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THE DEVELOPMENT OF A BONDED COMMON BULKHEAD FOR SATURN

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DOUGLAS

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INTRODUCTION

As a part of the development of the Saturn S-IV/S-IVB stage the Douglas Aircraft Company has pioneered in the development of the cryogenic common bulkhead. The term common bulkhead is derived from the design function of the bulkhead, which is to separate the two cryogenics, liquid hydrogen and liquid oxygen, in a single tank, thereby shortening the stage and eliminating the necessity for two separate bulkheads and the associated interstage structure. The common bulkhead is structurally adequate to withstand both the thermal and the pressure loads from both the hydrogen and the oxygen tanks, and it has sufficient insulation properties to prevent the liquid hydrogen from freezing the liquid oxygen. Another benefit from the common bulkhead is that it permits a reduction in the total length of the vehicle, thereby reducing the bending moments.

DISCUSSION

THE PRESENT BULKHEAD

Figure 1 shows the general arrangement of the Saturn S-IVB stage. The common bulkhead is shown installed on the aft dome. The bulkhead is designed to withstand the full pressure of either the liquid hydrogen tank or the liquid oxygen tank while the other tank is at ambient pressure. This is a rigorous requirement, considering the size of the bulkhead and the necessity for controlling weight. The basic components making up the common bulkhead are aluminum alloy forward and aft domes bonded to a phenolic fiber glass honeycomb core. The S-IV and S-IVB common bulkheads are spherical in shape and differ only in the basic diameter dimension and thickness, and in the details of the attachment to the aft dome. Figure 2 shows these S-IV common bulkhead components. Figure 3 shows the details of the meridian and the dollar joints and the ring attached joint. All these joints are single-pass methane inert gas (MIG) welds.

The present method of manufacturing the S-IV and S-IVB common bulkhead consists of the following major operations. First, the preformed aluminum gore segments are welded into complete forward and aft domes, including the dollar and the attach rings. Then, the aft dome is installed on a bonding fixture. The next assembly operation is to bond the honeycomb to the aft dome. However, because of slight distortions in the contour of both the forward and the aft domes, distortions arising both from forming operations and from welding of the segments together, it is necessary to sculpture the honeycomb to fit these distortions, or waves, in the fore and aft domes. To determine how to sculpture the core, the contour mismatch between the fore and aft domes is measured before the core is bonded to the aft dome. The method used at Douglas for measuring this contour mismatch is the Paulino block system. This method uses 350 small honeycomb blocks temporarily installed over the surface of the aft dome. Each small honeycomb block has a putty pad on top. The forward dome is then placed over the aft dome and lowered into its final position relative to the aft dome. In the process, the forward dome contacts all the putty pads. The dome is then removed and each small pad is measured to determine the variations in contour between the forward dome and the aft dome. Figure 4 depicts this measuring technique. Following this, the honeycomb core sections are fitted to the aft dome. After fitting, the core is removed, the dome is cleaned, and an adhesive film is placed on it. The core is then re-installed and bonded in an autoclave to the aft dome. Figure 5 shows the core bonded to the aft skin.

Following this bonding operation the core is sculptured. To accomplish this, the core is spot-faced according to the dimensions measured from the putty pads, as shown in Figure 6. This operation provides guide points for the manual sanding operation which is used to bring the core surface to contour. This hand-sanding operation is time consuming and subject to some human error. After this sculpturing operation is complete, the adhesive film is installed over the core, and the forward dome is placed over the assembly for the final bonding operation. The entire assembly is then put in the autoclave for the final adhesive cure cycle. A few problems have been encountered in this fabrication process; the major problems are welding and fitup. Some of the common bulkhead difficulties relating to these two problems are (1) weld porosity, (2) weld cracking, (3) skin debonding, and (4) skin wrinkling.

To some degree, weld cracks are now attributed to the aging of the weld metal during the adhesive bonding cycle. Figure 7 shows the effect of the bond cycle on weld ductility and, as this figure indicates, the ductility decreases considerably with the increasing numbers of bonding cycles to which the welds are subjected. Frequently, these cracks appear following the thermal shock induced by the initial propellant loading. Wrinkles have also been observed on the liquid hydrogen side of the S-IV-6 bulkhead and the S-IV dynamic vehicle. These wrinkles have been attributed to forcing the excess metal in the forward dome to conform to the honeycomb core surface. The records of difficulties experienced show that weld cracking or debonding has occurred during the cryogenic loading in most of the S-IV common bulkheads. Although all the S-IV stages performed successfully, this record indicates the desirability of improving the processing techniques.

As has been previously stated, the problems of fitup and weld-zoned cracks are inherent in the existing S-IV and S-IVB processes. The methods for fitting the domes to the core are time consuming and are marginal for providing the required bond-line fit. The repeated subjection of the weld-zone metal to the honeycomb adhesive bond cycles is an undesirable part of the existing process.

THE BONDED BULKHEAD CONCEPT

In an effort to overcome these difficulties, a program for investigating the bonded bulkhead concept was initiated. The most desirable approach is an all-bonded concept in which all the welding is replaced with bonding. However, no LO_2 compatible adhesive is available at the present time. Therefore, the program was limited to a bulkhead bonded on the hydrogen side only, hence, the one side bonded bulkhead. The basic concept is shown in Figure 8. The aft skin (the LO_2 skin) is identical to a standard S-IV bulkhead. The forward skin is made up in segments which are bonded, rather than welded, together. The joint details for this concept are shown in Figure 9. This design is based on the following four basic considerations:

1. The loads and design criteria will be the same as the S-IV.
2. The design should permit the maximum possible use of existing S-IV tooling. In fact, an S-IV size bulkhead was chosen because the tooling was available and was no longer needed for production use.
3. The bulkhead will utilize the same materials as the S-IV.
4. The finished bulkhead must have the capability of being installed in a S-IV aft dome for testing.

DESIGN

The primary design effort then went into the selection of the joint concept to join the hydrogen side segments, dollar, and attach ring. Three basic types of joints were considered. These types of joints, shown in Figure 10, included all bonded plus mechanical fastener joints and bonded plus mechanical fastener joints with an overseal. Including variations, this study covered approximately 25 different joint concepts. On the basis of a design evaluation, these 25 were narrowed to 3 joints, two bonded and one bonded plus mechanical fastener for specimen testing. The joints selected were joints numbers 3C, 4, and 8A, shown in Figures 11, 12 and 13, respectively. Test specimens were prepared for both tension and compression tests. The following are the five basic conditions from which the loads were derived (all loadings are limit):

1. Ground hold, LO_2 tank at ambient pressure--thermal shock from the start of the LH_2 tank fill, 0.5 psig (reverse).

2. Ground hold, LH_2 at ambient pressure--thermal shock from start of LO_2 tank fill, 0.5 psig internal in LO_2 tank.
3. Ground hold, the LO_2 tank loaded and pressurized--the LH_2 empty and at ambient pressure, 37 psig internal in LO_2 tank.
4. S-I burnout, LH_2 tank pressure minimum--LO_2 tank pressure maximum, 28.5 psig internal in LO_2 tank.
5. Ground hold, LH_2 tank full and pressurized--the LO_2 tank loaded and an ambient pressure. The resulting differential pressure = 23.8 psig reverse.

Condition I results in a tension stress of 72,000 psi with a nominal 0.025 in. thick LH_2 skin; 82,000 psi on a minimum 0.020 in. skin; and 58,600 psi on maximum 0.035 in. skin, or a critical tension load across the joint of 2,051 lb/in. This result takes place while the LH_2 skin and splice are at -423°F. Condition II results in a compression stress of 55,000 psi with nominal 0.025 in. thick LH_2 skin; 56,800 psi on minimum 0.020 in. skin gage; and 49,600 psi on maximum 0.035 in. skin gage, or a critical compression load of -1,736 lb/in. while the LH_2 skin and bond are at +120°F. A typical compression specimen is shown in Figure 14. The results of these tests are shown in Figures 15 and 16 for the tension and compression results, respectively. Included in the figures are the design requirements for the joints for ease of comparison. As these figures indicate, all the joints were satisfactory in tension and the scalloped doubler configuration, 4, and the mechanical fastener doubler configuration, 8A, were satisfactory in compression. The laminated doubler configuration, 3C, was a little under strength at the ambient temperature condition. On the basis of these results then, Configuration 3C was eliminated from further consideration.

To further evaluate the remaining two joint candidates, 3-ft test bulkheads were built to check the joint leak properties. Figure 17 shows one of these specimens. These bulkheads were tested in a test fixture in such a way that the top surface could be immersed in liquid hydrogen and pressurized to the pressures the full-scale bulkhead would experience. The all-bonded joint (4C) had leak rates less than 7×10^{-5} cc's per second of hydrogen after a hold time of 1 hour, which was considered an acceptable leak rate. Because the all-bonded joint concept was also preferable for production, this joint was selected for the full-scale experimental bulkhead.

