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FABRICATION PROCESS DEVELOPMENTS OF A STRUCTURAL MODEL FOR RESEARCH ON HYDROGEN-FUELED HYPERSONIC VEHICLES

by

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FOREWORD

This report is intended as documentation of the fabrication and process developments involved in the manufacture of a structural model for the National Aeronautics and Space Administration Langley Research Center.

This is the final fabrication and process development report. The task was performed under Contract NAS1-4017 by General Dynamics Convair division, San Diego.

SUMMARY

A structural model has been fabricated by General Dynamics/Convair - San Diego for the NASA Langley Research Center. The model was designed by NASA LRC to test a new structure and insulation concept and establish that it was practical to manufacture as part of a research study on hydrogen-fueled hypersonic vehicles (see ref. 1).

The model represents a fuselage section of a hydrogen-fueled vehicle. It has a welded outer structure of annealed Rene' 41. This primary structure is made of sheet metal skins, Zee stringers, and frames fastened together with resistance and fusion spotwelds. Machined ring forgings are fusion seam welded to the forward and aft ends of the structure. A liquid hydrogen tank is suspended within the primary structure by means of draw formed Inconel 718 bellows which permit expansion and contraction. The tank was made of 2219 aluminum machined and formed panels, explosive formed dome ends and access door. The tank components are joined by fusion welding. An access door bolts to the tank, and a plastic seal prevents leakage.

Making the model encompassed a wide spectrum of fabrication, processing, and testing procedures. There were no major deviations necessary to the original design. Some difficulty was experienced in obtaining a seal for the LH_2 tank that had a satisfactorily low leakage rate. All the manufacture processes planned for this hardware proved to be satisfactory, and it is believed that a full-scale vehicle of similar construction could be manufactured without any further requirement for manufacturing development or advancements in the state-of-the-art.

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INTRODUCTION

Designs of proposed new hypersonic vehicles incorporate structural materials capable of retaining strength at elevated temperatures together with tank structure and insulation materials suitable for cryogenic propellants. To test a new structural design and thermal protection system, a structural model for research on hydrogen-fueled hypersonic vehicles was designed by the NASA Langley Research Center. This model is representative of the type of fuselage structure that may be used on hypersonic vehicles. With an allowance made for the scaling effect, it is believed that the fabrication techniques employed and the problems encountered in making the model will be substantially the same as those involved in manufacturing full-scale hardware.

To convert these designs to flight hardware required the development of new fabrication and processing techniques, in many instances, plus the selective application of existing techniques.

General Dynamics/Convair - San Diego fabricated, as presented in appendix A, the above structural model for the Langley Research Center under NASA contract No. NAS1-4017. The model defined by contract specifications L-4091, dated May 1, 1964, and NASA drawing numbers LX 903-540 and -541 was built to the configuration documented in GD/Convair - San Diego drawing numbers, listed in appendix B. The drawings incorporate the revisions to the original design for improved producibility. However, several new fabrication processes were developed and applied in the program.

An austere fabrication approach employing prototype tooling and experimental shop procedures was used where possible since this was a one of a kind test article. This final report describes the model and the design principles, the process development, tank sealing, and the fabrication of the structural model.

STRUCTURAL MODEL

Description

The structural model resembles a truncated cone with an overall length of approximately 55.4 inches with base diameters of approximately 16.3 and 36.2 inches, as shown in figure 1. It consists of a heat resistant nickel-base alloy outer structure and an insulated aluminum LH_2 tank suspended inside the structure by means of corrugated skirts and special bellows.

The structure is made of annealed Rene' 41 alloy Zee-stiffened skin panels, stabilized with Y and box-section ring frames, and joined to machined rings on each end. The panels consist of an outer skin, Zee-stiffeners, and skin splice doublers. Variations in Zee-stiffener pitch exist between the top and bottom panels, the fore and aft panels, and the side panels. In each panel the pitch varies longitudinally, because the Zee-stiffeners are attached to the face sheet on the straight line elements of the conical surface. Panels are assembled from outside the model. The assembly procedure for the Zee-stiffened panel structure is described in the fabrication section, appendix A.

Ring frames consist of formed web sections, bulkheads, doublers and reinforcing angles joined by spotwelding.

Machined thrust fittings are located on the top and bottom of the tank forward of the Y-frame. Matching sheet metal thrust fittings are welded to the primary outer structure. The tank is installed through the large end of the model. Then the mating parts of the thrust fittings are engaged by rotating the tank several degrees to provide fore and aft thrust connections. The tank is fastened in place by bolting at the bellows joints. At the larger end of the tank, an access door is provided. The door is attached to the aft bulkhead with aluminum bolts and sealed with a Teflon gasket.

The basic tank is fabricated from 2219-T6 aluminum alloy. It consists of eight conical tank panel segments joined by fusion welding to form a truncated cone. A one-piece formed bulkhead is welded in the small forward end of the cone. An aft bulkhead weldment, made in four pieces with a hole and a bolt flange for attaching an access door, is welded in the large end of the cone. A tee frame weldment is welded midway in the conical tank section. The access door is a one-piece formed bulkhead with fill and vent fittings and an attach flange welded to it. The door assembly bolts to the aft bulkhead. A plastic seal prevents leakage.

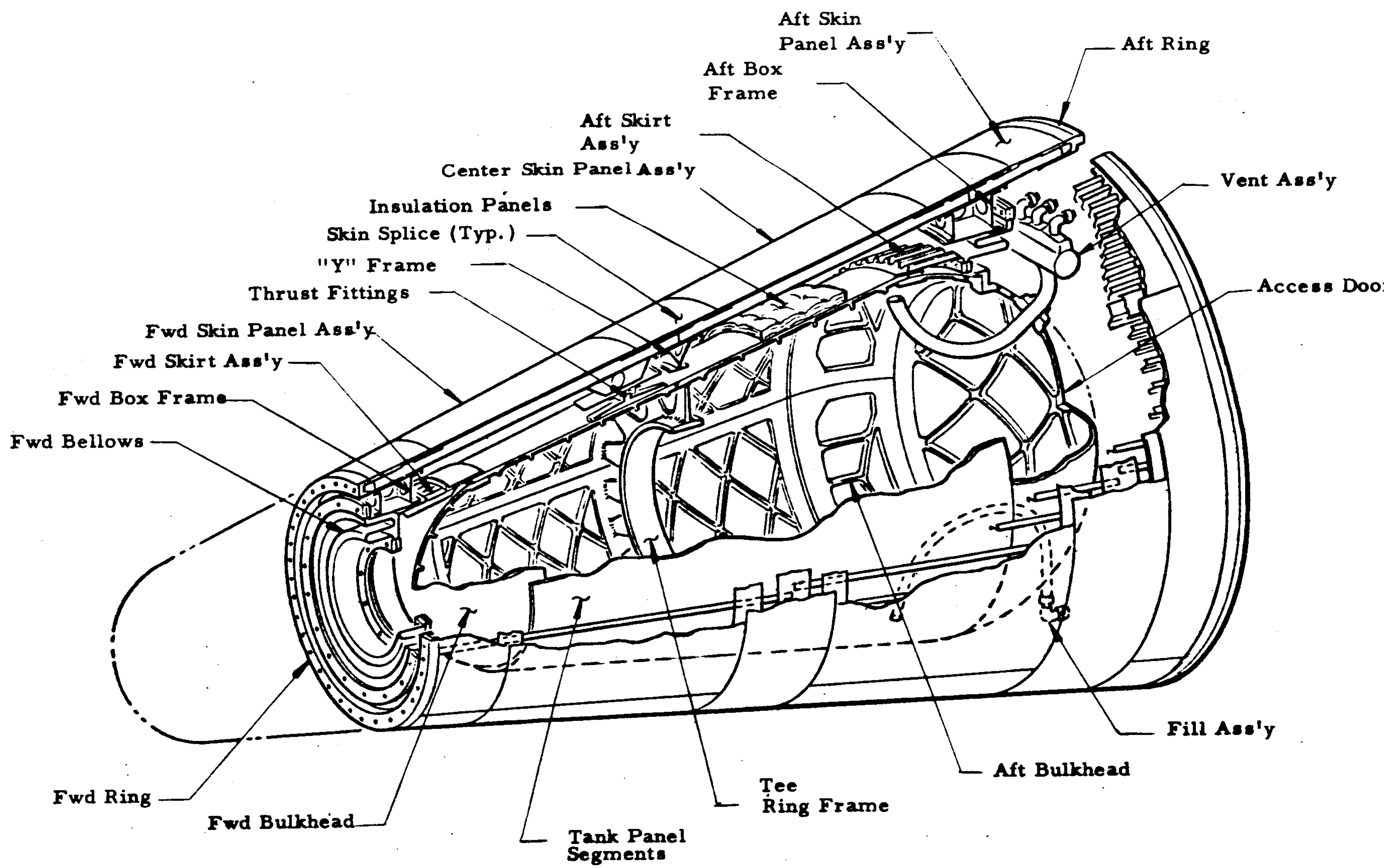


Fig. 1 Cutaway View of Assembled Structural Model

Fill and vent assemblies, consisting of formed tubes and machined fittings joined by fusion welding, bolt to matching fittings on the aft bulkhead. Plastic seals are used to prevent leakage.

At each end of the tank, corrugated skirts of Inconel 718 are riveted to short aluminum sleeves welded to the outside of the tank. A bellows is bolted to the corrugated skirt and to a structural ring frame. Bellows supporting the tank are formed from .040 inch thick annealed Inconel 718 sheet, reduced in thickness at the convolutions to produce the required longitudinal deflection at low force. Results of tensile tests on metallic materials for the structural model are given in appendix C.

Insulation panels are bonded to the outside surface of the tank and clipped to both sides of the corrugated skirts. Insulation panels consist of quartz fiber insulation contained by Fiberglas and quartz-cloth facings and quartz-cloth edging by machine stitching through the panels with Teflon-coated quartz thread. Joints in insulation panels are coincident with joints in the tank to permit inspection of the tank welds without requiring removal of the insulation.

Chromel-alumel instrumentation thermocouples are welded to the outer structure in 20 places and positioned in the tank insulation in 30 places. Copper-constantan thermocouples are welded to the outer surface of the tank in 10 places and placed inside the tank in 3 places. Terminal boards are provided for attaching the thermocouple lead wires.

Design Principles

The structural model was designed to be representative of a fuselage tankage structure of hydrogen-fueled hypersonic vehicles. Metal gages, insulation thickness, and wall thickness are equal to those required for a full-size vehicle. One exception to full scale is that the diameter of the model is considerably less than full size. However, the structural panels were designed on the basis that local buckling stress of the skin and of the flat elements of the Zee-stiffeners would be equal to panel buckling stress. The small radius of the model would not affect the load-carrying ability of the structure on a unit of circumference basis from that of a full-size vehicle because local buckling of the skin is not appreciably affected by the model radius.

The choice of stiffened skin panel construction instead of a lower mass, sandwich-panel structure is predicated on vehicle requirements where structural mass is not extremely critical such as the first stage of a reusable launch vehicle which formed the basis for design of the model. In such cases a more costly and complex sandwich structure would not be justified by the small improvement in performance. The Zee-stiffening of the panels was selected over the slightly more efficient hat section stiffening because of better accessibility; corrugation stiffening was also considered, but found to be significantly less efficient. The load-bearing skin of the Zee-stiffened panels forms a smooth aerodynamic surface although its thickness is only 0.018 inch. This smoothness results from the small pitch of the Zee-stiffeners, which also are of light gage (0.015 inch). Optimum panel proportions results in shallow depth Zee-stiffeners which tends to reduce thermal stress. To further avoid thermal stress, reinforced box-section ring frames are used instead of full-depth structural bulkheads. In addition, the primary structure is made by sub-assembly of the skin, doublers, and Zee-stiffeners into panels that are joined to another sub-assembly consisting of longerons and ring frames rather than separate Zee-stiffener stringers that are joined to ring frames followed by skins that are joined to the stringers. Thus the problem of fabrication is similar for the model and full size vehicle, the major difference being the increased number of panels required for the full size vehicle.

The primary structure is to operate to 1600°F; therefore Rene' 41 was selected as the structural material. Annealed material was used because it facilitates welded construction and it has more than adequate strength since the buckling stress is low at the low structural index encountered. Heat treated material would reduce the structural mass because heat treated Rene' 41 may have a considerably greater Young's modulus at temperature than annealed Rene' 41. Before heat treated material could be used, however, further development of heat treating large welded assemblies or welding of heat treated material is required. Also, the effect of the thermal cycles on Young's modulus of heat treated Rene' 41 must be determined.

Since the primary structure is not sealed, air must be prevented from cryopumping through the structure to the tank wall during ground-hold and atmospheric flight periods. The space between the structure is purged and lightly pressurized with carbon dioxide gas as described in reference 1. Joint design between panels of the primary structure is intended to offer relatively low leakage without resorting to seam welds to avoid intolerable helium requirements for ground-hold purging. The carbon dioxide concept incorporated in the design of the structural model uses helium to remove air from the space between the structure and tanks and to prevent the entrance of air through the structure during ground hold. Carbon dioxide gas is introduced into the helium during tank cool down. Some of the CO_2 solidifies as frost within the voids of the fibrous insulation. This frost contacts the tank wall and impregnates the inner thickness of the fibrous insulation. When the amount of frost required for thermal protection purposes is deposited, the CO_2 gas flow is stopped; however, helium purging is continuous throughout ground hold and early flight whereupon sublimation of the frost provides the required purge gas. The sublimation of the frost serves to block heat transfer to the fuel. And, since sublimation occurs at a low temperature of less than -110°F during flight, an aluminum alloy could be selected for the tank material and an adhesive could be selected for bonding the insulation panels to the tank wall. Thus, the carbon dioxide concept prevents cryogenic pumping of air with an unsealed structure and provides efficient thermal protection for the fuel and tank, thereby enabling selection of materials suited to low temperatures.

The tank is made of a weldable aluminum alloy (2219-T62). Its waffle plate and joint design is similar to that of the Saturn S-IV B stage to demonstrate that technology developed on other programs is applicable to the hydrogen-fueled hypersonic vehicles. However, the tanks of the hypersonic vehicle selected were considerably longer than the hydrogen tank of the Saturn S-IV B stage, so T-section ring frames are welded inside the tank to prevent general instability of the tank wall since the tank is to support internal fuel loads without depending on tank pressure.

A temperature difference of about 2000° F may exist between the primary structure and the tank of a hydrogen-fueled hypersonic vehicle. Therefore, longitudinal and diametrical expansion and contraction of these components must be permitted at little restraint to avoid serious thermal stress. The tankage suspension design used in the structural model approximates a simple support for the tank with negligible stress resulting from longitudinal changes in lengths. Corrugated skirts provide diametrical changes with negligible restraint since as the tank contracts, or as the structure expands, the corrugations gather in or spread out to suit changes in ring diameters caused by different ring temperatures at either end of the skirt. For loads acting normal to the longitudinal centerline of the fuselage, the skirt suspension prevents point loads on the tank and the bellows prevent point loads on the primary structure. In addition, the insulated skirt provides a long, low thermal conductance path from the hot structure to the cold tank. The bellows cannot provide thrust support; therefore, thrust fittings are positioned around the tank at half the distance from either bellows support. The thrust fittings impose localized loads on the tank and structure, but these loads are essentially in-plane with the tank wall and primary structure.

The suitability of the structural concept described and the design principles presented to full-scale hypersonic vehicles depends in part on successful process developments described in the following section of this paper.

PROCESS DEVELOPMENT

Most of the fabrication processes employed on the Test Model were applications of existing techniques. There were, however, areas of forming, welding and machining where process development was required. Emphasis was placed on development of processes that would be suitable for Hypersonic Vehicles.

Fabrication for the most part, except for welding, was performed in factory shops using existing factory facilities. This was done to provide a practical manufacturing approach as opposed to a laboratory type of fabrication.

Forming

Difficult non-standard forming operations such as: explosive forming of bulkheads, draw forming of bellows, and press brake forming of the tank panels were performed under direction of the Manufacturing Development department. Forming operations were performed on production equipment within the factory.

Explosive Forming Bulkheads - Forward and aft bulkheads and the access door for the LH_2 tank were explosively formed to contour from 0.50 inch thick 2219 aluminum alloy plate in accordance with the manufacturing plan.

The forward bulkhead was formed first to permit use of the explosive form die for the access door by enlarging the die cavity. Three draw stages, with intermediate anneals to remove work hardening, were required to form the 20.0 inch diameter starting blank to required depth as shown in Figure 2. Shaped charges of dynamite, in 1/2 lb. increments, provided the forming force. Wires were used to support the charge and maintain the required standoff distance, Figure 3. Plastic sheet, visible in the photograph, was used as an aid in obtaining a seal between the edge of the part and the die so that the required vacuum could be maintained during the forming operation.

A final sizing operation was performed after the parts were solution heat-treated to the T-42 condition. Two rings of 200 grain prima-cord, one near the top and one near the bottom, were used for this operation. Figure 4 shows a part being removed from the die following the final sizing operation. Parts were then aged to the final T-62 material condition.

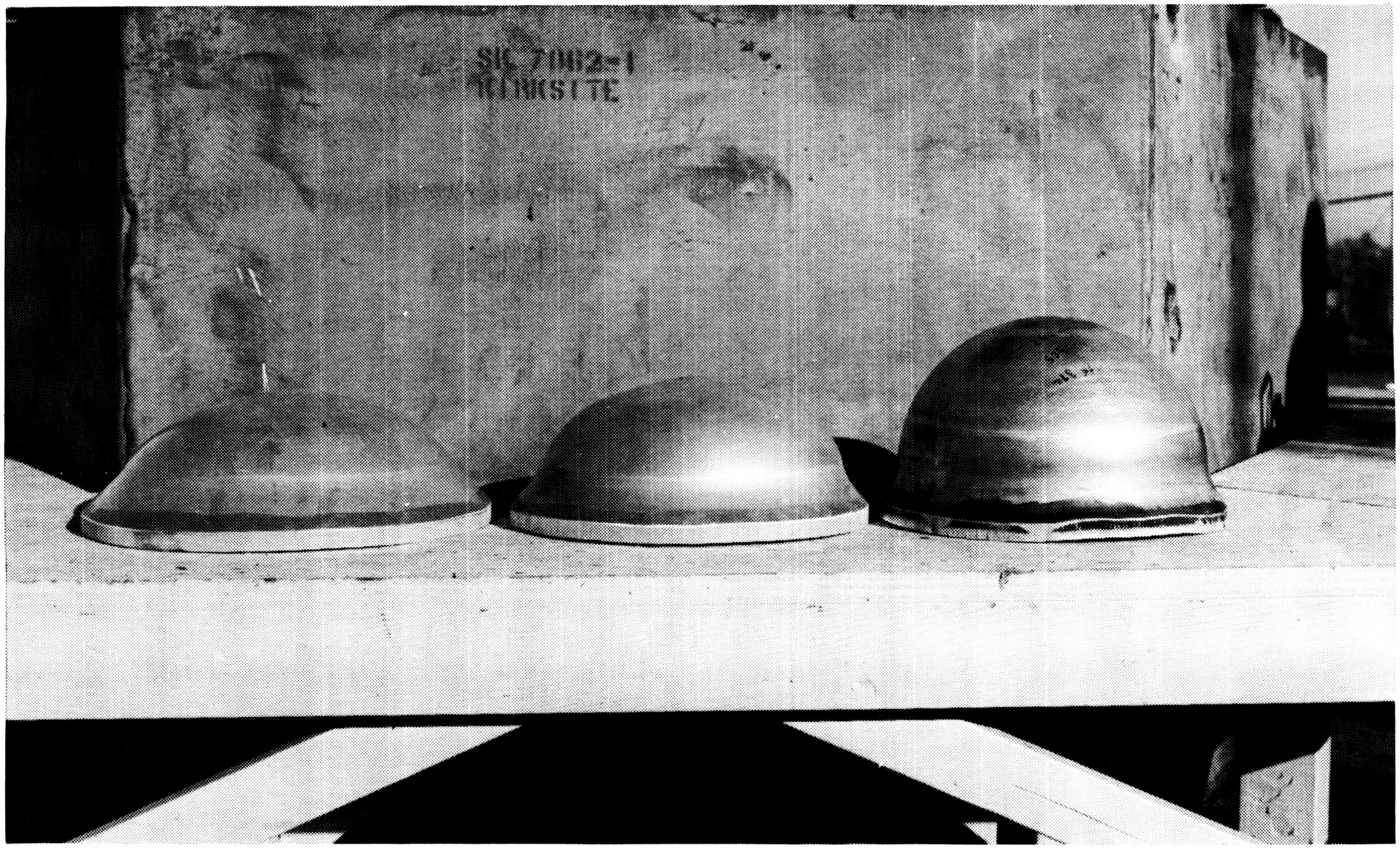


Fig. 2 Explosive Form Draw Stages for Forward Bulkhead

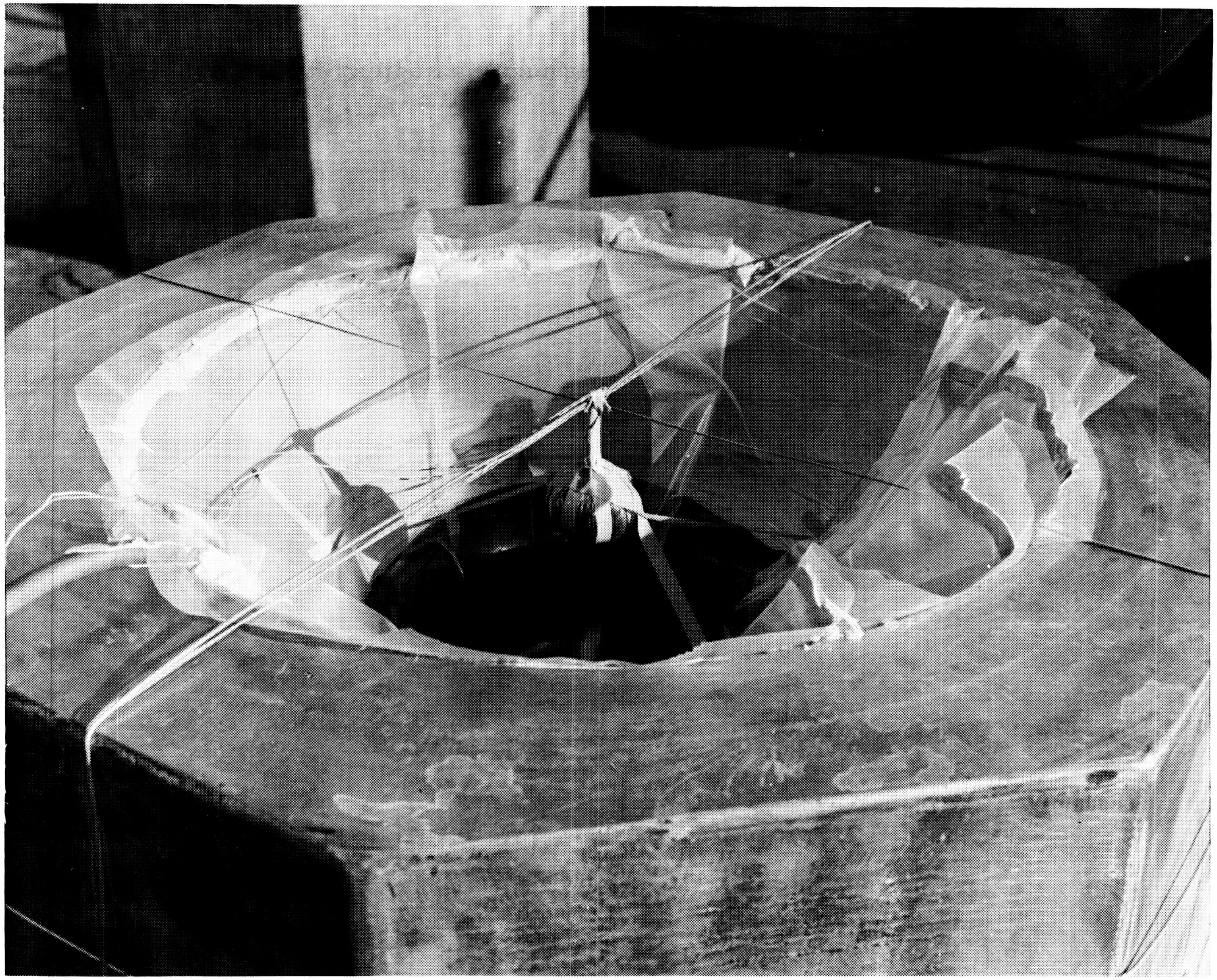


Fig. 3 Explosive Form Die Prepared for Final Draw

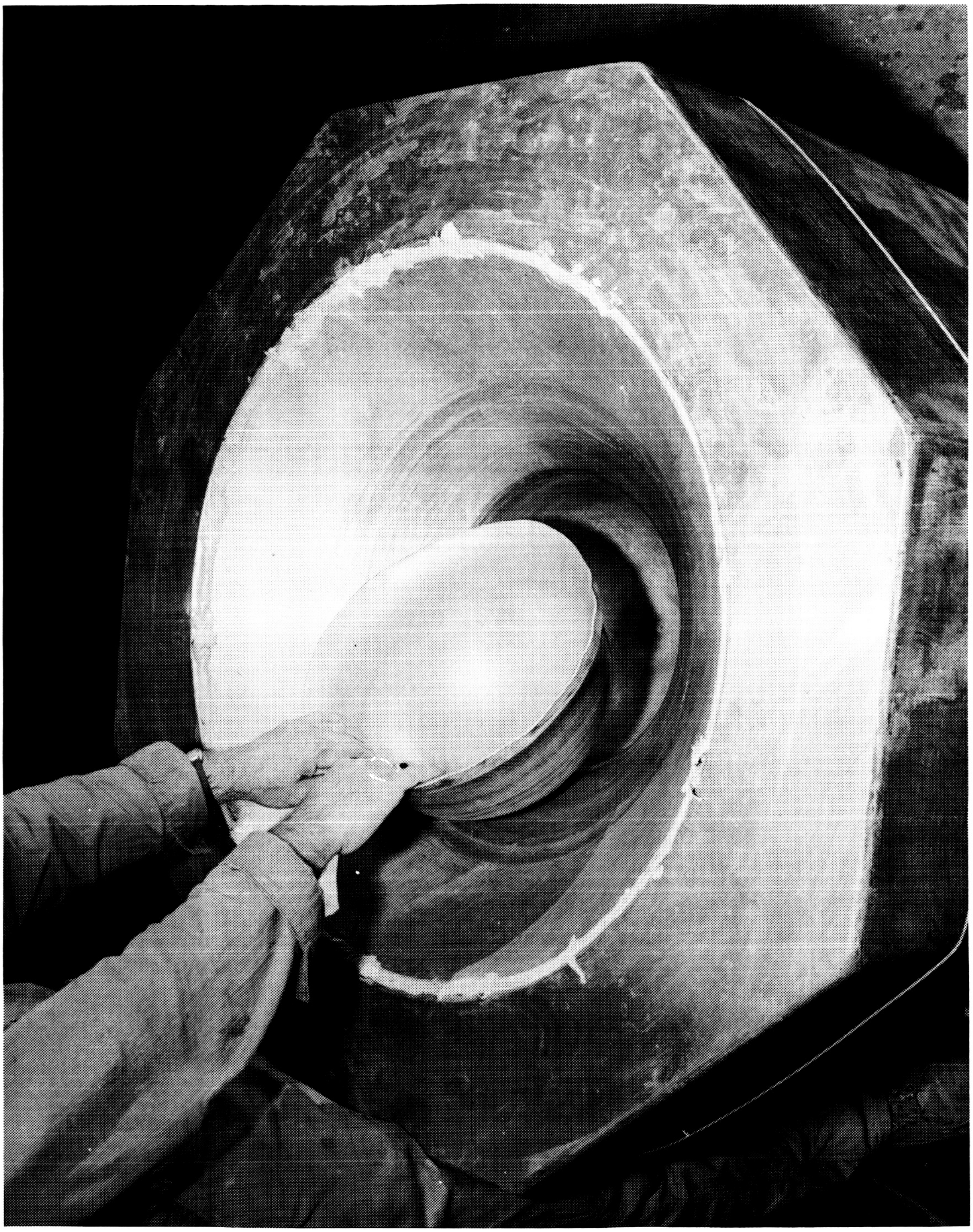


Fig. 4 Removing Final Formal Bulkhead from Die

The forward bulkhead and the access door were formed to net outside contour in the form die. A finish cut was then taken on the inner surface to provide a uniform starting wall thickness for chem-milling. This did not work as planned because variations in the external surface contour of up to 0.030 inch due to forming springback required selective etching during the pocket chem-milling to maintain uniform wall thickness. To overcome this problem, the aft bulkhead section was formed slightly oversize to permit the taking of a cleanup cut on both the outside and the inside surfaces to provide a uniform wall thickness of not to exceed $\pm$ .010 inch prior to chem-milling.

