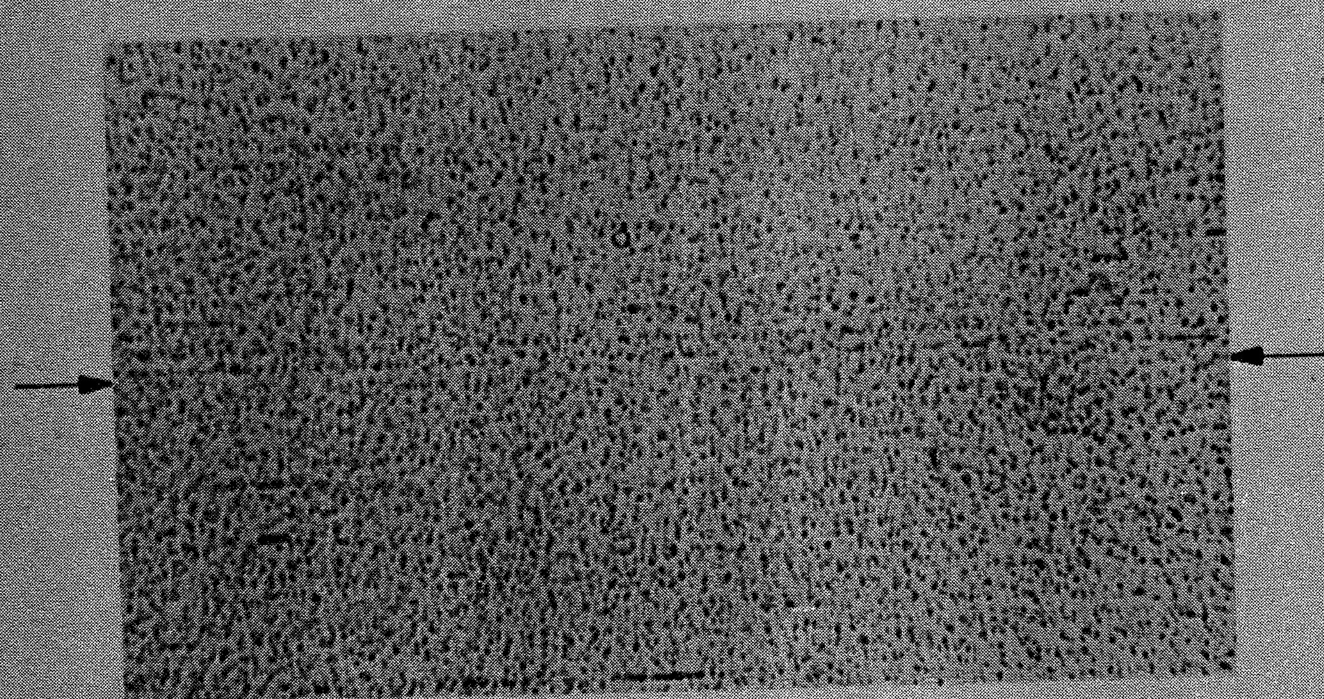


Figure 14.