FABRICATION

The fabrication of the bulkhead proceeded on the basis of this joint concept. Because the aft dome was identical to the production S-IV aft domes and a production type S-IV aft dome was available, the production type S-IV aft dome was used in the fabrication. This aft dome was fitted to the joining tool and cleaned in the standard manner with an etch solution consisting of sulphuric acid and sodium dichromate. An HT 424 prime coat was applied; then the HT 424 adhesive was applied to the prime surface and the HRP honeycomb core was assembled on the aft dome by means of a band of 6 lb/cu ft density honeycomb core 12 in. wide around the greatest circumference, and 4 lb/cu ft density honeycomb core for the remaining surface. The honeycomb was covered with a vacuum bag and bonded to the aft dome in the autoclave under 45 lb/sq in. pressure at 325°F. The bonding procedure up to this point was identical with previous production methods for the S-IV bulkhead except that the 6-lb density core was cut 1 in. wider to allow it to extend 1 in. further down under the forward ring for support of that ring. The other major difference was that the core was a net thickness of 1 in., rather than over-size, to allow for core sculpturing. This core was machined and hand sanded in the forward ring area to produce a proper fit with the forward ring, as shown in Figure 18.

After proper cleaning and adhesive application, the forward ring was bonded to the honeycomb core. Other than the fit of the forward ring to the honeycomb core, there were no sanding or machining operations performed on the core; thus, there was a considerable saving of manhours. Following this, the forward dome segments were individually fitted into place. Because of slight variations in the contour of the aft dome and the honeycomb, some trimming on assembly was performed on the segments to comply with the gap tolerances.

The forward gore segments and the dollar were then cleaned and primed in accordance with the same procedure used for the aft dome. The adhesive was applied and the bonding operation was completed with the same cure cycle used to bond the honeycomb to the aft dome.

When heating a large composite structure, consideration must be given to the stresses produced in the structure resulting from this uneven heating of the various areas of the structure and the different coefficient of expansion of the materials. In the standard S-IV bonding process, the first bond of the honeycomb core to the aft dome is accomplished in 30 hours, including the heat up, bonding time at temperature, and cool down. The temperature differential between thermocouples during heatup and cooldown is held to a maximum of 10°F.

However, when bonding an integral forward dome core assembly, particularly during cooldown, the two aluminum domes must contract together to avoid creating stresses that might damage the core. Therefore, the temperature differential between thermocouples is held to a maximum of 5°F during this last cycle. This closer tolerance on the temperature spread necessitates a slower cooldown rate and; consequently, this second bonding cycle requires 60 hours. When the forward dome is composed of individual segments such as the experimental bulkhead, these segments are free to expand or to contract as separate parts, reducing the buildup of stresses and allowing, therefore, larger temperature differentials between thermocouples. Under these conditions, the bonding of the forward gore segments and the dollar to the aft dome core assembly of the research bulkhead is accomplished with a bonding cycle of 30 hours duration, thereby effecting a savings of 30 hours of autoclave time.

Figures 19 and 20 show the bulkhead with the forward skin bonded in place. At this point, the only remaining operation was the bonding of the doublers over the joints in the forward dome segments dollar and ring. The doublers were cleaned in accordance with the same procedures used in cleaning the aft and forward domes. The gaps between the segments, however, required sealing to prevent cleaning solution from entering the core area. These gaps were sealed with a room-temperature curing, modified epoxy paste adhesive (Epon 934). This material is resistant to high and low temperatures and to acid. After cleaning, the doublers were bonded over the joints by means of a polyurethane adhesive (Narmco 7343). A vacuum pressure of 10 to 15 in. of mercury was applied after bonding to hold the doublers in place during cure. The cure cycle consisted of 24 hours at room temperature, under vacuum, followed by 24 hours at room temperature, without vacuum, and then 24 hours at 160°F. Subjecting the polyurethane to a temperature of 160°F for 24 hours is required for completing the cure when it is necessary to secure full strength of the adhesive immediately after cure. The adhesive will reach the same strength after approximately 2 months without the elevated temperature cure.

Figures 21 and 22 show the completed bulkhead with the doublers bonded in place. Upon inspection and careful examination of the joint detail shown on Figure 22, it was decided that the joint should be reworked to improve both the fit of the parts and their strength. To accomplish this, the meridian and equatorial doublers were cut approximately 1 in. from the problem area and heat was used to loosen the adhesive; and then the doublers were peeled off. All of the doublers in these affected areas were removed. New ones were made and fitted, then cleaned and bonded in place with the same polyurethane adhesive. In this application, however, the higher temperature cure cycle was not used because it was undesirable to re-heat the entire structure and the full strength capability of the adhesive was not required immediately. The rework of these areas is shown in Figure 23.

The design of the bulkhead calls for a seal weld between the forward ring and the aft ring which not only prevents liquid oxygen or hydrogen from entering the core cavity but also provides a stronger and more rigid structure. In an attempt to follow this procedure on the DA-103 bulkhead, it was discovered that during the core-bonding operation, some of the adhesive had migrated into the weld area in several places, thereby making a complete seal weld impractical because of the impossibility of securing adequate welding cleanliness. Therefore, the two rings were tack-welded at locations approximately 2 ft apart around the periphery to achieve the strength for handling and then were sealed with PR 1938, a silicone sealant.

As noted earlier, one of the requirements of the program was that the experimental bulkhead must be designed so that it could be installed in an S-IV aft dome for structural and functional tests. Because the bulkhead geometry and the attach rings (that attach the bulkhead to the aft dome) were essentially identical to production S-IV domes, this introduced no particular problem. The method of attachment, with huckbolts and welding, was also the same. However, prior to welding the bulkhead into the aft dome, a question arose concerning the possibility of deteriorating the polyurethane adhesive during the welding of the forward ring of the bulkhead to the aft dome as a result of the proximity of the adhesive and the heat from the welding operation. Strength tests were performed on lap shear coupons bonded with polyurethane adhesive and subjected to temperatures of 200°F, 250°F, 300°F, and 400°F for a period of 5 min. before testing at room temperature. The strength of these coupons remained constant through the 300°F exposure but fell sharply when exposed to 350°F and 400°F; consequently, 300°F was set as the critical limit. However, during the welding operation, as determined by temperature indicating materials, the temperature did not exceed 250°F.

INSPECTION

Nondestructive testing techniques were utilized throughout fabrication to ensure the quality of the finished product. Sonic (Growler) tests were performed on the gore segments to detect any unbonds between the aluminum domes and the honeycomb core; none were detected. The bond quality was as good or better than any production bulkheads. Both ultrasonic, pulse-echo tests and quality control test coupons were used to inspect the doubler bonding operations. Test coupons were processed with each doubler bond and pull tested to ensure the quality of the polyurethane adhesive. Upon completion of the doubler bonding operation, ultrasonic pulse-echo tests were performed on all the doublers. The calibration of the equipment for both the sonic and the ultrasonic inspections was accomplished by referencing to a standard containing an unbond of known size. The ultrasonic inspection of the doublers indicated approximately 80 areas of small unbonds along the meridian and circumferential doublers. These areas of unbond were scattered and did not individually exceed 1/2 in. in diameter. As a part of the rework of the doubler joints at the meridian-circumferential intersection described earlier, these ultrasonic inspection results were compared with the unbonds in the removed parts. The actual unbond size was found to be, in all cases, smaller than the indicated size. This exaggeration of size frequently occurs when the unbond area is smaller than the size of the ultrasonic transducer used in the test. The removal of the doublers did, however, reveal another problem. On some of the removed parts, there were small channels in the adhesive, most of them isolated, but some connected and occasionally extending to the edge of the doubler. The small size of these channels prevented them from being detected by the ultrasonic inspection procedure and although there would be no significant loss of strength as a result of these channels, they could conceivably serve as leak paths for liquid hydrogen into the interior of the bulkhead.

It would appear that the more costly and sophisticated ultrasonic C scan recording or infrared detector techniques could be employed to detect these small channel unbond areas. Both of these techniques have the capability of providing a tight scan recording of the entire part. The use of such equipment would be recommended for use on production bulkheads. For the experimental bulkhead, a seal coat of polyurethane adhesive was applied over all the doubler seams to seal these channels. This coat was left uncovered and was cured at room temperature.