Conclusions: Where chem-mill operations follow explosive forming of plate gage aluminum alloys, or precision contour is required, allowance should be made for finish machining both sides.

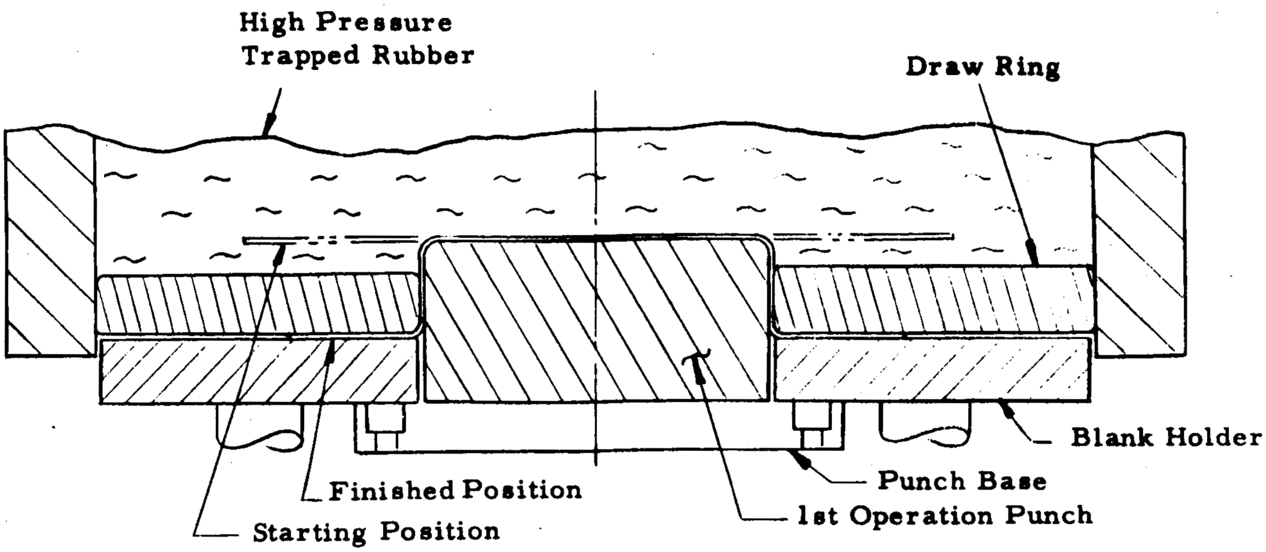
In developing the explosive forming procedures, for the bulkheads and the access door, it was found to be impractical to form in the T-31 condition, as originally proposed because of the depth of draw and difficulty in establishing the amount of material springback. This condition was aggravated by the scaling of the model (sharper radii were required) but will also be present in full scale flight hardware. It is therefore recommended that tank components for flight hardware be formed in the annealed condition, solution heat treated, re-hit for final sizing, then aged.

Draw Forming Bellows - The forward and aft bellows were draw formed from 0.040 inch thick annealed Inconel 718 sheet, and reduced to final thickness, by chem-milling after forming to provide required spring rate.

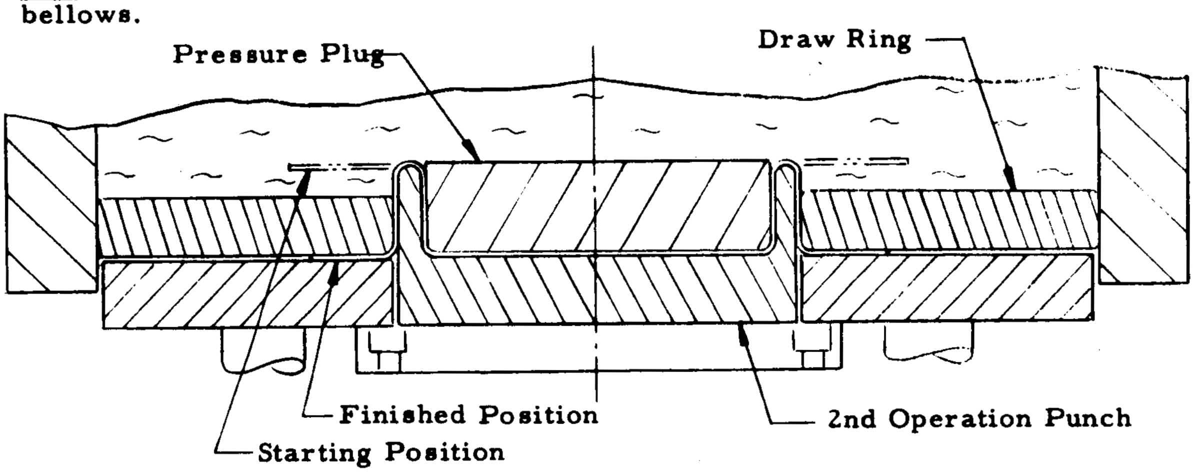
The forward bellows were formed from a 20.50 inch diameter starting blank in three draw stages starting with the inner convolution. Figure 5 shows the sequence of forming. The first draw reduction was in excess of the ductility of the material (average 52% elongation on material tensile tests). Rapid work hardening due to cold working of the material did occur, as anticipated, but this was overcome by annealing. Three interstage anneals were required, however, instead of the two originally planned. The second and third operations, both reverse draws, were true drawing operations with very little thinning. Figure 6 shows a finish formed bellows and a sectioned test part.

Finish formed bellows convolutions were chem-milled to 0.015 inch thickness. Inner and outer flange attach faces remained at starting material thickness, 0.040 inch, to simplify method of attachment.

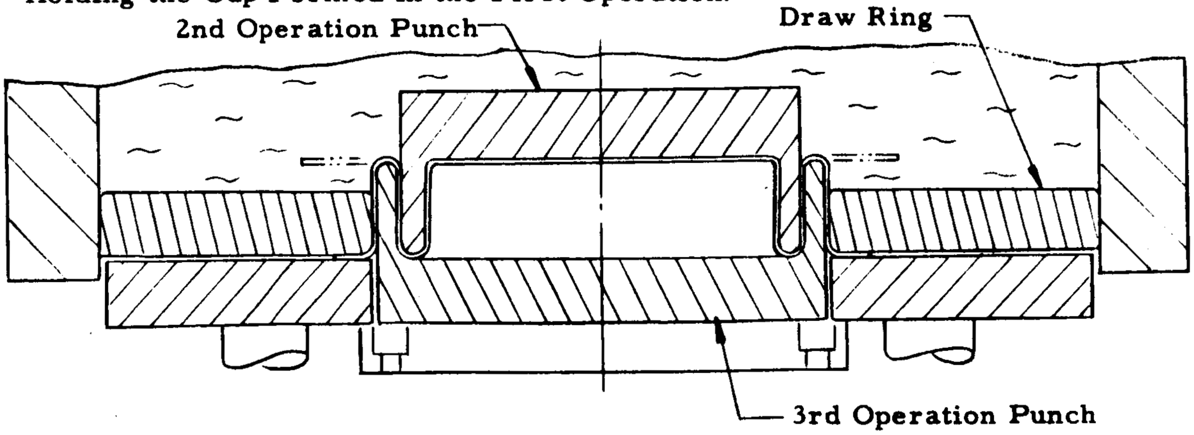
Following the initial chem-mill operation, a spring rate deflection test was performed. Test results indicated that material gage should be further reduced. A reduction to .007 inch thick was authorized. (This created a hole in one convolution.) A spring rate deflection test was then performed, Figure 7.. Results of this test are shown in Figure 8.. It will be noted that a load of 284 pounds was required to deflect the bellows .200 inches. A permanent deflection of .120 inches resulted from this load.



1st Operation - **Draw Pan with same diameter and depth as inner convolution of bellows.**



2nd Operation - **1st Reverse Draw Operation Reverses Outer Flange While Holding the Cup Formed in the First Operation.**



3rd Operation - **2nd Reverse Draw Operation Sequence of Forming Bellows.**

Fig. 5 Sequence of Forming the Bellows

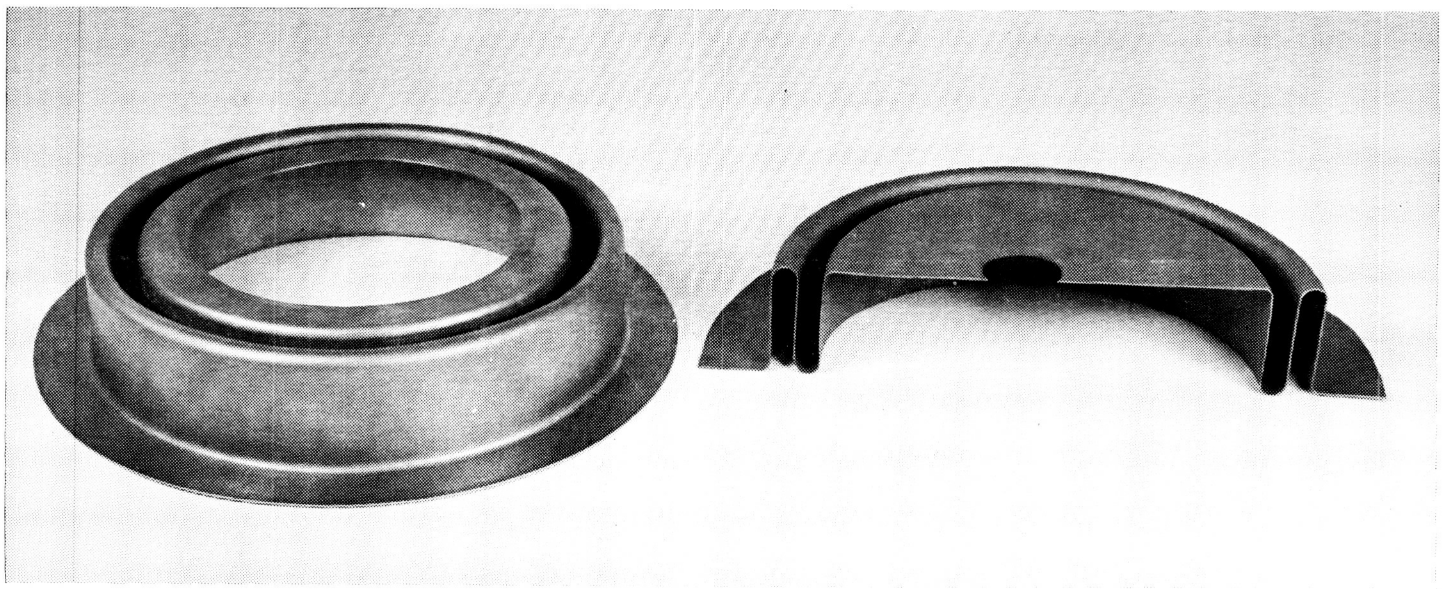


Fig. 6 Finish Formed Forward Bellows and Sectional Test Part

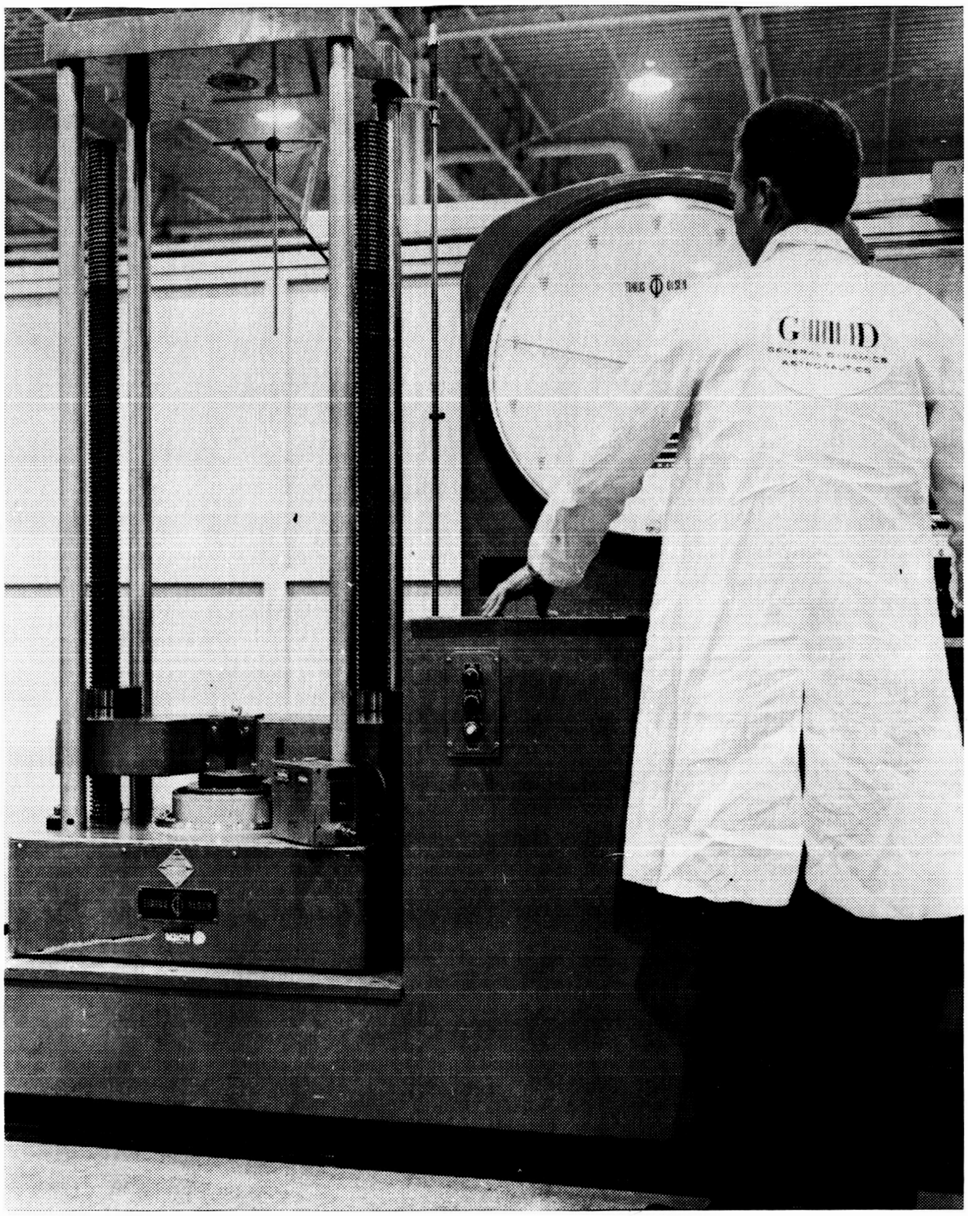


Fig. 7 Spring Rate Deflection Test on Forward Bellows

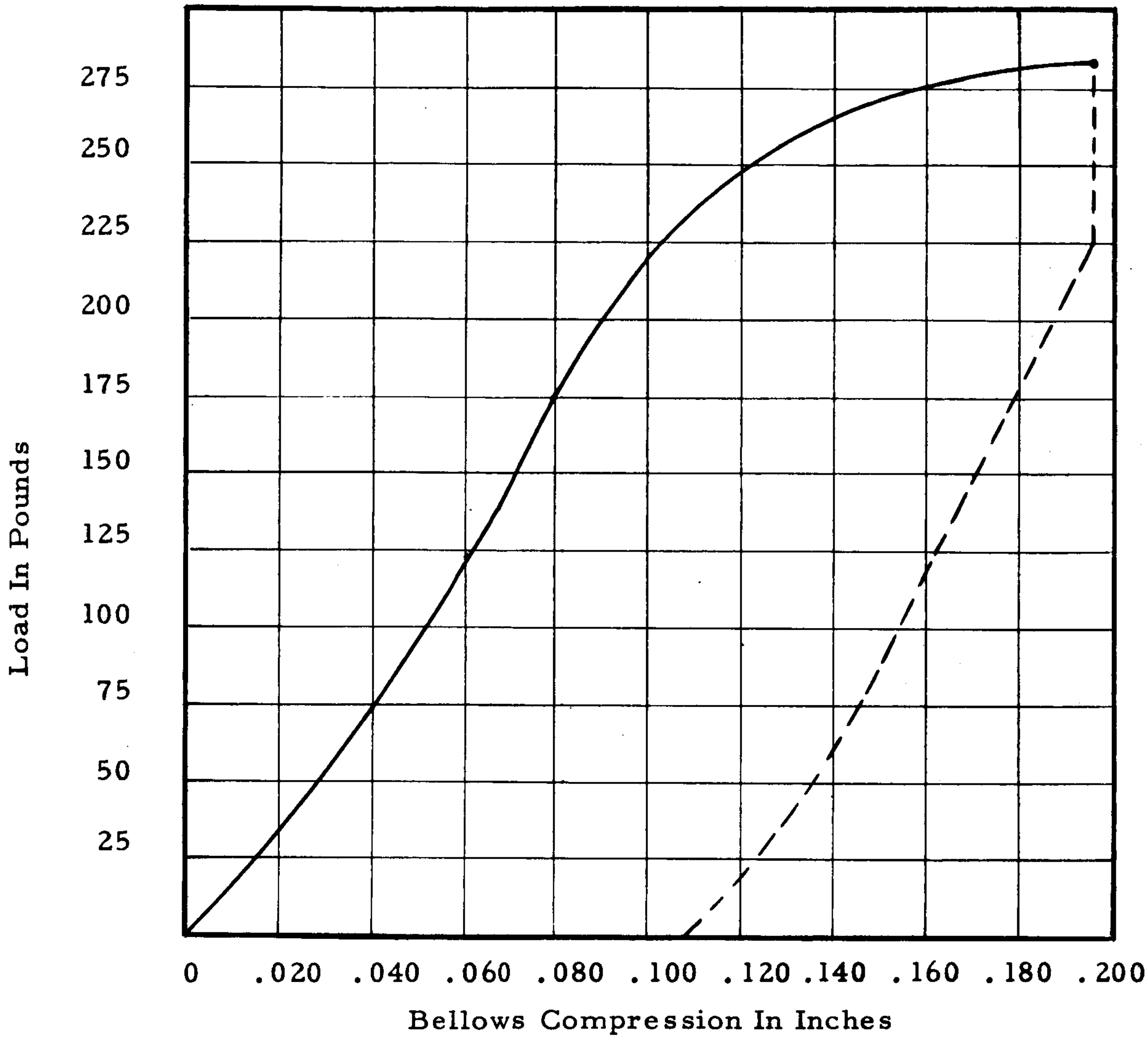
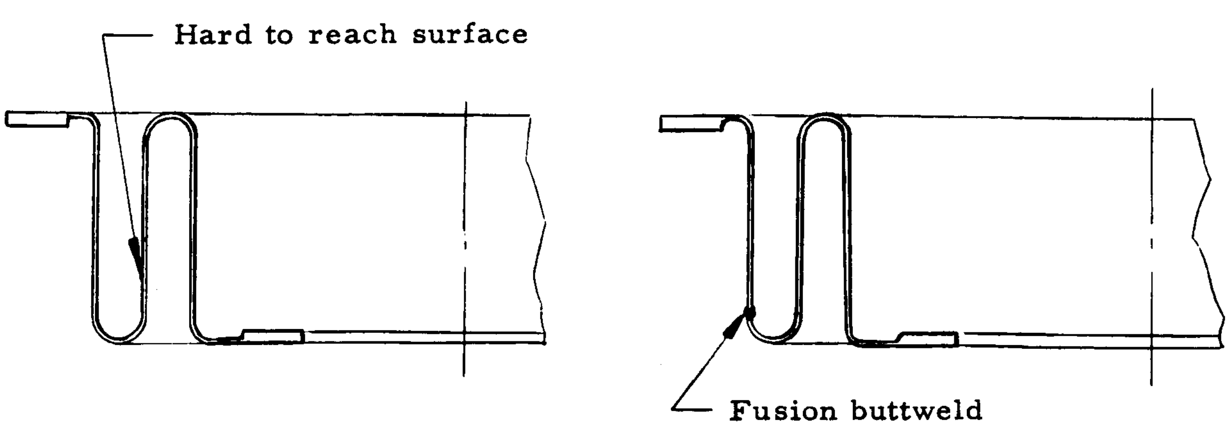


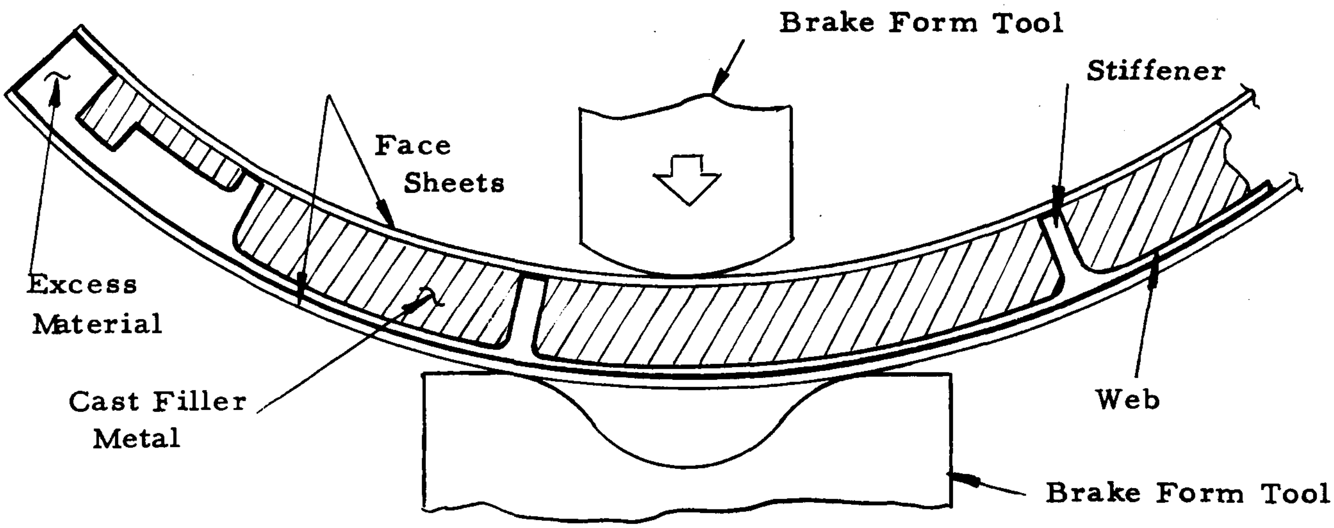
Figure 8 - Fwd Bellows Deflection and Spring Rate Test Results

The aft bellows were formed in two pieces to facilitate the chem-milling operation. Considerable difficulty was experienced in the forward bellows due to relative inaccessibility of the inner convolution.



Conclusions: Draw forming of bellows over three feet in diameter is not considered practical due to limitations in material size and machine capacity. Flight size bellows three feet in diameter and larger can be roll formed into hoops from pre-formed cross sections and joined by a resistance seam weld. In addition, permanent set may be avoided with the larger flight size bellows because space would be available for more convolutions and less curvature would exist.

Press Brake Forming - Tank Panel Segments - The eight conical tank panel segments (4 fwd and 4 aft) were formed to contour on a press brake after milling the pockets creating the waffle pattern. This permitted milling of the pockets while the panels were in the flat, thus eliminating a complex, 5 axis, milling or chem-mill operation on pre-formed panels. Panels were milled with material in the T-31 condition, then annealed for forming. Milled pockets in the panels were cast full of a low temperature (160°F) melting alloy to prevent buckling of the integrally milled stiffeners and to prevent the creation of flats across unsupported web of the pockets. Aluminum face sheets were used to prevent scoring of the panels during forming.



Surplus material was provided to retain the filler metal around the edges of the panel. Check templates were used to verify contour of formed parts. After forming, the filler metal was melted out of the pockets with hot water, Figure 9. The panels were then solution heat treated, aged to the T-62 condition, and trimmed to net size.

It was found necessary to fill the milled pockets in the panels with a low temperature cast metal, rather than a cast plastic, to provide support for the web skin during the brake forming operation. An excessive flattening of the skin across the pockets was encountered if there was insufficient support of the web during forming.

