NORTHROP CORPORATION
Aircraft Division
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FABRICATION OF TITANIUM THERMAL PROTECTION SYSTEM PANELS BY THE NOR-Ti-BOND PROCESS

NOR 71-202

By

Robert R. Wells

FINAL REPORT ON CONTRACT NO. NAS8-26810

October 1971

Prepared For:

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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SUMMARY

Six titanium thermal protection system panels, 50.8 cm (20-inch) by 99 cm (39-inch) were fabricated by the Northrop-developed titanium joining system called NOR-Ti-BOND. This method offers advantages compared with joining by mechanical fastening, resistance spot or seam welding, or fusion welding in that it has the potential for producing wide faying surface bonds to minimize temperature gradients and thermal stresses resulting during service at elevated temperatures. A satisfactory tooling system was evolved to apply joining pressure and retain the panel shape. Two NDT techniques, through transmission ultrasonics and X-ray, were set up to evaluate the joint quality.

The majority of the 2.54 cm (1-inch) by 40.2 cm (15.8-inch) joints were complete bondments. All of the joints were bonded at the center, but in some of the joints, there were areas near the edges that were unbonded. Even in these cases, the total bond area in the joint is significantly greater than could be obtained by spot welding or roll seam welding.

Concepts for improving panel quality and for more economical production are based on better forming techniques, judicious purchasing of raw stock, and a re-design of the tooling.

Five of the TPS panels, supporting specimens, and the tooling were shipped to the contracting office.

The results of this program indicate that the NOR-Ti-BOND process could be used to fabricate Space Shuttle thermal protection system panels. Inspection procedures that were used are sufficiently sensitive and reliable to insure successful bond joints in production panels. The method appears economically feasible for production, provided that appropriate equipment, tooling, and processing techniques are employed.

INTRODUCTION

Various thermal protection systems (TPS) are now being designed, fabricated, and tested for use on the Space Shuttle. The fabrication of all-metal TPS heat shield panels has required various fabrication techniques. Northrop Corporation contracted to fabricate two sets of TPS panels for testing this configuration in titanium with a complete joint across the 2.54 cm (1-inch) by 40.2 cm (15.8-inch) faying surface where each of the 12 hat-sections join the wave-shaped facesheet, NASA Drawing No. 31M01274, Revision A. A sketch of the panel is shown in Figure 1. Each set of TPS panels requires the fabrication of two 50.8 cm (20-inch) by 99 cm (39-inch) panels. The alloy used for this work was Ti-6Al-4V of 0.0508 cm (0.020-inches) in thickness. The NOR-Ti-BOND joining process was used to fabricate a wide faying surface joint so as to increase the heat conductivity of the panel. These panels are to be tested and evaluated by NASA.

MATERIALS AND PROCESSES

Description of the NOR-Ti-BOND Process

In thin-film diffusion brazing, a thin layer of a selected metal is reacted at elevated temperatures with the base material, forming a small amount of eutectic liquid which fills voids and forms small fillets. During continued exposure to temperature, extensive solid-state diffusion occurs about the joint region, reducing the concentration of the selected metal in the joint.

After various investigations, Northrop found that the most suitable element for thin-film diffusion brazing of titanium was copper.* Copper alloys or pure copper react with titanium at relatively low temperatures, are relatively easy to handle, and offer no health hazard. When a thin film of pure copper is placed upon titanium and heated, solid-state diffusion occurs, forming, as represented in the phase diagram of Figure 2, a series of solid solutions and compounds. As the temperature is increased to the eutectic temperature, 885C (1635F), a small amount of melting occurs. Since atomic diffusion is some 10,000 times faster in a liquid than in a solid, the liquid layer between the titanium and the copper quickly takes the remaining copper and some titanium into solution. This forms a thin layer of brazing liquid of the eutectic composition. This liquid wets the titanium and flows along it much like a conventional brazing alloy. The brazing liquid continues to dissolve titanium, shifting the joint composition toward the titanium side of the phase diagram, which raises the liquidus temperature and soon results in solidification of the liquid while holding at the joining temperature. Continued holding at this temperature allows further solid-state diffusion to occur, with copper entering the base material and titanium entering the joint. Sufficient diffusion time is allowed to transform the center of the joint to a beta-titanium alloy containing some 6 percent to 7 percent copper, which has a remelt temperature of 1350C (2460F).

*U.S. Patent No. 3,417,461, "Thin-Film Diffusion Brazing of Titanium Members Utilizing Copper Intermediates," — Process is called NOR-Ti-BOND.

STRINGER(HAT SECTION - TYP 12 PLCS.)

2.50 In
6.35 cm

3.19 In (PILOT HOLES, 8.1 cm 12-PLACES)

(PILOT HOLES 12 PLCS.)
1.94 In
4.94 cm

20 In
51 cm

FORMED SKIN PANEL

39 In
99 cm

.020 In
.0508 cm

PILOT HOLE ₵

STRINGER

SECTION A-A
(TYP. 12 PLACES)

0.50 In
1.27 cm

1.20 In
3.05 cm

.020 In
.0508 cm
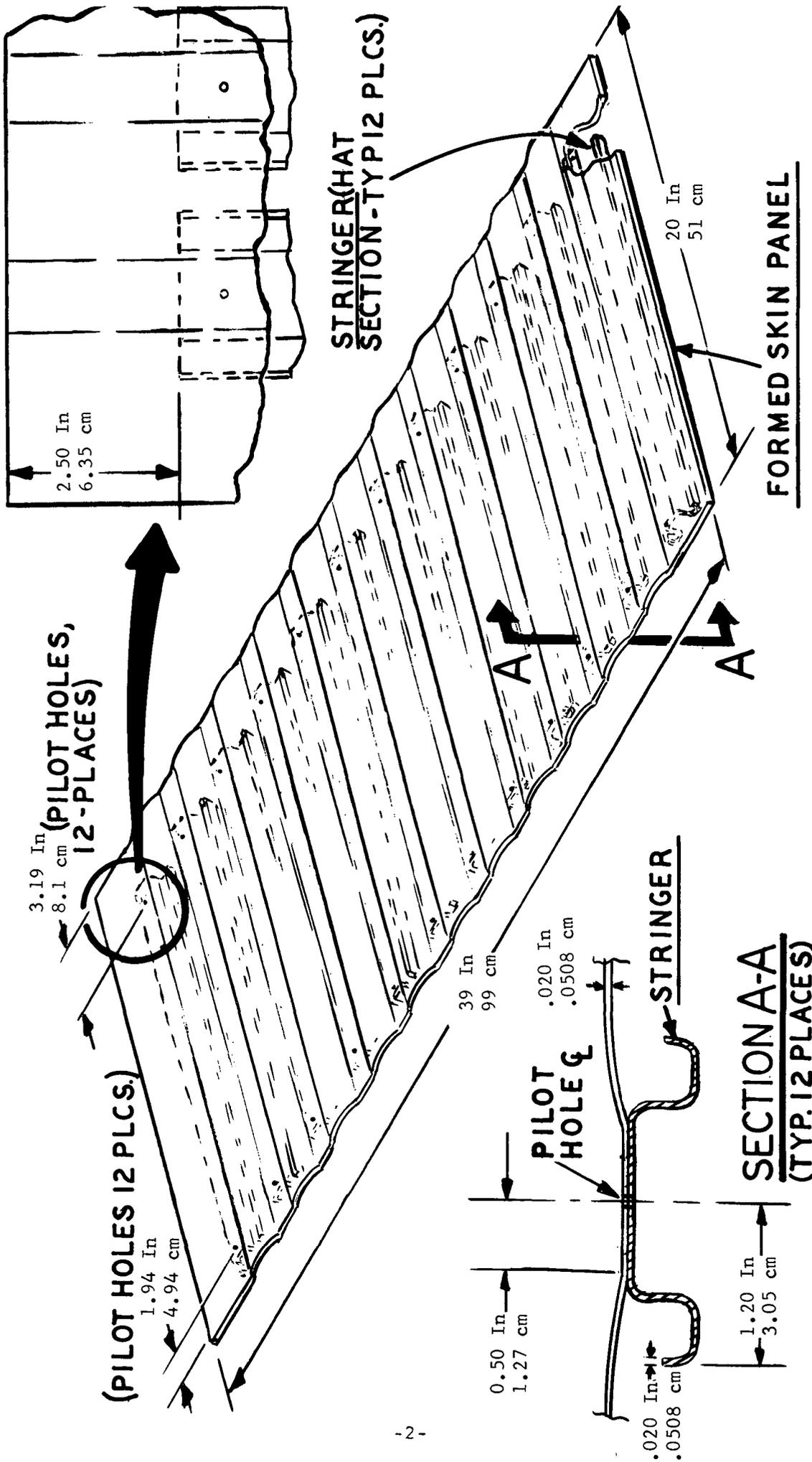
FIGURE I.

TITANIUM THERMAL PROTECTION SYSTEM PANEL

-2-

FIGURE 2. THE Ti-Cu PHASE DIAGRAM

Upon cooling, the copper-containing beta-phase titanium alloy will undergo a eutectoidal transformation occurring in the vicinity of 800C (1475F), as indicated in the phase diagram. The transformation products and the temperature of transformation will vary somewhat, depending upon the other elements present in the alloy. The products of this transformation are alpha Ti and the compound Ti_2Cu. The morphology of the transformation products is controlled by controlling the cooling rate. It is usually desirable to cool slowly enough to transform the beta in the range of 700C (1300F) as this produces a ductile joint with good strength.

A typical microstructure of a NOR-Ti-BOND joint is shown in Figure 3. The original liquid region represents about 1/4 of the apparent joint. The remainder of the Widmanstatten and other structures are the result of solid-state diffusion of copper into the titanium. This diffusion transformed the areas to beta titanium. The large, light-gray needles are alpha-titanium; the darker regions within the joint are a mixture of alpha-titanium and Ti_2Cu compound in a platelet structure similar to that of pearlite in steel.

The morphology of these joints can be controlled by thermal treatment. Joints were fabricated and diffusion treated at 925C (1700F) and cooled at a rate of 300C (500F) per minute to selected temperatures between 650C (1200F) and 870C (1600F), and isothermally transformed. At 815C (1500F), the transformation from beta to alpha plus Ti_2Cu is slow and does not go to completion within two hours. This transformation starts along the beta grain boundaries and in the lower copper-content regions where the transformation temperatures are higher. The remainder of the micro-constituents in the joints result from rapid cooling and are probably martensitic. At 700C (1300F), the entire transformation occurs very quickly, producing a rather fine structure of alpha plus Ti_2Cu. Quenching these joints produces a martensitic structure, as reported by Margolin, et al.[1]

Adaptation of NOR-Ti-BOND to the NASA TPS Panels

The TPS panel configuration, Figure 1, requires twelve (12) separate faying joints to be made between the hat-sections and the wave-shaped facesheet. An evaluation of the configuration led to a decision to apply the copper intermediate in foil form. Copper foil 0.00076 cm (0.0003-inches) thick was slit to the proper width and length and applied to the joint area. Thus, the formed titanium parts were only degreased and chemically cleaned prior to fabrication. No electroplating was required.

Due to the heavy retort and the support tooling requirements, the heating rates on these panels was about 200C per hour (350F per hour). A protective atmosphere was provided using hot titanium chip gettered ultra-high purity argon. Pressure was applied to control the configuration and to provide fit-up along the bond surfaces through the use of compression bars and a compression pad which will be described later.

The panels were heated to 925C (1700F) and held at this temperature for three hours to permit solid-state diffusion to occur and allowed to furnace cool. No attempts were made to heat treat this configuration; thus, the panels are in an annealed condition.

