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THE PRODUCTION OF LARGE TANKS FOR CRYOGENIC FUELS

E. HARPOOTHIAN
CHIEF ENGINEER
STRUCTURES DEPARTMENT
DEVELOPMENT ENGINEERING

PREPARED FOR PRESENTATION AT
DEUTSCHE GESELLSCHAFT FUR RAKETENTECHNIK UND RAUMFAHRT
(GERMAN SOCIETY FOR ROCKET TECHNOLOGY AND ASTRONAUTICS)

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TABLE OF CONTENTS

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ABSTRACT

Tanks for cryogenic fluids, as used in the Saturn space vehicles, have reached an advanced stage of design and development. Many of the structural features of the NASA/Douglas Saturn tanks, fabricated of 2014-T6 aluminum alloy, were first developed for the booster of the Thor ballistic missile, which later found extensive use in putting space vehicles into orbit.

There is a mutual dependence of important factors related to design concepts, selection of materials, processing techniques, and fabrication methods. It is shown that this mutual dependence must be considered if a successful vehicle is to emerge from design and development.

Details of vehicle structure, provision for insulation, and manufacturing methods are presented. Criteria for the selection of materials is shown to be dependent on strength, ductility, weldability, toughness, fabricability, behavior at cryogenic temperatures, and on manufacturing methods and inspection techniques.

THE PRODUCTION OF LARGE TANKS FOR CRYOGENIC FUELS

INTRODUCTION

Cryogenic fluids are the energy source for the propulsion of the advanced space vehicles of this era. These fluids are contained under pressure in booster tanks. The booster tanks may also function, in part, as supporting structure for thrust motors and for the upper stages of multiple stage space vehicles. The structure of such a vehicle is subject to a variety of loads in a complex and changing environment. It must be of light weight to achieve the required extreme of performance, and, therefore, it must function at high levels of stress. Performance must be highly reliable, because structural failure affects safety and cost, and may cause serious delays in the launching of important space projects. Costs must be carefully controlled in the design and production stages because the cost of a booster, which in present designs is not reusable, adds heavily to the cost of putting payloads into space. The use of cryogenic fluids may require insulation for the tanks. If cryogenic fluids are to be stored for long periods in an orbiting vehicle, high performance insulation is required and it becomes an important factor in design. Furthermore, although most metals are stronger at cryogenic temperatures, some are much more sensitive to defects.

The production of large tanks for cryogenic fluids does, indeed, present unique and challenging problems of structural design, of selection of materials, of processing tecnniques, of quality control, and of manufacturing methods. Experience has shown that these problems of engineering and production are mutually dependent if the goals of optimum performance and controlled costs are to be realized. These interrelated tasks are shown diagrammatically in Figure 1.

M-20131

ENGINEERING AND PRODUCTION TASKS

ENGINEERING

- DESIGN CONCEPTS
- SELECTION OF MATERIALS
- PROCESSING TECHNIQUES
- QUALITY CONTROL
- MANUFACTURING METHODS

PRODUCTION

FIGURE 1

The Douglas Aircraft Company produces the Thor, which has earned its reputation of a reliable high performance vehicle. Its record as a booster is well known. The Douglas Company is also producing the Saturn S-IV and S-IVB stages of the world's largest space vehicle, a program under the direction of the NASA-Marshall Space Flight Center. The Thor and the Saturn S-IV and S-IVB stages are representative examples of large cryogenic tank developments.

Design of the Thor booster was initiated in 1955 as a ballistic missile weapon, Figure 2. Later on it began to be used as a booster for space experiments. Many of the structural innovations introduced in the Thor design have been incorporated in the Saturn S-IV and S-IVB vehicles. The Douglas Thor and Saturn boosters are the subject of this discussion of design and development of large cryogenic tanks.

THOR

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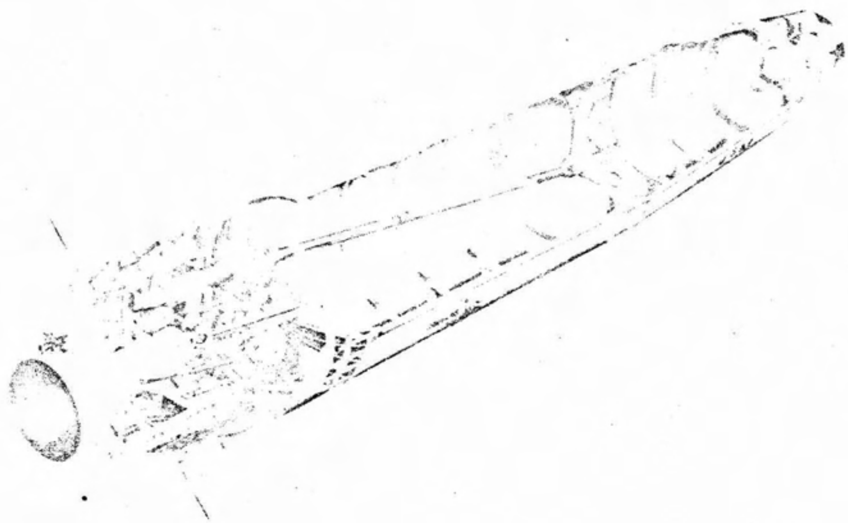

FIGURE 2

I. DESIGN CONCEPTS

The structure of a large booster tank for cryogenic fuels may require relatively thin walls for pressure loads because pressure requirements are usually not high. However, thin wall monocoque construction, a desirable type for its simplicity, requires increased wall thickness and, possibly, consideration of additional stabilization by pressurization for the higher buckling strength needed even for the low level intensity of thrust and flight loads. Additional stiffening and, possibly, pressurization is also needed to make practical the ground handling of such thin wall vehicles.

A major consideration which demands attention from the commencement of design relates to safety and reliability. Reliable structural performance must be achieved because structural failure affects safety and cost, and may cause serious delays in vital and expensive space projects. Reliability and safety are achieved through excellence of design, and their consideration will affect the structural configuration. Modifications of an existing design to achieve or enhance reliability sometimes yields the desired results, however, it often happens that the existing design incorporates features that do not lend themselves to good reliability. In such a case a major and expensive change is necessary before any improvement in structural performance can be obtained.

The Thor

In the evolution of the Thor design, consideration was given to the use of conventional skin and stringer construction, integrally stiffened shell, and monocoque shell. Monocoque shell was rejected for the reasons already mentioned. Conventional aircraft skin and stringer construction, which appeared to be a simple concept for stiffening tank walls, presented numerous problems of load transfer at joints, of fabrication and of sealing. Integral waffle-grid stiffening provided by ribs machined on the inner wall of the tank proved to be the most practical and efficient concept. The ribs run at an angle of $\pm 45^{\circ}$ to the axis of the tank, Figure 3. Rib height in the Thor

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CYLINDRICAL WALL WAFFLE CONFIGURATION

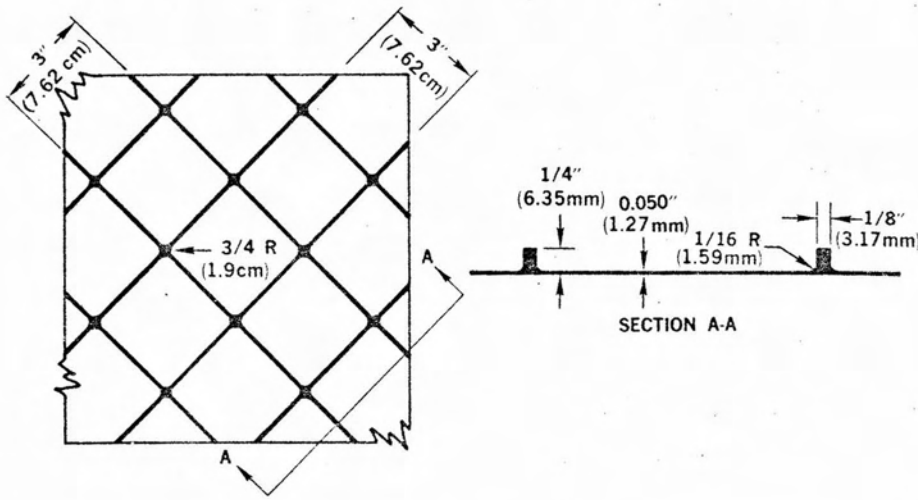

FIGURE 3

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THOR TANK

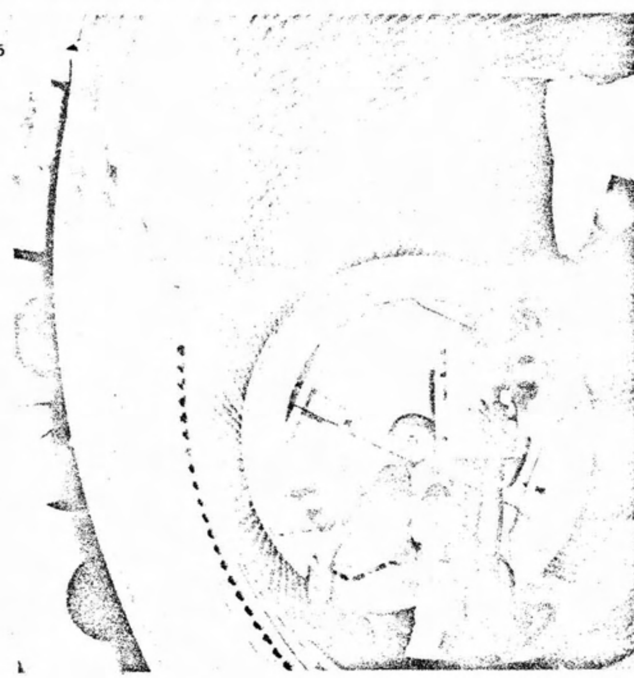

FIGURE 4

design is about five times the tank wall thickness. The ribs are produced by machining away square areas from plate stock. The edges of the plate are left full thickness to insure adequate strength of longitudinal seam welds in the tank, and to provide a good base for the attachment of the domes to the tank walls. After machining the waffle pattern, the plates are formed to the tank radius, and then three segments are joined by longitudinal butt welds, Figure 4, to form the 96 inch (244 cm) diameter cylinder. Additional tank stiffening for ground handling is provided by several small transverse frames. These frames do not increase the buckling strength of the cylinder. The ribs could also have been produced by chem-milling. However, machined ribs are usually a little more precise dimensionally and are not appreciably different in cost if the machining is done while the plates are flat. Chem-milling is usually preferred if the milling is to be done on curved panels.

The waffle stiffening design possesses several advantages over stringer stiffened tank walls. The advantage of being able to provide a thicker integral edge pad for welding or mechanical joining has been mentioned. Approximately 85% of the weight of the waffle structure is effective in resisting tank pressure loads. A much lower percent of stringer stiffened structure is effective in resisting pressure loads.

Fuel for the Thor consists of kerosene and liquid oxygen. These fluids are contained in tanks in the booster cylinder, Figure 2. Each tank has stiffened end bulkheads. These bulkheads, or end domes, are stiffened by integral meridianal ribs chem-milled on the convex side of the dome. The domes are stretch formed from single sheets before being chem-milled. A land of the full thickness of the sheet is left at the edges of the opening in the center of the dome, and at the edges at the bottom of the dome. These thicker edges facilitate the attachment of the access hole cover and the attachment of the dome to the tank wall. The rib stiffening on the domes is used to provide buckling strength for the small negative pressure loads which could occur under certain circumstances. The domes are joined to the tank walls by mechanical fasteners. Joints are made on the thick edges left by the machining and chem-milling. A fluid tight seal is provided by additionally joining the dome to the tank wall by a light weld.

The upper Thor tank contains the kerosene fuel. The lower tank contains the Lox oxidizer. Each tank has its own bulkheads. Since these tanks are not separated by a common bulkhead, there is no danger of the liquid oxygen freezing the kerosene and no insulation is required between the tanks. No insulation is provided for the cylinder walls of the oxygen tank. The oxygen tank is topped off at launch, and whatever ice has formed on the outside is rapidly melted off as the vehicle gathers speed.