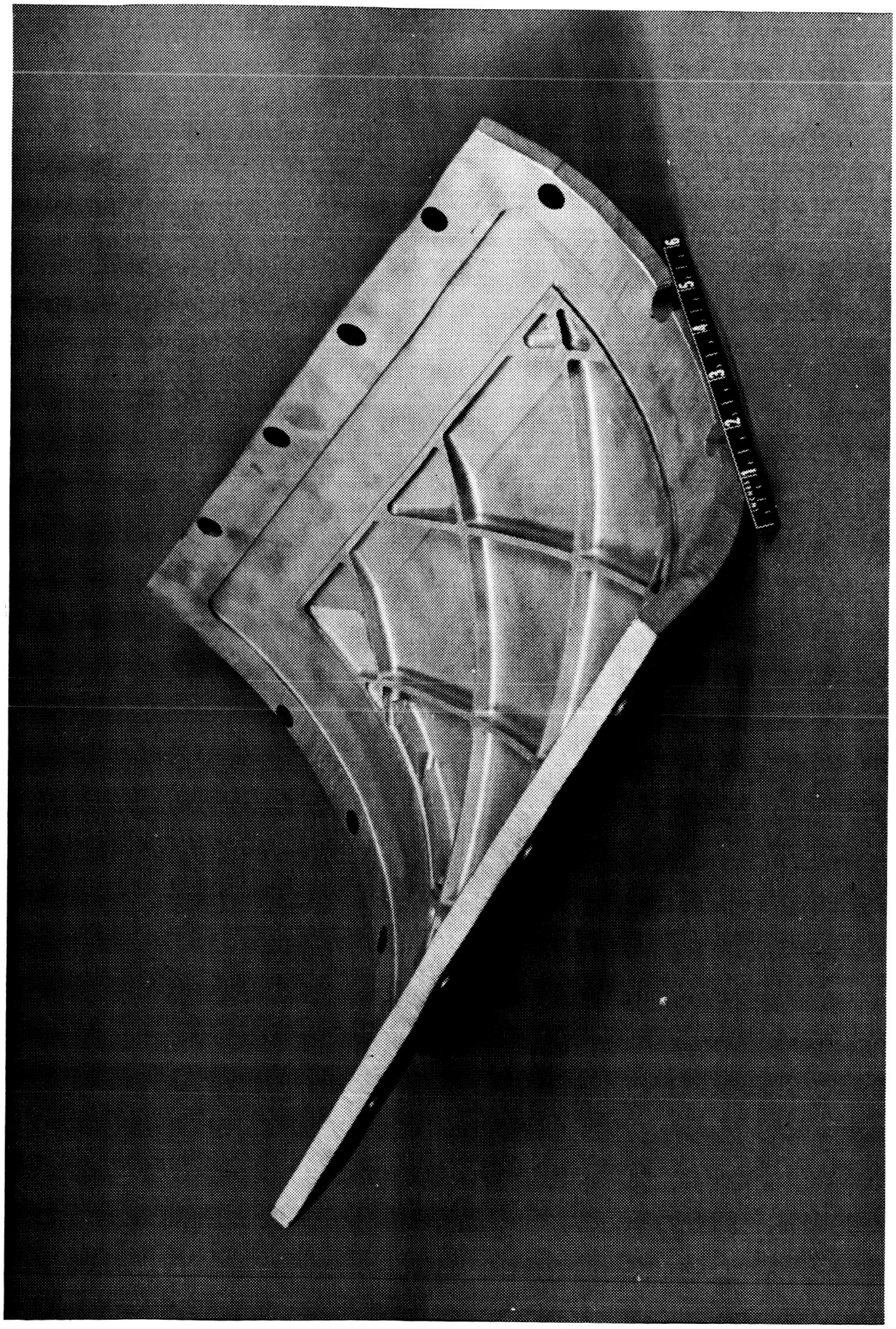
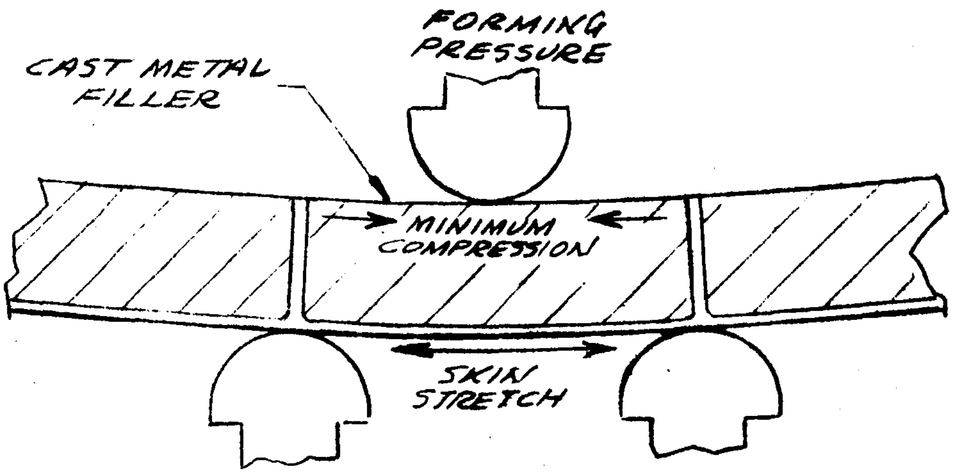


Fig. 9 Formed Tank Panel Test Part Before Trimming

Forming of the tank panel segments resulted in more stretching than anticipated and a slight lengthwise bow or saddle effect was encountered.

The increase in the panel width was due, it is believed, to the higher compressive strength of the cast filler metal versus the panel material resulting in a stretching of the skin with virtually no compression of the filler material.



This effect was anticipated but calculations and forming of test panels did not indicate that any appreciable increase in width would be encountered since the ratio of the pocket depth to the forming radius was quite small.

Lengthwise bowing or "saddle" effect encountered in forming the panels is believed due to the variation in the cross section: namely, the thick end sections on the panels. This shifts the neutral forming axis in the different sections, resulting in excessive stretch in the pocketed area of the panel skins.

Conclusions: It was found necessary to form the tank panels with material in the annealed condition due to the relatively small bend radii required for the structural model tank. On a full scale tank it should be possible to form the panels in the T-31 material condition which can then be aged to obtain the T-81 condition. This will provide significantly higher design allowables than the T-62 final material condition on the test model. Forming in the T-37 material condition for even higher allowables in a final aged material condition of T-87 does not appear practical because of excessive springback encountered in forming.

It is recommended that the size of the machined detail panels be carefully developed from full size test panels formed under exact production conditions prior to final machining of the production panels on any future programs.

To avoid the saddle effect encountered in forming on future programs, heavy end attachments should be minimized in panel designs. If this cannot be accomplished, a post forming hot "creep" sizing operation can be employed to straighten the panels during the aging cycle. This operation can be performed at the aging temperature (350°F) of the 2219 aluminum alloy but it requires special contoured heat treat fixtures capable of applying sufficient stretch to the material to obtain permanent deformation.

Welding

To provide the closest possible control over the welding processes and procedures used on the Structural Model, all welding was performed in the Manufacturing Development Laboratory under direction of welding engineers assigned to the program.

A summary of welding procedures is provided in Table 1, and results of tensile tests on fusion buttwelds are presented in Appendix D.

Resistance Spotwelding - Structure skins, Zee-stiffeners, doublers, frame webs and bulkheads were joined, where accessible with resistance spot welds. These parts were made from solution annealed Rene' 41 sheet. Work hardening during fabrication was removed by re-solution annealing prior to welding. Material gages included 0.015, 0.018, and 0.030 inch thick.

Forward and aft bellows attach skirt corrugations, made from 0.015 inch thick, solution annealed, Inconel 718 sheet stock, were also joined by resistance spot welds.

A 90 KVA, 3 phase spot welding machine with digitronic cycle control was used for all spot welding on the structural model, Figure 10. The machine was certified for both Rene' 41 and Inconel 718 while establishing weld schedules for the various gage combinations.

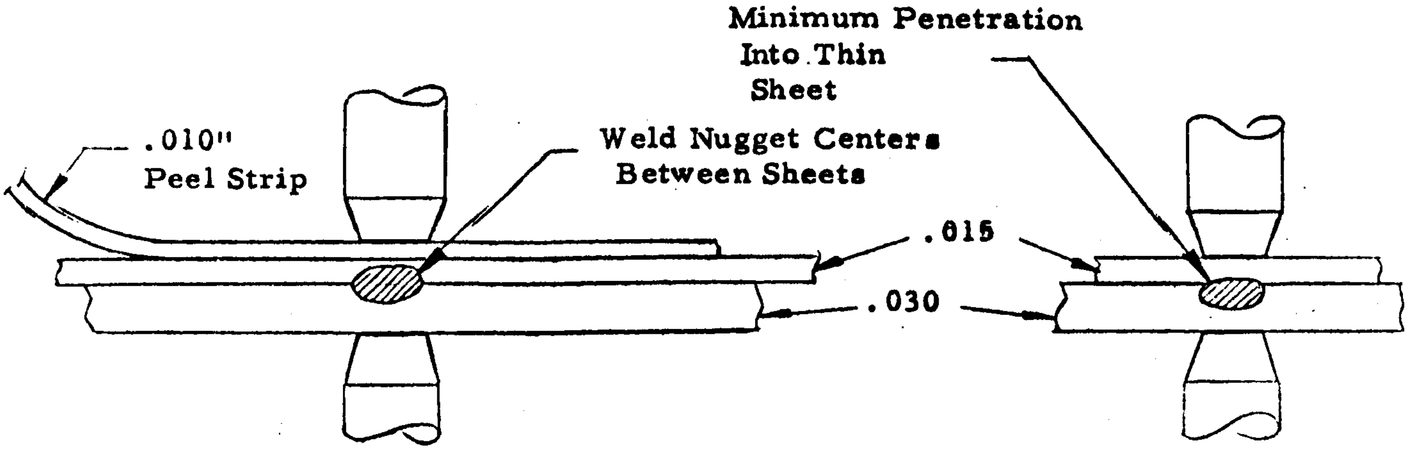
Size and shear strength of the spot weld nugget at the interface exceeded the contract specification(3 times the thickness of the thinnest sheet plus 0.040 inch). Compliance was verified by pulling and sectioning a tensile test coupon for every new setup plus coupon testing every hour thereafter.

Peel strips of type 301 CRES were used to draw the weld nugget toward the thin sheet to provide required penetration when the thickness ratio of the sheets is 2:1 or greater. This technique is particularly valuable in welding 0.015 inch thick Rene' 41 sheet. Peel strip is easily removed after welding.

Table 1. Summary of Welding Procedures

MATERIAL									
TYPE	CONDITION	GAGE COMB.	TYPE OF WELD	FILLER WIRE	TORCH GAS	BACKUP GAS	WELD JOINT REQUIREMENTS	TEST RESULTS	METHODS OF VALIDATION
Rene' 41	Annealad	.018/.015 .018/.016 .015/.030 .015/.030/.015 .015/.015/.015	Resistance Spot	None	None	None	55% of ultimate shear strength of parent material based on weld nugget diameter of 3 times the thinnest sheet plus .040" ± .010"	65% (Average) Nominal diameter ± .010"	Tension shear test pulled hourly to verify weld schedule Sectioned test coupon prepared hourly to verify weld schedule
Inconel 718	Annaalad	.015/.015	Resistance Spot	None	None	None			
Rene' 41	Annealed	.018/.015 .018/.018	TIG Fusion Spot	None	Helium	Argon			
Inconel 718	Annealed	.040/.200		None	Helium	Argon			
Rene'	Annealed	.036/Test Section	Automatic TIG Fusion Seamweld	Hasteloy-W	Helium	Argon	75% of ultimate tensile load per unit width of .036" thick combined skin/doubler (1.5 times .018" thick face skin material)	82% (Average)	(3) tensile test coupons simulating weld joint prepared and pulled to verify machine settings. Dye penetrant used to detect cracks.
2219 Aluminum	T-62	.380	Automatic TIG Fusion Buttweld	2319 Aluminum	Helium	None	65% of ultimate tensile strength of parent metal in the final material condition (T-62)	69% (Average)	(3) tensile test coupons prepared and pulled to verify weld schedule on machine. Dye penetrant used to detect cracks.
2219 Aluminum 6061 Aluminum	T-62 T-6	.380 .090	Manual TIG Fusion Plugweld	43S Aluminum	Helium	None	55% of ultimate tensile strength of the parent material.	76% (Average)	(3) tension shear test coupons prepared and pulled. Dye penetrant used to detect cracks.

Fig. 10 Weld Technicians Spotwelding Aft Panel Zee Stiffeners to the Frame Doubler



Conclusions: Rene' 41 is very susceptible to cracking and forge out (expulsion of molten metal) when resistance welding thin gage material (0.020" and below). Welding with material in the annealed condition is recommended whenever the design will permit. Use of relatively flat electrode tip radii and increased weld times at lower current values than used on conventional schedules is also recommended, particularly if material must be welded in the aged or partially cold worked condition. Equipment capable of precise control of cycle time, forge pressure and weld current is mandatory. Surface preparation is very important. Abrasive cleaning (hand sanding) of the surfaces to be welded just prior to welding plus a solvent wipe was found to be necessary in all cases. A minimum of 0.200 inch edge distance is recommended for thin gages to eliminate expulsion along the joint edges.

Fusion Spotwelding - Areas of the Rene' 41 structure that could not be reached by the resistance spot welder were welded with the TIG fusion spot welder pictured in Figure 11.

The equipment used was a 400 amp TIG fusion spot welding power supply with electronic tube counting system for precise slope and weld cycle control. The portable spot weld gun shown in use incorporates water cooling and inert (Helium) gas shielding provisions. Argon gas backup, not visible in the photograph, was provided by localized bagging.

Size and shear strength of the fusion spot weld nugget called for in the contract (3 times the thickness of the thinnest sheet $+0.040$ inch) were consistently complied with. Weld schedules were prepared for every combination of material gages to be welded. Size and shear values of the welds were verified by sectioned shear test coupons prior to start of welding on the actual structure and every hour thereafter.

A test section devised to test the spot welding sequence for joining the outer skin panel to the forward frame is shown in Figure 12. It includes a typical area inaccessible to resistance spot welding because of the frame bulkhead. Fusion spot welding was therefore used to join the 0.015 inch thick

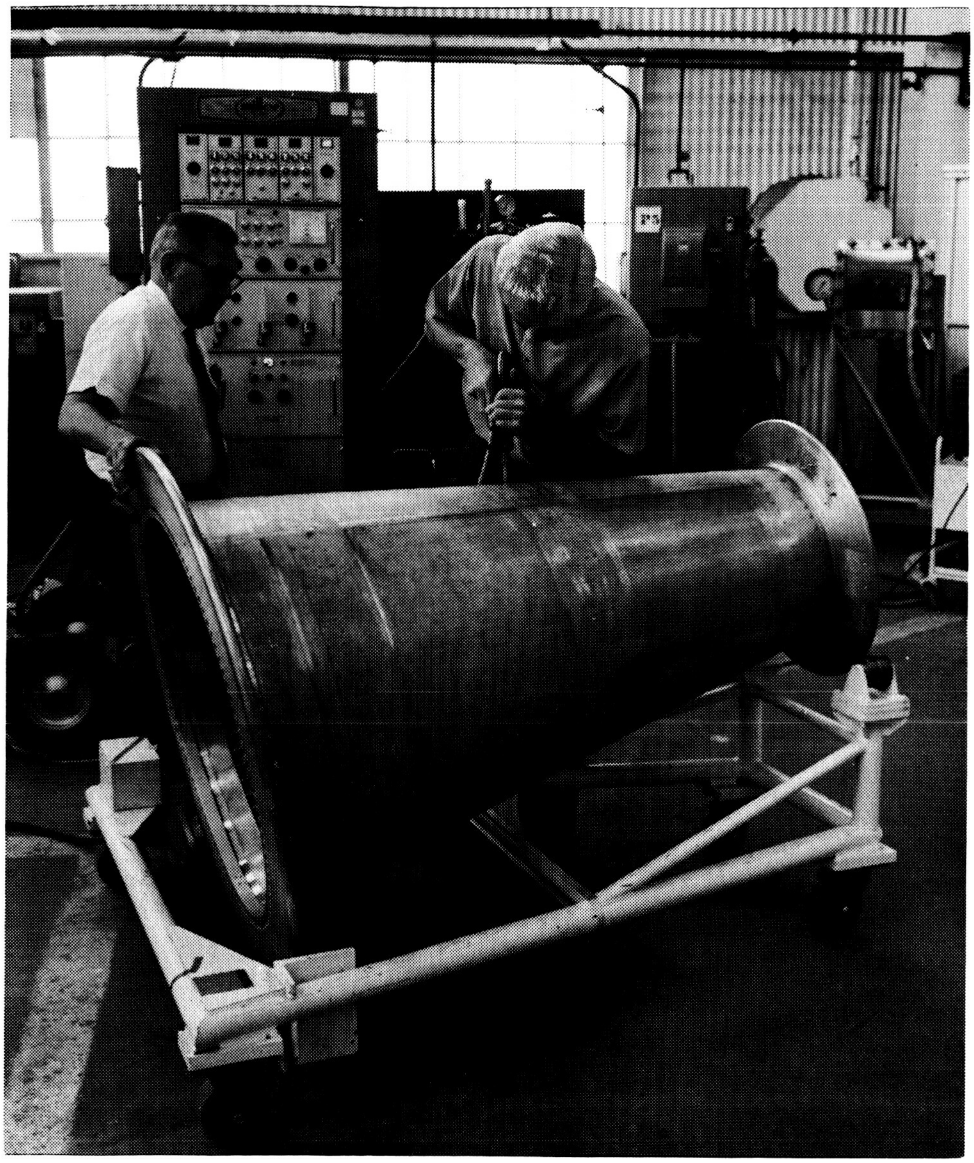


Fig. 11 Weld Engineer Supervises TIG Fusion Spotwelding of Structure Closure Skin

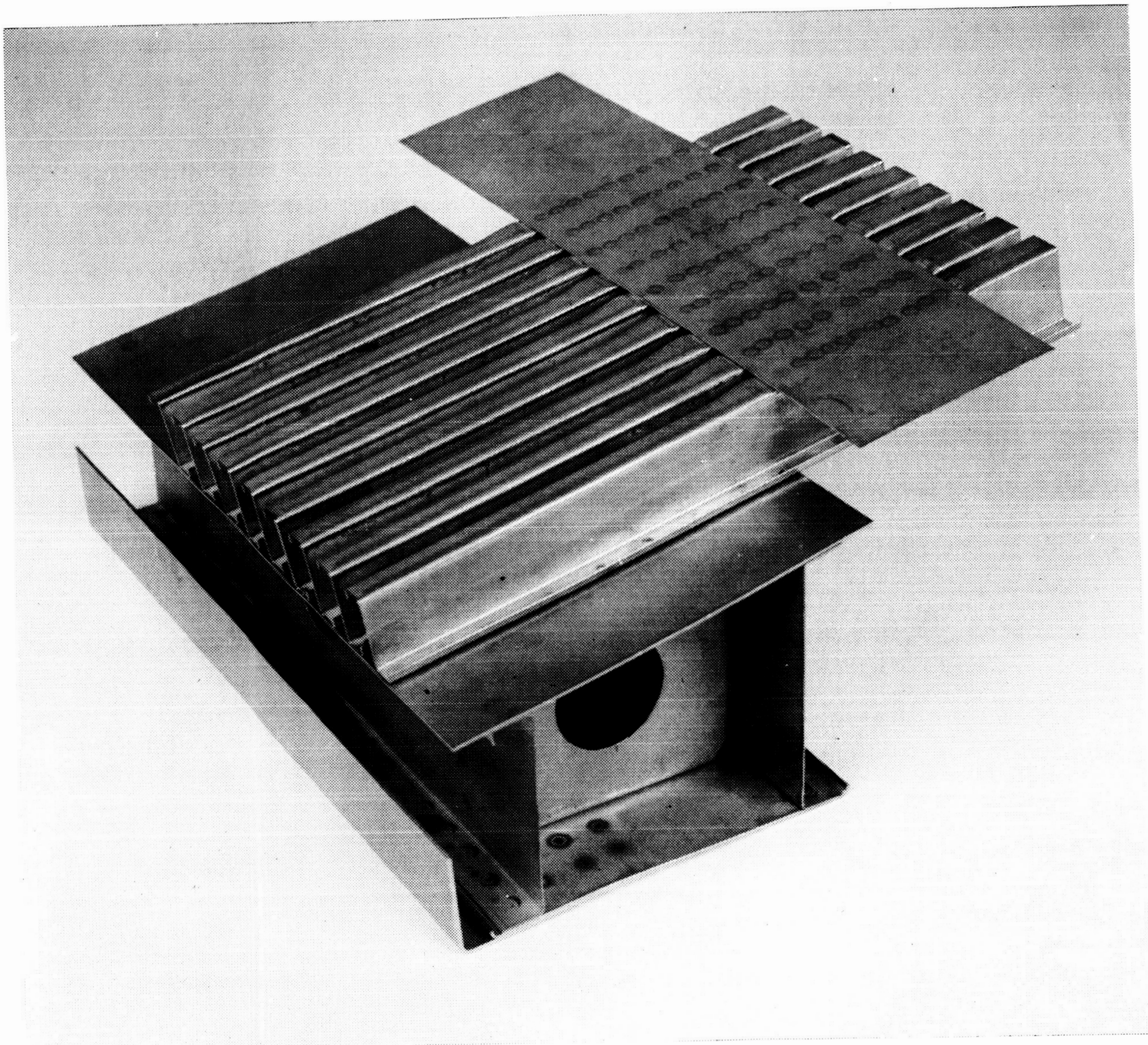
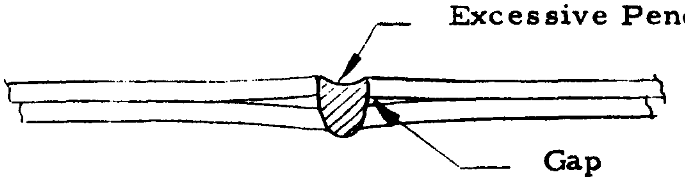


Fig. 12 Forward Frame Joint Test Section

Zee-stiffener to the 0.030 inch thick frame doubler. A special narrow tip was devised to permit welding under limited clearance assembly conditions. Excessive penetration will be noted on some of the spots due to improper fitup and difference in material gages being joined.

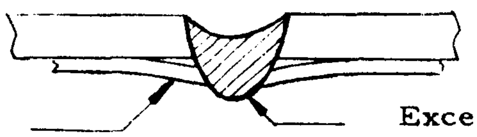


Effect of Improper Fit Up on Fusion Spot Weld

Tests were performed on specimens duplicating this condition, and it was found that welds showing evidence of excess penetration had nearly the same shear values as those that did not, though appearance was not good. Attempts to add filler wire were not very successful. Specimens simulating various degrees of excess weld penetration in the 0.018 inch thick outer skin and the 0.015 inch thick Zee-stiffeners had an average single shear strength of 560 pounds versus a calculated ultimate strength of 527 pounds per contract specifications. This is considered important because fitup problems are certain to exist in full scale flight hardware.

Welding of thick sheets to thin material was found to be impractical when the ratio of the skin gages exceeds 1.5: 1.0: This is due essentially to difficulty in controlling the drop through. Heat required to melt the thick outer sheet tends to buckle the thin inner sheet creating a gap. The slightest variable in sequence timing or joint fitup causes excess melting of the inner sheet and results in drop through.

Buckling



Excessive Drop Through

Effect of Welding Heavy Gage Material to Lighter Gage Material

The effect of fusion spot welding an 0.036 inch thick closure skin/ doubler to an 0.015 inch thick Zee-stiffener is shown on the test section simulating the original design of the forward skin panel joint Figure 13. Filler wire was added to some of the spot welds in an effort to counteract the drop through but proved very difficult to control. Lack of uniformity of the welds will be noted. The uneven surface of the channel reinforcements, resulting from weld distortion of the tack welds, created a fitup problem that further aggravated the fusion spot welding problem.

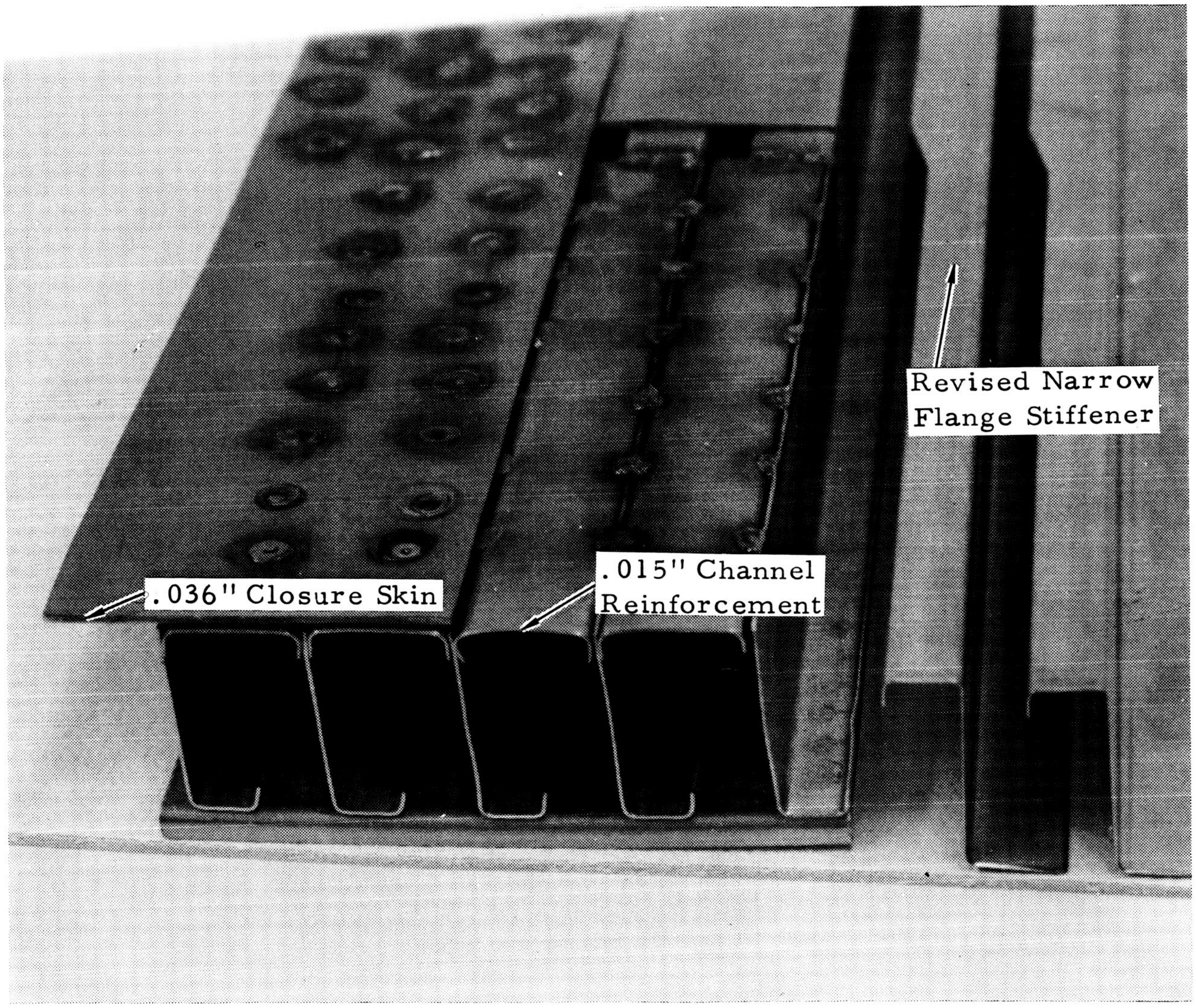
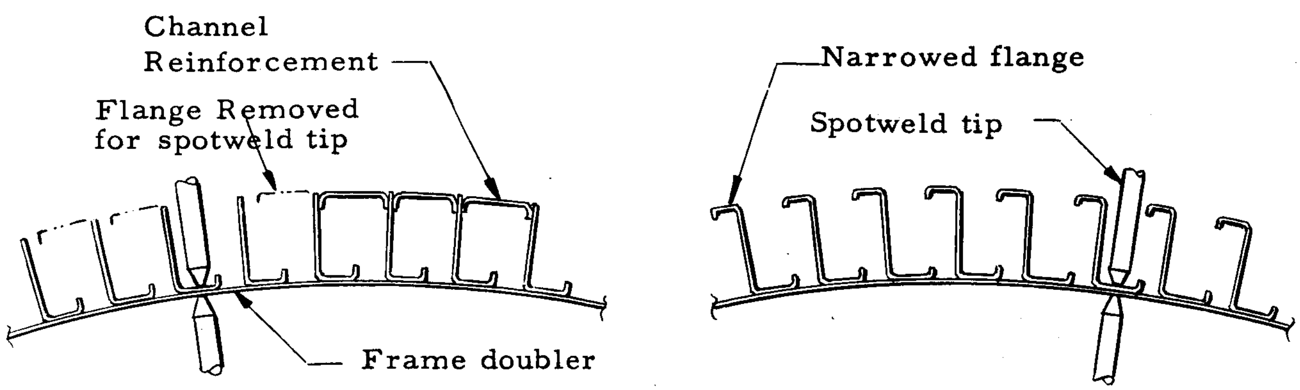


Fig. 13 Test Section Simulating Original Design of Forward Skin Panel Closure Joint

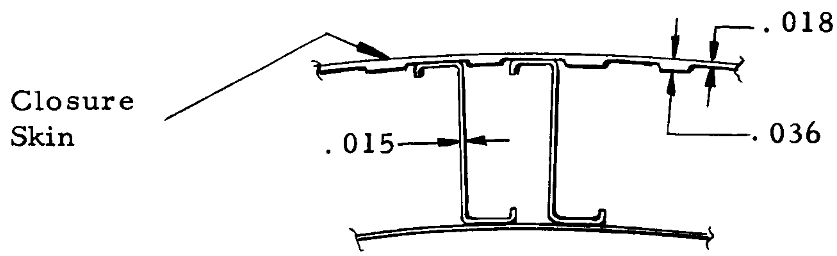
To overcome this problem, a different approach was taken to the joint design. Rather than removing the upper flange of the Zee-stiffener to provide required spot welding access for joining the stiffener to the frame doublers then replacing the flange with a channel section, it was proposed by NASA to simply narrow the flange at the ends of the Zee-stiffeners where they are joined to the frames.