DIFFUSION-BONDED CHROMIUM

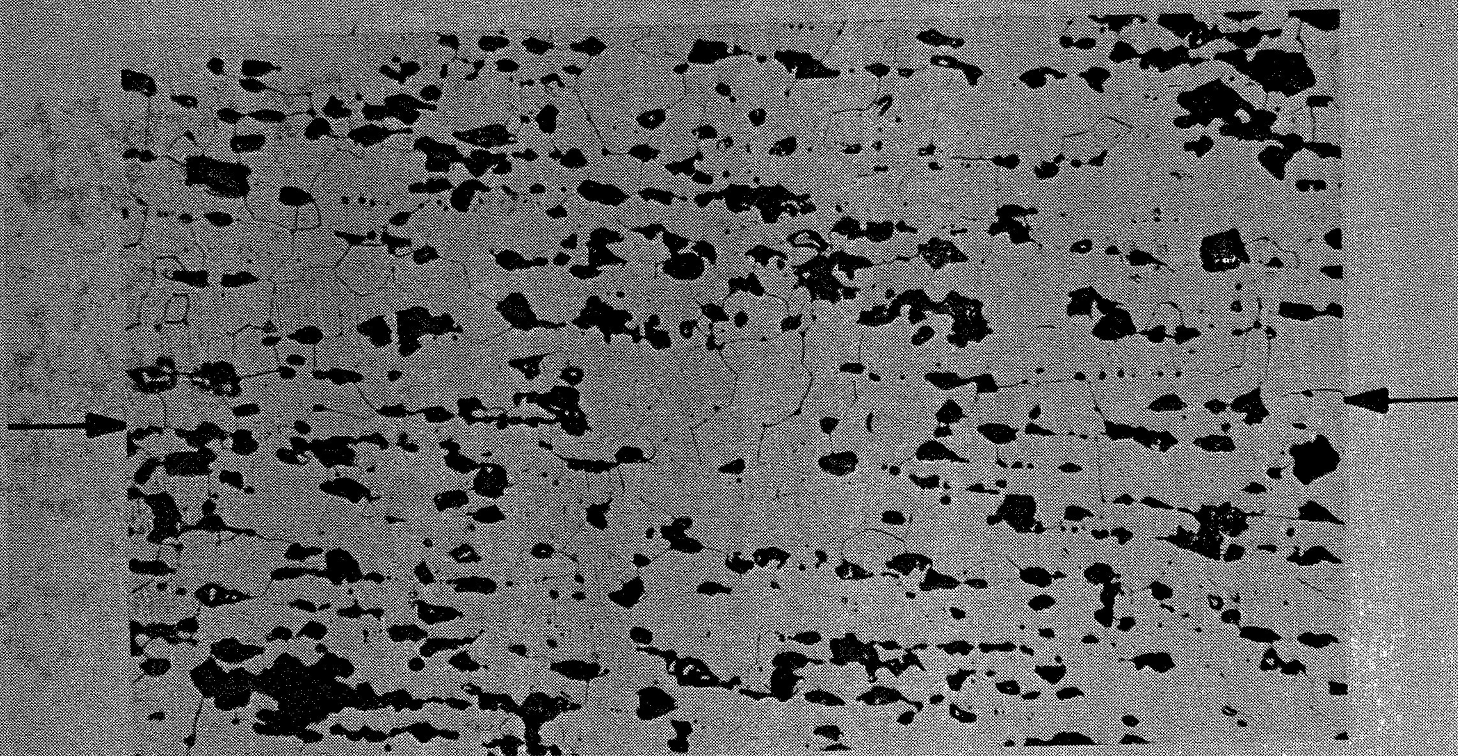
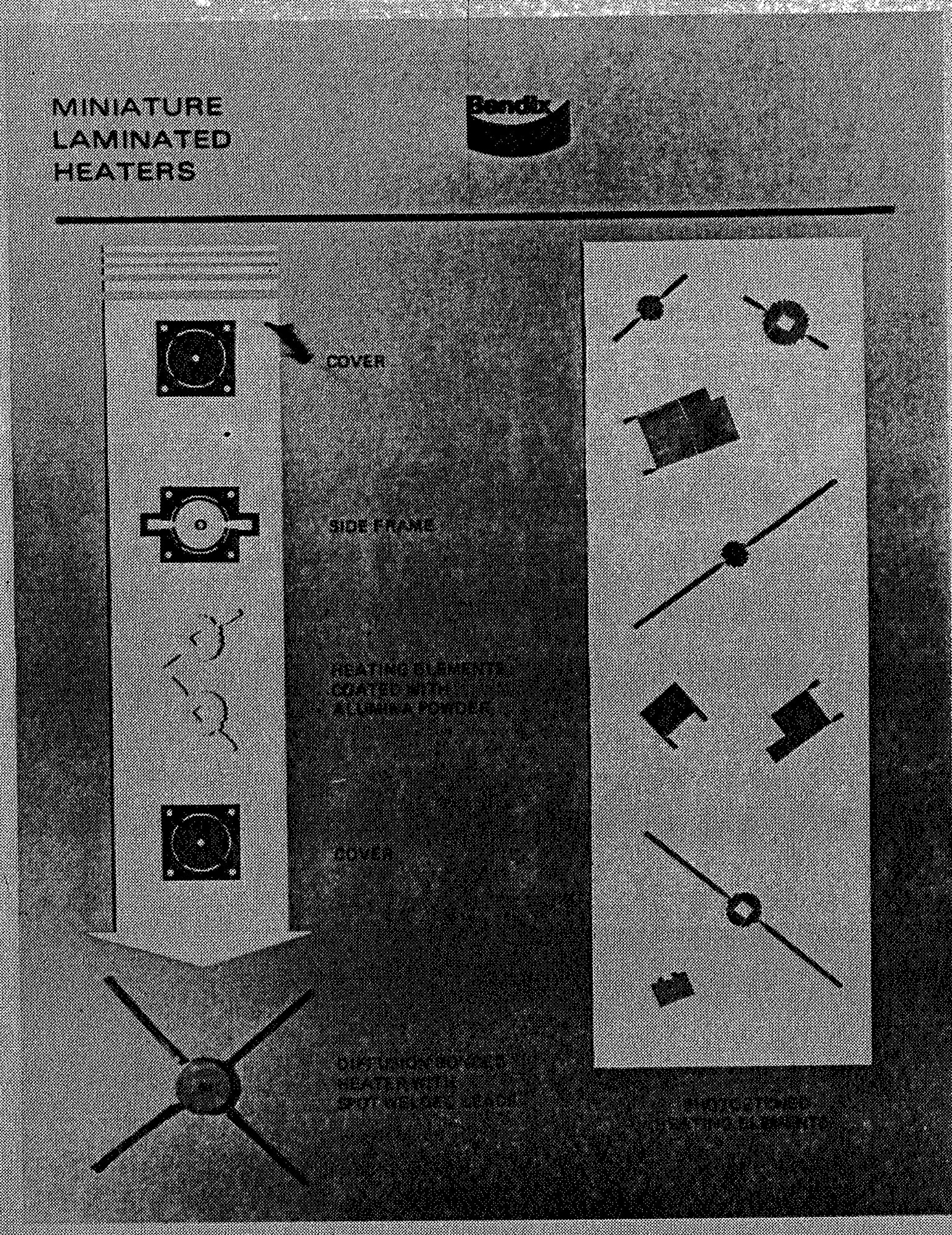


Figure 15.



MINIATURE
LAMINATED
HEATERS
Bendix
COVER
SIDE FRAME
HEATING ELEMENTS
COATED WITH
ALUMINA POWDER
COVER

Figure 16.