Tank walls and end domes are fabricated from 2014-T6 aluminum alloy plate and sheet stock. This alloy was selected because its welding characteristics were superior to those of other candidate alloys available at that time. Tank wall segments are joined by longitudinal butt welds made in two passes on opposite sides of the wall with 4043 welding rod. The weld rod is an alloy of aluminum and about five percent silicon. The welds are made by automatic welders with the edges of the tank segments clamped between quench bars.

The waffle-grid configuration of $\pm 45^{\circ}$ was chosen on the basis of test data from a variety of configurations. Figure 5 shows how the strength to weight ratio varies with variation of the waffle skew angle. The $\pm 45^{\circ}$ configuration gives an axial buckling strength of approximately 4500 psi ($3.16\ kg/mm^2$) for the Thor tank. This buckling strength is adequate for the axial and axial plus bending loads encountered. A monocoque cylinder of equivalent buckling strength would be about 40% heavier.

Figure 6 shows a Thor tank being readied for a pressure test. In this test the tank was pressurized by water, so the highest pressure was at the bottom of the tank. The tank was designed to withstand a pressure of 66.5 psi (4.52 atü) which corresponds to a wall hoop stress of 52,000 psi (36.56 kg/mm^2) on the equivalent effective wall thickness. The equivalent effective wall thickness is approximately 85% of the equivalent weight wall thickness. The tank burst at a pressure of 82 psi (5.58 atü), or an equivalent effective wall hoop stress of about 65,000 psi (45.70 kg/mm^2). Failure occurred away from the longitudinal weld joints, as seen in Figure 7.

VARIATION OF STIFFENER EFFECTIVENESS WITH SKEW ANGLE

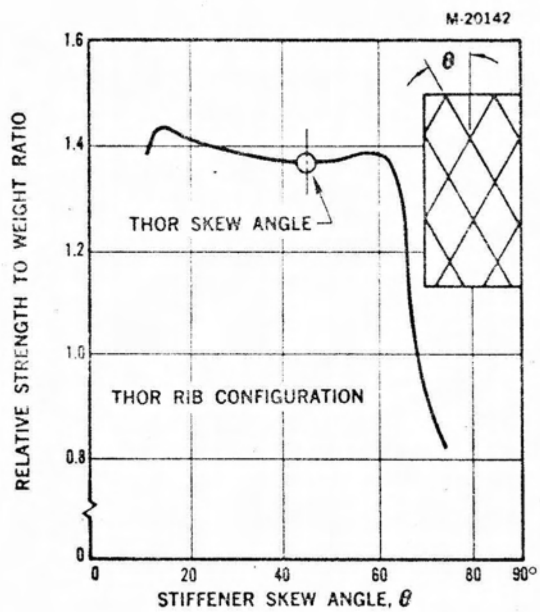

FIGURE 5

REF 1

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THOR TEST
SPECIMEN

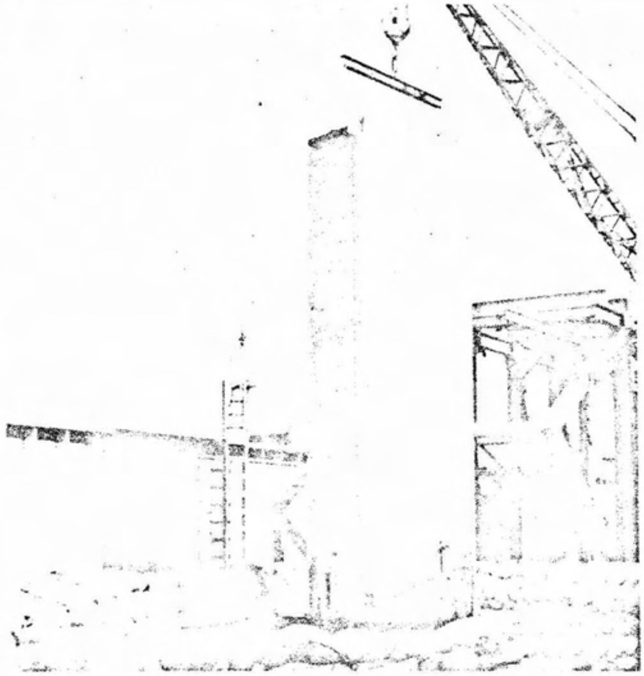

FIGURE 6

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THOR TEST
SPECIMEN

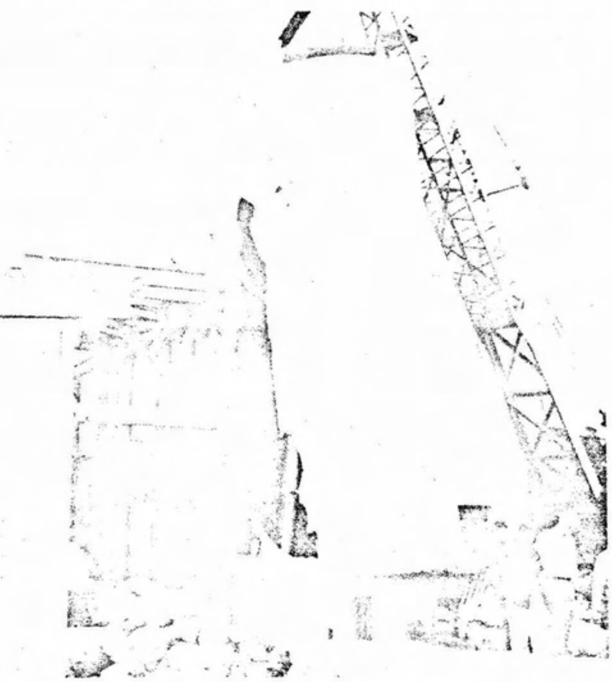

FIGURE 7

The Saturn S-IV and S-IVB

Many of the design concepts used in the Thor tanks were incorporated in the design of the Saturn S-IV and S-IVB tanks. Figure 8 shows the S-IV in the upper stage of the Saturn C-1 configuration. The positions of the S-IVB stage in Saturn configurations 1B and V are shown in Figures 10 and 11. The general dimensions of these boosters are given in Table 1.

A sketch of the Saturn S-IV stage, Figure 9, shows the tank configuration for this booster. Early studies showed that an appreciable saving in weight could be realized by using a common dome to separate the liquid hydrogen and liquid oxygen tanks. This dome also provides insulation between the tanks. Without the insulation, the liquid hydrogen would freeze the liquid oxygen.

Tank walls, end domes, and common bulkhead facings are produced from 2014-T6 alloy plate and sheet. Tank walls are stiffened by waffle-grid ribbing, following Thor practice. End domes are stiffened by integral meridianal ribs. The waffle pattern in the tank walls is machined in the plate before it is formed to the tank contour. Waffle patterns 9-1/2 inches (24.1 cm) square are machined in 1/2 inch (1.27 cm) plate for the S-IV and in 3/4 inch (1.9 cm) plate for the S-IVB. Rib angle of the waffle pattern is $\pm 45^{\circ}$. The ratio of rib height to tank wall thickness is about 5.5 for both tanks. The tank cylinder is formed by longitudinally butt welding the segments together in two passes. Both passes are made with automatic welders on the same side of the wall. This practice differs from that used in Thor production, and tooling and production costs are lower. Three segments are welded together to form the S-IV tank, and seven segments are used for the S-IVB tank. As in Thor production, 4043 welding rod is used. Allowable strength of the joints is based on as welded mechanical properties. Higher weld strength could be obtained by heat treatment, however, subsequent distortion of the tank and processing problems make these higher strengths impractical of achievement.

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DOUGLAS S-IV
SATURN C-1 SECOND STAGE

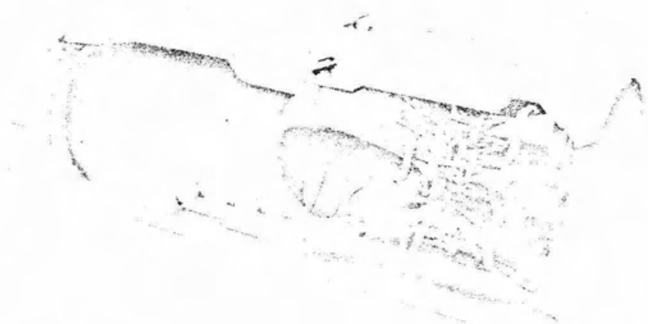

FIGURE 8

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SATURN S-IV STAGE STRUCTURE LOCATIONS

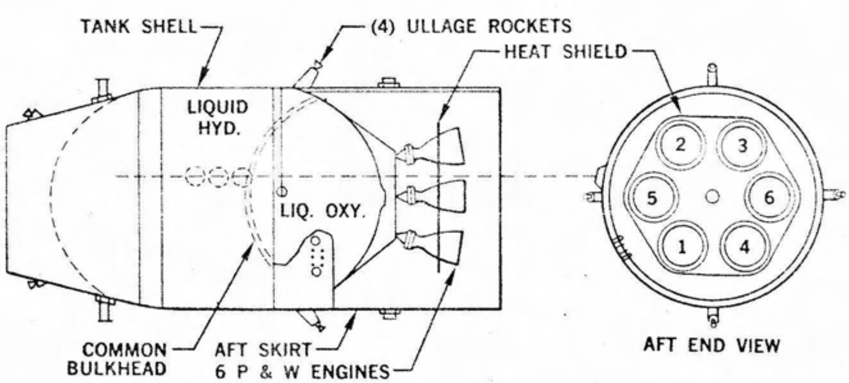

FIGURE 9

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DOUGLAS S-IVB
SATURN IB SECOND STAGE

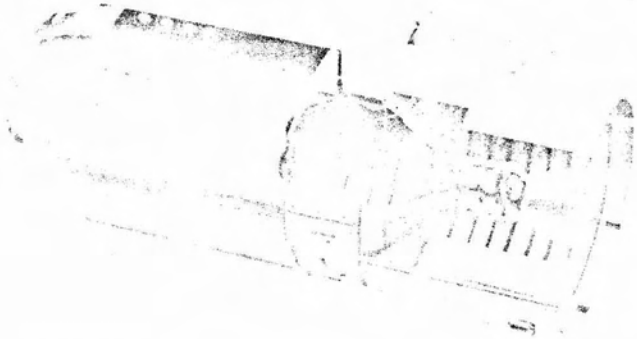

FIGURE 10

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DOUGLAS S-IVB
SATURN V THIRD STAGE

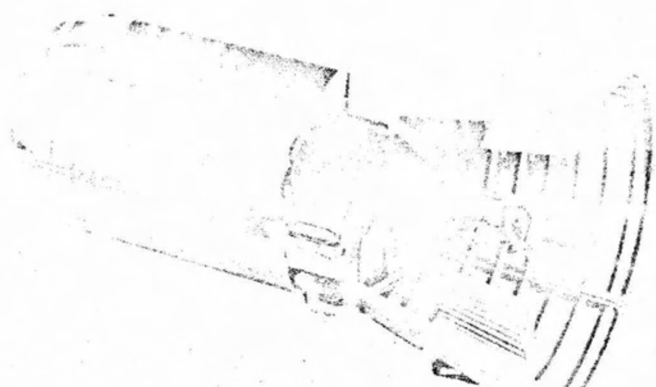


FIGURE 11

Tank structure of both stages is divided into two compartments which are separated by a common, constant radius bulkhead. The forward compartment contains the liquid hydrogen, and the aft compartment contains the liquid oxygen. The liquid hydrogen tank is formed by the forward hemispherical dome, the cylindrical section, the portion of the aft hemispherical dome forward of the common bulkhead, and the forward face of the common bulkhead. The structural arrangement is shown in Figures 8, 9, 10, and 11. The liquid oxygen compartment consists of the portion of the aft dome located aft of the common bulkhead joint, and the aft face of the common bulkhead.