Original Design

Revised Design

It was found that sufficient access for spot welding could be obtained by this method. Comparison of the two designs is shown in Figure 14. The stiffener upper flange now presents a smooth uniform surface for joining the closure skin to the stiffener. The closure skin and reinforcing doubler could then be combined in a single piece with chem-milled grooves to reduce the thickness where the skin spot welded to the stiffener. This resulted in a good thickness ratio for spot welding. These designs were selected for use on the structural model.



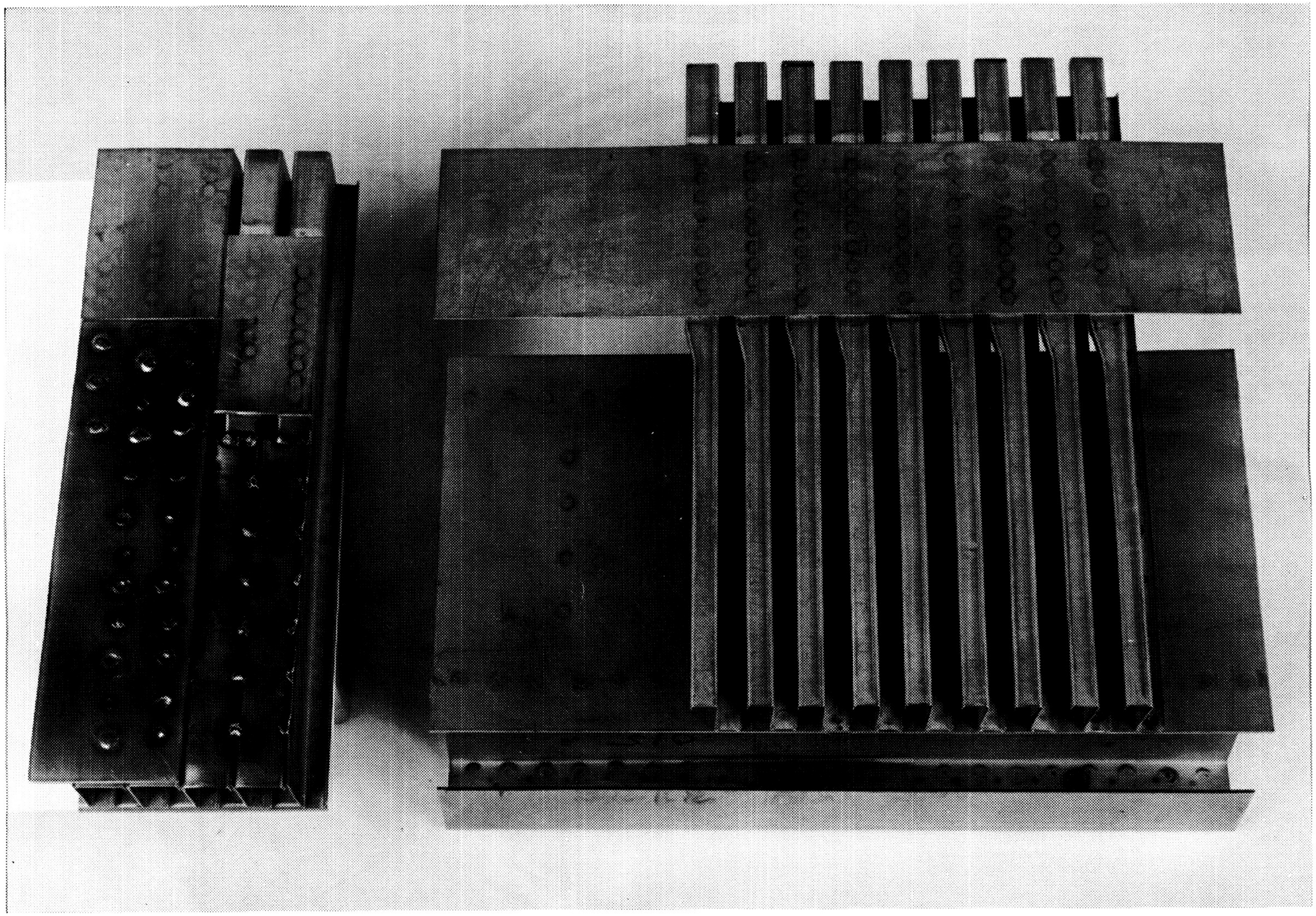


Fig. 14 Comparison of Original Skin Panel Joint Design:
Left, with Revised Design; Right, Employing Narrowed Stiffeners

Conclusions: Because TIG fusion spot welding is not as tolerant of slight gaps (0.005 - 0.010 inch) as resistance spot welding, metal to metal fitup is essential to provide uniform TIG fusion spot welds. In resistance spot welding, the initial squeeze, prior to actual welding, forces a metal to metal fit, assuming the mating parts are reasonably flexible. This is not the case with fusion spot welding where a gap, unless it can be removed by manually pressing the gun against the surface, remains a gap at the time of actual welding, resulting in excessive penetration. Welding of thin sheets to thick is much preferred unless sufficient backup can be provided to prevent buckling of the thin sheet on the reverse side.

Fusion Seamweld - Face skins and inner doublers 0.036 inch thick with chem milled recesses for stiffeners were fusion welded to machined rings on the forward and aft ends of the structure. A 300 amp fully automatic weldtronic power supply and controls with an automatic TIG welding head were used for this welding. The joints welded were a combination of lap and butt welds. Joints were tacked at 0.25 inch spacing with the TIG fusion spot weld equipment prior to fusion welding the seam. Hasteloy "W" filler wire was added to the joint. Weld speed was 12 inches per minute.

Fusion seam welds in the Rene' 41 material were required to have an ultimate tensile load per unit width of not less than 1.5 times the face sheet material or 75% of the combined sheet thickness of 0.036 inch (0.018 face sheet plus 0.018 finger doubler). To validate the strength of this joint, it was decided to prepare a test specimen, Figure 15, simulating the joint and then to cut sections from this specimen for tensile testing. An etched cross section of a tensile test coupon cut from the test specimen is shown in Figure 16. This figure indicates that increased penetration and a shift in weld centerline to a location midway between the end of the face sheet and the end of the lip of the bar would have produced a better weld. Coupon after tensile test is shown on Figure 17. Failure occurred in the upper leg at approximately 82% of the ultimate tensile value of the parent material.

X-ray inspection was attempted as a method of in-process inspection but the results were not very conclusive due to difficulty in obtaining a good shot of the joints. Some porosity was observed but was judged acceptable.

Proper fusion and weld penetration and absence of cracks were considered to be the most important elements of joint quality. Fusion and penetration was established by weld schedules developed for the joint. Dye penetrant was used to detect cracks. Several small cracks detected (.0.02 - 0.06 inch in length) were ground out and re-welded (manual).

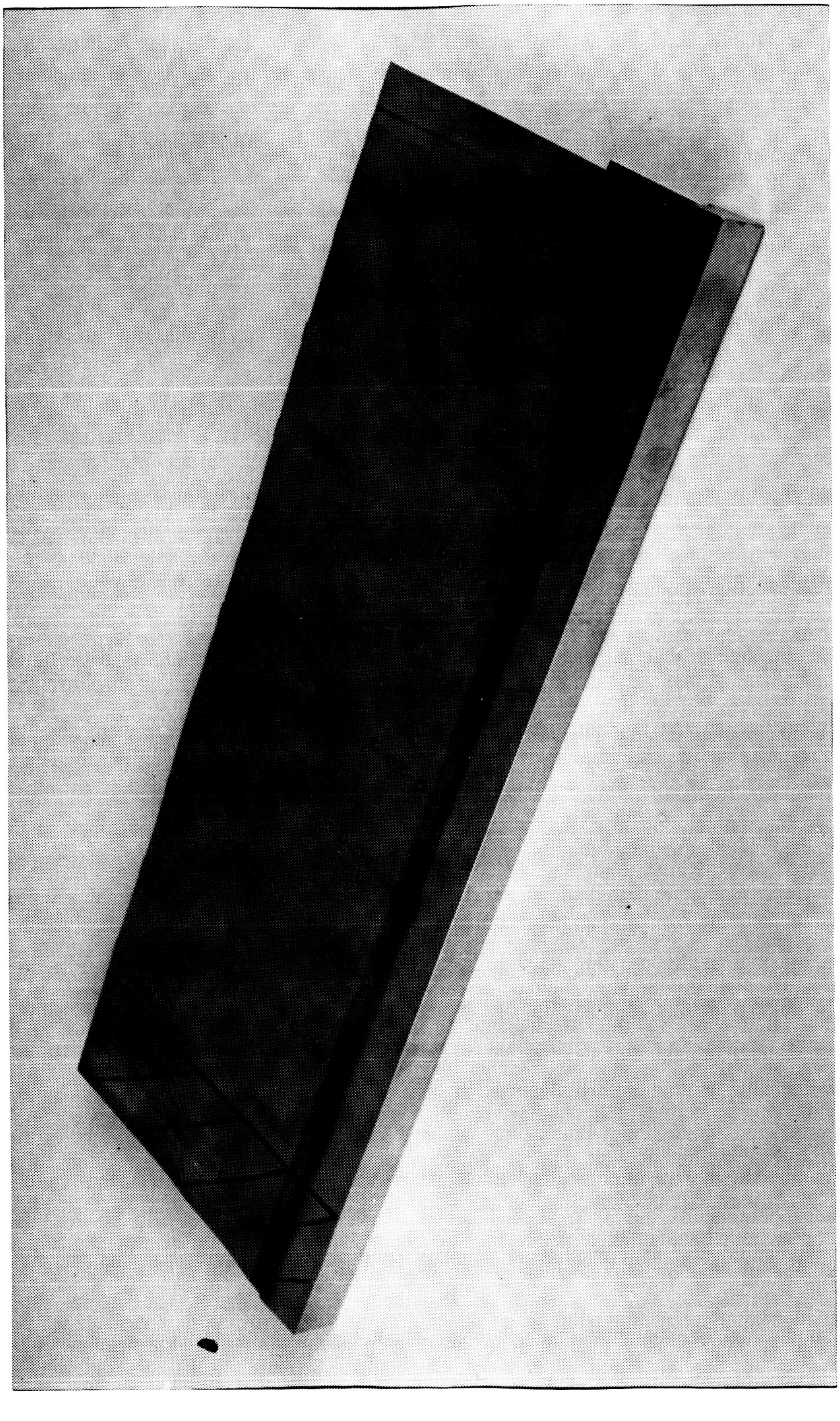


Fig. 15 Test Panel Simulating Aft Panel/Ring Joint

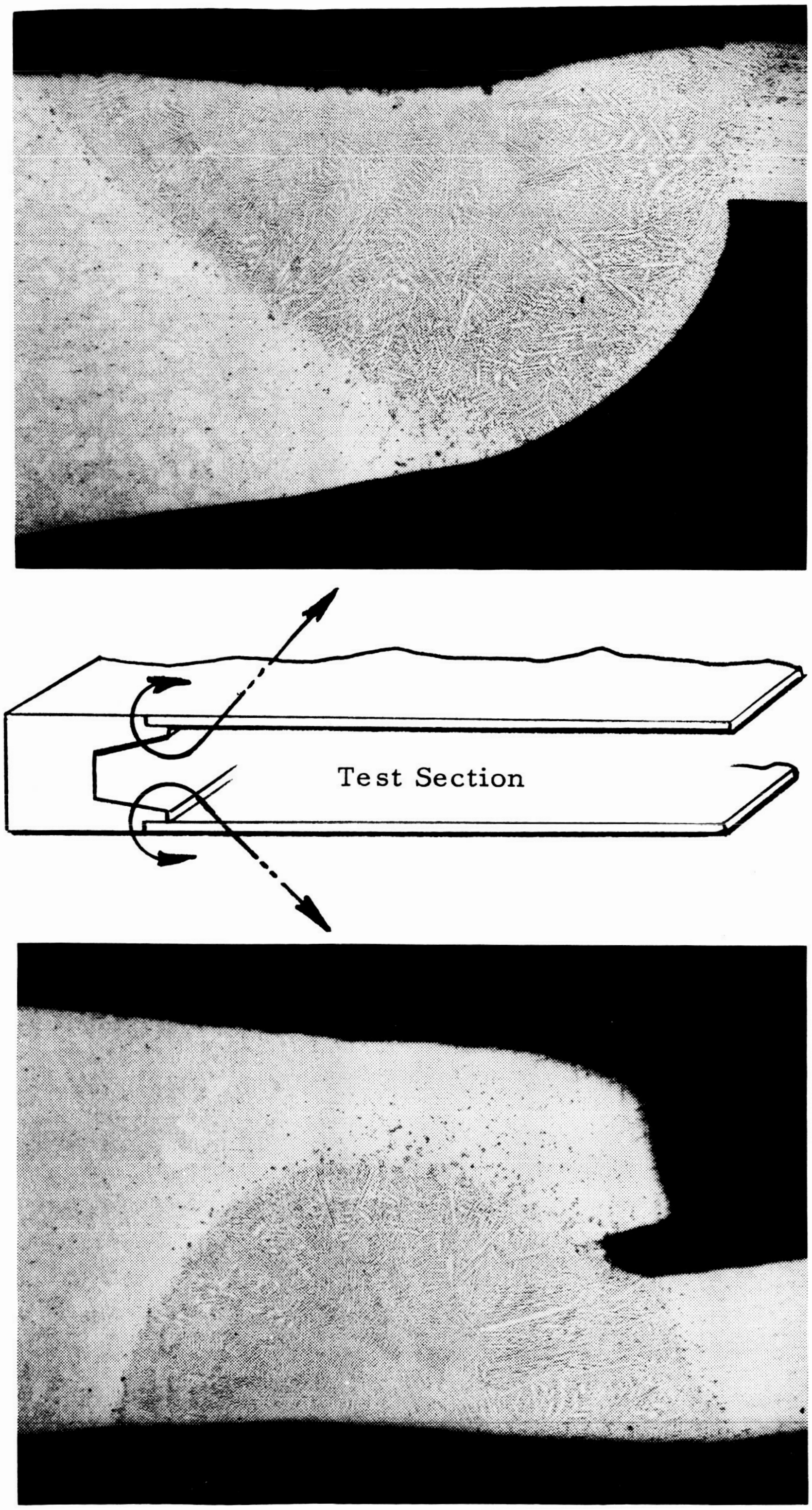


Fig. 16 20 X Macro Cross Section Photograph of the TIG Fusion Welded Aft Ring Joint

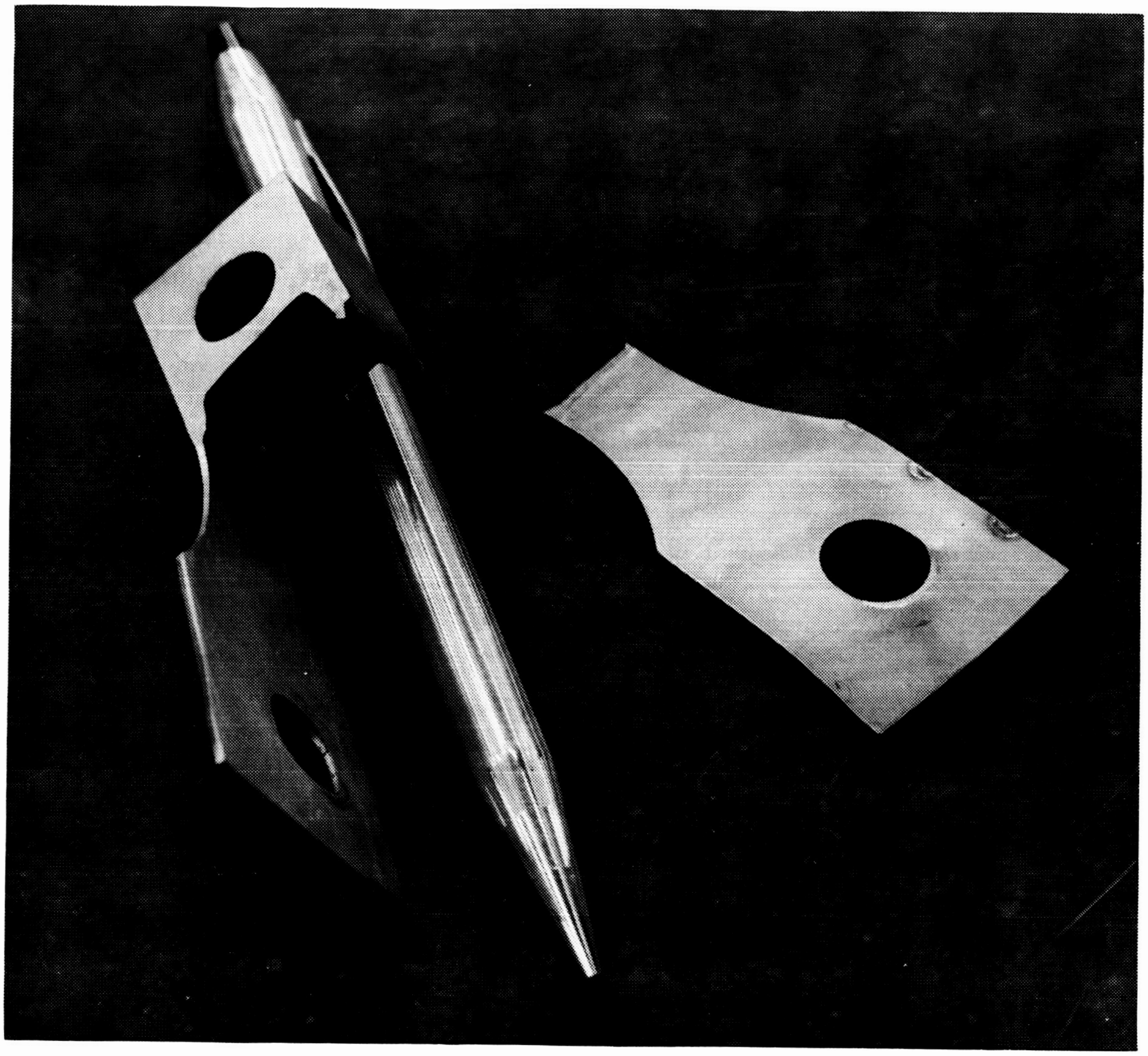
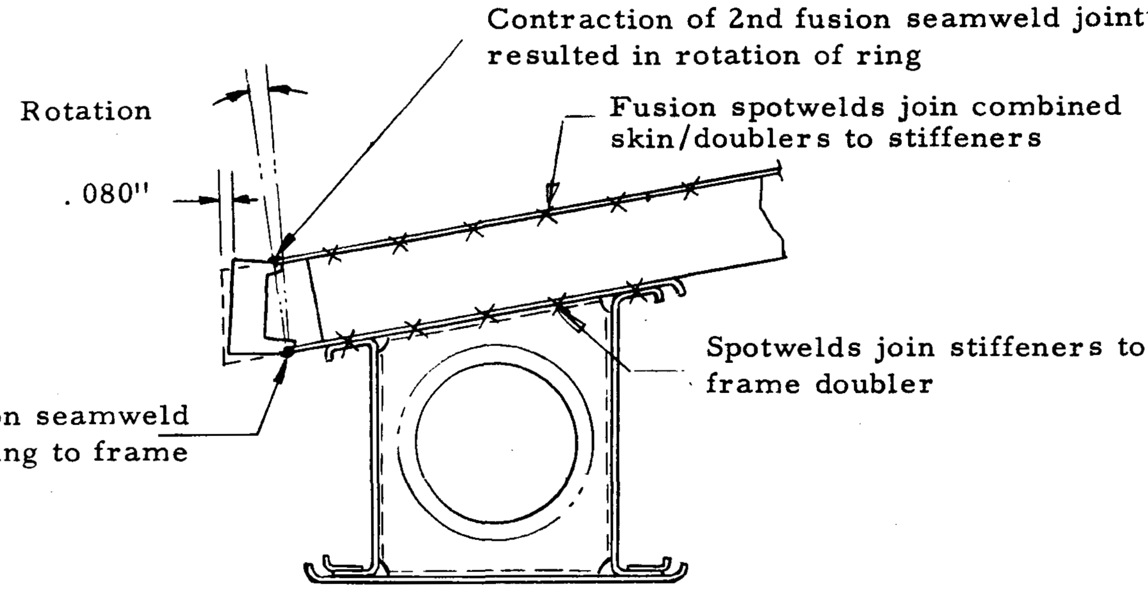


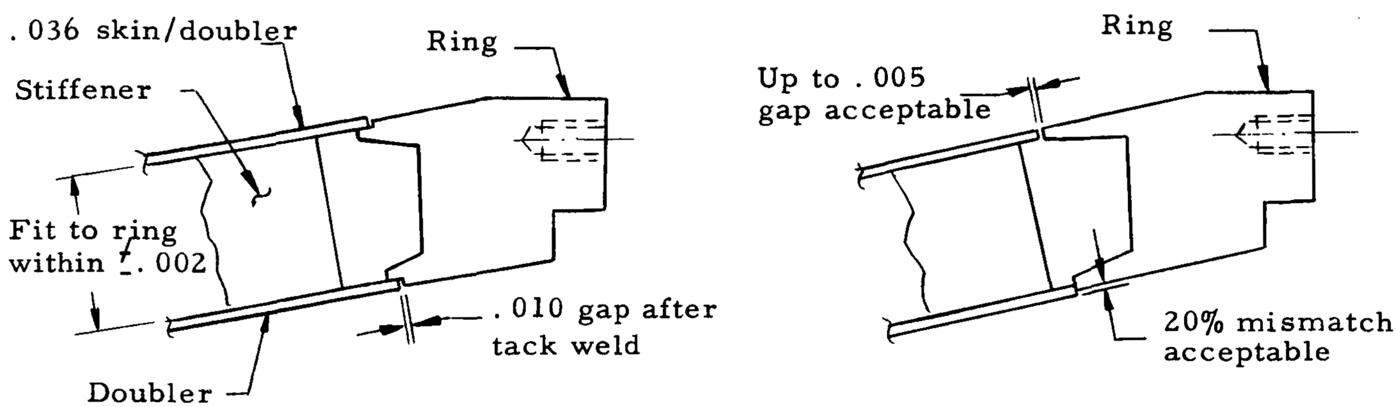
Fig. 17 Tensile Coupon Cut From the
Aft Ring Joint Test Panel

Discussion: Fusion welding of the machined forward and aft rings to the structure skin and doublers was considered to be one of the most critical fabrication tasks on the structural model -- considerable weld shrinkage was encountered although the rings were securely bolted to heavy tooling plates held apart by spacer bars. Shrinkage of the second seam weld on the forward ring resulted in approximately 0.080 inch rotation of the forward ring necessitating a cleanup machining operation.



To counteract the effect of joint shrinkage, and subsequent rotation of the aft ring, the inner doubler was not permanently joined to the stiffeners until the fusion seam welds were complete. There was therefore nothing the contracting weld could pull against to cause rotation so the ring remained flat.

Conclusions: True fusion buttwelds may be more desirable for joining rings to structure on flight vehicles.



Present Design Proposed Design

Present design requires a very exacting fitup that is hard to maintain when welding is started. Burndown of the inner flange lip proved difficult to control. Contamination is difficult to prevent along the faying surfaces. Standard tensile test coupons cannot be used to establish weld strengths.

It is recognized that the fusion buttweld joint would not eliminate fitup and weld distortion problems, but it allows a greater fitup variation, reduces weld contamination and provides a sounder weld.

Fusion Buttweld - Tank panels, bulkhead segments, access door and door rings made of 2219 aluminum alloy were welded in the aged T-62 material condition. Automatic fusion welding of tank components was performed on a 0.750 amp MIG/TIG Linde "Missile Maker" welder using D. C. straight polarity and helium gas shielding. Weld schedules were established to certify the welder. Multiple pass, automatic TIG welding was used to minimize the possibility of leakage and to reduce distortion. Square butt joints 0.38 inch thick were used. An initial penetrating root pass was followed by an oscillated cover pass from each side. Weld joints were hand scraped and solvent hand wiped immediately prior to welding. Welding was performed in the flat or "down hand" position using 2319 filler wire. Free hanging weld heads were used instead of a cast type weld head to eliminate the possibility of uneven chilling due to intermittent contact of the weld backup bar and to reduce tooling cost.

Tensile test coupons were prepared after establishing weld schedules. Average tensile strength of the 2219 T-62 welds was 38,800 psi. Average tensile strength of 2219 T-62 parent material was 56,200 psi. Ultimate tensile strength of the weld was 69% of the parent metal. 65% was required. Ref. Appendix. C.