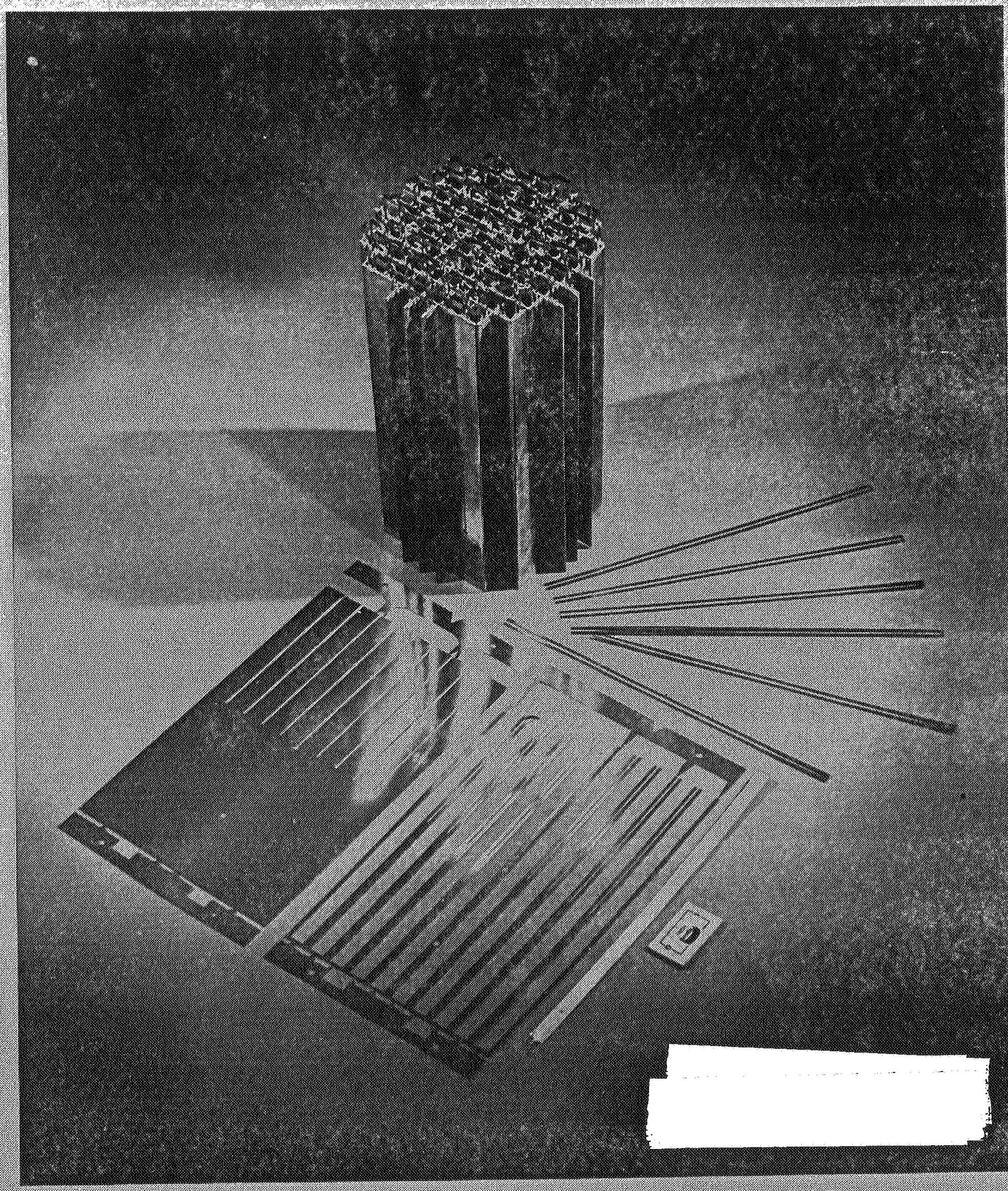


Figure 17. - Reaction bed for oxygen generator.

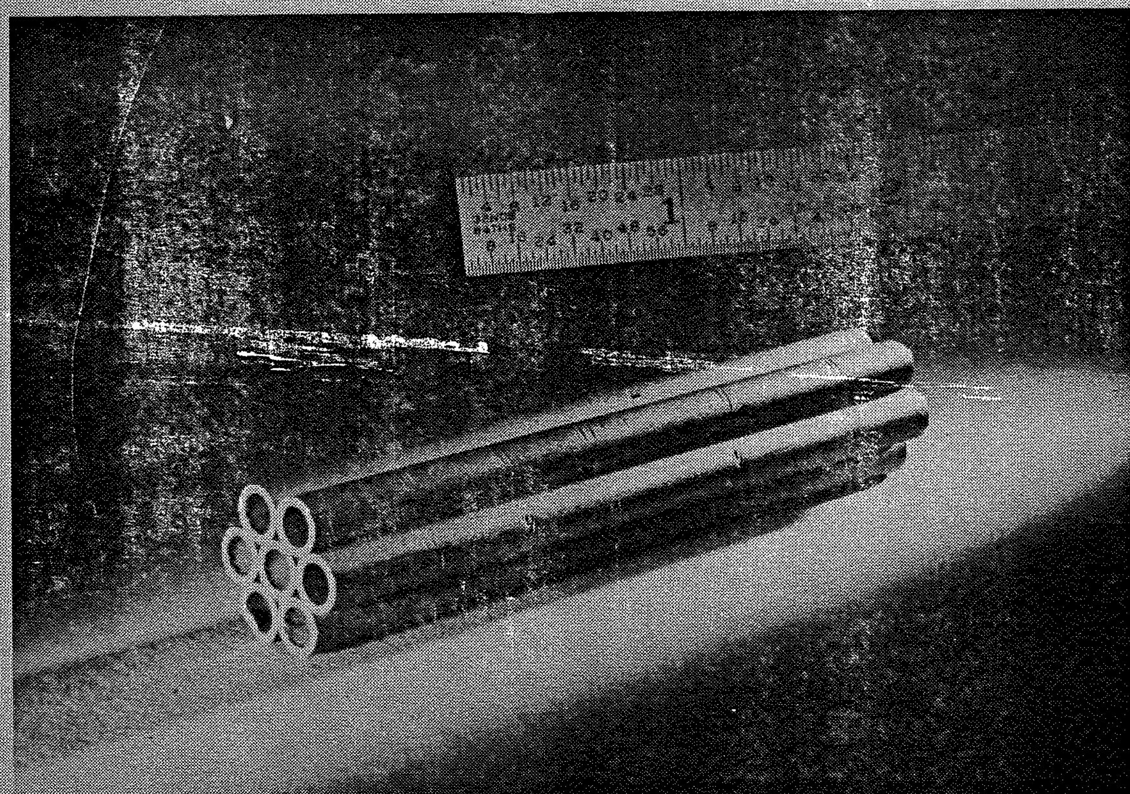


Figure 18. - Diffusion-bonded aluminum tubes.