The forward dome of the S-IVB is fabricated from nine spherical triangle segments butt welded together to form a hemisphere. The segments are first formed to the 130 inch (330 cm) radius from sheet stock and then chem-milled. The nominal wall thickness is 0.056 inch (1.42 mm). The edges, or weld land areas, are 0.113 inch (2.87 mm) thick. This greater thickness of the weld land permits stresses across the butt weld to be held below the yield stress of the material.

M-20141

DOUGLAS BOOSTERS

TABLE 1

	THOR	S-IV	S-IVB
LENGTH	53 FT 7 IN. (16.33 m)	41 FT 6 IN. (12.65 m)	58 FT (17.68 m)
DIAMETER	96 IN. (244 cm)	220 IN. (559 cm)	260 IN. (660 cm)
DRY WEIGHT	6443 LBS (2920 kg)	11500 LBS (5210 kg)	21700 LBS (9840 kg)
PROPELLANTS	JPL AND LO_2	LH_2 AND LO_2	LH_2 AND LO_2
PROPELLANT WEIGHT	101000 LBS (45800 kg)	100000 LBS (45400 kg)	230000 LBS (104300 kg)
ENGINES	YLR-79-13	6 P&W XLR-115	P&W J-2
TOTAL THRUST	170000 LBS (77100 kg)	90000 LBS (40800 kg)	200000 LBS (90700 kg)

The common bulkhead is a 1-3/4 inch (4.44 cm) thick sandwich of 2014-T6 alloy facings and a non-metallic honeycomb core. This bulkhead serves as an end dome for both the liquid hydrogen and liquid oxygen tanks, and it provides insulation to obstruct the flow of heat from the liquid oxygen to the liquid hydrogen. Without the insulation the liquid oxygen would freeze. The facings of the bulkhead are each fabricated from nine spherical triangle segments of 2014-T6 alloy sheet. The segments are formed to contour, chem-milled, and then butt welded. The peripheral edges of the dome facings are butt welded to 2014-T6 "Y" shaped extruded rings. The facings are bonded to the core, one face being bonded at a time. The assembled common dome is then attached to the aft dome by structural lap welds and by mechanical fasteners. The mechanical joint is made only in the liquid oxygen tank. Holes in the hydrogen tank are avoided if possible. The welded joints also serve as seals. The ring extrusions are lap welded to the facings of the common dome of the S-IV tank. Attachment to the aft dome is similar to that of the S-IVB.

The aft dome of the S-IVB is a more complicated bulkhead. This dome is also made from nine segments which are stretch formed from plate stock. The segments are chem-milled after forming. In addition to its function as a tank dome, it also supports the common bulkhead and the thrust structure, on which the engines are mounted. The forward part of the dome, between the attachment to the tank cylinder and the common bulkhead joint, is stiffened by integral waffle ribbing. The wall thickness between the common dome and thrust structure joints is less than it is aft of the thrust structure joint. Engine thrust loads reduce the tension in the dome forward of the thrust structure joint.

Access to the hydrogen tank is through a 33 inch (84 cm) diameter manhole in the center of the forward dome. A similar opening in the aft dome provides for access to the oxygen tank.

Inasmuch as the geometry of the waffle stiffening used on the Saturn tanks differs from that used on the Thor tanks it was deemed necessary to conduct tests to determine the buckling strength of the tank cylinder. Figure 12 shows a section of a Saturn S-IVB tank being prepared for a test. The test specimen and loading fixtures are shown in Figure 13. This tank test specimen was loaded with an axial load of 164,500 (74,700 kg), a shear load at the top of the tank of 42,000 pounds (19,100 kg) and a bending moment at the top of the tank of 14,700,000 inch pounds (16,950,000 cm kg). The compression stress developed near the midsection of the tank for this ultimate design loading condition was approximately 4,380 psi (3.08 kg/mm^2). In a subsequent test to failure, the tank cylinder developed a shell buckling stress of 6,900 psi (4.85 kg/mm^2) and a shear stress of 3,480 psi (2.45 kg/mm^2).

S-IVB TEST SPECIMEN

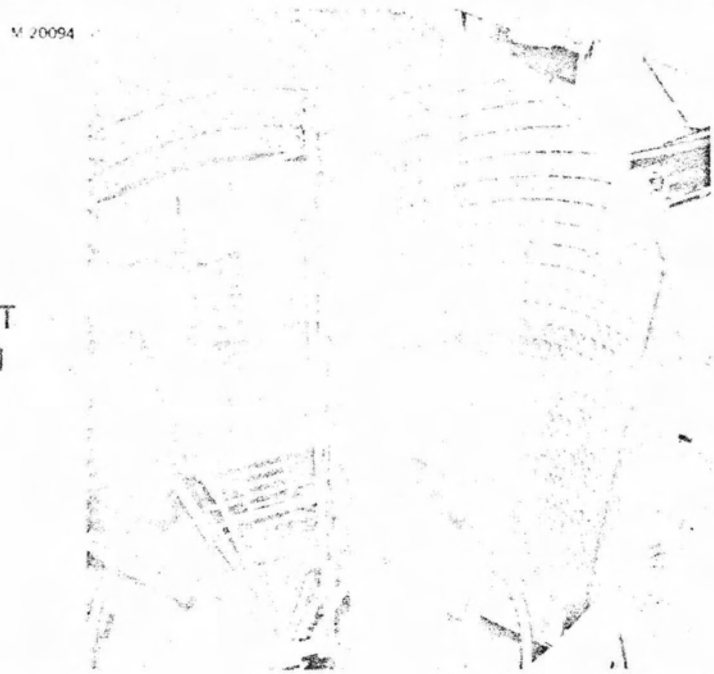
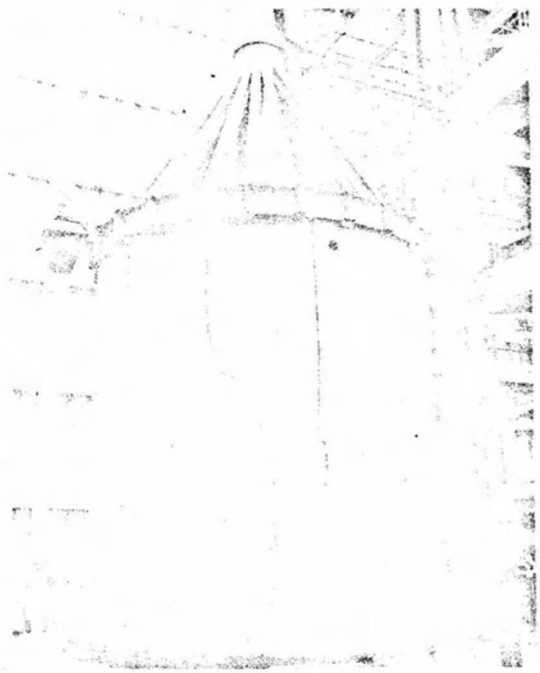


FIGURE 12



SIVB TEST
SPECIMAN

FIGURE 13

Insulation

Boil-off of the liquid hydrogen from the tanks of the S-IV and S-IVB is held to a minimum by internal insulation. Tank walls and the forward end dome are insulated by specially reinforced polyurethane foam liners. These liners are in turn covered by a fiberglass cloth impregnated with polyurethane resin to prevent the fuel from seeping into the insulation.

Without a highly efficient insulation system the boil-off rate of liquid hydrogen would be much too high. Furthermore, the liquid oxygen in the condensed air on the outside surface of the liquid hydrogen tank would constitute a hazard during the ground hold phase of the launch operation. For these and other reasons some kind of effective insulation must be used on the liquid hydrogen tanks. Whether an external or an internal insulation is used depends on several factors.

The fiberglass membrane used to cover the internal insulation in the Saturn tanks transfers the pressure to the tank wall through the reinforced polyurethane foam. The foam insulation, therefore, is designed to withstand the compression forces involved in transferring the pressure load to the wall. The insulation is also subjected to stresses induced by thermal contraction and by vibration.

All equipment, personnel, and materials required to install the internal insulation are brought into the tank through the 33 inch (84 cm) diameter access door in the forward dome. Extreme precautions are taken to assure cleanliness, to obtain good bonding, and to avoid damage to the insulation.

External insulation is proposed for an advanced version of the S-IVB vehicle. This insulation is more effective and would permit storage of fuel in an orbiting vehicle for an extended period. Booster performance would be improved by its use because it is lighter in weight and would, therefore, permit more payload to be carried. This insulation consists of multiple layers of aluminized mylar sheets. These sheets would be assembled into blankets of, perhaps, 100 layers. One type blanket would be sealed in vacuum, the other would be sealed and then purged with helium gas. Both types would expand to several times their original thickness when the ambient pressure is low. Vent systems permit escape of excess gas at low ambient pressure. Both blankets afford effective thermal protection for an orbiting vehicle.

Metal shrouds would be used to protect the insulation while the vehicle is on the ground and during ascent. As the vehicle moves out of the atmosphere the shrouds would be broken away and ejected by an ordnance device, Figure 14.

M 20112

EXTERNAL
INSULATION
SCHEME

FIGURE 14

II. MATERIAL SELECTION

A structural material suitable for fabrication of a cryogenic tank must possess certain mechanical properties, and these properties must not be adversely affected by acceptable fabrication practices or by exposure to cryogenic temperatures. No one material ideally possesses the required properties. A good choice becomes, then, a judicious compromise.

Structural performance of a cryogenic tank is limited by residual stresses and defects induced in the structure during fabrication, and by the ductility and fracture toughness of the tank metal and its welded joints. Strength, ductility, weldability, toughness, and fabricability of a metal must be satisfactory and well established before a material is seriously considered for a high performance tank. Too much optimism about marginal characteristics could be cause for expensive and major changes when a program reaches an advanced stage of development. A good design is determined by a well planned program of pretesting, that is, by testing representative structure. The objectives of such a program are not just to produce data, but rather to produce information which is needed to evaluate a design concept, to reveal shortcomings of design, fabrication, and inspection, and to determine alternate designs. In general, a program would include tests of welded joints, of stiffened structure, of bonded or mechanically joined structure, and, perhaps, of photoelastic models to determine the magnitude of stress concentrations. Inspection techniques must complement fabrication techniques, or the soundness of a structure will not be determinable.

The mutual dependence of all these parameters forms the criteria for the selection of a material.

At the commencement of design studies for the Thor, several candidate metals were selected for consideration. The Douglas Company had extensive experience with 2024 and 7075 alloys in the fabrication of primary structure for aircraft, with 6061 alloy in the fabrication of other structure, and with 2014 alloy in forgings, extrusions, and sheet for aircraft structure.

It was evident that sealing a tank for cryogenic fluids would be a serious problem unless major parts of the tank structure were joined by welding. Welding characteristics of 2024 and 7075 alloys were not satisfactory for this application. Welding characteristics of 6061 alloy were known to be quite satisfactory, but a serious weight penalty would result if this alloy were selected. The choice narrowed to 2014 alloy or, perhaps, a new alloy. In 1955, 2014 alloy was the only aluminum alloy which seemed to be suitable for the job. Before making a definite choice of 2014 alloy, an extensive development study of butt welded joints in this alloy was undertaken. During this study welding techniques were developed to the point where strength and weld reliability were no longer considered a problem. It was decided, however, to design the welded joints for relatively low stresses, because operational experience was lacking for a high performance vehicle assembled by welding.

When design studies for the Saturn S-IV began a relatively new aluminum alloy, 2219, which was originally introduced for service at elevated temperature, had just been shown to develop high strength and good ductility in welded joints. Furthermore, its joint efficiency under biaxial loading was found to be higher than could be obtained with other high strength weldable alloys. This material required post weld heat treatment and aging to develop the superior properties of welded joints. This kind of processing would be a practical impossibility with a tank the size of the S-IV Saturn vehicle. Without post weld heat treatment the weld elongation properties are low and there is no strength advantage over 2014 alloy. For these reasons and in view of the successful production experience with the Thor it was decided that 2014 alloy would be used in Saturn production.