Welding of the access door ring to the aft bulkhead transition section Figure 18 is typical of the circumferential welds on the tank. Sciaky weld positioner, shown in the photograph, was used to rotate the parts for welding. Feed rate was 16 inches per minute for this operation. Tank segments were clamped in a universal holding fixture mounted on the welder while the weld head moved past on a special track mounted carriage. Feed rate for this weld operation was also 16 inches per minute.

Fill and vent fittings were manual TIG welded into the access door. Joints were chamfered to facilitate multi-pass manual welds. External fillet welds joining the bulkheads to the tank conical section were made with automatic TIG equipment. Internal welds, because of access problems, employed manual TIG equipment. Fill and vent assemblies made from 6061 T-6 aluminum alloy were manual TIG welded.

Discussion: The principal problem encountered was joint mis-match. This was due to a lack of uniformity in the detail parts that is an inherent problem in a minimum tooling experimental type of program. The only area where leaks were encountered was the manual weld fill and vent fittings. These leaks were repaired by re-welding.

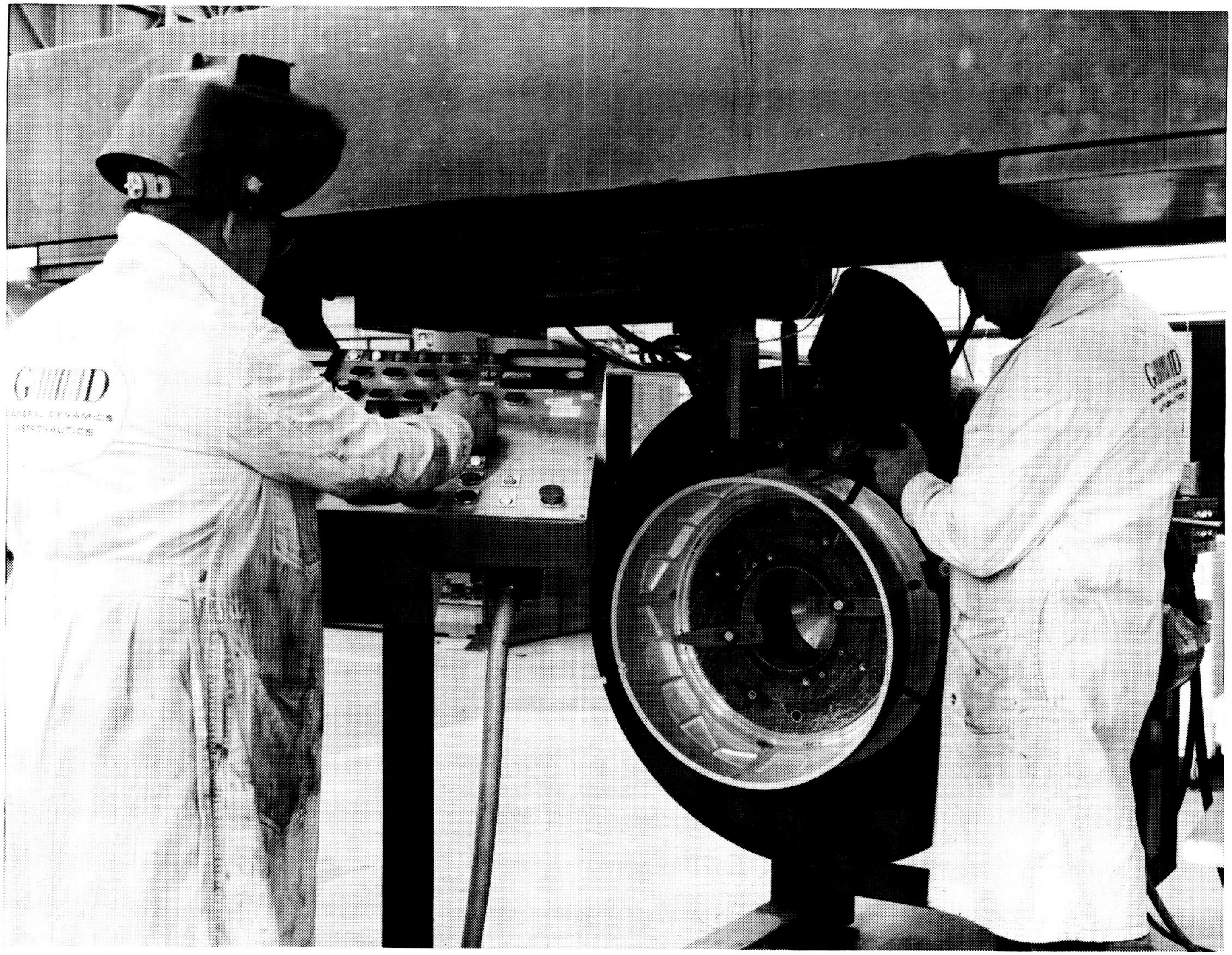


Fig. 18 Weld Engineer Supervising Automatic TIG Fusion Welding of Door Ring to Aft Bulkhead

In making the final automatic TIG fillet weld joining, the aft bulkhead transition section to the tank conical section, entrapped gas in the interface created a hole by expelling the molten weld puddle before it could solidify. The hole was repaired by manual welding.

Conclusions: Weld procedures employed on the test model tank were judged suitable for flight size vehicles. It is recommended, however, that automatic welding be employed, wherever possible, because of superior process control.

Fusion Plugweld - Plug welds joining the 6061 T-6 skirt sleeve assemblies to the 2219 T-62 tank assembly were made with manual TIG equipment. Tensile test coupons simulating this joint had an average ultimate tensile value equivalent to 76% of the parent material versus a required 55%, Ref. Appendix C. All failures occurred in the heat affected zone of the 6061 material and did not shear any weld nuggets.

Milling

Waffle pocket milling requirements for the tank panels and bulkheads and sculpturing of the structure skins and bellows provided an opportunity to compare numerically controlled machining with chemical milling for relatively shallow pockets (less than 0.50" deep). Both methods were found to have good applications for hypersonic vehicle structure.

Numerical Control (N/C) Milling - The waffle pattern in the tank panel segments was milled in the flat using a 3 axis numerically controlled milling machine, Figure 19. Panels were machined complete including pockets, weld lands and tapered skin thickness transitions. A 0.320 inch diameter ball end mill was used to generate the tapered transitions. Hand polishing was employed to remove the feed marks. Panels were machined in the as received T-31 heat treated condition, to provide good chip formation. Panels were subsequently annealed prior to the forming operation. An additional panel of each of the two configurations was machined to proof the tapes and serve as forming test parts. These parts were machined first.

Discussion: N/C machining was selected for the panel segments rather than conventional milling equipment employing templates and tracing equipment because it was felt that this method would be most representative of flight size hardware manufacture. It reduced the unit machine time per panel, simplified the tooling and insured identical panels. Chem milling was not used because of the added operations required to provide the small fillet radii and the skin thickness required.

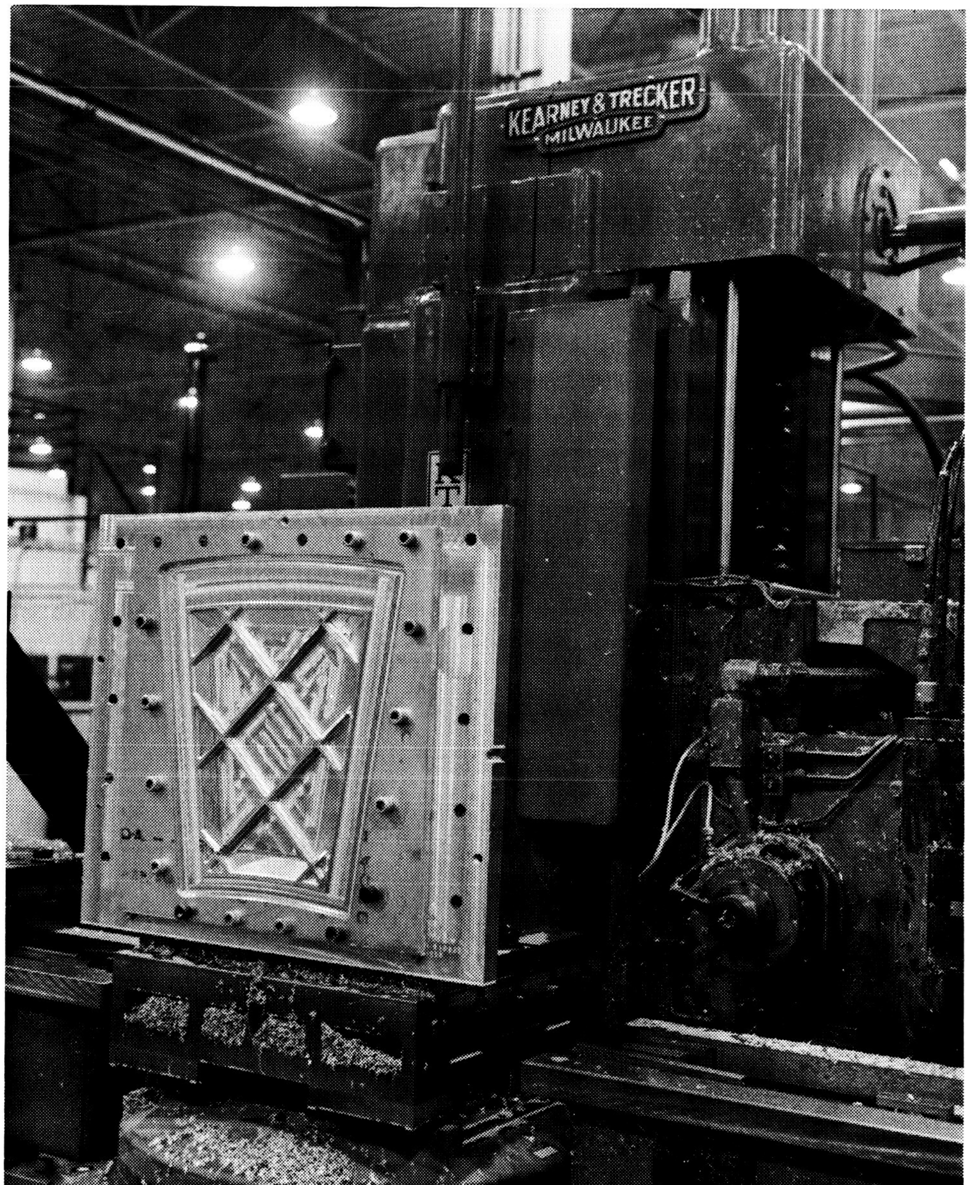
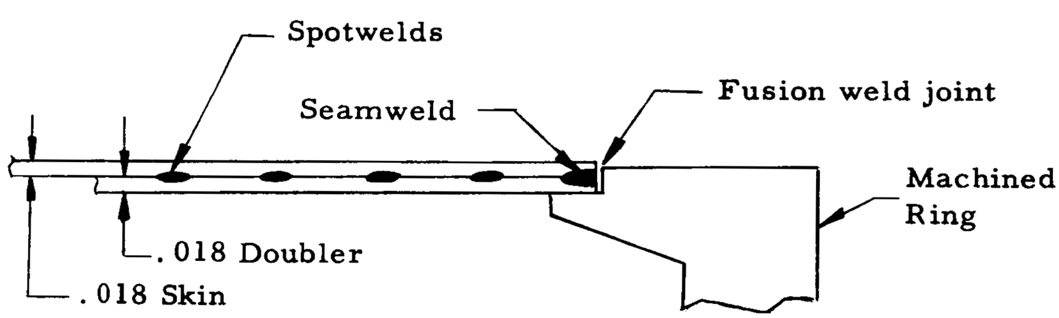


Fig. 19 N/C Milled Forward Tank Panel Segment

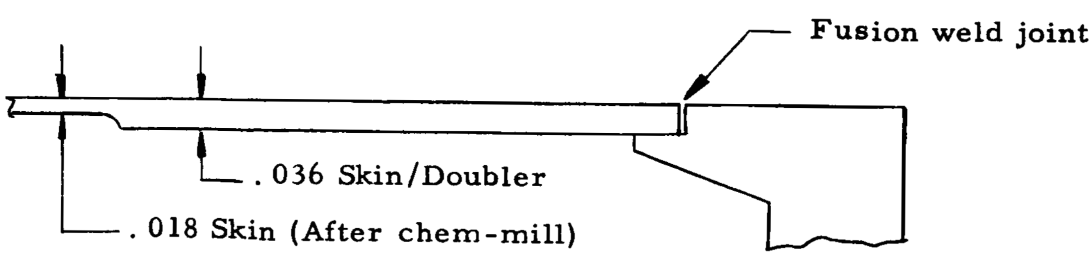
To reduce material cost and procurement time, 0.50 inch thick 2219 T-31 plate stock, which was available as an "off-the-shelf" item, was used for the tank panels. Thickness of this plate did not permit a cleanup on the outer skin surface and did not appear necessary. Some evidence of surface corrosion was later detected, however, on the outer surface of two of the eight panel segments. Slight variations in flatness of the plate surface (up to 0.005 inch) was also encountered which contributed to variation in the web thickness. An initial cleanup cut on the outer skin surface should be planned to prevent these conditions.

Chem Milling - Masking and chem mill operations were subcontracted to Chem-Tronics Corp., Santee, California. Close liaison with the vendor was established to obtain full benefit of the process for the structural model program.

Rene' 41 - Outer structure skins and reinforcing doublers made from annealed Rene' 41 sheet were combined into a single part by chem milling the doubler pattern into an initially thicker outer skin. The original design employed separate 0.018 inch thick doublers joined to an 0.018 inch thick skin by resistance spot welding. An overlapping seam weld joined the skin and doubler to provide an edge suitable for fusion welding to the machined attach rings.



Original Design



Final Design

The final design, made possible by chem milling, provides a single thickness of material eliminating the possibility of inter-layer contamination which could seriously effect the quality of the fusion weld joint. It also eliminated a difficult and time consuming spot and seam weld operation and the associated warpage problem.

Special etch templates coordinated to the master loft layout, were used to control the location and pattern of the chem milling. The etch rate was uniform and required very little hand finishing. A final surface finish approaching 32 RMS was obtained.

Inconel 718 - Chem milling was employed to reduce the thickness of the annealed Inconel 718 forward and aft bellows from an as formed thickness of 0.040 inch to a thickness that provided an acceptable spring rate. It was not possible to form the bellows in a thinner gage material. Thickness, after chem milling, averaged 0.007 inch in the case of the forward bellows and 0.015 inch for the aft bellows.

Deep convolutions of the bellows proved difficult to chem mill. A small hole was etched through the forward bellows during the final chem milling operation. The aft bellows were made in two pieces to provide better access for chem milling.

2219 Aluminum - Pockets in the inner spherical surfaces of the forward and aft bulkheads were produced by chem milling. Conventional machining of the pockets was impractical due to the compound contoured surfaces and limited access. Etch pattern was controlled by a master lines layout on a plaster male form representing the inner surface of the bulkheads, Figure 20.

Fillet radii called out for the pockets in the original tank design drawings were too small for conventional chem milling without extensive handwork. Since this method is not considered practical for flight size hardware, the designs were revised to reflect practical production chem milling dimensioning and tolerances as permitted by the contract specifications.

Tapered transitions into the pockets were obtained by progressive masking and etching in a series of steps until the bottom of the pocket was reached. Hand finishing was then employed to blend out the individual steps. Finish chem milled forward bulkhead after trim is shown in Figure 21.

Web thickness dimensioning was revised to hold thickness at the center of the pocket only. The etch rate in pocketed areas is non-uniform. Etching is slightly faster in the center than around the edges. Approximately 0.010 inch taper was experienced from the center out in the pocketed areas of the bulkheads.

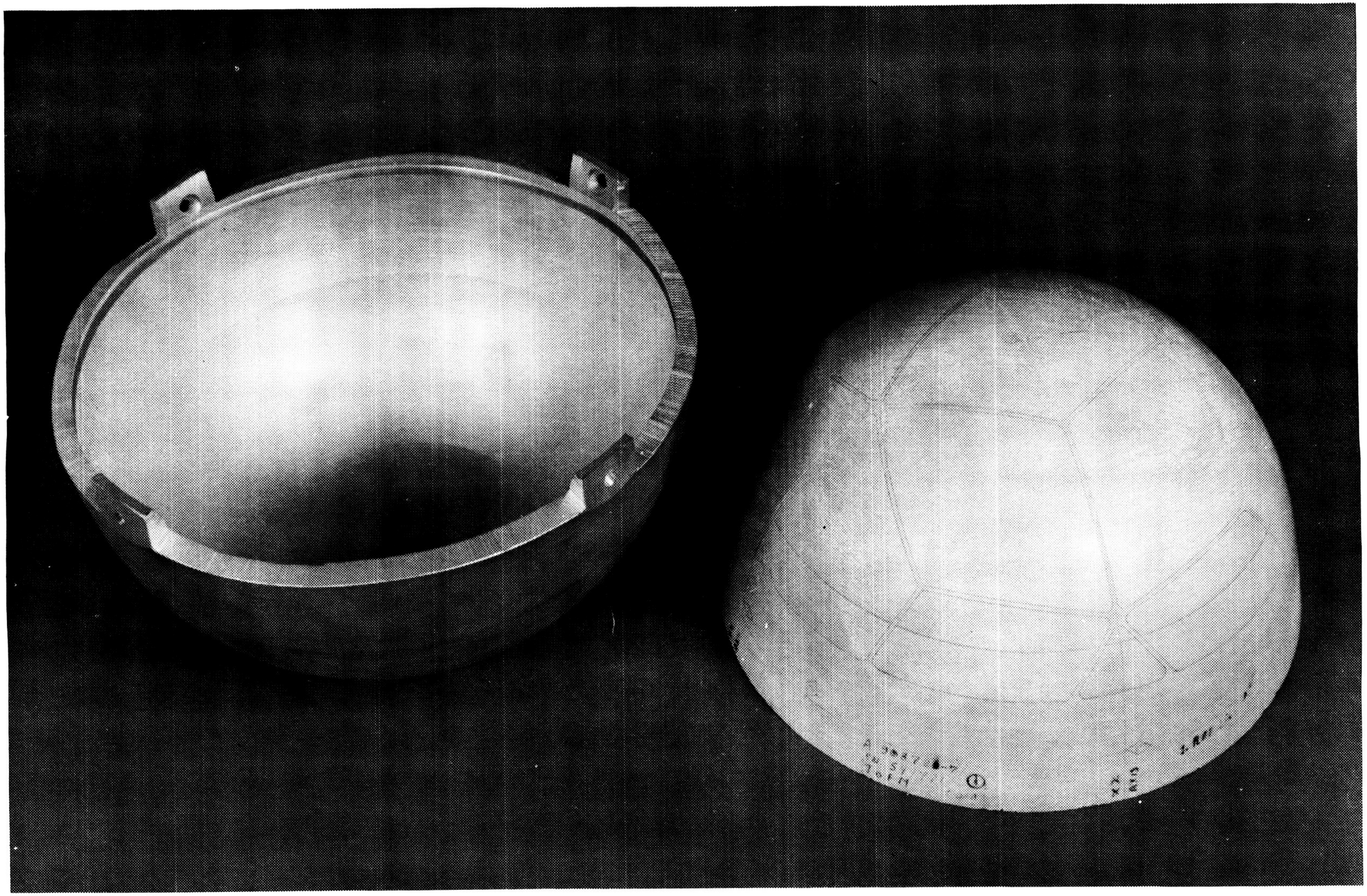


Fig. 20 Forward Bulkhead: Left, Prior to Chem-Milling with Master Form; Right, Showing Etch Pattern Layout

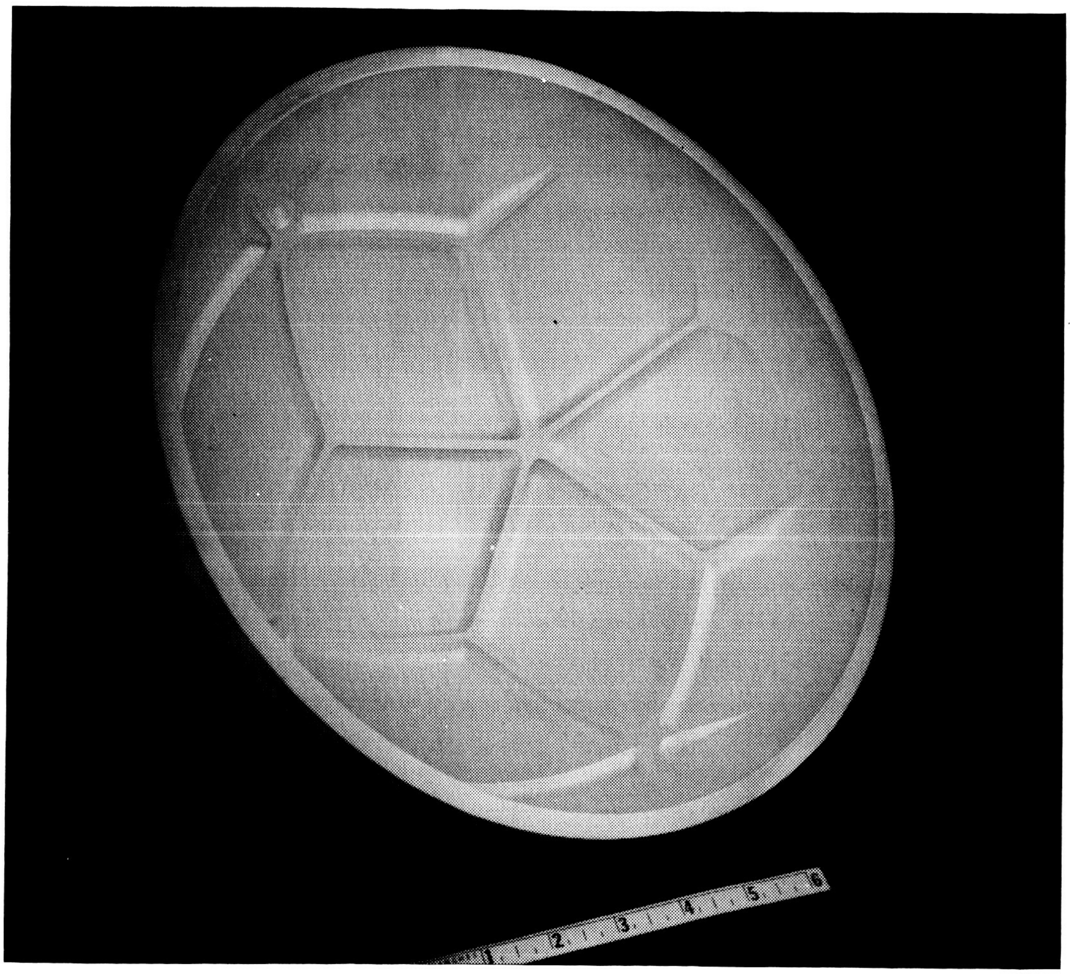
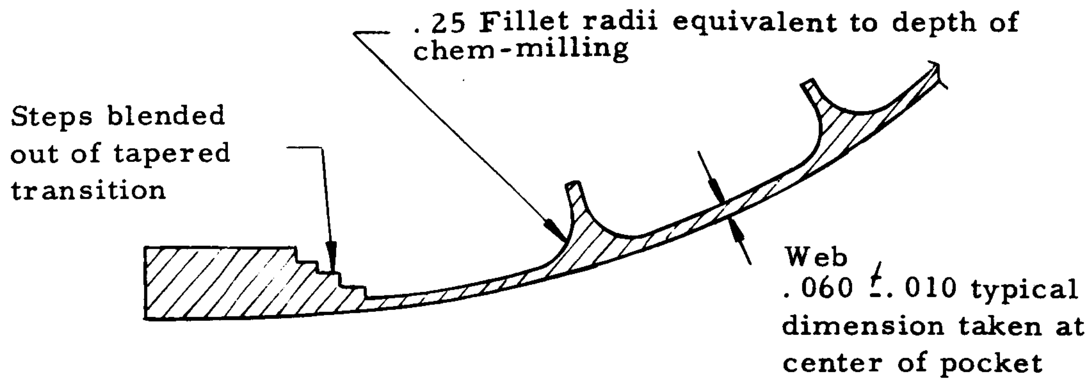


Fig. 21 Finish Chem-Milled Forward Bulkhead After Trim



Test coupons used to develop etching procedures and masking set back allowances showed that 2219 aluminum should be etched in the aged condition to avoid excessive hand work. Surface finishes of 63 RMS or better can be expected. Material that was not aged prior to etching had a coarse grained irregular appearance indicating an uneven, selective etching action.

TANK SEALING

Sealing of the LH_2 tank access door and the fill and vent fittings was recognized as a problem area from the beginning of the program because of the allowable leak rate and the nature of the fluid contained.

The permissible seal leak rate was very demanding "less than that of the Grade "A" leakage rates as specified in MIL-S-8484". (1 cc of air/lineal inch of seal/year). It is interesting to note that Grade "A" seals, as defined by this specification, developed in June 1954, were obtained at that time only by fusion of metallic and/or ceramic materials, and did not include any bolt together joint seals. During the past few years, however, several new and promising bolt joint seals have been developed (see ref. 2 to 7) that appeared capable of meeting the seal requirements. The new seals included both plastic and metallic types, each with certain advantages.

It was not within the scope of this program to evaluate all seals suitable for LH_2 tank access doors but only the selection of a seal that would fulfill the requirements of the structural model. This seal, at the same time, was to be suitable for use on flight size vehicles.

Seal Test Plan

In order to select a seal without waiting for the structural model tank to be finished, which the schedule would not permit, a seal test program was conducted using a company funded seal test tool shown in Figure 22 which simulated the access door joint.

The seal test program was divided into two parts. An initial leak test at room temperature, and a cryogenic test. Seals failing the room temperature test were replaced and retested. A second failure cancelled further testing of that particular type of seal saving the expense of the more costly cryogenic testing. Seals were rated with respect to leak rate, flange seal pressure, surface finish required, and cost in that order.

A sectioned view of the seal test tool ready for cryogenic leak testing is shown in Figure 23. A combination of spacers permitted testing of a variety of seals in the same tool. The same number of 5/16 inch diameter bolts (48) as used in the structural model tank access door, were provided for clamping the test tool together. Flange faces were machined flat with a finish of 10 RMS to minimize the effect of surface finish on the seals. Vacuum jackets provide

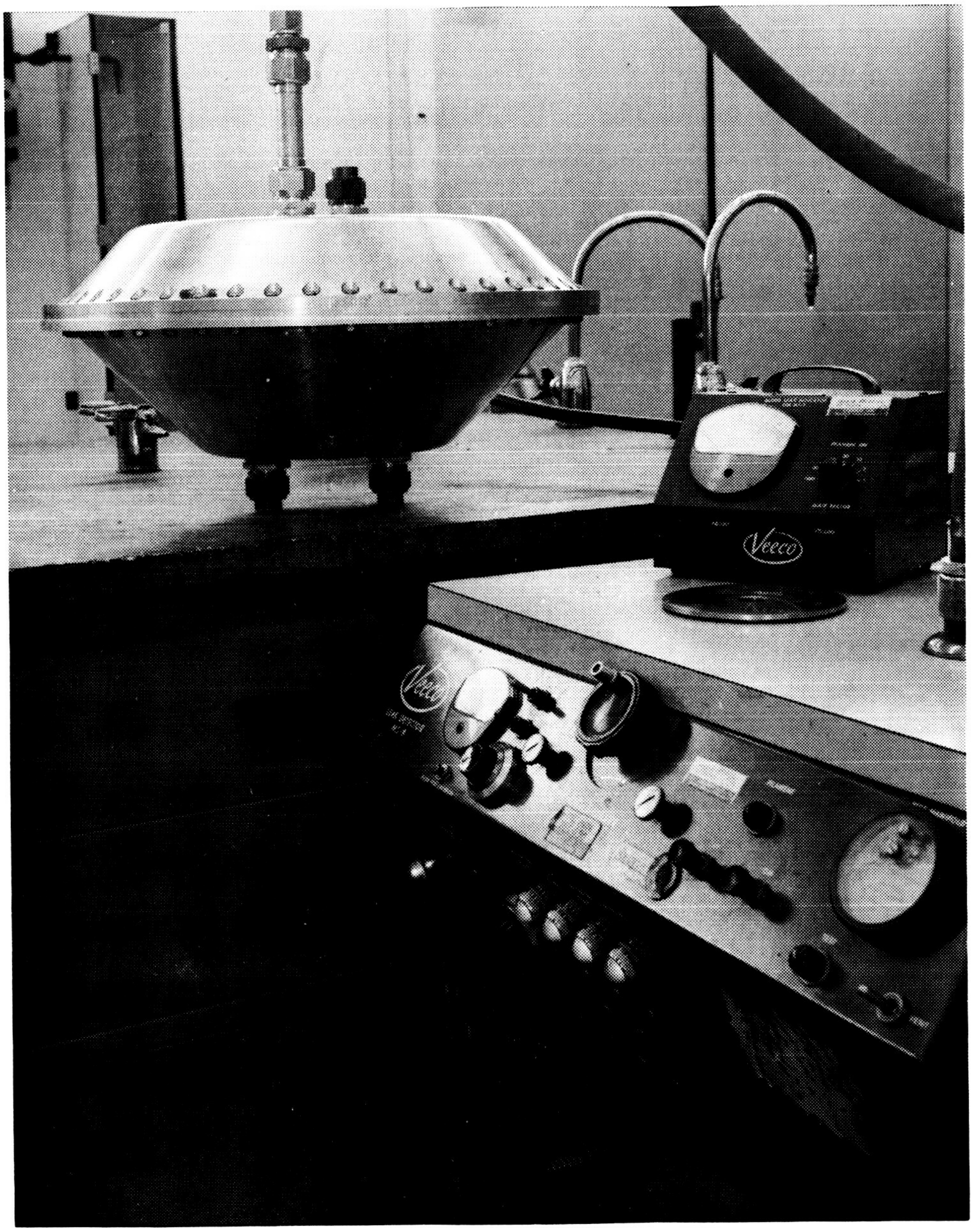


Fig. 22 Seal Test Tool and Helium Mass Spectrometer Used in Seal Testing

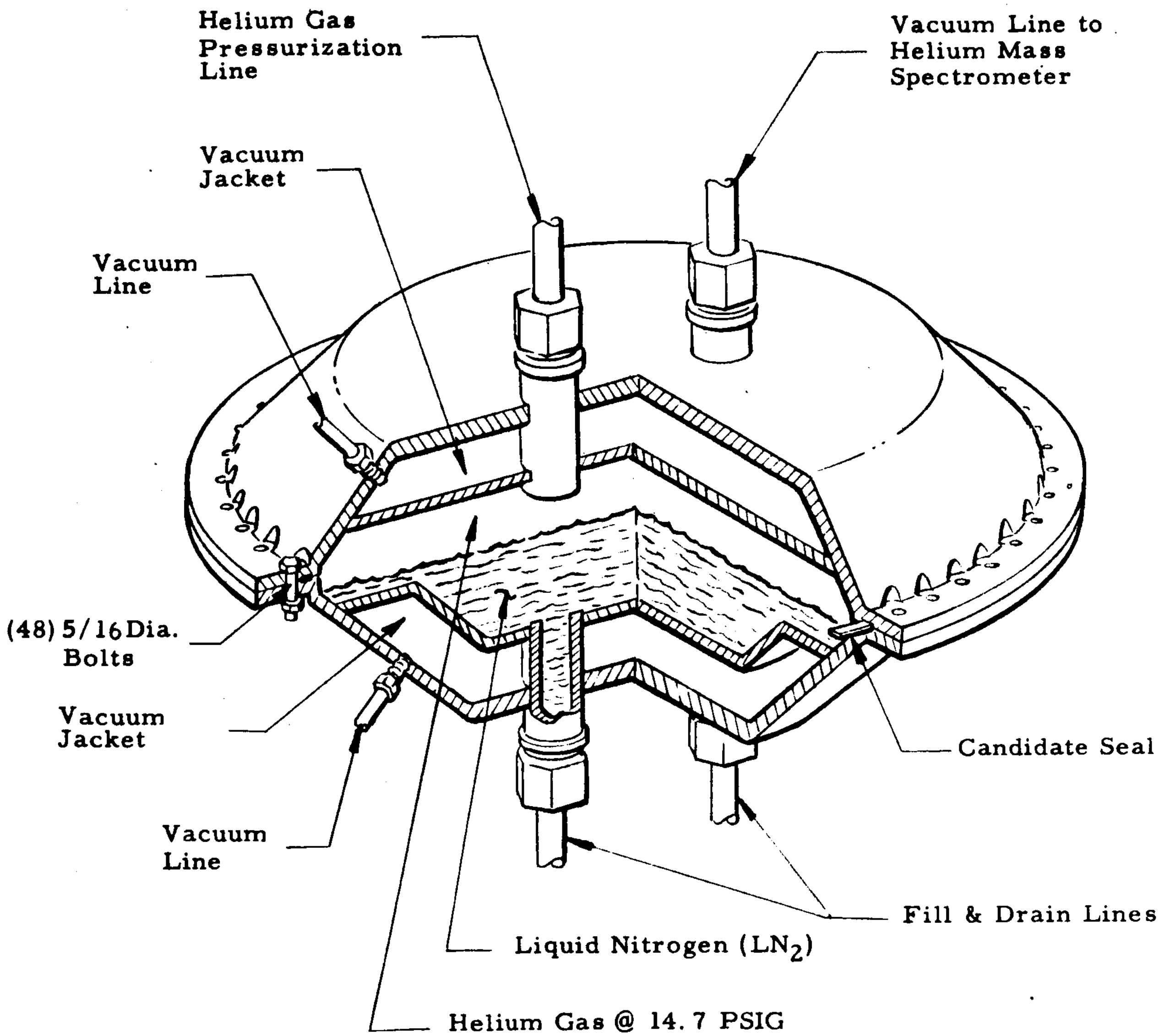
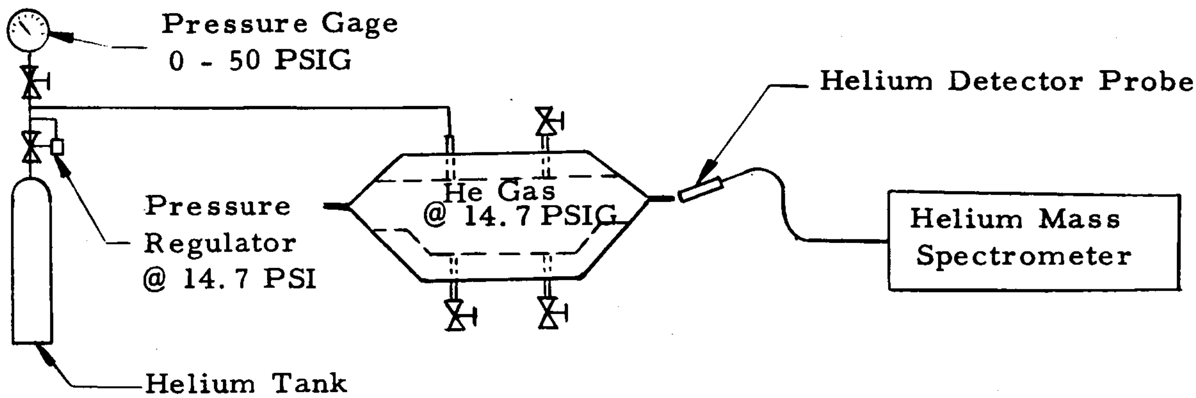


Fig. 23 Sectional View of Seal Test Tool

a degree of insulation during cryogenic testing. Fittings on the tank permit filling the tool with LN_2 for cryogenic testing and pressurizing with helium gas.

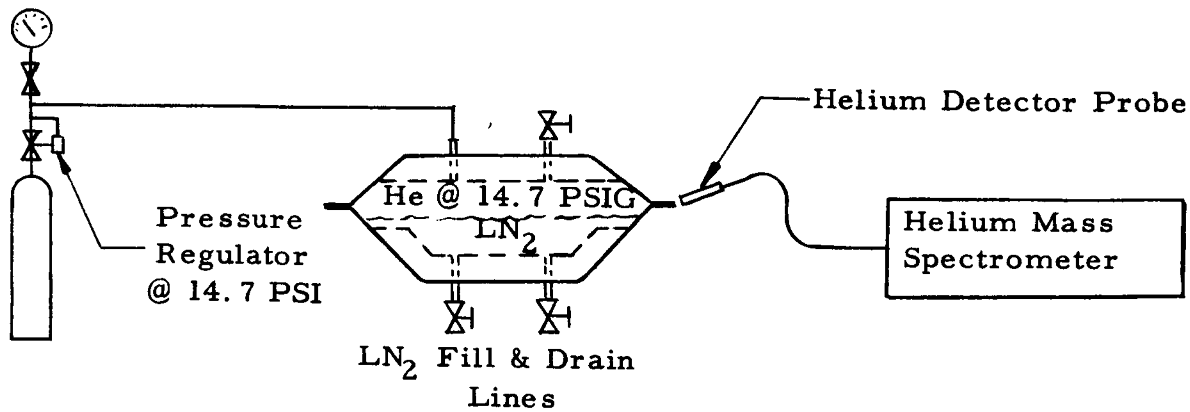
Initial Leak Testing - An initial test of each seal was performed at ambient temperature after the seal has been installed in the test tool and compressed the proper value. First the tool was internally pressurized to 14.7 PSIG with helium. Next the perimeter of the seal was examined for leaks, first with an amplified sound leak detector, then with a helium mass spectrometer sensing probe. Leakage rate was noted on the seal evaluation chart.



Initial Leak Test

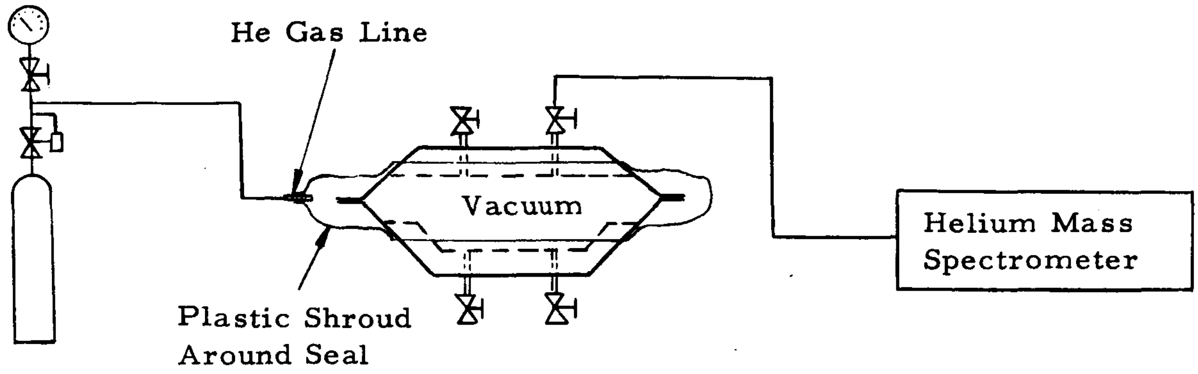
Cryogenic Leak Testing - Following initial leak tests, with the seal still in place, the vacuum jacket was evacuated to provide sufficient insulation of the tool to permit filling the test tool with liquid nitrogen (LN_2). Helium gas was fed into the tool and a pressure of 14.7 PSIG maintained by means of a pressure regulator.

After a ten minute soak the perimeter of the seal was examined once again for leaks using the helium mass spectrometer probe. LN_2 was then removed from the test tool allowing the tool to return to ambient temperature. Helium gas was re-introduced followed by another leak check.



Cryogenic Leak Test

Quantitative Leak Testing - A final quantitative leak test using internal vacuum with a helium mass spectrometer and externally supplied helium gas was used for a precise measurement of the seal leak rate. The seal flanges were completely shrouded with a plastic film containing helium gas during this operation.



Quantitative Leak Check

Note: The above method was also used to determine the overall leak rate of the actual structural model tank, as described later in this section of the paper.

Seal Testing

Six different seals were considered for the access door. Three were of the plastic type and three were of the metallic type. The plastic seals were selected for test first because:

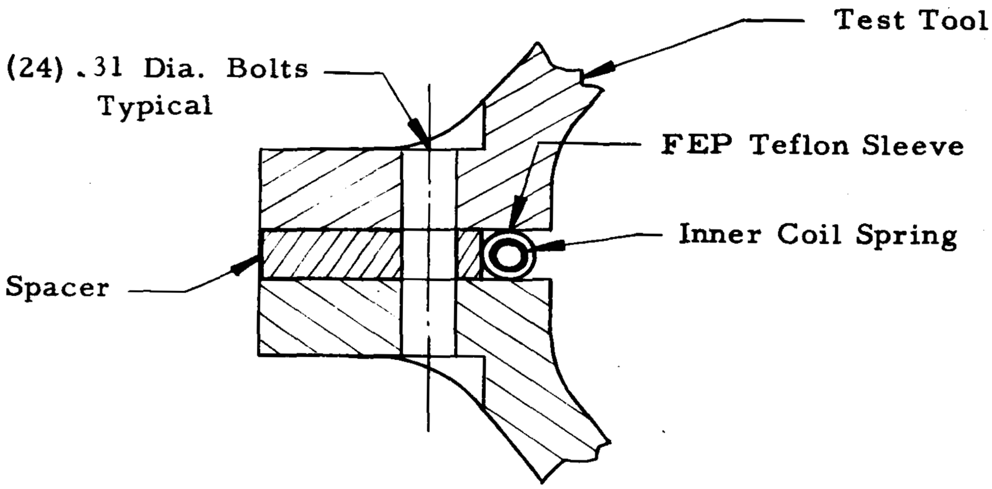
a) All three of the proposed plastic seals could be tested without re-machining the test tool flange faces.

b) Lower flange clamping pressure is required permitting the use of aluminum bolts that have a coefficient of expansion that is compatible with the flanges.

c) Plastic seals do not require as fine a surface finish as metal seals and are less subject to damage in handling and installation.

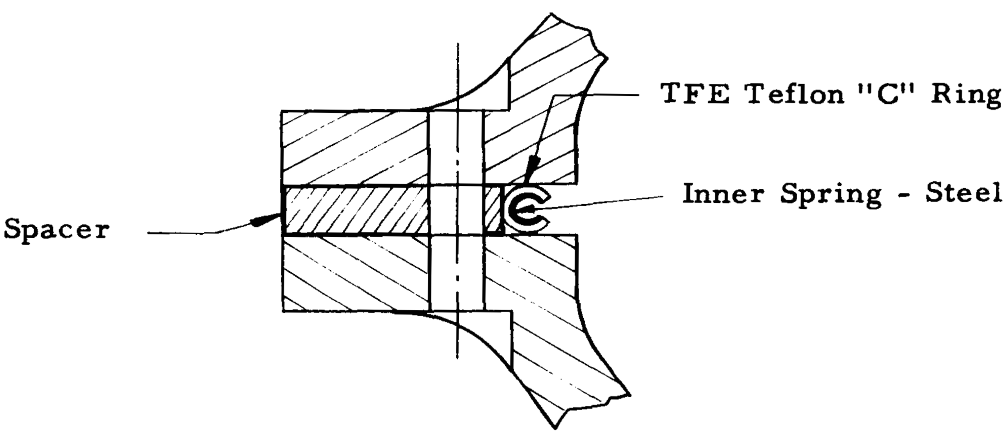
d) The flat flange faces required for plastic seals are more practical to machine and maintain for flight vehicles than the concentric grooves, sharp corners, and ridges required for shear and crush seals.

Based on the supplier's data and preliminary user reports, the torus type seal looked most promising and was, therefore, tested first. Results were disappointing. Leak rates, at room temperature, were in excess of 250 cc/year for the seal, far more than permissible. Testing was discontinued when the inner coil spring separated.



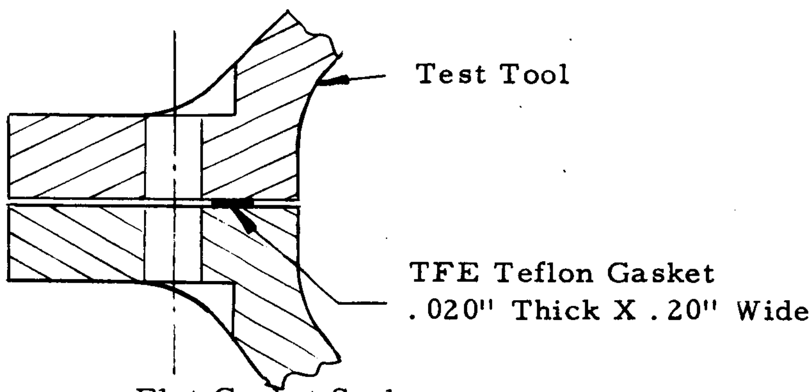
Torus Ring Seal

The spring loaded "C" ring seals also looked promising though considerably more expensive. Samples of these seals were obtained for testing and results, again, were disappointing. Room temperature leakage was in excess of 450 cc/year, for the seals tested. No cryogenic tests were conducted.



"C" Ring Seal

It was decided at this point to try a simple gasket type seal made from sheet TFE Teflon 0.020 inch thick to minimize cold flow and high thermal contraction of the material. Corrosion resistant steel (CRES) bolts were used on the test tool rather than aluminum bolts to insure sufficient flange clamping pressure to compress the gasket. Room temperature leak testing of this gasket was encouraging. A leak rate of approximately 40 cc/year was observed. The seal, still mounted in the test tool, was then subjected to a leak test at cryogenic temperatures (-320°F). An increase in the leak rate to a total of approximately 80 cc/year for the seal was then detected. The leak rate decreased to 50 cc/year when the tool returned to room temperature. Cold flow of the seal material and the difference in thermal coefficients of the seal bolts and flange materials were suspected of reducing flange clamping pressure permitting increased leakage.



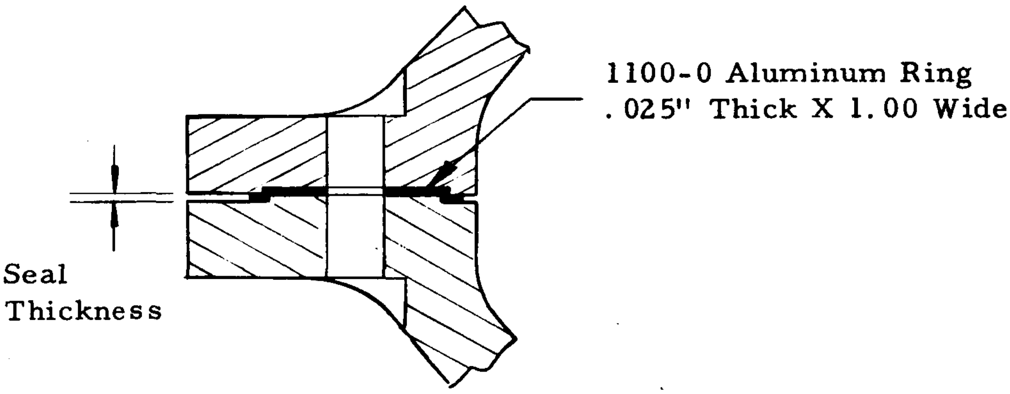
Flat Gasket Seal

The TFE Teflon seal was replaced by an FEP type Teflon with a lower thermal coefficient of expansion and better compressibility at cryogenic temperature in order to reduce the thermal effect. Steel flange bolts in the test tool were accordingly replaced by aluminum bolts. Room temperature leak testing of this seal showed an average leak rate of 24 cc per year. Cryogenic leak testing at -320°F showed an increase in the leak rate, but the rate was reduced to an acceptable 40 cc per year by re-tightening the bolts to compensate for initial cold flow of the Teflon. This seal was judged suitable for use on the structural model.

Three metallic seals were also considered. They were not tested for this application simply due to the limited funding and time available for selection of seals for the structural model.

Hollow torus ring seals have been effectively used by GD/Convair over the past several years for vacuum and cryogenic liquid joint seals and have proved reliable. Most applications of this seal at GD/Convair, however, employ CRES (corrosion resisting steel) torus rings and mating flanges. Use of CRES torus rings with aluminum flanges is not recommended due to the embedding or "Brinnel effect". Use of aluminum torus seal rings for the structural model was not investigated due to the difficulties involved in procurement.

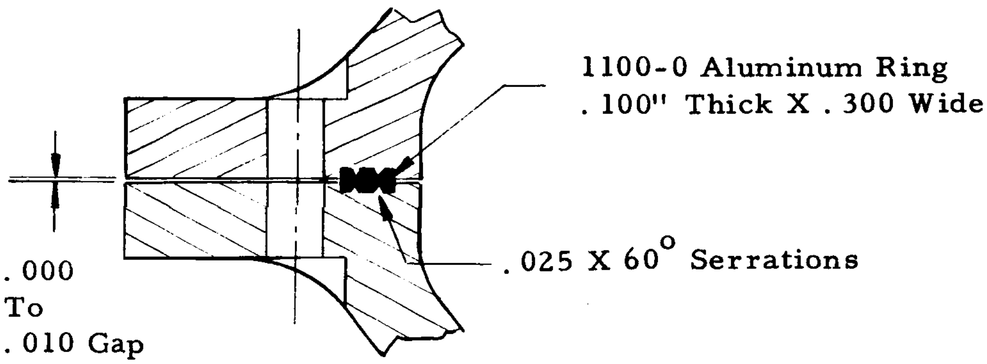
Shear seals were considered that employ a double shear of a soft aluminum flat gasket ring to obtain a seal. Flange bolts are located between the inner and outer shear edges to balance the shear force and minimize the joint deflection. A significant difference in hardness between the flange and the seal is mandatory to permit shearing of the seal and to avoid damaging the shear edge of the flange for reuse. The inner shear is employed as a seal while the outer shear is used to balance the shear load.



Shear Seal

Pressure required to shear the gaskets necessitates high strength flange bolts and a heavy flange cross section. Flange ridges and grooves must be concentric to within 0.005 inch TIR to ensure proper shearing of the seal and have a surface finish of 32 RMS or better.

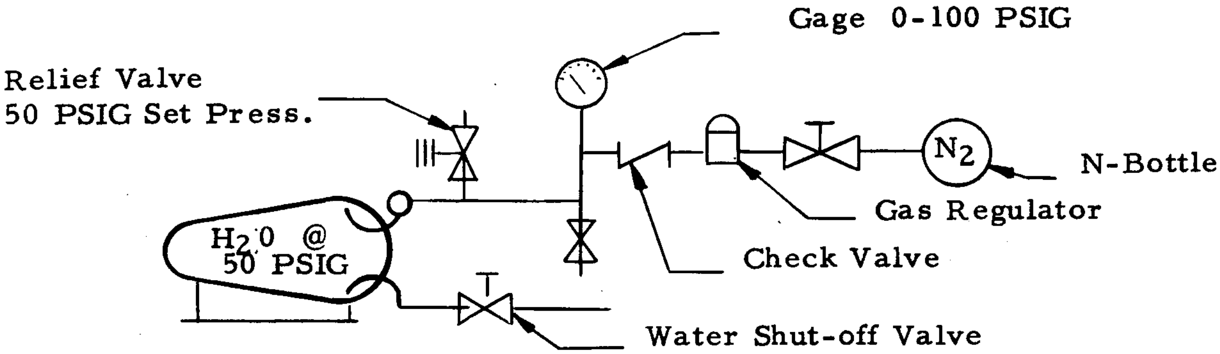
The crush seal joint is somewhat similar to the shear seal and has been demonstrated to have a very low leak rate at cryogenic temperatures. There are, however, certain inherent disadvantages in using this seal for airborne applications. The pressure required to crush the flange serrations into the soft aluminum seal is very high. This results in a heavy flange cross section and many high strength flange bolts. Further, the off center load tends to introduce rotation into the flange joint. Recessed seal grooves and serrations must be machined to close tolerance with a surface finish of 32 RMS or better.



Crush Seal

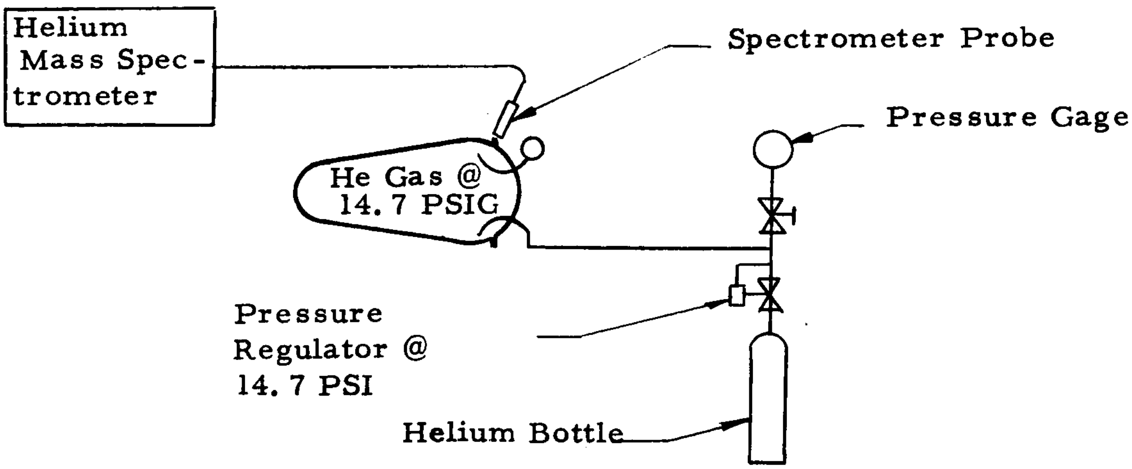
Conclusions: Seal test results are summarized in Table 2. On the basis of the tests conducted, a flat Teflon gasket seal was selected for use on the structural model tank, since it provided a satisfactory solution to the sealing problem. Seals of this type can probably be further improved by the addition of filler or reinforcing material to counteract the cold flow and shrinkage of the Teflon at cryogenic temperatures. Another promising but untested seal is the crush type previously described using Teflon instead of aluminum for the seal material.

Tank Leak Test - The fill line, vent, Teflon seals and access bulkhead were installed and a hydrostatic test at 50 PSIG was performed. No leaks were detected.



Hydrostatic Test

A preliminary leak test was conducted with the tank internally pressurized with helium gas at 14.7 PSIG. The assembled tank was progressively examined for leaks starting with the fusion welded tank joints and ending with the mechanical bolt joints. A crack detected in the vent tube during this test was repaired by welding. Support brackets were added to the vent manifold and fill line to reduce the probability of damage to these assemblies during handling and test. A small pin hole leak in the bulkhead vent fitting weld, which was 0.380 inch thick, was also detected and repaired. Some small leaks were detected in the threaded vent fittings that were stopped by tightening the fittings.



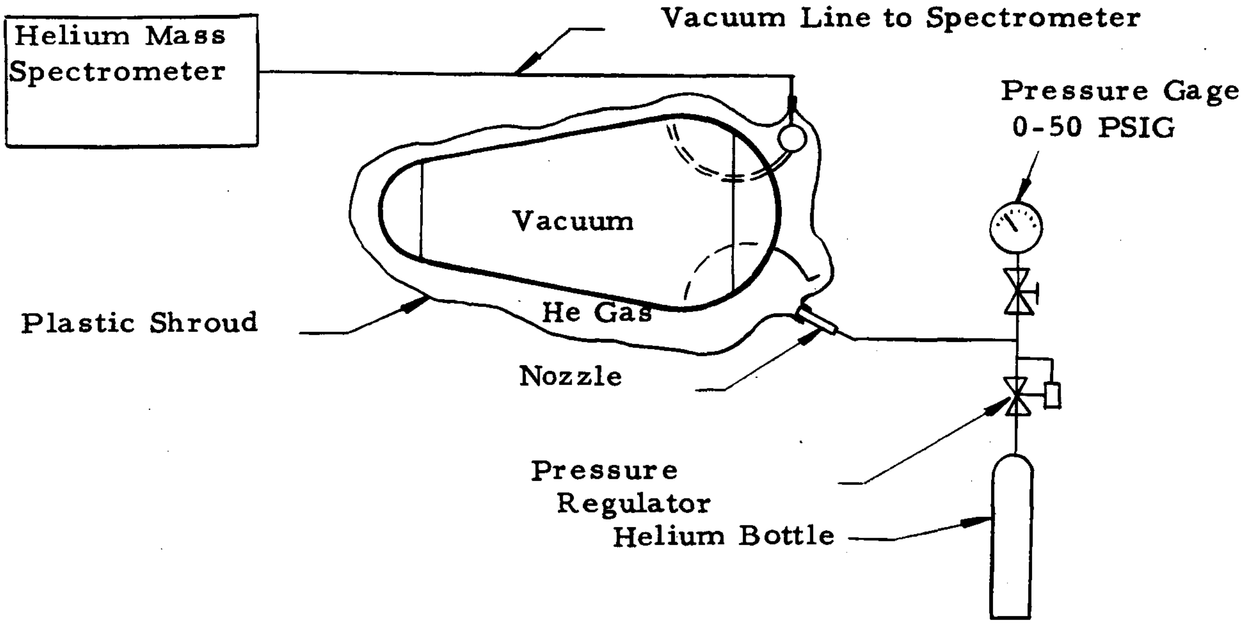
Preliminary Leak Test

Table 2. Seal Test Results

SEAL TYPE	PLASTIC SEALS			METALLIC SEALS	
	TORUS RING	"C" RING	FLAT GASKET	SHEAR	CRUSH
MATERIAL	FEP TEFLON	TFE TEFLON	FEP TEFLON	1100-0 ALUM.	1100-0 ALUM.
1. Seal Cost $ (Quantities of 6)	55.00 (Actual)	190.62 (Actual)	44.60 (Actual)	120.00 (Estimated)	80.00 (Estimated)
2. Flange Pressure Lbs/Linear Inch	40	20 Spacer Limits Pressure	400	800	2000 Double "V" Serrations
3. Flange Type	Flat-Spacer Limits Pressure	Flat-Spacer Limits Pressure	Flat	Doubler Shear (1-Sealing)	Double "V" Serrations
4. Flange Surface Finish - RMS (Recommended)	63	32	32	32	63
5. Aver. Leak Rate * Room Temp (70°F)	Over 250 cc	Over 450 cc	32 cc	Not Tested	Not Tested
LN_2 Temp (-320°F)	Not Tested	Not Tested	60 cc	Not Tested	Not Tested

* cc of He linear inch of seal/year = 61.8 cc Max. accept. leak rate for 20" dia. seal.

Figure 24 shows the setup employed to measure the overall leak rate of the assembled tank. At this point in testing, weld joint leaks had been eliminated and it was now a question of how much the seals were leaking. To accomplish this, internal vacuum was used to permit the collection and precise measurement of externally supplied helium gas with a mass spectrometer.



Seal leakage detected during this test was determined to be approximately 34 cc per year versus an allowed leak rate for the three seals of 79 cc per year. The completed tank assembly, following leak check, is shown in Figure 25.

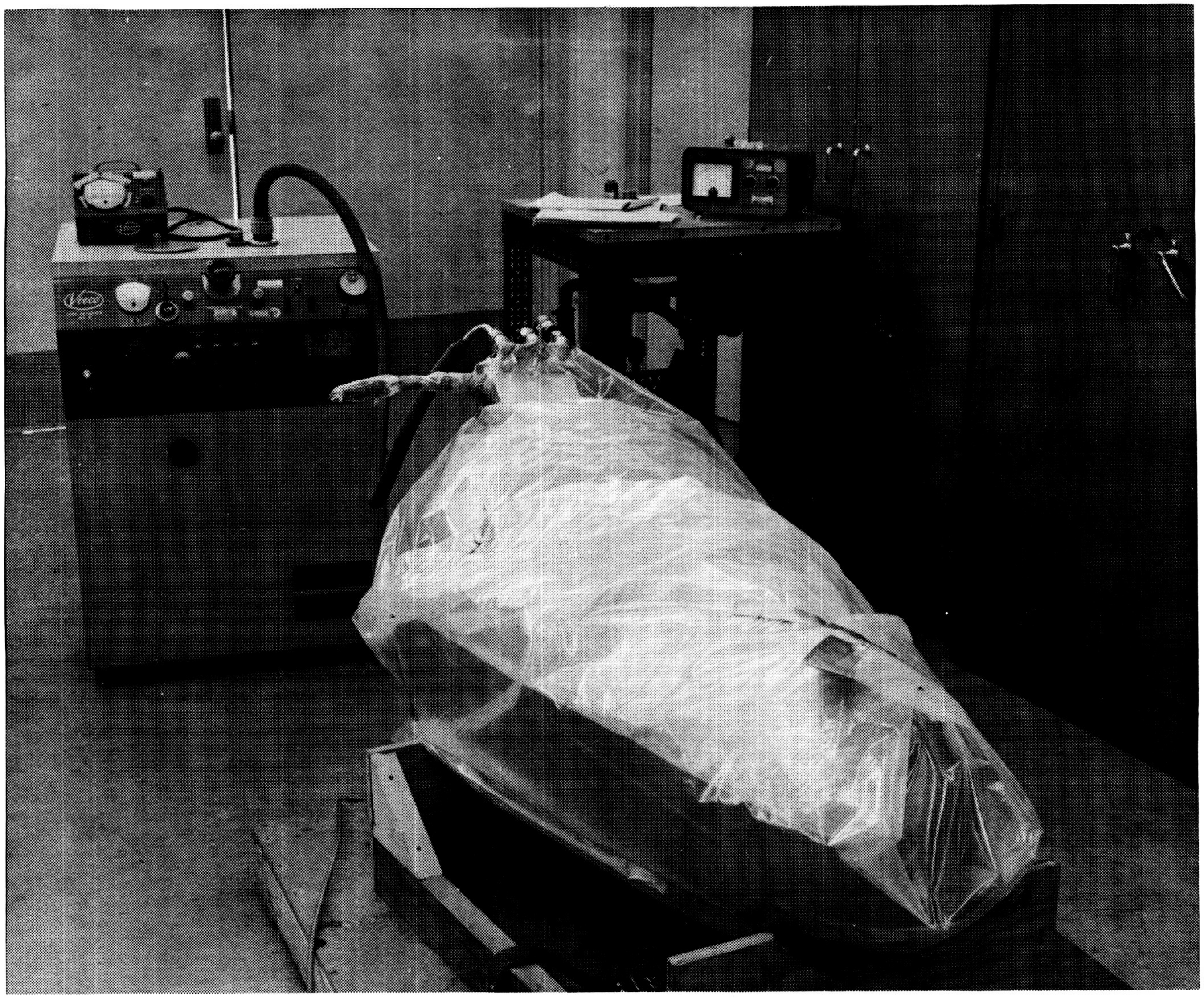


Fig. 24 Measuring Tank Total Leak Rate With Helium Mass Spectrometer

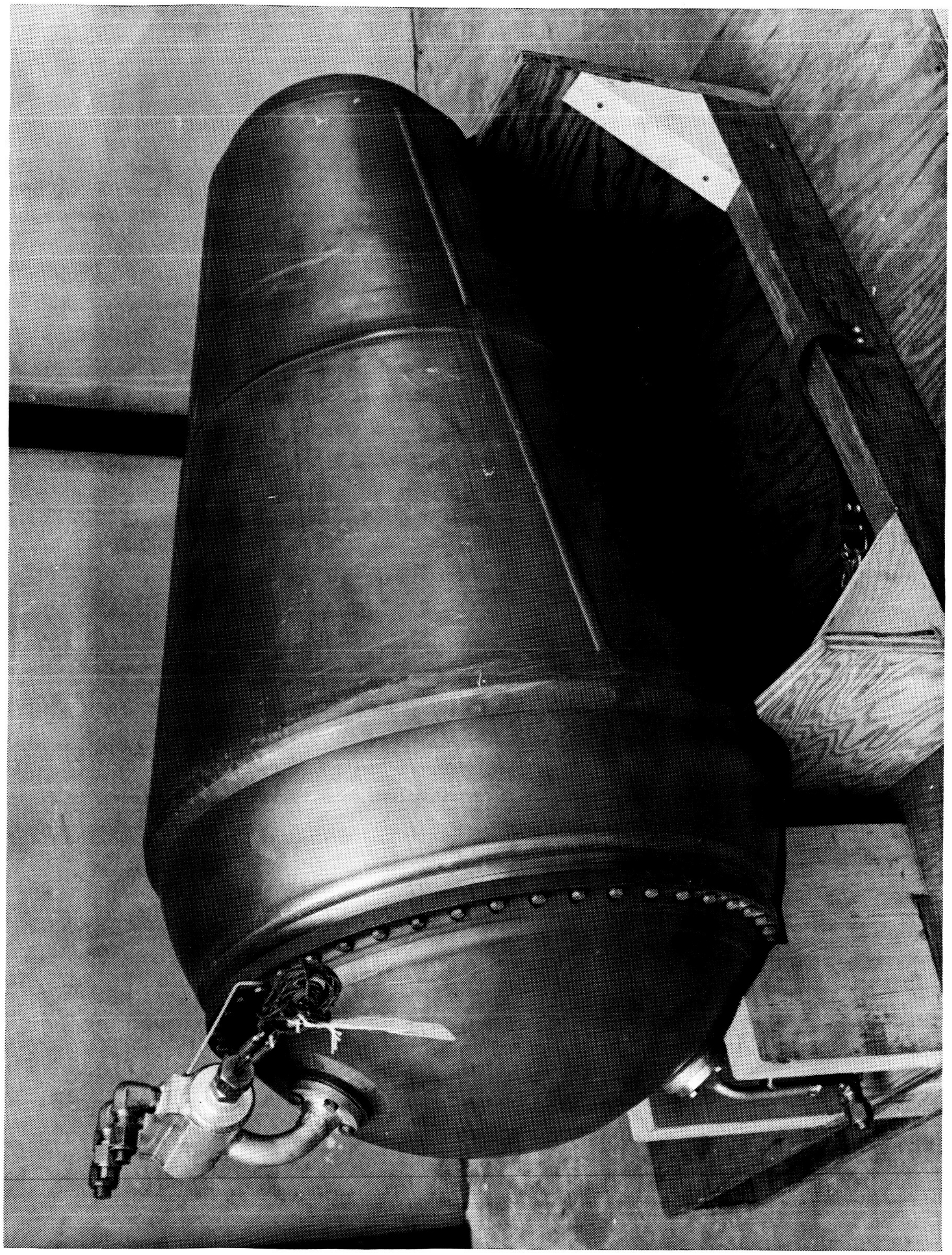


Fig. 25 Basic Tank Assembly

CONCLUDING REMARKS

The process developments and fabrication of the structural model has led to the following conclusions:

1. The design of the structural model as presently conceived is considered auitable for fabrication in a full scale or flight size version.

2. TIG heliarc fusion spotwelding is a practical method of joining thin gage Rene' 41 structure. It has good reliability, it permits spotwelding in areas otherwise inaccessible and simplifies tooling.

3. Machining of pockets in single element curve 2219 aluminum tank panels is best performed by numerical control milling. Chem milling is best applied for compound contoured tank bulkhead sections. It is also very useful in providing heavied up areas in Rene' 41 and Inconel 718 sheet metal details.

4. Explosive forming used to form the 2219 aluminum tank bulkheads for the model is suitable for larger tanks. Material should be formed in the annealed condition. Allowance should be made for a cleanup cut on both the outside and inside where contour and surface finish is critical.

Experience gained from the performance of the contract leads to the following recommendations:

1. Seals for liquid hydrogen tank access doors merit further investigation. A satisfactory seal was selected for the structural model, but it is recognized that this is not the final answer. Additional seals should be tested along with improved seal joint designs.

2. Fusion weld joints in 2219 aluminum tankage should be kept as heavy as possible to reduce the possibility of leakage where the rate is critical. Some leakage was encountered in one of the fusion weld joints on the structural model tank despite a joint thickness of 0.380 inch and a multipass weld.

APPENDIX A

Fabrication of the Structural Model

The manufacturing breakdown and assembly sequence of the structural model is shown in figure 26. Methods suitable for production of full size vehicles were selected where a choice existed.

Fabrication of the primary structure was accomplished with a single master form tool, shown in figure 27, and loft layouts were used to control contour, spot weld patterns, and the location of various components. Skin splice sheets that had finger doublers chem milled on the inner surface were sandwiched between two half-hard 0.060 inch corrosion resistant steel cover sheets during rolling to minimize flattening due to the difference in sections. Frame webs were impact formed over segmented male form blocks by means of a trapped rubber die-head mounted in a drop hammer. All parts subjected to cold forming were solution annealed before welding to prevent weld cracks.

The primary structure consists of the following sub-assemblies: twelve panels, three ring frames, and four longerons. A partially completed center panel consisting of a skin, doublers, and Zee-stiffeners is shown on figure 28. The outer cap of the ring frames and the longerons were assembled in a fixture, figure 29, then the panel assemblies were resistance welded at the overlap of the Zee-stiffeners on the caps of the ring frames and at the overlap of the skin on the longerons. The assembly was completed, figure 30, by resistance welding splice doublers over butting Zee-stiffeners, resistance and fusion spot welding a face sheet over the splice doubler, and by welding the ring frames to their respective caps inside the model.

Assembly of the tank consisted of machine welding of sub-assemblies shown on figure 31. The forward dome and the access bulkhead were explosively formed. Material was annealed before forming, formed, solution heat treated to T-42 condition, restruct, and aged to the T-62 condition. Four aft bulkhead segments were trimmed to size from annealed plate, formed on a press brake to conical segments, and fusion butt welded. The cone was then explosively formed to a spherical surface, solution heat treated, aged to T-62 condition, and machined inside and outside. Spherically formed parts were chem milled to form the waffle pattern. The eight conical tank wall segments were machined in the flat using numerical milling equipment to form the waffle

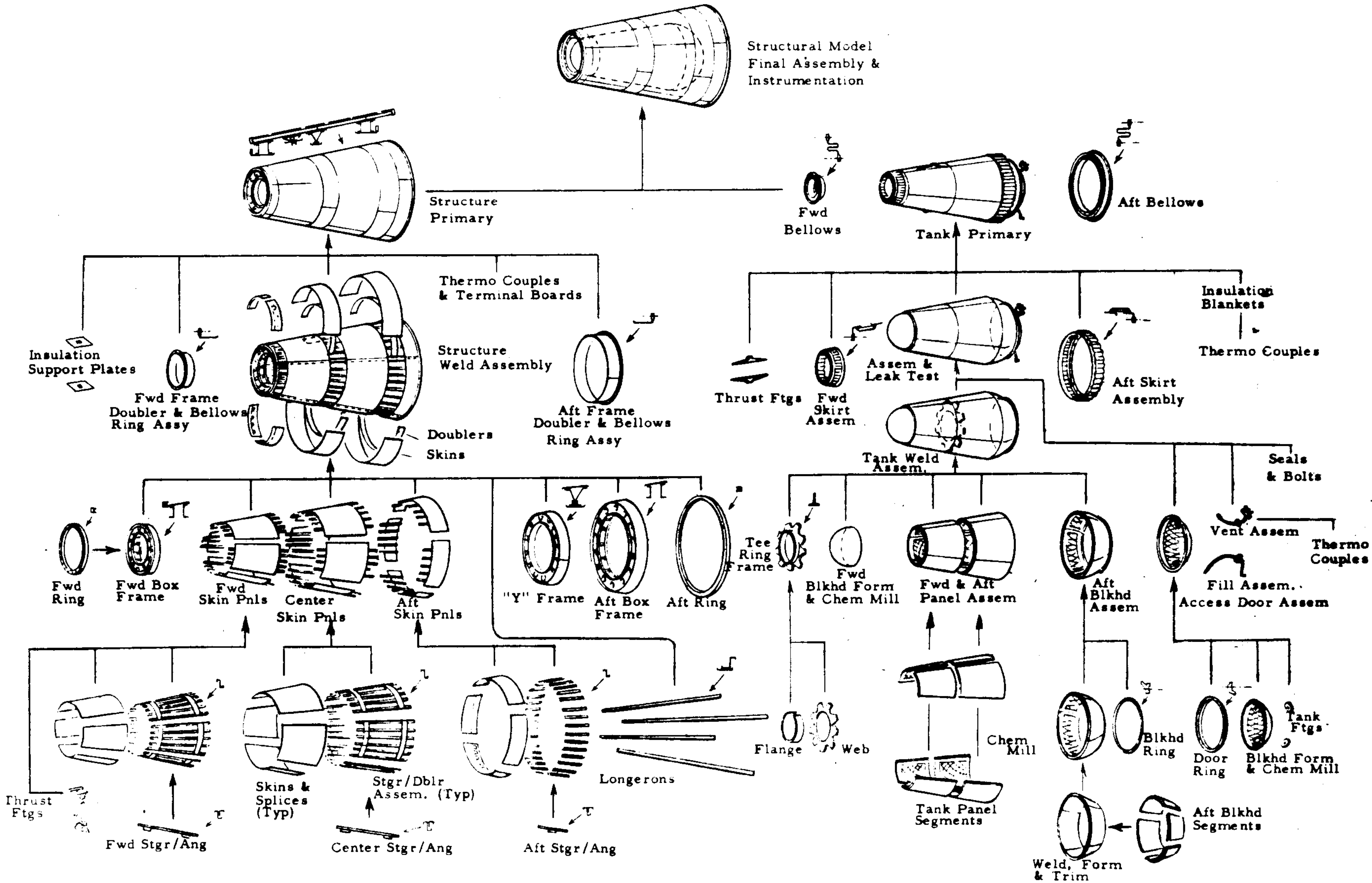


Fig. 26 Manufacturing Breakdown and Assembly Sequence

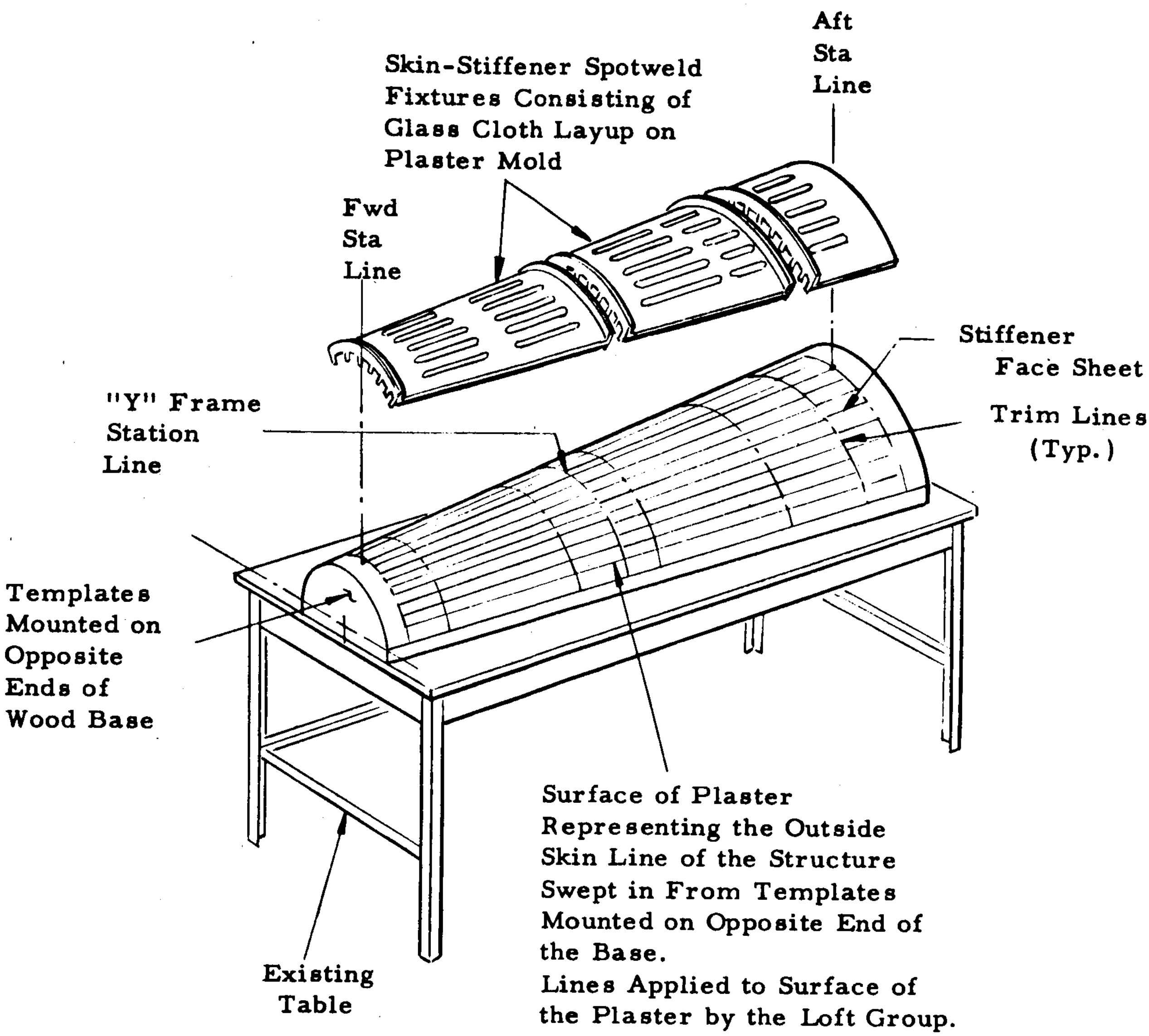


Fig. 27 Outer Structure - Plaster Model

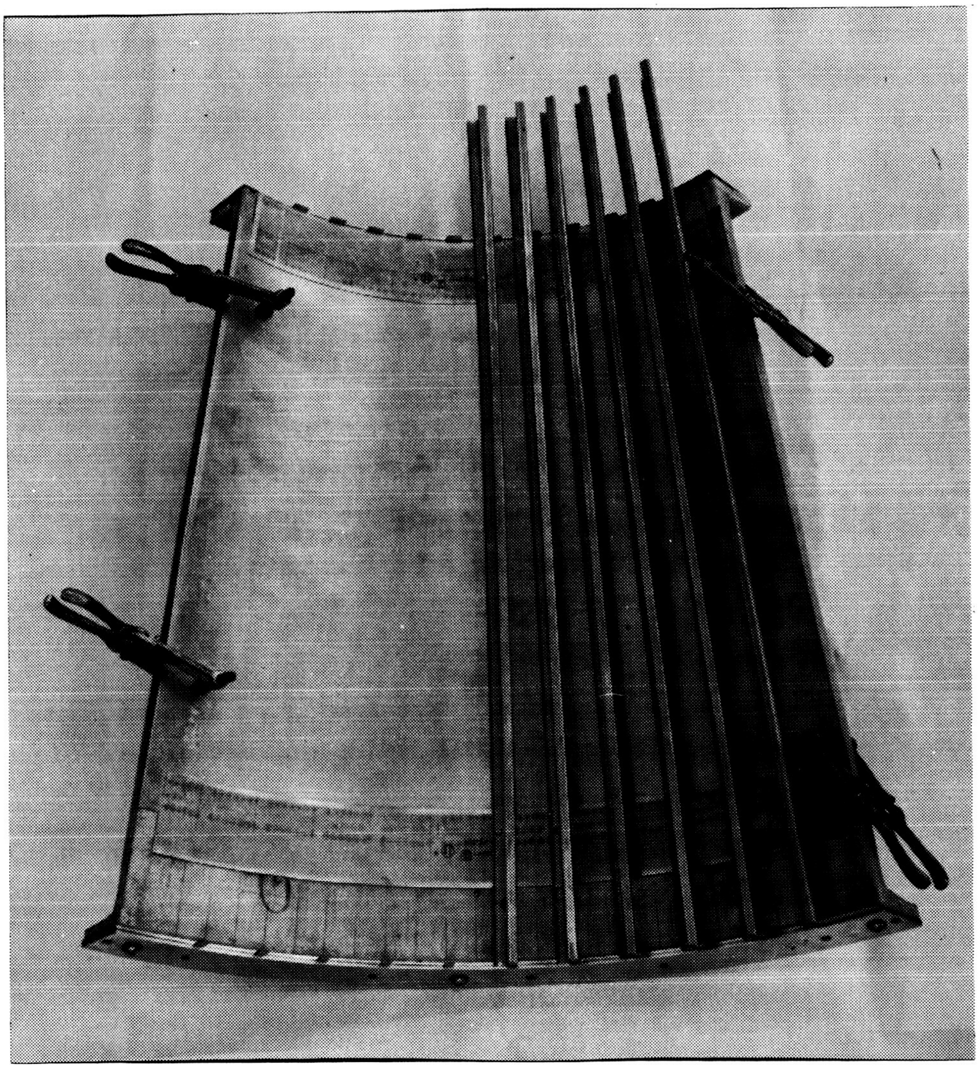


Fig. 28 Partially Completed Center Skin/Zee Stiffener Panel Subassembly in Spotweld Tool