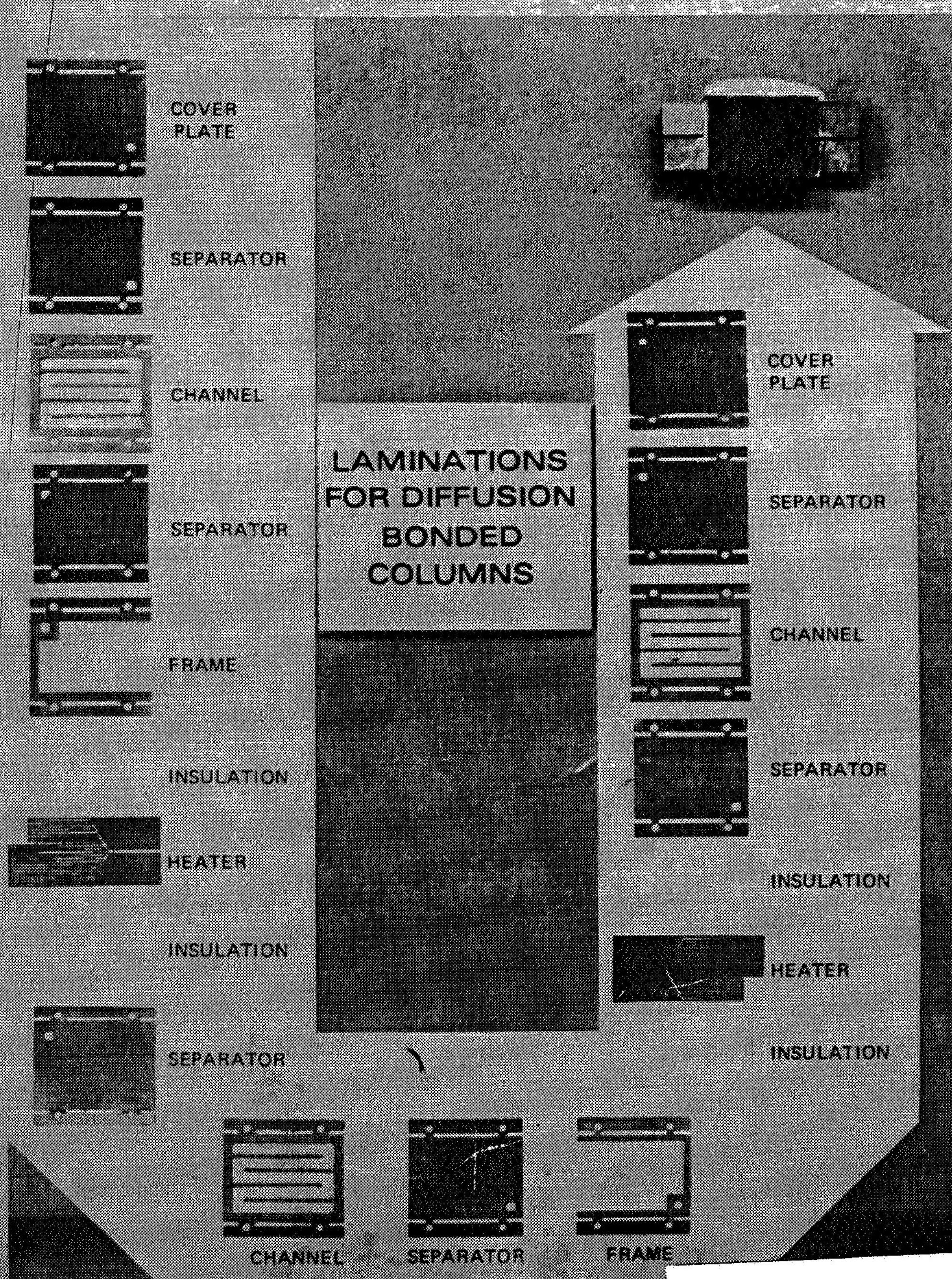


Figure 19. - Laminations for diffusion-bonded gas-handling columns.

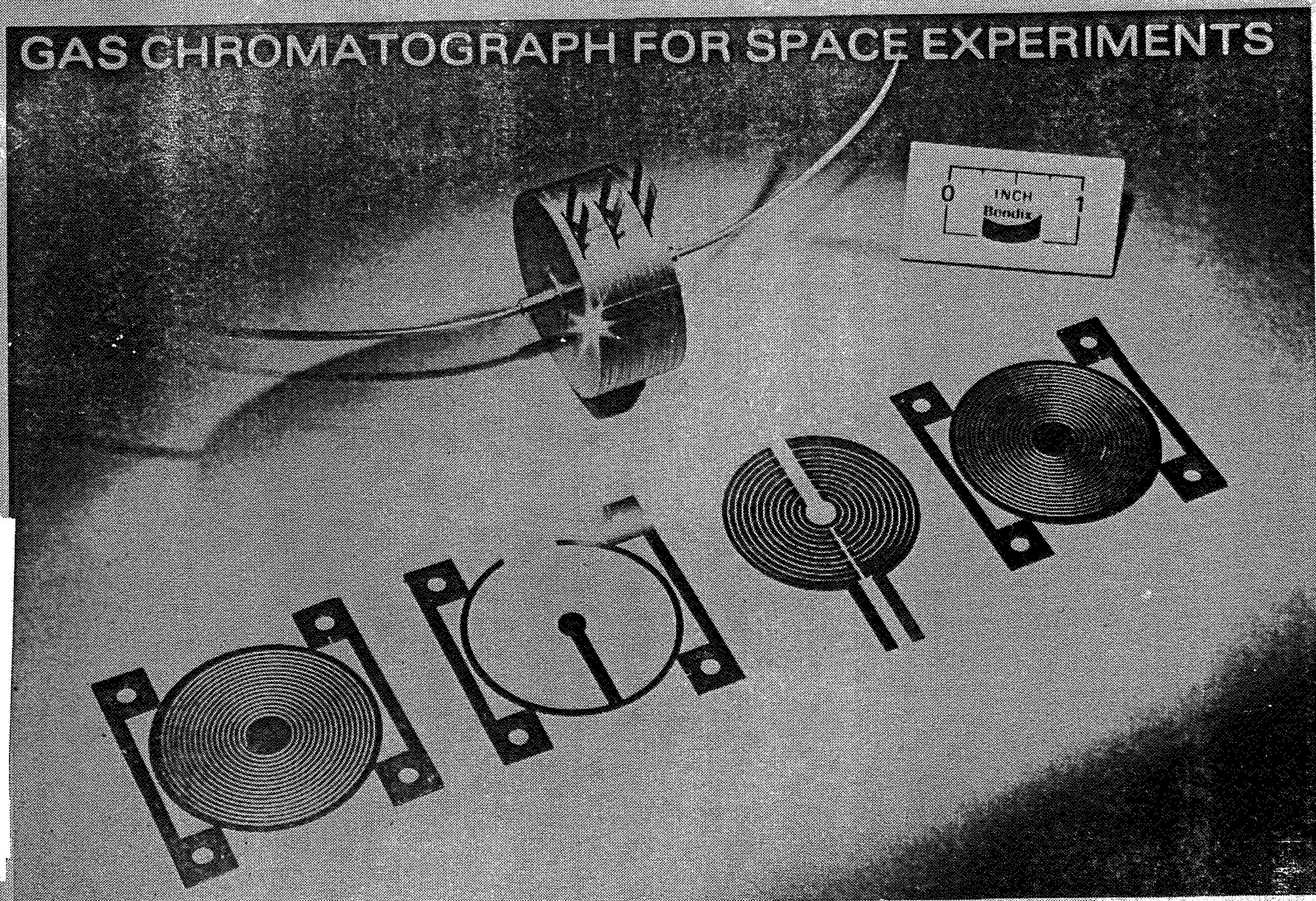


Figure 20.

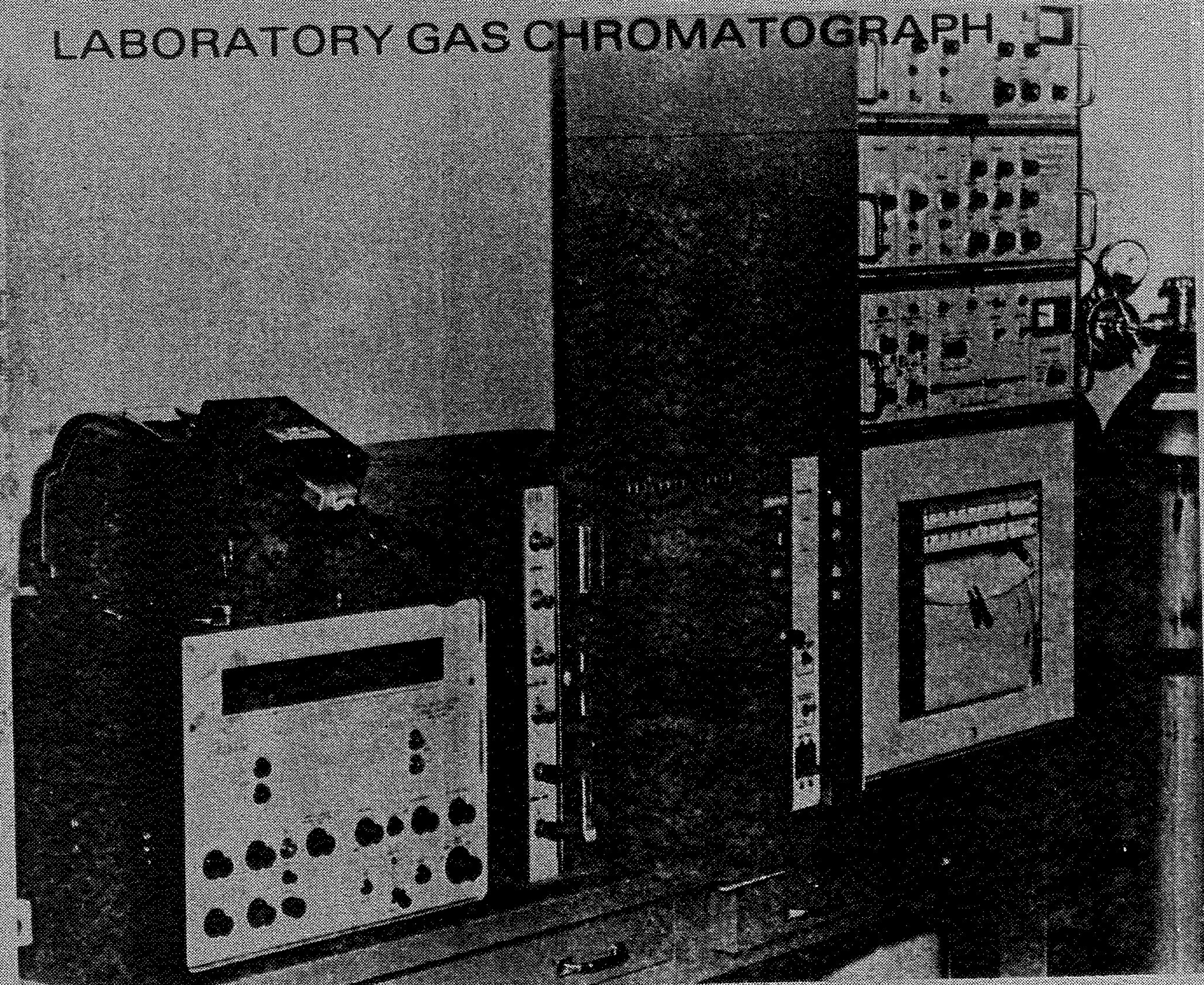


Figure 21.

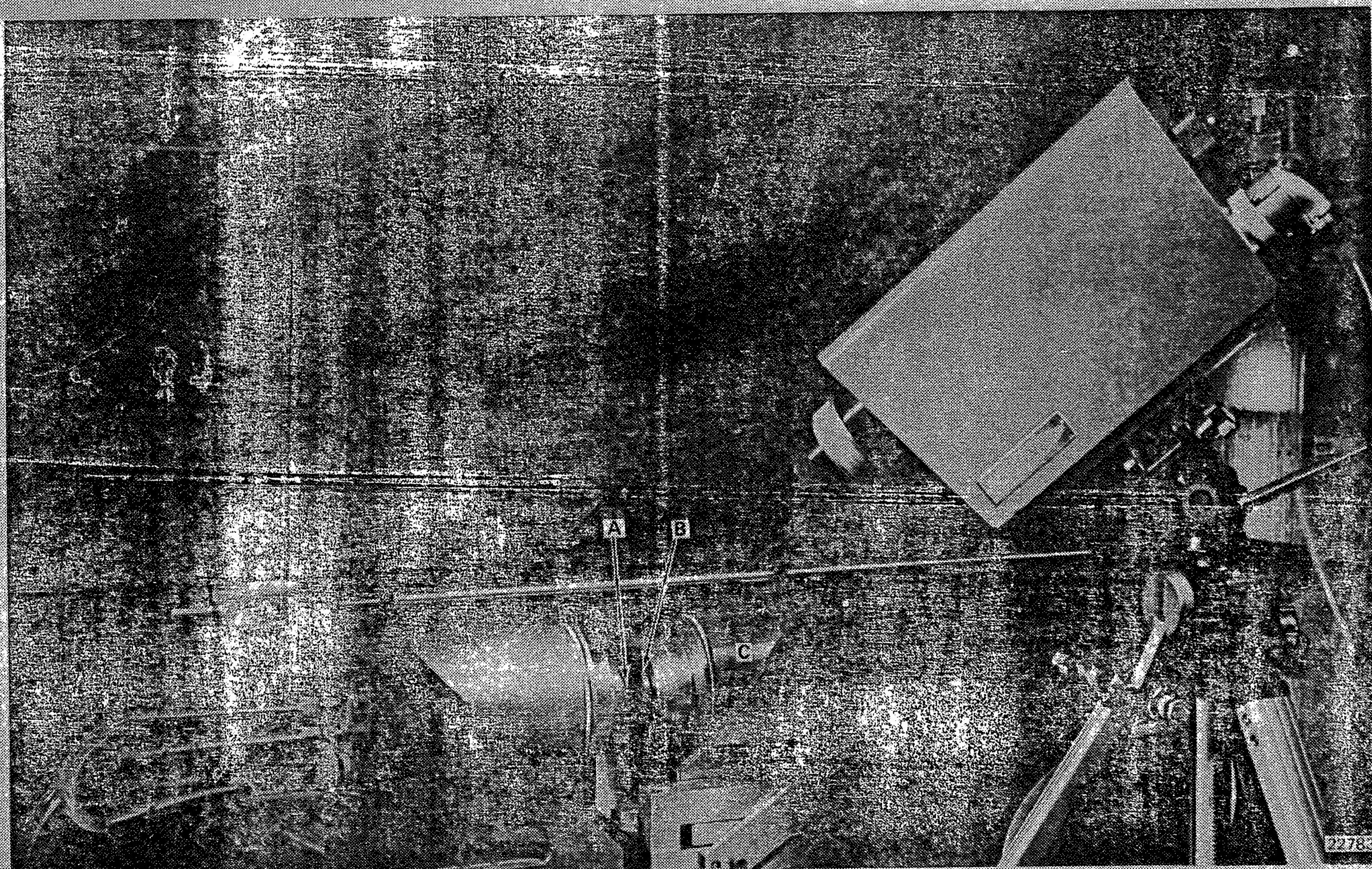


Figure 22. - Experimental Yield-Point Bonder
A - Workpiece
B - Chuck
C - Sliding quartz sleeve for atmosphere control