The ultimate tensile and yield tensile strengths of 2014-T6 alloy are superior to 2024-T6 alloy, and, as with most aluminum alloys, the strength increases as the temperature decreases. The variation of strength with temperature is shown in Figures 15 and 16. A very significant increase in strength is available for those design conditions which are critical at cryogenic temperatures.

ULTIMATE TENSILE STRENGTH OF 2014 ALUMINUM

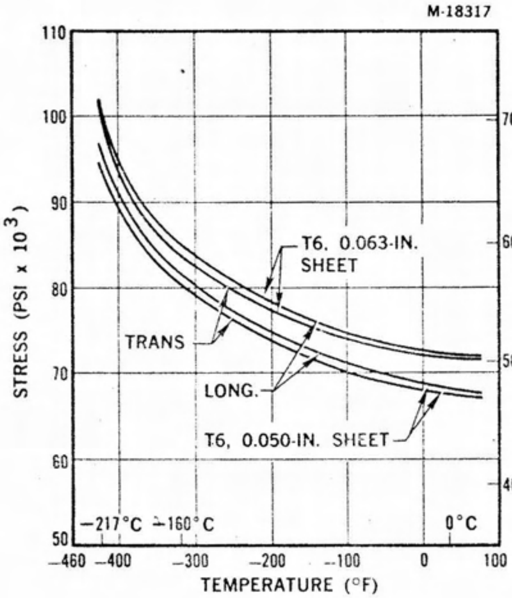


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FIGURE 15

YIELD TENSILE STRENGTH OF 2014 ALUMINUM

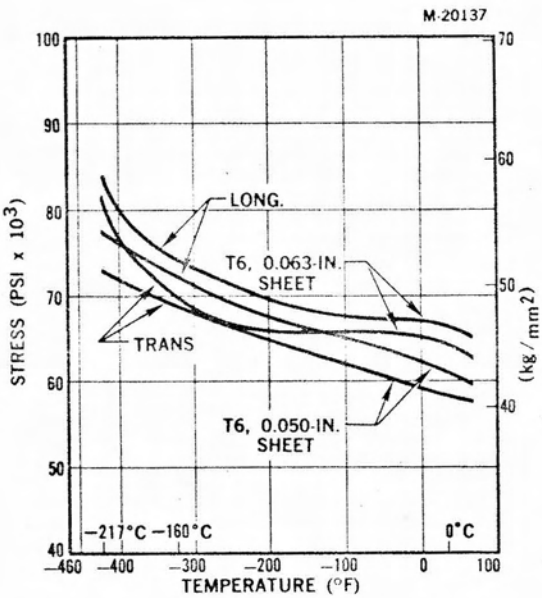

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FIGURE 16

Elongation also increases as the temperature decreases. However, it is of greater significance that the elongation in the weld area decreases appreciably as the temperature decreases, Figure 17. Modulus of elasticity, Figure 18, is higher at lower temperatures, and this is also of advantage if shell buckling is critical at cryogenic temperatures.

A comparison between the strengths of 2014-T6 and 2219-T81 alloys is presented in Figure 19. The strength advantage of 2014-T6 throughout the temperature range is apparent. The advantage of 2219-T81 would be in the strength of fusion welded joints, if post heat treatment was not necessary.

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ELONGATION OF 2014 ALUMINUM

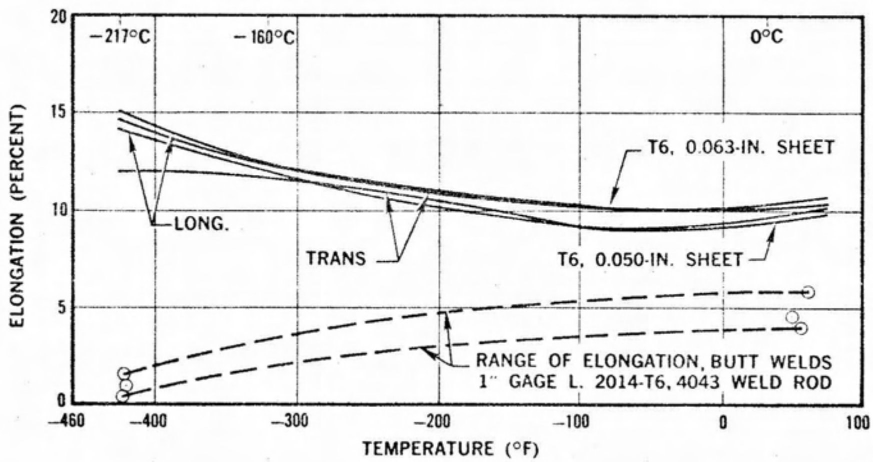

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FIGURE 17

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MODULUS OF ELASTICITY OF 2014 ALUMINUM

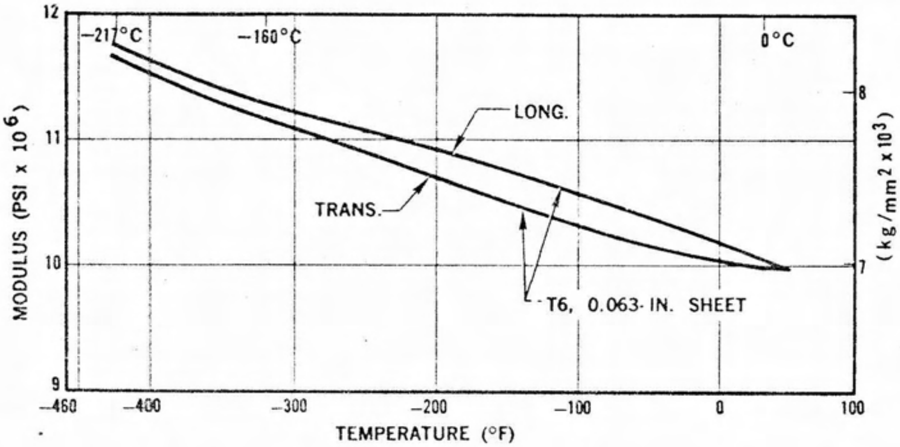

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FIGURE 18

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TENSILE STRENGTHS OF 2014-T6 AND 2219-T81 ALUMINUM

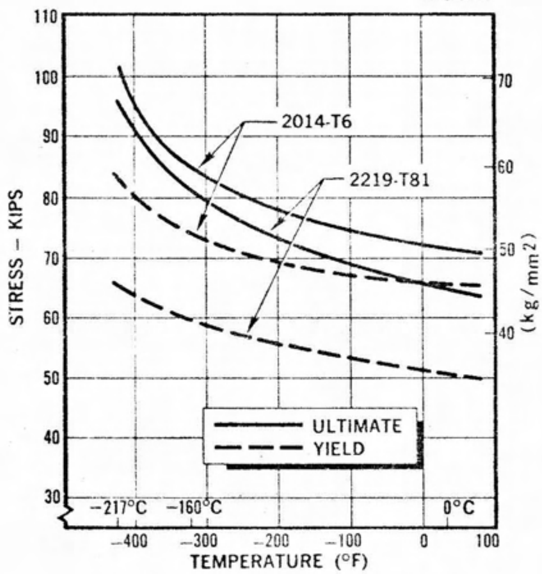

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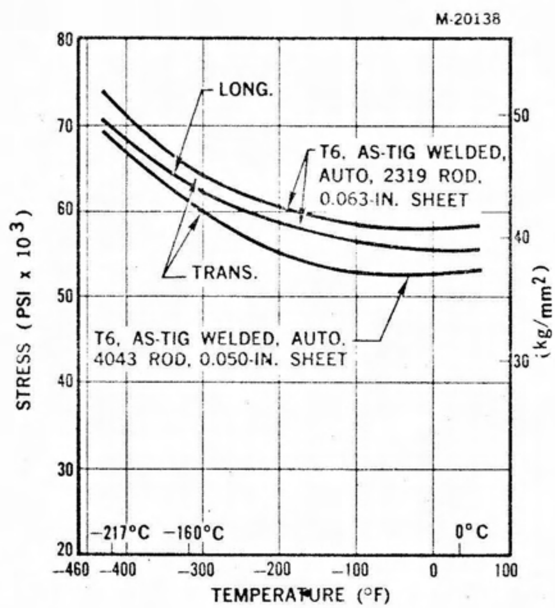
FIGURE 19

The effect of temperature on the strength of butt welded joints in the 2014-T6 alloy is given in Figure 20. Strength and elongation properties of butt welds in 2219 alloy are given in Table 2. These values are for room temperature. Elongation is even lower at cryogenic temperature. After post weld heat treatment the strength and elongation are quite good, but the condition is impractical of achievement in a large tank. Strength as given for both alloys is from test coupons loaded in simple tension normal to the weld line. Strength and elongation are lower in the welded structure of a tank assembly as a consequence of residual stresses and several kinds of defects which are common to welded joints. These residual stresses and defects are not subject to as complete control as is desired. Shrinkage of the weld introduces residual stresses, which can, occasionally be a serious problem in a large tank assembly. Allowance must be made for these less controllable factors. Designing welded joints to work at reduced stress levels is an effective means of obtaining a structurally reliable joint. Stresses normal to a weld line are readily reduced by making the weld in a locally thicker section. A locally thicker section may be of no help in reducing stresses parallel to a weld line. Care must be exercised in

BUTT WELD TENSILE STRENGTH OF 2014 ALUMINUM



REF 3

FIGURE 20

designing a structure to prevent critical combinations of stresses from occurring along a weld line. If the weld does not possess sufficient ductility, cracking transverse through the weld may result. Heavier gauges may have to be used over a major portion of the structure to obtain lower stresses. If this should be the case, a lower strength material with superior welding characteristics might be a better choice, for it may permit the use of a higher stress level.

TABLE 2

M-20135

TYPICAL AND SUGGESTED MINIMUM MECHANICAL PROPERTIES OF 2219 ALLOY BUTT WELDS

	TENSILE ULTIMATE (KSI)	TENSILE YIELD (KSI)	ELONGATION (% IN 2")
TYPICAL, AS WELDED -T81, -T87	41 (28.8)*	30 (21.1)	3
SUGGESTED MINIMUMS	35 (24.6)	–	–
TYPICAL, -T31 AGED TO -T81 AFTER WELDING	45 (3[illegible].6)	39 (27.4)	2
TYPICAL, REHEAT TREATED AND AGED TO -T62 AFTER WELDING	57 (40.0)	39 (27.4)	8
SUGGESTED MINIMUMS	50 (35.1)	–	–
TYPICAL, REHEAT TREATED, SHOT PEENED AND AGED TO -T81 AFTER WELDING	63 (44.3)	49 (34.4)	8

*(kg/mm^2)

REF 2

TABLE 3

M-20136

PROPERTIES OF 2014-T6 BUTT WELDS

	TENSILE ULTIMATE (KSI)	TENSILE YIELD (KSI)	ELONGATION (% IN 2")
DESIGN ALLOWABLE	35	25	4-6
STRENGTHS, -T6			
AS WELDED			
4043 WELD FILLER	(24.6)*	(17.6)*	

*(kg/mm^2)

REF 1

Design allowable stresses for welded joints should be based on extensive test data. The allowable strengths for butt welded joints presented in Table 3 are statistically based on Douglas test data.