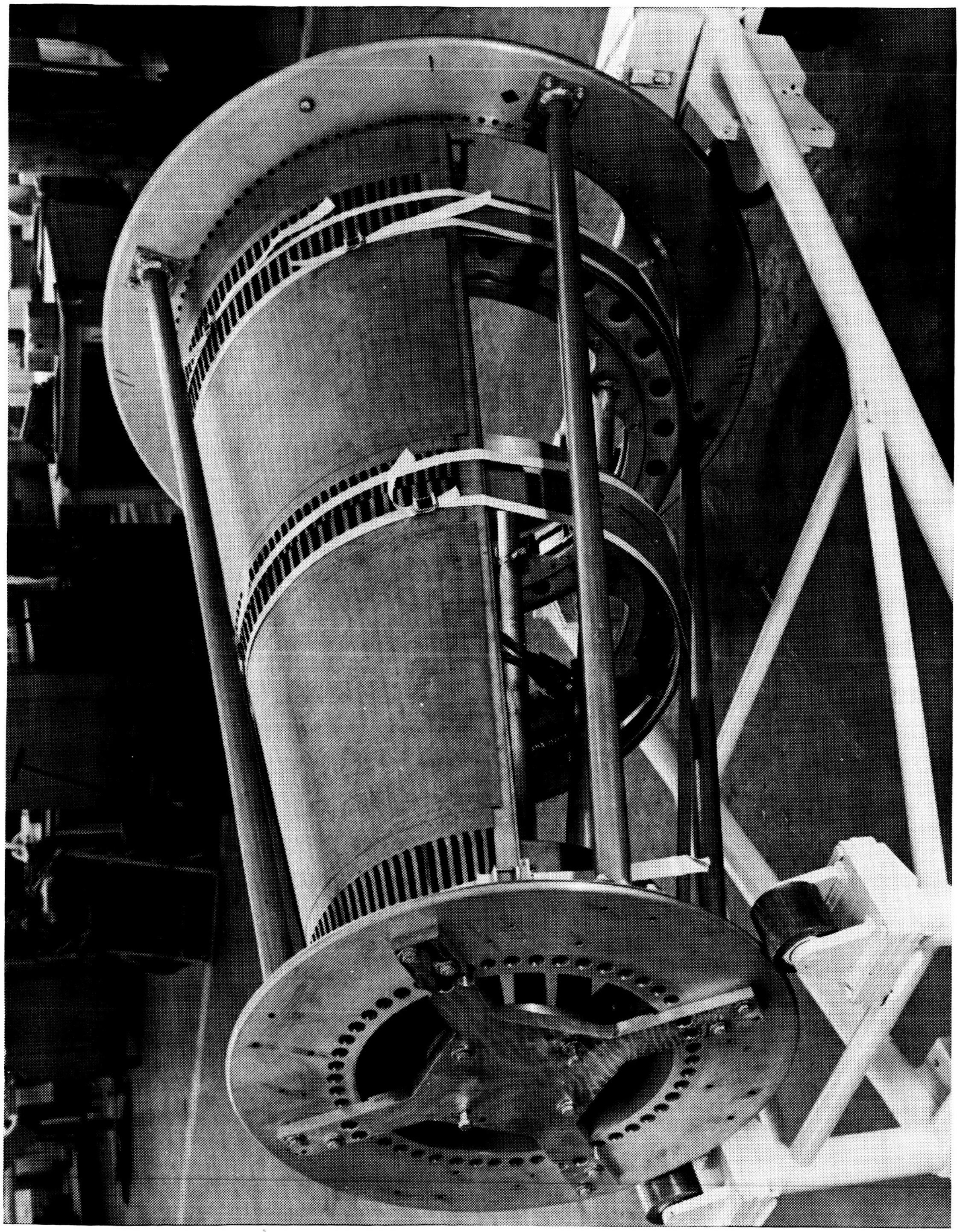


Fig. 29 Fitting of Skin Panels, Longerons, and Ring Frames in Assembly Fixture Prior to Weld

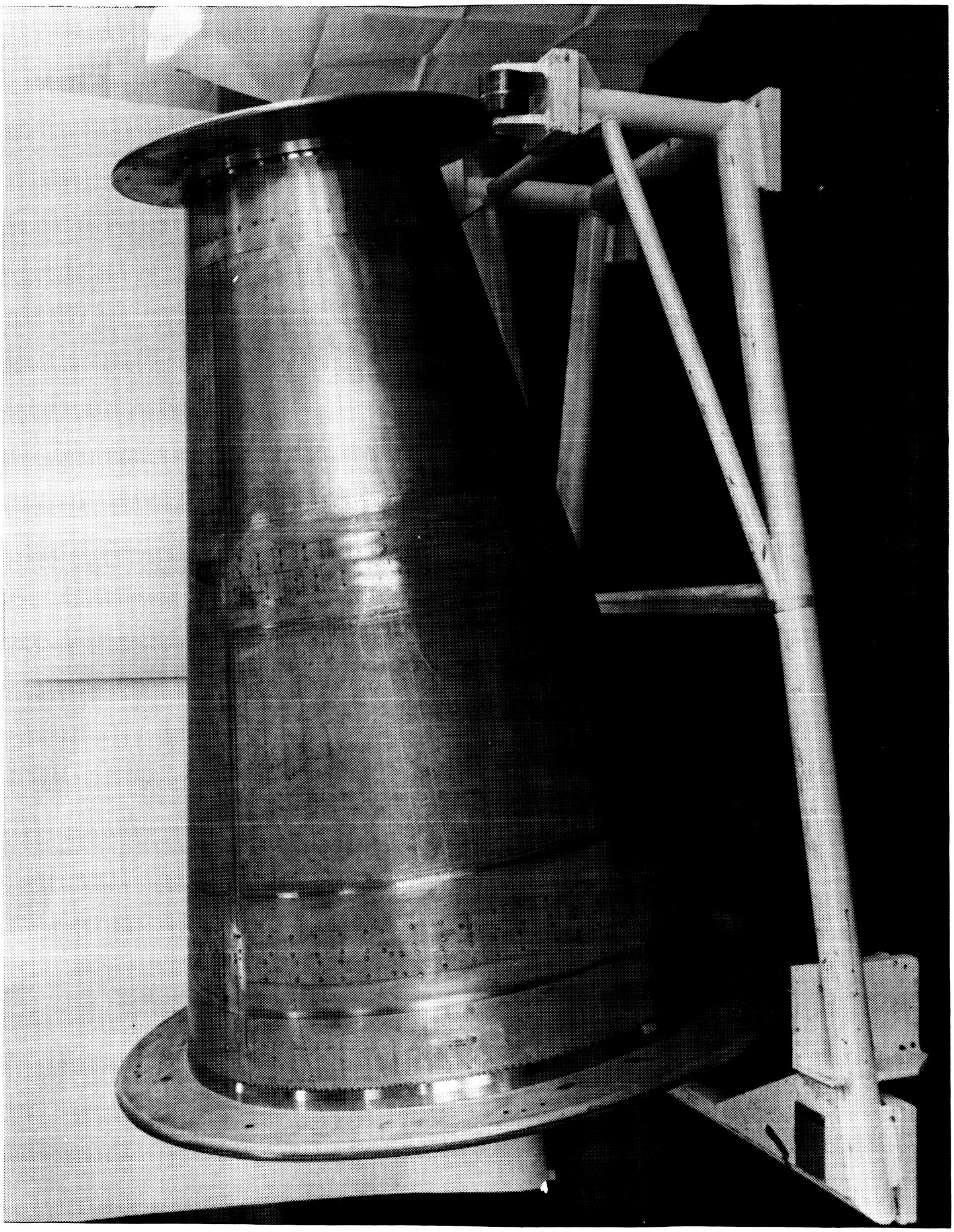


Fig. 30 Outer Structure After Final Fitup and Tackweld of Closure Skins

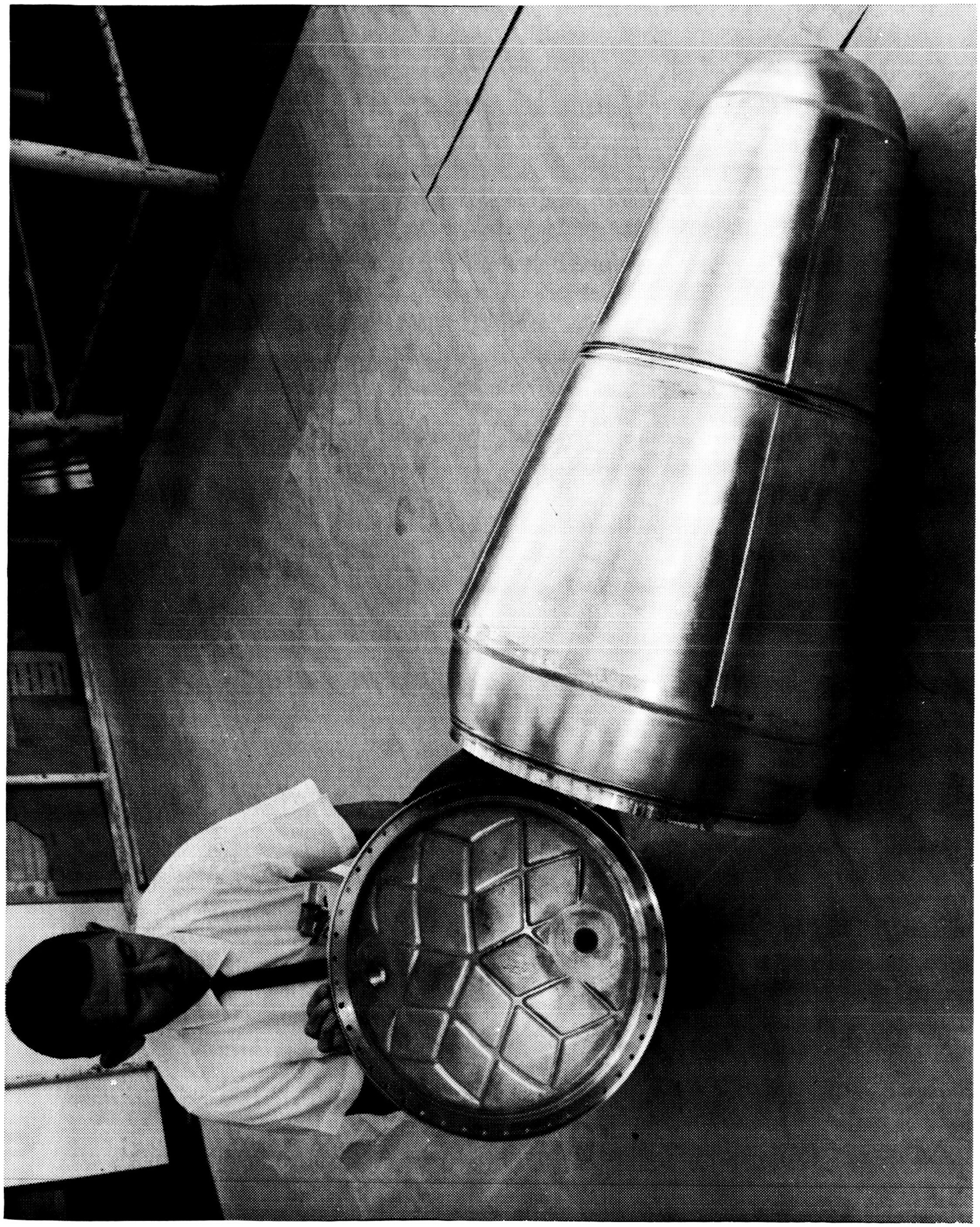


Fig. 31 Tank Weld Assembly and Access Door

pattern in the T-31 condition. The panels were then annealed, the machined pockets were filled with a low melting temperature alloy, and the panels were press brake formed between protective face sheets. The panels were then solution heat treated and aged to the T-62 condition prior to welding. Leak testing the assembled tank was performed as described in the process development section of this paper.

Forward and aft skirt assemblies, figure 32, were riveted to aluminum sleeves that were fusion plug welded to the tank. Bellows, draw formed and chem milled to thickness, were bolted to the skirts. Insulation panels were bonded to the tank and clipped to each side of each skirt, and thermocouples were welded to the primary structure, installed within the insulation and tank, and welded to the tank wall during fabrication.

The completed tank assembly and primary structure are shown on figure 33 prior to final assembly, and the final assembled structural model is shown on figure 34.

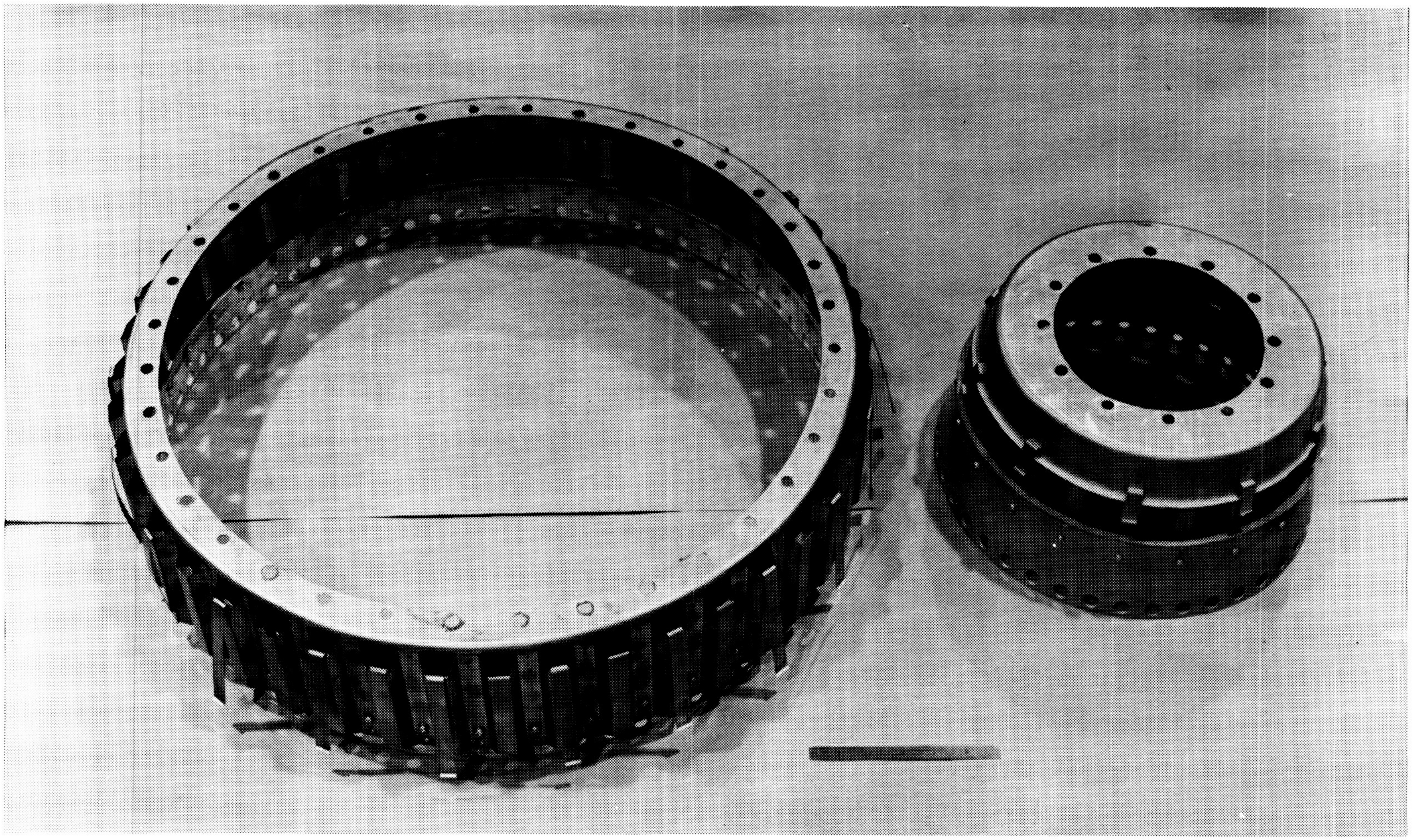


Fig. 32 Forward and Aft Skirt Subassemblies

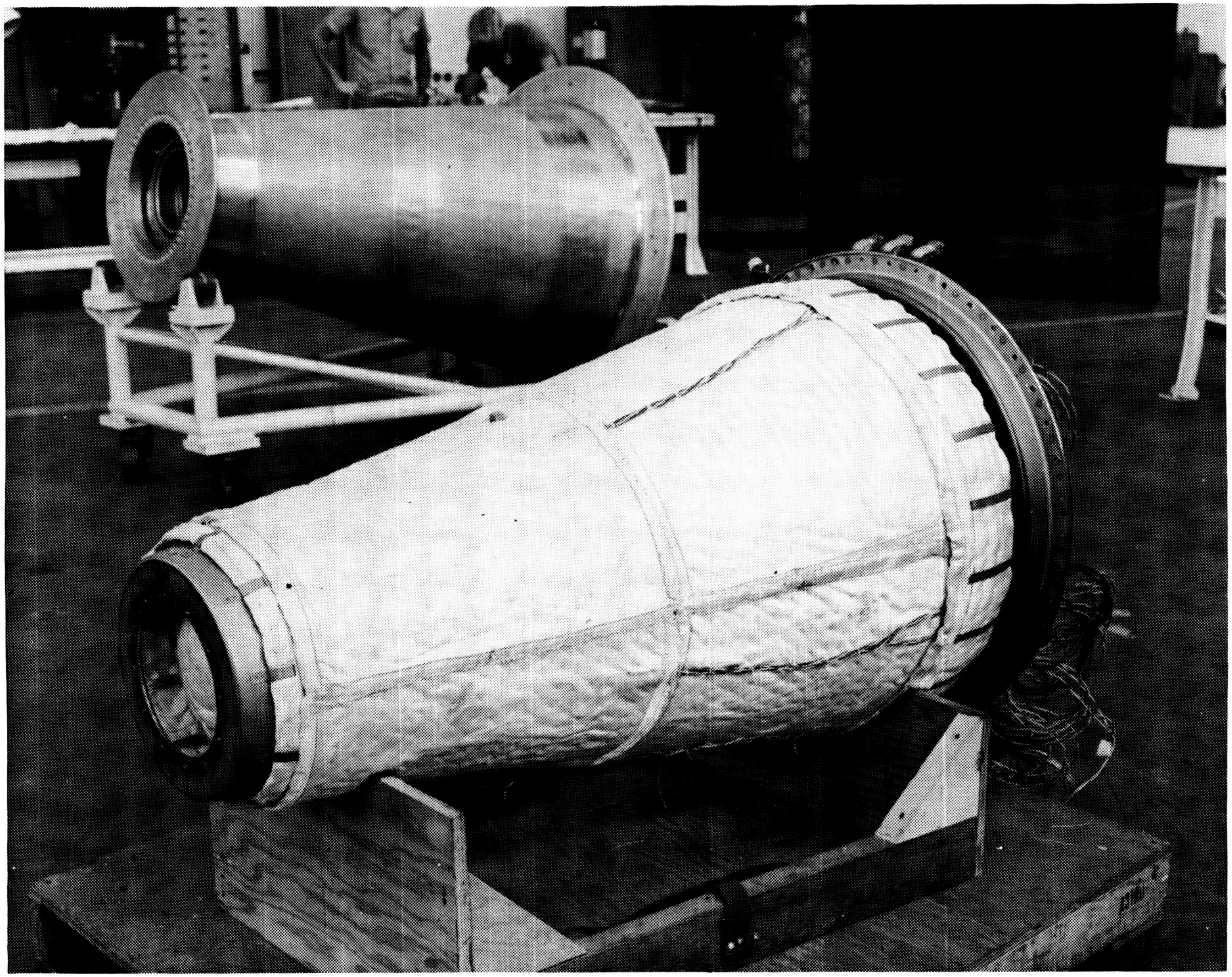


Fig. 33 Completed Tank Primary Assembly Prior to Mating with Outer Structure Primary in the Background

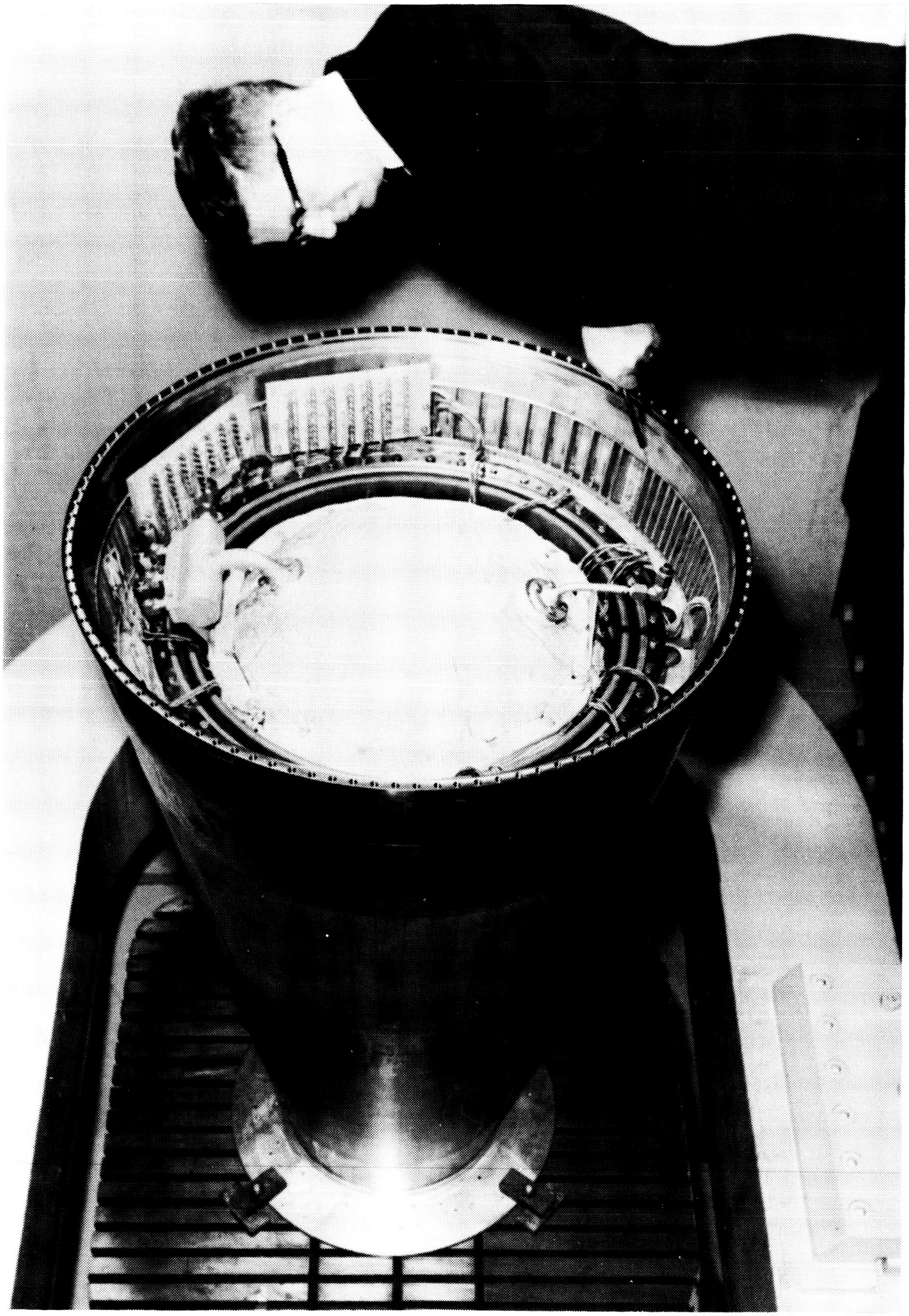


Fig. 34 Rear View of Completed Structural Model

APPENDIX B

Fabrication Drawings For Structural Model

No.		Sheets	D/C	Title
A903	543	2	O/D	Final Assembly & Instrumentation
A903	600	1	O/D	Tank Primary Assembly
	610	1	A	Fwd Bellows
	620	1	C	Aft Bellows
	630	1	O/D	Thrust Fitting
	640	2	A	Fwd Skirt Assembly
	650	2	A	Aft Skirt Assembly
A903	700	1	A	Tank Assembly & Lead Test
	710	1	A	Aft Bulkhead Ring Blank
	720	2	C	Tank Weld Assembly
	730	1	O/D	Access Bulkhead Ring Blank
	740	1	C	Access Bulkhead
	750	1	O/D	Inlet Assembly
	760	2	O/D	Inlet Assembly
A903	800	1	O/D	Structure Primary Assembly
A903	900	3	D	Structure Assembly
	910	1	A	Ring - Fwd
	920	4	C	Fwd Box Section Ring
	930	2	B	Panel Assembly Fwd
	940	2	B	Panel Intermediate
	950	1	B	Panel Aft
	960	1	O/D	Longeron Assembly
	970	4	B	"Y" Ring Frame
	980	5	D	Aft Box Section Ring
	990	1	A	Ring Aft

APPENDIX C

Results of Tensile Tests on Materials for Structural Model

1. Tensile data for Rene' 41:

Ga. (Inch)	Avg. Tensile Strength-psi 6 Specimens	Avg. % El.
0.015	134,600	44.5
0.018	145,200	37.3
0.030	147,100	40.1
0.036	140,000	50.1

2. Tensile data for Inconel 718:

Ga.	Avg. Tensile Strength-psi 6 Specimens	Avg. % El.
0.015	119,100	46.9
0.042	122,800	52.4

3. Tensile data for 2219T62 Parent Metal:

Ga.	Avg. Tensile Strength-psi 6 Specimens	Avg. % El.
0.500	56,200	13.6

4. Tensile data for 6061 T6 Parent Metal:

Ga.	Avg. Tensile Strength-psi 6 Specimens	Avg. % El.
0.090	45,900	11.0

Specimens tested per contract specification L-4091
Appendix "A", Section "C", Par. (1) g

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APPENDIX D

Results of Tensile Tests on Fusion Buttwelds

Tensile data for automatic TIG fusion buttwelds in 2219-T62 Aluminum

Ga. (Inch)	Avg. Tensile Strength-psi 3 Specimens	Avg. % El.
0.375	38,800	6.0

Specimens tested per contract specification L-4091
Appendix "A", Section "C", Par. (1) g

Remarks: Average tensile strength of 2219T62 fusion welds is 38,800 psi. Average tensile strength of 2219T62 parent metal is 56,200 psi. Ultimate tensile strength of weld is 69% of parent metal. 65% was required.

Shear Strength of Manual Plug Welds in 6061-T6.

Plug weld specimens were 1.5000 inch in width and 0.090 inch thickness. Diameter of plug welds was 0.43 in. All failures occurred in the heat affected zone of the weld and did not shear any weld nuggets. The tensile strengths of the 3 specimens were 13,000 psi, 11,850 psi, and 16,200 psi. The minimum ultimate tensile strength of 6061-0 is 18,000 psi. Failure occurred at 72%, 66%, and 90% of parent metal strength.

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