-4-
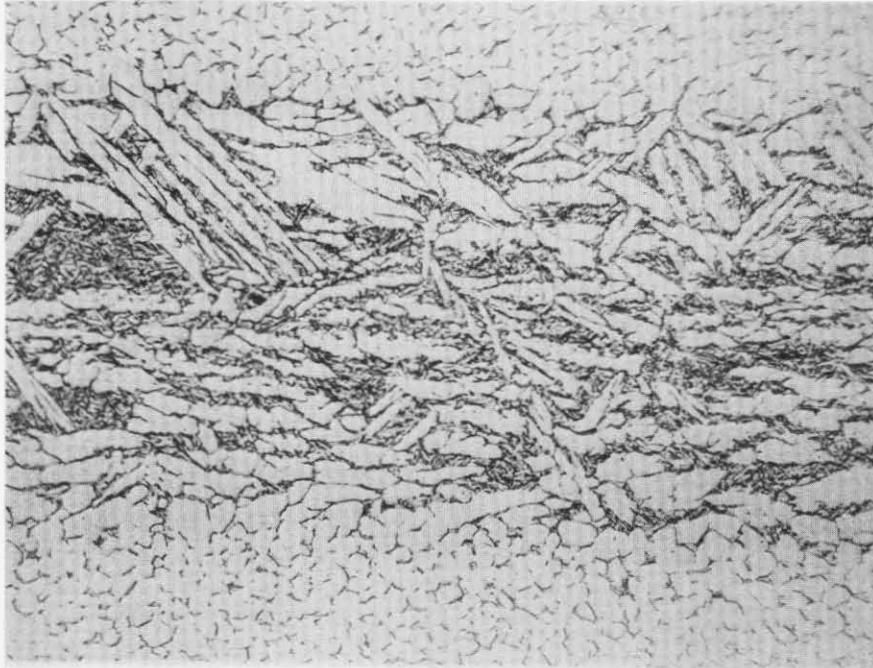
Etch: Krolls   Mag 250X

FIGURE 3   JOINT MICROSTRUCTURE FROM NASA TPS PANELS
            NO. 1.   MAXIMUM COPPER CONTENT 6.4%

Materials Used in the Program

The titanium sheet used for the panels came from three heats of Ti-6Al-4V. The first subsize panel and the trial-run, full-size panel (No.1) were made of Ti-6Al-4V from TMCA Heat No. K-4590. This particular heat of material was purchased as 0.0508 cm (0.020-inches) in thickness. It turned out to be somewhat thicker and had to be chemically milled to the proper size. Panels No. 2, 3, 4, and 5 were fabricated from TMCA Heat No. K-4587 and, finally, Panel No. 6 was fabricated from Heat No. K-6716. The chemical analysis and certified mechanical properties are listed in Table I.

The electrolytic tough pitch (ETP) annealed copper foil used for the program was purchased from Laminated Shim Somers Thin Strip, Inc. This foil was 0.00076 cm (0.0003-inches) in thickness by 6.2 cm (2.44-inches) wide, and its nominal composition was 99.90 minimum copper. The foil weighed 7.75 milligrams per square centimeter (0.00176 oz/in^2)

The zirconia compression pad material used has the trade name Zircar, and it is produced by Union Carbide. This ZYF200 material is composed of yttria-stabilized zirconia fiber and is approximately 0.424 cm thick (0.167-inches).

Other materials used for the program were commercial grade ATSI Type 321 stainless steel and miscellaneous pieces of Ti-6Al-4V alloy and molybdenum foil for tooling purposes.

Materials Cleaning

The Ti-6Al-4V sheet material was degreased, chemically cleaned, and dried by:

1. Warm water and soap wash.
2. Water rinse and dry.
3. MEK wipe.
4. Two minutes in a solution of 30%-38% HNO_3, 1%-2% HF, add H_2O to 100%.
5. H_2O rinse.
6. Alcohol dip.
7. Air dry.
8. Wrap in Kraft paper.

The copper foil was degreased with an MEK wipe.

All stainless steel parts were degreased prior to use with a warm water and soap wash, rinse, dry, and MEK wipe.

The Development of the Pressure Tooling

Several techniques were evaluated for applying a uniform pressure across the wide faying surface to be joined. The first of these used stainless steel bars, which had been flame-sprayed with zirconia, and 14-gauge copper wires which would act as crushable gaskets between the fused silica heated die and the stainless steel bars (Figure 4A). Another variation used stainless steel

TABLE I

CERTIFIED ANALYSIS AND PROPERTIES

| | CHEMICAL ANALYSIS | | | | | | MECHANICAL PROPERTIES | | | | |
| | | | | | | | Y.S. | | T.S. | | ELONG. |
HEAT NO.	C	Fe	N	Al	V	H	Kg/mm²	PSI	Kg/mm²	PSI	%
K-4590*	.022	.13	.010	6.0	4.2	.004	94.1	133,800	100.3	142,600	12.0
							94.7	134,700	102.9	146,300	13.5
K-4587**	.026	.12	.014	6.0	4.1	.007	100.3	142,600	105.5	150,?00	11.0
K-6716*	.022	.08	.009	6.0	4.2	.008	95.1	135,300	102.5	145,800	9.0
							101.5	144,400	108.3	154,000	13.5

Certified by:

* Titanium Metals Corporation

** Universal Titanium Corporation

A.

FLAME SPRAYED
ZIRCONIA EDGES

COPPER
WIRES

AISI TYPE 321
STAINLESS STEEL
TOOLING BAR

B.

FIBERFRAX PRESSURE
PADS

Ti-6Al-4V TOOLING
BAR

C.

ZIRCAR PRESSURE PAD
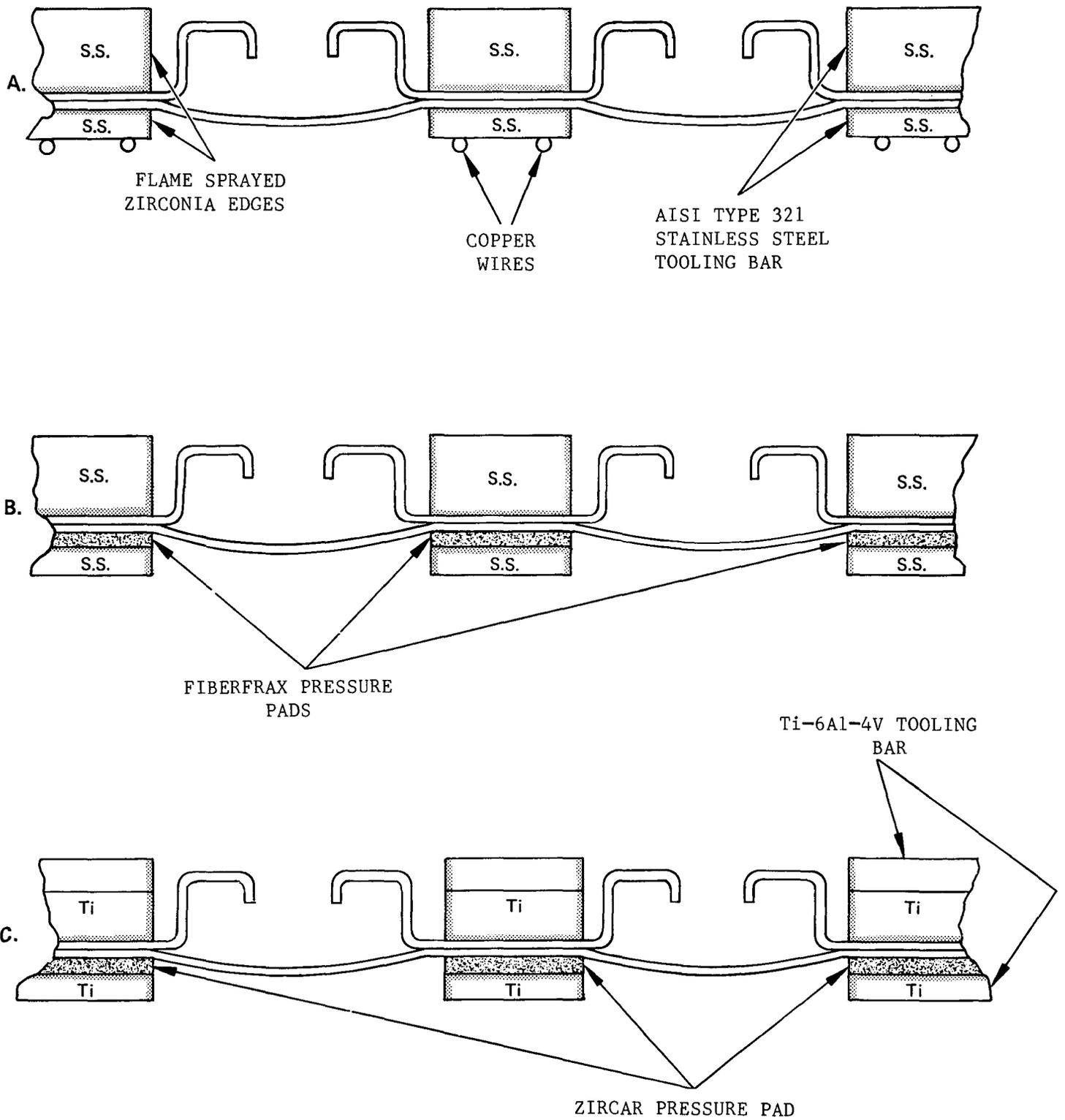
FIGURE 4. TOOLING TO ACHIEVE PRESSURE ON THE JOINT

bars and a layer of Fiberfrax* between one bar and the titanium parts (Figure 4B). Based on the test results, we concluded that the most reliable technique for achieving good fit-up on a wide faying surface was to use a compressible fiber-like material such as Fiberfrax.

The binder and the silicon dioxide portions of the Fiberfrax were found to contaminate the surface of the titanium. Therefore, we evaluated a second compression pad using the zirconia fiber material, Zircar**. This pad produced good fit-up between the titanium surfaces and does not contaminate the surface of the titanium either visually or microstructurally. The problem with this material is that it is a very loosely bound pad and is therefore quite fragile.

Wave-shaped facesheet wrinkling, which was very noticeable in the first full-size trial-run panel, was thought to be associated with the difference in thermal expansion between the stainless steel and the titanium parts. Therefore, the stainless steel bars were replaced with titanium bars, resulting in the final tooling configuration shown in Figure 4C. This final pressure tooling appeared to apply a uniform pressure with no contamination across the entire faying surface of the channels and wave-shaped facesheet.

The Evolution of the Shaped Tooling

Another important tooling requirement was that of maintaining the shape of the formed Ti-6Al-4V parts. The initial concept was to braze the panel with the hat-sections up and the channel edges supported using a molybdenum foil formed as shown in Figure 5A. The panels brazed with this tooling exhibited dimpling and sinusoidal undulation across the curved surfaces of the wave-shaped facesheet. Several causes and corrections for this problem were postulated; e.g., non-uniform heating, caused by a difference in heat sink between the pressure tooling and lightweight wave area, constrained expansion and contraction due to the tooling pressures, etc. This resulted in changing of the pressure bars to titanium and in clamping the wave form with two curved pieces of stainless steel. These pieces fit one on each side of the wave-shape like a clamshell, as illustrated in Figure 5B. At first, a molybdenum foil shape was used to control the configuration of the channel flanges and match the clamshell. This configuration straightened out the wave form sheet. However, sticking occurred between the molybdenum foil and the titanium hat-sections. This resulted in the final tooling evolution in which a stainless steel sheet box beam was made to keep the channels separated and to support the stainless steel clamshell (Figure 5C). In addition, at this time, the panel was rotated 180 degrees such that it was brazed with the hat-sections down and the wave-form facesheet up. This tooling arrangement is the one used for brazing panels 3, 4, 5, and 6.

Figure 6 shows a cross-section of the panel with the stainless retort, stainless steel slip sheets, titanium slip sheets, titanium bars, Zircar pad, and the shape control tooling as used for the final four panels. Table II presents a summary of the TPS panel fabrication tooling.