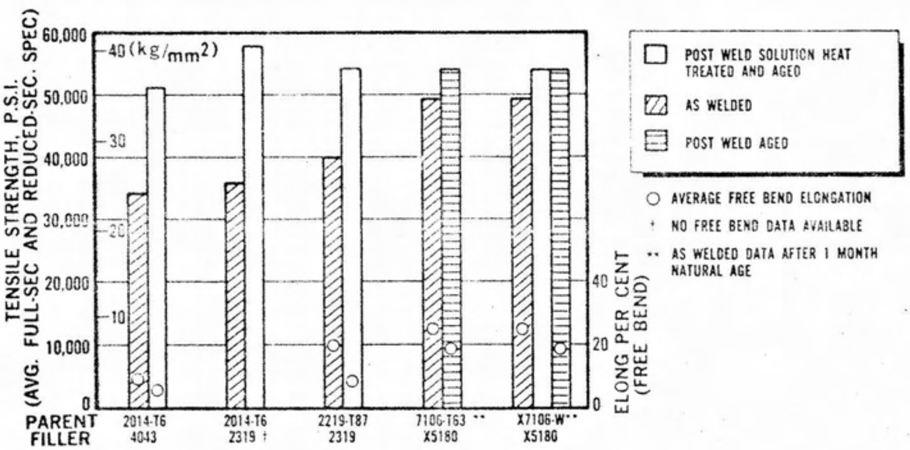
A comparison of the strengths of butt welded joints in 2014-T6, 2219-T87 and a new alloy, X7106, is presented in Figure 21. The as welded strength and ductility of the new alloy, an ALCOA proprietary product, is seen to be very much superior to that of better known high strength weldable alloys. The notch sensitivity of this metal at $-320^{\circ}F$ ($-160^{\circ}C$) is also much superior to other weldable alloys, Figure 22. If a new design were being initiated at this time, very serious consideration would be given to the use of this new alloy.

Other materials might also be considered in the design of a new cryogenic tank. Some of the titanium alloys would certainly be potential materials. Beryllium and beryllium-aluminum alloys (which are not alloys in a metallurgical sense) and composite materials might also be considered. Some of these materials are much more expensive than aluminum alloys, however, in the fabricated state the cost difference, if any, would be of little consequence. Titanium alloys are now in use for some smaller tanks. For example, titanium bottles, fabricated from 6AL-4V alloy, are used for pressurization of the liquid oxygen tanks of the Saturn S-IV and S-IVB vehicles. These tanks, which contain helium under pressure, are immersed in the liquid hydrogen tank. Some of the titanium alloys are very sensitive to the presence of small cracks at cryogenic temperatures, and selection of a material for use at these temperatures must be made with proper allowance for fracture toughness. If a titanium alloy were to be selected for a large tank, stabilization of the wall structure by pressure, at least in part, should be considered. It might, for example, be an efficient design for a cryogenic tank which is suspended inside a shell which is designed to carry axial, shear, and bending loads induced in the stage.

Beryllium has been used in space vehicle inter-stage structure, but has not as yet been used in tank design. The metal is difficult to fabricate and has low fracture toughness. These shortcomings are overcome to a large extent in the new beryllium-aluminum alloys. Much study will have to be given to these new alloys to determine whether other of their characteristics render the metals useful for tank design.

M-20133

STRENGTH AND DUCTILITY OF BUTT WELDS IN HEAT TREATABLE ALUMINUM ALLOYS



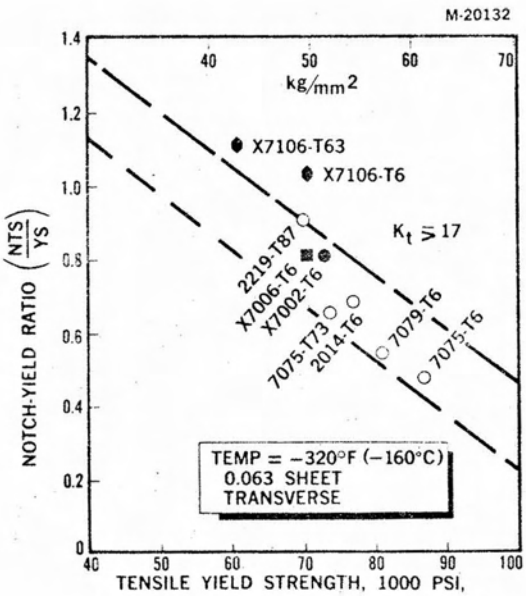
REF 2

FIGURE 21

Fiberglass composites are used for some bottles and tanks. However, this construction has not proven to be satisfactory for cryogenic tanks. The matrix tends to crack and leak when used to contain liquid hydrogen. Studies are being made to determine the characteristics of metal lined fiberglass tanks, which appear to show some advantage and may prove adequate for certain kinds of cryogenic tanks. Fiberglass constructed tanks exhibit a significant loss of strength after a relatively few number of cyclic pressurization loadings.

RELATIONSHIP BETWEEN NOTCH-YIELD RATIO AND TENSILE YIELD STRENGTH

BAND FOR COMMERCIAL 2000, 6000 AND 7000 ALUMINUM ALLOYS ARTIFICIALLY AGED



REF 2

FIGURE 22

III. QUALITY CONTROL

The exhaustive engineering and development efforts required for the design of a space vehicle would be totally nullified without an appropriately designed and executed quality control program. The quality control methods utilize established techniques and employ well developed tools. Quality control is exercised from the time of procurement of raw material to the actual flight of the vehicle.

Manufacturing personnel are trained and certified for such functions as welding, soldering, adhesive bonding and sealing. In addition, quality control personnel are trained in similar functions and also receive special training in inspection techniques, such as in the use of ultrasonics and radiography.

Raw materials are controlled to specific requirements established by the design function, and are chemically and physically examined to assure conformance to applicable specifications.

Tooling and equipment used for fabrication purposes are inspected and certified at regular intervals. Measuring equipment used is calibrated to standards established by the United States National Bureau of Standards.

Structural welding is accomplished by certified welders in the presence of a welding engineer. Weld samples are taken prior to the initiation of a production weld and are tested for acceptability to a standard established by engineering. The inspection techniques used to determine weld conformance are:

1. A detailed visual examination, including measurement of weld penetration.
2. Dye penetrant inspection for indications of surface cracks or other surface imperfections.
3. Radiography for determining other than surface defects.

All weld defects are removed, and the affected areas are rewelded and re-inspected for conformance to the original standards.

Ultrasonic shear wave standards are being established, and may be used to supplement weld inspection techniques.

A surface replication method for defect determination is being studied. This method shows promise of finding minute flaws, which extend to the surface, but are not detectable by the dye penetrant method.

Insulation is applied to the interior of cryogenic tanks in a carefully controlled atmosphere by certified personnel. Adhesion of such insulation is verified by pulse-echo ultrasonic techniques. Where lack of adhesion is evident, the insulation and old adhesive is removed, replaced and re-inspected.

In addition to the product quality controls noted above, an extensive qualification and test program is required to assure both manufacturing and design integrity. This program for the Saturn S-IVB stage, for example, consists of:

1. "Static" test firing stage, made of heavy gauge stainless steel, which is required to prove the major design components of the propulsion system. Information from test firings, which are accomplished early in the program, provide data for design changes, thereby improving reliability and performance.

2. A "Dynamics" stage is required to determine lateral and torsional vibration characteristics for each vehicle configuration.

3. An "All-Systems" stage is required to verify tankage capacity, insulation, pneumatic systems, and general compatibility with all associated equipment.

4. A "Facilities" stage is required to checkout interfaces with other system stages, and also to permit development of loading, unloading and pressurizing techniques.

5. A "Structural Test Cylinder" is required to determine the ability of the cylinder to withstand compression loads.

In addition to the comprehensive test program, each flight stage is hydrostatically tested to a proof pressure of five percent (5%) above the limit load, and is also subjected to a full duration static firing.

IV. MANUFACTURING METHODS

The Saturn S-IVB stage is manufactured, for the most part, at the new Douglas Space Center. Special tooling located at other Douglas facilities is used in some fabrication operations. Technologies used in the manufacture of Thor and Saturn S-IV and S-IVB tanks include metal removal by machining and by chemical milling, forming by stretching and bending, chemical bonding, welding, and mechanical fastening. These technologies have reached a high state of development, and in the production of cryogenic tanks these advancements are exploited wherever possible.

The discussion of manufacturing methods is in relation only to the production of the Saturn S-IVB tanks, inasmuch as similar methods are used in production of the other tanks.

Production begins with machining the waffle pattern in flat plates for the tank walls and with stretch forming of flat plates for tank domes. The waffle pattern is machined on a Giddings and Lewis horizontal skin mill, Figure 23. A close up of the waffle pattern is seen in Figure 24. After the plate segment is machined, it is formed to the contour of the tank. Without some support the ribs would buckle during the forming. Support is provided by square polyethelene blocks which replace the material which was machined away. Placement of the blocks is shown in Figure 25. With the blocks in place, the wall segment is ready for forming. In this operation the tank wall segment is progressively formed on a Verson Press, as shown in Figure 26. After the segment has been formed to the proper contour it is ready for welding. Seven tank wall segments are assembled in a special fixture which holds them in the proper positions for welding. This piece of tooling is shown in Figures 27 and 28. The fixture with its tank segments is placed beneath a Pandjiris automatic welder, which butt welds together the two segments at the bottom of the fixture. All welds are made with the consumable electrode MIG (metallic inert gas) process using Type 4043 filler welding rod. However, TIG (tungsten inert gas) welding is used to install all fill, drain, pressurization, and vent line fittings. The edges of the segments, which are stepped in a previous machining operation, are clamped in proper

M-20145

WAFFLE GRID MACHINING

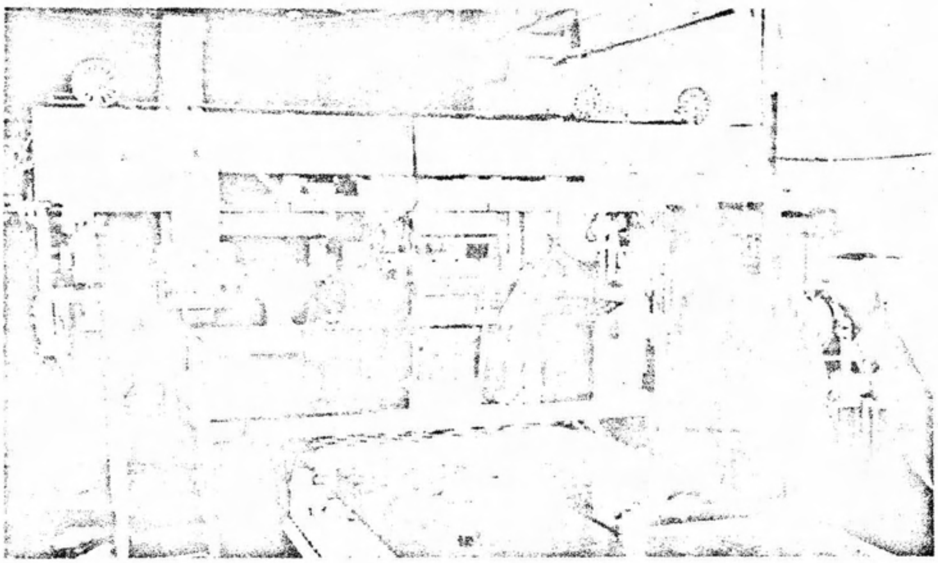
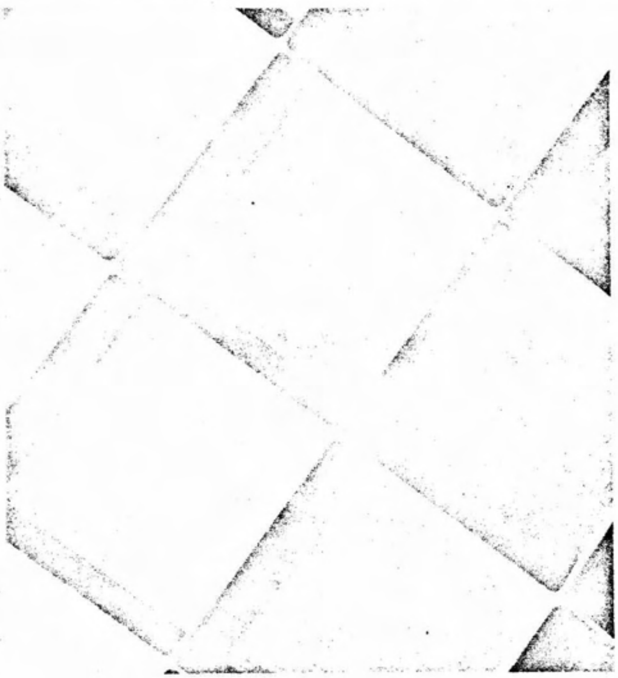