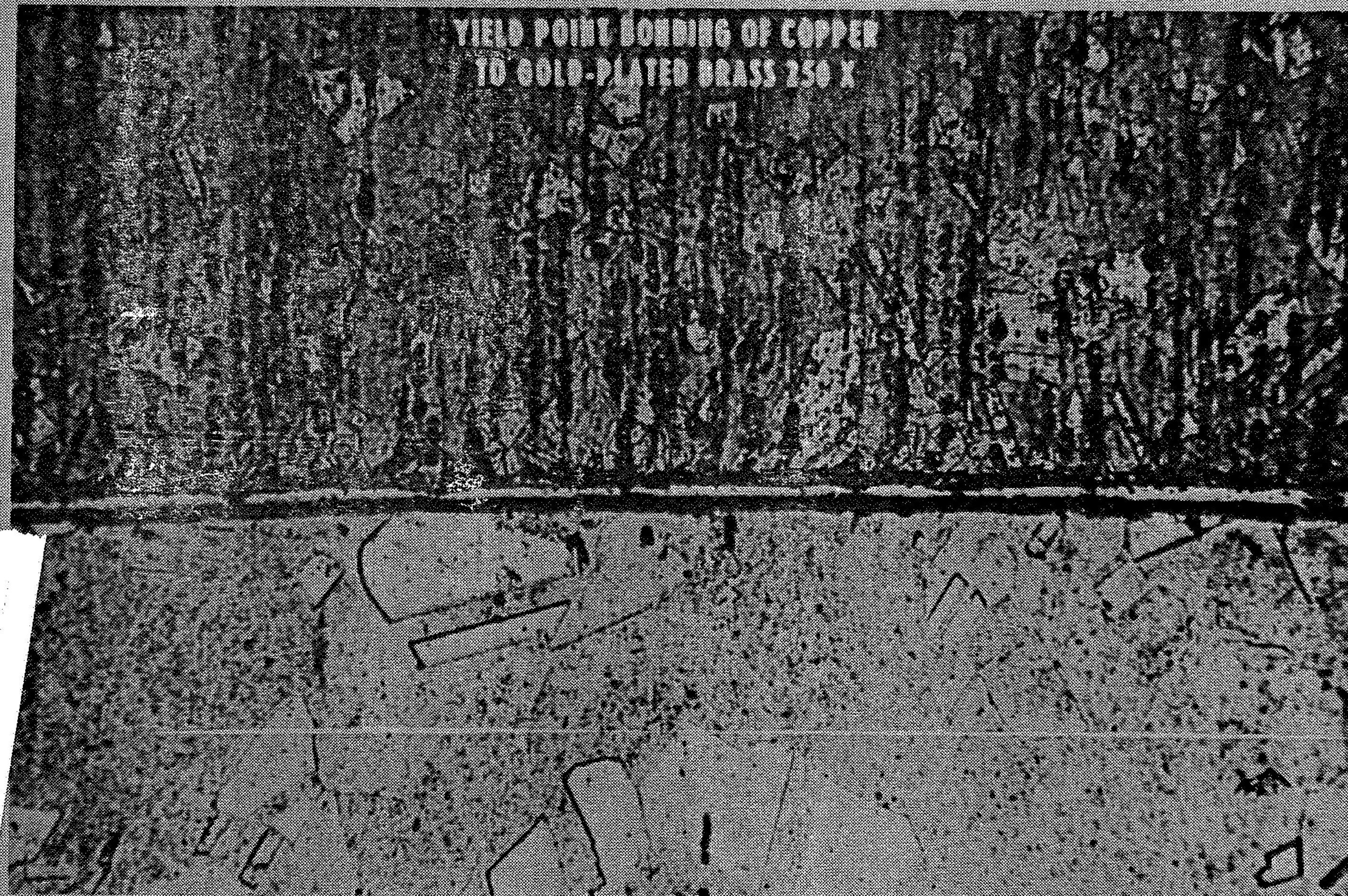


Figure 23.

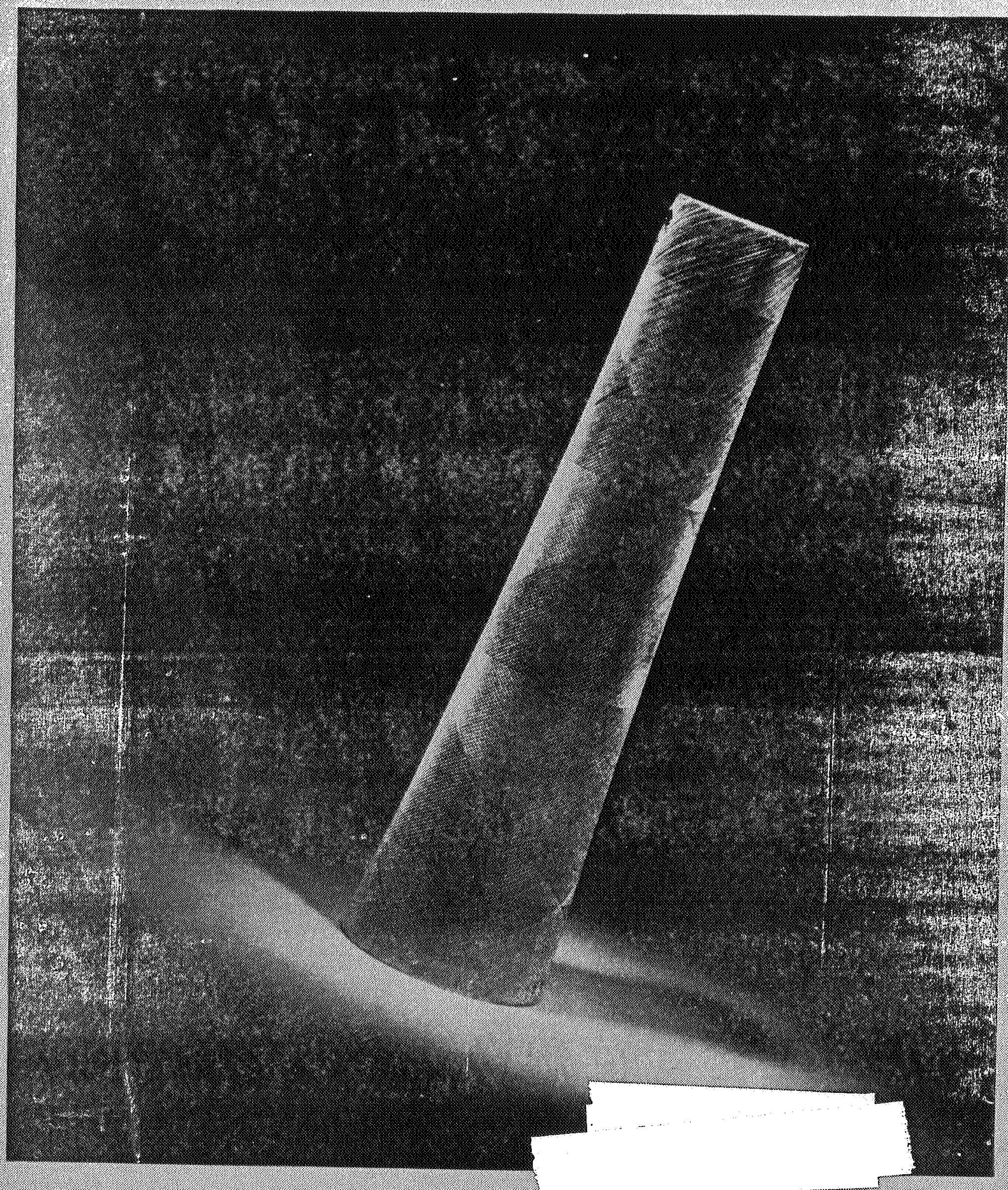


Figure 24. - Poroloy ® - flattened wire wound on mandrel and diffusion-bonded.

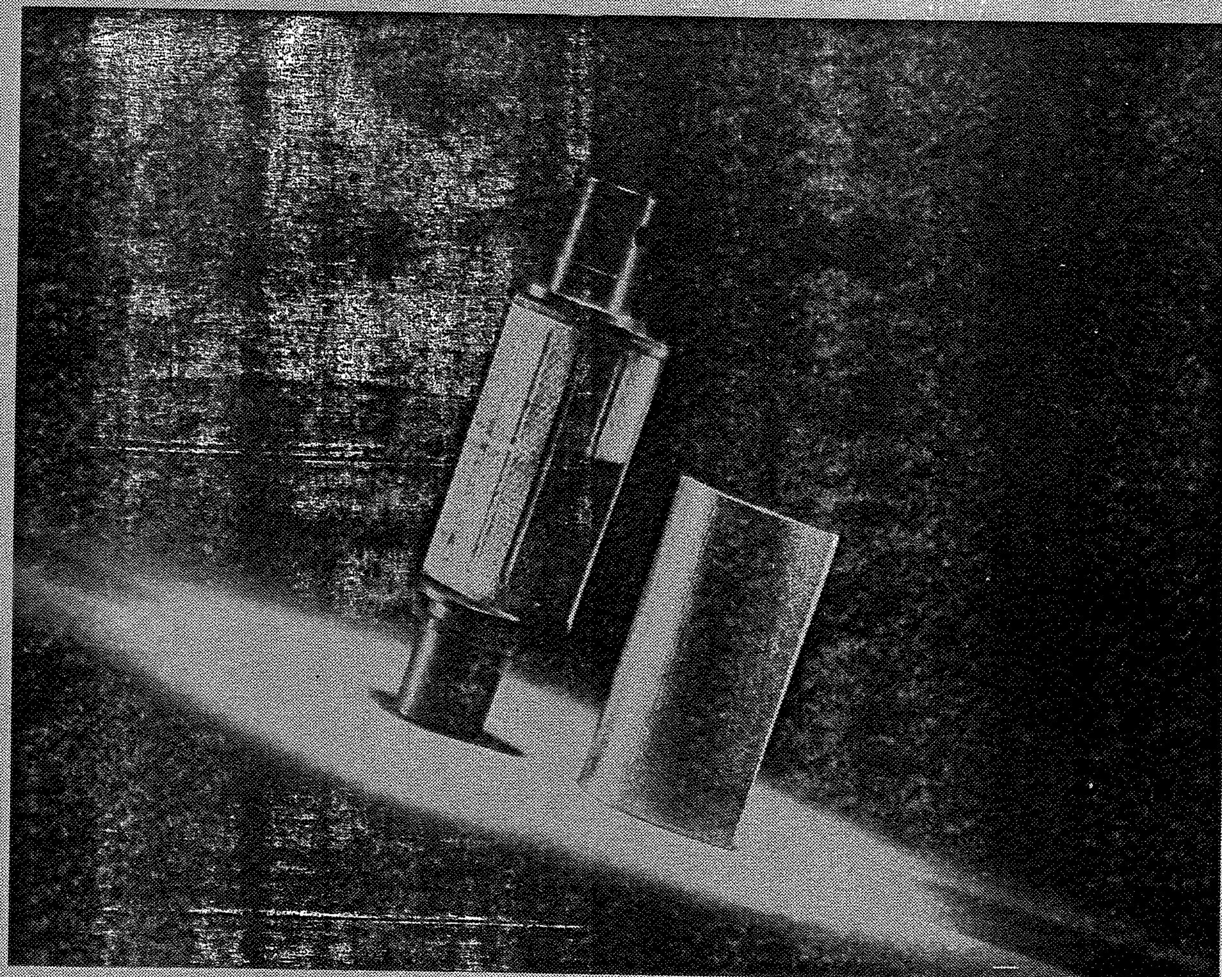


Figure 25. - Turbine Engine parts made from Poroloy ®.