*Registered Trademark - Carborundum Company
**Registered Trademark - Union Carbide Corporation
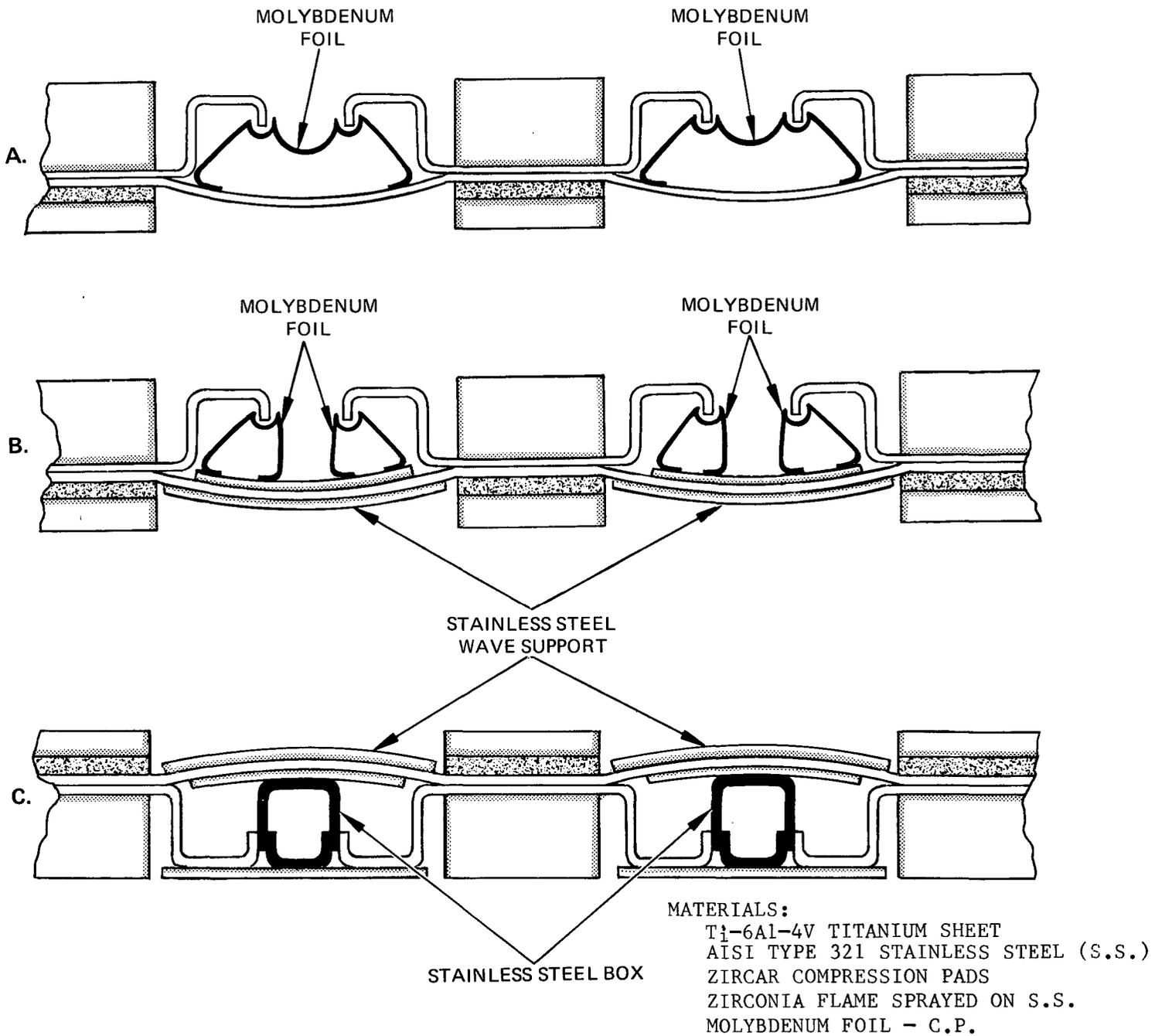
FIGURE 5. SUPPORT TOOLING FOR HOLDING SHAPE
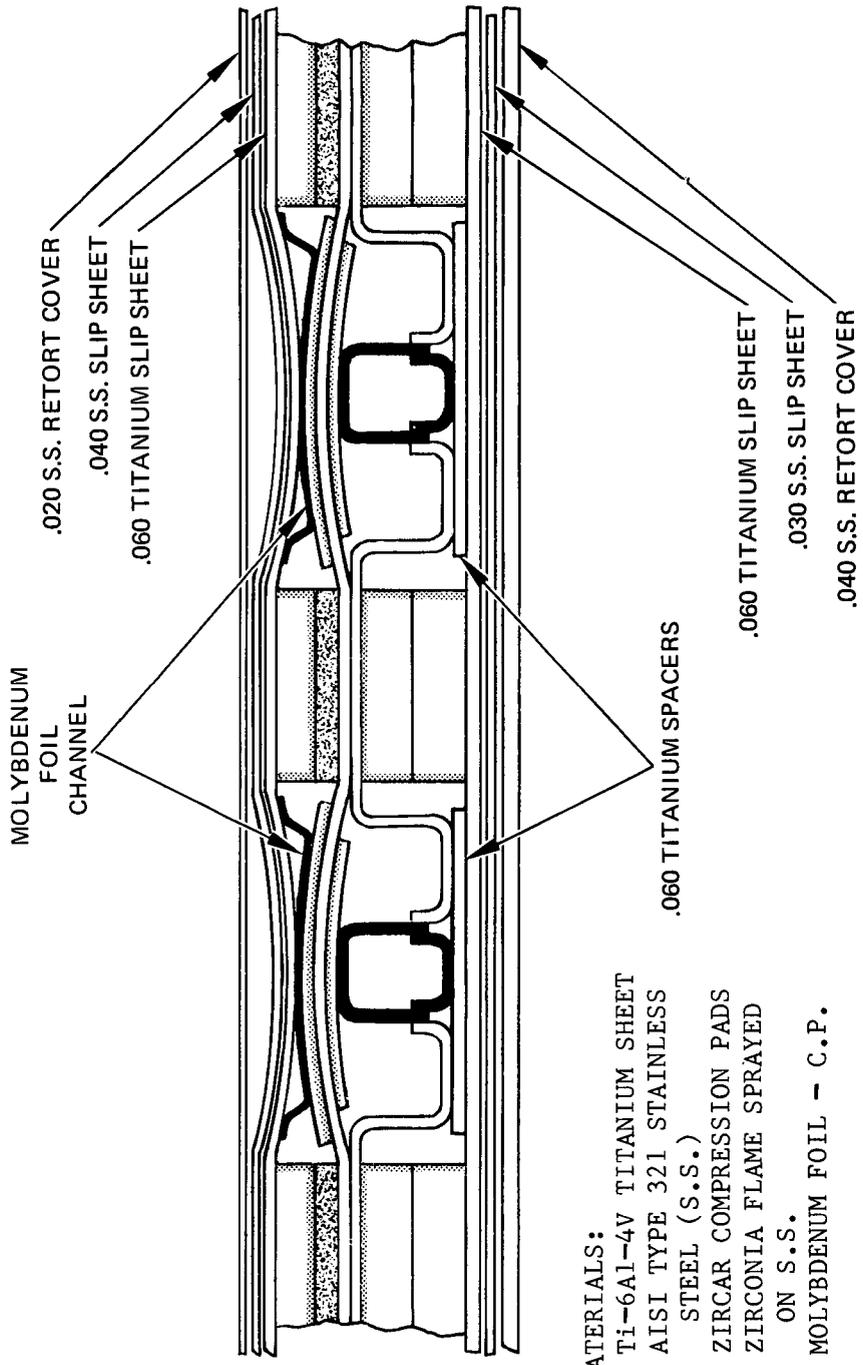
MATERIALS:
Ti-6Al-4V TITANIUM SHEET
AISI TYPE 321 STAINLESS STEEL (S.S.)
ZIRCAR COMPRESSION PADS
ZIRCONIA FLAME SPRAYED ON S.S.
MOLYBDENUM FOIL — C.P.

.020 S.S. RETORT COVER

.040 S.S. SLIP SHEET

.060 TITANIUM SLIP SHEET

.060 TITANIUM SLIP SHEET

.030 S.S. SLIP SHEET

.040 S.S. RETORT COVER

MOLYBDENUM
FOIL
CHANNEL

.060 TITANIUM SPACERS

MATERIALS:
Ti-6Al-4V TITANIUM SHEET
AISI TYPE 321 STAINLESS
STEEL (S.S.)
ZIRCAR COMPRESSION PADS
ZIRCONIA FLAME SPRAYED
ON S.S.
MOLYBDENUM FOIL - C.P.

FIGURE 6. RETORT, TOOLING AND PANEL ASSEMBLY FOR BRAZING TPS PANELS

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TABLE II

SUMMARY OF TPS PANEL FABRICATION

PANEL	FABRICATION NOTES	REMARKS
Sub Size	Used copper wire gasket and Fiberfrax Figures 4A,4B, & tooling as per Figure 5A. Varied copper foil width. Diffusion treated 925C (1700F). 2.5 hrs.	Fiberfrax compression pads produced best joints. 1" wide copper foil best, 7.1% copper in joint after 2½ hrs. at 925C (1700F).
No. 1	Used stainless steel compression bars & Zircar compression pads as per Figure 4B. Tooling as per Figure 5A. Included Q.C. test section with copper foil cutouts. Increased diffusion time to 3 hrs. at 925C (1700F).	Joints appeared good & uniform. Joint microstructure good, Figure 2, & maximum copper was 6.4%. Waves in facesheet had dimples.
No. 2	Used titanium compression bars & Zircar as per Figure 4C, with support tooling as per Figure 5B. Diffusion treated 925C (1700F).	Stainless steel clamshells decreased dimples but molybdenum tooling stuck to part. Edges of hats were bent slightly due to height of molybdenum tooling. Ridges at ends of hats due to slippage of end tooling.
No. 3	Tooling as per Figure 4C, 5C, & Figure 6. Diffusion treated 925C (1700F) 3 hrs.	Very good visual appearance.
No. 4	Tooling as per Figure 4C, 5C, & Figure 6. Diffusion treated 925C (1700F) 3 hrs.	Very good visual appearance.
No. 5	Tooling as per Figure 4C, 5C, & Figure 6. Diffusion treated 925C (1700F) 3 hrs.	Very good visual appearance.
No. 6	Tooling as per Figure 4C, 5C, & Figure 6. Diffusion treated 925C (1700F) 3 hrs.	Overall appearance satisfactory but had ridges at ends of hats due to tool slippage.

Copper Quantity Control

The exact quantities of copper for optimum joint characteristics vary somewhat with the configuration of the panel being joined, with tooling, with fit-up pressures, and with heating rates. Therefore, the first evaluation made in the program was that of copper quantity. Copper foil 0.00076 cm (0.0003-inch) in thickness in various widths was used. The microstructures of these various test widths indicated that there was insignificant squeezing-out of liquid and that the final joint width was essentially that of the copper foil. Therefore, a 2.54 cm (1.0-inch) wide strip of copper foil was used to match the width of the flat on the wave-shaped facesheet.

For the subsize panel brazement, a diffusion treatment of 2-1/2 hours at 925C (1700F) was used. An electron microprobe analysis determined that the maximum copper concentration at the joint center was 7.1 percent. Therefore, we adjusted the diffusion treating cycle to three hours at 925C (1700F). This resulted in a microstructure with a coarse basket-weave of alpha needles and dispersed grains of alpha plus Ti_2Cu compound in a perlitic form (Figure 3). After this treatment, the microprobe analysis indicated a maximum copper concentration of 6.4 percent.

Manufacturing Procedures

The Ti-6Al-4V sheet was shear cut to size prior to forming the hat-sections and the wave-shaped facesheet. The parts were power-brake formed at room temperature. Therefore, normal power-brake forming tolerance and residual stresses are encountered during brazing of these panels. Tighter tolerances and higher production rates would result from automated or closely controlled forming techniques.

After forming and cleaning, the component parts were assembled in the following sequence. Figure 7 shows many of the small component parts of the panel and tooling on the table ready to start assembly. Figure 8 shows the stainless steel brazing retort with the internal slip sheets and the compression bars which are also used to guide the hat-sections. There are small, shaped sections placed on the end of each of these bars to allow for the thickness of the titanium hat-sections. These sections prevent warping of the wave-shaped facesheet at the ends of the hats. Figure 9 shows the positioning of the hat-sections with a copper foil tack welded into position on each hat. Figure 10 shows the stainless steel spacer beams placed between the hat-sections. The stainless tooling to support the ends of the wave section are put into place at this time. Figures 11 and 12 show the clamshell, stainless steel curves placed around the wave-shaped facesheet using tack welded pieces of foil to hold the stainless steel in place. Figure 13 shows the wave-shaped facesheet in place over the channels with a strip of Zircar and a titanium compression bar across each bond area. Figure 14 shows the final slip sheet in position. The cover of the retort is then put on and welded. After a vacuum leak check, the retort is placed into the fused silica die facility shown in Figure 15. The large, white blocks are the heated fused silica tools. The retort is then evacuated to below 4 torr and held overnight. As the panel temperature reaches 540C (1000F), the tools are clamped against the retort, applying a load of 1.76 Kg/cm^2 (25 psi) to the faying surfaces. Simultaneously, the retort is backfilled with hot titanium chip gettered high purity argon to 380 torr. During heating to 925C (1700F), the argon expands and the tool pressure is
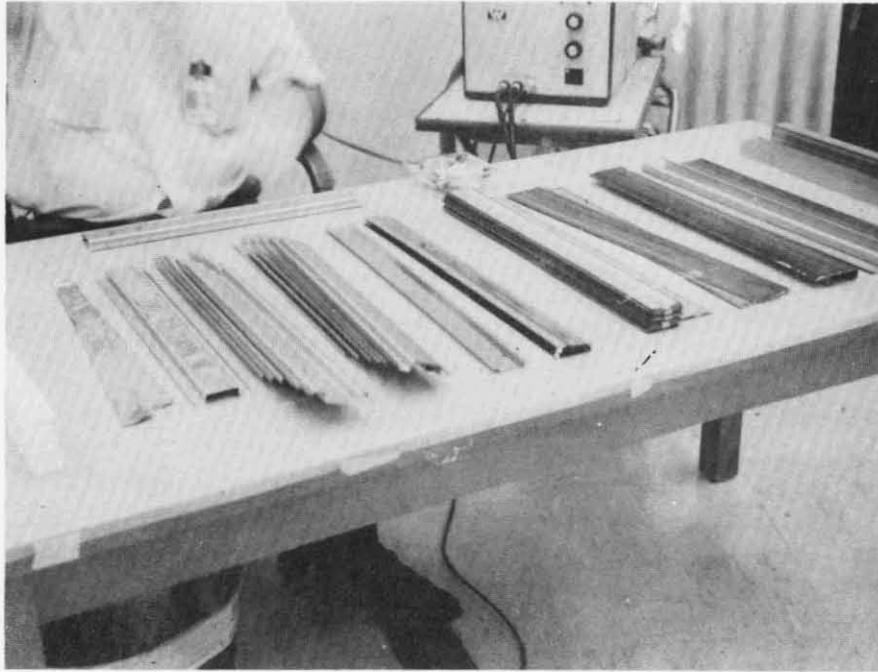
FIGURE 7   SOME OF THE COMPONENTS AND TOOLING USED TO
            BRAZE A PANEL
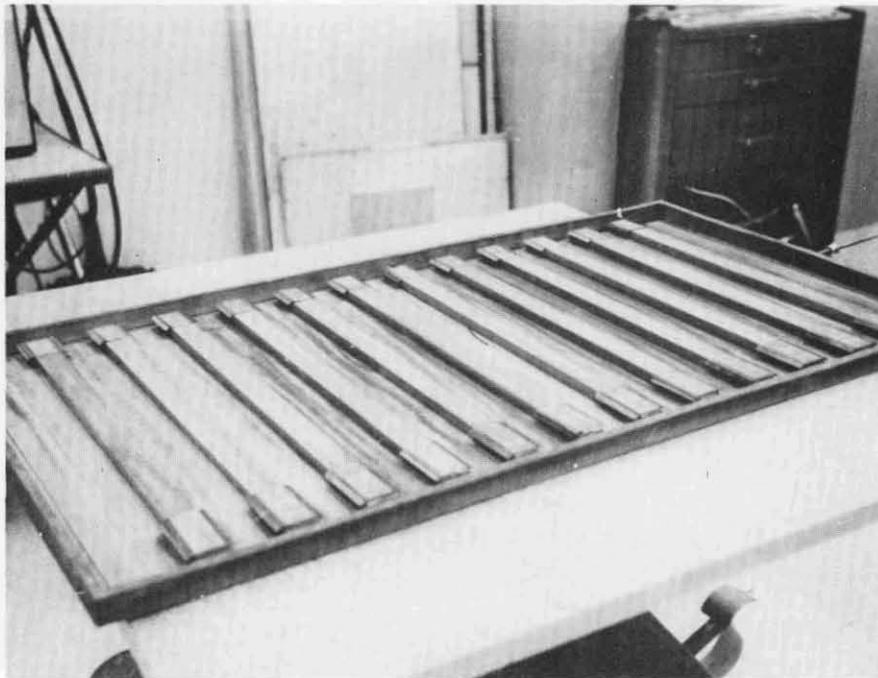
FIGURE 8   STAINLESS STEEL BRAZING RETORT WITH HAT-
            SECTION GUIDE TOOLING IN PLACE

-14-
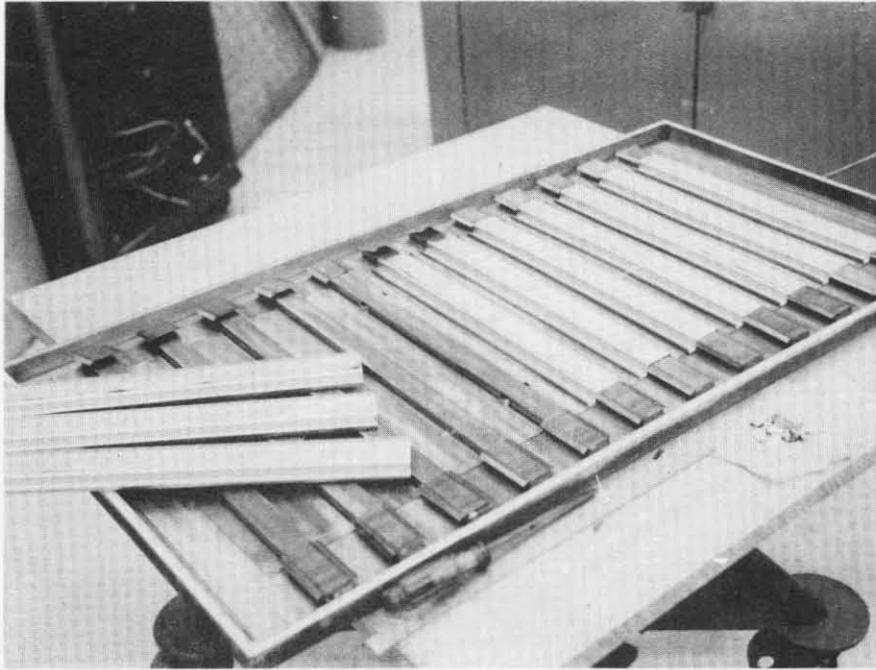
FIGURE 9   HAT-SECTIONS WITH COPPER FOIL ARE PLACED
             INTO THE RETORT
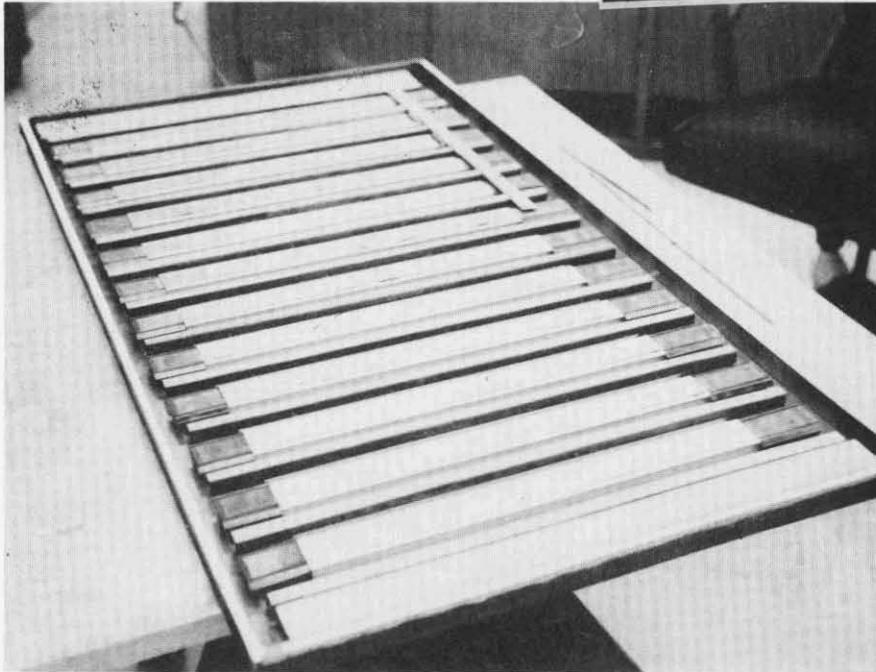
FIGURE 10   HAT-SECTIONS WITH TOOLING IN PLACE
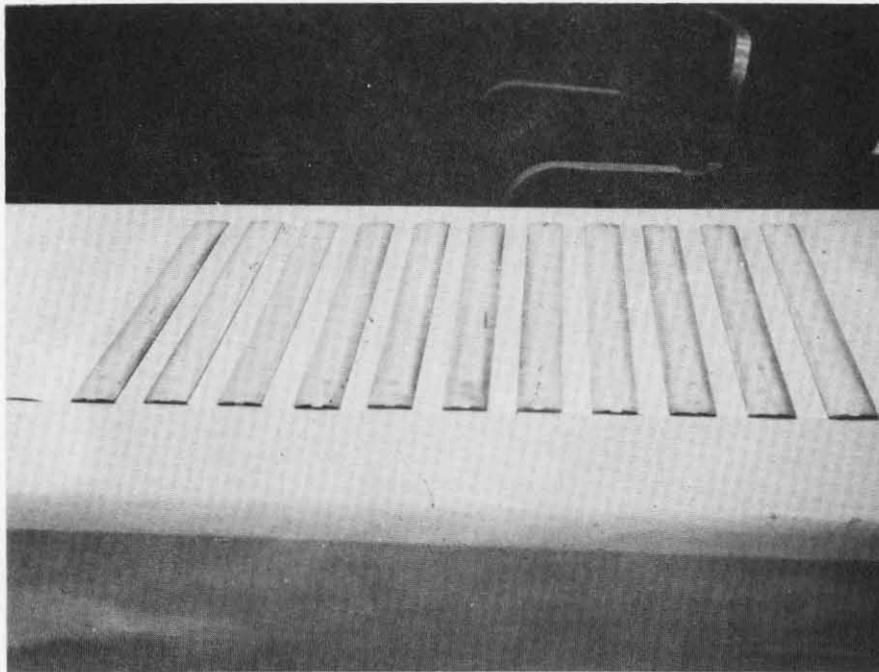
FIGURE 11   STAINLESS STEEL CLAMSHELLS IN PLACE ON THE
WAVE-SHAPED FACESHEET
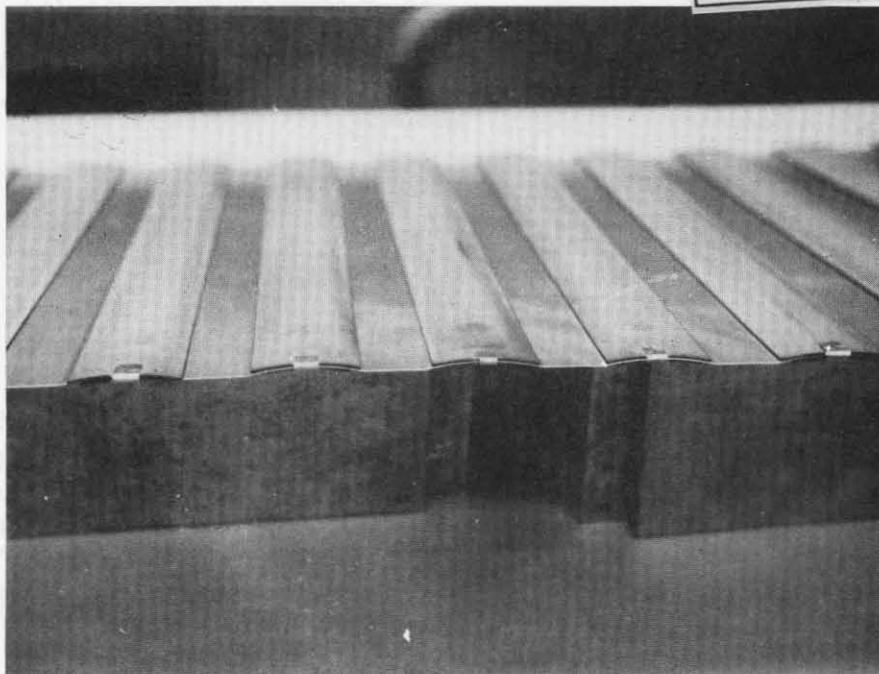
FIGURE 12   SIDE VIEW OF CLAMSHELLS
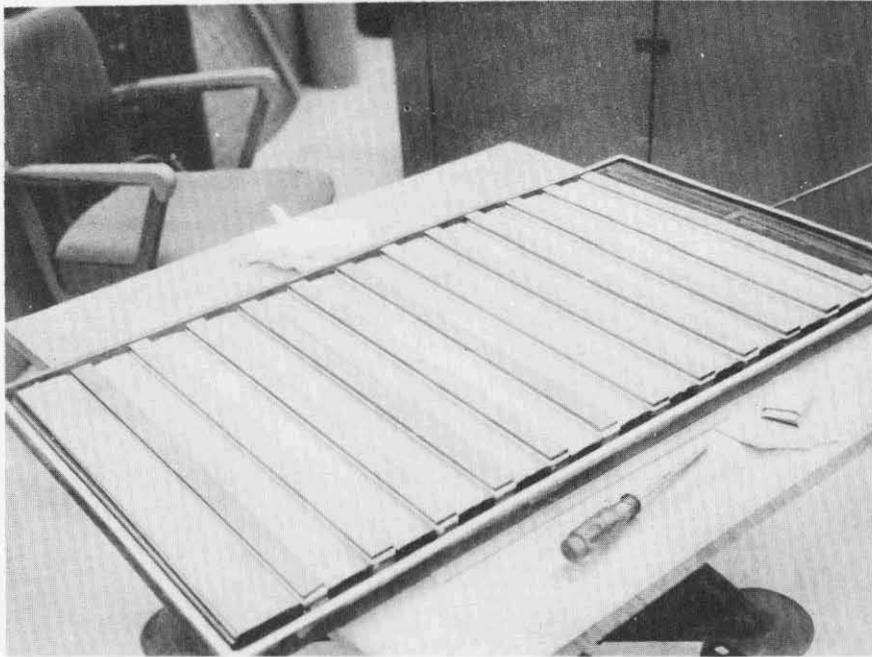
FIGURE 13   COMPRESSION PAD TOOLING IN PLACE ON THE
WAVE-SHAPED FACESHEET
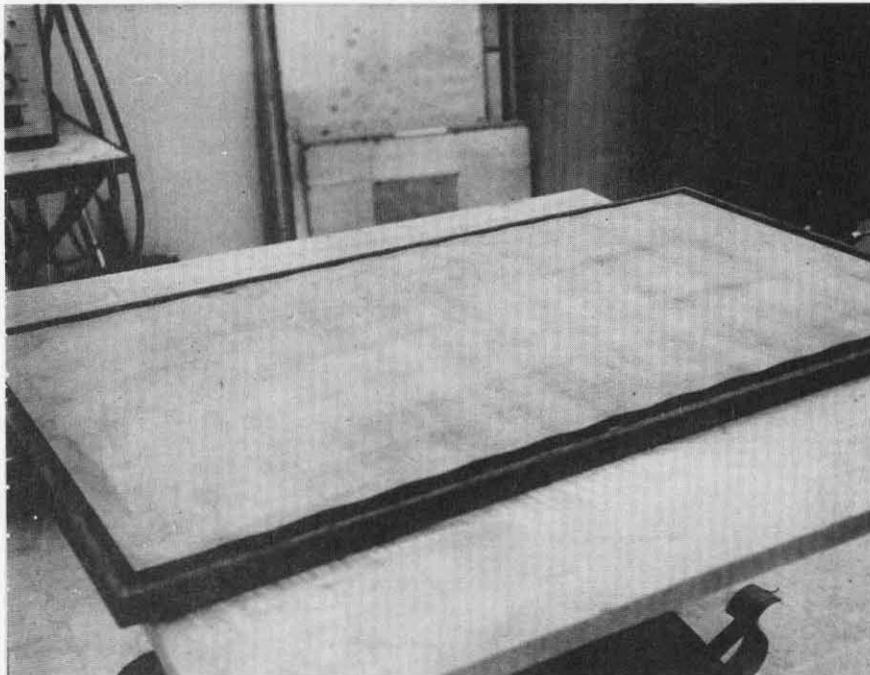
FIGURE 14   ASSEMBLED PANEL READY FOR SEALING IN THE
RETORT
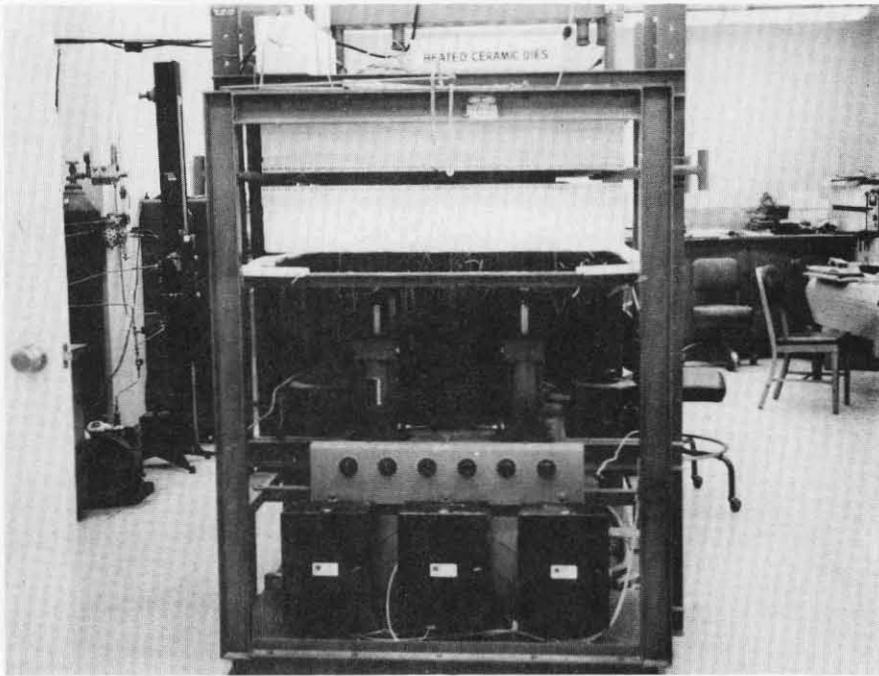
FIGURE 15   SEALED RETORT BETWEEN THE FUSED SILICA
BRAZING TOOLS
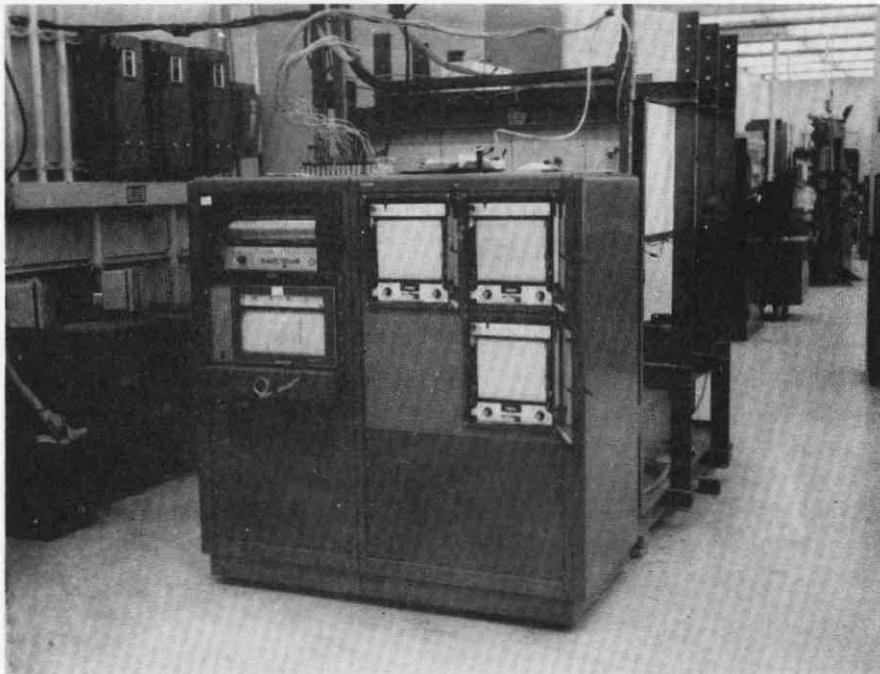
FIGURE 16   BRAZING THE PANEL

FIGURE 17   TPS PANEL AFTER REMOVAL FROM BRAZING
             RETORT
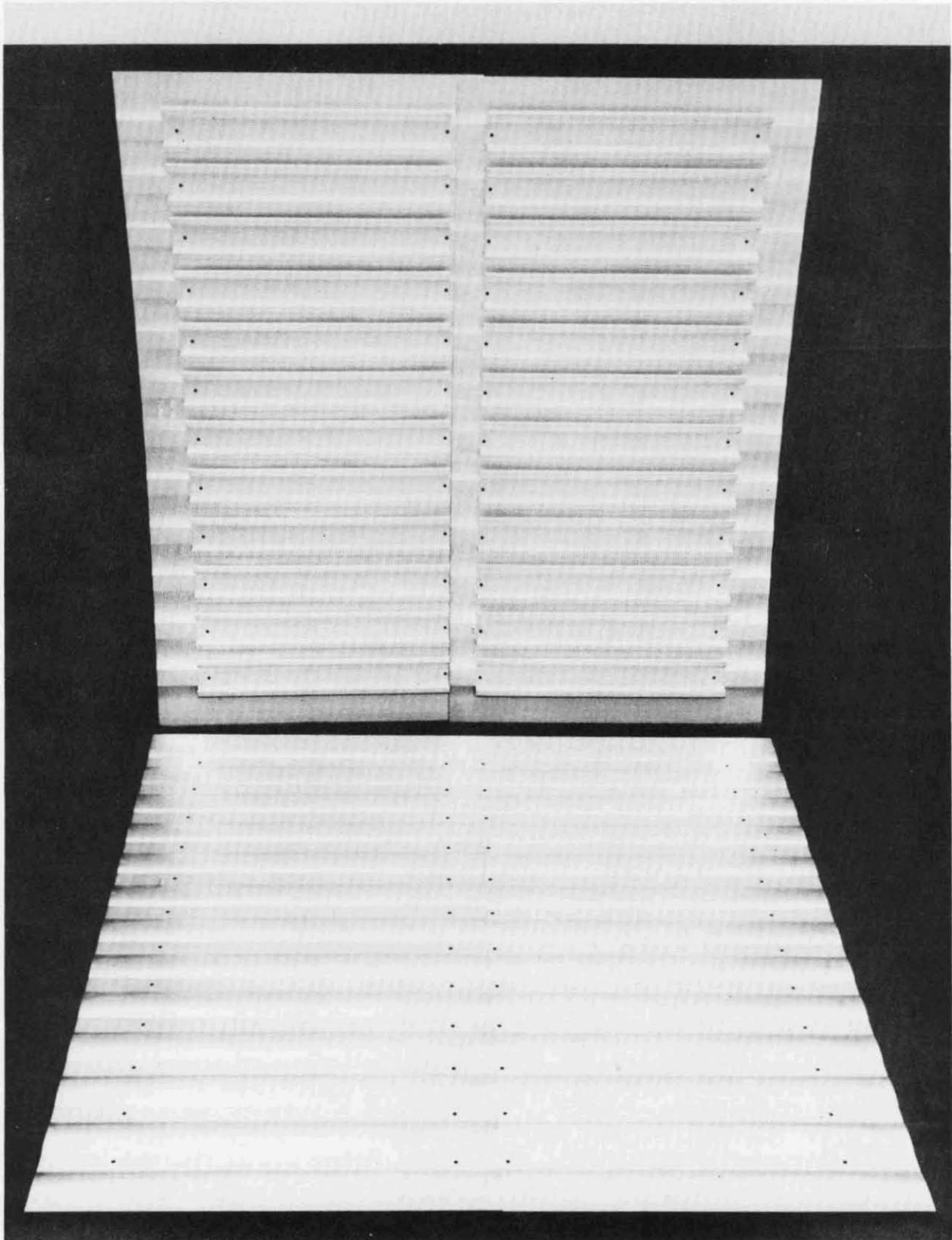
FIGURE 18   FINISHED TPS PANELS

increased to maintain a faying surface clamping pressure of 26.8 Kg/cm^2 (38 psi). Pressure is reduced for the diffusion cycle to about 8.9 Kg/cm^2 (12.7 psi). Figure 16 shows the operating configuration for the brazing facility, complete with the side insulation in place. The brazed TPS panels are shown in Figures 17 and 18. After cleaning, all metal tooling parts are reusable. Due to crushing, the Zircar compression pad is not reusable.

## Nondestructive Testing of the Panels

The ultrasonic testing techniques were standardized based upon the subsize panel and the first full-size panel, both of which were sectioned. To establish the through transmission ultrasonic driving force criteria, the same joints were scanned with power setting varying from 24 to 36 decibels. These areas were also X-rayed and the suspect regions were sectioned and examined microstructurally. Based upon the joint width as determined by microstructure and X-ray, an ultrasonic scanning power was set at 28 db. This power level is a compromise for inspecting the entire area of the panels, as any void or the joint width could be made to look large or small, depending upon the driving force used. It was found that this level gives most realistic indications of joint width. Unfortunately, this power setting tends to exaggerate other areas of questionable quality. Thus, areas which appear as a void in a few of the joints are, in reality, a partially joined region in which small voids, perhaps of 0.050 cm (0.020-inch) to 0.070 cm (0.028-inch) in diameter, alternate with bonded areas of similar size. However, the exact correlation of these ultrasonic indication areas with X-ray and microstructure was not accomplished during the course of this program. Such determinations could be developed with suitable standards which could be fabricated for calibrating the equipment and then sectioned to verify the structures.

The through transmission ultrasonic C-scans were made with a 725 Immerscope using a 1.29 cm (1/2-inch) SIL transducer with a frequency of 2.25 Mhz. It was set up as follows:

STC—0
Sens — 9
Dampening — 10
Gate Level — 190
Rej. Off PRF — 1250
Attenuation — 28 db

The C-scan was parallel to the hat-sections.

Various details of the joints were discernable using the X-ray technique. The X-ray films identify the actual joint width and differentiate between the joint width and areas along the sides of the half sections where voids are present. In some areas within the joints, ultrasonic indications of voids appear to have a somewhat mottled or spotted appearance on the X-ray. Perhaps this indicates a sensitivity to the amount of copper.

It is believed that the X-ray technique is sufficiently sensitive to detect copper concentration changes of only a few percent. Thus, correlations could be made between the X-ray film density and the actual shear

strength and, perhaps, fracture toughness of the joints. This would require the development of a series of standards which could be studied for copper concentration, strength, and toughness. This development was beyond the scope of this program.

The X-ray photographs were made with a Picker 160KUP unit using a tungsten target tube. It was operated at:

    5 ma
100 KV
234 cm (92-inch) Focal Length
  2.5 Minute Exposure

The Kodak Type M film was developed with standard procedures.

Preparation of Samples for NASA Test

The 5.08 cm (2-inch) gage length tensile specimens were cut from scrap portions of the K-4587 stock. Half of the specimens were left "as-received" and the others were exposed to the complete bonding cycle.

Other pieces of this sheet stock were set up and brazed to form lap joints. An overlap of 0.080 cm (0.030-inch) to 0.100 cm (0.040-inch) was striven for, giving overlaps of 1.45T to 1.8T. One specimen slipped, giving a 2.3T overlap of 0.130 cm (0.05-inch). These specimens were NOR-Ti-BONDED using the copper foil, step tooling argon atmosphere retort, and diffusion cycle to approximate the brazing cycle used for the TPS panels.

Hat-sections to wave-shaped facesheet joints were cut from hats 9, 10, and 11 of TPS panel No. 1. The sections were 10 to 18 cm from the channel end.

All of these specimens were shipped to NASA for evaluation.

ANALYSIS

Analysis of the Fabrication Steps

Many things can be done to increase fabrication efficiency of these panels. To start with, consider the basic steps in the fabrication of the panel:

1. Shear, layout, and brake form the metal components.

2. Clean the components.

3. Cut the copper foil and the Zircar compression pads.

4. Clean the retort and various pieces of tooling, including tool repair.

5. Tack weld copper foil onto the hat-sections.

6. Place the hat-sections into the retort tooling, along with the box beam tooling for supporting the clamshells.

7. Weld the clamshells around the wave-form facesheet.

8. Locate the wave-shaped facesheet and top slip sheets.

9. Weld the retort closed and vacuum check.

10. Place the retort into the brazing facility and check the facility prior to brazing.

11. Braze the panel.

12. Disassemble the brazing facility and open the retort.

13. Inspect the panel.

Several things can be done to increase the efficiency in fabricating these panels. A hot feeder die machine, such as the one which Northrop has developed, could be used to fabricate long lengths of the hat-section more accurately than they can be formed as individual pieces. An added advantage would be that the hat-sections would be stress relieved. These long lengths could then be cleaned, cut to size, and given a final cleaning.

Likewise, more efficient procedures could be used to fabricate the wave-shaped facesheet. These improvements would be helpful in two ways. One, the tolerance variations would be less from piece to piece, and, secondly, they would be more economical.

Cleaning could be performed on larger batches of parts, resulting in a large number of pieces being cleaned for approximately the same cost as cleaning the components for two panels at a time.

The copper foil could be purchased slit to width such that it could be stretched out and cut to length on the job. Hopefully, improvements can be made in compression pad materials such as Zircar such that it would also come in cut-to-width strips and be less fragile. At this time, Zircar does not appear to be a satisfactory production material as the handling of this fragile material is difficult. Certainly, improvements would have to be made or else another type of compression pad would have to be found before large quantities of these panels could be economically fabricated.

The tooling which was developed piece-meal for this program could be fabricated with far fewer pieces such that the set-up and cleaning time would be reduced. Closer tolerances resulting from automated fabrication of both the hats and the wave-shaped facesheets would also speed up the set-up of parts prior to the brazing operation.

Most of the handling of these components and certainly the time required for brazing is the same whether you are constructing 51 cm (20-inch) by 99 cm (39-inch) panel or a 91 cm (36-inch) by 99 cm (39-inch) panel. Thus, cost reductions could be realized by fabricating larger sections. This, of course, only holds true up to a point where the large size of the panel makes it awkward for people working with the parts. When this

point is reached, set-up time will increase. An ideal size, economically, would be about 200 cm (79-inches) square. The brazing operation itself can be automated with only periodic checks by an operator. One operator could probably be working with two or perhaps three brazing fixtures at one time.

The time required for nondestructive testing can be reduced as more automated techniques and better standards are used and as operator familiarity with the panels is developed.

Interpretation of NDT Results

For purposes of this detailed discussion, a reduced-in-size reproduction of the ultrasonic scan and the X-ray films will be used from TPS panel No. 2. The full-size inspection data for each of the five panels is shipped with the panels. An examination of the ultrasonic trace (Figure 19) and of the X-ray prints (Figures 20, 21, and 22) shows that hat-sections No. 2, 5, 7, and 9 are well joined, full width joints. Hat-sections 1, 4, 6, 8, 11, and 12 are well joined but have a somewhat narrower joint width. Hat-sections No. 3 and 10 have narrow joint widths (W-W) occuring along their length. In almost all cases, it would appear that no significant voids occur throughout the center portion of the joints. Small disbonds are noted on the ultrasonic traces at the ends of hat-sections 2, 3, and 4(A). However, the X-ray only shows a small void at the end of section 3. Various reasons can be given for these defects. The slight end defect on hat-section No. 3 probably occurred due to a slip of the shimming stock used to support the end during joining.

The joint width problems are a little more difficult to pin down. They can be caused by slight crowning during the forming operation of the flat of the facesheet or of the flat of the hat-section, or by the tendency for the Zircar to powder around the edges, or by unevenness of the flame sprayed-pressure bar, or by the tooling height which supports the clamshells on the wave portion of the facesheet. If this height were incorrect, it would tend to lift the sheet, causing a larger gap between the sheet and the hat-section.

The corrections for these problems would be to modify the tooling as follows: carefully check the thickness and position of the end shim to eliminate the end gaps. This condition is aggravated by slight changes in the thickness of the hat-sections such that consistent errors will not occur in this region. The joint width problems can be corrected by better forming of the parts, by widening the bars and the compression pad to a greater width such that edge effects will not show up in joint quality, by improving the flame-sprayed bar, and, finally, by carefully matching the clamshell support tooling to the height of the waves in the facesheet. Part of this problem can be related to inconsistencies in hand forming of the wave-shaped facesheet and part of the correction would be to fabricate more consistent facesheets.

A few of the areas which show up on the ultrasonic trace and which show very dimly on the X-rays can be pointed out on the side of hat-section 2(B), at the top side of hat-section 3(C), and along the side near the top of section 4(D), and near the center top of section 5(E). Each of these indicate that something has occurred in this region. The exact

-24-
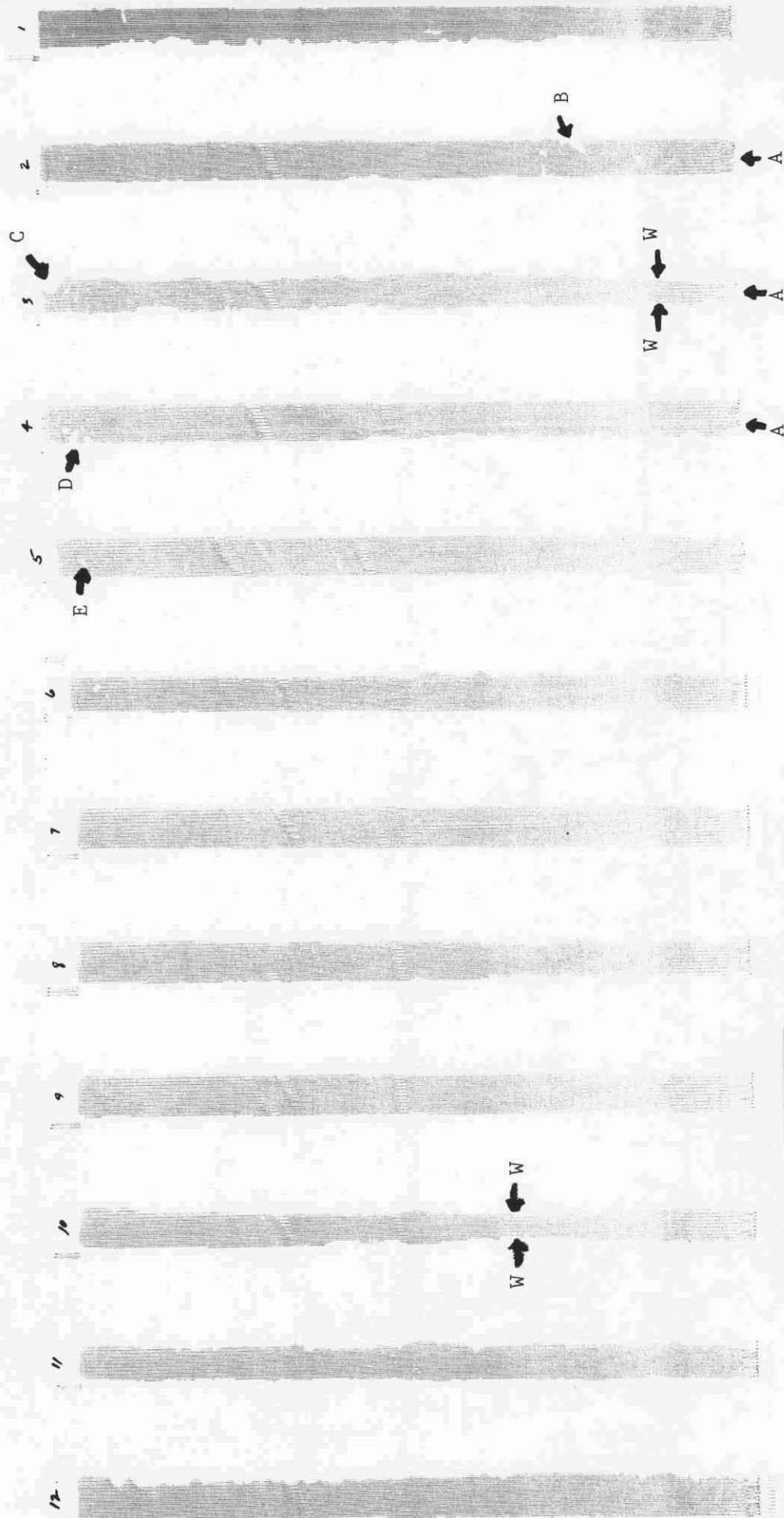
FIGURE '19   ULTRASONIC TRACE FROM TPS PANEL NO. 2.   APPROX. 1/4 SIZE.

-25-
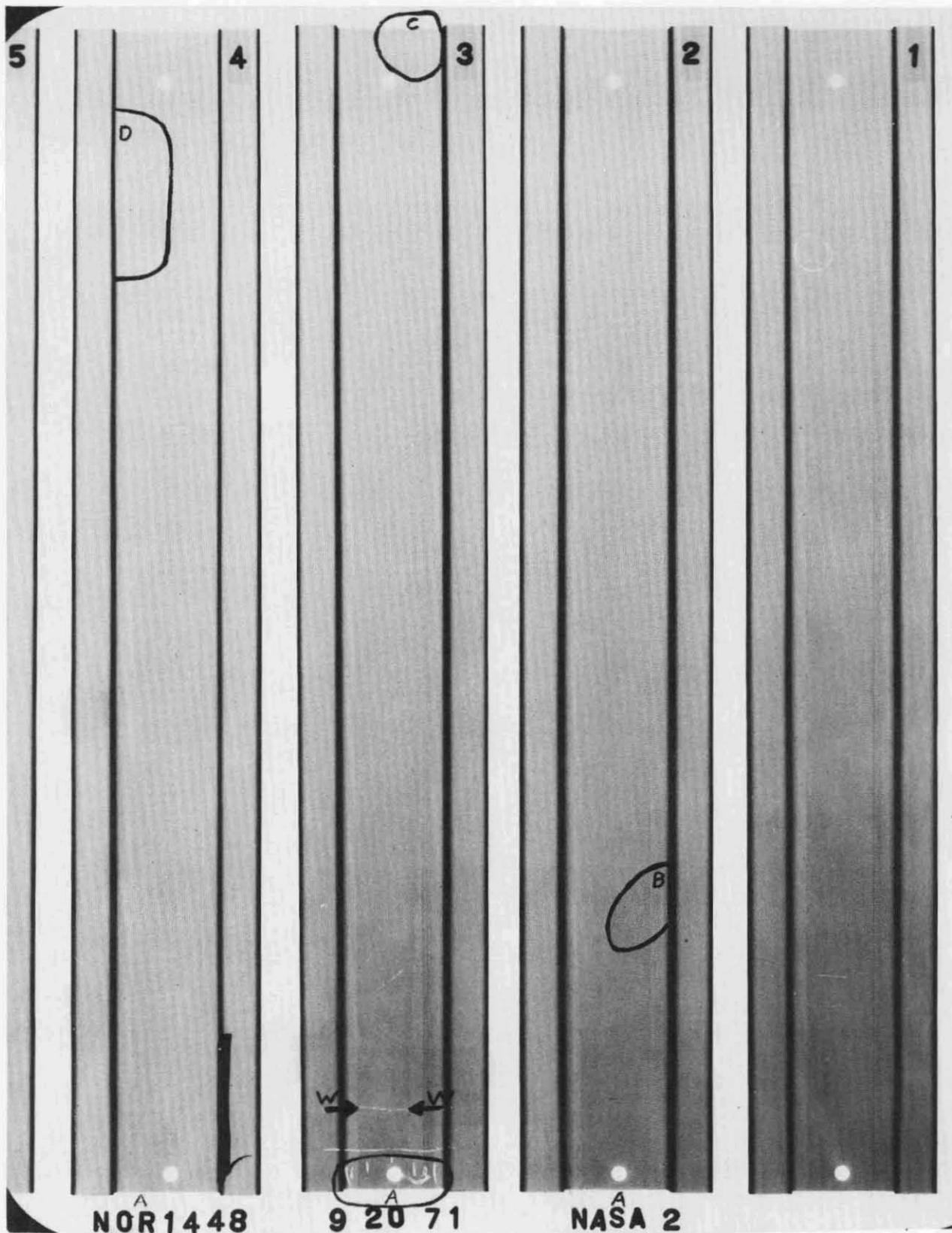
FIGURE 20   X-RAY OF HATS 1 TO 4 OF TPS PANEL NO. 2.   0.6 SIZE
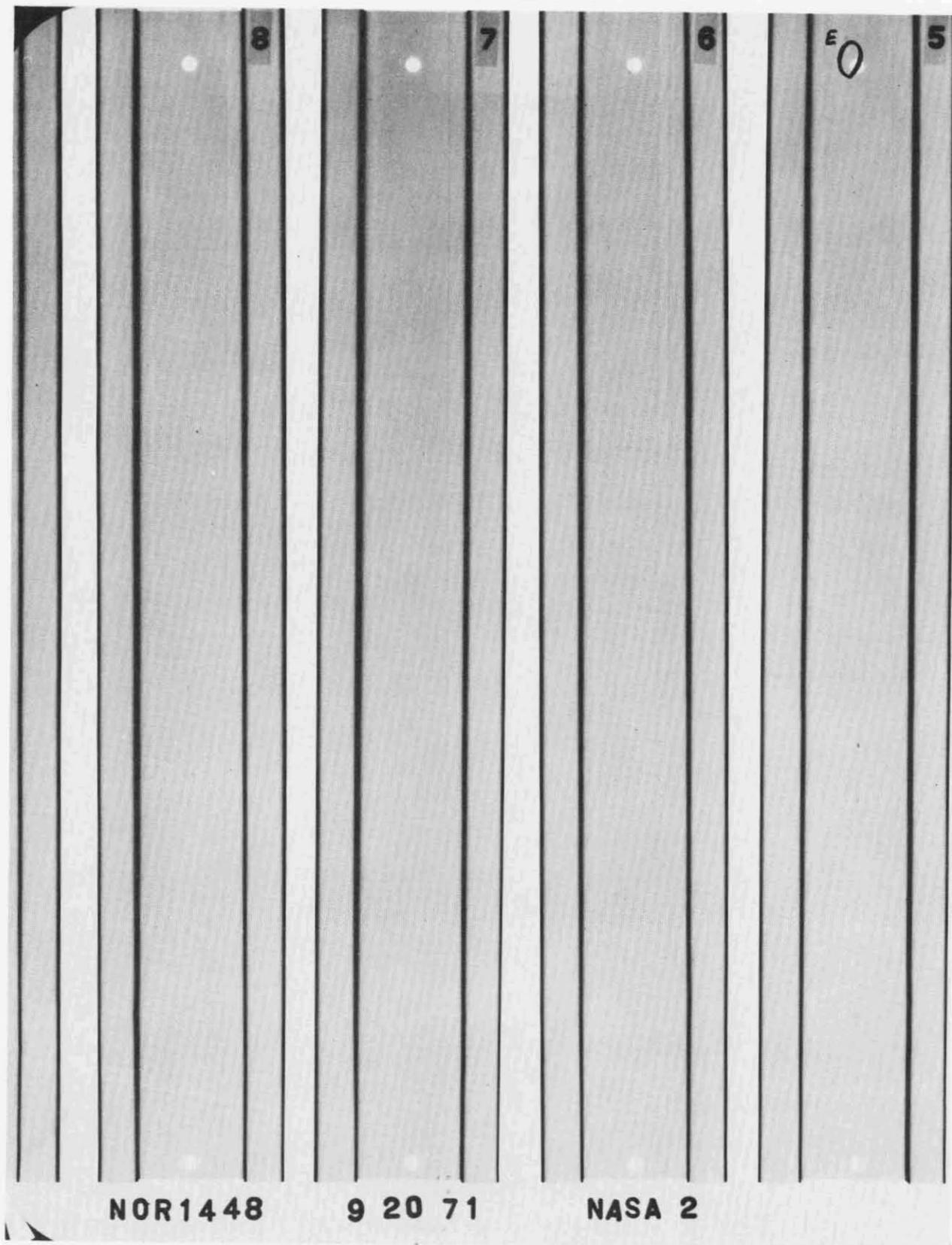
FIGURE 21   X-RAY OF HATS 5 TO 8 OF TPS PANEL NO. 2.   0.6 SIZE
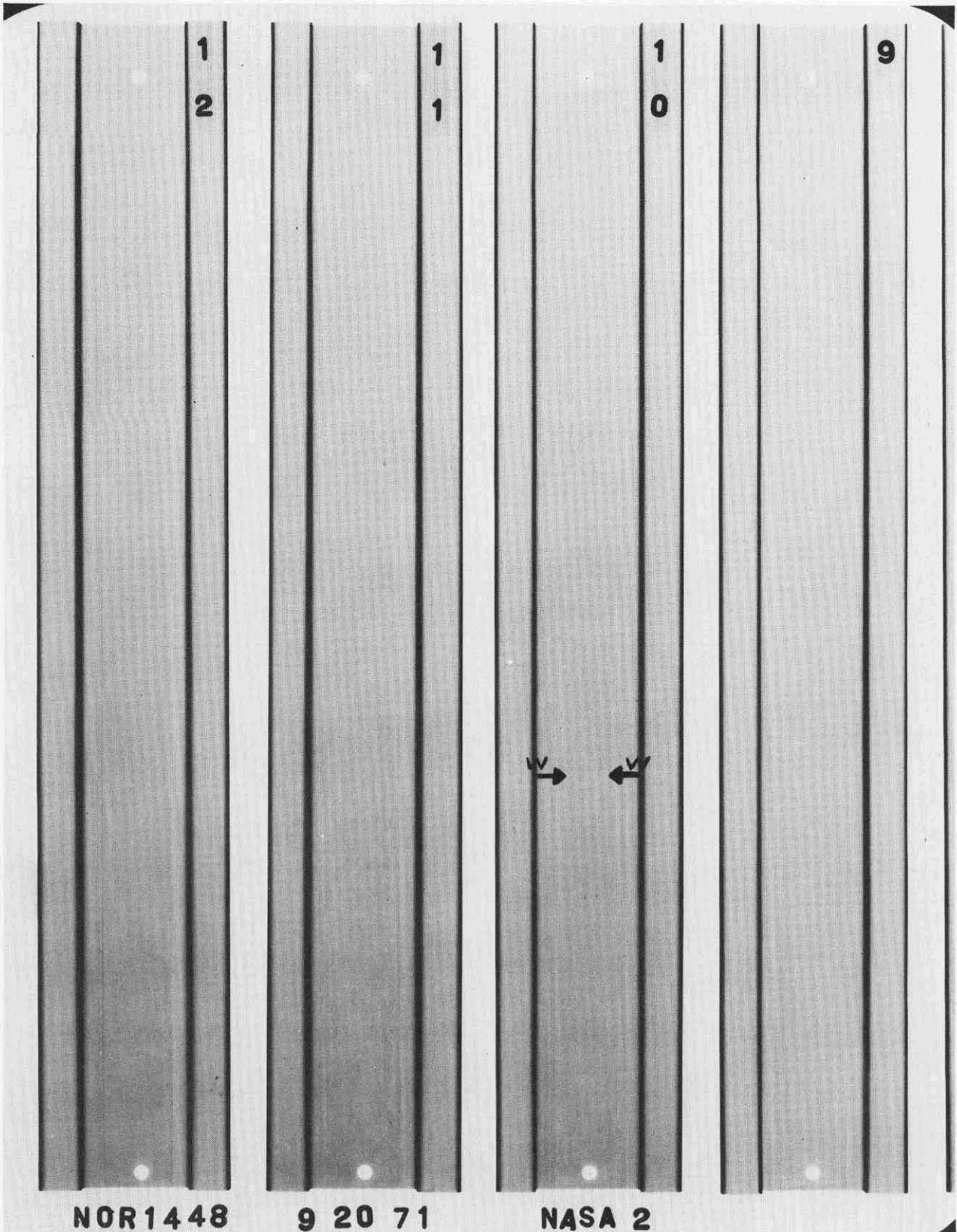
FIGURE 22   X-RAY OF HATS 9 TO 12 OF TPS PANEL NO. 2.   0.6 SIZE

interpretation of these spots is uncertain as panels could not be sectioned. It is possible, but somewhat doubtful, that these are voids. More likely, they are partially joined regions, that is, a mixture of void and joint, or even an area in which the composition of the joint varies from that of the surrounding area. The X-rays indicate that these areas are slightly less dense than the surrounding area. These slightly less dense indications could be that of a void or it could also be areas in which the copper-containing liquid has been squeezed out, thus minimizing the quantity of copper in that region. Or it could be that a wrinkled copper foil was used, which entrapped argon gas, causing a small gas pocket to be formed. Insufficient standards are available at this time for confirming what these indications really mean.

NDT Analysis of Individual Panels

TPS Panel No. 1 - This first full-size panel was fabricated as a combination NDT Standards panel and tooling check-out panel. It indicated some tooling difficulties in that the wave portion of the wave-shaped facesheet contained ripples. As indicated before, several ideas were postulated as to why this had occurred, and various tooling corrections were made. The panel was used for microstructural tests and as an NDT specimen in that, after inspecting the panel, we were able to cut it apart and investigate the indicated areas. In this manner, we were able to reject false indications and accept other indications as being reliable.

TPS Panel No. 2 - This panel shows visual improvement over No. 1 in that fewer ripples occurred in the wave-shaped facesheet. However, several creases occurred across the flats at the end of the hat-section to facesheet joint. These creases occurred on hat-sections No. 3, 5, 9, 10, 11, and 12. Their cause was traced to a shifting of the spacer pieces used to compensate for the thickness of the hat-section.

The curvature of the wave appeared satisfactory, and the general configuration of the hat-sections is satisfactory. Some opening of the hat-section channels occurred. This led to a change in tooling for supporting the hat-section bends of the next panel. Two NDT inspections were conducted using through transmission ultrasonics and X-ray. The results of these two tests collaborate that hat-section No. 1 has some disbond on the one side of the faying surface. No. 2 seems to be quite good with a couple of small indications occurring which, at this time, cannot be adequately verified or identified. Hat-section No. 3 has a somewhat narrow joint with some disbond along either side of the hat-section. Nos. 4, 5, 6, 7, 8, and 9 are good joints. No. 10 is the narrowest joint on the panel. In one section of No. 9, the faying surface is only 1.5 cm (0.59-inch) in width. Hat-section Nos. 11 and 12 had some disbond along one side, but are reasonably good.

TPS Panel No. 3 - The appearance of the wave-shaped facesheet is quite good with only a couple of very small ripples and dents occurring. The hat-sections themselves appear to be quite well formed and reasonably well spaced.

The ultrasonic traces on Panel No. 3 indicate that it is reasonably well joined. There is, perhaps, some void along one part of the side of channel No. 1. However, this also appears to be associated with an area

in which the channel has an excess bend and it may be that it is bent
somewhat out of the plane of the ultrasonic trace. The X-ray for the
same area does not, in this case, clarify whether this is a void or
merely an area with a different copper content than the surrounding areas.
Hat-section No. 2 appears to be quite well bonded, No. 3 has just a little
edge disbond, No. 4 is excellent, No. 5 is probably the narrowest of the
bonds, about 2 cm (0.79-inch) wide in some areas. Nos. 6 through 12 are
reasonably well bonded. Hat-section Nos. 7 and 8 had a bend-over region
similar to No. 1.

TPS Panel No. 4 — The visual appearance of the wave-shaped facesheet
is excellent with very little rippling occurring over the entire sheet.
The hat-section side of this panel appears quite good. The spacing of the
channels was improved due to a changing in the clamshell support tooling
to the rectangular-shaped beam.

The ultrasonic traces show that hat-section No. 1 has a narrow fay-
ing surface, tapering down to 1.5 cm (0.59-inch). Again, this is only
partially verified with X-ray and is associated with some bending in the
hat-section. No. 2 shows the same thing at the other end of the hat-sec-
tion and is again associated with bending in the channel. No. 3 is the
same as Nos. 1 and 2. No. 4 appears to be an excellent bond, and this
particular channel does not appear to have this bending problem in the
hat-section. No. 5 apparently has the bending problem again. No. 6 is
an excellent joint, Nos. 7 and 9 show a narrower joint, which once again
is associated with the bending of the hat-section. No. 9 is a good joint,
Nos. 10 and 11 appear to have bending of the hat-section, and No. 12 is a
good joint.

TPS Panel No. 5 — This panel has the best overall appearance of the
panels. NDT inspection indicates that hat-section Nos. 1 and 2 have a
slight narrowing of the joint. Nos. 3 and 4 appear to be excellent joints.
No. 5 has a narrow end, 1.8 cm (0.71-inch) wide, Nos. 6 and 7 have a slight
narrowing of the joint, No. 8 is excellent, and No. 9 is good, except for a
local serration indicated on one side near the mid-point of the hat-section.
This does not appear on the X-ray and, therefore, the meaning of the indi-
cation is not known. No. 10 is an excellent joint, No. 11 has a couple of
small serrations on the side which do not appear on the X-ray. No. 12 is
an excellent joint. Overall, this panel appears to be the best of the
panels fabricated.

TPS Panel No. 6 — This panel repeated the earlier creases running
across the flat of the wave-shaped facesheet at the end of the joint to
the hat-section. This crease appears in section Nos. 1, 2, 3, 5, 6, and
11. The channels are well spaced. A 1 cm (0.39-inch) long crack opened
in the bend radius of channel No. 12. A visual examination of the hat-
section to wavesheet joints at the ends where the creases occur indicate
that there is a void at the end of hat-section Nos. 2, 6, and 11 which
match the creases. Each of these is 0.2 cm (0.079-inch) to 0.4 cm (0.158-
inch) in size.

The NDT testing results indicate that well-bonded joints were achieved
on Nos. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11, with a couple of small voids
which are not verified by X-ray. A few void areas near the end are appar-
ently associated with the drilled holes and cannot be correlated with any-

thing else on the X-ray. Hat-section No. 12 shows several small void areas and one rather large void area. In this case, comparison with the X-ray indicates that there is a slightly mottled or spotted appearance on the X-ray associated with the large void on the ultrasonic trace. A previous comparison of this type of appearance on the X-ray and ultrasonic indicated that the area is probably somewhat unbonded, having some 50% to 60% of the area joined and the rest being void. Apparently, it is not a large, single void.

In summary, if the ultrasonic traces for panel Nos. 2, 3, 4, 5, and 6 are laid out so that sections No. 1 through 12 on the panel Nos. 3, 4, 5, and 6 match sections No. 12 to No. 1 for panel No. 2, certain trends become obvious. First of all, on the end hat-sections, the narrower joint region always occurs on the inside panel side of the joint. Hat-section No. 2 tends to be a mediocre joint in most of the panels. No trend can be given for the third joint — it varies from rather narrow to quite good. The fourth joint tends to be quite good throughout the five panels, and the fifth joint tends to be consistently narrow, with a narrow section occurring in the same location in 4 out of the 5 panels. The sixth hat-section is consistently good throughout the panels. The seventh joint is sporadic. No. 8 tends to be somewhat narrower on all panels. Nos. 9 also tends to be somewhat narrower at one end on all panels. Nos. 10 and 11 are sporadic. These trends of similar patterns appearing in all five panels indicate that the portions of the tooling which were consistent in all five panels had something to do with the width of the joint. The only consistent component in these is the flame-sprayed tooling bar which fits inside the hat-sections. This tooling bar was flame-sprayed with zirconia, and this spraying is somewhat non-uniform in thickness. Therefore, it would appear that the use of new tooling, with a more uniform thickness of zirconia, would produce uniformly wider joints throughout the entire panel. These results also indicate the reasonable consistency in the fabrication of the panels and confirm the reliability of the ultrasonic trace inspection technique.

CONCLUSIONS AND RECOMMENDATIONS

The NOR-Ti-BOND process can be used for fabrication of Space Shuttle thermal protection system panels to produce stiffener-to-facesheet joints with a high percentage of bonded area. This will minimize temperature gradients and thermal stresses resulting from service at elevated temperatures, as compared with panels fabricated by mechanical fastening, resistance spot or seam welding, or fusion welding. Further improvements in the amount of bonded area in the joints, as well as more economical production, could be obtained by appropriate tooling modifications, forming techniques, and modifications in raw material form. Inspection procedures appear to be sufficiently sensitive and reliable to insure successful bonds in production panels. Similarity of joints from panel to panel indicate that the process is reproducible.

Some specific steps that can be taken to improve panel quality further and lower production costs are:

1. Use fewer loose pieces of tooling.
2. Use wider pressure bars with smooth, flame-sprayed surface.
3. Use a thinner compression pad with greater handling strength.
4. Have copper foil pre-slit to size.
5. Fabricate larger panels when possible.

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   ium Alloys," WADC Technical Report 56-146.

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