FIGURE 23

M-20114



SATURN WAFFLE GRID

FIGURE 24

M-20098

FORM BLOCKS FOR PRESS FORMING

FIGURE 25

M-20097

VERSON BRAKE FORMING

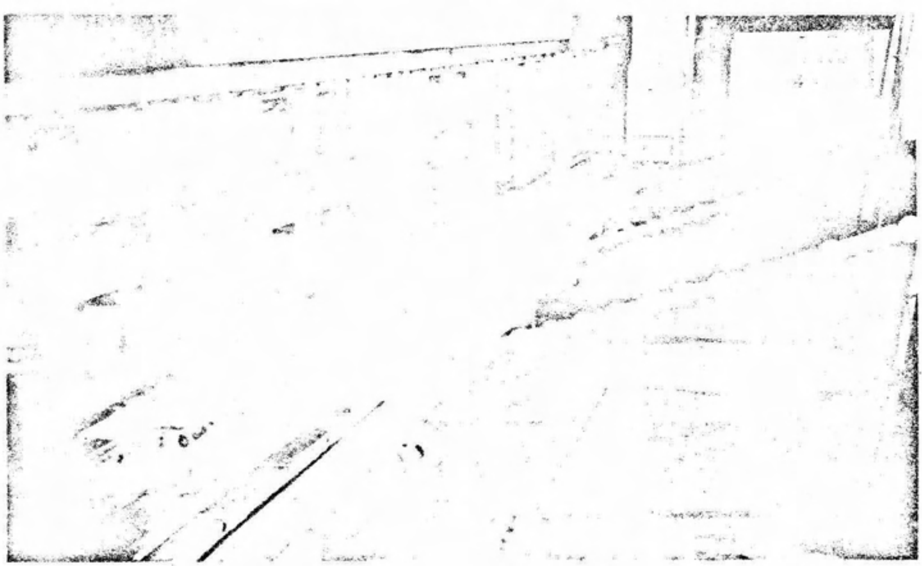


FIGURE 26

M 20109

S-IVB TANK
CYLINDER

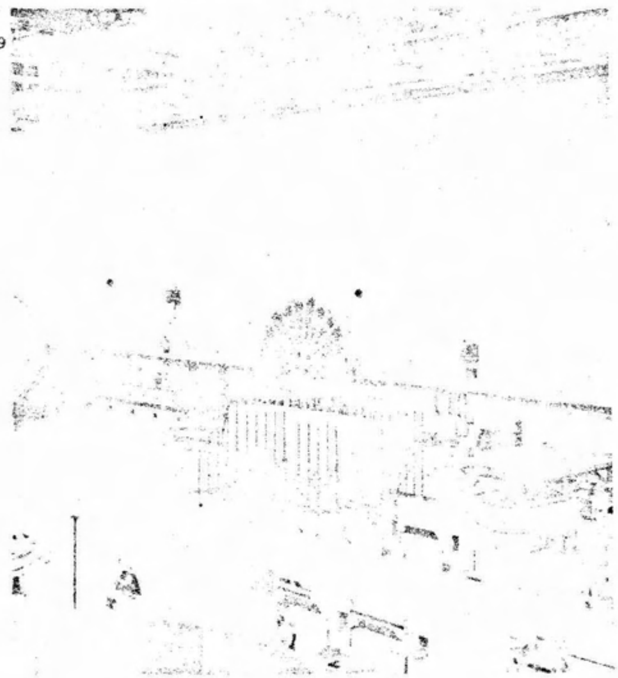


FIGURE 27

M-20096

S-IVB TANK CYLINDER

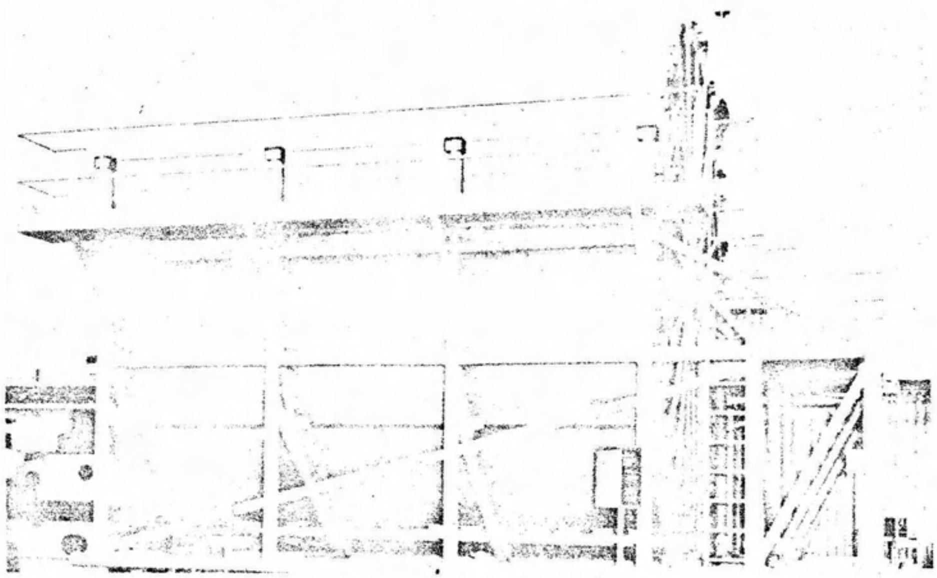


FIGURE 28

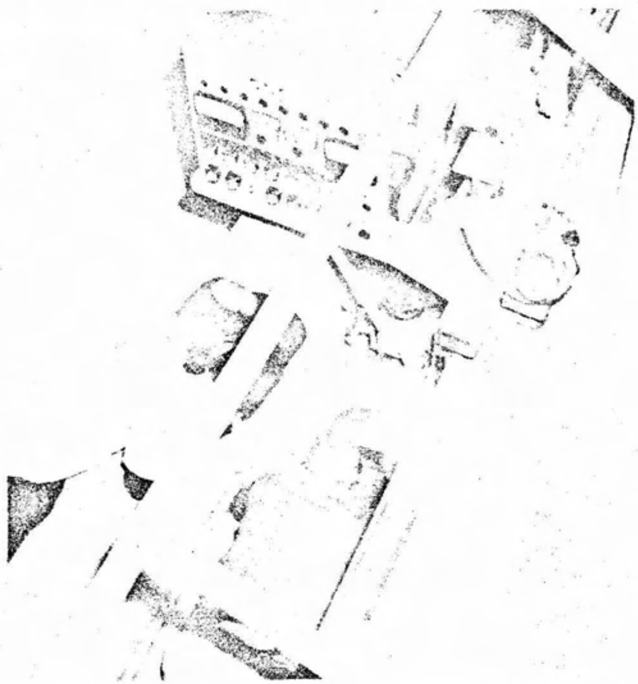
position with copper quench bars, and then the segments are butt welded together in two passes, as the Pandjiris welder moves over the seam, Figure 29. All welds are made with the work under the welding head, and in the Saturn tanks all welds are made from one side of the wall. Molten metal is drawn by gravity force to the bottom side of the joint and weld penetration is controlled by controlling the size of the bead formed on the bottom side of the weld seam. As stated, thick segments are welded in two passes. A close up of the welding operation is shown in Figure 30. A welded tank cylinder is shown in Figure 31. The edges of the cylinder are machined, Figure 32, before the end fittings are attached. Stretch formed extruded angles are butt welded to each end of the tank cylinder. One flange of the angle extends outward from the tank wall to provide a means for handling the tank and for attaching interstage structure.

Segments for the tank domes are stretch formed over male dies, Figure 33. Dimensions of the plate are of such size that two spherical triangle tank dome segments are cut from each stretch formed plate. Stretch forming is done with the plates in the annealed condition. After the first stretch, the plates are solution heat treated and then stretched again before natural aging occurs. The second stretch is made to remove contour distortions which result from the heat treatment. After the second stretch the plates are to contour within a tolerance of $\pm$ 1/32 inch ($\pm$ .79 mm) on the 130 inch (330 cm) spherical radius. After the plates have been cut to form the spherical triangle segments they are chem-milled. Meridianal ribs and lands for welding are left on the plates in the chem-milling operation. The forward part of the aft dome also has a waffle pattern chem-milled in the part of the dome forward of the attach point of the common bulkhead. After chem-milling has been completed the segments are prepared for welding. Nine spherical triangle segments are butt welded together to form a dome. The segments are held in place in a special welding fixture, Figure 34. This fixture is used to weld the fore and aft end domes and the common dome faces. The common bulkhead segments are shown in the fixture in Figure 34. End dome segments extend to the base of the fixture, Figure 35. The fixture rotates the work under the welding head, which is shown at the top of the picture. Edges of the common bulkhead segments are clamped in place by titanium