In retrospect, throughout the entire bonding operation there were only three problem areas of any consequence: (1) the channeling of the polyurethane of adhesive, (2) the misfit of the doublers, and (3) the migration of the HT 424 foam into the seal weld area. These problems appear to be easily resolved in the future. The channeling of the polyurethane adhesive appears to be caused by entrapping air under the doubler when it is laid down on the adhesive, and it may be aggravated by the vacuum used to hold the parts together during cure. This condition could be resolved by the use of modified adhesive application techniques and perhaps by the use of weights or clamping pressure to hold the doublers in place instead of the vacuum pressure. The misfit of the doublers is merely a matter of proper production tooling. The migration of the HT 424 foam into the seal weld area could be resolved either by the use of a more thixotropic material in place of the foam or by the insertion of a blocking part to prevent the foam migration into the weld area.

RESULTS AND CONCLUSIONS

Since the structural tests have not been performed, it is not possible to draw final conclusions on this bonded bulkhead concept. However, on the basis of the work accomplished to date, certain preliminary results and conclusions regarding the fabrication, rework, weight, and cost of this concept indicate that the bulkhead has proved to be much easier to fabricate than the standard production design; potential problems and weight are reduced, and a considerable cost savings might be realized.

Significant advantages of this simplified and improved fabrication are as follows:

- Probably the most significant factor is the elimination of the core sculpturing. As noted earlier, the core sculpturing was eliminated and still the bulkhead sonic inspection showed excellent bond line fit and bond.

- In addition, the tolerances on the gore and dollar trim dimensions were relaxed. The gap tolerance (between parts) on the S-IV welded segments is 0 to 0.015 in. and the gap tolerance on the bonded segments is 0 to 0.090 in., which simplifies considerably the trim and fitup of the parts.

- Furthermore, this concept has the potential of eliminating the chem milling of the gores and dollars. This was not accomplished in the experimental bulkhead because aluminum sheets in the required thicknesses (0.025-0.032) are not available in the widths required (120 in.). Thicker sheets available in the required thickness were used and chem-milled to the design thickness. However, by increasing the number of segments and thereby reducing the sheet widths required, the chem milling could be eliminated.

- On the basis of the experimental fabrication, it would appear that the skin wrinkling problem has been solved although, admittedly, if the wrinkling is to occur, it probably will appear during cryogenic tests.

- The bulkhead is simple to rework, as demonstrated by the rework of the meridian equatorial doublers. The doublers can be removed by simply heating them, with a portable heater, and peeling them off.

- The weld cracking problems are obviously reduced because there are fewer welds in the bulkhead and in the ultimate, all-bonded concept there are no welds at all.

- Because the bonded joint is lighter than the equivalent welded joint, the bulkhead weight has been reduced. For the research bulkhead, it is approximately 25 lb lighter than a standard bulkhead, and for an all-bonded bulkhead, the weight saving would be of the order of 50 lb.

- The experimental bulkhead fabrication process also suggests that considerable cost savings might be realized. For example, the manhours used in the bonding operation of the research bulkhead were approximately 50% of the hours used in the bonding operation of a production bulkhead. This is particularly significant when it is realized that the bonding operations for the experimental bulkhead actually included the bonding of the doublers, over and above the normal honeycomb to skin bonding done on production bulkheads. To this saving could be added the saving in welding manhours. These have not been estimated.

The manufacturing of the bulkhead is complete. At the present time, the bulkhead is being prepared for structural testing. If the bulkhead does, in fact, perform structurally as it is designed to do, the program will have demonstrated a fabrication technique that would appear to offer significant advances in the fabrication of composite structures of this type.

SATURN IB SECOND STAGE

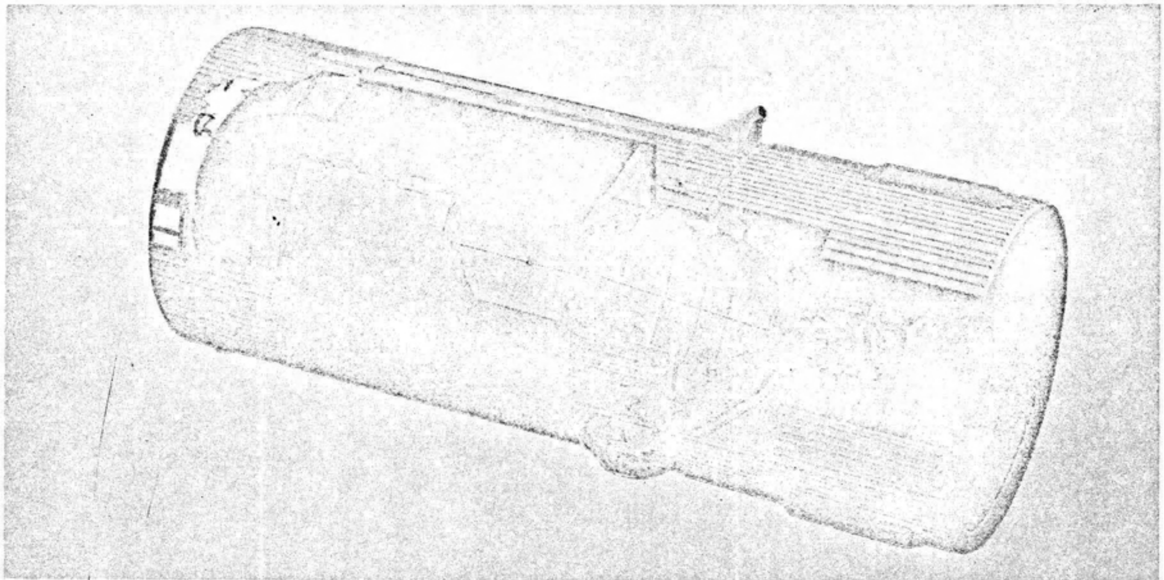
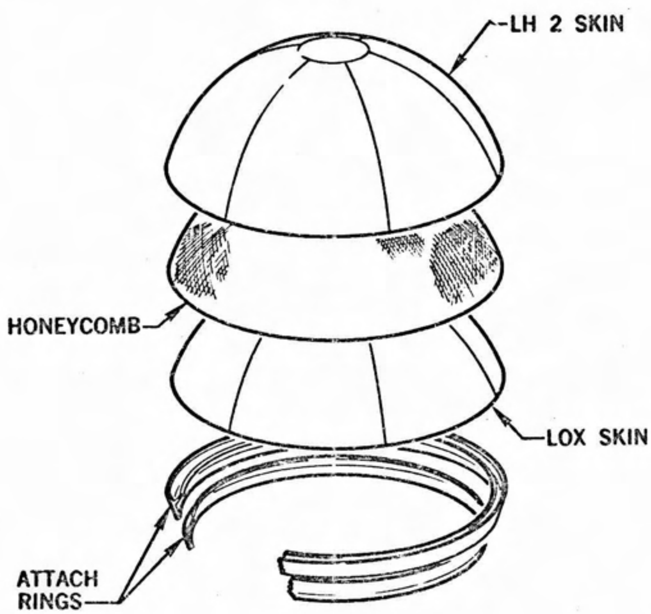


FIGURE 1

M-19561



S-IV BULKHEAD COMPONENTS

FIGURE 2

M-19558

S-IV JOINT DETAILS

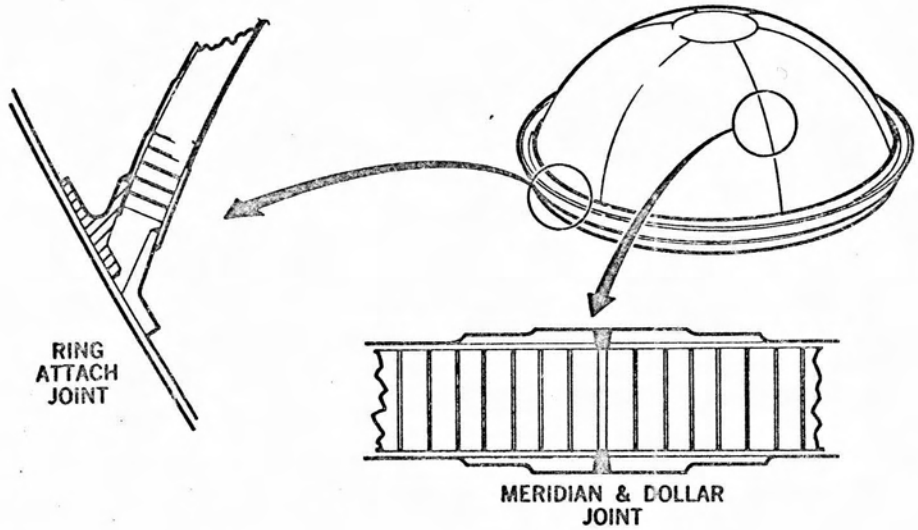


FIGURE 3

FITTING THE AFT DOME

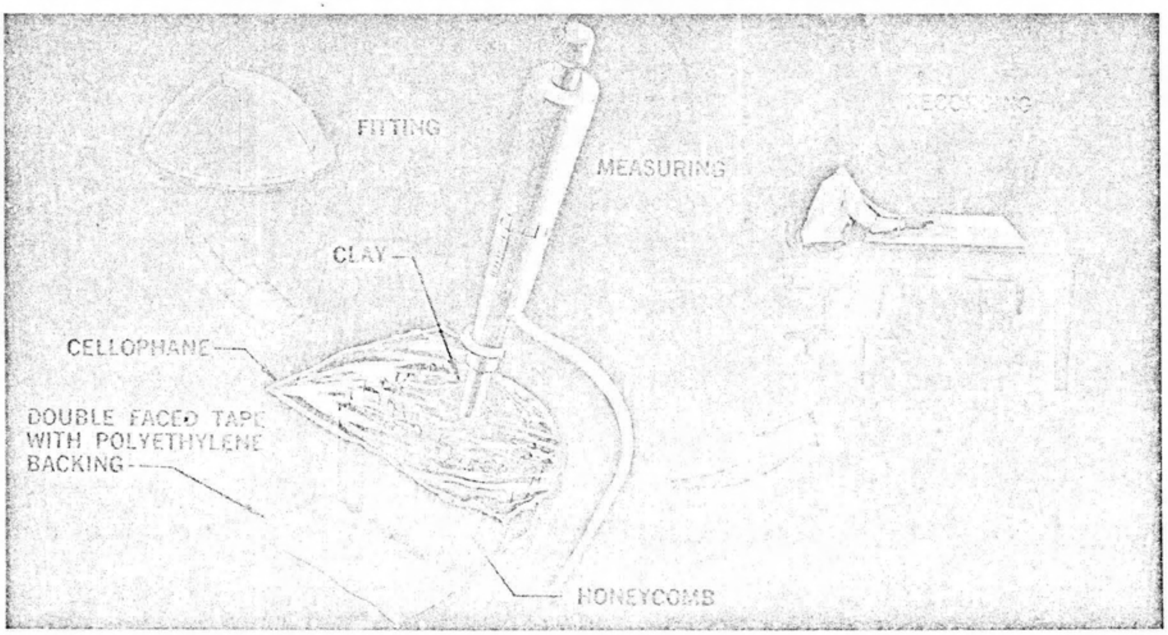


FIGURE 4

CORE BONDED TO AFT DOME

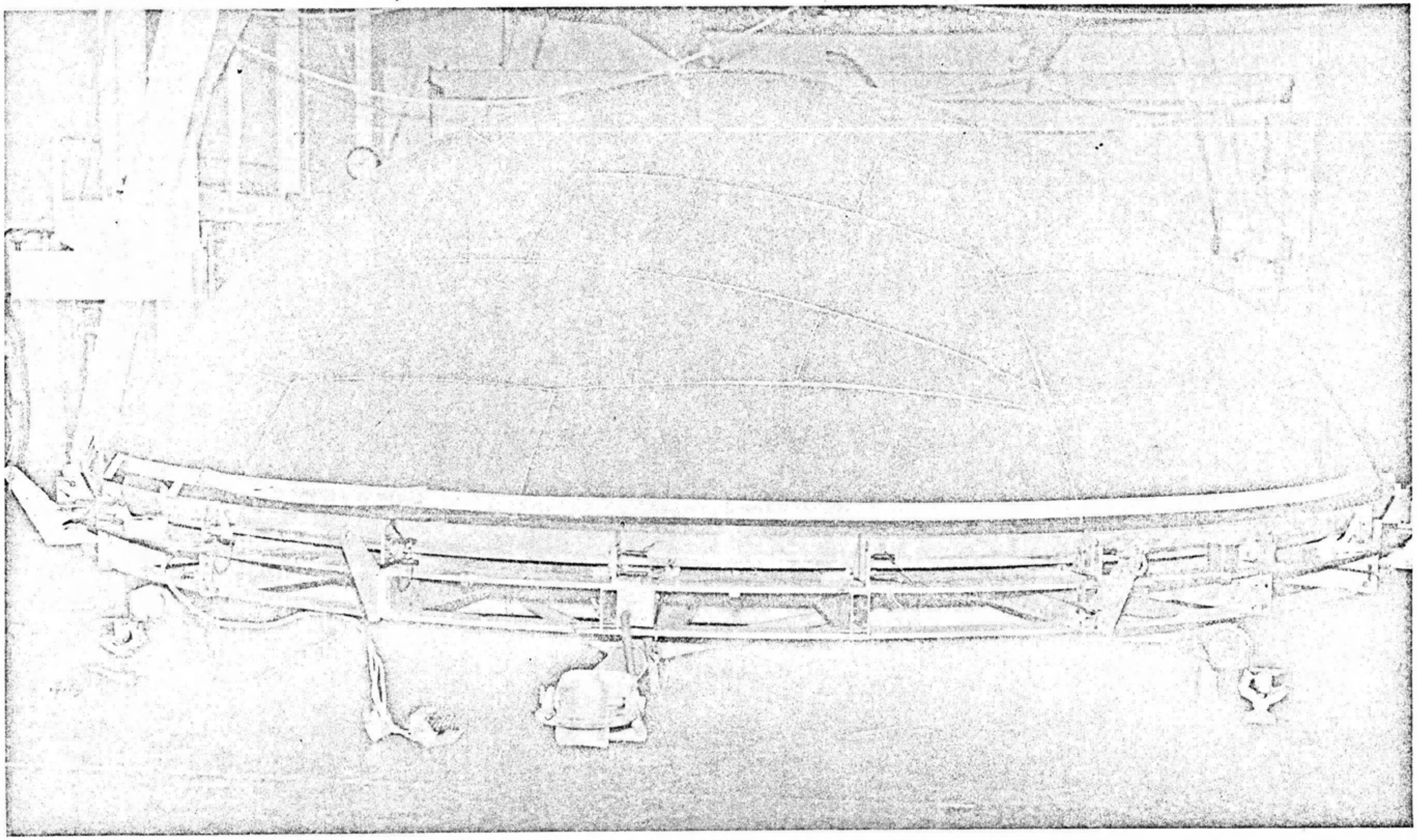


FIGURE 5

SPOT FACE SAND AND FIT CHECK FORWARD BULKHEAD

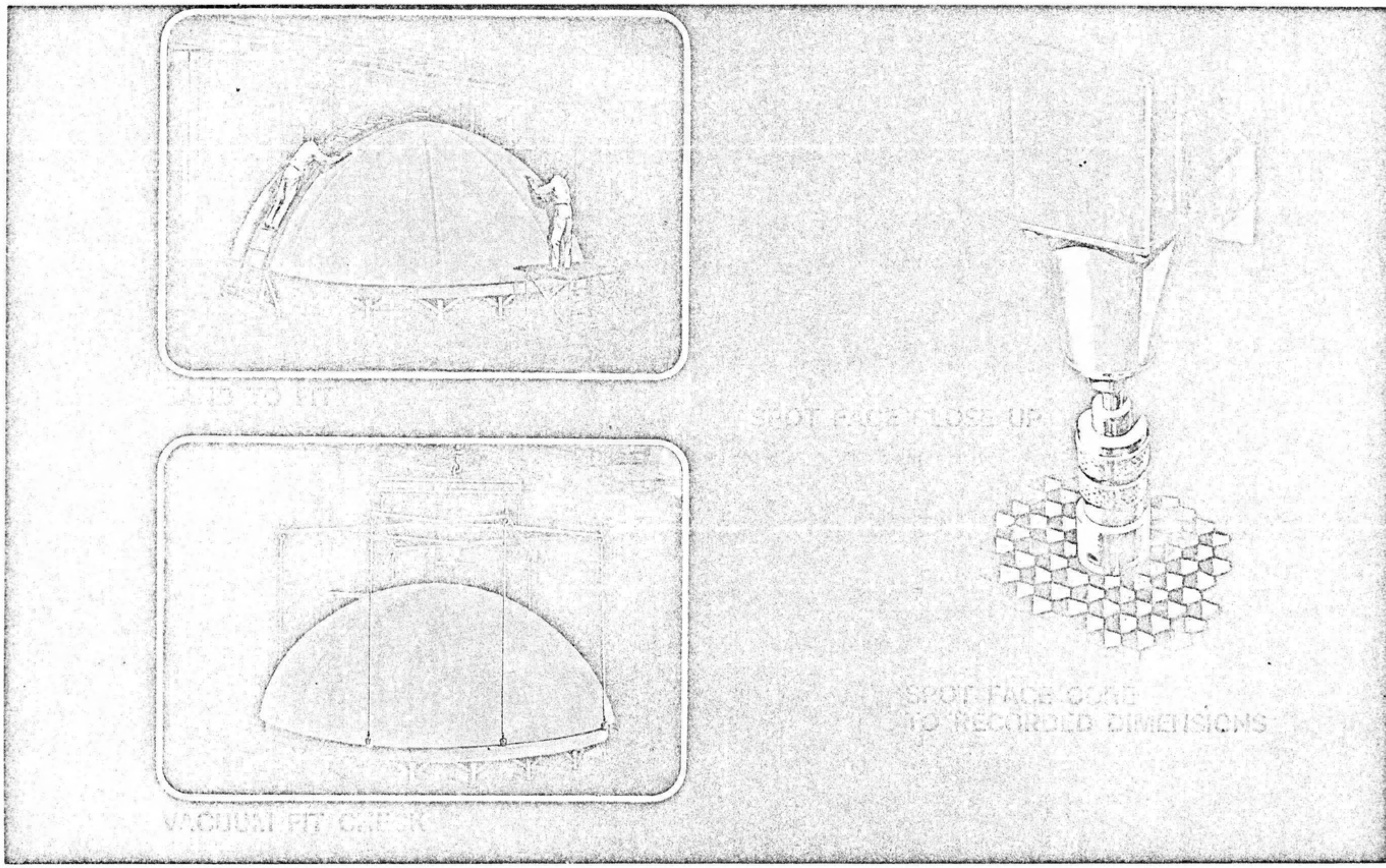


FIGURE 6

M-32087

EFFECT OF BOND CYCLE ON WELD DUCTILITY

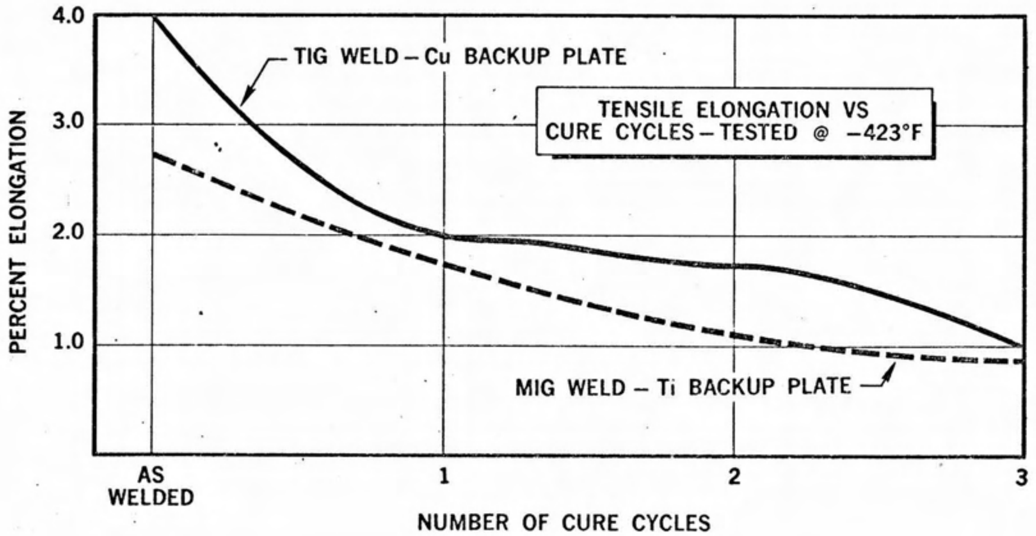


FIGURE 7

M-19559A

NEW BULKHEAD COMPONENTS

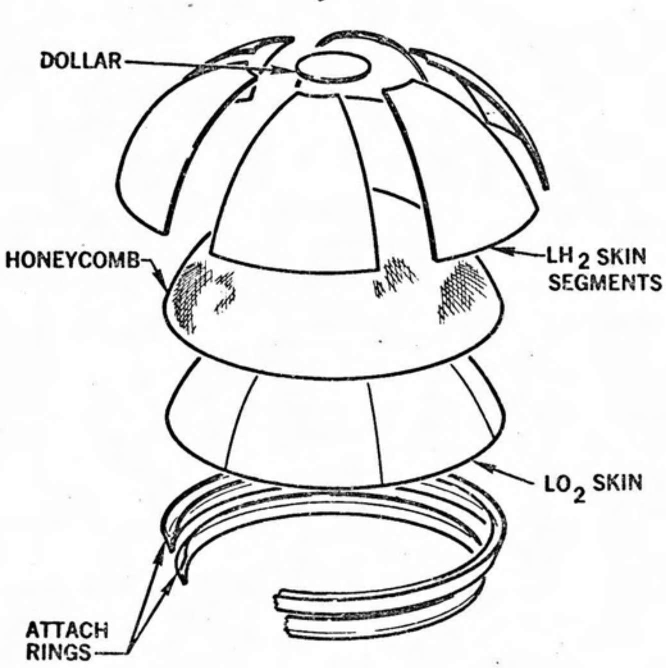


FIGURE 8

M-19560

NEW BULKHEAD JOINT DETAILS

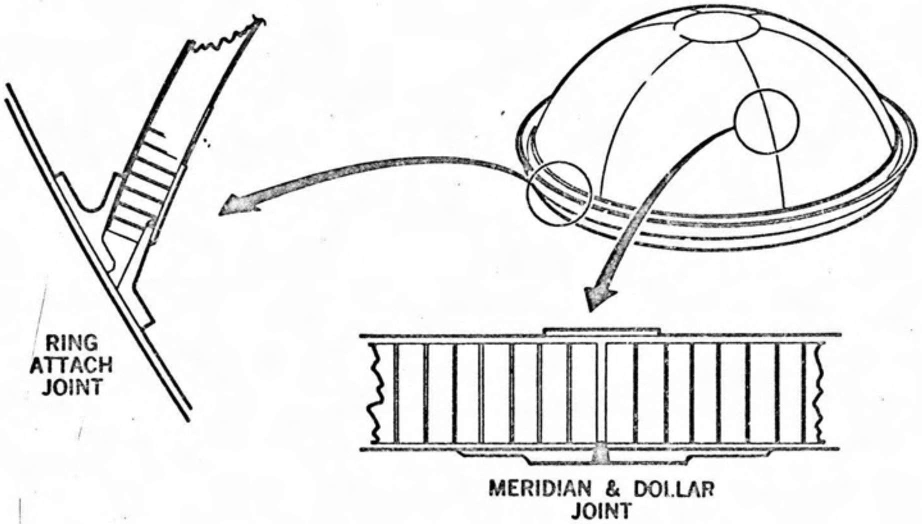


FIGURE 9

M-19556A

TYPES OF JOINTS

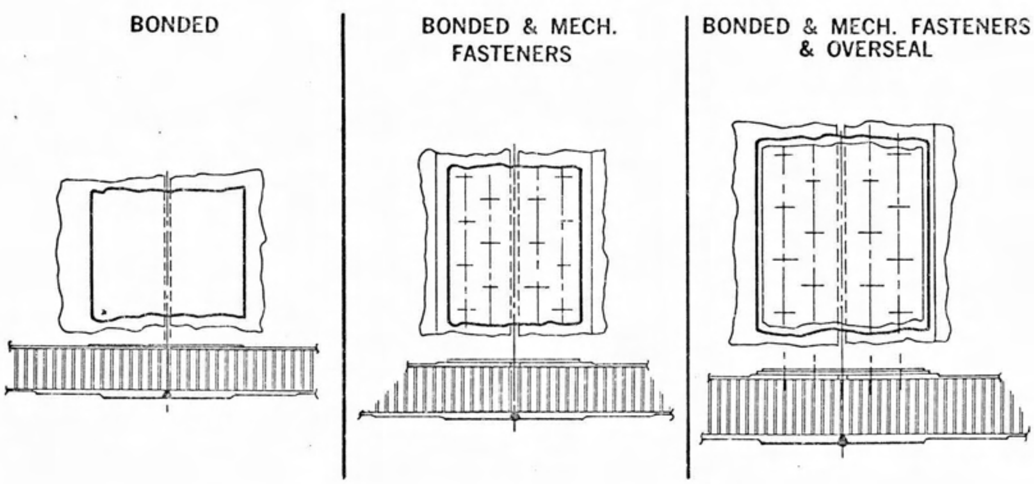
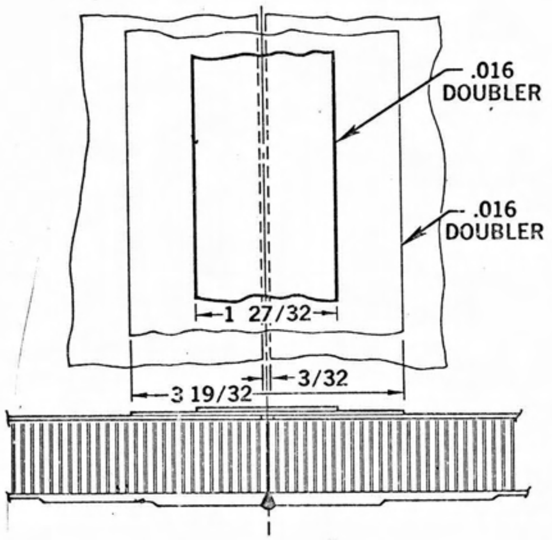


FIGURE 10

M-19557

CONFIG. 3C

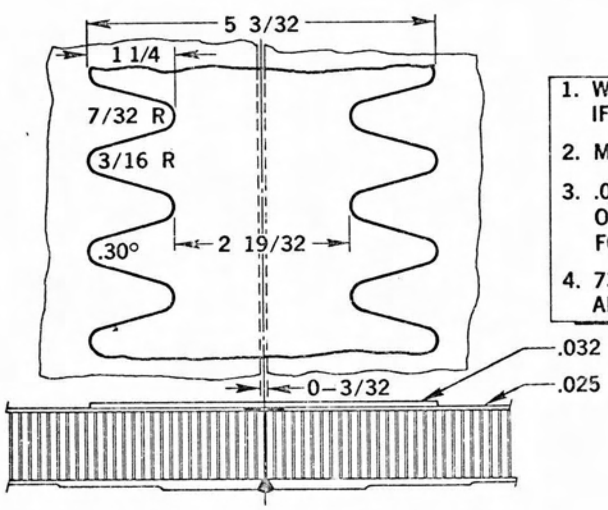


1. WEIGHT FACTOR = .230
2. MARGIN OF SAFETY = 24%
3. .016 DOUBLER + .016 DOUBLER OVER .025 SKIN. DOUBLERS TO BE INSTALLED FLAT (NO FORMING).
4. 7343/7139 ADHESIVE FOR STRENGTH AND SEAL.

FIGURE 11

M-19544

CONFIG. 4

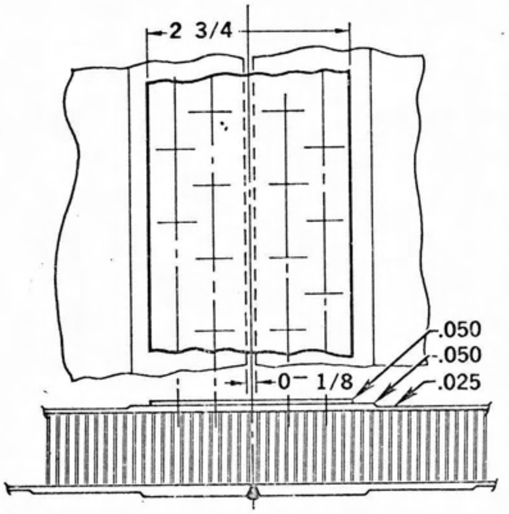


1. WEIGHT FACTOR = .315 IF .032; .395 IF DBR IS .040
2. MARGIN OF SAFETY = 28%
3. .030 OR .040 FINGERED DOUBLER OVER .025 SKIN, DOUBLER TO BE FORMED TO SPHERICAL RADIUS.
4. 7343/7139 ADHESIVE FOR STRENGTH AND SEAL

FIGURE 12

M-19546 /

CONFIG. 8A



1. WEIGHT FACTOR = .8
2. MARGIN OF SAFETY = 19%.
3. 5/32 A-286 STAINLESS STEEL FLUSH BLIND BOLTS WITH JACKETS.
4. .050 DOUBLER OVER .050 STEPPED LANDING ON .025 SKINS.
   DOUBLER TO BE FORMED TO SPHERICAL RADIUS.
5. 7343/7139 ADHESIVE ON FAYING SURFACES FOR SEAL.

FIGURE 13

COMPRESSION TEST PANELS

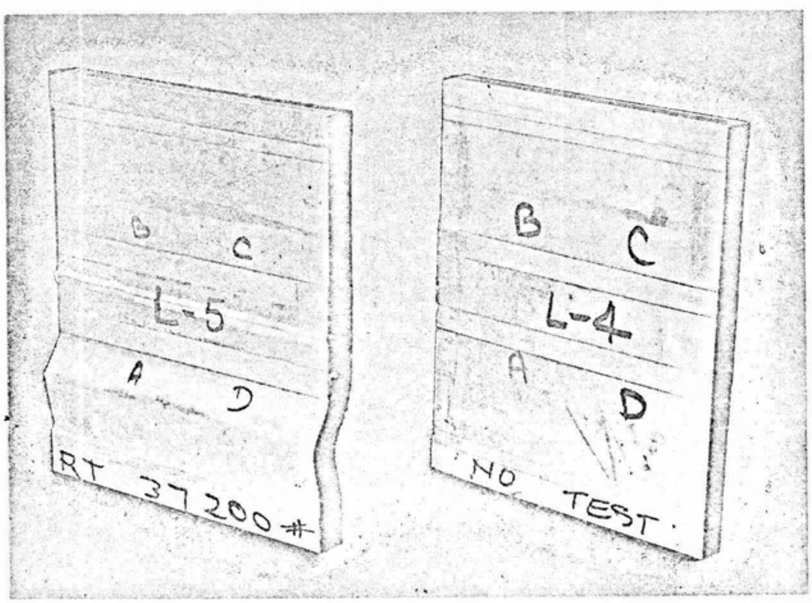


FIGURE 14

M-22156

TENSION PANEL TEST CURVES

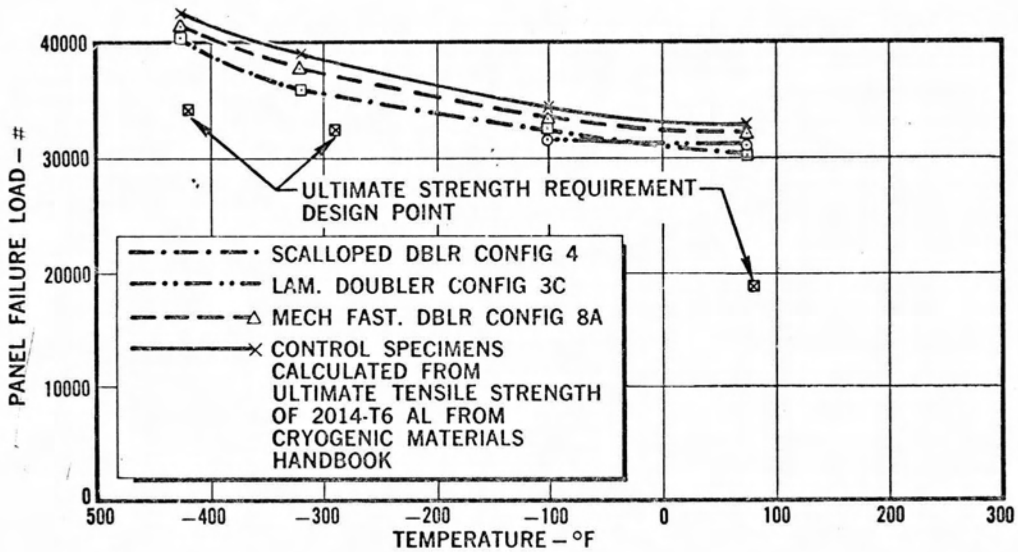


FIGURE 15

M-22157

COMPRESSION TEST PANEL CURVES

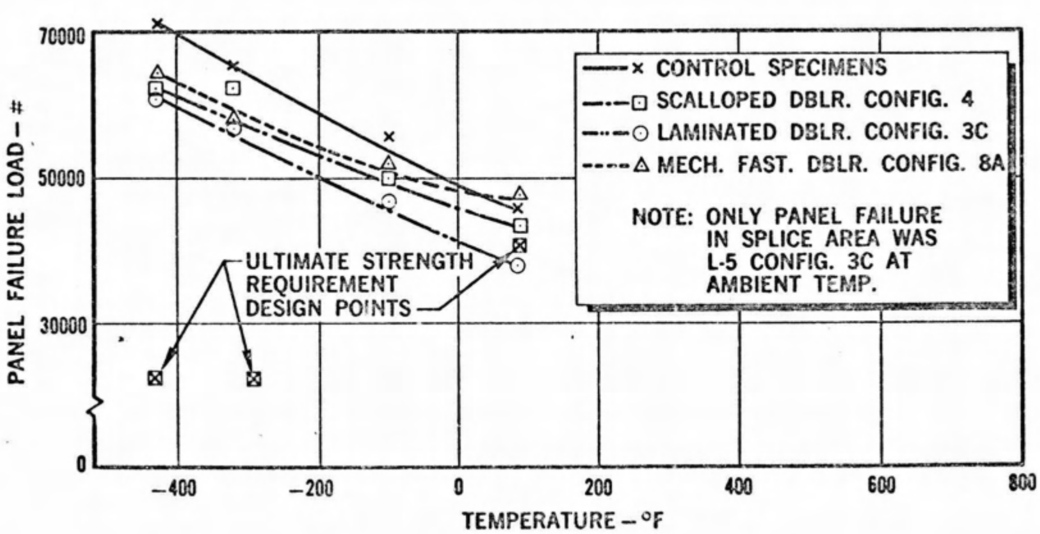


FIGURE 16

SUBSCALE BULKHEAD

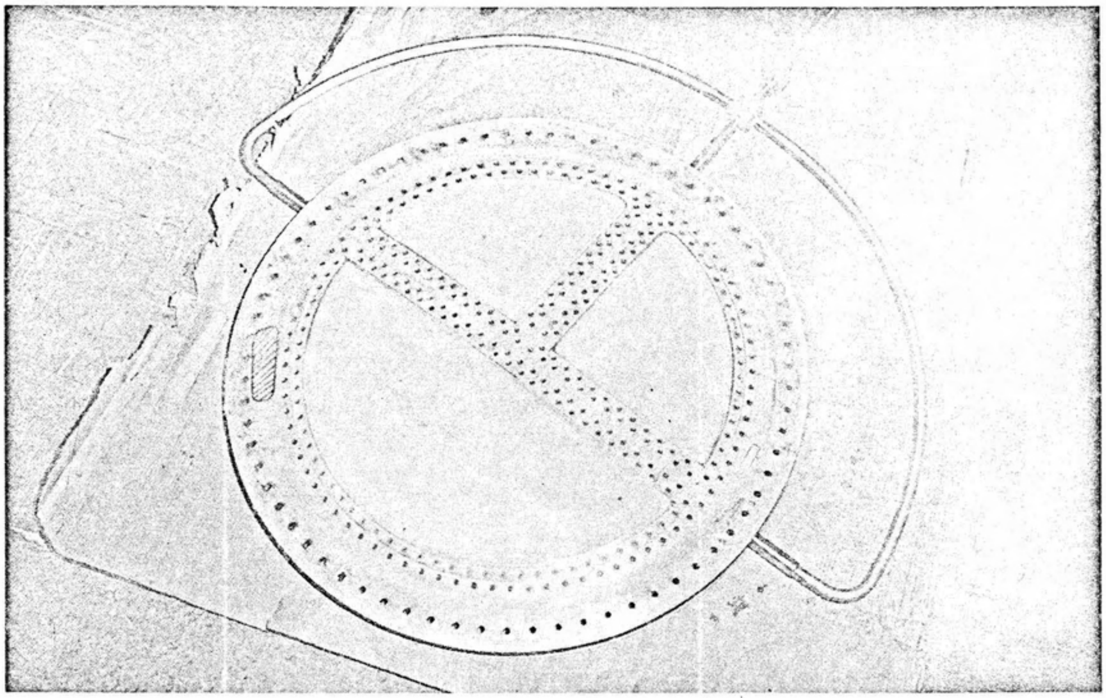
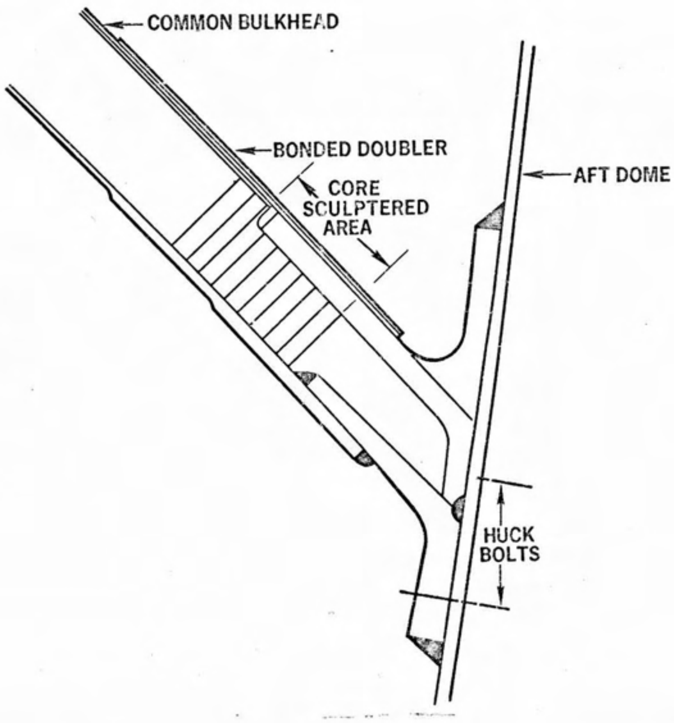


FIGURE 17

M-32104



RING ATTACH JOINT DETAIL

FIGURE 18

FORWARD SKIN BONDED IN PLACE

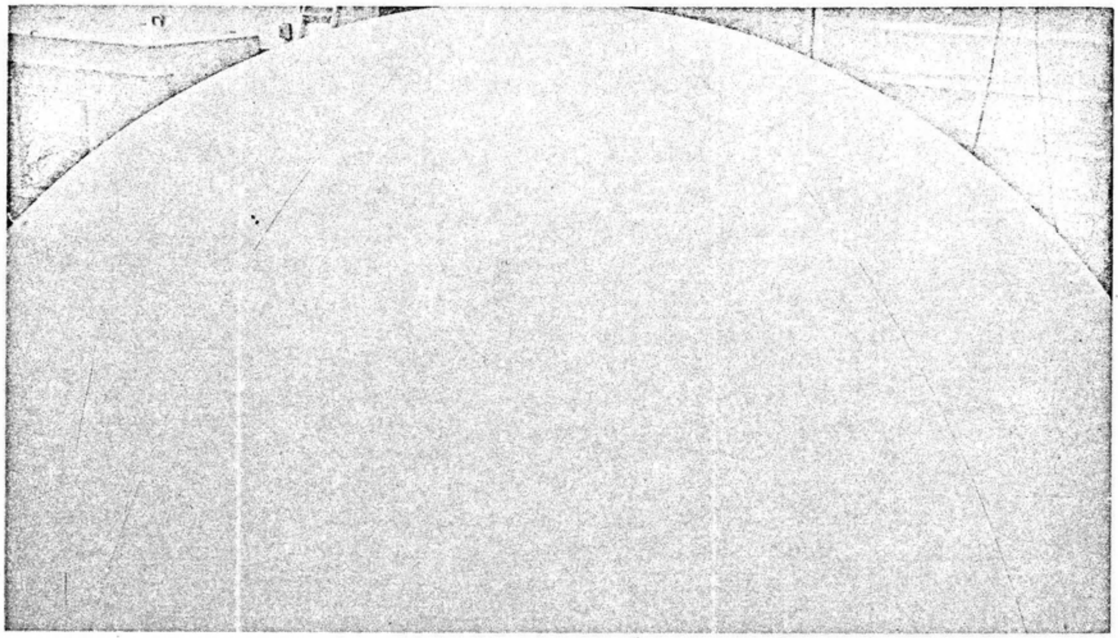


FIGURE 19

FORWARD SKIN
BONDED IN PLACE

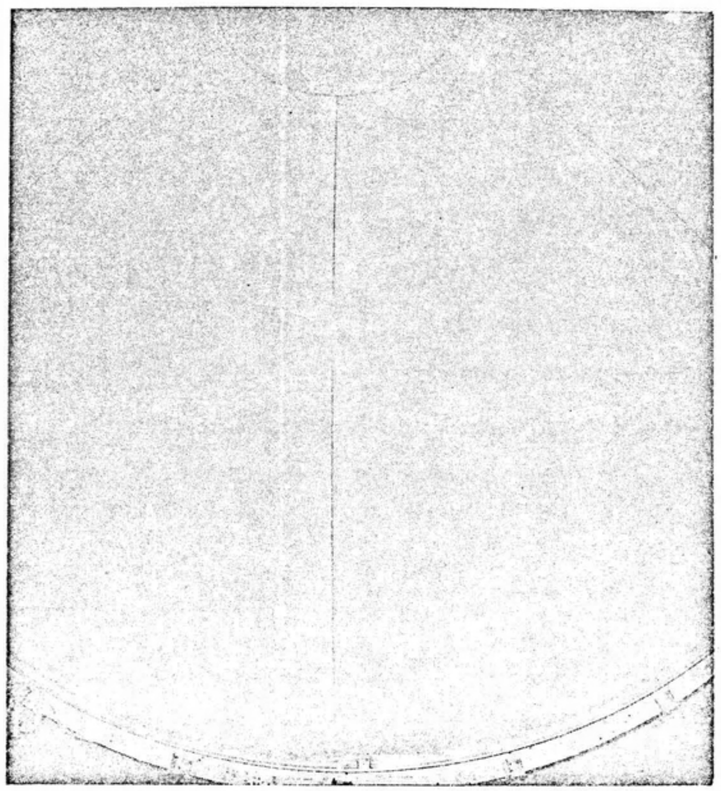


FIGURE 20

COMPLETED BULKHEAD

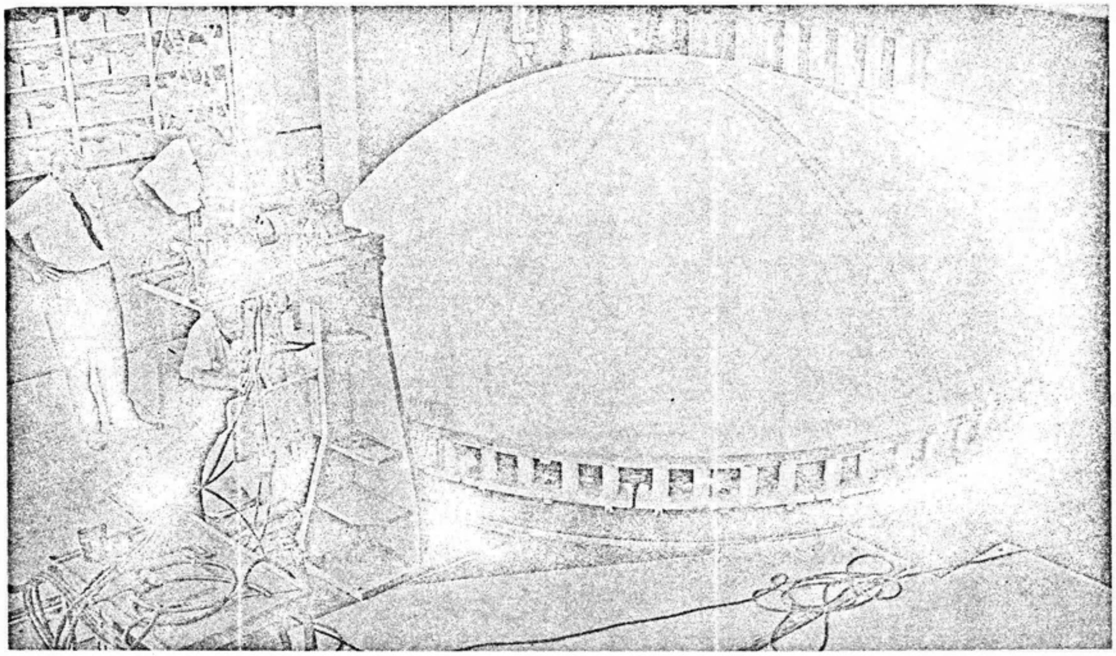


FIGURE 21

COMPLETED BULKHEAD JOINT DETAIL

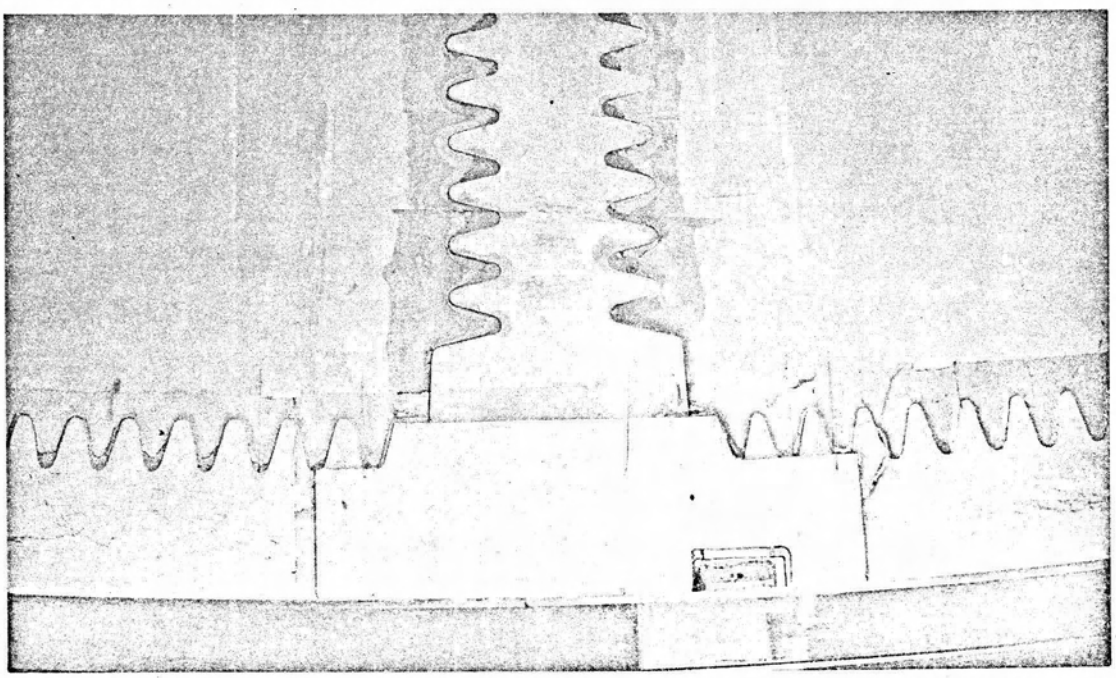


FIGURE 22

REWORK JOINT DETAIL

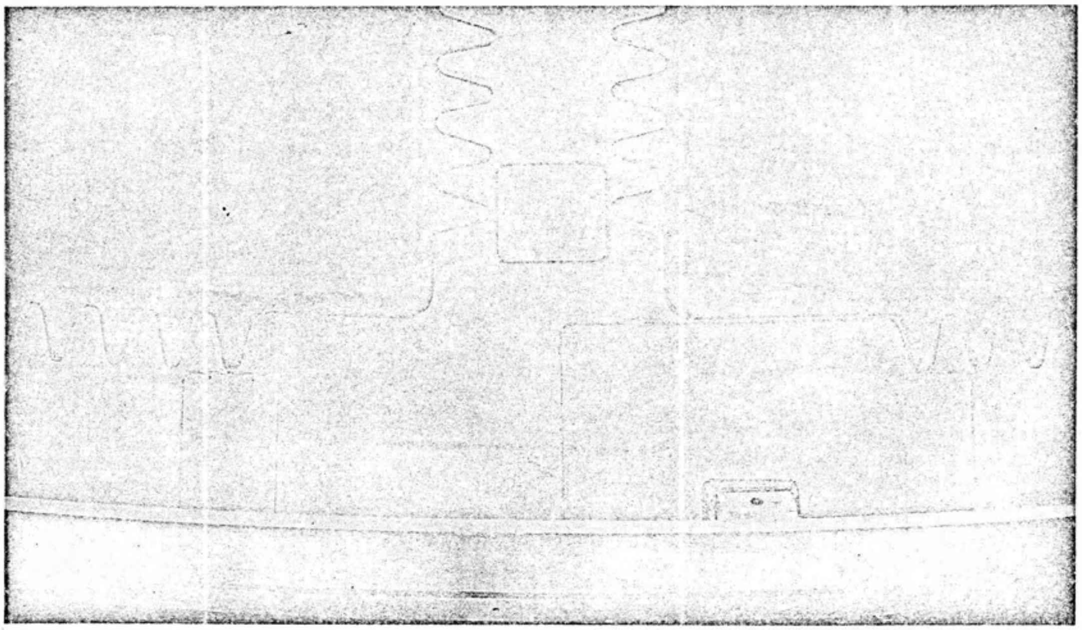


FIGURE 23

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RESULTS & CONCLUSIONS

- SIMPLIFIED & IMPROVED FABRICATION
  - ELIMINATE CHEM MILLING
  - TOLERANCES ON TRIM DIMENSIONS RELAXED
  - ELIMINATE CORE SCULPTURING
  - IMPROVED HONEYCOMB-SKIN BONDING
- NO SKIN WRINKLING
- REDUCED WELD CRACKING
- REDUCED WEIGHT 25 LBS
- SIMPLE REWORK
- REDUCED COST

FIGURE 24