BONDS IN POROLOY MADE FROM GE-1541 AS FABRICATED

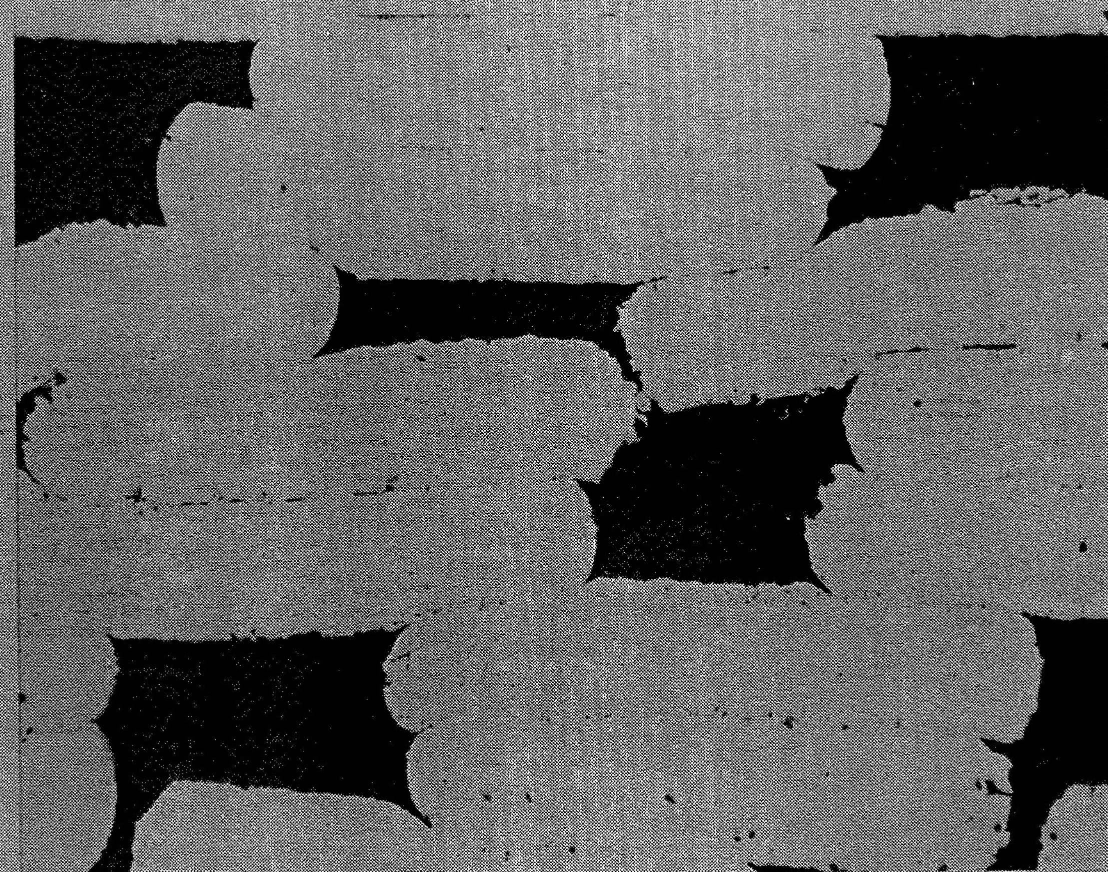


Figure 26.

BONDS IN POROLOY MADE FROM GE-1541 AFTER OXIDATION, 600 hr, 2,000° F

Figure 27.

AIR FLOW THROUGH POROLOY BEFORE AND AFTER OXIDATION

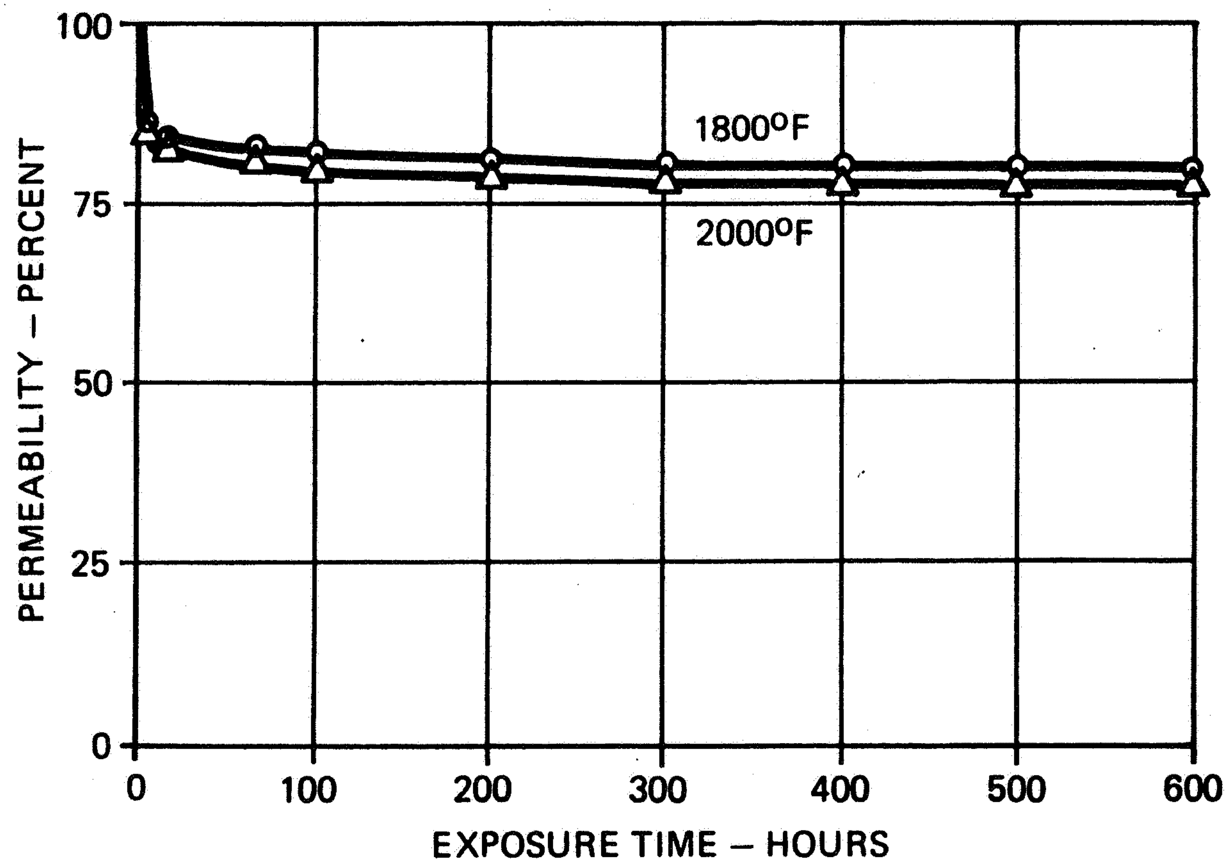


Figure 28.

ALLOYS BONDED

HIGH TEMPERATURE ALLOYS

- INCONEL 600
- GE 1541
- RENÉ 41
- HAYNES 25
- HOSKINS 875
- UDIMET 500
- STAINLESS STEELS

DISSIMILAR METALS

- NICKEL – 304 SS
- COPPER – BRASS
- COPPER – CAST IRON

COPPER ALLOYS

- COPPER
- BRASS
- MONEL

ALUMINUM ALLOYS

- 2024
- 5052
- 6061

Figure 29. - Alloys bonded at Bendix Research Laboratories.

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