M-20107

AUTOMATIC
WELDING OF
S-IVB TANK

FIGURE 29



M-20113

PANDJIRIS
WELDING HEAD

FIGURE 30

M-20014

WELDED TANK CYLINDER

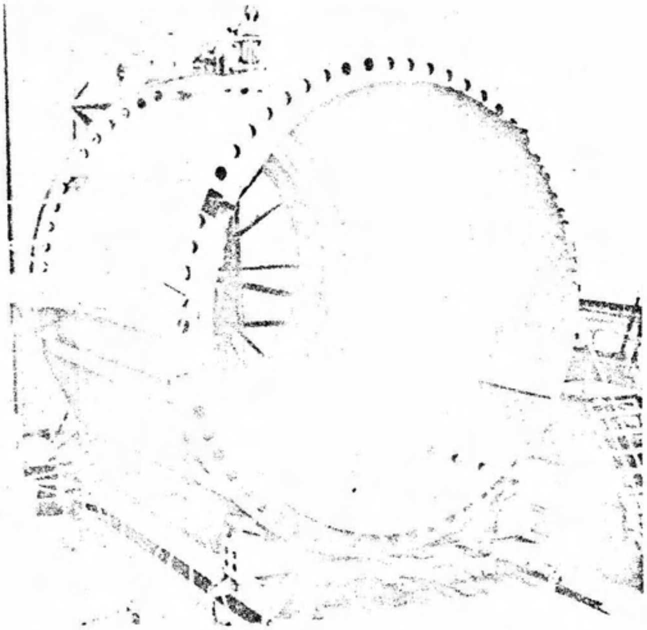


FIGURE 31

M-20103

TRIMMING S-IVB TANK CYLINDER

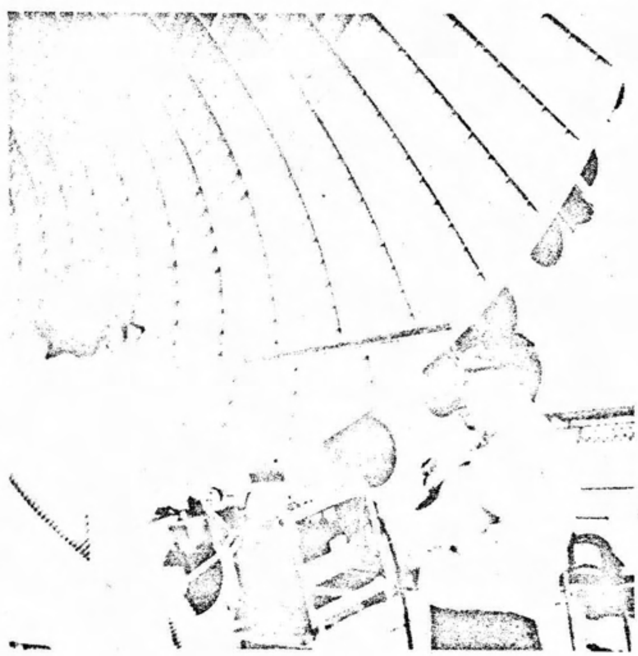


FIGURE 32

M-20143

STRETCH FORMING DOME SEGMENTS

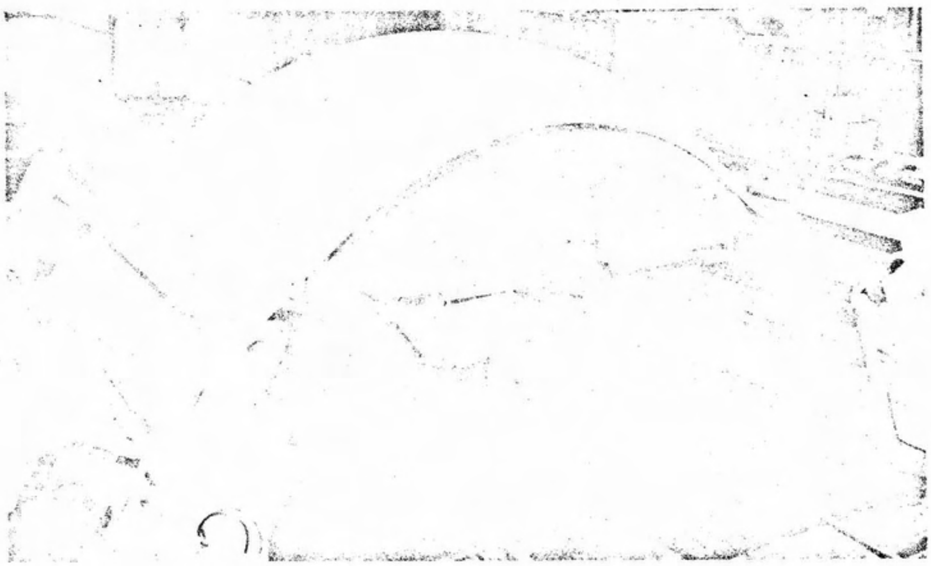


FIGURE 33

M-20115

DOME WELDING FIXTURE

FIGURE 34

M-20099

DOME WELDING FIXTURE

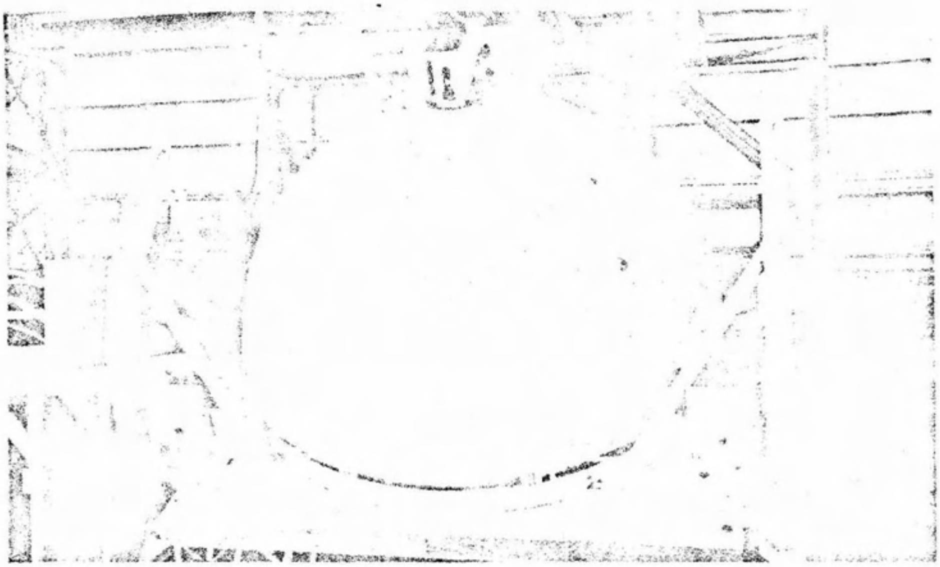


FIGURE 35

quench bars. Copper bars are used to clamp the segments of the forward and the aft domes. Titanium quench bars are required for the common bulkhead faces because the faces of this dome are thinner than the end domes, and heat flow from the weld zone must be controlled to a different rate.

After the common bulkhead faces are welded, a circular plate plug is butt welded to the land areas at the center of the faces. All weld seams are then trimmed to present a smooth surface for bonding to the honeycomb core. Stretch formed "Y" shaped extrusions are welded to the peripheral edges of the common bulkhead faces to permit attachment of the common bulkhead to the aft dome. On the S-IV stage, the extrusions are lap welded to the faces, whereas on the S-IVB stage the joint is a butt weld, Figure 36.

The common bulkhead sandwich structure is fabricated on a spherical male die. This die is equipped with a suction unit, which is employed to hold the aft face of the bulkhead firmly against the die while the honeycomb core is being bonded to the face. The die is contained in a pressure chamber, as shown in Figures 37, 38, and 39.

The aft face of the common bulkhead is thoroughly cleaned and then secured to the spherical die by suction. A film of epoxy resin, for bonding, is laid over the face, and then fiberglass honeycomb core is laid in place in sections as large as 18 inches (45.7 cm) by 48 inches (122 cm). After the core is in place, the assembly is covered by a sheet of mosite rubber, Figure 37. Air is then evacuated from the honeycomb, drawing the rubber cover tight against the core and the core against the face. While under this pressure the aft bond is given a first cure at 330°F (166°C).

Contour checking and hand finishing of the forward face of the core is necessary prior to bonding the core to the forward face of the common bulkhead. After the core is brought to required contour a film of epoxy resin is laid over it, and the forward face of the dome is set in place. The assembly is covered by a sheet of mosite rubber, which is used to make a seal for the core section of the assembly. The core is evacuated, the

M-20144

COMPARISON OF BULKHEAD FABRICATION

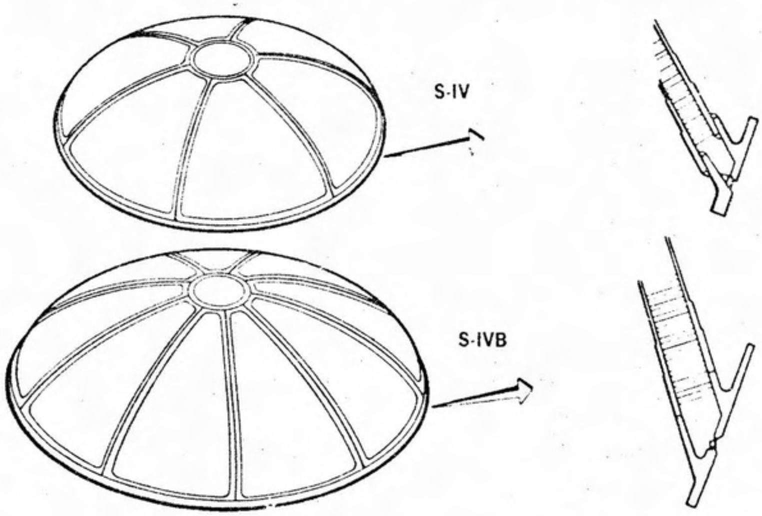


FIGURE 36

M-20101

COMMON DOME BONDING FIXTURE

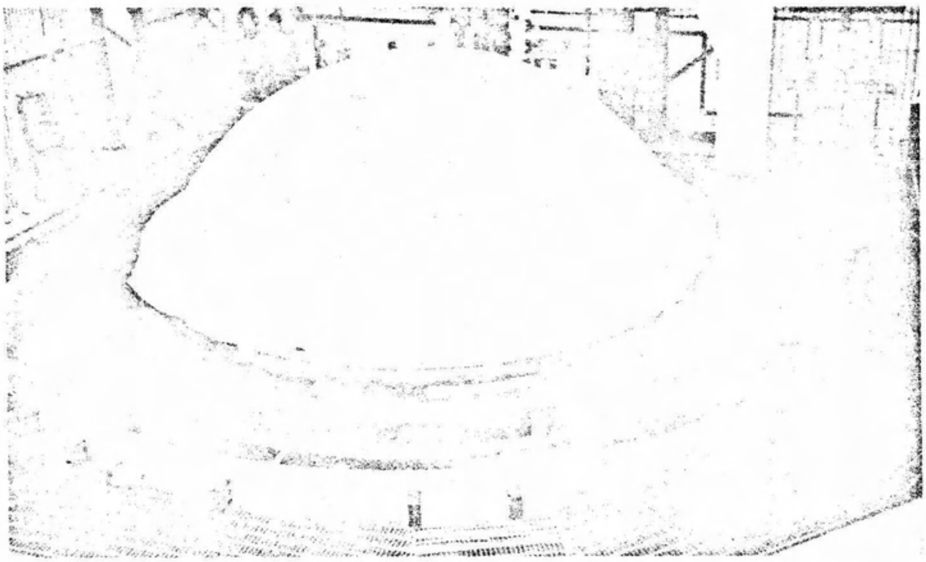


FIGURE 37

M 20100

COMMON DOME BONDING FIXTURE

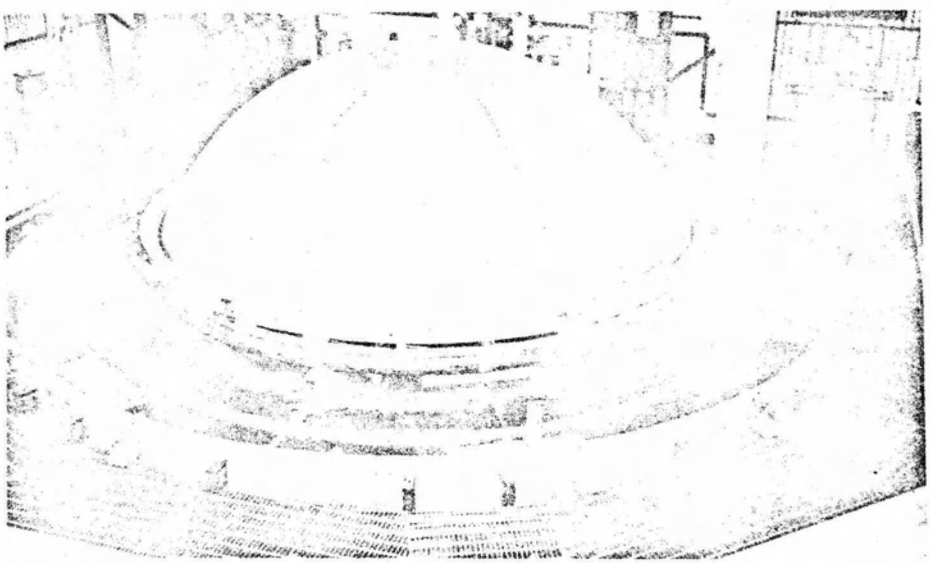


FIGURE 38

M-20105

BONDING
PRESSURE
CHAMBER

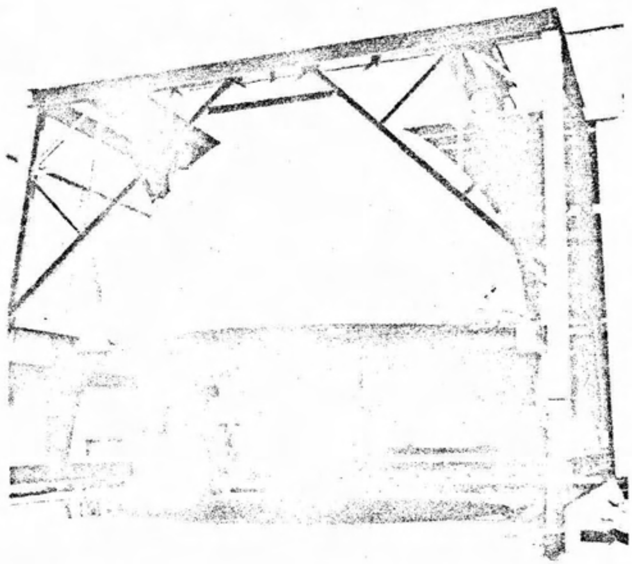


FIGURE 39

lid of the pressure chamber is closed, Figure 39, and a pressure of 45 psi (3.06 atü) inside the chamber is used to force the faces against the core. Bonds are cured at 330°F (166°C).

