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MEMORANDUM**

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**CRYOFORMED 301 STAINLESS STEEL FOR
PRESSURE VESSELS**

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*George C. Marshall Space Flight Center
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16. ABSTRACT <p>The manufacture and qualifying results of cryogenically formed 301 stainless steel bottles for storage application, especially for helium in either a liquid oxygen or liquid hydrogen environment, are reviewed. No apparent distortion to the prototype vessels occurred during the course of testing. Survival of the test specimens through the qualification tests indicates that the developed manufacturing technology results in predictable properties and verifies the reliability of the techniques for the proposed applications. The cryoformed 301 stainless steel vessels should be considered for future launch vehicle and space applications, especially when weight is critical or a liquid or gaseous oxygen environment may be encountered or when temperatures vary from 394.3°K (250° F) to liquid hydrogen or helium temperatures.</p>			
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CRYOFORMED 301 STAINLESS STEEL FOR PRESSURE VESSELS

SUMMARY

The objective of this report is to provide the results of several years work in developing and qualifying cryoformed 301 stainless steel for pressure vessel applications. Manufacturing techniques have been established to cryoform vessels for application as helium bottles in lox tanks of the S-IC Stage, Saturn V Vehicle. Were the currently extruded aluminum alloy 2014-T6, S-IC Helium Bottles replaced with cryoformed 301 stainless steel, anywhere from 726 to 998 kilograms (1600 to 2200 pounds) weight savings could be had. Also, verified techniques have been established for application as helium spheres in the liquid hydrogen tank of the S-IVB. If the S-IVB's titanium alloy 6 Al-4V spheres were replaced with cryoformed 301 stainless steel, the hazard from exposure to oxygen would be eliminated. For future applications such as the space station and space shuttle concepts, cryoformed 301 stainless steel should be considered for pressure vessel application where the major needs are reliability and light weight plus the compatibility with fluid, e. g. , oxygen storage or lox surrounding.

INTRODUCTION

The major problem area in fabricating high pressure vessels is to ensure that the fabricating processes result in a material that has good repetitive engineering properties, viz. , weldability, notch toughness, compatibility with the fluid stored and surrounding environment, and repeatability. In addition, the vessel must be light weight for aerospace usage and competitive in cost. Reliability of proven processes and material is foremost. Costs too are important, but secondary to proven reliability or safety to the customer — the astronauts.

MSFC's activities in cryoforming development stem from an interest in improving the reliability and reducing the weight of helium pressure bottles.

These containers are used throughout the Saturn V vehicle for propellant tank pressurization. Helium pressure bottles are exposed to a variety of mediums including liquid oxygen and liquid hydrogen which limit the materials which can be used for construction. Presently, these bottles are fabricated from aluminum or titanium.

Process Description

Cryogenic stretch forming (or the ARDEFORM-process¹) is a means of fabricating high strength pressure vessels from 300 series stainless steel, principally AISI 301. In this process, an undersize preform is first constructed (by welding or other means of producing a closed pressure vessel). The preform is annealed (to relieve all machining and welding stress), immersed in liquid nitrogen and then pressurized internally with pumped, liquid nitrogen to stretch the preform the desired amount (about 10 percent). During deformation at liquid nitrogen temperatures, the metastable austenite transforms to martensite [1]. This, coupled with the cold working of the metal, imparts high strength to the entire vessel including end closures and all welds. If desired, additional strength can be had by aging the material [for 20 hours at 700° K (800° F)].

Purpose

The first objective was to develop manufacturing techniques for cryogenically stretch-forming 301 stainless steel pressure vessels applicable as future replacement of: (1) the current 2014-T6 extruded aluminum alloy helium bottles in the lox tank of the S-IC stage, and (2) the current 6 Al-4V titanium alloy S-IVB helium spheres. The material, type 301 stainless steel, was selected because of its lox compatibility and potential weight savings over 2014 aluminum alloy.

The second objective was to certify the developed manufacturing technology through approved MSFC qualification testing programs (coordinated and monitored by cognizant Astronautics Laboratory personnel in their technical areas of responsibility such as design, testing and materials).

1. Subject of U. S. Patent No. 3197851.

Both of these objectives have been accomplished. Arde Inc. , Paramus, New Jersey, undertook contractually the development and fabrication of the prototype hardware while Lockheed Missiles and Space Company, Santa Cruz Test Base, Santa Cruz, California, and Ogden Technology Laboratories, Inc. , Jack Rabbit Trail, Beaumont, California, conducted the test programs.

This report will describe briefly the successful fabrication and testing of the prototype hardware. For complete details, the reader is referred to Final Reports [2, 3, 4, and 5].

PROTOTYPE S-IC HELIUM BOTTLE DEVELOPMENT

Process Development

Orientation. Early in 1965, as a result of a review of titanium versus cryogenically stretch-formed stainless steel for S-IC helium bottle application [6], the conclusion was reached that the state-of-the-art in titanium bottle fabrication had advanced beyond that of cryoforming relatively heavy gauges of AISI 301 and that the primary effort should be replaced on titanium development. It was noted, however, that AISI 301 was still very attractive for this type of application since it offers a weight saving potential similar to titanium [7] and is not lox sensitive. Consequently stretch-forming 301 ss in liquid nitrogen (78°K or -320° F) to obtain ultra-high strength pressure bottles was investigated [2]. The configuration of the bottles duplicated those immersed in the liquid oxygen tank of the S-IC Stage of the Saturn V Vehicle on a subscale basis. Two designs were fabricated. One design utilized standard rolling procedures for the production of a welded vessel. The other design incorporated seamless tubing and spun heads for welding in machined boss fittings (one at each end of the bottle).

Design. Design parameters were established to represent conditions in a full scale S-IC helium bottle. These were:

a. Size

Length to Diameter Ratio 3 to 5.

0.24 meter (10 inches) minimum diameter.

Thickness Ratio: $\frac{\text{Full Scale}}{\text{Subscale}} = 1$.

b. <u>Pressure at 78° K (-320° F)</u>	<u>Full Scale</u>	<u>Subscale</u>
Working (N/m ²)	2275 × 10 ⁴ (3300 psi)	3034 × 10 ⁴ (4400 psi)
Proof (N/m ²)	3102 × 10 ⁴ (4500 psi)	4551 × 10 ⁴ (6600 psi)
Burst (N/m ²)	4136 × 10 ⁴ (6000 psi)	6729 × 10 ⁴ (9760 psi)

Material. Arde Inc. utilized a 17 percent chromium 7 percent nickel austenitic stainless steel alloy containing over 0.4 percent silicon for the bottles. This is a standard grade of AISI 301 and useful down to lox operating temperature in the unaged condition. Since optimum mechanical properties for cryogenic prestraining are of utmost importance, type 301 ss was specified as vacuum induction melt from high purity raw material followed by a consumable electrode remelt. This process provides increased notch toughness through the reduction of oxygen and hydrogen content and the minimization of flaw sizes. The material was metallurgically evaluated prior to commitment for fabrication.

Tables 1 through 3 provide a comparison of some engineering properties of typical pressure bottle materials at room, lox and LH₂ temperature, respectively.

Weld Development. A weld development program with flat, 0.635 cm (0.25 inch) plate material was undertaken to establish the following parameters: heat settings, feed, speeds, weld preparation, filler rod size, and weld bead control. Double pass and single pass welding was investigated. Single pass TIG, pressurized gas backup, was selected over conventional double pass technique because of less chance of lack of fusion between passes and reduced carbide growth. Problems resolved were undercutting, sagging and drop-through.

Eight tensile specimens were cryogenically prestressed to $1600 \times 10^{+6}$ N/m² (232 000 psi) and then loaded in a bent beam specimen holder at 1267 N/m² (184 000 psi) at room temperature (Fig. 1). The specimens were placed in a 0.75 normal salt solution for five months with the following results:

TABLE 1. PROPERTIES OF TYPICAL PRESSURE BOTTLE MATERIALS
AT ROOM TEMPERATURE

Property	Sheet Materials			
	T1-6Al-4V EL1 (Annealed)	Inconel 718 (Aged)	2219-T62	Cryoformed 301 ss (Unaged)
Tensile (ksi)	135	195	59	245
Yield (ksi)	127	164	43	245
Elong. in 2 in.	14	15	10	4
Str. to Density Ratio $\frac{F_{ty}}{\rho}$ (10-5)	7.9	5.5	4.3	8.2
Notched/Unnotched Tensile Ratio (Kt = 10)		0.96	0.92	1.08
Weld Joint Efficiency	95%	85%	75%	100%
Corrosion Resistance - Salt Solution	Good	Good	Poor	Good

TABLE 2. PROPERTIES OF TYPICAL PRESSURE BOTTLE MATERIALS
AT LOX TEMPERATURE

Property	Sheet Materials			
	T1-6Al-4V ^a EL1 (Annealed)	Inconel 718 (Aged)	2219-T62	Cryoformed 301 ss (Unaged)
Tensile (ksi)	218	256	73	305
Yield (ksi)	202	197	51	300
Elong. in 2 in.	13	20	15	11
Notched/Unnotched Tensile Ratio (Kt = 10)	0.94	0.85	0.9	
K _{IC}		114	58	85
a. Must be protected -- not lox compatible				

TABLE 3. PROPERTIES OF TYPICAL PRESSURE BOTTLE MATERIALS
AT LH₂ TEMPERATURE

Property	Sheet Materials		
	T1-6Al-4V EL1 (Annealed)	Inconel 718 (Aged)	2219-T62
Tensile (ksi)	263	265	93
Yield (ksi)	248	204	58
Elong. in 2 in.	7	21	17
Notched/Unnotched Tensile Ratio (Kt = 10)		0.81	0.81
			Cryoformed 300 ss (Unaged)
			346
			342
			2
			0.63

No indications of stress corrosion.

One specimen pulled at room temperature failed at $1572 \times 10^6 \text{ N/m}^2$ (228 ksi).

One specimen pulled at 78°K (-320°F) failed at $2068 \times 10^6 \text{ N/m}^2$ (300 ksi).

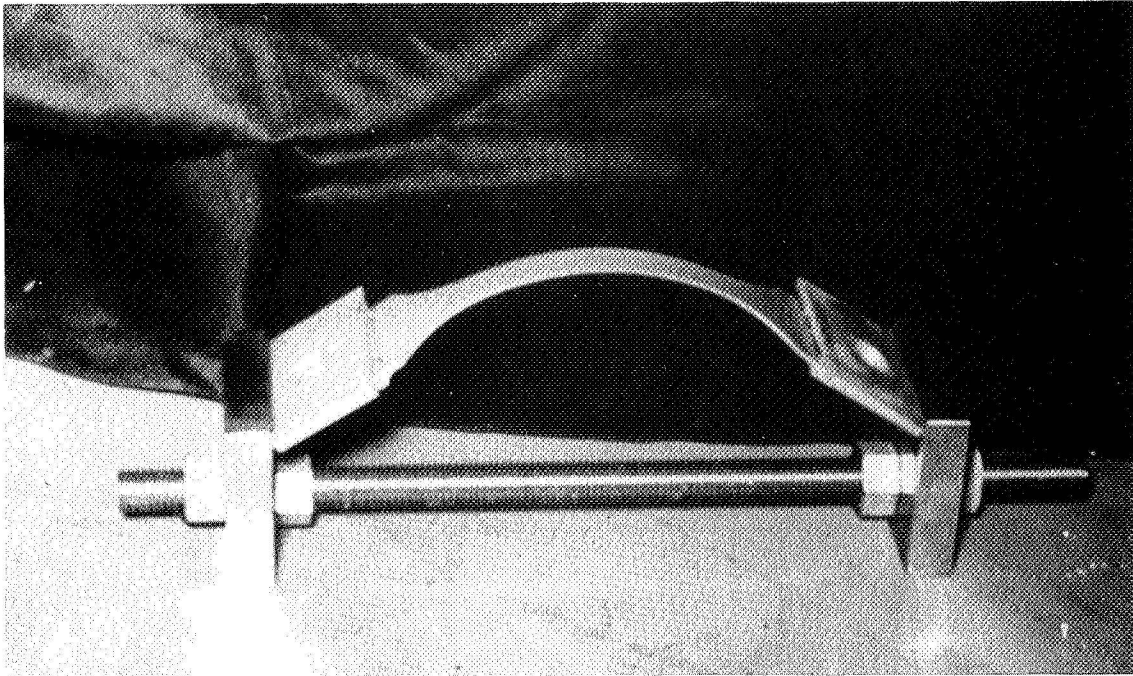


Figure 1. Stress corrosion specimen.

Manufacture

Welded Vessel. Four welded vessels were fabricated using standard rolling, hydroforming, and machining techniques controlled through Arde process specifications. The vessels incorporated three girth welds, two diametrically opposed longitudinal welds and two boss to head welds to simulate full scale vessel welding.

The hydroforming process is a relatively inexpensive and reliable means of converting sheet or plate stock to simple curved surfaces. This process was used for forming the hemisphere bottle ends (Fig. 2). For this purpose, 0.547 cm (0.216 inch) thick plate stock was sheared to blank size and placed over a male mandrel. Forming was accomplished by applying a hydraulic force behind a thick rubber pad, thus forcing the material over the male die (Fig. 3). Close dimensional control was achieved.

After hydroforming, the hemispheres were machined on the outside surface 0.368 cm (0.145 inch) thickness nominal. Holes were machined to receive the bosses.

Short cylindrical sections for the vessel body were rolled to shape and size. The sections were then longitudinally butt welded with 308 weld wire.

The next operation was to trim the lengths of the cylinders to prepare them for girth welding. One end of each cylinder was machined to reduce the thickness for 0.547 cm to 0.368 cm (0.216 inch to 0.145 inch) to match the head thickness (Fig. 4). The opposite end was trimmed flush. After welding, the parts were dye checked, radiographically inspected and cleaned.

Bosses were welded into the heads (Fig. 5) and these in turn welded to the cylinder assembly (Fig. 6). All parts, after being welded, were dye checked, X-ray inspected, cleaned, annealed (See Figure 7 for view of bottle being quenched after heating) and cold pickled in accordance with appropriate Arde control specifications.

It is to be noticed at this point that the vessels have been completely welded but not yet cryogenically stretch formed. For this operation, a cylindrical stretch die calculated to give about 10 percent stretch is used to confine the cylindrical portion of the vessel and control the diameter. A "free-form" stretch, wherein no die is employed, can result in a barrel-shaped vessel.

The forming tank in the pit is filled with liquid nitrogen to a level covering the die (Fig. 8). When the die has cooled down, the vessel to be formed is next inserted into the die and the vessel cooled down by flowing liquid nitrogen through it as well as being surrounded by liquid nitrogen. (As is known, liquid nitrogen has a blast effect when a warm object is dropped into it. Accordingly, blast protection was placed over the pit as a precaution.)

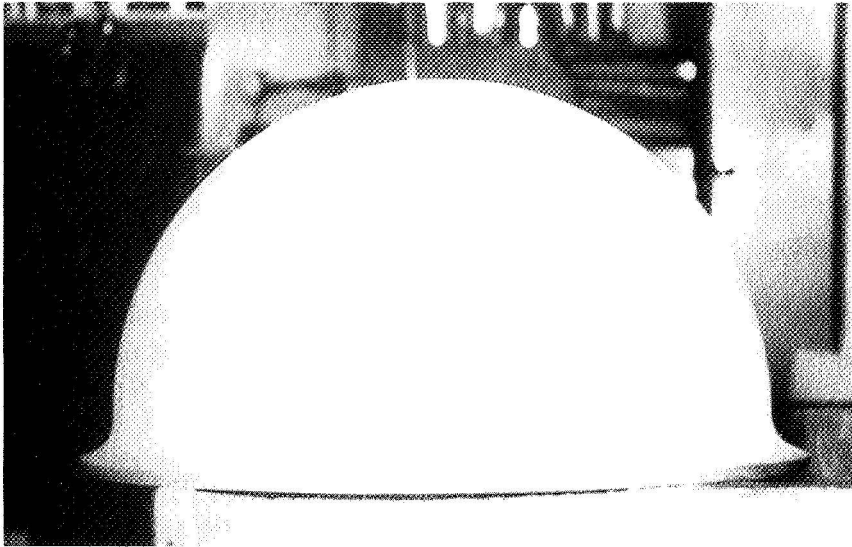


Figure 2. Hydroformed hemisphere.

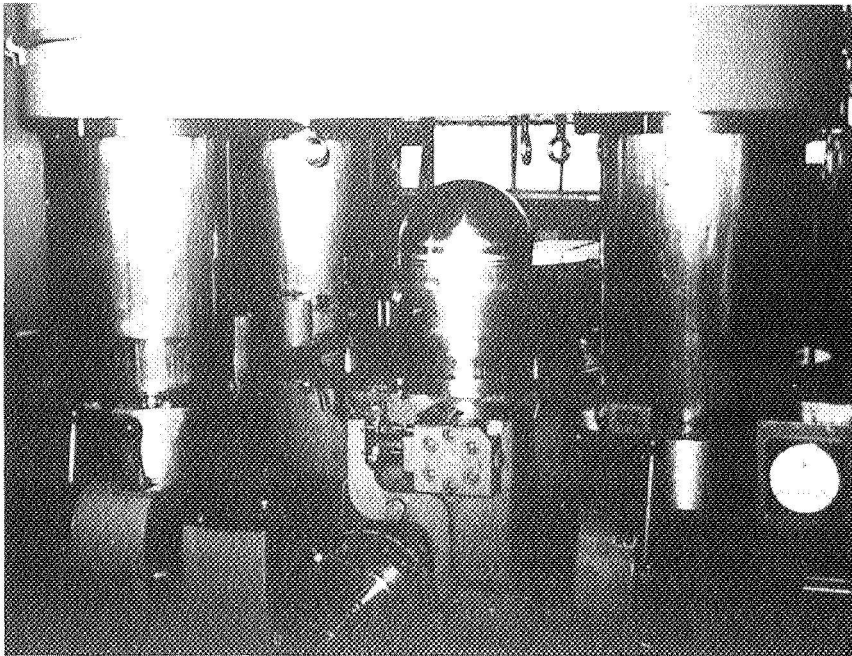


Figure 3. Press hydroforming die.

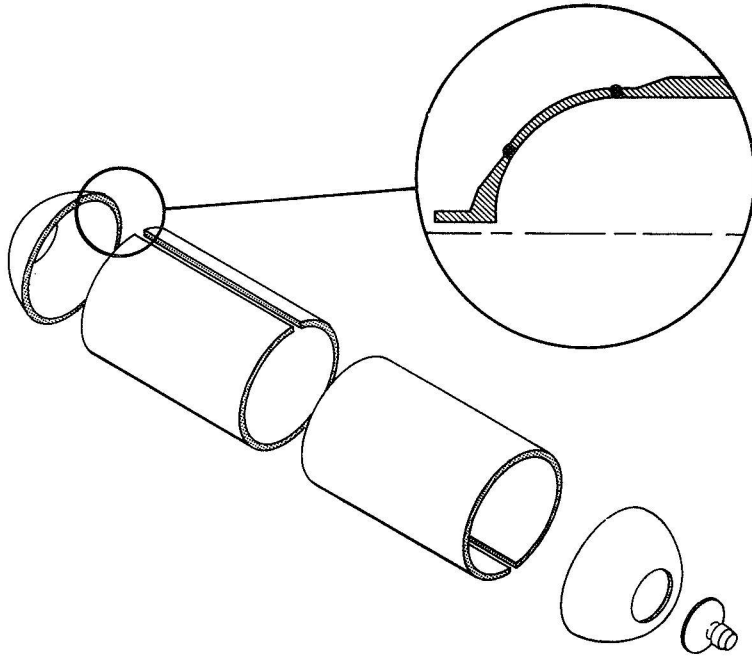


Figure 4. Assembly of welded bottle.

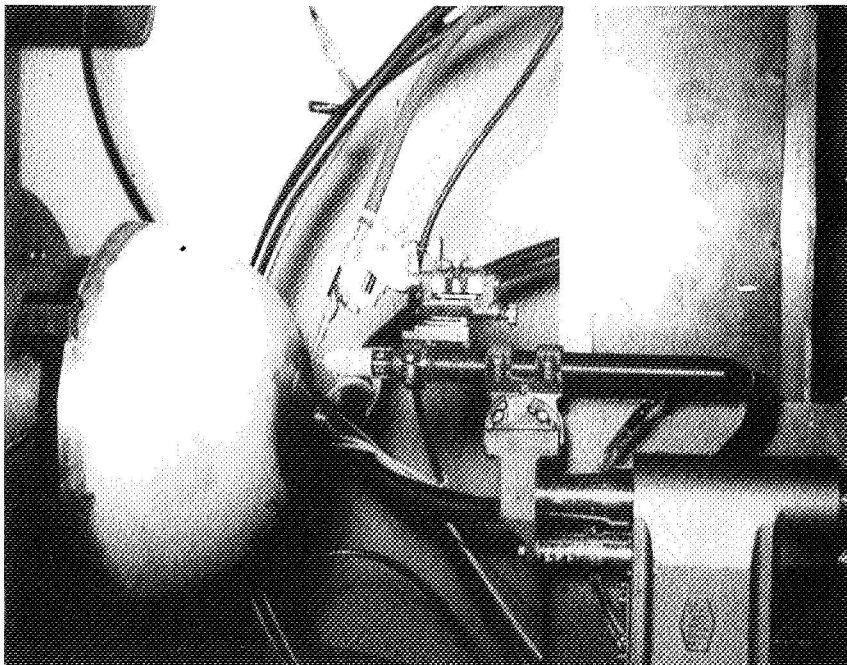


Figure 5. Boss welding.

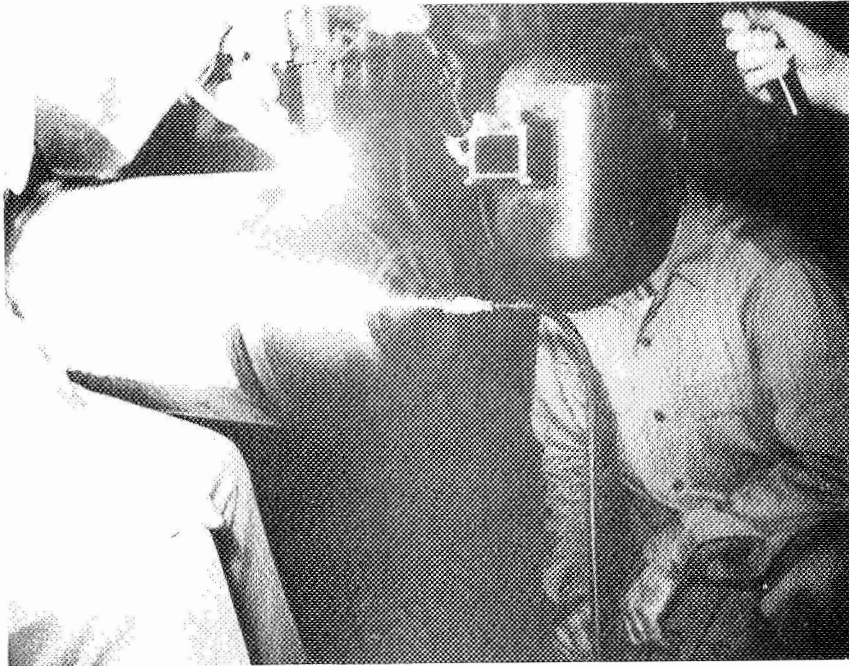


Figure 6. Welding head and cylinder.

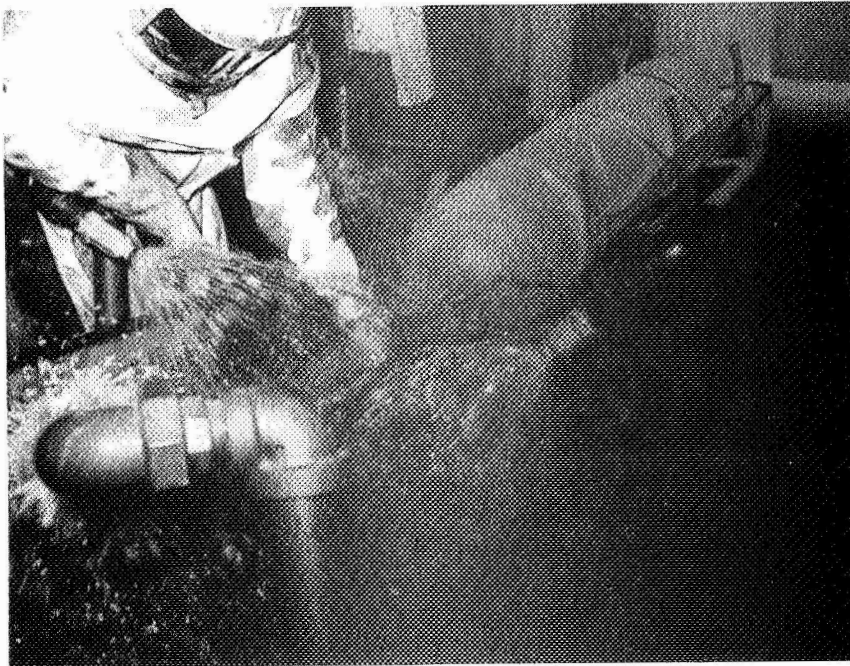


Figure 7. Quenching welded preform.

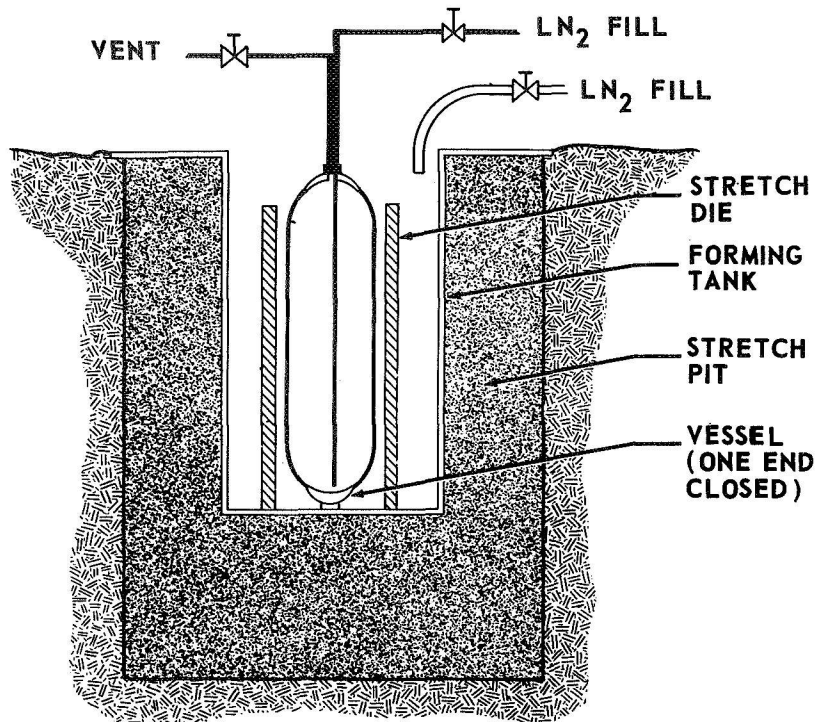


Figure 8. Cryogenic stretch forming process.

When cool down was achieved, the vent valve was closed and the pressure brought to $6.8947 \times 10^{+7} \text{ N/m}^2$ (10 000 psi). This pressure readily formed the entire vessel. The vent valve was opened after forming and the system bled down to atmospheric pressure. Each formed vessel was easily removed from the die because of "springback" when the pressure is relieved. Dimensional checks before and after stretching were taken. The variations amounted to about 0.254 cm (0.1 inch) diameter.

Integral Vessel. In the integral vessel fabrication, billets were converted to forgings. The forgings were inspected and machined on the O.D. and I.D. to fit the mandrel of a shear forming machine used to flouturn the seamless cylinders. This process utilizes three cam-positioned pressure rollers to work the forging against a hardened mandrel. As the forging diameter is cold reduced, the metal is forced out along the rotating mandrel by the rolls in the traversing carriage (Fig. 9). In the course of this development, the first unit failed in process at 50 percent cold reduction after five successive flouturning passes without annealing. Therefore, interpass annealing was instituted on the remaining parts after each third pass. In order to achieve the desired wall thickness, three interpass anneals were used on each cylinder.

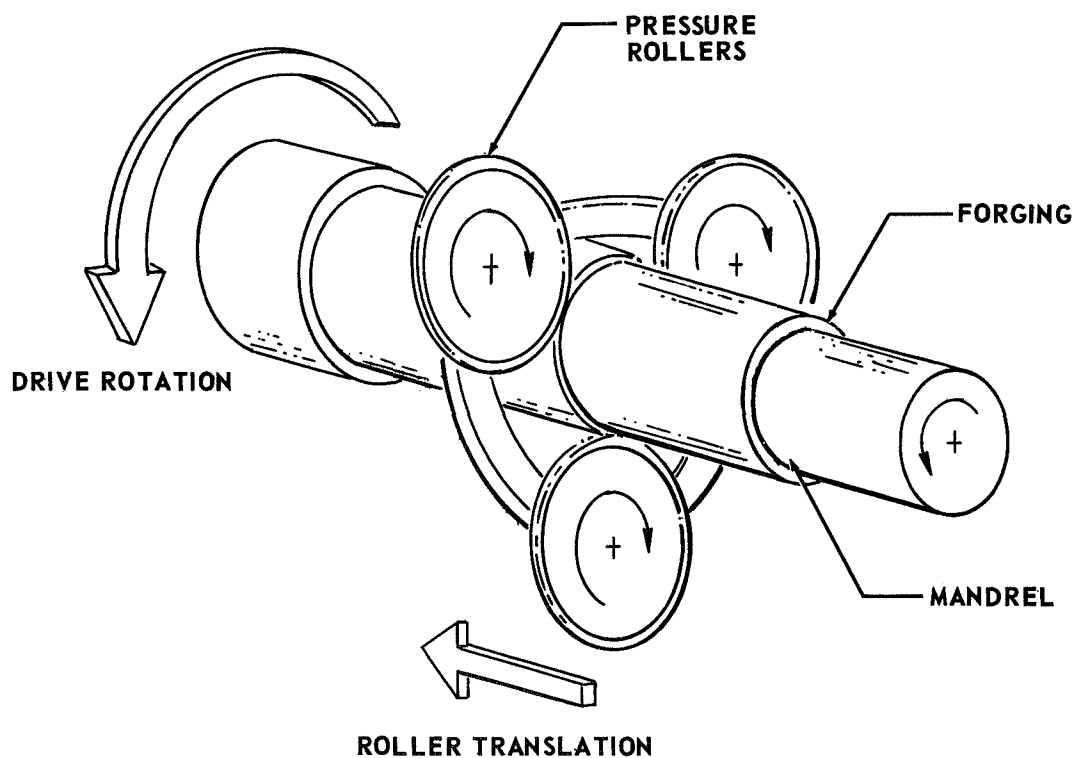
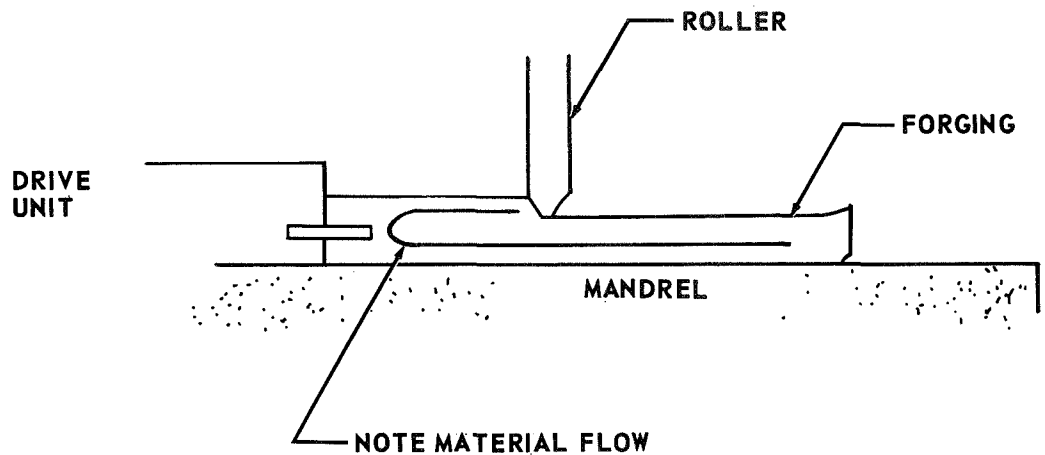


Figure 9. Fluturning process.

Hot spinning of the integral heads on the seamless cylinders was accomplished with both one and two pass operations at a single temperature (Fig. 10). Four cylinders were completed with 46 to 56 percent usable closures. Tracer machining was required to remove both the inside and outside of the spun heads surface cracks. Through cracks at the edge of the boss opening were removed by machining larger boss openings. After welding the bosses in place (Fig. 11), the parts were annealed, cleaned, and cryogenically stretch-formed.

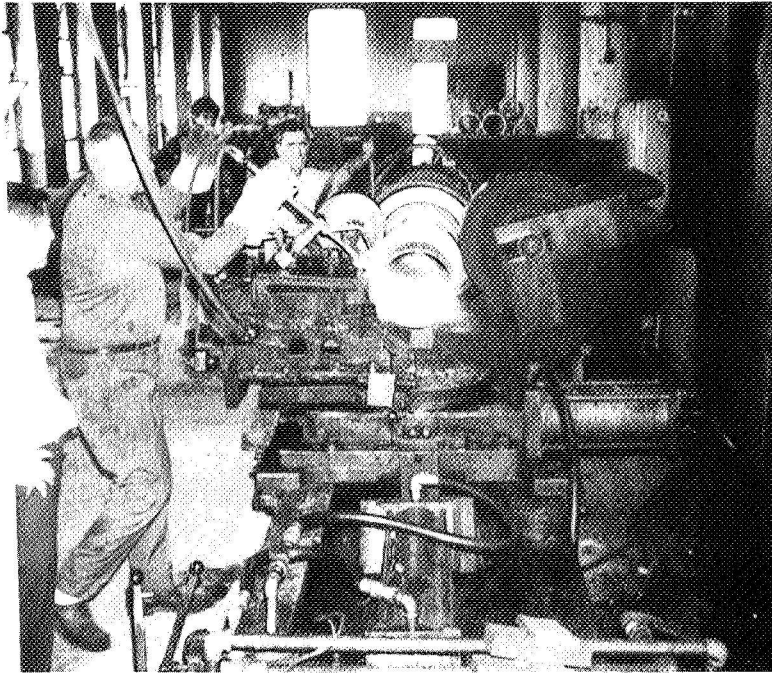


Figure 10. Hot spinning bottle head.

Testing

Three subscale S-IC helium bottles were tested to the "Test Requirements for Subscale Cryogenic Stretch-Formed Bottle listed in Appendix A." The testing was conducted by Lockheed's Santa Cruz Test Base, California. Their Final Report [4] describes the testing performed for the purpose of verifying the reliability of the technology to produce bottles having high weld efficiency. Testing included measurement of strain and temperature, subjected to pneumatic and hydraulic pressure cycling at

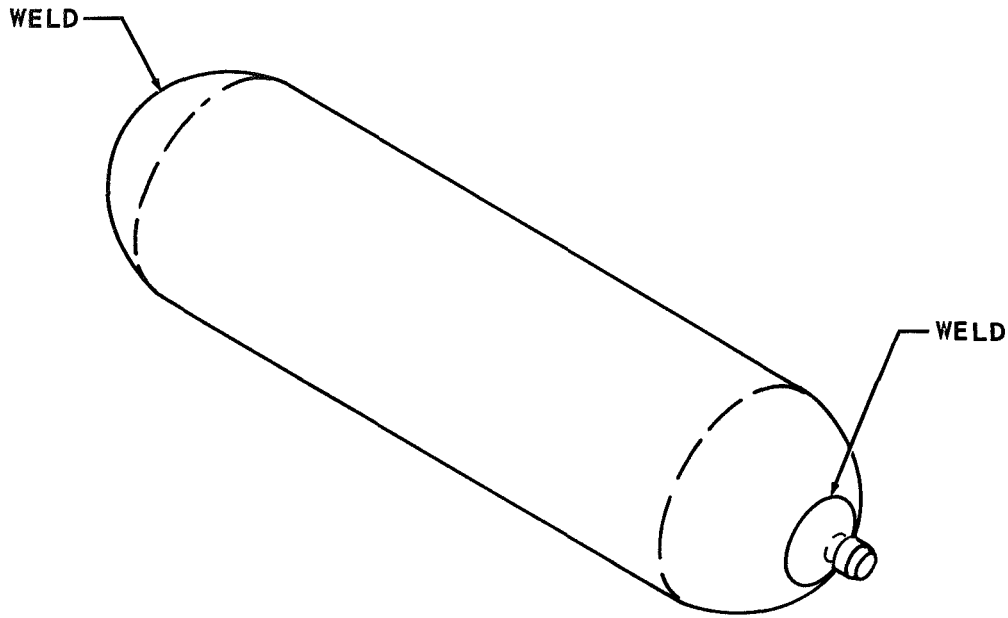


Figure 11. Assembly of shear spun bottle.

elevated and cryogenic temperatures. No damage to the bottles occurred during testing. Table 4 lists the weight and volume measurements before and after testing for each bottle as well as the test burst pressure.

Metallurgical investigation was performed on tensile specimens from the heat of material used for the welded fabrication. Tensile specimens consisted of parent and weldments of AISI 301 composition in tensile test bar form. Eighty-seven specimens were cryogenically prestressed in liquid nitrogen at $1620 \times 10^{+6} \text{ N/m}^2$ (235 000 psi). After prestressing, the specimens were divided into smaller groups for testing at room temperature and 78°K (-320° F). Half of the specimens were used for plain strain fracture toughness (K_{IC}). The effect of material rolling direction was also observed. A brief summary of results follows:

TABLE 4. S-IC PROTOTYPE BOTTLE TEST RESULTS

Test Article	Weight		1st Volume		2nd Volume		Burst Pressure	
	kg	lb	cc	ft ³	cc	ft ³	N/m ²	psig
S/N 3	44.57	98.25	78 025	2.7554	78 535	2.7734	7.3567×10^7	10 670
US-2	57.48	126.75	97 025	3.4264	97 075	3.4282	6.9499×10^7	10 080
US-5	52.04	114.75	87 530	3.0911	87 550	3.0918	7.347×10^7	10 656

a. Room Temperature Results

Parent Material

1517×10^6 N/m² (220.2 ksi) average yield

12.2% average elongation — parallel specimens

11.5% average elongation — transverse specimens

112.8×10^6 N/m² $\sqrt{\text{meter}}$ (102.6 ksi $\sqrt{\text{in.}}$)

Average K_{IC} (center notch)

117.4×10^6 N/m² $\sqrt{\text{meter}}$ (106.8 ksi $\sqrt{\text{in.}}$)

Average K_{IC} (single edge notch)

Weld Bead

1507×10^6 N/m² (218.6 ksi) average yield

113.9×10^6 N/m² $\sqrt{\text{meter}}$ (103.6 ksi $\sqrt{\text{in.}}$)

Average K_{IC} (center notch)

b. 782°K (-320° F) Results

Parent Material

2084×10^6 N/m² (302.3 ksi) average yield

10.6% average elongation — parallel specimens

10.0% average elongation — transverse specimens

92.2×10^6 N/m² $\sqrt{\text{meter}}$ (83.9 ksi $\sqrt{\text{in.}}$), average K_{IC}

Weld Bead

$206 \times 10^{+6}$ N/m² (298.8 ksi) average yield

95.3 N/m² $\sqrt{\text{meter}}$ (86.7 ksi $\sqrt{\text{in.}}$) average K_{IC}

PROTOTYPE S-IVB HELIUM SPHERES DEVELOPMENT

Manufacture

Material. Low silicon (less than 0.1 percent), 18 percent chromium — 7 percent nickel stainless steel alloy in the cryoformed and aged condition was used to fabricate the prototype helium spheres in the liquid hydrogen tank of the Saturn S-IVB. One reason for this selection was based on the strength and toughness characteristics found by NASA's Lewis Research Center. Their investigation [7] showed good performance characteristics of the welded material in the aged condition at LH₂ temperatures.

Material acceptance procedures were established by Arde, Inc. including:

- a. Independent check analyses of heat chemistry.
- b. Metallographic examination for inclusion distribution as well as size, grain size, and intergranular carbides.
- c. Visual and dimensional checks of the milled product.
- d. Radiographic examination to establish that the material is free of surface defects.
- e. Material cleanliness requirements for the production of reliable welds in preforms.
- f. Mechanical property testing.

Material failures can occur during the cryogenic stretching operation from rather large size exogeneous inclusions (over 25 microns diameter). Also high levels of both oxygen and hydrogen (over 60 PPM oxygen, and

2 PPM hydrogen) can be detrimental to the fracture toughness of cryogenically stretch formed material, particularly at LH_2 temperatures. For these reasons, double vacuum melts may be preferable to single vacuum melts since material cleanliness and chemistry analyses can be closer controlled.

Design. The sphere is described, after stretching the preform assembly about 12 to 15 percent and machining, in Arde Drawing SKE 10392 (Fig. 12). The yield strength of the material, as determined from uniaxial tests, dictated the final minimum thickness of the vessel. Conventional elastic stress analysis was used to evaluate the spheres including their ports and bosses under combined internal and external "g" loads. The four clevis bosses for tie-down purposes are a distinctive feature of the design (Fig. 13). This is an alternative to the original design (for titanium 6 Al-4V, ELI grade) which used straps to mount the vessel (Fig. 14). Straps can create crevices which might in the case of type 301 stainless steel lead to pitting corrosion problems. Normally one does not associate corrosion problems with a stainless steel. However, the analogy is somewhat similar to that of a stainless steel coffee pot. The stainless steel will not corrode as long as oxygen is present in the coffee. But let the pot sit a long time with the lid on, the stainless steel loses its passivation (since oxygen is excluded from the coffee) and pits. Of course at cryogenic temperatures it can be argued logically that no corrosion problems would start. But if the prototype S-IVB spheres were installed under ambient conditions and moisture were entrapped by straps thus excluding air (or oxygen), pitting corrosion could over a long storage period conceivably weaken the sphere. What could be serious, however, over a shorter period of time is hydrogen embrittlement of the cryoformed material. Local oxygen concentration cells (set up as a result of the difference in concentration of oxygen in the water trapped in the crevice and moisture exposed to air) break down the passivation and cause, as previously explained, a pitting corrosion attack. Nascent atomic hydrogen, a product of pitting corrosion, may be the real culprit since it could cause embrittlement under such service conditions (straps used to mount the vessel).

Fabrication. Four spheres were initially (for test purposes) fabricated from single vacuum melts. As a hedge, 2 addition spheres were fabricated later on from double vacuum melts.

Essentially, the fabrication of the spheres followed first building a spherical preform then stretching the preform (from 12 to 15 percent) at 78°K (-320°F), final machining and aging. No forming die was used in the

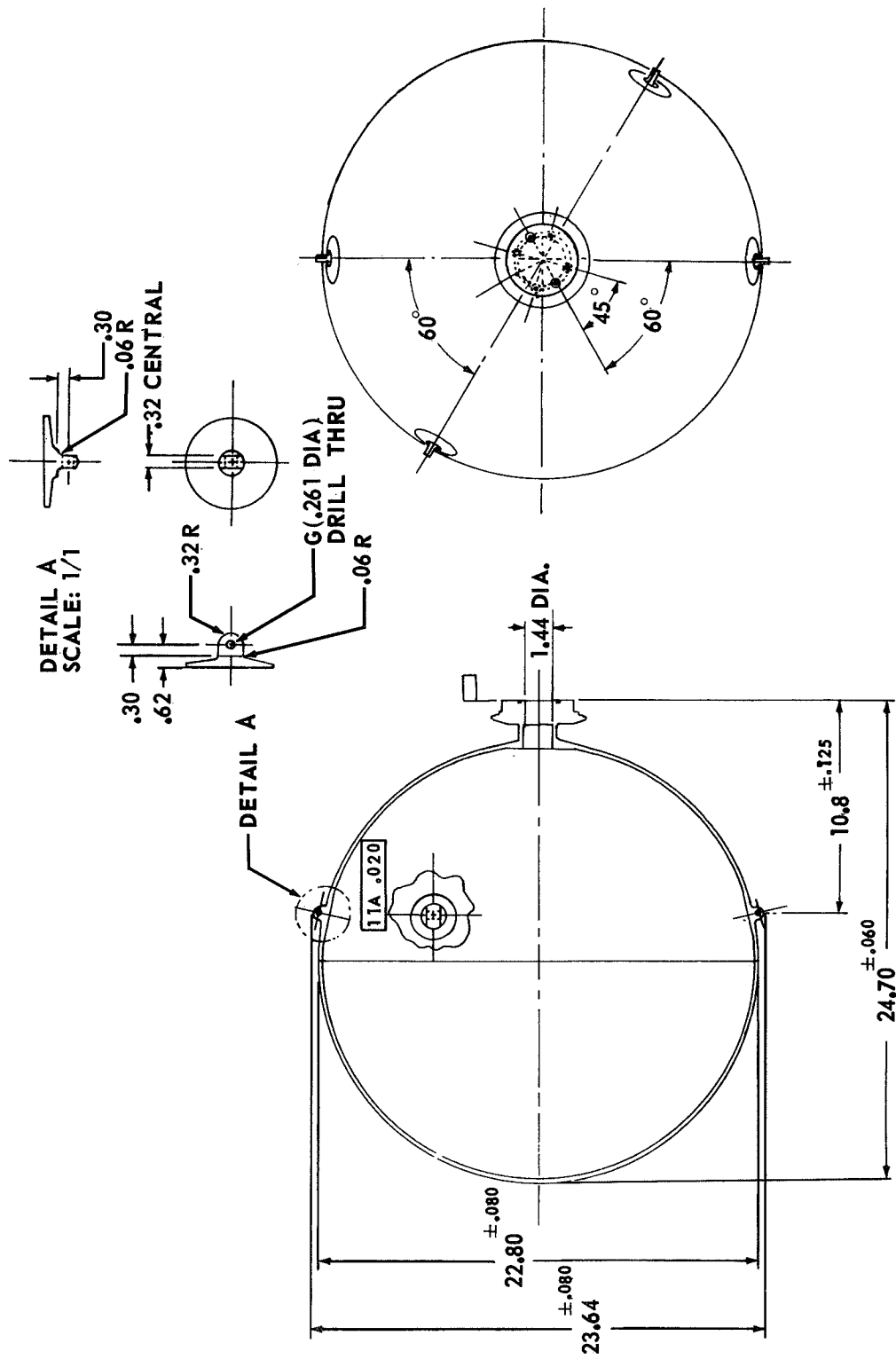


Figure 12. Saturn S-IVB helium storage vessel, PNE 3590.

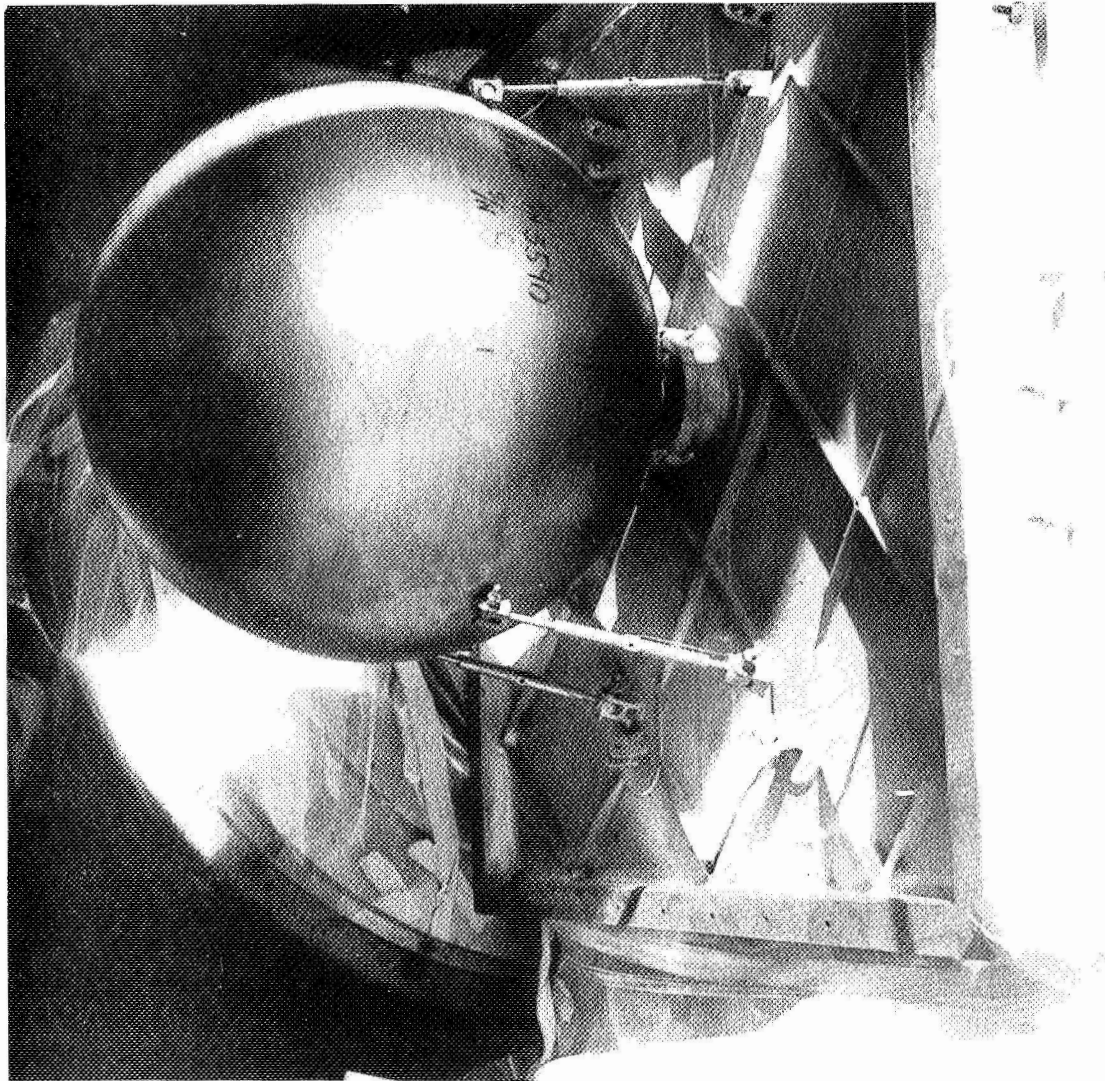


Figure 13. Vibration X-axis, visual inspection post vibration, showing damage to tie-down clevises.

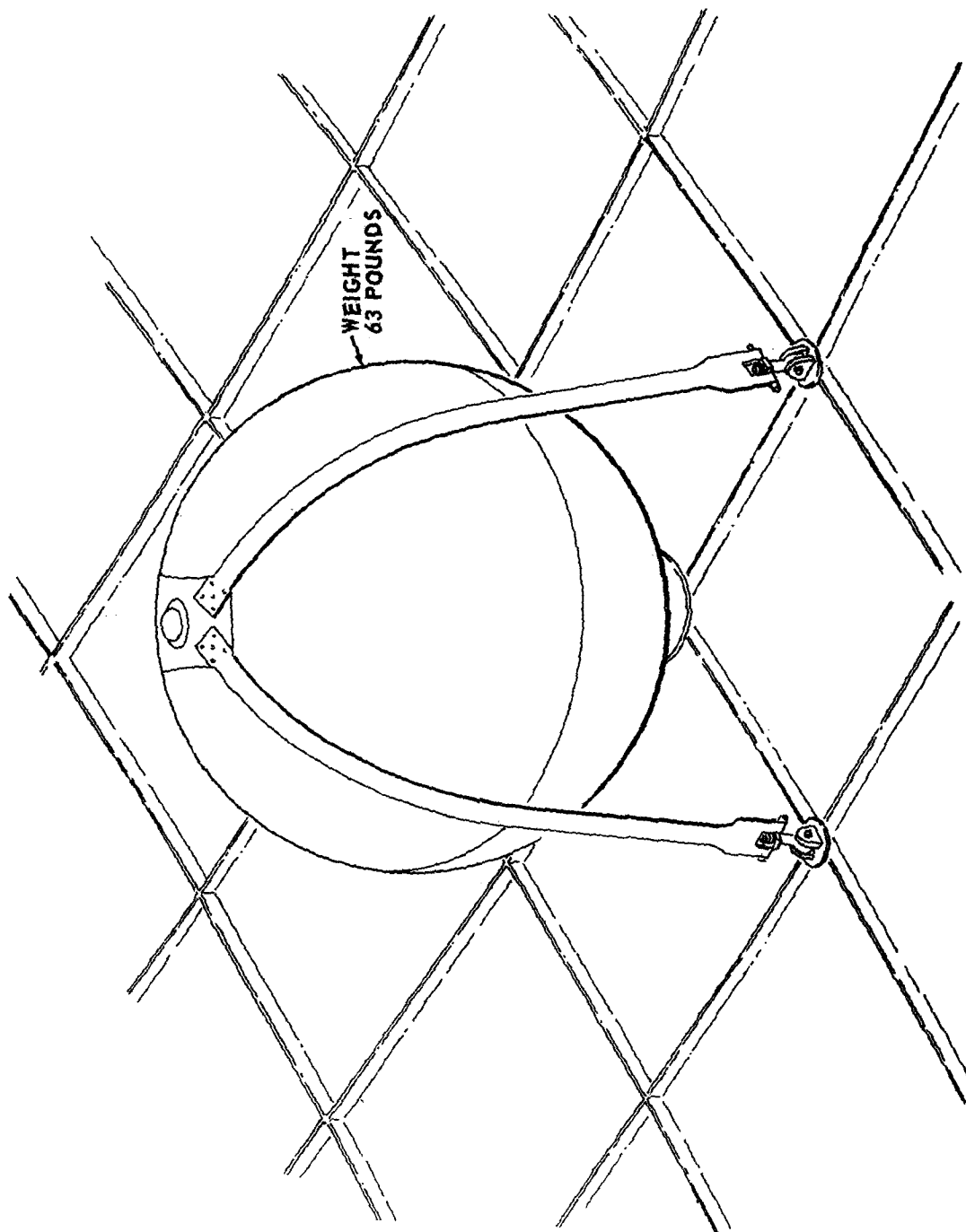


Figure 14. Titanium S-IVB bottle.

cryogenic stretching operation as was the case for the prototype S-IC bottles. Also, aging of the material was used for the prototype S-IVB spheres whereas this was not the case for the prototype S-IC bottles. Complete details are reported in the Final Report, NASA CR-61251 [3].

Testing

Five cryoformed spheres (Arde Part No. D3590) were tested to the "Qualification Tests for Cryoformed Spheres" listed in Appendix B. The testing was conducted by Ogden Technology Laboratories, Inc., Beaumont Facility, Beaumont, California. Their Final Report [5] describes the testing performed for the purpose of verifying their reliability. All five spheres were taken through the proof, ambient, proof cold, leak ambient and thermal shock tests successfully. Four spheres were tested for service life. These too passed successfully. Since three of these spheres were from single vacuum melts, further testing of additional spheres wasn't deemed necessary. Vibrational testing was conducted on two spheres of the single vacuum melts that had gone through all of the other tests. These test results were also successful. No apparent deformation, leaks or other damage to the spheres was revealed. Had the single vacuum melt spheres failed during vibrational testing, other spheres from the double vacuum melts would have been tested.

Of particular interest is that one of the spheres warmed from 33°K to 371°K (-400° F to 208° F) while undergoing sinusoidal vibration in the X-axis. Visual inspection at ambient pressure and temperature, post sinusoidal and random vibration revealed that three out of the four tie-down lugs on the test panel had torn away (Fig. 13). Weld repairs to the tie-down clevises were effected and no further troubles were experienced for the remainder of the test program. This experience is, however, related to illustrate how tough the sphere material is as the sphere was subjected to "stresses above the call of normal punishment."

Burst tests were conducted on the two spheres that were vibrationally tested and had also been subjected to all of the other tests. Attempts to burst the spheres at 25°K (-412° F) and $6205 \times 10^{+4}$ N/m² (9000 psig) were carried out — a pressure well above the minimum of 4895×10^4 N/m² (7100 psig) required by the Qualification Tests. Bursts, however, were obtained at ambient temperatures using gaseous helium.

CONCLUSIONS

The feasibility of cryogenically forming AISI type 301 stainless steel for Saturn V helium gas application was demonstrated. Vessels were produced with 100 percent efficient welds. All objectives of the weld development program were met, as indicated by the results of both the vessel testing and mechanical testing program. It was shown the full strength ground welds were produced with notch toughness and yield strength values comparable to those of the parent material.

The materials evaluation program gave clear indication to the value of double vacuum melt heat in terms of cleanliness and minimum flow size. This is especially true in terms of manufacturing costs. Marginal material likely will result in rejects when the preforms are cryogenically stretched at liquid nitrogen temperature. That is, if the material is defective, cryoforming invariably will rupture the preform while it is being expanded — a costly reject since manufacturing costs were incurred to fabricate the preform.

Final verification of the reliability of the manufacturing technology used for the production of prototype S-IC helium bottles and S-IVB helium spheres was proven when they successfully passed qualification testing. Since the testing requirements were quite severe (See Appendix A and B), the fact that no sphere or bottle failed is a significant milestone.

RECOMMENDATIONS

Certification through final testing of the finished hardware; especially the 57.4 cm (22.6 inch) diameter, cryoformed 301 stainless steel helium sphere; at liquid hydrogen temperature, represents final determination of satisfactory material properties. Consequently, the cryoformed 301 stainless steel vessels should be considered for future launch vehicles and space applications, especially when weight is critical or a liquid or gaseous oxygen environment may be encountered or when temperatures vary from 394.3° K (250° F) to liquid hydrogen or helium temperatures.

APPENDIX A²

TEST REQUIREMENTS FOR SUBSCALE CRYOGENIC STRETCH-FORMED BOTTLES

Number of Bottles to be Tested

Three bottles as identified below are to be tested according to tests identified below. The fourth bottle (Fig. A-1) is to be used for strain gage calibration, fixture model or spare.

S/N 3 (Fig. A-2) Rolled and Welded — Test

S/N 4 (Fig. A-2) Rolled and Welded — Spare

S/N US-5 (Fig. A-3) Integral Head — Test

S/N US-2 (Fig. A-4) Integral Head — Test

Instrumentation

One pressure, six temperature and ten strain gage (depending on type of bottle) (0 to 5000 in./in.) measurements are required. Installation of these measurements is shown in Figures A-1 through A-4. Internal fluid temperature may be accomplished by means of probes or other satisfactory methods. Record temperatures, strain gage readings and pressure throughout all tests. Motion picture coverage will be utilized during burst test.

Weight and Volume Measurements

Conduct measurements prior to starting tests and record.

2. Information in Appendix A courtesy of Mr. L. A. Hein, Astronautics Laboratory, MSFC.

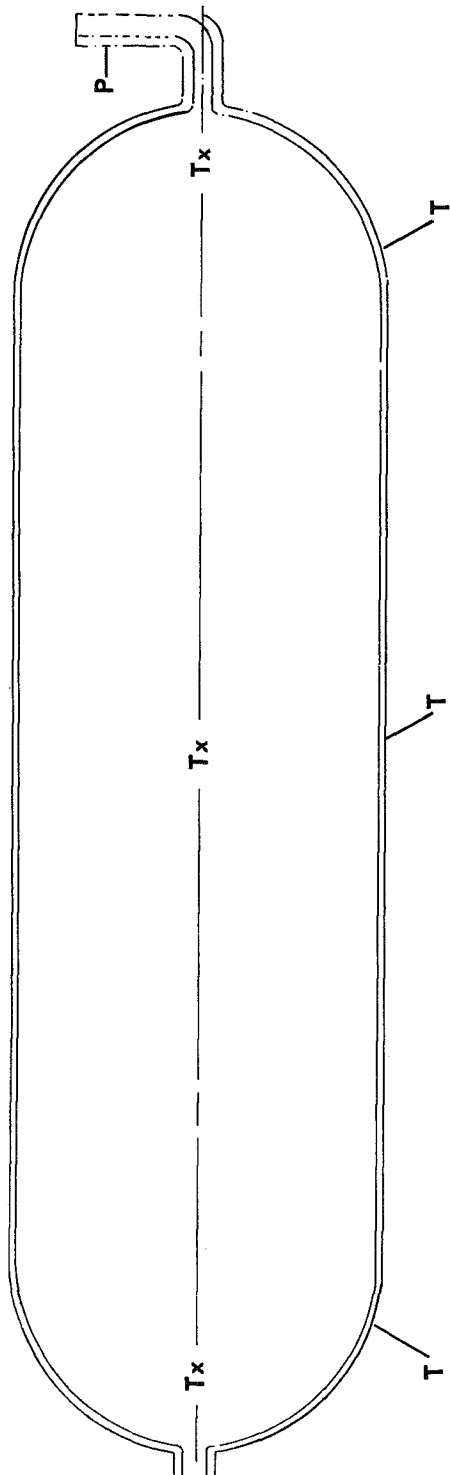


Figure A-1. Alternative-internal fluid temperature.

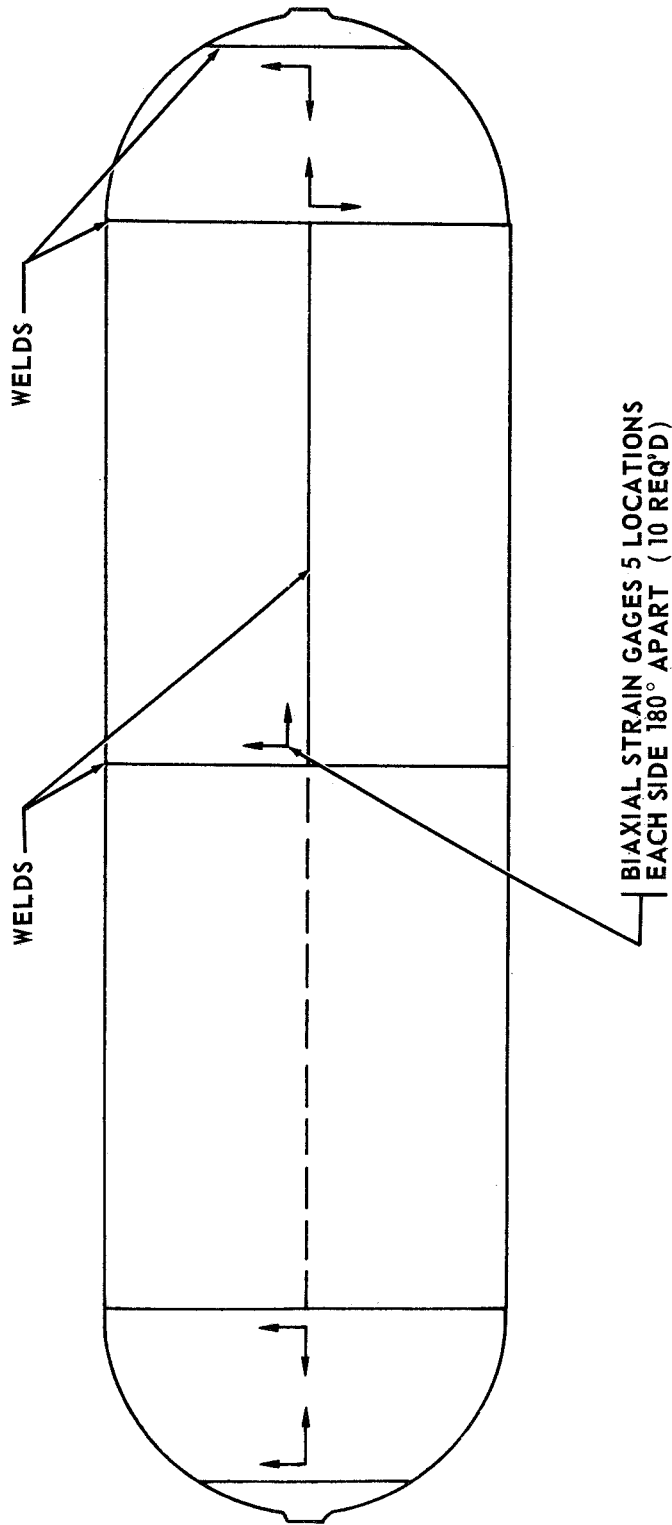


Figure A-2. Strain gage locations for rolled and welded pressure vessel S/N 3 and S/N 4.

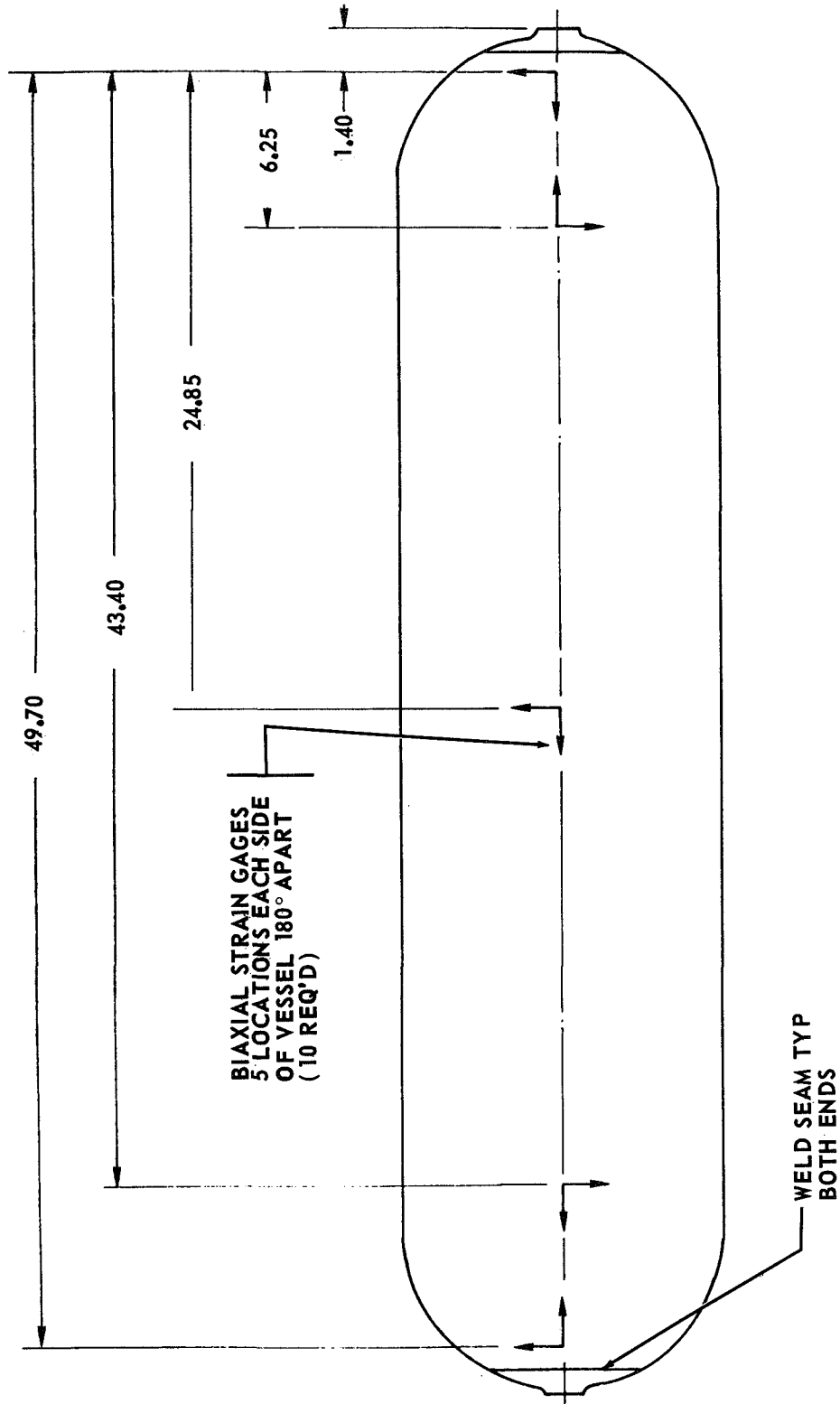


Figure A-3. Strain gage locations for integral head pressure vessel S/N US-5.

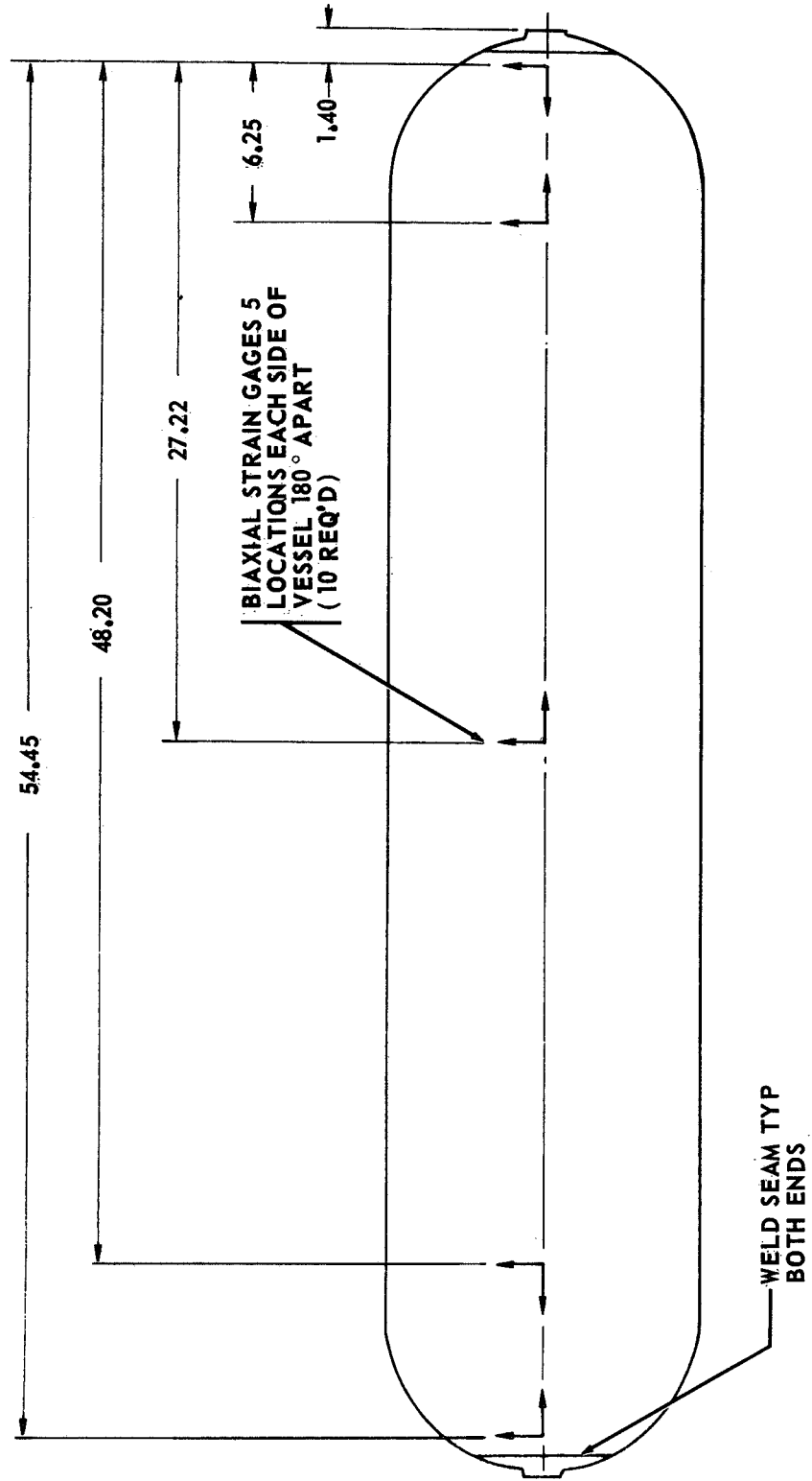


Figure A-4. Strain gage locations for integral head pressure vessel S/N US-2.

Proof Pressure Test

Proof pressure test using H₂O at room temperature for 0 psig to 5900 psig \pm 50 psig in not less than 10 minutes and hold at 5900 psig for a minimum of three minutes. Check for leakage. Purge before conducting next test.

Elevated Temperature Testing

While mounted vertically, the bottle shall be heated to +165° F and shall be subjected to five pressurization cycles of 0 to 2350 to 0 psig using helium at a temperature of +165° F. The bottle shall be pressurized and vented through the lower end. The time to pressurize the bottle from 0 to 2350 psig shall be four (plus one, minus zero) minutes.

The bottle shall be hydraulically pressurized using hydraulic fluid at +250° F for 1000 cycles from 0 to 2350 to 0 psig. Cycling rate shall not exceed two cycles/minute. At room temperature, hydraulically pressurize to proof pressure and check for leaks. Purge before conducting next test.

Low Temperature Pressure Cycle Test

While mounted vertically, the bottle shall be submerged in an atmospherically vented bath of liquid nitrogen. The bottle shall be subjected to five pressurization cycles of 0 to 5080 to 0 psig with gaseous helium. The bottle shall be pressurized and vented through the lower end. Pressurization time for 0 to 5080 to 0 psig shall not be less than eight minutes.

The bottle shall be heated to +250° F \pm 10° F and, within 10 minutes after temperature stabilization, submerge in liquid nitrogen. The bottle shall be hydraulically pressurized for 1000 cycles for 0 to 5080 to 0 psig (1-cycle) using liquid nitrogen. The cycling rate shall not exceed two cycles/minute. At room temperature, hydraulically pressurize to proof pressure and check for leaks.

Conduct Volume Measurement

Prior to burst test, conduct volume measurement and record.

Low Temperature Burst Test

The bottle shall be internally pressurized to 7610 psig using liquid nitrogen while submerged in liquid nitrogen and this pressure held for five minutes. The time to increase pressure from 5080 psig to 7610 psig shall not be less than two minutes. If an all welded vessel is being tested and no leakage is detected, it shall be pressurized to 10 000 psig and this pressure maintained for five minutes. If an integral head vessel is being tested it shall be pressurized to 9300 psig and this pressure maintained for five minutes. Pressurization time from 7610 to 10 000 psig or from 7610 to 9300 psig shall not be less than ten minutes. If rupture of a welded vessel does not occur after five minutes at 10 000 psig or at 9300 psig in the case of an integral head vessel, the internal pressure shall be slowly increased until rupture occurs.

APPENDIX B³

QUALIFICATION TESTS FOR CRYOFORMED SPHERE P/N D3590

Qualification Tests

Proof Test (Ambient).

Requirements. The specimen shall be stabilized at $+70^{\circ} \pm 10^{\circ}$ F and pressurized to 3500 psig with ambient helium gas. The pressure shall be maintained for two minutes. There shall be no structural failure or permanent distortion.

Proof Test (Cold).

Requirements. The specimen shall be stabilized at $-412^{\circ} \pm 12^{\circ}$ F. The specimen shall be pressurized to 5340 psig and maintained for two minutes. There shall be no structural failure or permanent distortion.

Leak Test (Ambient).

Requirements. The temperature of the specimen shall be stabilized at $70^{\circ} \pm 10^{\circ}$ F. The specimen shall be pressurized with ambient helium gas to 2100 psig and maintained for two minutes. There shall be no decay or internal leakage from the sphere.

Thermal Shock Test.

Requirements. The specimen temperature shall be stabilized at $70^{\circ} \pm 10^{\circ}$ F. The specimen shall be simultaneously pressurized to 500 psig with helium gas and cooled in a liquid hydrogen bath. Pressurization and cooling shall be accomplished in 90 seconds or less. There shall be no permanent distortion or structural failure.

3. Information in Appendix B courtesy of Mr. R. H. Veitch, Astronautics Laboratory, MSFC.

Service Life Test (Cold).

Requirements. The specimen shall be placed in cryostat and pressurized to 500 psig. The temperature shall be stabilized at $-412^{\circ} \pm 12^{\circ} \text{F}$. The pressure shall be increased to 3700 psig within three minutes and then decreased to 500 psig within three minutes. The pressure cycle shall be repeated 500 times. There shall be no permanent distortion or structural failure. Upon completion of the service life test the ambient leak test shall be repeated.

Stress Coat Test.

Requirements. Stress coat shall be applied to the specimen for each pressure cycle. The specimen temperature shall be stabilized at $70^{\circ} \pm 10^{\circ} \text{F}$ and hydrostatically pressurized three times; 0 to 500 to 0 psig, 0 to 750 to 0 psig, and 0 to 1000 to 0 psig. One sphere P/N D3590 shall be tested and the photographic results shall be compared for similarity with photographic results of a stress coat test on a S-IV flight configuration cold helium sphere P/N 7851834.

Burst Test.

Requirements. The specimen shall be filled with pellets, placed in a cryostat and submerged in liquid hydrogen. Gaseous helium at $-412^{\circ} \pm 13^{\circ} \text{F}$ shall be applied to the sphere at a constantly increasing pressure until burst occurs. The minimum burst pressure shall be 7100 psig.

Vibration Test.

Requirements. The test sphere will be mounted through flight bracketry to a 30 by 40 in. section of the LH_2 tank wall. The total assembly will be supported on appropriate test fixtures to insure that uniform vibration inputs are maintained at the panel support area. The following sine and random vibration levels will be imposed in three mutually perpendicular axes and controlled at the sphere support bracket/ LH_2 tank wall interface. The test specimen will be subjected to the appropriate flight operating temperature and pressure requirements during vibration testing.

Specifications.

1. Sine sweep 5-2000-5 cps at/octave/min

5-28 cps @ 0.085 in. DA

28-125 cps @ 3.5 g. pk.

125-190 cps @ 0.0043 in. DA

190-2000 cps @ 8 g. pk.

2. Random Vibration.

20-40 cps @ 0.014 g²/cps

40-100 cps @ +6db/octave

100-700 cps @ 0.079 g²/cps

700-2000 cps @ -3 db/octave

Test tolerances shall be as stated in IN-P&VE-S-63-1, revised September 11, 1964.

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APPROVAL

TM X-53978

CRYOFORMED 301 STAINLESS STEEL
FOR PRESSURE VESSELS

By C. N. Irvine

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



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