After the bonds have been cured, the bulkhead is removed from the chamber and the two "Y" flanges are butt welded together, Figure 36. The outboard face of these flanges is then machined to fit the contour of the aft dome.

In the next operation, the common bulkhead is attached to the aft dome. But beforehand, the aft dome is placed in a fixture for machining of the 33 inch (84 cm) access hole cover attach flanges, Figure 40. A similar machining operation is done on the forward dome. The flanges of the common bulkhead are bolted to the aft dome. All bolt attachments are made to the liquid oxygen tank. The forward edge of the flange on the forward face of the common bulkhead is fillet welded to the aft dome with the tank in a horizontal position, as in Figure 41. The aft edge of the aft flange of the common

M-20111

MACHINING AFT DOME ACCESS HOLE

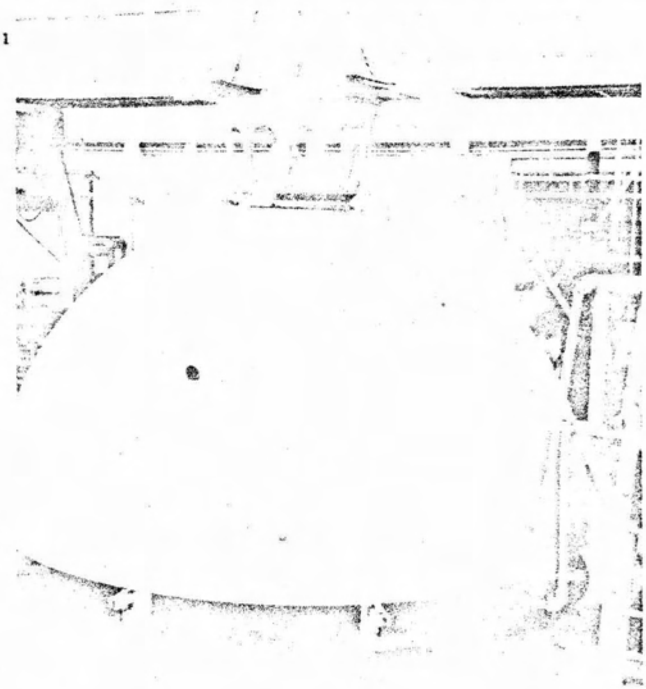


FIGURE 40

M-20120

LOX TANK

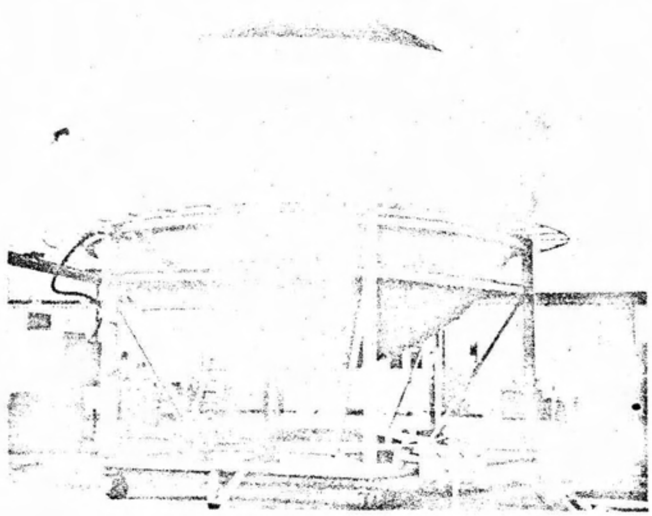


FIGURE 41

bulkhead is fillet welded to the aft dome with the tank at right angles to its former position, that is, with the axis of symmetry of the tank in a horizontal position. The aft weld is made with a tool which reaches into the liquid oxygen tank through the access hole. Both welds are made with a fixed welding fixture; the tank is rotated about its axis of symmetry to advance the weld. Figure 41 shows a liquid oxygen tank ready to be placed in the tooling tower for assembly of the liquid hydrogen tank.

After the liquid oxygen tank is arranged in the lower end of the tooling tower, Figure 42, the tank cylinder is lowered into place. The assembled structure is shown in Figure 43. A fillet weld is made on the inside of the tank cylinder to connect the cylinder to the aft dome, Figure 44. This weld is made with a welding head which reaches down into the tank, Figure 45. The welding head remains stationary and the work rotates. The forward dome is then arranged in the tooling tower at the upper end of the tank cylinder. In this position a fillet weld is made on the outside of the forward dome connecting it to the tank wall, Figure 46. The whole tank is then turned upside down and repositioned in the tooling tower. The outside weld of the

M-20119

LOX TANK IN TOOLING TOWER

FIGURE 42

M-20121

LIQUID HYDROGEN TANK CYLINDER

FIGURE 43

M-20122

TANK CYLINDER WELD TO AFT DOME

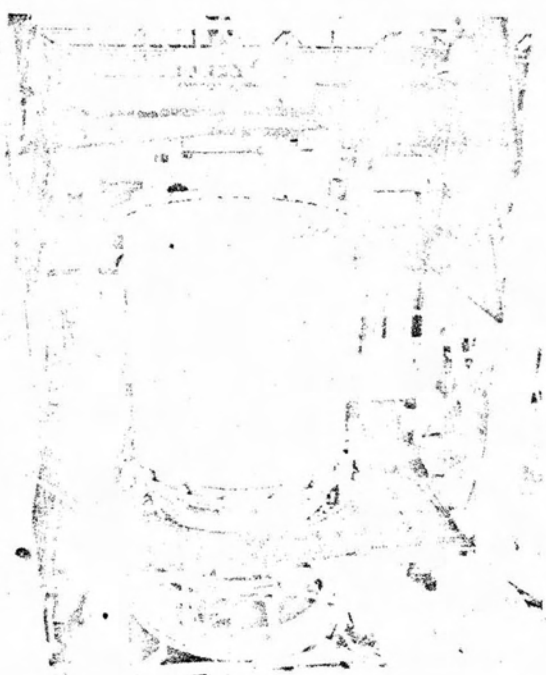


FIGURE 44

M-20106

INTERNAL DOME
WELDING TOOL

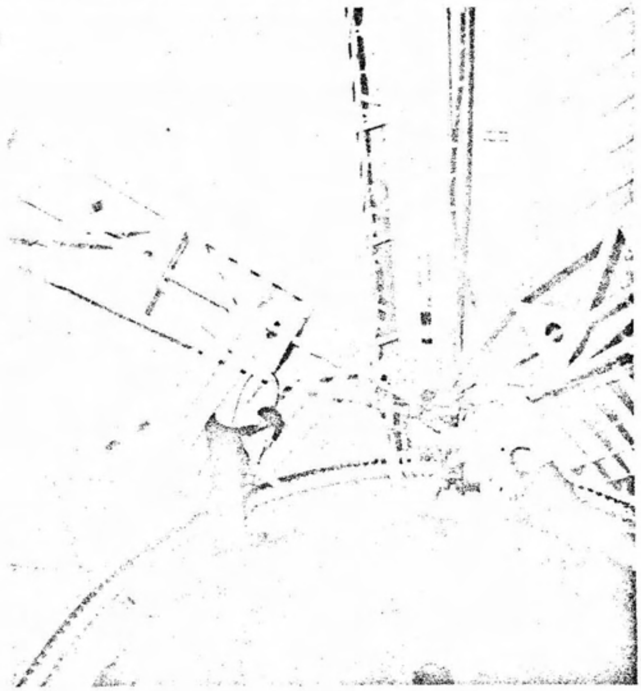


FIGURE 45

M-20123

TANK DOME
WELDING

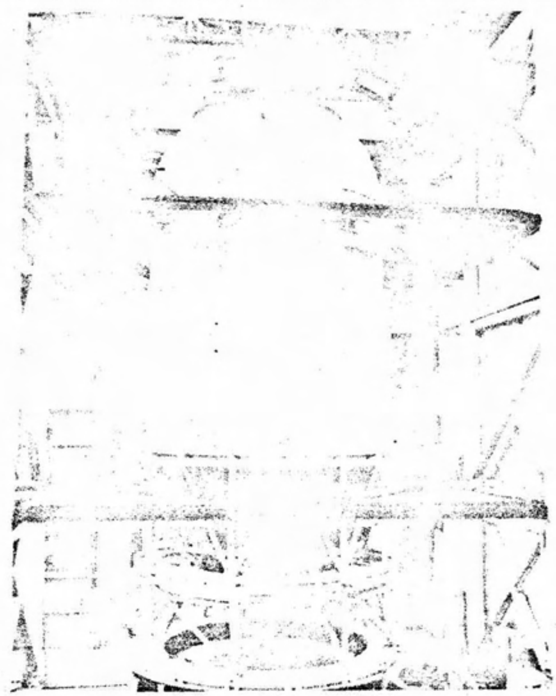


FIGURE 46

aft dome, which is now at the top, is made with a fillet joint. Finally, the inside fillet weld of the forward dome is made with a welding tool which reaches up into the tank through the access hole.

The finished S-IVB tank, as shown in Figure 47, is ready for the installation of thrust structure, interstage structure and various accessory equipment.

M 20117

SATURN SIVB TANK

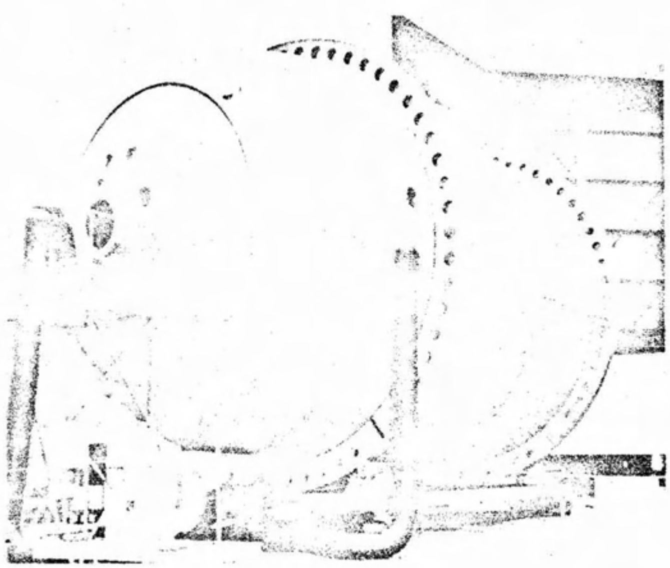


FIGURE 47

V. CONCLUDING REMARKS

Although considerable discussion has been given to the various techniques which are involved in producing a tank for cryogenic fluids, no special discussion has been given to processing techniques. These techniques are utilized, directly or indirectly, in all of the tasks which were discussed, and the success or failure of any task is in some measure dependent on the characteristics and results of the processing techniques involved.

Optimization of the various tasks and their interrelationship yields the essence necessary to a reliable, high performance product, and some measurement of how well this has been accomplished can be obtained by observing the performance of the product. Numerous qualification tests, for observance of performance, are made as development progresses. These tests provide insight into the quality of the product, but, the first comprehensive test of performance is the first flight of the vehicle. This spectacular flight of the S-IV stage in the Saturn 1 configuration took place on January 29, 1964, Figure 48. The flight was almost flawless, and it appears that a good beginning has been made for what, hopefully, will be a long and successful history of the Saturn S-IV and S-IVB space vehicles.

M-20102

FIRST LAUNCH
SATURN I

FIGURE 48

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3. Cryogenic Materials Data Handbook, U. S. Department of Commerce.

4. ASD-TDR-62-258, Part II, Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment.