NASA CR-134384

Contract NAS9-12540
DRL T-701
DRL Line Item 3
DRD MA-183
MCR-73-214

Final Report

Firefighter's Compressed Air Breathing System Pressure Vessel Development Program

PRICES SUBJECT TO CHANGE

AUGUST 1974

(NASA-CR-134384) FIREFIGHTER'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM Final Report (Martin Marietta Corp.) CSCL 06K G3/05 N74-30497 Unclas 46381

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

Prepared by

MARTIN MARIETTA

N74-30497

Contract NAS9-12540
DRL T-701
DRL Line Item 3
DRD MA-183
MCR-73-214

FINAL REPORT

FIREFIGHTER'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM

August 1974

Prepared by

E. J. Beck
E. J. Beck
Program Manager

PRICES SUBJECT TO CHANGE

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

MARTIN MARIETTA CORPORATION
P. O. Box 179
Denver, Colorado 80201

FOREWORD

The work described in this report was performed by the Martin Marietta Corporation under Contract NAS9-12540 for the Lyndon B. Johnson Space Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Crew Systems Division with Mr. Pat McLaughlin as project manager.

Mr. Emory J. Beck served as Martin Marietta program manager. Mr. Don Dulaigh was responsible for conducting the experimental test program. The author gratefully acknowledges the assistance and consulting services rendered by the following colleagues: Robert D. Keys, Fred R. Schwartzberg, Dr. Arthur Feldman, and Dr. A. A. Holston.

The report is submitted in compliance with the data requirements list (DRL), line item 3, "Report Final," of Exhibit A, T-701, DRD MA 183T of this contract.

ABSTRACT

The objective of this contract was to design, fabricate, test, and deliver a pressure vessel which will be the main component in an improved high-performance firefighter's breathing system.

The principal physical and performance characteristics of the vessel which were required are:

1) Maximum weight of 9.0 lb;

2) Maximum operating pressure of 4500 psig (charge pressure of 4000 psig);

3) Minimum contained volume of 280 $in.^3$;

4) Proof pressure of 6750 psig;

5) Minimum burst pressure of 9000 psig following operational and service life;

6) A minimum service life of 15 years.

A vessel designed within the framework of these requirements would yield a minimum breathing capacity of 40 standard cubic feet (scf) of air which is normally considered to be sufficient for approximately 20 min of normal breathing time. Another restrictive guideline, and of paramount importance, was that the vessel be manufactured using existing technology in a manner that would result in a per-unit production cost not exceeding $40.

The vessel developed by Martin Marietta Corporation to fulfill the requirements described was completely sucessful, i.e., every category of performance was satisfied. The average weight of the vessel was found to be about 8.3 lb well below the 9.0 lb specification requirement.

CONTENTS

APPENDICES

I. BACKGROUND

A survey of firefighting organizations shows a critical need for improvements in portable breathing systems. Present systems are heavy and have limited air capacity in relation to their weight and bulk. The air storage tank or vessel is that part of a portable breathing system where the two areas of needed improvement can be made. The improvements can be made in one of two ways--maintain the present air capacity but significantly reduce the weight, or greatly increase the air capacity with a modest weight savings. Both are valid approaches. Concurrent programs were sponsored by NASA for development of a vessel which would satisfy each approach. Martin Marietta's program dealt with development of a 40 standard cubic foot vessel which was designed for minimum weight.

Although an improved breathing system could be used in many areas of endeavor, the pressure vessel design described in this report was intended to be used primarily as firefighter's compressed-air breathing system. Thus, the unique problems presented by firefighting applications are of prime concern in the design. This portable breathing system used improved materials and technology, much of which has resulted from previous NASA programs, to develop a lightweight, durable, and low-cost pressure vessel that will be capable of satisfying the safety objectives of federal and local regulatory agencies.

II. INTRODUCTION

Before the individual problems of material selection, stress analysis, fabrication or economics were addressed, a basic design approach was selected on the basis of all design requirements. However, two principal design requirements that were focal points of our basic design selection were:

1) The pressure vessel should contain 40 standard cubic feet (scf) of air when charged at 4000 psig at 70°F;

2) The vessel should be designed for minimum weight (target of 9.0 lb) and minimum cost (target of less than $40 manufacturing cost).

The rationale used to arrive at what seemed to be a most logical design approach using the two above-listed principal design requirements is described below. The specific vessel requirements are in Appendix A of this report.

The simplest way to improve pressure vessel efficiency with no increase in weight is to increase the strength level. This approach is usually unsatisfactory because the toughness characteristics of alloy steels at strength levels over 200,000 psi are so poor that regulatory agencies would not qualify such a vessel for commerical marketing. Changing to an steel alloy of improved toughness, such as D6AC, is also unsatisfactory because the increase in toughness is minimal.

Alternative types of steels are the first positive steps that can be made. These steels include the family of maraging high-nickel steels and the precipitation hardenable austenitic stainless steels, such as A-286. In both cases, we can obtain the required strength by heat treatment. Although toughness would be excellent and the majority of the technical requirements could be easily achieved, cost would be prohibitive because the raw materials costs would be approximately equal to our arbitrarily-selected maximum cost goal of $40.

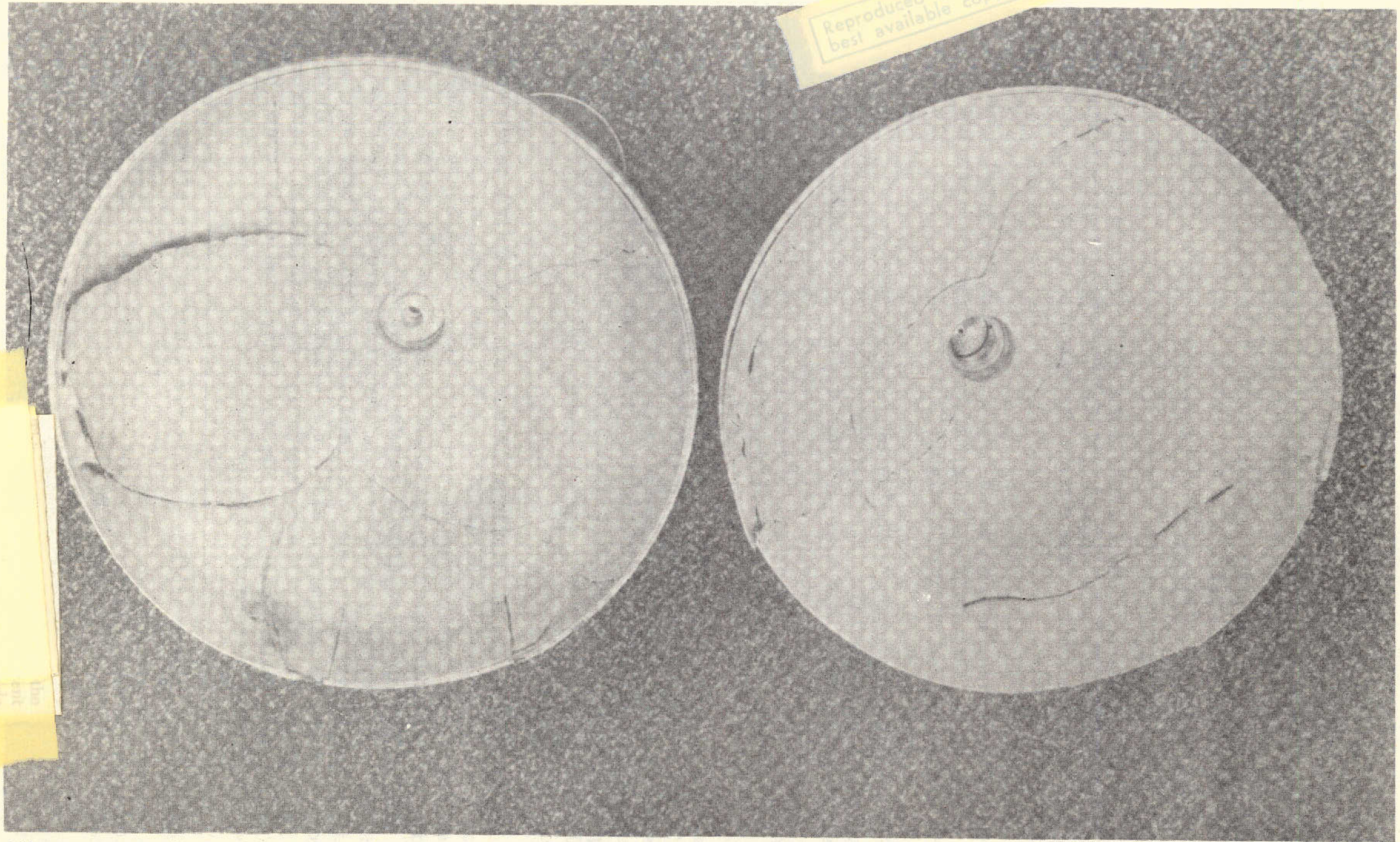
Therefore, we find the simple material substitution approach is impractical for achieving performance improvement at the same or slightly reduced weight because the less expensive steels are not sufficiently tough at higher strength levels, and the tough, high-strength steels are prohibitively expensive.

The next direction to pursue is that of alternative design and manufacturing methods. Consider first the design of the currently manufactured vessel. The cylindrical vessel with hemispherical ends is not fully efficient because the stresses in the domes and in the axial direction are only one-half the hoop stress in the cylindrical section. In other words, a uniform wall vessel is carrying extra material in the domes and axial direction. Although thinning the domes does improve efficiency, we obviously cannot alter the thickness in the cylindrical section. However, we can reinforce the cylindrical section in the hoop direction and increase the pressure in the vessel so the domes are at a higher operating stress. This reinforcing can be achieved by overwrapping in the hoop direction. Therefore, we can develop the efficiency of a spherical tank (an awkward shape for the intended application) with a cylindrical shape. The various approaches to solving the problem, using a composite overwrapped design, are reviewed below.

The simplest approach is to overwrap the present vessel with glass or wire in the hoop direction. Although quite satisfactory and quite inexpensive, overwrapping of the present steel vessel would result in increased weight. Although this is the minimum cost improvement that can be achieved, the increased weight was unacceptable.

The strength level of the 4130 steel can be increased to permit a decreasing wall thickness (and, therefore, weight), then overwrapping to achieve strength. Although this approach can be tailored to maintain the current weight, the higher strength level of the unwrapped domes causes concern with respect to toughness. This compromise approach to weight and toughness was not fully satisfactory.

The approach described in the previous paragraph can be quite satisfactory if the vessel is completely overwrapped. When a vessel is overwrapped with sufficient reinforcement so that fracture of the metallic liner occurs at a stress less than the fracture stress of the overwrap, the overwrap can completely contain the fragmented liner. Martin Marietta has evaluated such vessels and proved the concept. Figure II-1 shows the interior of a high-strength steel/glass-overwrapped vessel taken to burst. The liner fully fractured, but did not fail the reinforcement. Before sectioning, visual examination of the vessel exterior could not confirm that the vessel had actually failed, but it could no longer be pressurized. Therefore, a fully overwrapped vessel can exhibit a safe mode of failure even with a low-toughness metal liner.



Reproduced from best available copy.

Figure II-1 Interior of Ruptured Overwrapped Steel Vessel

Note that fully overwrapping a vessel costs only slightly more than hoop overwrapping. Although the overwrapped steel vessel is satisfactory, the weight effeciency of the vessel is only fair.

Based on this approach, alternatives such as overwrapping high strength, tougher material (e.g., cryo-stretch-formed stainless) provide little additional improvement in weight, and an intolerable increase in cost.

The remaining approaches are based on eliminating the steel liner and incorporating alternative liner materials that will provide significant decreases in total weight.

The first option frequently considered is a polymeric- or elastomeric-type material. The main advantage of such a liner is that elastomeric materials have a lower density and would, therefore, contribute to a generous weight savings. However, wall thickness of this type liner is not stress-controlled in our design, but is controlled by permeation of diffusion rates that result in wall thickness requirements of up to 3/8 in., negating the beneficial weight aspects of a nonmetallic liner. Although some (5%/year) pressure decay could be tolerated in our vessels, diffusion of gas into the polymeric material at high pressure and the subsequent formation of bubbles in the liner when the vessel is depressurized ultimately may cause liner failure.* Therefore, an all-nonmetal system would appear to be a questionable selection for our application.

The next candidate was an aluminum liner--an outstanding candidate because of its high strength/density ratio, low modulus, outstanding toughness, and environmental compatibility. Completely overwrapping an aluminum vessel permits achievement of the weight goal, toughness, and flaw growth requirements, and, most important is low in cost. Other important considerations are that fabrication is relatively simple, and the regulatory agencies have approved unwrapped aluminum vessels for similar applications. Therefore, we conclude that the best compromise to meet design requirements would be realized with an aluminum liner completely overwrapped by a fiberglass-epoxy composite.

---

*Another major concern of the elastomeric liner is the effect of high temperature exposure. In general, the mechanical and diffusion properties of elastomeric materials are drastically affected by temperatures above 300°F.

III. MATERIAL SELECTION

After the selection of the basic design approach, a fully-overwrapped aluminum vessel, considerations were given to the specific aluminum alloy and overwrapping fiber to best meet the requirements. The details of these selections are given in the following discussions.

A. LINER MATERIAL SELECTION

Several requirements were obvious from the program outset. The liner must:

1) Have a good strength to weight ratio;

2) Be easily fabricated into dome-ended cylindrical shapes;

3) Have good fracture characteristics including both fracture toughness and stress corrosion resistance in the presence of notches;

4) Be inexpensive.

Considering these four factors, the decision for an aluminum alloy liner seemed mandatory. Many higher-strength materials are used in aerospace applications (where strength-to-weight ratio overrides most other considerations), but these materials are often very costly and difficult to fabricate--titanium, superalloys, and stainless steels are examples.

The choice of liner alloys can be quickly narrowed from scores of aluminum alloys when they are considered from the standpoint of fabricability. The 6000 series alloys have been favored by aluminum forgers for many years. This was an important factor in alloy selection since it was paramount that the fireman's pressure vessel be produced with state-of-the-art methods, thus precluding new fabrication methods and new alloy development experiments. At the present time most aluminum tanks or pressure bottles are made with 6000 series aluminum alloys.

The 6070 aluminum alloy in the T6 temper was the final liner material choice. From the data presented in Table III-1, it may be seen that 6070-T6 has higher strength properties than 6061-T6 or 6351-T6 but retains similar ductility. The material has good forging characteristics, it has a production history with aluminum forgers, and good stress corrosion resistance. Fracture properties for 6070 are similar to those for higher strength alloys such as 2014-T6 and 7075-T6.

The 6000 series aluminum alloys in general have properties which meet the desired liner requirements. They are resistant to brittle fracture, are readily formable, and have good stress corrosion resistance. Disadvantages lie mainly in low-to-moderate strength properties and some welding difficulties. However, welding can be completely avoided by using a forging technique of manufacture.

Originally one other alloy, 7075 in T73 temper, was considered as an attractive alternate to 6000 series alloys. 7075-T73 has good stress corrosion properties in contrast to the T6 condition of the same alloy. Although the alloy has high potential design strength, forming difficulties for deep draws and additional annealing cycles required in fabrication make the alloy not suitable for this program. This conclusion is verified to some degree by the complete lack of use of this material in currently-manufactured pressure vessels.

B. OVERWRAP MATERIAL SELECTION

From the standpoint of program vessel requirements of low cost, high strength, and long-term durability, fiber glass was the only commercial overwrap material which seemed adequate. It has excellent strength, low density, low cost, and has been used commerically for years in composite applications.

There are two principal glass fiber types that can be obtained in significant production quantities--E- and S-glass. There is approximately a 40 to 50% difference in the fiber strength of the two types, E-glass having reported values of fiber strength up to about 500,000 psi and S-glass comparable at 700,000 psi. These strengths, however, are not realized in production parts because they are highly dependent on the length of fiber tested and fiber quality control. A typical strength value measured by ASTM D-ring methods for E-glass fiber would be 250,000 psi, and, for

Table III-1 Comparison of Typical Mechanical Properties†

Alloy and Temper	Tensile Strength, Ultimate psi	Tensile Strength, Yield psi	Elongation in 2 in., Percent (1)	Elongation in 2 in., Percent (2)	Brinell(3) Hardness	Shear Strength, psi	Endurance Limit, psi
*6070-0	21,000	10,000	20	--	35	14,000	9,000
*6070-T4	49,000	30,000	20	--	90	30,000	13,000
*6070-T6	57,000	52,000	12	--	120	34,000	14,000
*6071-0	21,000	10,000	20	--	35	14,000	9,000
*6071-T4	49,000	30,000	20	--	90	30,000	13,000
*6071-T6	57,000	52,000	10	--	120	34,000	14,000
6061-0	18,000	8,000	25	30	30	12,000	9,000
6061-T6	35,000	21,000	22	25	65	24,000	13,000
6061-T6	45,000	40,000	12	17	95	30,000	14,000
2014-0	27,000	14,000	--	18	45	18,000	13,000
2014-T4	62,000	42,000	--	20	105	38,000	20,000
2014-T6	70,000	60,000	--	13	135	42,000	18,000
6351-T4	42,000	27,000	--	20	60	22,500	13,500
6351-T6	47,000	43,000	--	13	95	29,000	13,500
6066-0	22,000	12,000	--	18	43	14,500	--
6066-T4	52,000	30,000	--	18	90	29,500	--
6066-T6	57,000	52,000	--	12	120	34,000	16,000

* Tentative Values
(1) 1/16 in. thick specimen
(2) 1/2 in. diameter specimen
(3) 500 KG Load - 10mm Ball
†From Alcoa Green Letter, See Appendix D.

short-time application, a design stress value based on this figure may be justified. Comparing glass properties like high tensile strength, low density (approximately 0.07 lb/in.^{3}), and a high modulus of 10-12 million psi, it becomes obvious that glass fibers could be used to great advantage as a structural reinforcement.

The final selection of an E or S glass fiber was based upon a trade off between cost and weight. In production quantities (July 1973), commercial grade S-glass was priced at $1.75 per lb while E-glass fiber cost about $0.38 per lb giving E glass a better than 4:1 advantage in this category of consideration. Weight was, however, considered to be a more important consideration in the program and test data as discussed later, show that S glass exhibits about 90,000 psi higher tensile strength than E glass. This difference in strength allows about a 1-lb weight savings to be realized if S glass is the selected fiber. Another consideration in this trade off study, was the possibility or probability that the difference in cost between E and S glass would shrink in the future and compare more favorably economically. The weight savings realized from the S-glass design became the dominant criterion and the S glass fiber was selected.

Although glass has tremendous tensile strength, its strength is time dependent, especially if water is present. Glass is very susceptible to stress corrosion cracking in a moist environment. This problem is resolved by appropriate selection of the operating stress level to allow for long-term degradation.

Glass fibers are not wound on a pressure vessel or any structure by themselves. They require a matrix binder or resin to hold them in place and to distribute them uniformly on the wound surface. The resin contributes little to the tensile strength of fiber but is extremely important for transferring shear loads and offers considerable protection from mechanical abrasion and direct environmental exposure and redistributes nonuniform loads, especially when fibers are cut or damaged.

The selection of glass fiber, E or S, and the resin system to be used with the fiber was based primarily on NOL ring data which follows.

Only epoxy resin systems were considered for our pressure vessel design primarily because of thier better high temperaure performance characteristics as a group. Epoxies generally not only exhibit high temperature strength (some are recommended for use in environments to 500°F) but have high shear strength. They are also very resistant to chemical attach by acids, bases or solvents. Epoxies can be formulated into very hard, tough, abrasive resistant material when cured and can leave a very smooth, clean attractive surface if properly handled. The typical curing temperature of about 300°F for 2-3 hours will not overage or degrade the properties of 6070-T6 aluminum. This type of resin system is of the thermoplastic type thus exposure to temperatures above 300 or curing temperature does not soften the resin. A cured epoxy resin is generally impervious to water.

Table III-2 NOL Tensile Strength - Baseline Room Temperature (Ultimate Fiber Stress, ksi)

Kaiser E/ 828/MPDA	Owens Corning E/ 828/MPDA	Owens Corning S-2/ 828/MPDA
233.0	221.7	293.0
230.6	213.2	337.6
237.9	219.6	336.6
235.7	200.9	335.2
		321.4
234.3 Avg	213.9 Avg	324.8 Avg

Note the similarity of strength between the two E fibers and the significant strength advantage, at least 42%, of the S-glass fiber over either E fibers.

The high performance nature of our design with the requirement for minimum weight led to the selection of Owens Corning S-2 fiber glass as the overwrap material for our design. It was felt that the significant strength advantage of this fiber offset the higher cost, especially with prospects of lower future cost on this particular fiber as demand became greater.

Resin selection was also made on the basis of NOL ring test results but here the screening factor instead of room temperature strength was strength retention after hot boiling water exposure. Four resin systems were evaluated. They were: Epon 828/MPDA (baseline system), Epon 828/871/MPDA, Epon 828/Jeffamine D230, and EPON 828/1031/NMA/BDMA. The additives to the basic 828 system normally would enhance performance or flexibilize the basic system to curtail resin crazing, a normal phenomena occurring during vessel pressurization. Reducing the degree of crazing can offer protection from long-term degradation by eliminating or reducing the number of paths moisture could enter.

Test exposures were made by loading NOL ring samples to typical sizing stress levels at ambient conditions and then exposing each ring to boiling water environment for four hours while maintaining stress levels on the ring consistent with operating stress levels that would occur in the pressure vessel. The test proved to be quite severe as only the basic Epon 828/MPDA and the Epon 828/1031/NMA/BDMA system survived. Data from these two systems representing remaining tensile strength after exposure are shown in Table III-3.

Table III-3 NOL Ring Tensile Strength (ksi) after Stressed 4-hr Water-Boil (200°F) Exposure, S-2 Glass Fiber

Resin System	Epon 828/ MPDA System	Epon 828/1031/ NMA/BDMA
	239.9 231.0 234.8 244.9 247.4	288.5 286.6 305.7 272.0
	239.6 Avg	288.2 Avg

As a result of this test, the Epon 828/1031/NMA/BDMA* resin system was selected for use with the S-2 fiber glass. Quantities of the overwrap material to be applied are computed in the manner given in the next section of this report.

---

*50 pbw Epon 828, 50 pbw Epon 1031, 90 pbw nadic methyl anhydride, and 0.5 phw drops benzyl dimethylamine.

IV. DESIGN AND STRESS ANALYSIS

A. FIBER GLASS OVERWRAPPED METAL LINERS

A major problem with any overwrapped metal liner is its mechanical compatibility with the overwrap material, i.e., the strain imparted to the liner during pressurization and the corresponding strain of the glass overwrap must be reversible during depressurization of the vessel. Furthermore, it must be reversible for each cycle without liner malfunction.

Having a modulus of about 12 million psi, fiberglass (S-2) can exhibit at least 2% elastic strain without failure. However, there is no metallic alloy which can remain elastic to this strain level. Thus, with the first charge pressurization, an overwrapped metal liner could be plastically deformed. And upon unloading, the liner would be forced into elastic compression, hopefully without buckling. This problem can be alleviated by using a liner thick enough to prevent buckling and/or by allowing the design to operate completely in the elastic range at low stress. Both of these solutions decrease the efficiency of the vessel but may be incorporated with reasonable design success. The concept used in the design of the FBS vessel did not incorporate either of the approaches mentioned. This concept is discussed in detail in the following paragraphs.

The mechanical compatibility problem can be overcome by using a concept developed by NASA.* This approach allows a force balance between a liner prestressed in compression and its overwrap prestressed in tension to be obtained before the vessel is placed in service. By correctly matching the material stresses, the liner may operate elastically through a greatly increased strain range and the overwrap can be used at efficient stress levels. The prestress condition is obtained by putting a newly-fabricated vessel through a "sizing" pressurization cycle where the liner is strained beyond its proportional limit and yields perhaps as much as 2%.

---

*R. H. Johns and A. Kaufman: "Filament Overwrapped Metallic Cylindrical Pressure Vessels." *Journal of Spacecraft and Rockets*, July 1967, p 872.

When depressurized, the desirable stress state is attained because the metal unloads elastically and is forced into compression by the elastic overwrap.

The concept of sizing and its effect upon operating stress levels for the FBS design is shown graphically in Figures IV-1(a) and IV-1(b). These figures show the stress levels attained in the liner and fiberglass filaments in the cylindrical section of the vessel (hoop direction) when the overwrapped vessel is subjected to a sizing pressure (immediately after fabrication) and the subsequent operating cyclic stress range of these structural components during normal operation of the vessel. Note, that the liner is forced into compression during sizing and is thereafter constrained by the overwrap material to operate in an increased elastic strain range extending from compression (-28.4 ksi) in the unpressurized condition to tension (+19.9 ksi) at the maximum operating pressure of 4500 psig.

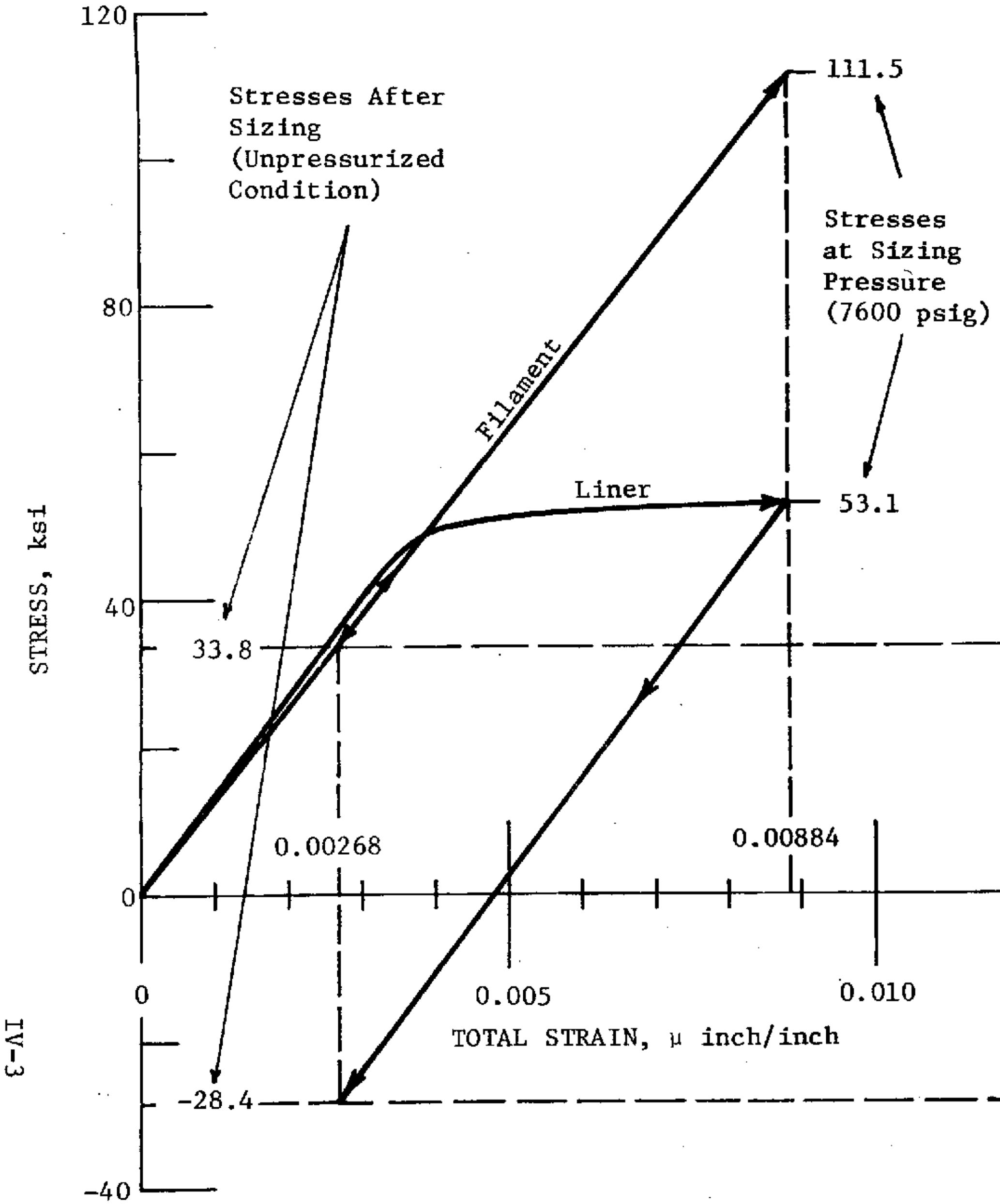


Figure IV-1(a) Sizing Cycle Stress Behavior for Liner and Fiberglass Filament

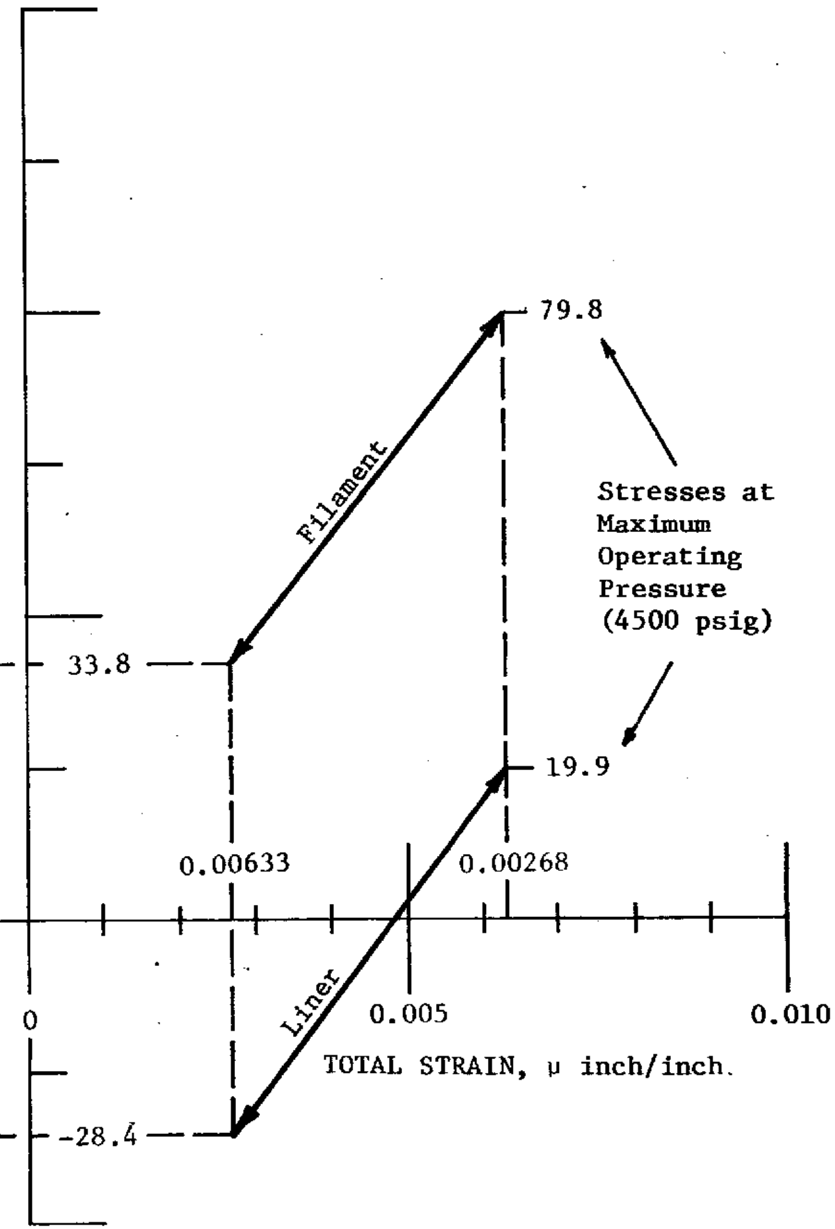


Figure IV-1(b) Operating Stress Range for Liner and Fiberglass Filament (Post-Sizing)

B. COMPUTER PROGRAM

Design of glass fiber overwrapped vessels having load-sharing liners can be done by manual calculations for spherical vessels and for dome-ended cylindrical tanks having only hoop oriented overwrap to strengthen the cylindrical section. Completely overwrapped cylindrical tank designs are considerably more detailed and require computer assistance. A valuable computer program* has been developed under NASA Contract NAS3-6292 for design of such vessels, and was used for the preliminary design values of the fireman's bottle developed under this contract.

The required computer program input parameters include pressure vessel geometry, liner material properties, filament material properties, filament and longitudinal metal stresses present upon winding, and design limit conditions, (see Table IV-1). Seven optional variables are included and four of these must be input:

1) The tensile hoop strain in the metal liner at design pressure;

2) The tensile longitudinal strain in the metal at design pressure;

3) Filament stress at design pressure;

4) The design pressure;

5) Liner thickness;

6) Overwrap thickness at vessel equator; and

7) The metal hoop stress upon winding.

The program output includes: (1) optimum head contours at both ends of the pressure vessel; (2) filament and metal stresses and strains at desired pressure levels; hoop wrap thickness required for the cylindrical portion of the vessel; and (3) the weight, volume, and filament path-length for the complete vessel and components. Stress and strain values for specific pressure and temperature conditions for the vessel may be obtained, but room temperature is assumed for all information at the zero internal pressure level.

---

*Computer Program for the Analysis of Filament Reinforced Metal-Shell Pressure Vessel. NASA CR-72224. Aerojet General Corp. May 1966 (Contract NAS3-6292).

Table IV-1 Required Input Parameters for Pressure-Vessel Computer Program

Parameter	Specific Input Value
General	
Vessel length determined by volume requirements	17.2 in.
Vessel radius	2.56 in.
End boss radius	0.80 in.
In-plane or helical winding pattern key value	Helical
Liner Properties	
Thickness	0.133 in.
Density	0.098 lb/in^3
Coefficient of thermal expansion	12.7 x 10^{-6} in./in.°F
Compressive yeild strength on buckling stress limit	52.5 ksi
Elastic modulus	10 x 10^6 psi
Plastic modulus	80 x 10^3 psi
Poisson's ratio	0.33
Overwrap Properties	
Density	0.074 lb/in.^{3}
Coefficient of thermal expansion	3.1 x 10^{-6} in.in.°F
Elastic modulus of filament	12.6
Volume fraction of filament	0.65
Fixed Design Conditions	
Design Pressure	9500 psig
Stresses after winding	0 (assumed)
Temperature at zero pressure and sizing	75°F
Design temperature	75°F
Filament design stress	125 ksi

Some shortcomings of the computer program should be noted. The program uses a "netting" analysis for the overwrap and linear membrane theory for the liner, assuming a liner with sufficient stiffness to resist buckling without being bonded to the overwrap. It further assumes that liner stress in the meridional direction is constant. However, liner membrane theory for ellipsoidal shells under internal pressure* shows that the ratio of meridional stress at the apex to that at the equator is given by the ratio of major-to-minor axes of the ellipse. Furthermore, it has been shown, both analytically† and experimentally,§ that elliptical torospherical closures can buckle under internal pressure and that the meridional stress is not constant before buckling.

The computer program assumes that filament stress is constant with fiber orientation, whether that of a planar or geodesic wrap (Clairaut's law). For pressure vessels without liners, the geodesic wrap produces constant filament stress, but the planar wrap produces a variable stress.¶ Thus, the assumption of constant filament stress is not valid for planar wraps without liners and does not seem likely for either wrap with a liner. The design method of the computer program further assumes that liner buckling in the dome is governed by an empirical equation based on test data for overwrapped cylinders. However, studies of isotropic cylinders, spherical caps, elliptical closures, and other shell shapes show that the buckling process is very complex and strongly depends on shell shape. Despite the foregoing restrictions, the computer program remains extremely useful for preliminary design values.

---

*R. A. Clark and E. Reissner: "On Stresses and Deformations of Ellipsoidal Shells Subjected to Internal Pressure," *Journal of Mechanics and Physics of Solids*, Vol 6, 1957, pp 63-70.

†G. A. Thurston and A. A. Holston, Jr.: *Buckling of Cylindrical Shell End Closures by Internal Pressure*. NASA CR-540. Martin Marietta Corporation, Denver, Colorado, July 1966.

§J. Adachi and M. Benicek: "Buckling of Torispherical Shells under Internal Pressure," *Experimental Mechanics*, August 1964, pp 217-222.

¶J. C. Schultz: *"Netting" Analysis of Filament-Wound Pressure Vessels*, ASME 63 WA-223.

C. SELECTION OF INPUT PARAMETERS

The variable program input parameters selected for this vessel design were: liner thickness, filament design stress, design pressure, and sizing pressure. Other selected parameters were dictated by performance requirements, e.g., vessel length and diameter which affect volume (see Appendix A), or were dictated as a result of material selection, e.g., density, modulus and Poisson's ratio. Variables such as metal liner thickness and winding pattern were largely selected on the basis of manufacturing ease.

The program output included such data as: dome contour, axial and hoop overwrap thickness, stress values (at sizing pressure, zero pressure, operating pressure, proof pressure, and at required minimum burst pressure--9000 psig), along with projected vessel component weights and volumes.

Metal liner (Alloy 6070-T6 strength) values were based on Alcoa published data and Martin Marietta Aluminum typical test data as shown in Figure IV-2. A representative engineering stress-strain curve for the material was fitted with a bilinear representation (as shown in Figure IV-3) required for the program. Numerical values for initial modulus (E_1), secondary modulus (E_2), and yield stress were obtained from the bilinear plot.

1. Liner Thickness

Liner thickness was selected from three considerations: fracture mechanics criteria, manufacturing limits, and buckling resistance. Adequate thickness to prevent compressive buckling after sizing was calculated from the expression for buckling of cylinders,

$$t_{min} = 2r \quad \frac{\sigma_{cr}}{150{,}000\ E_m} \times 1.3 \text{ safety factor,}$$

where σ_{cr} is taken as the compressive yield strength, r is the liner radius, and E_m is its primary modulus of elasticity (E_1).

All liner thicknesses considered were far in excess of the minimum required thicknesses required to preclude buckling. In fact, the lower limit was fixed by manufacturing considerations. The liner fabricators felt that boss end closure forging could not be accomplished without column buckling in material thicknesses below 0.100 in. The selected liner input thickness for computation was 0.133 in. which allowed for manufacturing tolerances.

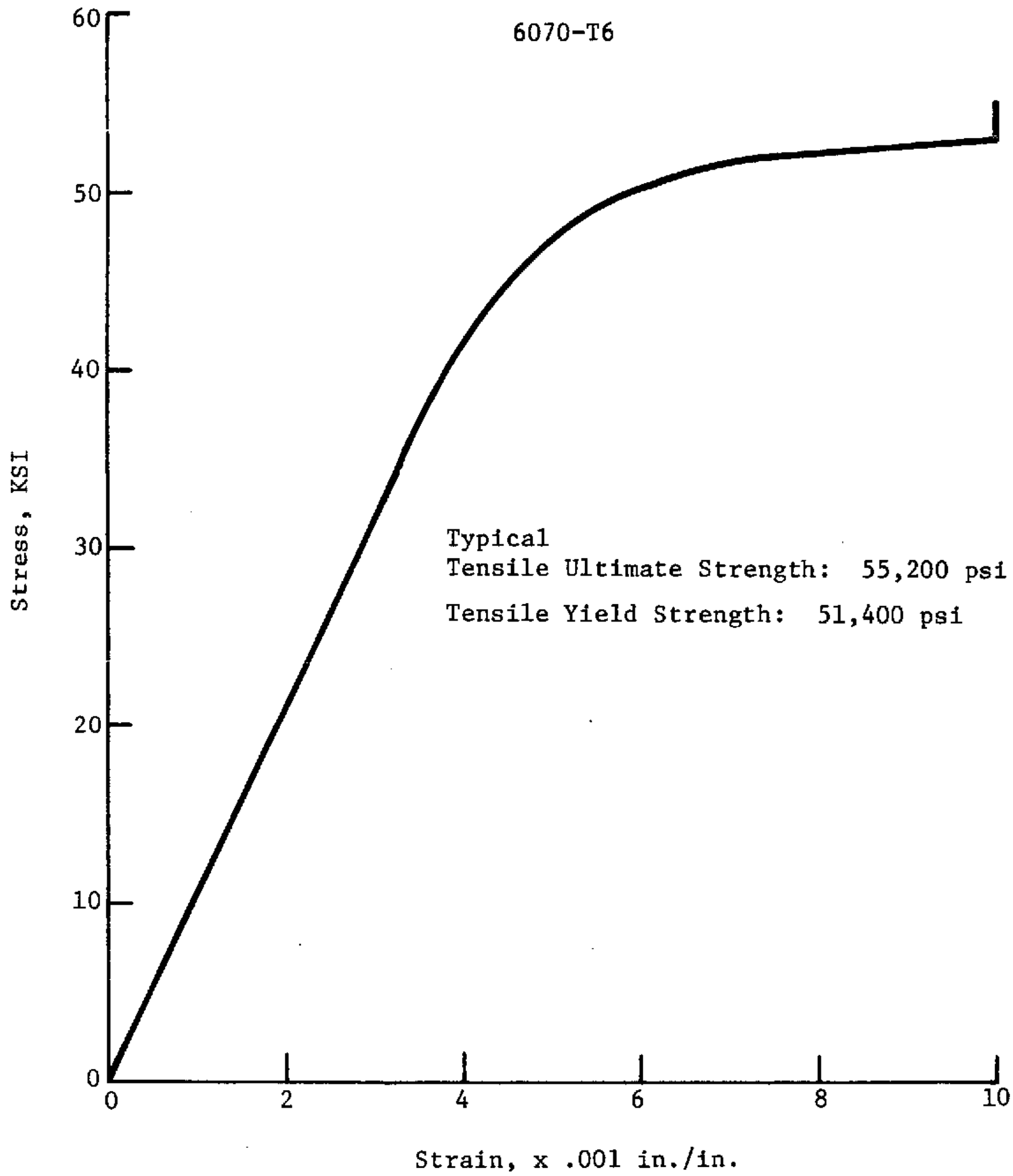


Figure IV-2 Typical Stress-Strain Curve for 6070-T6 Aluminum

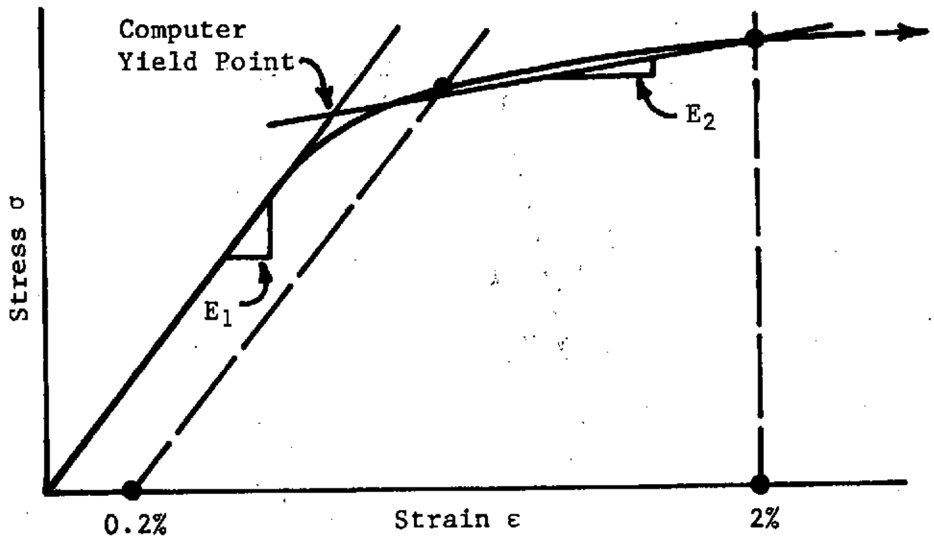


Figure IV-3 Bilinear Approximation of Stress-Strain Curve

2. Filament Design Stress

The selection of a filament or glass fiber design stress was complicated by the fact that fiber glass is subject to stress corrosion or time-dependent degradation of strengths when exposed to moisture. Although a fireman's pressure vessel would hardly be operating submerged in water, it does become wet from time to time and must be designed as though moisture were present and acting in a deleterious manner throughout its 15-year design life. To assess the degree of degradation, a high degree of confidence was placed in the data shown in Figure IV-4* which represents a compilation of static fatigue data for E-glass fiber. Although these data are for E-glass, it has been used to select our S-glass design stress level.

NOL ring tensile test data for our selected S-2 fiber glass and epoxy resin system (Chapter III.B) showed a fiber strength level of 300 ksi. Extrapolation of this data in Figure IV-3 shows only 40% strength retention after 15 years. This would produce failure at a fiber strength level of 120 ksi. Some degree of uncertainty must be placed upon such a procedure, thus a design stress level of 80,000 psi was selected as the maximum allowable fiber stress at operating, 4000 psig, vessel pressure or 88,000 psi at the maximum operating pressure--4500 psig.

*D. J. Soltysiak and J. M. Toth: "Static Fatigue of Fiberglass Pressure Vessels from Ambient to Cryogenic Temperatures." Douglas Aircraft Co., Inc. Report 59004, May 1966.

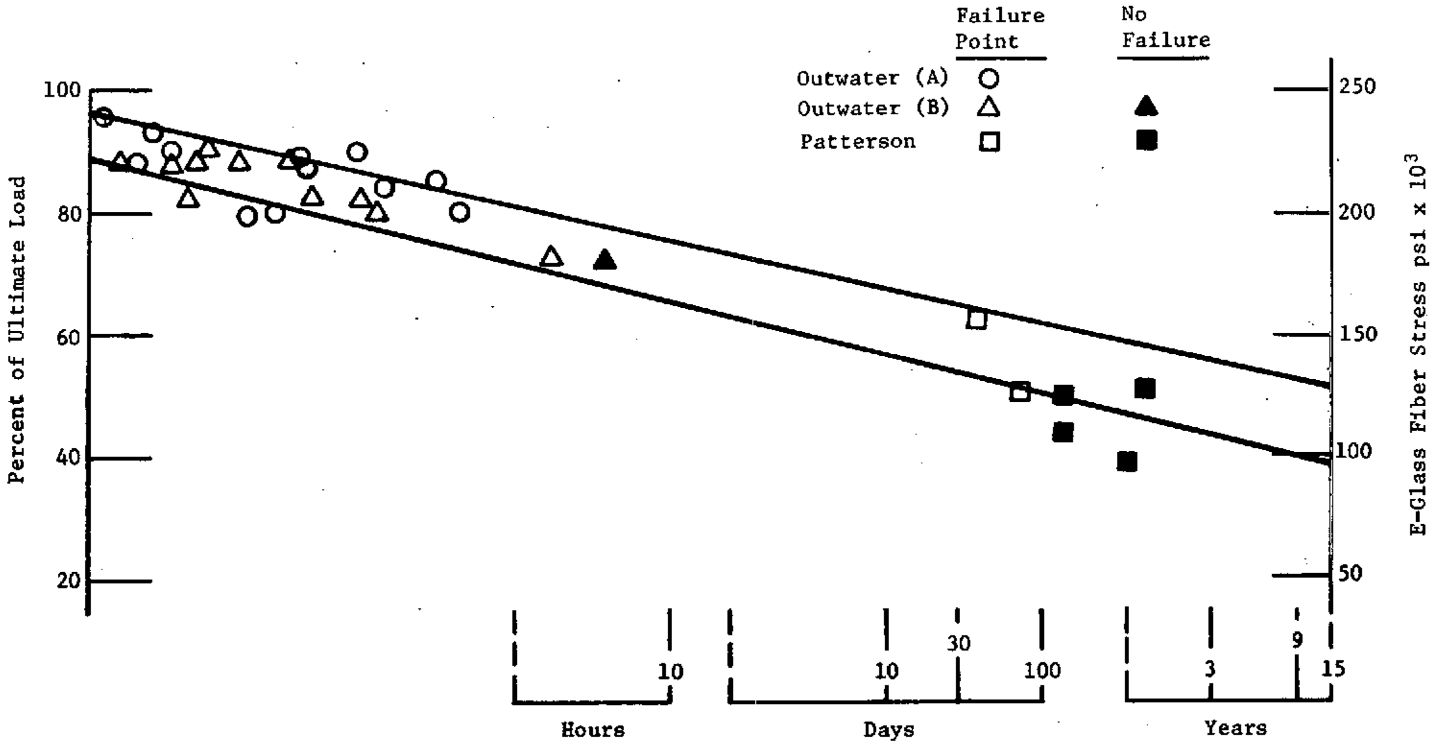


Figure IV-4 Static Fatigue Behavior of E-Glass Fiber-Overwrapped Pressure Vessels in an Environment

3. Design Pressure and Sizing Pressure

Design and sizing pressures were adjusted in an iterative manner to observe their effect on output values of liner and fiber stress. Acceptable levels of liner stress were based upon yield strength and fatigue properties of 6070-T6 aluminum. A maximum operating stress of 30,000 psi was selected on the basis of these two controlling factors. This same time-limiting stress was observed in both tension and compression--compression occurring after sizing when the plastically-deformed liner was depressurized.

The design pressure selection describes a situation where polar and hoop fiber stresses are equal. As the design pressure is increased above the operating stress, the unbalance between longitudinal and hoop stresses increases and vessel efficiency or performance factors decrease. Lowering the design pressure closer to operating pressure causes glass stresses to become excessive, above our selected limit of 80,000 psi. The design pressure is strictly a computer input parameter and must not be construed as the failing pressure level of the vessel nor is it significant to any operating pressure-level requirement. A final selection of 9500 psig was made for the design pressure.

Another important computer design input was the sizing pressure. As previously implied, the sizing and design pressures are interrelated and must be changed independently to observe the effect of either. The principal effect of this variable is to balance the liner compressive stresses after sizing and liner tensile stresses at operating pressures. A lower limit of 6750 psi (proof pressure) was dictated for this variable to preclude a subsequent proof to this level and its attendant effect upon operating stress levels. The effect of this variable was studied in the range of 6750 to 10,000 psig but a rather efficient balance was obtained at 7600 psig.

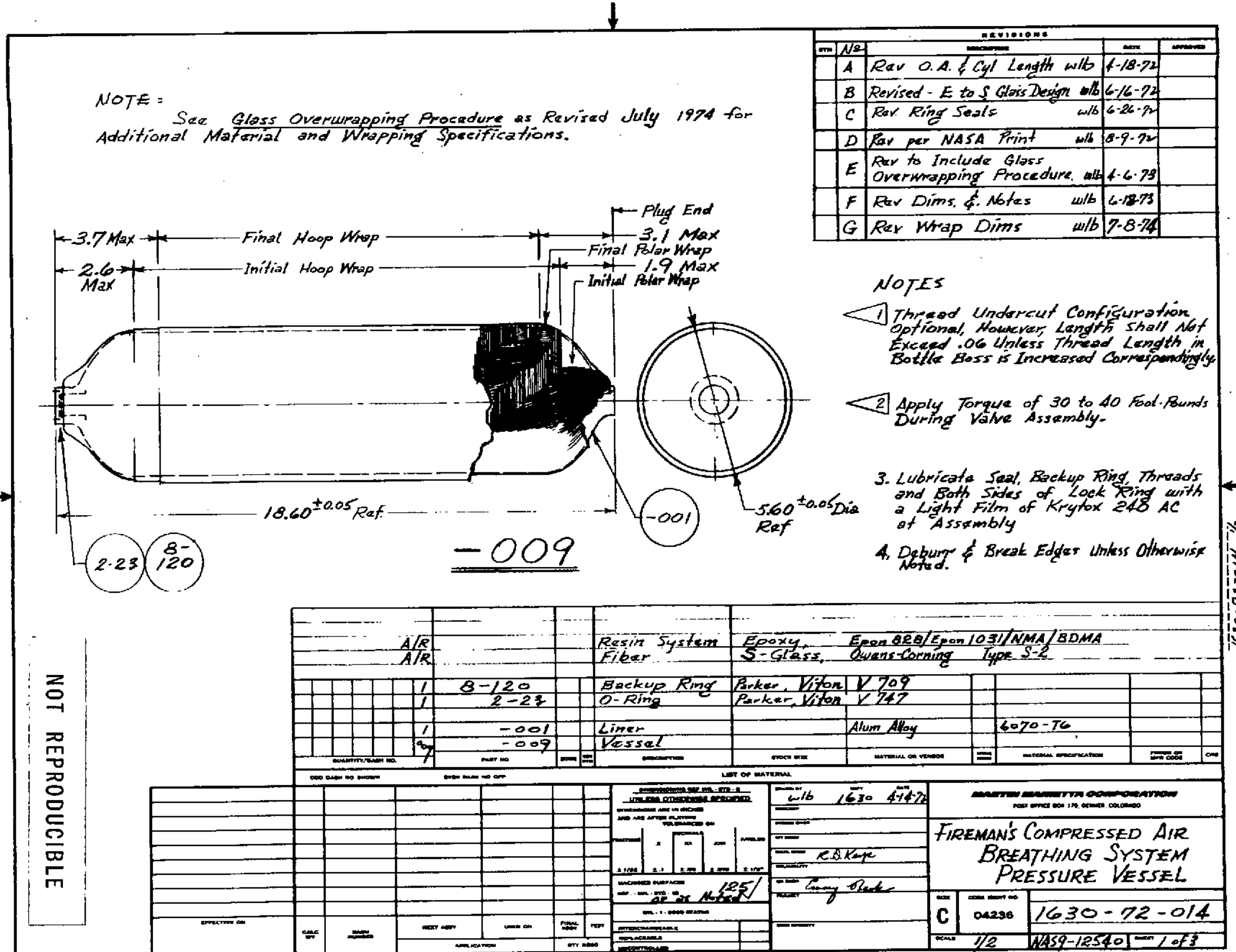
4. Computer Output Data

Using the aforementioned selections of computer input values, computed design stress output values were obtained and are shown in Table IV-2. These stresses fell within an acceptable range and are the predicted stress levels to be expected in the pressure vessel as manufactured under this contract. Other outputs obtained as fallout from the computer program (e.g., contour, shape, and overwrap thicknesses and quantity) dictated the final design configuration which is shown in Figures IV-5 and IV-6.

Table IV-2 Final Overwrapped Vessel Stress Values Using S-Glass Fiber

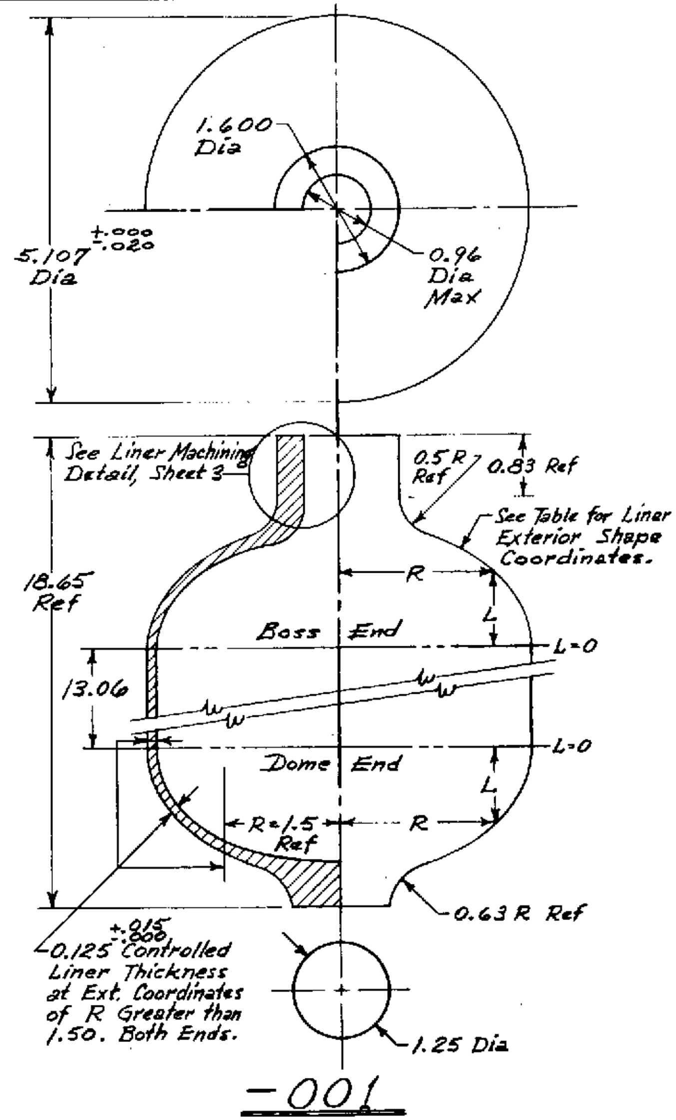
Liner Alloy, 6070-T6 Aluminum Alloy		Sizing Pressure, 7600 psi
Liner Thickness, 0.133 in.		Design Pressure, 9500 psi
Post Sizing Liner Stress	Hoop - -28.4 ksi	Axial - -7.5
Post Sizing Filament Stress	Hoop - 33.8	Axial - 25.0
Liner Stresses at 4500*	Hoop - 19.9	Axial - 28.3
Filament Stresses at 4500*	Hoop - 79.8	Axial - 50.0
Liner Stresses at 6750*	Hoop - 44.0	Axial - 46.2
Filament Stresses at 6750*	Hoop - 102.7	Axial - 62.5
Liner Stresses at 9000*	Hoop - 53.6	Axial - 53.5
Filament Stresses at 9000*	Hoop - 142.2	Axial - 110.5

All computer stress values are assumed to be accurate to 10% and an adjustment to manufactured products will be made accordingly.
*These values are pressures in psig.



NOT REPRODUCIBLE

Figure VI-5 Pressure Vessel Design Drawing



NOTE: Liner (-001) Shall Not Exceed 4.0 lbs Total Weight and Shall Have a Minimum Contained Volume of 280 cubic inches.

LINER EXTERIOR COORDINATES

	Ref No	R	L
Boss End	23	0.8 Ref	3.190
	22	0.8 Ref	2.360
	21	0.812	2.250
	20	0.870	2.100
	19	0.975	1.975
	18	1.134	1.882
	17	1.256	1.842
	16	1.412	1.775
	15	1.554	1.705
	14	1.695	1.608
	13	1.823	1.509
	12	1.934	1.411
	11	2.030	1.311
	10	2.134	1.186
	9	2.222	1.061
	8	2.297	0.935
	7	2.360	0.809
	6	2.413	0.683
	5	2.455	0.556
	4	2.488	0.430
	3	2.513	0.304
	2	2.528	0.177
	1	2.553 Ref	0.0
Cyl Sect		See Part Detail	
Dome End	1	2.553 Ref	0.0
	2	2.528	0.177
	3	2.513	0.304
	4	2.488	0.430
	5	2.455	0.556
	6	2.413	0.683
	7	2.360	0.809
	8	2.297	0.935
	9	2.222	1.061
	10	2.134	1.186
	11	2.030	1.311
	12	1.934	1.411
	13	1.823	1.509
	14	1.695	1.608
	15	1.554	1.705
	16	1.412	1.775
	17	1.256	1.842
	18	1.134	1.882
	19	0.950	1.950
	20	0.767	2.100
	21	0.675	2.250
	22	0.63 Ref	2.400

Tolerance for Liner Shape Coordinates to be ±.020 Unless Otherwise Noted.

REVISIONS

No	Description		Date	Approved
B	Redrawn	wlb	6-16-72	

Size	Code Ident No.	
C	04236	1630-72-014
Scale: Full	NAS 9-12540	Sheet 2 of 3

1630-72-014

Figure VI-6 Liner Detail Drawing

D. END BOSS DESIGN

Due to the potentially hazardous nature of an end boss failure at pressures of 4000 psi or above, the design of the pressure vessel end bosses received careful attention from both NASA and Martin Marietta. An outlet design was developed using a threaded throat section backed up by a shallow recess captive O-ring static seal (see Figure IV-6). Seal extrusion is prohibited by tight clearance tolerances between the liner and plug walls and by use of a seal backup ring. It will be mandatory to replace both the O-ring and backup ring each time the end plug is removed from the vessel and reinstalled.

Severe mechanical test requirements for the pressure vessel forced development of an end-plug/valve body design which would protect the liner outlet boss in service. A wide flange on the end-plug/valve body prevents accidental bending or damage to the lip of the outlet boss in service and puts that portion of outlet boss above the threads in slight axial compression (after tightening the end-plug to 30 or 40 ft-lb torque). A lock-tab washer is used to anchor the assembly after tightening.

The 1.062 - 12 UN3A internal thread for the end boss was intended for hardware standardization. Threads are continuous into the tank dome, permitting the internal boss end radius to generate a vanishing thread and minimize thread-exit stress concentrations. In service, the threads, O-ring, backup ring, and lock washer faces are to be lubricated with a light film of Krytox 240AC before assembly.

Design stress values for the outlet end boss are as follows:

	Pressure	
	4500 psig	9000 psig
End Boss Hoop Stress in Threaded Region	13,600 psi	27,200 psi
End Boss Hoop Stress in Seal Region	16,300 psi	32,600 psi
Thread Shear Stress (Including Fitting Torque)	7,300 psi	14,600 psi

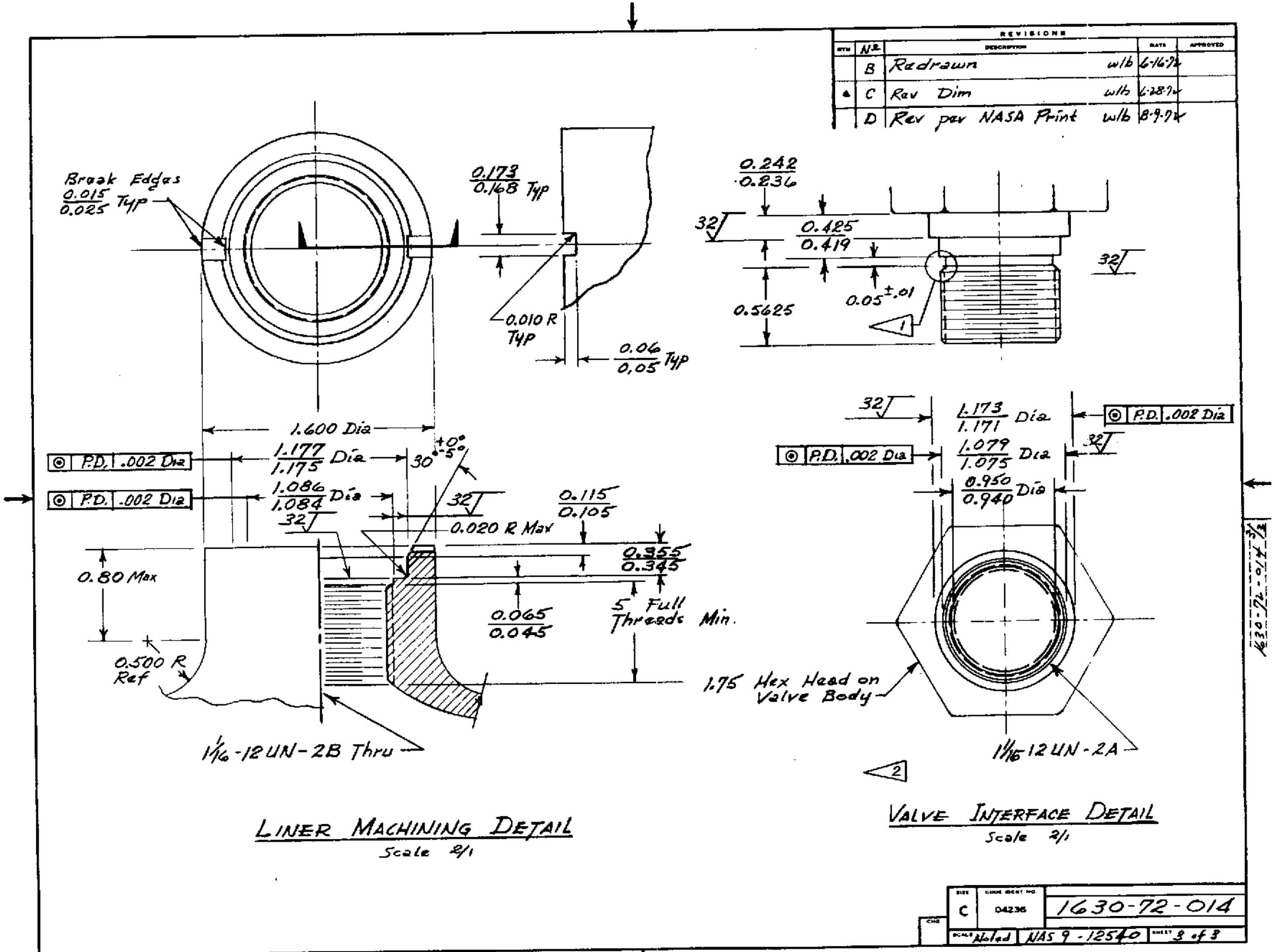


Figure VI-7 Boss End Detail

A simulated integral end boss was designed to remain inherent with the liner base after external contour machining. The "dummy" boss provides a shoulder to simplify winding, a center for lathe turning, and an exposed liner portion for inspection stamping or affixing metal identity plates.

E. FRACTURE MECHANICS ANALYSIS

A brief fracture mechanics approach to liner design was used to insure leakage before catastrophic failure in the event the pressure vessel is punctured in service. The liner thickness requirement for potential plane-strain conditions is indicated from the ASTM guideline by solving the ratio:

$2.5 \left(\frac{K_{I_c}}{\sigma_{ys}}\right)^2$. For 6070-T6 aluminum alloy, with an estimated K_{I_c} of 24 ksi $\sqrt{in.}$ and σ_{ys} of 52 ksi, this ratio gives a minimum required thickness of 0.53 in. A liner wall thickness of about 0.130 in. would then insure plane stress conditions exist and a more ductile flaw behavior.

If a through-crack were induced in a 0.130 in. thick overwrapped liner wall in service at 4500 psi maximum operating pressure, with a maximum liner stress of 25 ksi, the critical flaw length (2a) can be developed from the "Griffith Crack" expression for a through-crack in a semi-infinite panel. Using a K_c of 40 ksi $\sqrt{in.}$ (conservative) for this thin-gage material, we obtain

$$K_c = \sigma\sqrt{\pi a}$$

$$a = \frac{K_c^2}{\sigma^2\pi} = \frac{1}{\pi}\left(\frac{40,000}{25,000}\right)^2 = 0.8 \text{ in.}$$

The critical crack length (2a) would then be approximately 1.6 in. long--far in excess of any requirement for the vessel. It has been observed that flaws growing from pressure vessel cyclic stresses normally grow through-the-thickness and cause depressurization by leakage before reaching critical flaw length. Moreover, the relatively large plastic zone size for aluminum material promotes crack tip blunting for extremely deep surface flaws, thus promoting plane stress conditions and through-crack behavior.

Sample liner sections were surface notched and cyclic loaded at 30 ksi tensile stresses beyond anticipated pressure vessel life (20,000 cycles). No appreciable flaw growth was detected, thus indicating a normal vessel life expectancy in the presence of manufacturing notches and scratches.

Liner thicknesses most favorable from the fracture mechanics approach were those not exceeding 0.5 in. with operating wall stresses below 30,000 psi. The final vessel design fitted within these guidelines.

V. PRESSURE VESSEL FABRICATION

Fabrication of the pressure vessel is accomplished by first forging a 6070 aluminum liner into the design shape shown in Figure IV-5. After heat treatment, the liner is overwrapped with S-2 fiber glass and an epoxy resin system. Once the resin fiber glass composite is cured, each vessel is subjected to a sizing pressure of 7600 psig. These three steps in vessel fabrication are described in detail in the following sections of this chapter.

A. LINER FABRICATION

Much of the difficulties encountered in previous overwrap vessel contracts were associated with weld defects and the geometrical perturbation caused by welding. To alleviate this concern, it was our primary goal to pursue a liner fabrication technique which would eliminate the need for welding, its attendent problems, and higher manufacturing costs. A study was conducted early in this program to determine the feasibility of manufacturing an integral one-piece aluminum liner using forging or deep-drawing techniques.

It was immediately evident that a forging process would be more economical than multiple-step deep-drawing to form the cylindrical section of the vessel. But, the main production problem to overcome was to resolve the method of boss end closure. Two possible methods of closure were studied: namely, spin forming or forging. Attempts to spin-form to the configuration dictated by computer analysis were largely unsuccessful, resulting in low-angle curvature and considerable section build-up. Forging appeared to be the most promising closure method as successfully demonstrated by Martin Marietta Aluminum on 6061-T6.

Martin Marietta Aluminum was contracted to produce the limited quantity of vessels necessary to complete our test program and the field qualification test articles that we were required to deliver to NASA (a total quantity of 48 liners were procured)*.

----

*An additional quantity of 55 vessels were manufactured later in the program to support long term environmental exposure tests. Details of this task are given in Appendix F.

This pressure bottle, our part number is 1630-72-014-001, required the need for a relatively high-strength, light-weight, and good corrosion resistant material. The material selected, aluminum alloy 6070-T6, has the above characteristics, and Martin Marietta Aluminum's Torrance facility had extensive experience in producing this alloy in impact extruded products.

The basic procedure for fabricating the pressure bottles involved impact extruding a tubular blank with a solid base, neck forming the open end to obtain the contoured reduced section, final heat treating and machining.

Although the die-formed necking process had been proven successful in other applications, inherent difficulties were encountered with this pressure bottle that necessitated the evaluation of four different procedures to obtain optimum results.

1. <u>Evaluation of Neck Forming Operation</u>

The die-formed necking process basically involves placing the tubular blank in a solid die which is contoured to the final part configuration. In the process, the die is heated to a relatively high temperature and the open end of the tubular blank is pressed into the die cavity. Although the blank is at ambient temperature before forming, the worked area is immediately heated and softened by intimate contact with the die. During the forming operation the unheated tubular portion of the part must retain a column strength sufficient to withstand the forming pressure. Figure V-1 illustrates the hot forming die and a part after the neck forming operation.

The original lot of parts produced, and subsequently shipped to Martin Marietta's Denver division for evaluation, consisted of neck forgingin a "one-pass" hot die operation with the extruded blank in the as-impacted condition. After heat treatment to the final temper representative parts were sectioned and examined for macrostructure and visual surface appearance in the heavily-reduced neck area. Although material in this area must gather causing a thickening of the wall during forming, these initial parts showed a heavy wrinkling condition of the I.D. of the part with some cracking at the root of the folds. This condition was attributed to the highly elongated, as-extruded grain structure present in the part during forming. The macrostructure in this area after heat treat showed a coarse recrystallized grain structure caused by the critical amount of work induced during the hot die-forming operation on the unrecrystallized grain structure of the as-extruded blank.

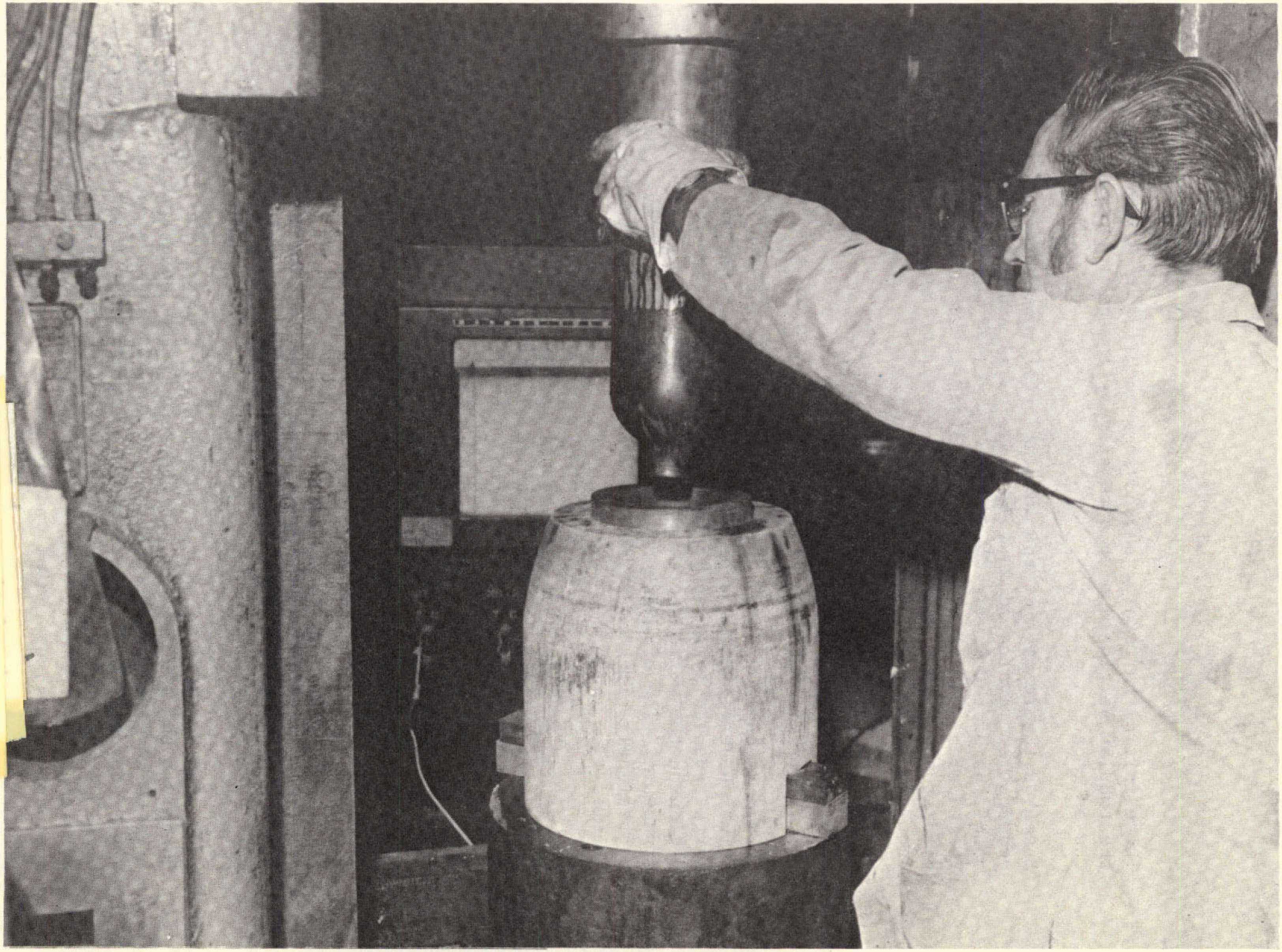


Figure V-1 Hot Die Neck Forming Operation

These initial parts also showed some buckling or deformation in the tubular section due to a relatively low column strength in the as-impacted blank.

Based on the results of the initial trial run, three other procedures were evaluated in an attempt to a) minimize the wrinkling condition of the inside neck area, b) reduce the grain size in the formed area, and c) increase the column strength of the impacted blank to eliminate any buckling or deformation on the tubular section.

The first evaluation consisted of solution heat treating the impacted blanks to the T4 temper prior to the neck forming operation. This was done in an attempt to refine the grain structure and also add more strength to the tubular section. The parts were neck formed in one operation through the hot forming die and then re-solution heat treated and aged. Sectioning of representative parts revealed a marked improvement in the surface wrinkling condition on the inside neck area and a fine recrystallized grain structure. The strength of the tubular section, however, was not sufficiently high to prevent some buckling during the forming operation.

The second experimental group consisted of solution heat treating and artificially aging the impacted blanks to the T6 temper prior to neck forming to obtain maximum column strength. The blanks again were formed in one operation through the hot forming die. No deformation or buckling was encountered in the tubular section and the wrinkling on the inside neck area of the bottle was reduced to an acceptable level. Macrostructure examination of the formed area after final heat treat showed a fine and uniform recrystalized grain structure.

Although the second experimental group provided an acceptable procedure for neck forming the blanks, one more evaluation was made that incorporated two additional modification to refine the process.

In this final evaluation, the impacted blanks were again solution treated and aged prior to forming. The closed ends of the blanks were then contour machined prior to forming to afford better vertical alignment of the parts during the necking operation. (This machining was formerly done as a final operation in the procedure). The neck forming operation was then carried out in two die operations to further minimize the wrinkling condition. The first operation was performed in the hot-forming die which had been slightly modified to increase the radius of contour in the neck area. The second operation was performed in a cold sizing die which provided the final contour of the formed area.

The results of this processing sequence showed a very satisfactory surface condition in the neck formed area which was a slight improvement over parts produced in the second evaluation process. This procedure was tentatively established as the optimum processing sequence to be used and the entire contract of 48 units was produced in this manner.

2. Metallurgical Evaluation

Sample parts representing the final evaluation group were selected for metallurgical review which included macrostructure and visual examiniation of the neck formed area, macrostructure of the contoured base and mechanical properties of the tubular section. Listed in Table V-1 are the results of mechanical properties obtained from three longitudinal tensile specimens taken 120 degrees apart in the tubular section of the bottle.

Figure V-2 is a sketch of the pressure bottle showing the test location for macrostructure and mechanical property evaluation.

Figure V-3 represents the macrostructures of Section A-A in Figure V-2 showing the grain flow in the cross-section of the neck formed area. This section shows a relatively fine recrystallized grain structure and a slight amount of wrinkling in the area where the wall thickened to form the neck end of the bottle.

Figure V-4, which is the same section as shown in Figure V-3, illustrates the wrinkle condition on the inside of the bottle which is typical when the metal gathers to from the reduced neck area. The wrinkles are very shallow and show no signs of folds or cracks.

Illustrated in Figure V-5 is a transverse macrostructure of section B-B in Figure V-2 showing the base of the neck formed area of the bottle. The grain structure and wrinkle condition are very satisfactory and typical for a forming operation of this type.

Figure V-6 illustrates the macrostructure of the contour-machined base area of the bottle (Section C-C in Figure V-2). The cross-section shows a very fine and uniform recrystallized grain structure.

Table V-1 Life-Support Pressure-Bottle Blank (Part No. 1630-72-014-001 Alloy 6070-T6)

Mechanical Properties		Yield Strength psi	Ultimate Strength psi	Elongation % in 2 in.
Test Specimen(1)	Test Direction			
1	Longitudinal	52,600	56,400	11
2	Longitudinal	52,500	56,600	13
3	Longitudinal	51,900	56,500	13
Minimum Property Requirements	Longitudinal	45,000	48,000	6

(1) Specimens taken from tubular section 120° apart.

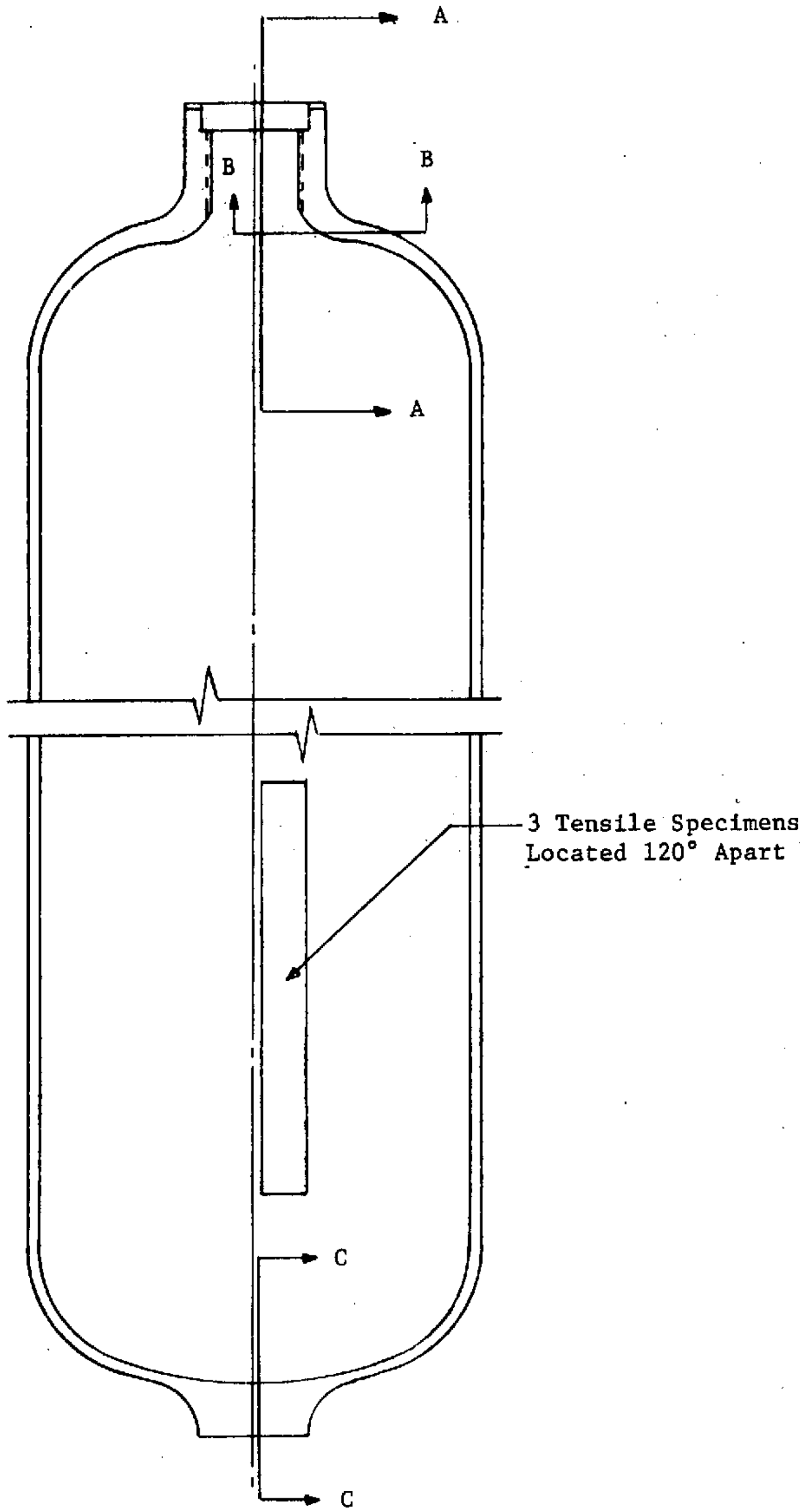


Figure V-2 Specimen Location for Mechanical-Property and Macrostructure Examination

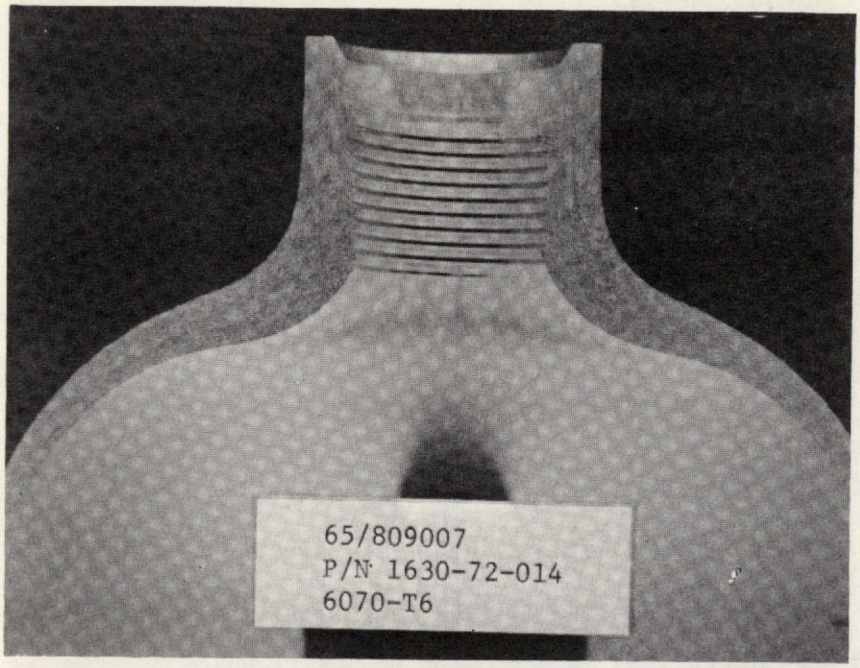


Figure V-3 Photomacrograph of Section A-A (Figure V-2) Showing Grain Flow Pattern in Neck Formed Area of Bottle, (Part Shows Relatively Fine Recrystallized Grain Structure Throughout Cross-Section.) Mag: IX Etch: Caustic

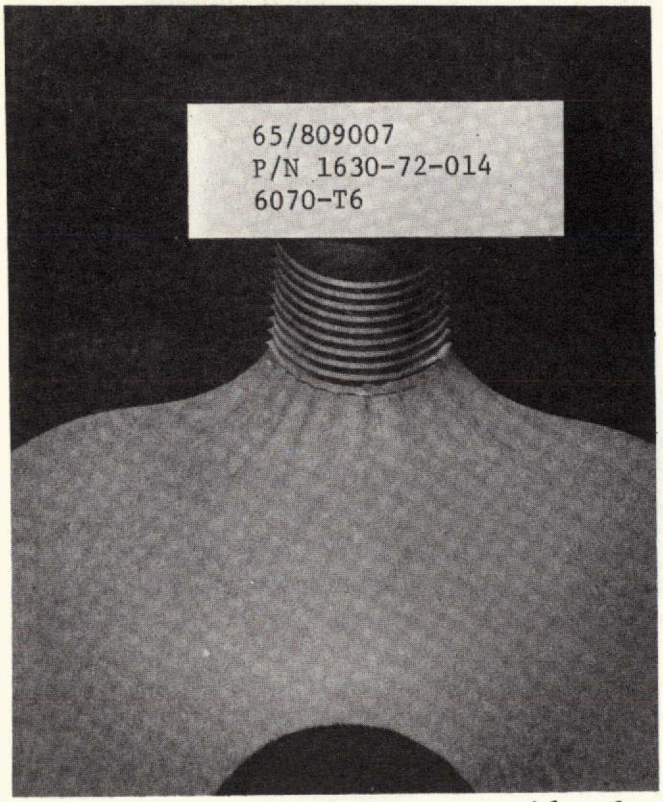


Figure V-4 Cross-Section of Inside of Bottle in Neck Formed Area Showing Slight Wrinkling where Material Gathered during Forming. Mag: IX Etch: Caustic

This page is reproduced at the

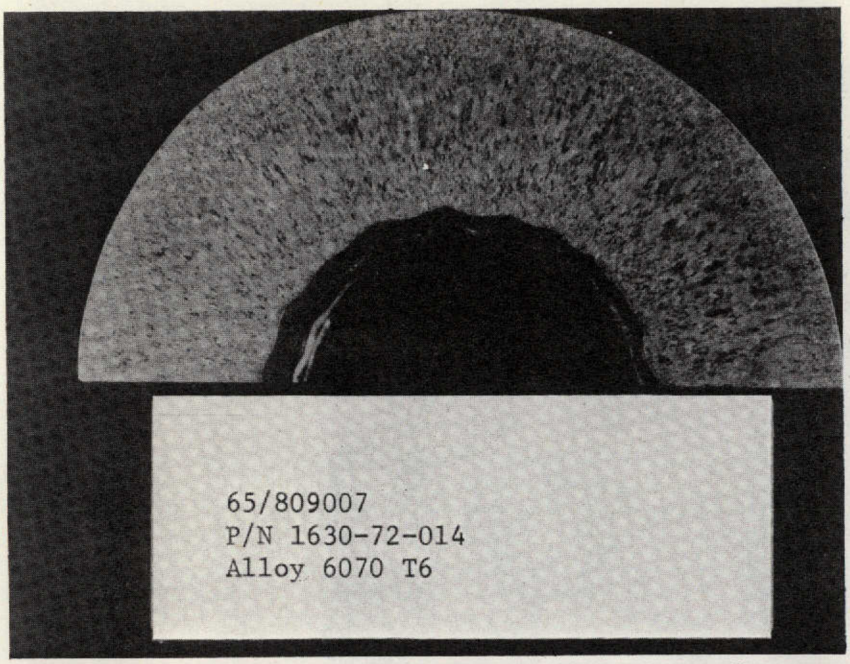


Figure V-5 Transverse Macrostructure of Section B-B (Figure V-2) Showing Base of Neck Formed Area of Bottle (Wrinkles Due to Metal Gathering During Forming are Very Shallow and Show no Folds or Cracks.) Mag: 2X, Etch: Caustic

This page is reproduced at the
better detail.

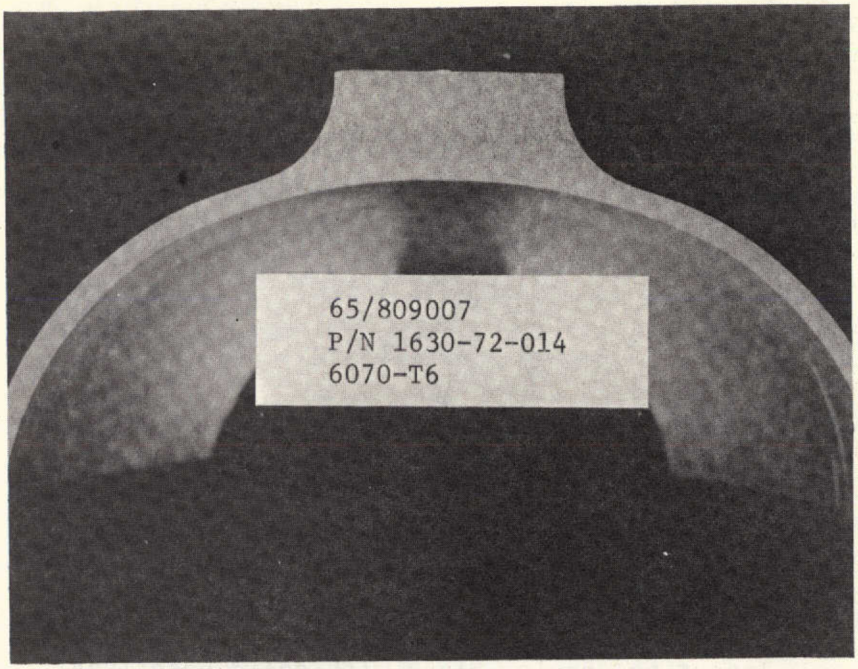


Figure V-6 Macrostructure of Contour-Machined Base Area of Bottle-Section C-C of Figure V-2 (Cross-Section Shows Very Fine, Uniform Recrystallized Grain Structure) Mag: 1X, Etch: Caustic

3. <u>Process Procedure</u>

The evaluation of the various procedures used to produce the optimum pressure bottle blank resulted in the following tentative processing procedure:

Process Sequence	Operation
1.	Saw stock to required length.
2.	Face and machine corner radius of stock blank.
3.	Anneal stock blank per MIL-H-6088
4.	Clean and apply phosphate-bonderlube coating.
5.	Impact to tubular blank with solid base (See Figure V-7).
6.	Trim to length.
7.	Inspect for surface condition.
8.	Contour machine closed end (See Figure V-8).
9.	Heat treat and age to T6 temper per MIL-H-6088.
10.	First neck form operation - hot die (See Figure V-9).
11.	Final neck form operation - cold die (See Figure V-10)
12.	Re-heat treat and age to T6 temper per MIL-H-6088.
13.	Submit test sample to Laboratory for metallurgical testing and job release.
14.	Machine port end (See Figure V-11) and identify.
15.	Chemical clean.
16.	Inspect - visual, dimensional, weight and volume.

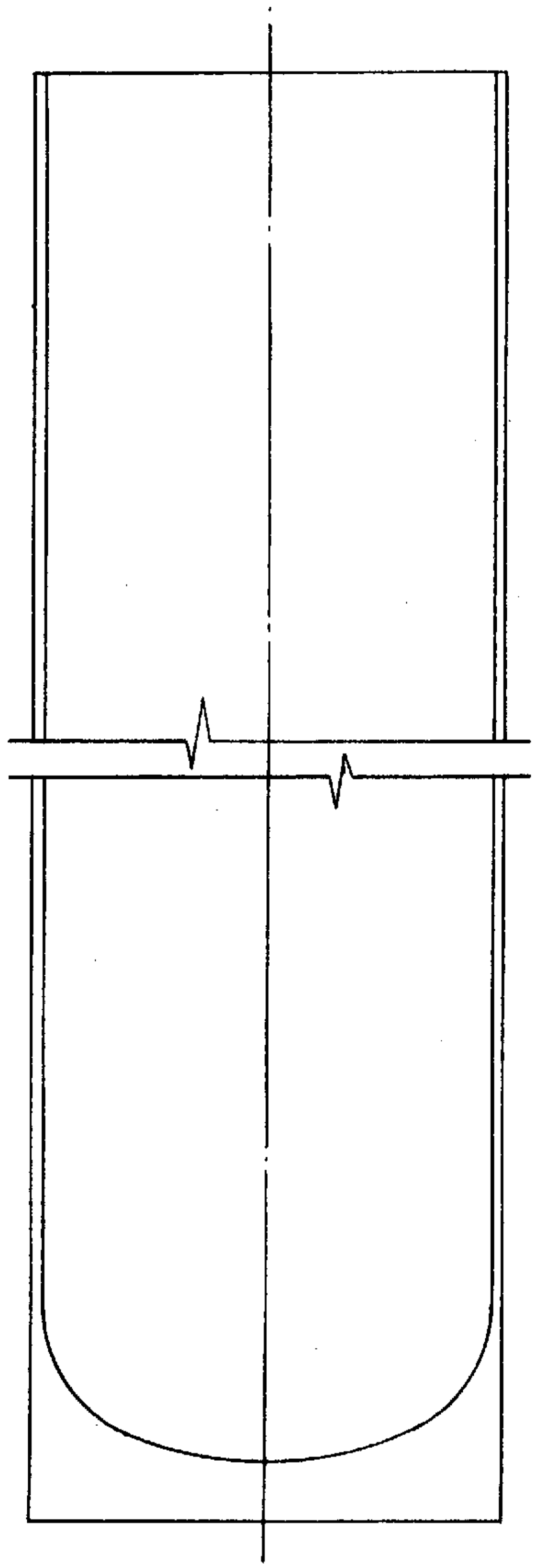


Figure V-7 Impacted Tubular Blank

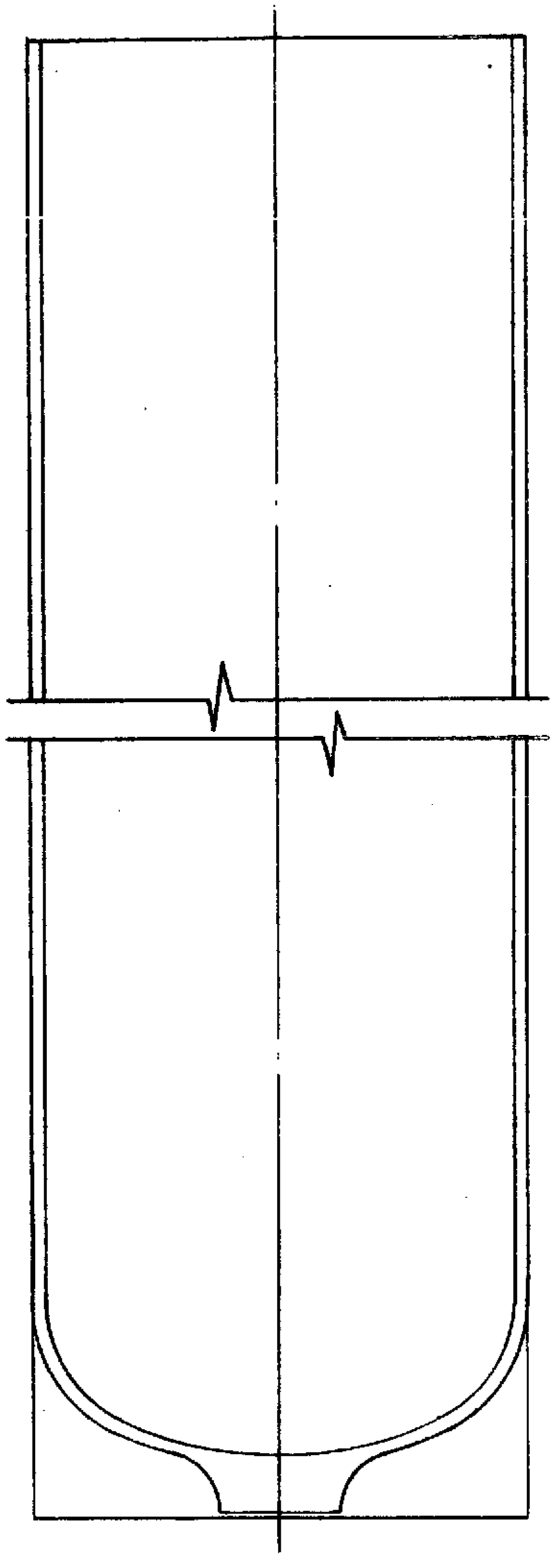


Figure V-8 Contour-Machined Closed End

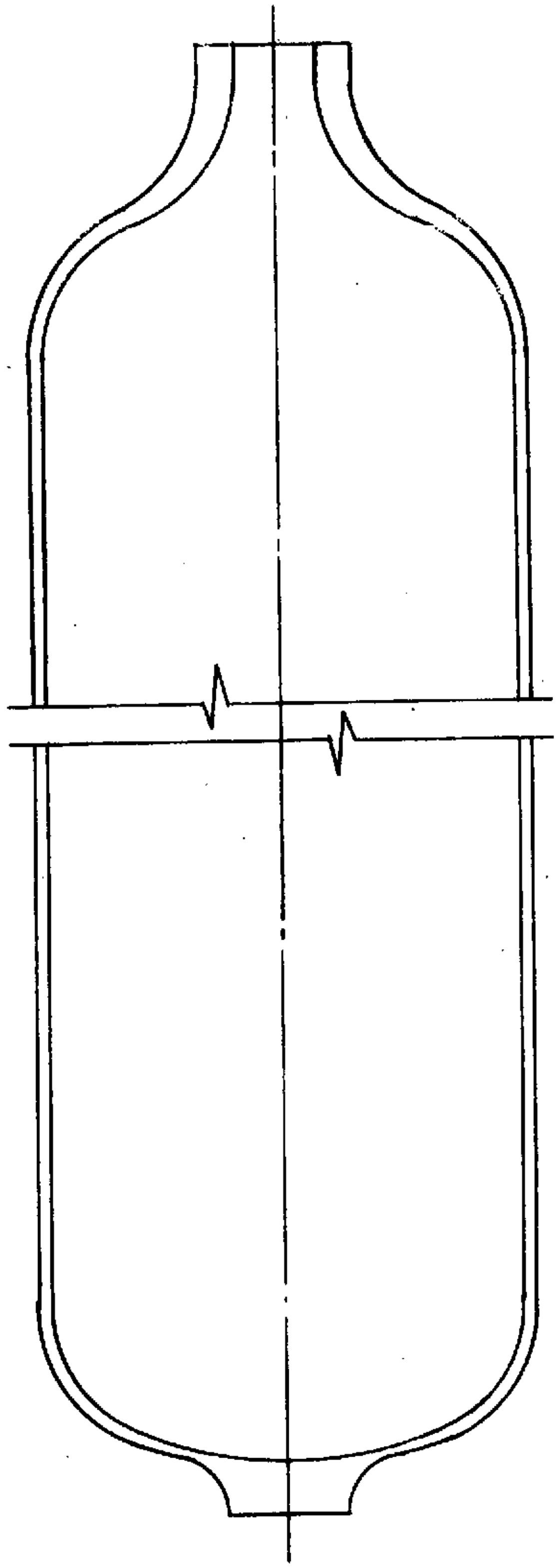


Figure V-9 First Neck-Form Operation

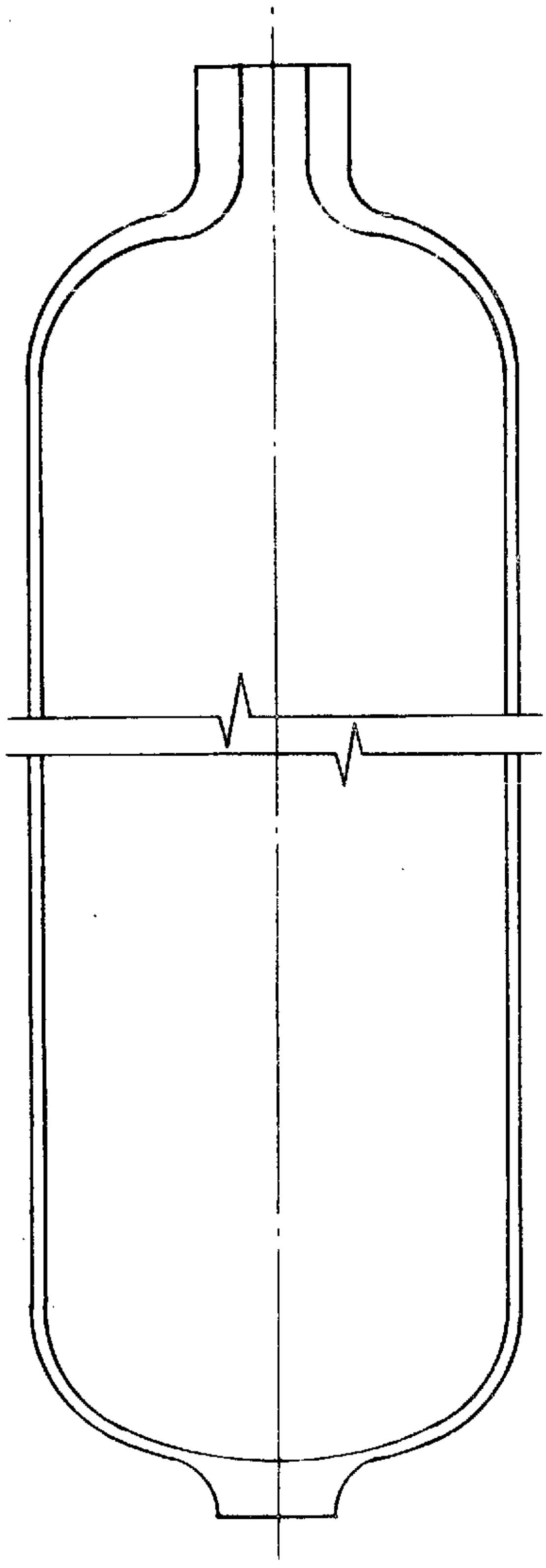


Figure V-10 Final Neck-Form Operation

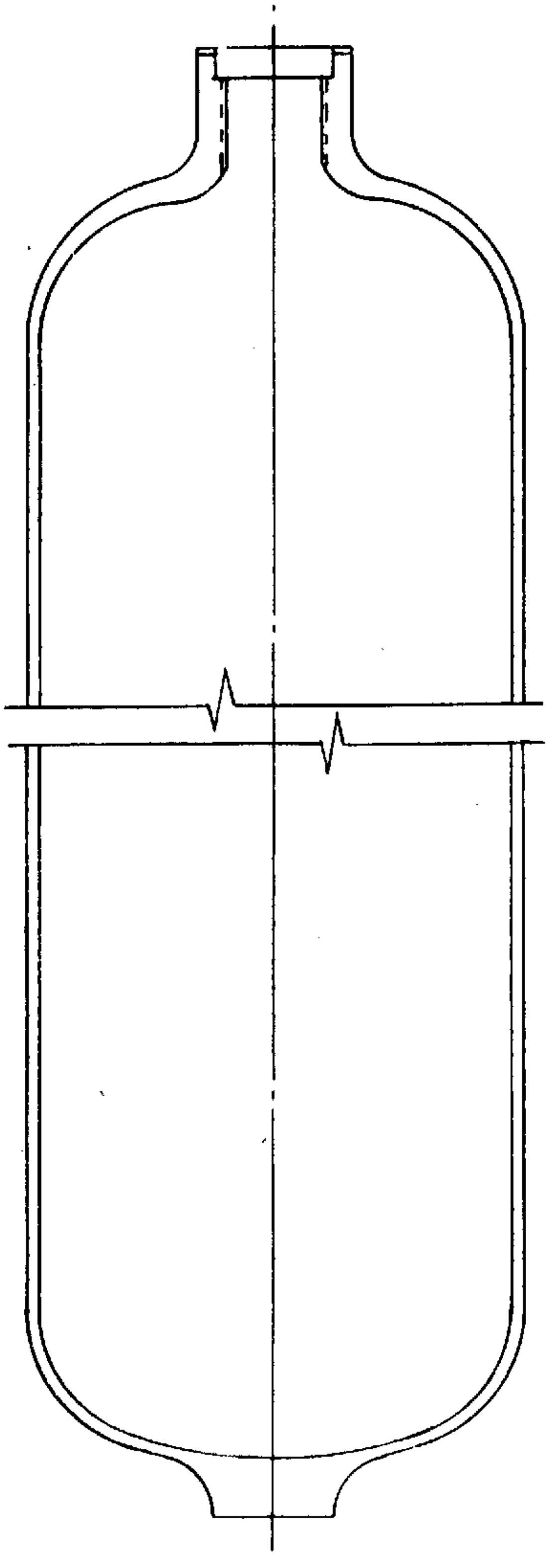


Figure V-11 Final Machining of Port End

4. <u>Liner Inspection and Preparation for Overwrapping</u>

A preliminary liner inspection was performed at Martin Marietta Aluminum. This was to insure that each liner shipped to Martin Marietta's Waterton facility met our design requirements, especially, weight, volume, shape, and thickness. Each vessel was also pressurized to about 40 psig to check for leakage and proper thread engagement of the male pressure fitting.

The 48 delivered liners had pertinent dimensions in the range noted below:

Weight range	3.81 to 3.92 lbs
Volume range	280 to 282 $in.^3$
Liner diameter	5.079 to 5.094 in.
Liner length	18.55 to 18.68 in.

The metal thickness in cylindrical areas was ultrasonically determined on all liners. The acceptable range was 0.125 to 0.140 in. thick. Proper heat treatment of the liners was controlled by taking test samples from the production run. Mechanical and chemical properties of material taken from samples in the production run conformed to acceptable limits delineated by Alcoa in Appendix D.

After this preliminary inspection, all acceptable liners were shipped to our facility for final inspection and selection and preflawing of test article liners. Each test article liner was flawed in three locations: one flaw in the cylinder area and one in each dome area. The flaws were 0.006 in. deep by 1.0 long and were produced by using a sharp razor blade.

Each vessel was visually examined prior to overwrapping with special emphasis on surface imperfections, e.g., dents, scratches, and scuffs.

Those vessels passing inspection were shipped to Advanced Composits, Inc., Salt Lake City, Utah, for overwrapping.

B. VESSEL OVERWRAPPING

As discussed in the preceding chapter, S-2 fiber glass with epoxy resin was chosen as the composite overwrap material for the fireman's breathing vessel. The amount of overwrap material, and the method and angle of application to the vessel, had been determined by analysis. The economic influence in our design work had dictated the necessity of overwrapping the vessel with a wet-winding technique instead of using preimpregnated glass roving.

Several condidate overwrapping contractors were approached in regard to our requirements which resulted in the selection of Advanced Composites Inc. (ACI), Salt Lake City, to perform this important function.

1. Qualifying Material and Development of Winding Technique

NOL ring test samples were prepared by ACI from the S-2 (20 end) fiber glass material using the selected epoxy resin system. Data from these NOL ring tests are given in Chapter III. The strength of the material was in the normal range expected.

Rejected aluminum liners were used as dummy models to develop reasonable winding procedures in regard to speed, offsets, fiber tension, pattern, winding and head travel limits, and other minor adjustments to the equipment. The temperature of the resin was also a very important variable: when the resin temperature becomes too high, slippage occurs, but if it is allowed to cool to room temperature, it becomes unworkable causing excessive resin buildup and poor fiber wetting.

2. Alternating Layer Technique

Initial vessels overwrapped using the conventional technique of first applying all polar-oriented material and then adding the hoop reinforcing material showed a failure site originating at the junction of the polar and hoop wrap material. The failure pressure, although far above requirements (typically about 11 to 12,000 psig), occurred at theoretically-low fiber stresses. It was felt this difficulty was being caused by the inablility to adequately reinforce the junction* of the dome areas where higher

---

*A wet winding technique offers little resistance to sluffing when one is attempting to hoop wind out to the cylinder-dome junction without external support. Therefore, little hoop reinforcement of this area can be realized.

hoop stresses in the cylinder section are changing to more balanced, lower stress areas in the dome. As a conceivable solution to this problem, it was decided to alternately wrap the vessel in four steps rather than the conventional two-step technique. This allows extension of the hoop-wrap material into the dome areas because this unsupported material is subsequently laced down with polar material prior to staging of the resin (most slippage occurs when the resin becomes extremely liquid during staging). As increase of approximately 12% or 1300 psig was realized by incorporating this technique with no increase in weight. The location of failure, however, was still unchanged indicating a greater margin of strength still exists in the hoop or cylinder area of the vessel.

3. Fiber Glass Overwrapping Procedure

The procedure used to overwrap all 6070-T6 aluminum liners which were subsequently used as test articles to satisfy the test requirements of this contract is given in Appendix E as a Martin Marietta procedure specification MCR-73-86. This particular procedure identifies the method by which specific design quantities of the selected overwrap material as discussed in previous chapters have been applied to the 6070-T6 aluminum liners to achieve the required vessel performance.

4. Vessel Sizing

Before sizing, all deliverable and test article vessels were measured for various physical properties. A listing of these properties is given in Table V-2. The volume of some vessels was obtained after sizing. These values are also given in the table.

Each vessel must be sized using a pressure of 7600 psig to realize optimum design performance of the vessel. This procedure effectively causes the liner to operate in a compression-tension stress zone instead of tension-tension which extends the cyclic life of the vessel.

Sized vessels will exhibit crazing which, at least to the experienced eye, will be quite apparent. The degree of crazing is highly dependent upon the resin content at the surface of the vessel, i.e., a resin rich surface will craze more extensively than a dry surface. Normally a drier surface is more desirable, but in either case the effect upon performance was found to be minimal.

5. Fabrication Costs

At the time of this writing, production rate (5000 quantity lots) costs of this vessel are indicated to be:

Liners (6070-T6 aluminum)	$16.00 each
Overwrap Materials (S-2 and resin)	10.00 each
Overwrapping, Sizing, and Quality Control	10.00 each
	$36.00 each

Table V-2 Dimensions of Manufactured FBS Vessels
(All dimensions before sizing except as noted)

No.	Length (in.)	Weight (lbs)	Diameter (in.)	Volume (in.^{3})	Liner Weight (lbs)	Liner Diameter (in.)	Volume* (in.^{3})	Diameter* (in.)
Delivered Vessels								
8	18.59	8.24	5.62	280.9	3.84	5.08		
10	18.55	8.74	5.63	281.4	3.83	5.09		
16	18.54	8.26	5.63	281.2	3.88	5.08		
17	18.59	8.21	5.63		3.85	5.08		
20	18.55	8.35	5.65		3.85	5.09		
27	18.58	8.44	5.64		3.86	5.09		
29	18.59	8.60	5.65	282.3	3.86	5.09		
30	18.55	8.33	5.63		3.88	5.09		
31	18.56	8.41	5.63		3.89	5.09	283.0	5.62
36	18.55	8.39	5.63		3.87	5.09	283.2	5.62
37	18.59	8.40	5.63		3.89	5.09		
39	18.57	8.24	5.64		3.85	5.09		
44	18.58	8.16	5.63	282.1	3.84	5.09		
45	18.54	8.40	5.65		3.88	5.09		
46	18.57	8.37	5.63		3.84	5.09		
47	18.57	7.86	5.56		3.83	5.09	283.5	5.58
48	18.58	8.30	5.61	281.6	3.83	5.09		
60	18.58	8.21	5.62	280.0	3.90	5.09		
62	18.59	8.66	5.65		3.92	5.09		
64	18.60	8.47	5.65		3.90	5.09		
65	18.64	8.18	5.63	280.6	3.81	5.09		
66	18.60	8.35	5.63		3.84	5.09		
67	18.63	8.22	5.61		3.92	5.09		
68	18.56	8.34	5.63	279.7	3.90	5.08		
69	18.66	8.34	5.62		3.84	5.08		
70	18.68	8.30	5.63		3.88	5.09		
71	18.68	8.39	6.63	280.7	3.86	5.08		
72	18.66	8.27	5.55		3.91	5.09		
73	18.59	8.16	5.62	280.7				
74	18.68	8.14	5.55		3.82	5.08		
76	18.62	8.55	5.64		3.90	5.09		
77	18.64	8.19	5.55	280.7	3.82	5.08		
79	18.67	8.34	5.63	281.9				
Development and Test Vessels								
3	18.60	8.98	5.61	281.0	3.92	5.09		
4	18.57	9.08	5.65	281.2	3.84	5.08		
5	18.56	8.07	5.58	281.4	3.82	5.09		
6	18.55	7.83	5.59	281.4	3.84	5.09		
7	18.55	7.91	5.62		3.81	5.09		
13	18.57	8.34	5.60	281.4	3.84	5.09		
14	18.58	8.34	5.63	281.4	3.86	5.08		
15	18.58	8.09	5.57	281.6	3.85	5.09		
18	18.60	8.38	5.57	282.2	3.82	5.09		
19	18.56	8.43	5.65	280.7	3.84	5.09		
21	18.62	8.13	5.55	281.5	3.86	5.08	282.7	5.56
22	18.62	8.20	5.57	283.4	3.82	5.09		
34	18.59	8.54	5.62	281.2	3.85	5.09		
35	18.54	8.02	5.69	281.4	3.89	5.09		
75	18.82	8.23	5.61	284.4	3.90	5.09		

* Vessel dimensions after sizing

VI. VESSEL TEST EVALUATION

The pressure vessel developed in this program required an intense test evaluation before it could be considered for use in a fireman's breathing system (FBS). The general requirements for this evaluation were specified by NASA and are presented in Appendix A.

To satisfy these general test requirements, a specific test plan and procedure were prepared. Before embarking on our planned test sequence, several preliminary development tests were conducted. These will be discussed initially.

A. DEVELOPMENT TEST RESULTS

The minimum burst pressure requirement for this vessel was 9000 psig. It should be noted however, that this requirement is to be attained after a complete series of test exposure conditions that include: cyclic pressure testing at proof (6750 psig) and operating (4000 psig) pressure levels, impact tests, thermal exposure tests, and several other environmental exposure tests. With this background, it was decided that a 12,000 psig or higher virgin burst pressure was desirable.

The first vessel that was tested for virgin burst data was improperly manufactured, having twice the original required polar wrap material accidentally applied and was also damaged by excessively sanding of dome areas in an attempt to smooth the stepped contour. This vessel is referred to as serial number 3. The serial numbers used for all vessels are synonymous with liner numbers listed in Chapter V. All preliminary burst test results are given in Table VI-1.

A somewhat unexpected low burst pressure of 11,420 psig from the S/N 3 vessel led to the manufacture of S/N 4. This vessel and S/N 6 were wrapped next and the corresponding burst pressure results are shown in the table.

Table VI-1 Preliminary Burst Test Results

Vessel (S/N)	Manufacturing Variable	Burst Pressure, psig	Weight, lbs
3	Twice the required wrap material was accidently applied; dome areas were sanded	11,420	8.98
4	Twice the required polar wrap material was purposely added; no sanding	15,000	9.08
6 •	Vessel was wrapped as originally designed	11,520	7.83
5	Alternating polar and hoop wraps (4 steps) with original design quantities; wrap extended over domes	12,300	8.07
13	Like S/N 5 but with a 25% additional polar oriented overwrap material	13,600	8.34

A comparison can be made between S/N 6 which was overwrapped with original design quantities of fiber glass, and S/N 4 which exhibited a higher burst strength of 15,000 psig by doubling the original design quantities of polar-oriented overwrap material at the expense of added weight and design stress imbalance at operating pressures.

The failure mode in all three vessels was essentially the same, at the junction of polar and hoop overwrap material at the boss end of the vessel. This led to the conclusion that the junction area was not being adaquately reinforced with hoop-oriented material. This condition allows failure levels of stress to occur in the polar-oriented material as a result of high unrestrained loads being applied in the hoop direction.

Since the virgin burst strength of S/N 6 was slightly lower than desired, it was decided to attempt to reinforce the junction of the cylinder and dome areas of the vessel by extending the hoop overwrap material. This seemed like a more efficient approach to enhance performance rather than just arbitrarily increasing the amount of polar overwrap material.

The wet winding overwrapping technique was not readily amenable to extending hoop overwrap material over the complete cylinder region of the vessel into the critical junction area because of the tendency of the fiber glass to slip immediately when the roving tape leaves the cylinder area of the liner and approaches the dome. To alleviate this problen, it was decided to overwrap the vessel using an alternating layer technique. This technique provides support for a buried hoopwrap layer which can then be extended into the critical area.

Using this basic approach, vessels S/N 5 and S/N 13 were overwrapped. Vessel 5 was overwrapped with original design quantities of S-2 fiber glass while vessel 13 was overwrapped with 25% more polar-oriented material. The resulting burst pressure improvement is obvious.

Before a final decision was made to increase the amount of polar-oriented material, a vessel, S/N 35, was alternately overwrapped with original design quantities of S-2 fiberglass, inspected and sizes. This vessel was then subjected to 10,000 pressurization cycles at 4000 psig and 100 cycles at a proof pressure of 6750 psig. A residual burst strength value of 9,100 psig was obtained from S/N 35 following this cyclic exposure. Although this value was above the minimum required burst strength of 9000 psig, the margin of performance was felt to be inadequate.

All contract vessels used as test articles in the official test program (summarized below) and all computed stress values shown in Table IV-2 are compatible with a beefed-up design which incorporated 25% additional polar-oriented material than was used as a computed original design quantity.

B. SUMMARY OF TEST PROGRAM RESULTS

Seven vessels were used to perform the test program. Each vessel was subjected to a particular sequence of tests as outlined in Table VI-2. Each type of test is described in detail in the test procedure, Section F of Appendix B, and is referenced by procedure paragraph in Table VI-2.

The test sequences shown were selected to qualify the vessel to the performance requirements delineated in Appendix A. The most rigorous performance requirement was for the vessel to burst above 9000 psig after subjection to pressure cycling tests (10,000 cycles at 4000 psig and 100 cycles at 6750 psig), impact tests (six 10-ft drops at -60°F and six 10-ft drops at +200°F), and thermal cycling tests (20 alternating exposures to -60 and +200°F).

Table VI-2 Test Program and Burst Test Results

Test	Vessel S/N 18	21	14	19	15	34	47	App C Proc Para
Examination of Product	X	X	X	X	X	X	X	6.1
Volume Determination	X	X	X		X	X		6.1
Sizing and Proof	X	X	X	X	X	X	X	6.2
Volumetric Expansion	X	X			X	X		6.2
Functional Capability		X	X		X	X		6.3
Operating Pressure Cycles		X	X	X				6.4
Proof Pressure Cycles		X	X	X				6.5
Impact		X**	X	X				6.6
Thermal Cycling		X**	X*	X				6.7
Additional Proof Cycles		X**						6.5
High Temperature		X						6.9
Flaw Growth						X		6.12
Drop							X	6.13
Fragmentation Resistance					X			6.14
Burst Pressure Test	X	X		X		X	X	6.15
Burst Pressure	12,800	12,800		10,000		12,200	10,200	

*Vessel ruptured during second hot cycle, Ref Paragraph D.3.g

**These tests deviated from the normal test procedure only in the number of exposures imposed. Refer to detailed test discussions, Appendix C, for more information.

All vessels satisfactorily completed their test sequences by exhibiting a final burst pressure above 9000 psig, except for S/N 14 which failed during the thermal cycling test. This failure was attributed to deletion of the final curing step in the vessel overwrapping procedure. To prove that a vessel manufactured in a proper manner could sustain the same rigorous test sequence, S/N 19 was subjected to the same test sequence as S/N 14. S/N 19 survived and exhibited a residual burst strength of 9990 psig, considerably above requirements.

For more detailed test result information, refer to Appendix B which contains a description of the complete test history of each vessel, test data sheets, and photos of each test setup and vessel failure.

A flame test was also performed with the FBS vessel, not as part of the original test program requirement, but in response to a DOT request for Bureau of Explosive approval of the safety relief device before shipment of the vessels under DOT special permit could be obtained. The flame test consisted of suspending a pressurized (4000 psig) FBS vessel fitted with valve and pressure relief device over a kerosene soaked stack of pine boards; igniting the wood and recording temperature and pressure versus time until the pressure relieved or the vessel ruptured.

Two flame tests were performed; one slow fire--less kerosene and one quick fire both which completely surrounded the test article with flames.

Both tests were completely successful as the relief device relieved pressure as required before maximum operating pressure (4500 psig) of the vessel was exceeded.

The external surface of both tanks was charred but no visible broken fibers were noticed. The vessel, S/N 79, which showed the most visual charring from the slow-fire flame test was burst and failed at 11,820 psig, indicating very little if any degradation in strength as a result of being in the flames for several minutes.

VII. DISCUSSION OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The vessel designed, manufactured, and tested in this contract was completely successful. To recap some experimental results:

- The virgin burst strength of the vessel was typically around 13,000 psig (reference S/N 18, 12,800 psig; S/N 13, 13,600 psig).

- Vessels subjected to the life-expectancy service test sequences which included cyclic, impact, and thermal testing (duration and severity of these test sequences were excessively rigorous for the 15-year life expectancy of the vessel) failed at residual burst levels of 12,800 (S/N 21) and 10,000 psig (S/N 19), again far exceeding the required 9000 psig.

- The fragmentation resistance test (S/N 15) showed that the vessel could sustain rifle fire while under a maximum pressure of 4500 psig and remain intact (see Figures VII-1, 2, and 3).

- The flaw growth test, S/N 34, showed the superior toughness of a fiber glass overwrapped vessel. Exterior flawing of the overwrap material, to the extent that the outer layer of hoop wrap material was completely severed for a length of 1.0 in., did not significantly affect the final burst strength (12,200 psig) even though this vessel had been subjected to 1000 pressurization cycles to 4000 psig. No flaw growth occurred during pressurization cycling of this vessel. This vessel did not fail during final burst through the imposed flaw, but in the typical overwrap junction region as shown in Figure VII-4.

It would not be expected that significant flaw growth could be exhibited in a fiber glass-epoxy composite material. Although an individual glass fiber is extremely susceptible to brittle fracture, once it has been broken, the transfer of stress to fibers in the very localized region like the bottom of a sharp flaw (scratch or cut) is by resin shear which is transmitted over some distance and certainly does not produce another immediate stress riser.

- The most severe physical battering that was imposed on a vessel, S/N 47, occurred during the drop test. The damage can be observed in Figures VII-5, 6, and 7. This 16-foot drop test with a simulated man-like weight of 200 lb strapped to the vessel caused

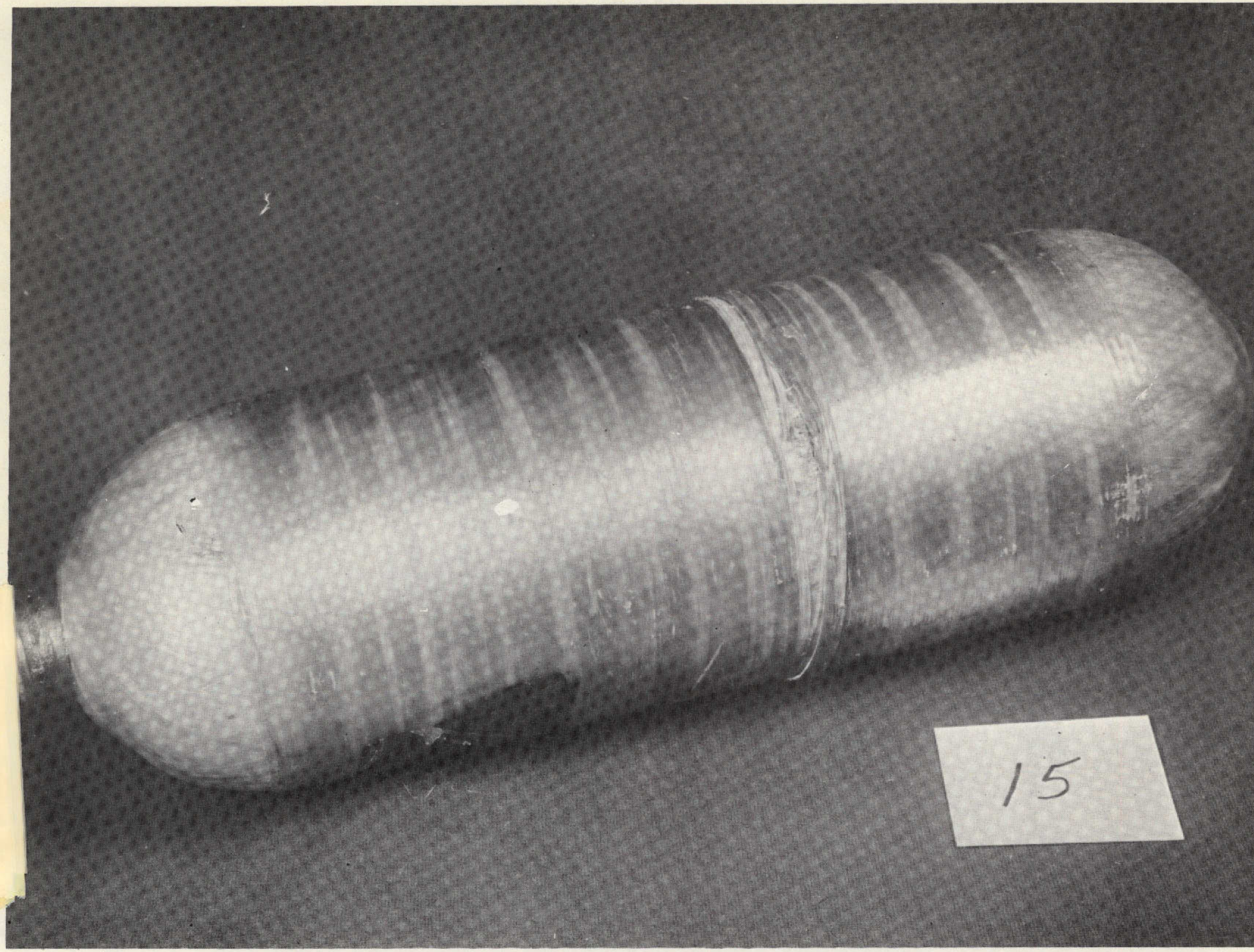


Figure VII-1 Vessel S/N 15 After Fragmentation Test

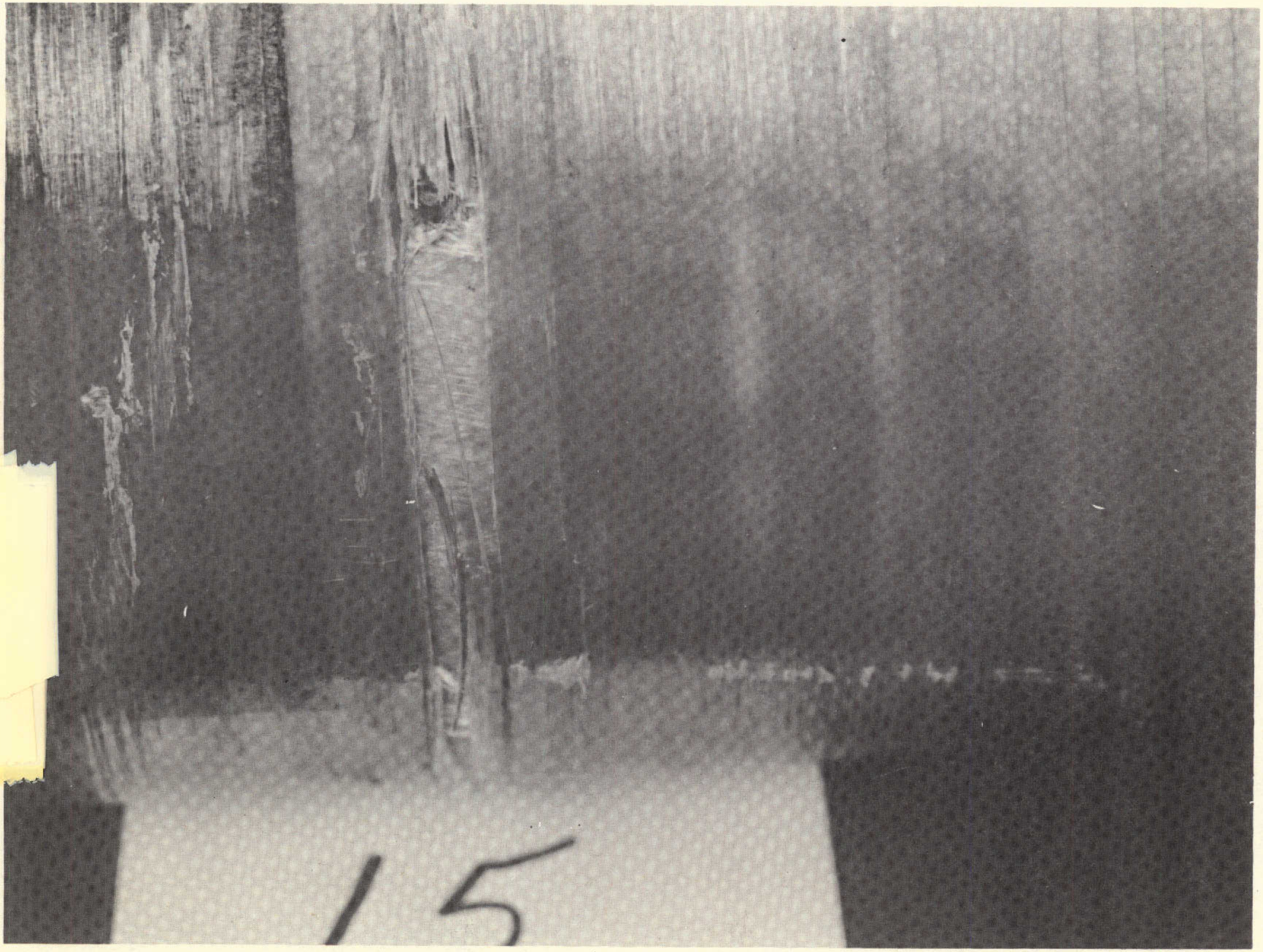


Figure VII-2 Vessel S/N 15 Bullet Entry Hole

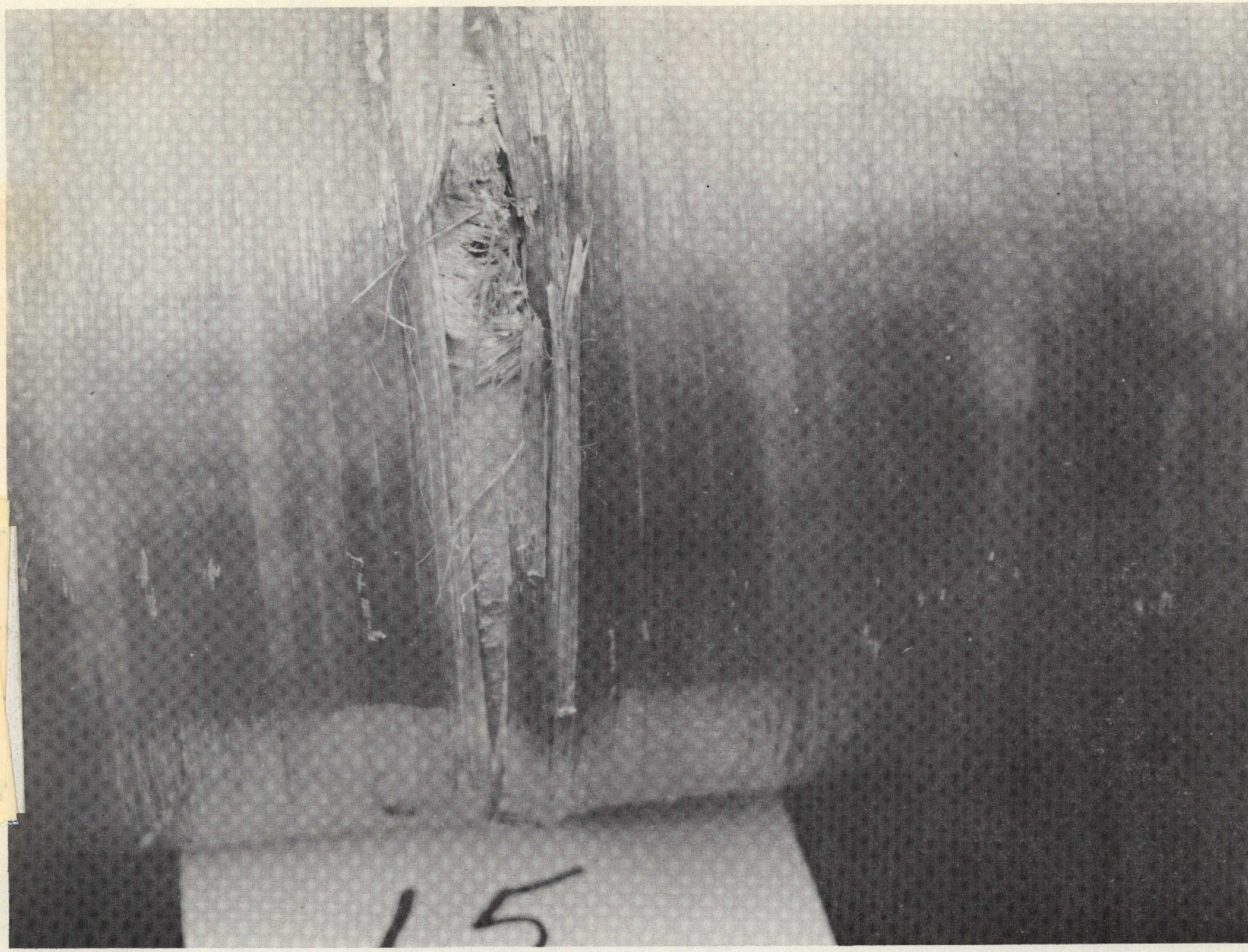


Figure VII-3 Vessel S/N 15 Bullet Exit Hole

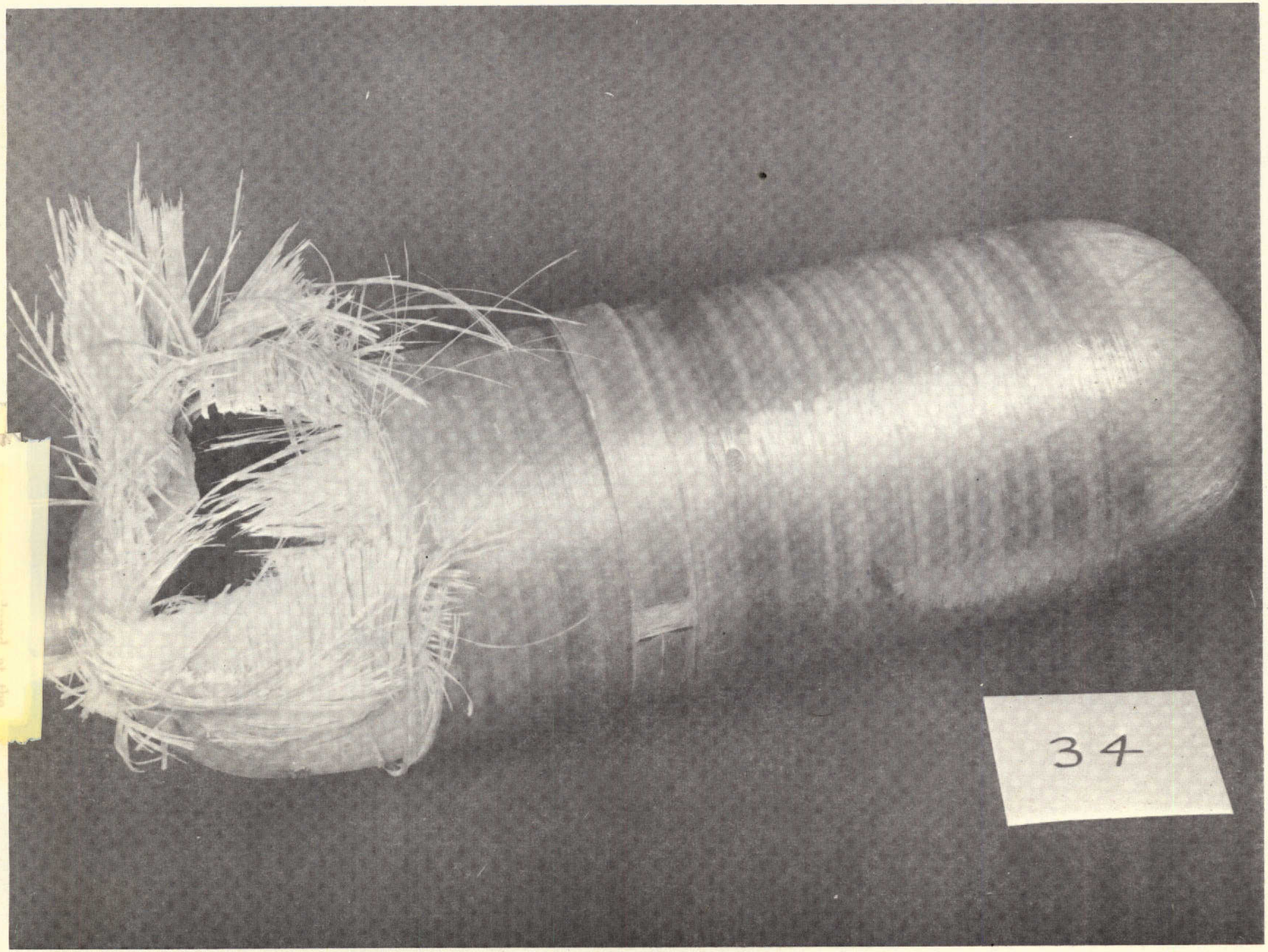


Figure VII-4 Vessel S/N 34 After Burst Test

THIS PAGE INTENTIONALLY LEFT BLANK

Preceding page blank

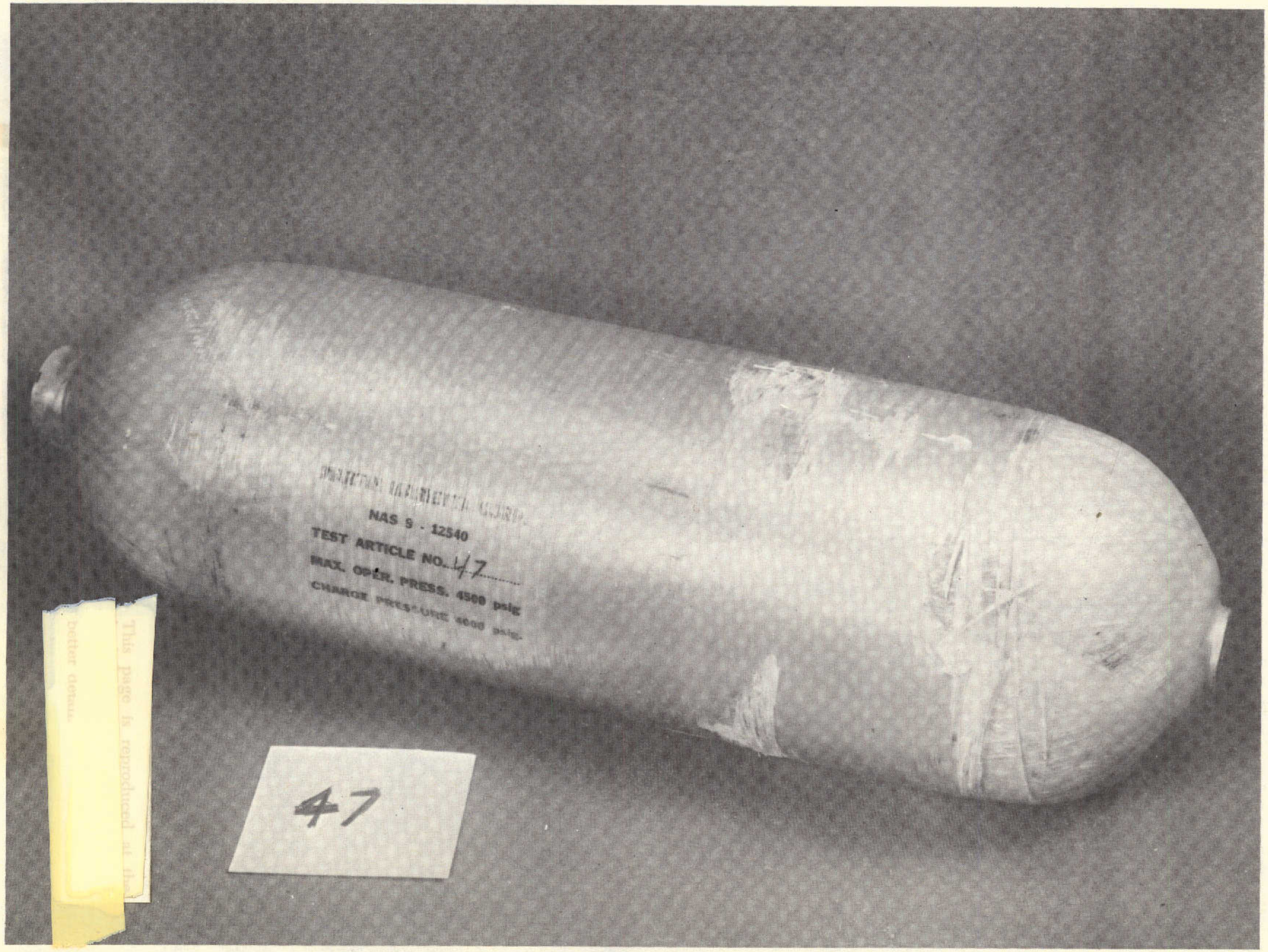


Figure VII-5 Vessel S/N 47 After Drop Test

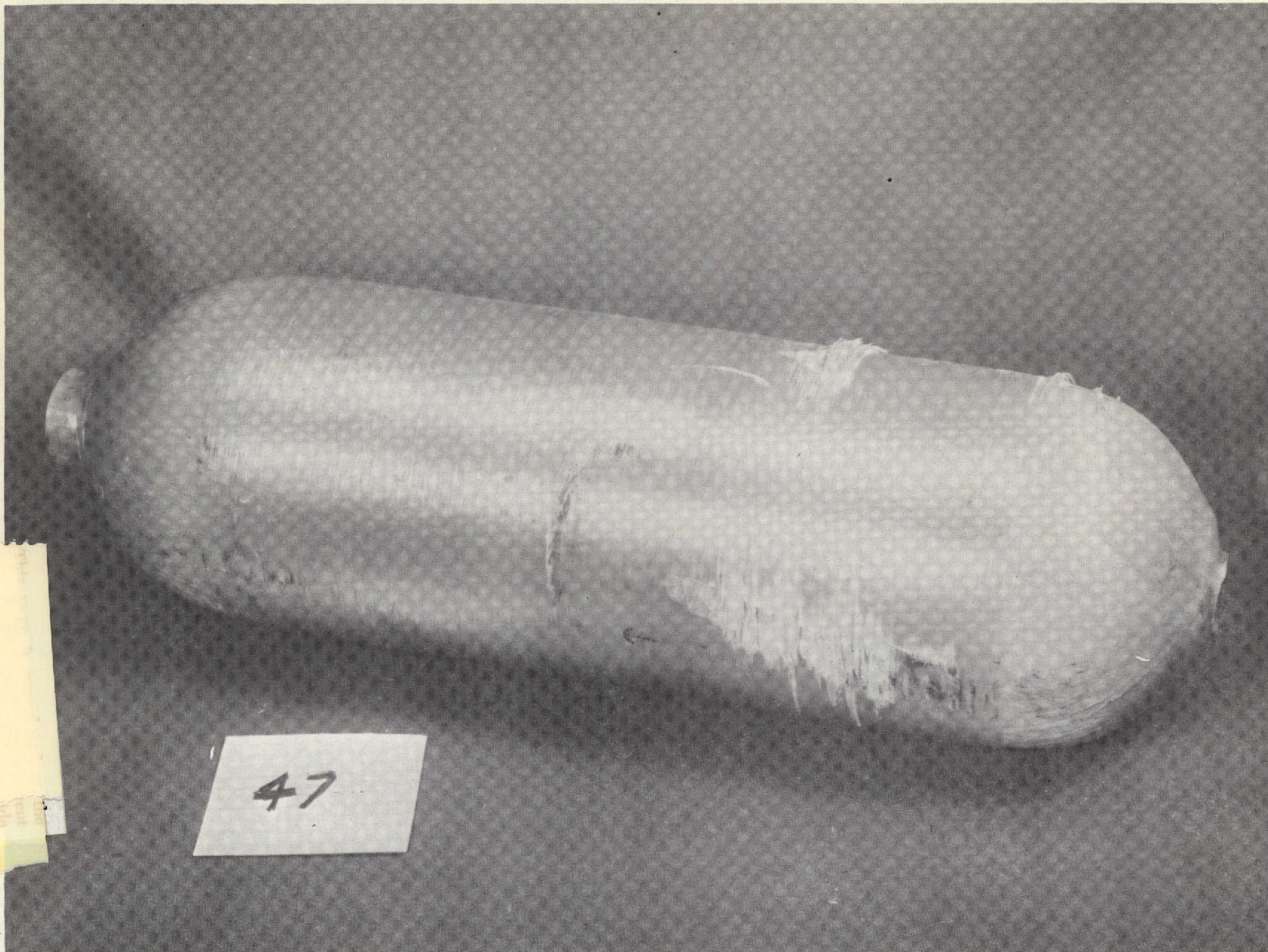


Figure VII-6 Vessel S/N 47 After Drop Test

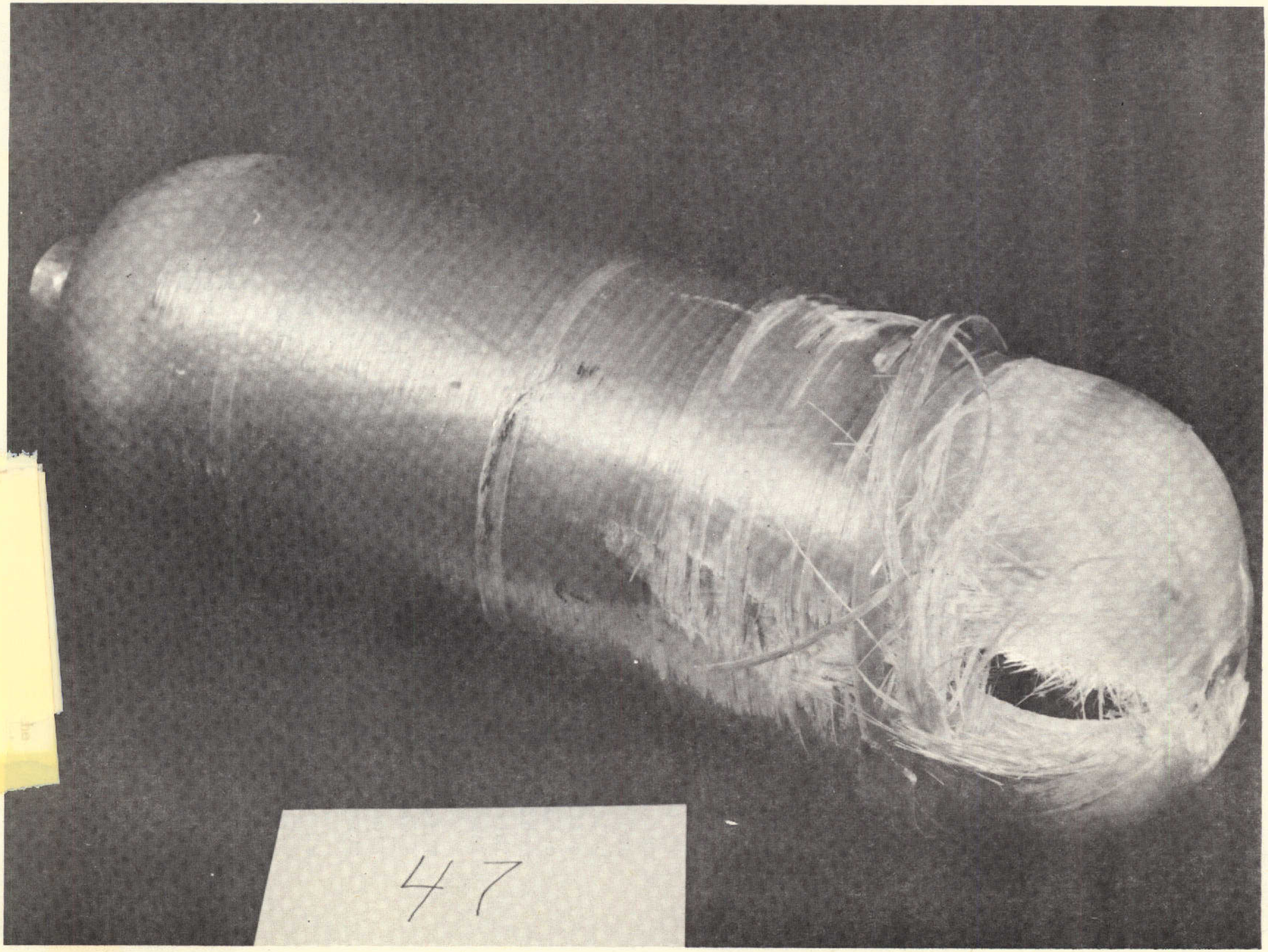


Figure VII-7 Vessel S/N 47 After Burst Test cuts several inches long, which penetrated through two layers of hoop wrap material into polar material, to be inflicted into the vessel. This severe damage reduced the final burst pressure to 10,200 psig. Failure originated at the cut in the junction region of the vessel.

The most stringent physical requirements of this vessel were that it weigh less than 9.0 lb and yet have at least 280 $in.^3$ of internal volume which when pressurized (4000 psig) would yield 40 ft^3 of breathable air. These requirements demanded the development of a high performance vessel. Test results indicate that this aluminum fiber glass-overwrapped vessel design is structurally sound and that the physical characteristics of the design exceeded requirements; e.g., the average vessel weighed 8.3 lb and had 283 $in.^3$ of internal volume).

Although the overwrapped pressure vessel developed in this contract is inherently a very safe vessel, its additional safety is only realized in the event of liner failure; i.e., leak or fracture of the liner causes no fragments to be ejected but are contained within the overwrap. If, however, failure initiates in the overwrap material, it can be catastrophic. To preclude this occurrence and for certain design efficiencies, each vessel is sized at 7600 psig as the final step in fabrication. This is certainly an adequate procedure to guarantee safe performance for some time as demonstrated in our test program results. But, it would be recommented that each vessel be periodically repressurized (3-year intervals seem adequate) to 7600 psig to preclude overwrap relaxation and to demonstrate that a large margin of safety remains.

This program has also discovered the potential hazard of placing a vessel into service which has been improperly cured. The fabrication procedure must assure that each vessel has been completely cured; an uncured vessel cannot be visually detected.

It should also be stated that all boss end seals must be replaced after each valve insertion: reused seals leak.

It is also highly recommended that a general standard for acceptability be established for composite overwrapped pressure vessels. This standard or specification should require that a potential manufacturer demonstrate that he has performed a detailed stress analysis by providing computed stress values throughout the vessel at operating and proof pressure conditions for each vessel design contemplated.

Each vessel design should be subjected to a qualitative test program to demonstrate the structural integrity of the vessel: here standards of acceptability must be established; e.g., minimum burst to operating pressure ratio. Environmental and service life tests must be a most important part of each test program. Very little tolerance for even minor design changes should be allowed once a particular design has met the specification and acquired DOT permit for shipping.

The integrity of manufacturing vessels must be maintained by strict quality control procedures. One of the more useful quality checks that should be incorporated in a manufacturing process is the measurement of volume change during proof or the sizing operations. Normal limits of volume change can be obtained during the test program and can be utilized to detect lack of sufficient reinforcement or defective liners. Weight control is also a good indication of fabrication consistency and should be monitored for all vessels.

In summary, a group representing the DOT, Johnson Spacecraft Center (NASA), and potential manufacturers of these composite reinforced vessels should establish criteria for a general specification of performance, testing requirements, and manufacture of composite pressure vessels.

APPENDIX A

REQUIREMENTS FOR A FIREFIGHTER'S
BREATHING SYSTEM PRESSURE VESSEL

APPENDIX A--REQUIREMENTS FOR A FIREFIGHTER'S BREATHING SYSTEM PRESSURE VESSEL

1.0 SCOPE

This attachment establishes the requirements for the performance of a compressed gas pressure vessel. The pressure vessel is to provide a portable breathing gas reservoir for firefighting applications.

This compressed gas pressure vessel consists of a cylinder with approximately hemispherical ends with one port located at one end of the pressure vessel. The pressure vessel is sized for approximately 40 scf of air when charged to 4,000 psi at 70°F.

2.0 APPLICABLE DOCUMENTS

MIL-STD-810A	Environmental Test Methods for Aerospace and Ground Equipment
MIL-D-1000	Drawing, Engineering, and Associated Lists
MIL-S-7742	Screw Threads, General Specification for

3.0 REQUIREMENTS

The pressure vessel shall be capable of satisfying the requirements contained herein. Also, the pressure vessel shall withstand the broad range of severe conditions imposed by the requirements of firefighting.

3.1 General

3.1.1 Materials and processes shall be subject to approval by NASA. They shall conform with applicable specifications and shall be of high quality, suitable for the purpose.

3.1.2 Any material or process which is considered "new" by virtue of the chemicals, composition, heat treatment, techniques or noval use of materials shall be specifically brought to the attention of NASA.

3.1.3 Material Selection

Material properties which shall be considered, in addition to ultimate and yield strengths, are fatigue, 3.1.3 (Continued)

creep, impact, fracture toughness, stress-corrosion cracking, hydrogen stress-cracking, and corrosion rates. All materials used shall be suitable for the design, structural, and environmental requirement.

3.1.4 Surface Protection

The surface of the vessel shall not be dependent on coatings or covers to protect the surface of the vessel from abrasion, nicks, scratches, or dissimilar material.

3.1.5 Stressed Areas

Stress concentration shall be avoided or minimized.

3.1.6 Mounting Provisions

The unit is intended for strap mounting and thus requires no separate mounting provisions. The material shall be suitable for strap mounting.

3.1.7 Threads and Fittings

The unit shall be provided with a single entry boss and fitting located at one end of the cylinder. The fitting shall be recessed as far as possible to minimize protrusion from the bottle end. The treaded connection shall be per AND10050-12.*

3.1.8 Dissimilar Materials

The effect of dissimilar materials, which may be used for strap mounting and the shutoff valve, shall be considered in the pressure vessel material selection. The dissimilar materials may include carbon steel, corrosion resistant steel, bronze, and aluminum.

3.1.9 Service Life

The pressure vessel shall have a service life of 15 years.

3.2 <u>Design Requirements</u>

This pressure vessel shall be designed to satisfy the following requirements.

* Subsequently modified see Fig. IV-7

3.2.1 Nominal Charge Pressure

The pressure vessel shall be designed for a nominal charge pressure of 4,000 psig at 70°F.

3.2.2 Maximum Working Pressure

The pressure vessel shall be designed to a maximum working pressure of 4,500 psig.

3.2.3 Envelope

The pressure vessel shall be sized for a minimum volume of 280 cubic inches. It is desired that the external envelope not exceed 5¼ inches O.D. and 18 inches in length (including boss).

3.2.4 Weight

Weight of the pressure vessel shall be a minimum consistent with reasonable production cost and adequate structural safety. A weight not exceeding 9 pounds is desired.

3.2.5 Working Fluid

The pressure vessel shall be capable of operating within the requirements of this specification with breathing air as the working fluid. The working fluid may contain water vapor resulting in condensation of water in the pressure vessel.

3.2.6 Pressurization Cycles

The pressure vessel shall be capable of operating with the requirements of this specification after 10,000 pressurization cycles applied over a 500 hour period. One cycle shall be defined as a pressurization to 4,000 psig and back to 0 psig.

3.2.7 Working Temperature

The pressure vessel shall be designed to satisfy all requirements of this document over a temperature range of -60°F to +200°F.

3.3 Structural Requirements

3.3.1 Proof Pressure

Proof pressure for the unit shall be 6,750 psig minimum. The unit shall be capable of operating within the requirements of this specification following 100 proof cycles. One proof cycle shall be defined as a pressurization to 6,750 psig for a five minute period, followed by a return to zero psig.

3.3.2 Burst Pressure

The pressure vessel shall not rupture, but may permanently deform when pressurized to 9,000 psig. The burst pressure requirement shall exist following exposure to all other design, structural, and environment requirements (except for the induced flaw of Section 3.3.3).

3.3.3 Flaw Growth

Fracture mechanics analysis shall be applied to show that the vessel will fail in a leaking rather than a catastrophic mode. This requirement shall be demonstrated by introducing a flaw on the surface of the vessel in an area subject to the highest stress. The length of the induced flaw shall be approximately one inch at the surface of the vessel and shall be cut to a depth of approximately half the wall thickness. The vessel shall be cycled to failure at working pressure. Failure shall occur in the leaking mode. The test fluid for the demonstration shall be a compressed gas.

3.3.4 Flaw Simulation

Surface flaws, the depth of each shall be equal to 5% of the wall thickness and the length one inch, shall be induced into each test pressure vessel in 3 different orientations. The 3 flaws shall be located in high stress areas. The flaws shall completely penetrate any protective coatings. All requirements of this document shall be satisfied with the pressure vessel containing these flaws.

3.3.5 Impact Test High and Low Temperature

The pressure vessel shall be capable of operating within the requirements of this specification after having dropped 10 feet to impact on a rigid steel plate. The vessel shall be pressurized to 4,000 psi and a simulated valve in place for the impact test. The vessel shall withstand the following with no leakage, permanent deformation or structural damage:

a. Impact on valve end of vessel, vessel temperature -60°F.

b. Impact on valve end of vessel, vessel temperature 200°F.

c. Impact on end opposite valve, vessel temperature -60°F.

d. Impact on end opposite valve, vessel temperature 200°F.

e. Impact on side of vessel, vessel temperature -60°F.

f. Impact on side of vessel, vessel temperature 200°F.

The above sequence shall be repeated two times.

3.3.6 Drop Test

The pressure vessel shall not leak or rupture, but may permanently deform when subjected to the following drop test. The test shall consist of dropping the unit from a height of 16 feet on to a rigid steel plate. The pressure vessel shall be strap mounted to a typical "backpack" mounting frame. The mounting frame shall be attached to a 200 pound sand bag so as to approximate the impact of a human falling upon the pressure vessel. A simulated valve shall be located in the fitting. The unit shall be pressurized to 4,000 psig* and shall be repeated five times at various drop angles.

*Subsequently revised to 4500 psig

3.3.7 Fragmentation Resistance

The cylinder shall be resistant to fragmentation when penetrated by a projectile. The cylinder shall, when pressurized to 4,000*psig, be subjected to gunfire of .30 caliber amour piercing ammunition with a muzzle velocity of 2800 ± 100 feet per second. The cylinder, when tested, shall remain in one piece, and the greatest dimension of the opening (cut plus tear) created by the projectile shall not exceed the dimension of one hole (cut) created by the projectile by more than three inches in any direction. "Cutting" shall be considered as the actual section of the cylinder cut by contact with the projectile, and a "tear" shall be considered as any extension beyond the cut.

3.3.8 Volumetric Expansion

The unit when subjected to the first proof cycle shall show a maximum permanent volumetric expansion of one percent of the temporary volumetric expansion.

3.3.9 Leakage - Leakage shall not exceed 5% per year of initial charge pressures.

3.4 Environmental Requirements

3.4.1 Thermal Cycling

The vessel shall be capable of operating within the requirements of this specification after having been subjected to a thermal cycling test consisting of alternately quenching the unit in water at 200°F and water-glycol at -60°F for 20 cycles at ten minutes in each bath. The unit shall be precharged to 4,000 psig at 70°F and closed. The time between high temperature and low temperature exposure shall not exceed three minutes.

3.4.2 Humidity

The unit shall be capable of operating within the requirements of this specification after having been subjected to a humidity test in accordance with MIL-STD-810A, Method 507.1, except that within a five-minute period

*Subsequently revised to 4500 psig

3.4.2 *Humidity (continued)

after the conclusion of the humidity test and prior to operation and inspection the unit temperature shall be decreased to $0^{o}F$ and remain exposed to $0^{o}F$ for one hour period with a maximum humidity of 100% R.H. including the condensation of water and frost.

3.4.3 High Temperature Exposure

The vessel shall be capable of operating within the requirements of this specification after having been subjected to a temperature of $600^{o}F$ for a period of five minutes. The vessel shall be at a temperature of $200^{o}F$ and a pressure of 2,000 psi at the start of the $600^{o}F$ exposure. The $600^{o}F$ exposure shall be accomplished by a five minute soak in an environmental chamber at atmospheric pressure and with a minimum air velocity of 5 mph over the surface of the pressure vessel.

3.4.4 *Sand and Dust

The unit shall be capable of operating within the requirements of this specification after having been subjected to a sand and dust test in accordance with MIL-STD-810A, Method 510.1.

3.4.5 *Salt Atmosphere

The unit shall be capable of operating within the requirements of this specification after being subjected to a 1% salt solution, by weight, at a temperature of $95^{o}F$ for a 48-hour period in accordance with MIL-STD-810A, Method 509.1.

4.0 QUALITY ASSURANCE

4.1 General

An adequate quality control program shall be defined, as a part of the design, to ensure that all materials are of uniform quality and suitable for the intended application.

*Humidity, salt tog, and sand and dust tests were deleted in favor of other testing considered more stringent. See test program results, Appendix B.

4.2 Test Requirements

Confidence in the ability of the unit to meet regulatory agency requirements must be established upon completion of prototype fabrication. A test plan shall be prepared as part of the design to ensure the unit will satisfy the requirements specified in Section 3.0. The following tests shall be conducted:

Pressurization cycles, operating
Proof pressure test
Pressurization cycles, proof
Burst pressure test
Flaw growth
Impact test, high and low temperature
Drop test
Fragmentation resistance
Volumetric expansion
Leakage
Thermal cycling
*Humidity
High temperature exposure
*Sand and dust
*Salt atmosphere

4.3 Production Acceptance Test

The design effort shall define the required production acceptance tests.

NOTE 1 Paragraphs (3.3.3) (3.3.5) (3.3.7) and (3.4.3) above are not mandatory program requirements, but are considered as desirable objectives. The tests must be conducted, but the successful demonstration is not mandatory.

*These tests were deleted in favor of other tests considered more stringent.

APPENDIX B

TEST PROGRAM RESULTS

APPENDIX B--TEST PROGRAM RESULTS

This appendix delineates the procedure and results of the Phase III test program. A summary of test results is presented beginning on Page VI-4 of this report.

A. INSTRUMENTATION

All measurements of pressure and temperature were obtained using instrumentation that is in a continuous maintenance and calibration cycle, thus assuring a high degree of accuracy.

All permanent test records, e.g. oscillograph recordings, will be retained for 6 months by the Engineering and Propulsion Laboratory at Martin Marietta Corporation, Denver Division, for further inspection or analysis.

B. TEST ITEM

Each pressure vessel was a cylinder with approximately hemispherical ends. A port was located at one end of the vessel. A minimum volume of the vessel, an aluminum liner with a glass fiber overwrap, was designed for a minimum volume of 280 $in.^3$. Working pressure was 4000 psig and rated burst pressure was 9000 psig. Each test pressure vessel contained six deliberate flaws. Three flaws were in the liner to a depth of approximately 5% of liner thickness. Three flaws were in the overwrap to a depth of approximately 5% of overwrap thickness. All six flaws were approximately one inch long. The data sheets reflect the depth of only the three flaws that were placed on the external surface of the vessel in the overwrap material. Additional physical characteristics of these test vessels are given in Chapter V, Table V-1.

approximately 5% of overwrap thickness. All six flaws were approximately one inch long. The data sheets reflect the depth of only the three flaws that were placed on the external surface of the vessel in the overwrap material. Additional physical characteristics of these test vessels are given in Chapter V, Table V-1.

C. TEST RESULTS

1. Test Results - Vessel S/N 18

a. Examination of Product and Volume Determination - As required by paragraph 6.1 of the test procedure (Reference Appendix C) the vessel was examined for evidence of damage, poor workmanship, and unintentional defects. The flaws were located and recorded. The vessel was weighed and measured and the volume was measured. Vessel weight was 8.38 pounds and the measured volume was 282.2 $in.^3$. The original test data is included as Table B-1.

b. Preliminary Burst - The vessel was pressurized hydrostatically at a rate of 2000-3000 psi per min until rupture occurred. At 12,800 psig, the liner failed in the upper dome and one fragment approximately 4x4.5 in. was forced through the glass wrap. The test data sheet is included as Table B-2 and a photograph of the vessel after failure is shown in Figure B-1.

Table B-1 Test Data, Examination of Product

Pressure Vessel S/N: 18

Test Date: 4/13/73

Test Engineer: J. LeBeau

Parameter	Allowable	Actual
Workmanship	Workmanlike	
Damage	None	
Defects	None	
Weight	9.0 lb max	8.38 lb
Diameter	5.6 in. max	5.57 in.
Length	18.7 in. max	18.6 in.
Volume	280 $in.^3$ min	282.2 $in.^3$
Deliberate Flaws (Overwrap)		
Flaw No. 1		
Location	(Record actual location)	Upper Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.
Flaw No. 2		
Location	(Record actual (location)	Cylinder Section
Depth	Approx 0.002 in.	0.075
Length	Approx 1 in.	1.0 in.
Flaw No. 3	(Record actual location)	Lower Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.

Table B-2 Test Data-S/N 1B

Test: Burst Pressure

Vessel S/N: 18

Date: 4/30/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Burst Pressure	9000 psig min	12,800
Volume increase Enter burette readings at pressure _____ prior to pressurization _____		
difference (volume increase)	N/A	N/A
Failure mode	N/A	Glass Failure*
Other Observations	N/A	

*Upper dome ruptured. One fragment approximately 4 x 4.5-in. was propelled through the glass wrap. The AN bulkhead tee, threaded into the bottle lidding, broke due to violent motion of the vessel.

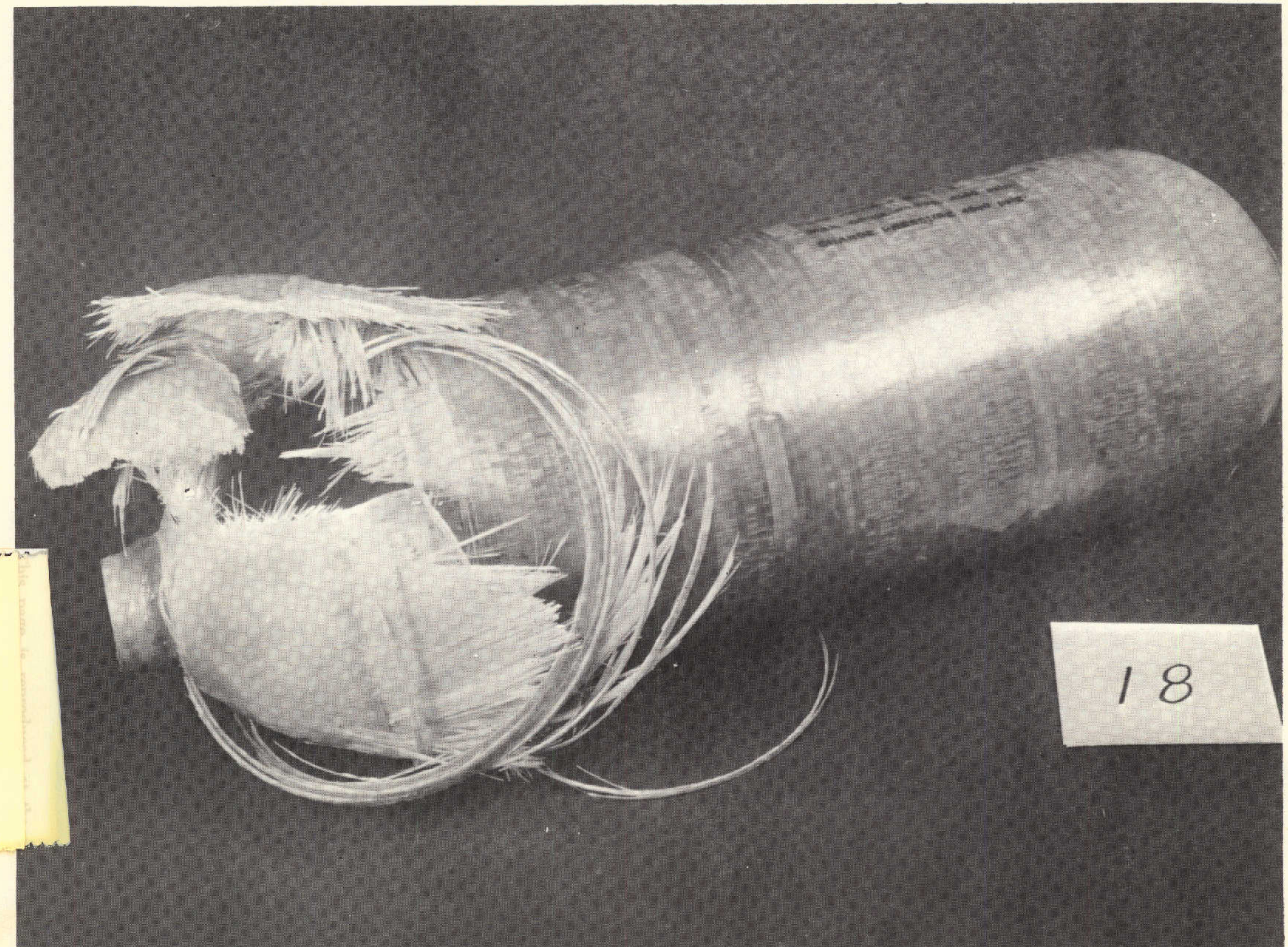


Figure B-1 Vessel S/N 18 After Burst Test

2. Test Results - Vessel S/N 21

a. Examination of Product and Volume Determination - As required by paragraph 6.1 of the test procedure (Reference Section D of this appendix) the vessel was examined for evidence of damage, poor workmanship, and unintentional defects. The flaws were located and recorded. The vessel was weighed and measured and the volume was measured. Vessel weight was 8.15 pounds and the measured volume was 281.5 $in.^3$ The original test data is included as Table B-3.

b. Sizing, Expansion and Proof Test - As required by paragraph 6.2 of the test procedure the vessel pressure was increased hydrostatically to 7600 psig at a rate not exceeding 500 psig per min and then was decreased to ambient. Next the pressure was increased hydrostatically to 6750 psig at a rate not exceeding 500 psig per min, maintained for 5 min, and then decreased to ambient.

During the test the permanent volumetric expansion of the vessel was measured as 36% of the total change in volume during the sizing test and as 0% permanent expansion during the proof test. There was no evidence of damage or physical degradation of the vessel. The test data is included as Table B-4 and a photograph of the test setup is shown in Figure B-2.

c. Functional Capability Test - As required by paragraph 6.3 of the test procedure (Reference Section D of this appendix) the vessel was submerged in water and pressurized with GN_2 to 4000 psig. This pressure was maintained for 30 min while the surface of the water was monitored for an indication of leakage. The vessel pressure was then reduced to ambient.

No gas bubbles were observed coming from the vessel. Had any bubbles been observed they would have been collected and measured with an inverted graduated cylinder. The test data sheet is included as Table B-5 and a photograph of the test setup is shown in Figure B-3.

d. Operating Pressure Cycle - As required by paragraph 6.4 of the test procedure (Reference Section D of this appendix) the vessel pressure was changed hydrostatically from 0 psig to 4000 psig to 0 psig at approximately 4 cycles per min, for a total of 10,000 cycles.

Table B-3 Examination of Product

Pressure Vessel S/N: 21

Test Date: 4/13/73

Test Engineer: J. LeBeau

Parameter	Allowable	Actual
Workmanship	Workmanlike	
Damage	None	
Defects	None	
Weight	9.0 lb max	8.13 lb
Diameter	5.6 in. max	5.55 in.
Length	18.7 in. max	18.62 in.
Volume	280 $in.^3$ min	281.54 $in.^3$
Deliberate Flaws (Overwrap)		
Flaw No. 1		
Location	(Record actual location)	Upper Dome
Depth	Approx 0.002 in.	0.0035 in.
Length	Approx 1 in.	1.0 in.
Flaw No. 2		
Location	(Record actual location)	Cylinder Section
Depth	Approx 0.002 in.	0.0075 in.
Length	Approx 1 in.	1.0 in.
Flaw No. 3		
Location	(Record actual location)	Lower Dome
Depth	Approx 0.002 in.	0.0035 in.
Length	Approx 1 in.	1.0 in.

Table B-4 Test Data - S/N 21

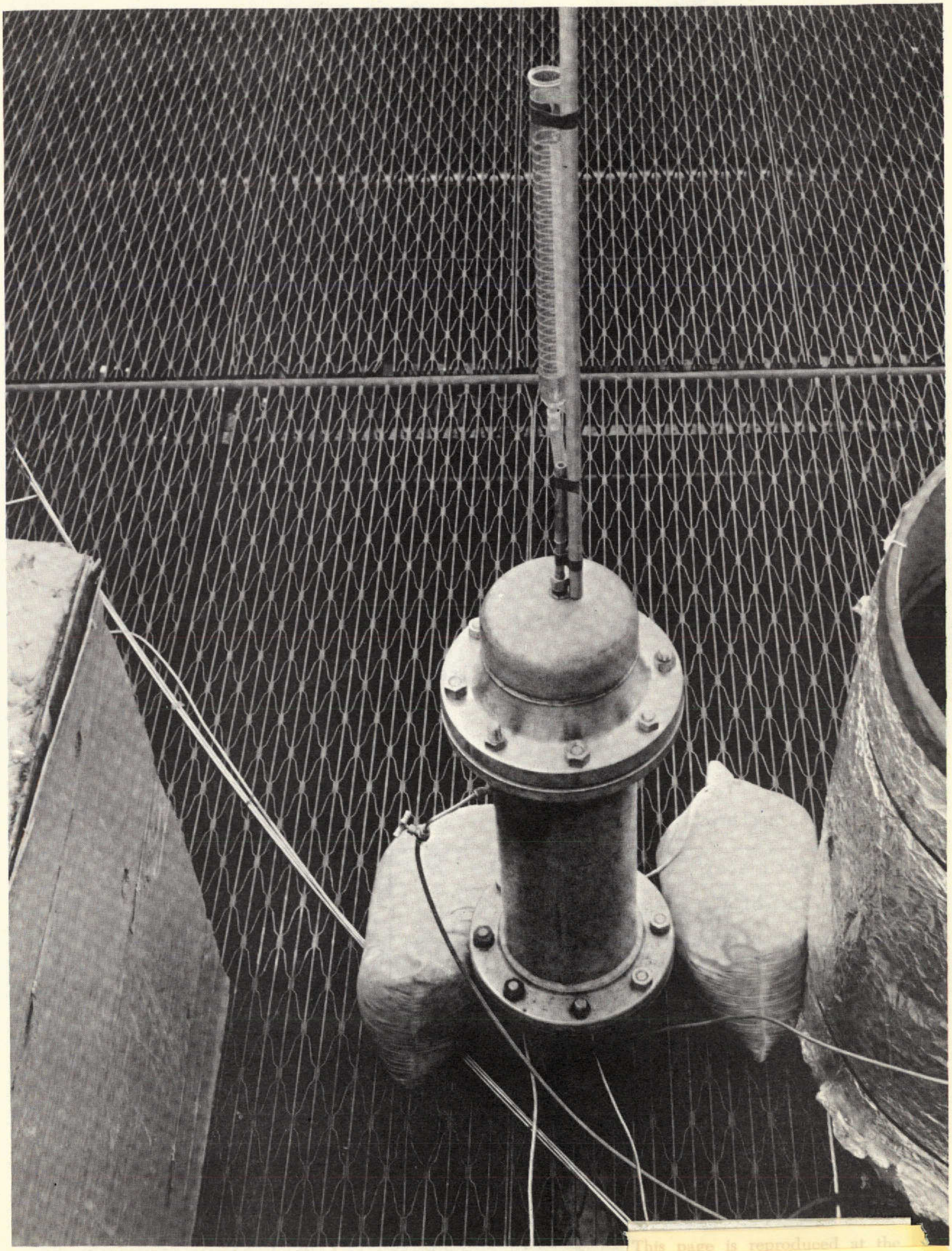
Test: Sizing, Volumetric Expansion, and Proof Pressure

Vessel S/N: 21

Date: 4/20/73

Test Engineer: D. E. Dulaign

Paremeter	Allowable	Actual
Sizing Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 128 Prior To Pressurization 0 At Pressure 128 After Pressurization 46 Difference (A) 128 Difference (B) 82 % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(128) - (82)}{(128)}$ (100) = 36% Vessel Damage	7600 ± 50 N. A. None	7600 Psig 36% None
Proof Pressure Time At Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 121 Prior To Pressurization 46 At Pressure 121 After Pressurization 46 Difference (A) 75 Difference (B) 75 % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(75) - (75)}{(75)}$ (100) = 0% Vessel Damage	6750 ± 50 5 Min 1% None	6750 Psig 5 Min 0% None



This page is reproduced at the

Figure B-2 Volumetric Expansion Test Setup

Table B-5 Test Data-S/N 21

Test: Functional Capability

Vessel S/N: 21

Date: 4/23/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure	4000 ± 50 psig	4000 psig
Time at pressure	30 min	30 min
Leakage rate	6.5 scc/hr max	0
Damage	None	None

Table B-6 Test Data-S/N 21

Test: Operating Pressure Cycling Test

Vessel S/N: 21

Date: 5/1/73 thru 5/9/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	10,000	10,000
Max Pressure	4000 ± 50 psig	4000 ± 50 psig
Min Pressure	0 to 100 psig	0 to 100 psig
Damage	None	None*
Post-Functional		
Pressure	4000 ± 50 psig	4000 psig
Time	30 min	30 min
Leakage	6.5 scc/hr max	None
Damage	None	None

*Except: Outer hoop wrap has peeled for approximately 3.0 in. to a depth of the intentional flaw and adjacent thereto.

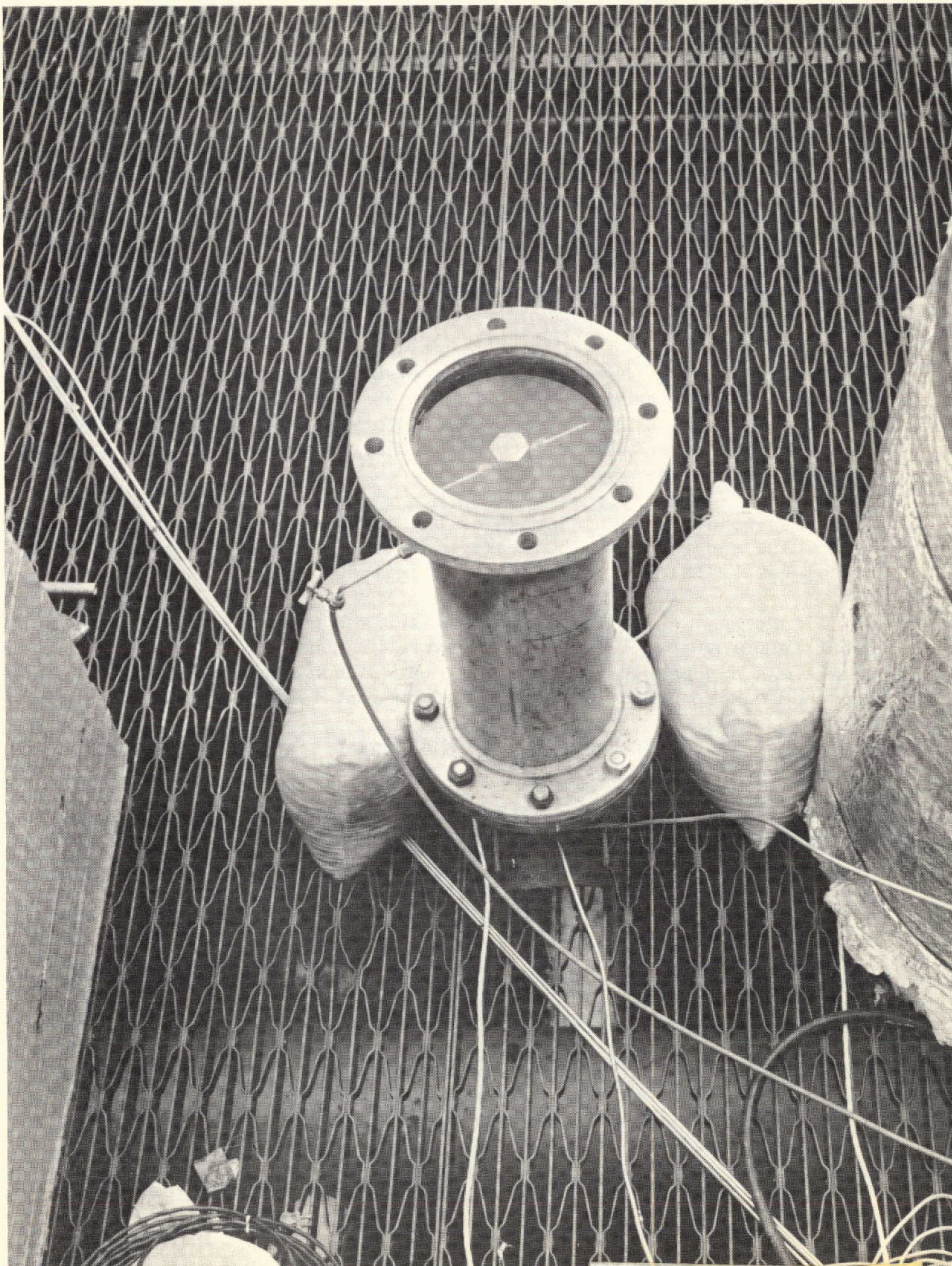


Figure B-3 Functional Capability Test Setup

There was no evidence of damage or physical degradation after the 10,000 cycles except the outer loop wrap had peeled approximately 3 in. to a depth of the intentional cylindrical section flaw. This peel apparently caused no degradation in vessel performance during this or subsequent tests. There was no leakage during the subsequent functional test and the test data sheet is included as Table B-6.

e. *Proof Pressure Cycle Test* - As required by paragraph 6.5 of the test procedure, the vessel was pressurized hydrostatically to 6750 psig, maintained at 6750 psig for 30 sec, and then reduced to ambient for a total of 100 cycles. The test procedure and the setup were modified slightly to allow use of a Haskel hydrostatic pump instead of the GN_2 source.

There was no evidence of damage or physical degradation after the 100 cycles and there was no leakage during the subsequent functional test. The test data sheet is included as Table B-7.

f. *Impact Test* - The vessel was pressurized to 4000 psig at ambient temperature. The vessel pressure was then isolated and the vessel was dropped 10 ft onto a 1/2-in. carbon steel plate. This sequence was repeated three times at ambient temperature.

The vessel successfully completed the impact test as described. The test data sheet is included as Table B-8.

g. *Thermal Cycle Test* - The vessel was pressurized to 4000 psig at ambient temperature, locked off, and submerged in a -60 ± 20°F bath for 10 min. The vessel was then removed from the cold bath and submerged in a hot water bath, 180 ± 20°F for 10 min sequence was repeated for a total of three cycles.

The vessel successfully completed the three thermal cycles with no evidence of damage or degradation. The test data sheet is included as Table B-9.

h. *Additional Operating Pressure Cycle* - The vessel was charged hydrostatically from 0 psig to 4000 psig to 0 psig at approximately 4 cycles per min, for a total of 10 cycles.

There was no evidence of damage or physical degradation after the 10 cycles. The test data sheet is included as Table B-10.

Table B-7 Test Data-S/N 21

Test: Proof Pressure Cycling Test

Vessel S/N: 21

Date: 5/10/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	100	100
Vessel Temperature	Ambient	58°F
Max Pressure	6750 ± 100 psig	6750 ± 100 psig
Min Pressure	0 to 100 psig	0 to 100 psig
Damage	None	None
Post-Functional		
Pressure	4000 ± 50 psig	4000 psig
Time	30 min	30 min
Leakage	6.5 scc/hr max	None
Damage	None	None

Table B-8 Test Data S/N 21

Test: Impact
Vessel S/N: 21
Date: 6/1/73
Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual Sequence 1
Valve End,		
Pretest Pressure	3050-4050 Psig	4000 Psig
Predrop Temp	Ambient	Ambient 80°F
Damage	None	None
Opp. End.		
Pretest Pressure	3050-4050 Psig	4000 Psig
Predrop Temp	Ambient	Ambient 80°F
Damage	None	None
Side,		
Pretest Pressure	3050-4050 Psig	4000 Psig
Predrop Temp	Ambient	Ambient 80°F
Damage	None	None
Note: This test is for information only and there is no failure criteria.		

Table B-9 Test Data-S/N 21

Test: Thermal Cycling

Vessel S/N: 21

Date: 6/6/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	3	3
Transfer time	3 min max	40 sec
Cold bath temp	-60 ± 10°F	-620°F
Hot bath temp	180 ± 10°F	174°F
Damage	None	None

Table B-10 Test Data - S/N 21

Test: Additional Operational Pressure Cycling Test

Vessel S/N: 21

Date: 6/7/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	10	10
Max Pressure	4000 ± 50 psig	4000 psig
Min Pressure	0 to 100 psig	100 psig
Damage	None	None

i. High Temperature Exposure - The vessel was installed in a chamber similar to that in Figure B-4, except that two additional thermocouples were added to the vessel. The burner was operated to obtain a stable vessel temperature of 200°F, the vessel was pressurized to 2000 psig, and then vessel environment temperature was increased to 600°F and maintained for 5 min. The burner was secured and the vessel was removed and inspected. There was no evidence of damage or discoloration.

Although the environment control thermocouple was located within 0.75 in. of the vessel, the temperature gradient was so severe that the vessel temperature rose only to 190°F. To determine the proper vessel temperature an expended vessel was placed in a 600°F oven and it was noted that the vessel temperature rose to 430°F in 5 min. Vessel S/N 21 was then subjected to a flame exposure hot enough to increase the vessel temperature to 430°F in 5 minutes.

After the second test the vessel still showed only slight discoloration. No other damage or degradation was apparent. The test data sheet is included as Table B-11 and photographs of the test setup are shown in Figures B-5 and B-6.

j. Burst Test - The vessel was pressurized hydrostatically at a rate of 200-300 psi per min until rupture occurred. Rupture occurred at 12,800 psig, originated in the lower dome, and was due to a glass failure. The test data sheet is included as Table B-12 and the oscillograph recordings made during this test will be available at the Engineering Propulsion Laboratory for six months for further inspection and analysis. A photograph of the vessel after rupture is shown in Figure B-7.

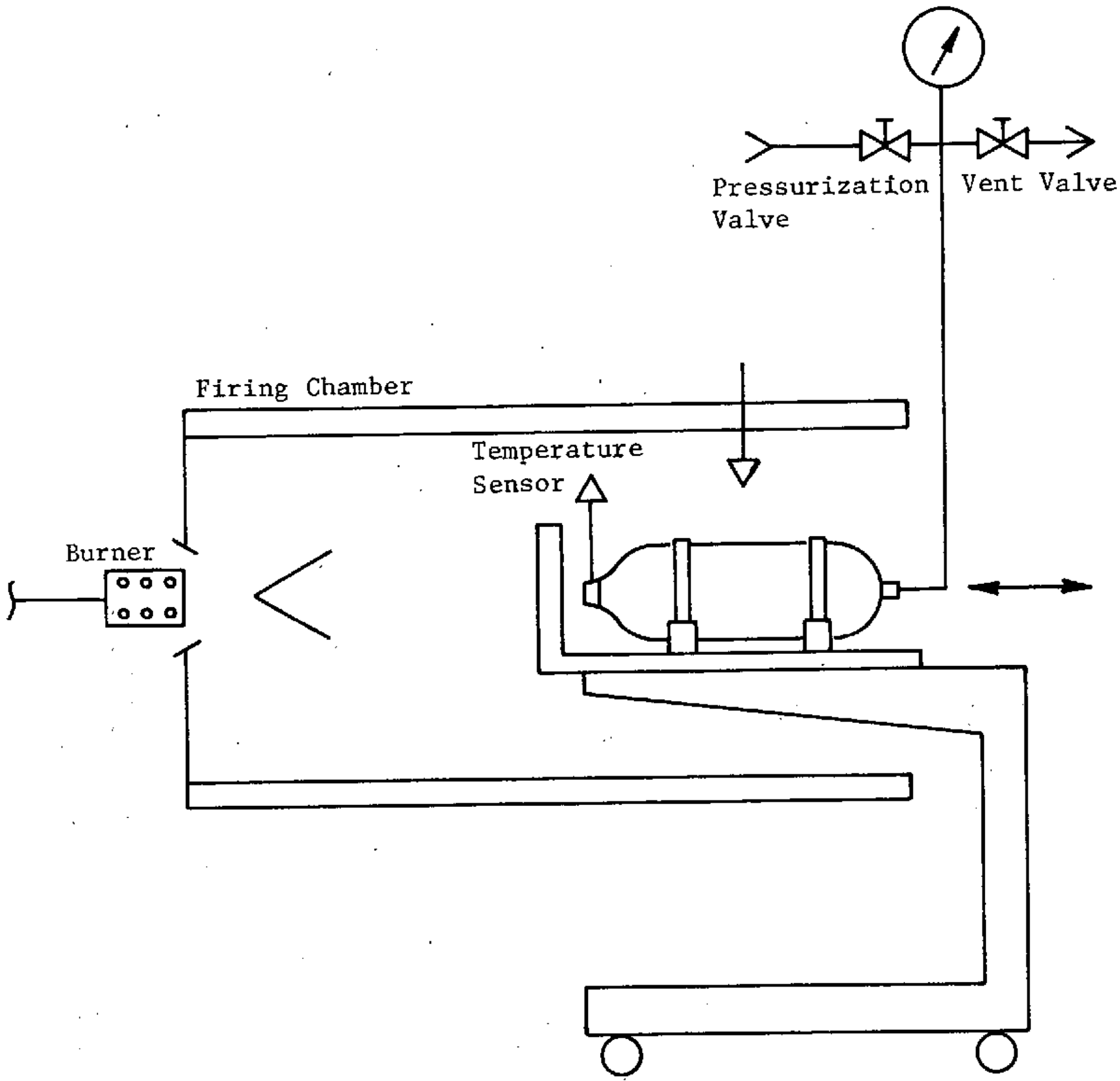


Figure B-4 High Temperature Exposure

Table B-11 Test Data - S/N 21

Test: High Temperature Exposure*
Vessel S/N: 21
Date: 6/12/73
Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Bath Temperature Chamber Velocity Chamber Temperature	200 ± 10°F 5 Mph Minimum 600 ± 50°F	180°F > 5 Mph 600 ± 40°F
Vessel Pressure And Temperature (Record At 30 Sec Intervals)		Min / Press / Temp 0 / 2000 Psi / 180°F .5 / 1990 / 181 1.0 / 1980 / 182 1.5 / 1970 / 183 2.0 / 1960 / 184 2.5 / 1950 / 185 3.0 / 1940 / 186 3.5 / 1930 / 187 4.0 / 1920 / 188 4.5 / 1910 / 189 5.0 / 1900† / 190
Damage	None	†This Pressure Decay Was Apparently The Result Of Seal Leakage.

Note: This Test Is For Information Only And There Is No Failure Criteria.

*This Test Was Repeated By Increasing Vessel Temperature To 430°F (T2) While Maintaining Pressure at 2000 Psig. The Temperature Criteria of 430°F Was Determined by Placing S/N 15 In A 600°F Oven for 5 Min and Temperature T-2 Rose To 430°F. S/N 21 Showed Slight Discoloration Due To Heat. No Other Damage.

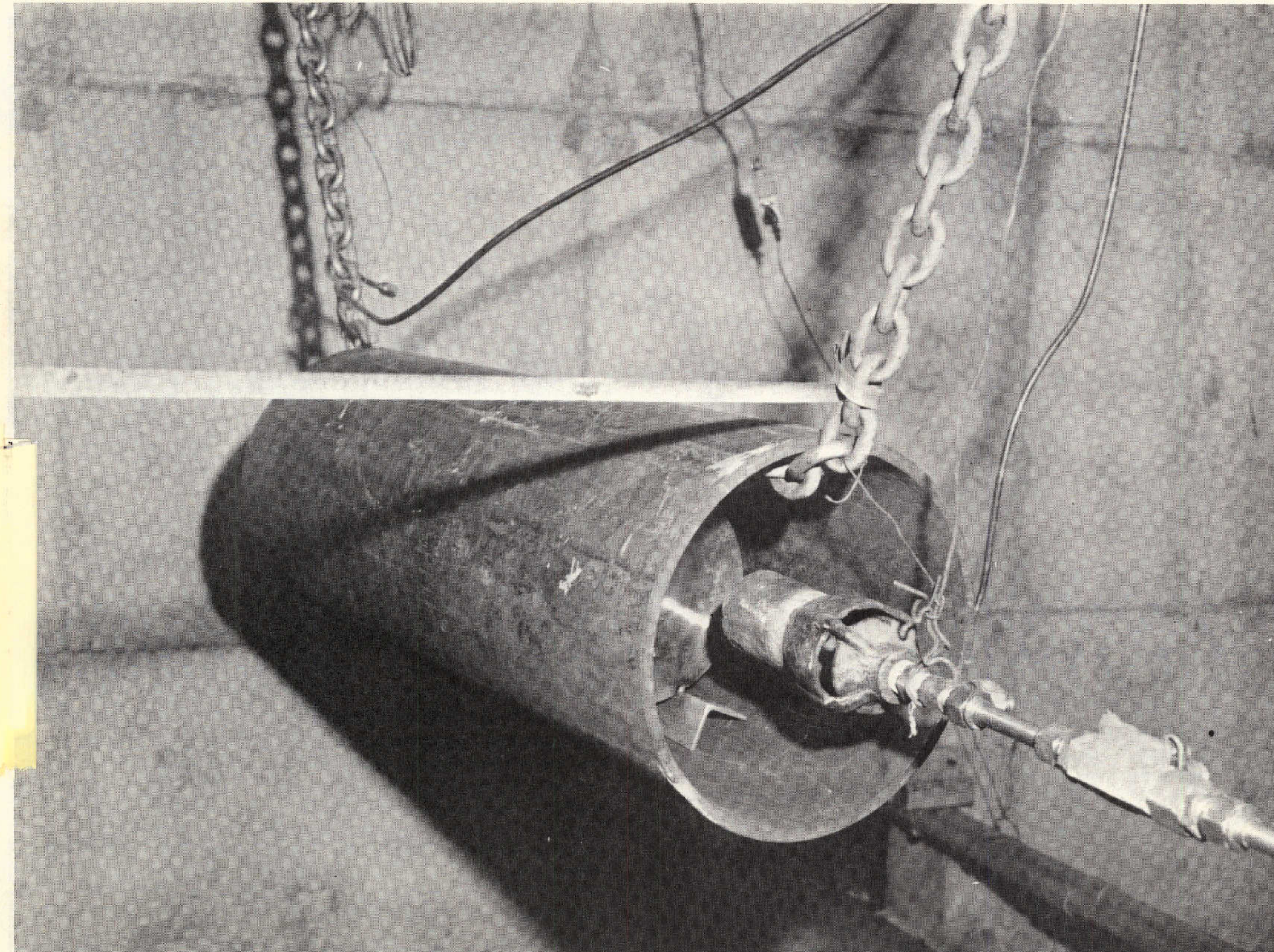


Figure B-5 High Temperature Exposure Test Setup

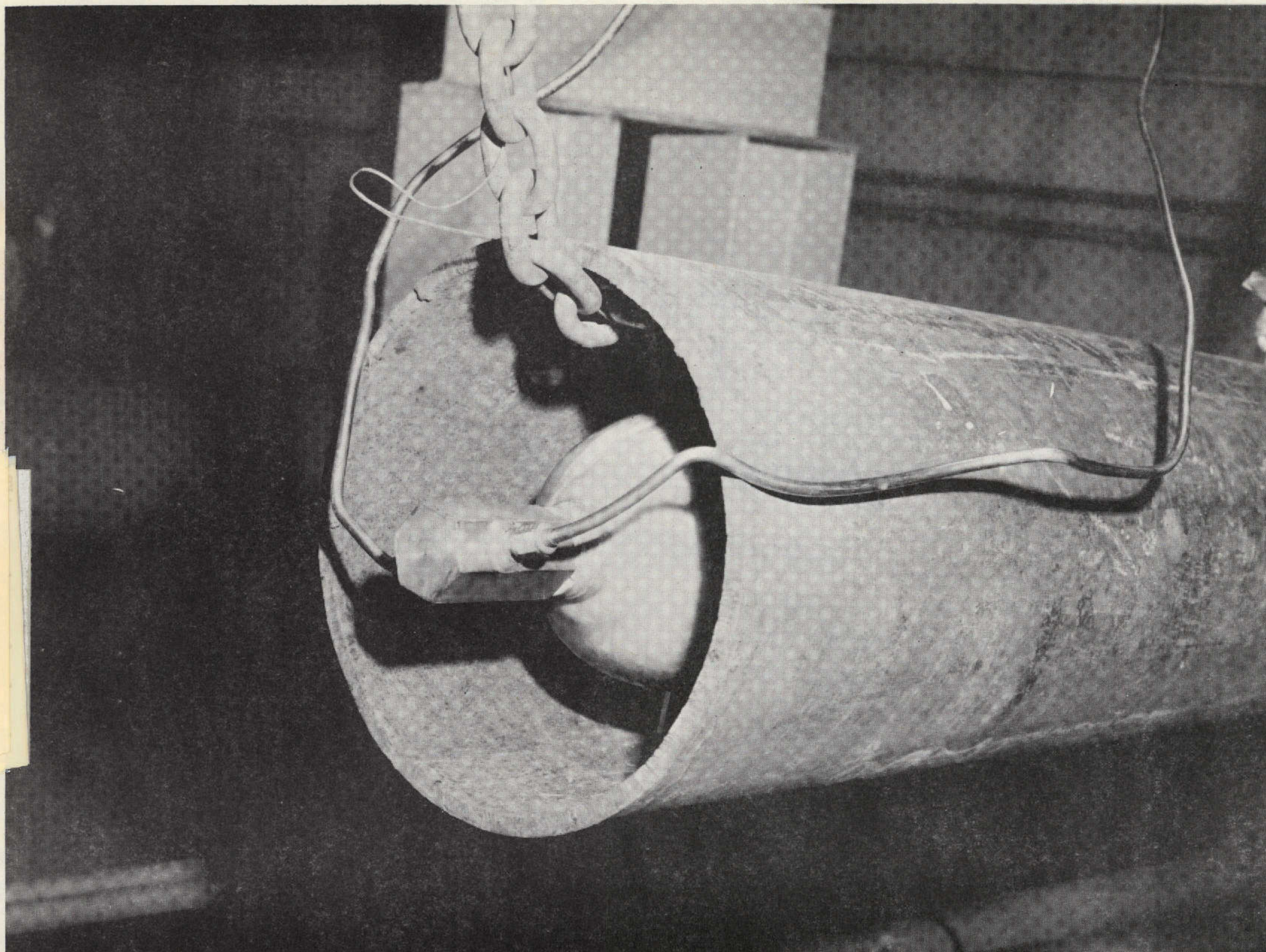


Figure B-6 High Temperature Exposure Test Setup

Table B-12 Test Data - S/N 21

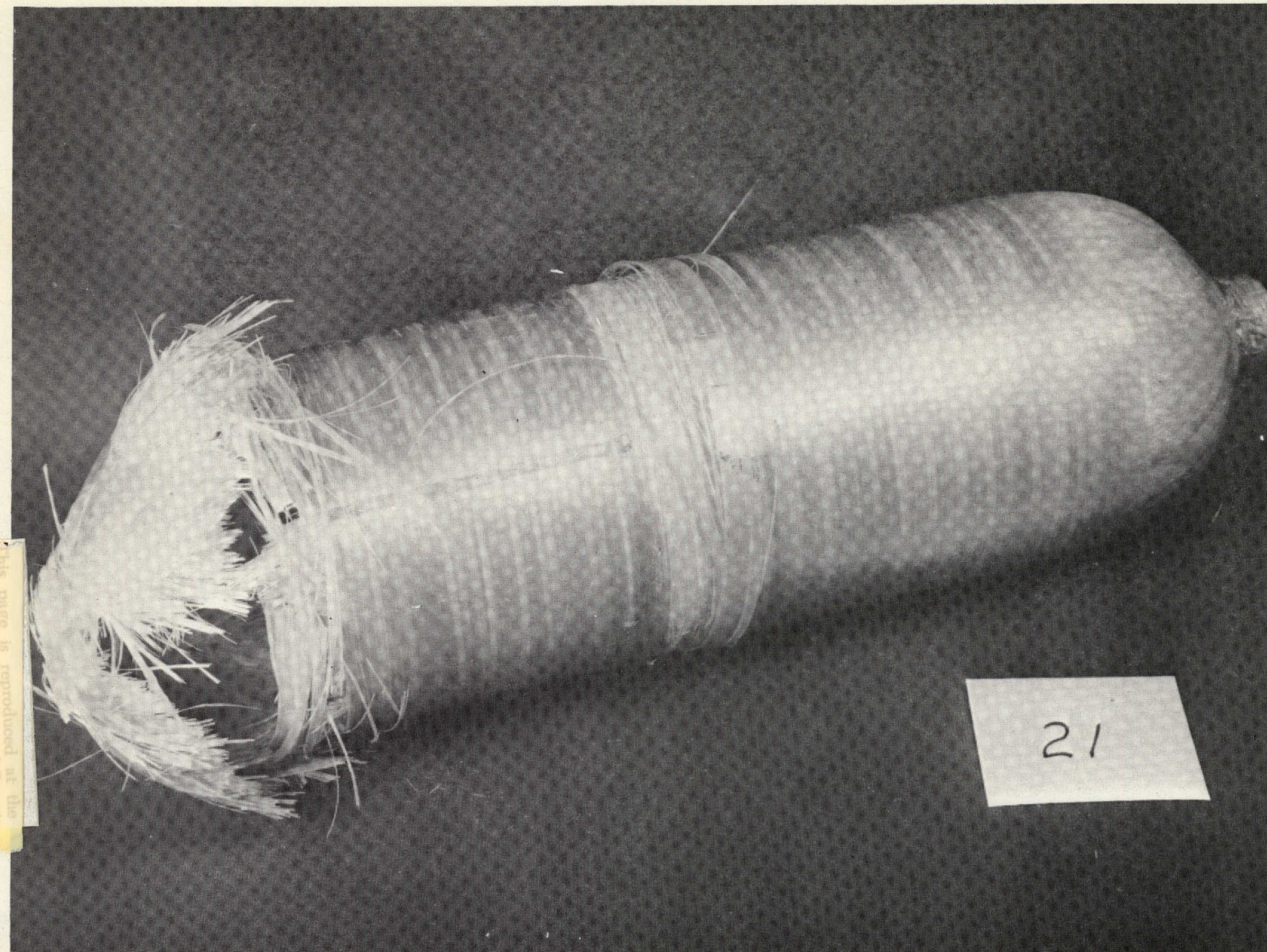
Test: Burst Pressure

Vessel S/N: 21

Date: 6/15/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Burst Pressure	9000 psig min	12,800 psig
Volume increase Enter burette readings at pressure _____ prior to pressurization _____		N/A
difference _____ (volume increase)	N/A	
Failure mode	N/A	Lower End Dome-Glass Failure
Other Observations	N/A	



This page is reproduced at the back of the report by

Figure B-7 Vessel S/N 21 After Burst Test

3. <u>Test Results - Vessel S/N 14</u>

a. *Examination of Product and Volume Determination* - As required by paragraph 6.1 of the test procedure (Reference Section D of this appendix) the vessel was examined for evidence of damage, poor workmanship, and unintentional defects. The flaws were located and recorded. The vessel was weighed and measured and the volume was measured. Vessel weight was 8.34 pounds and the measured volume was 281.4 $in.^3$. The original test data is included as Table B-13.

b. *Sizing, Expansion and Proof Test* - As required by paragraph 6.2 of the test procedure the vessel pressure was increased hydrostatically to 7600 psig at a rate not exceeding 500 psig per minute and then was decreased to ambient. Next the pressure was increased hydrostatically to 6750 psig at a rate not exceeding 500 psig per minute, maintained for 5 minutes, and then decreased to ambient.

During the test the volumetric expansion of the vessel was measured as 0% permanent expansion during the proof test. Volumetric expansion data during the sizing test was lost due to a test facility leakage problem. There was no evidence of damage or physical degradation of the vessel. The test data is included as Table B-14 and a photograph of the test setup is shown in Figure B-2.

c. *Functional Capability Test* - As required by paragraph 6.3 of the test procedure (Reference Section D of this appendix) the vessel was submerged in water and pressurized with GN_2 to 4000 psig. This pressure was maintained for 30 min while the surface of the water was monitored for an indication of leakage. The vessel pressure was then reduced to ambient.

No gas bubbles were observed coming from the vessel. Had any bubbles been observed they would have been collected and measured with an inverted graduated cylinder. The test data sheet is included as Table B-15 and a photograph of the test setup is shown in Figure B-3.

d. *Operating Pressure Cycle* - As required by paragraph 6.4 of the test procedure, the vessel pressure was changed hydrostatically from 0 psig to 4000 psig to 0 psig at approximately 4 cycles per min, for a total of 10,000 cycles.

Table B-13 Examination of Product

Pressure Vessel S/N: 14

Test Date: 4/13/73

Test Engineer: J. LeBeau

Parameter	Allowable	Actual
Workmanship	Workmanlike	
Damage	None	
Defects	None	
Weight	9.0 lb max	8.34 lb
Diameter	5.6 in. max	5.63 in.
Length	18.7 in. max	18.58 in.
Volume	280 $in.^3$ min	281.4 $in.^3$
Deliberate Flaws (Overwrap)		
Flaw No. 1		
Location	(Record actual location)	Upper Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.
Flaw No. 2		
Location	(Record actual location)	Cylinder
Depth	Approx 0.002 in.	0.0075
Length	Approx 1 in.	1.0 in.
Flaw No. 3		
Location	(record actual location)	Lower Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.

Table B-14 Test Data

Test: Sizing, Volumetric Expansion, and Proof Pressure

Vessel S/N: 14

Date: 4/19/73

Test Engineer: D. E. Dulaigh

Paremeter	Allowable	Actual
Sizing Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure ___ At Pressure ___ Prior To Pressurization ___ After Pressurization ___ Difference (A) Difference (B) ___ % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(\quad) - (\quad)}{(\quad)}$ (100) = ___ Vessel Damage	7600 ± 50 1% None	7600 Psig Data Lost Due To Facility Leak None
Proof Pressure Time At Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 75 At Pressure 75 % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(75) - (75)}{(75)}$ (100) = 0% Vessel Damage	6750 ± 50 5 Minutes 1% None	6750 Psig 5 Minutes 0% None

Table B-15 Test Data-S/N 14

Test: Functional Capability

Vessel S/N: 14

Date: 4/24/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure	4000 ± 50 psig	4000 psig
Time at Pressure	30 min	30 min
Leakage Rate	6.5 scc/hr max	0
Damage	None	None

Table B-16 Test Data-S/N 14

Test: Operating Pressure Cycling Test

Vessel S/N: 14

Date: 5/1/73 thru 5/9/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	10,000	10,000
Max Pressure	4000 ± 50 psig	4000 ± 50 psig
Min Pressure	0 to 100 psig	0 to 100 psig
Damage	None	None
Post-Functional		
Pressure	4000 ± 50 psig	4000 psig
Time	30 min	30 min
Leakage	6.5 scc/hr max	None
Damage	None	None

There was no evidence of damage or physical degradation after the 10,000 cycles and there was no leakage during the subsequent functional test. The test data sheet is included as Table B-16.

e. *Proof Pressure Cycle Test* - As required by paragraph 6.5 of the test procedure, the vessel was pressurized hydrostatically to 6750 psig, maintained at 6750 psig for 30 sec, and then reduced to ambient for a total of 100 cycles. The test procedure and setup were modified slightly to allow use of a Haskel hydrostatic pump instead of a GN_2 source.

There was no evidence of damage or physical degradation after the 100 cycles and there was no leakage during the subsequent functional test. The test data sheet is included as Table B-17.

f. *Impact Test* - Due to vessel seal leakage the vessel was preconditioned to -60 ± 20°F or 200 ± 20°F while 4000 psig pressure was maintained. The vessel pressure was then isolated and the vessel was removed from the bath and dropped 10 ft onto a 1/2-in. carbon steel plate. This sequence was repeated at the cold temperature and then at the hot temperature for a total of 12 drops.

The vessel successfully completed the impact test as described and there was no indication of leakage during the subsequent functional test. A history of temperature versus time for typical cold and hot cycles is also shown in Table B-18. The test data sheet is included in the table.

g. *Thermal Cycle Test* - As required by paragraph 6.7 of the test procedure, the vessel was pressurized to 4000 psig at ambient temperature, locked off, submerged in a -60 ± 20°F bath for 10 min and then submerged in a 200 ± 20°F bath for 10 min. This sequence was to be repeated for a total of 20 cycles.

During the second hot cycle the vessel failed catastrophically in the upper part of the cylindrical section forcing the hot water container downward through the support grating.

The test data sheet is included as Table B-19. A photograph of the ruptured vessel is shown in Figure B-8, and a photograph of the test setup after rupture is shown in Figure B-9.

Table B-17 Test Data-S/N 14

Test: Proof Pressure Cycling Test

Vessel S/N: 14

Date: 5/10/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	100	100
Vessel Temperature	Ambient	58°F
Max Pressure	6750 ± 100 psig	6750 ± 100 psig
Min Pressure	0 to 100 psig	0 to 100 psig
Damage	None	None
Post-Functional		
Pressure	4000 ± 50 psig	4000 psig
Time	30 min	30 min
Leakage	6.5 scc/hr max	None
Damage	None	None

Table B-18 Test Data - S/N 14

Test: Impact
Vessel S/N: 14
Date: 5/16/73
Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual Sequence 1	Sequence 2
Valve End, -60°F			
Predrop Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 10°F	-60	-50
Predrop Temp	-60 ± 20°F	-42	-40
Damage	None	None	None
Valve End, +200°F			
Predrop Pressure	4000 ± 50 Psig	4050	4050
Temp In Bath	200 ± 10°F	193	190
Predrop Temp	200 ± 20°F	180	180
Damage	None	None	None
Opp End -60°F			
Predrop Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 20°F	-60	-56
Predrop Temp	-60 ± 20°F	-53	-40
Damage	None	None	None
Opp End, +200°F			
Predrop Pressure	4000 ± 50 Psig	4050	4050
Temp In Bath	200 ± 20°F	196	193
Predrop Temp	200 ± 20°F	175	178
Damage	None	None	None
Side, -60°F			
Predrop Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 20°F	-56	-60
Predrop Temp	-60 ± 20°F	-40	-45
Damage	None	None	None
Side, +200°F			
Predrop Pressure	4000 ±50 Psig	4050	4050
Temp In Bath	200 ± 20°F	190	190
Predrop Temp	200 ± 20°F	180	180
Damage	None	None	None
Post-Test Functional			
Pressure	4000 ± 50 Psig	4000 Psig	4000 Psig
Time At Pressure	30 Min	30 Min	30 Min
Leakage Rate	6.5 Scc/Mr Max.	None	None
Damage	None	None	None

Note: This test is for information only and there is no failure criteria.

Table B-18 Test Data - S/N 14

Test: Impact
Vessel S/N: 14
Date: 5/16/73
Test Engineer: D. E. Dulaigh

Typical Cold Cycle (Both Temp - 80°F):	
T = 0 Sec	Bottle Temp 72°F (T_B) Start Pressurization
T = 30	End Pressurization
T = 80	T_B = 134°F And Increasing - Dunk In Cold Bath
T = 82	T_B = 22°F And Decreasing
T = 220	T_B = -60°F And Decreasing Very Slowly - Out Of Bath
T = 250	T_B = -50°F Drop Occurs
Typical Hot Cycle (Bath Temp = 190°F):	
T = 0 Sec	Bottle Temp 72°F - Start Pressurization
T = 60	End Pressurization T_B = 113°F And Increasing
T = 110	T_B = 134°F And Stable
T = 150	Dunk In Hot Bath
T = 154	T_B = 166°F
T = 350	T_B Had Increased Slowly To 190°F - Out Of Bath
T = 390	T_B = 180°F - Drop Occurs

Table B-19 Test Data

Test: Thermal Cycling

Vessel S/N: 14

Date: 5/16/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	20	1 1/2
Transfer Time	3 min max	50 sec
Cold Bath Temp	-60 ± 10°F	-680°F
Hot Bath Temp	200 ± 10°F	191°F*
Damage	None	*

*Vessel ruptured catastrophically after 13 min in the second hot bath immediately before being pulled out. Two cold soaks and one hot soak had successfully been completed. Vessel temperature was 183.9°F.

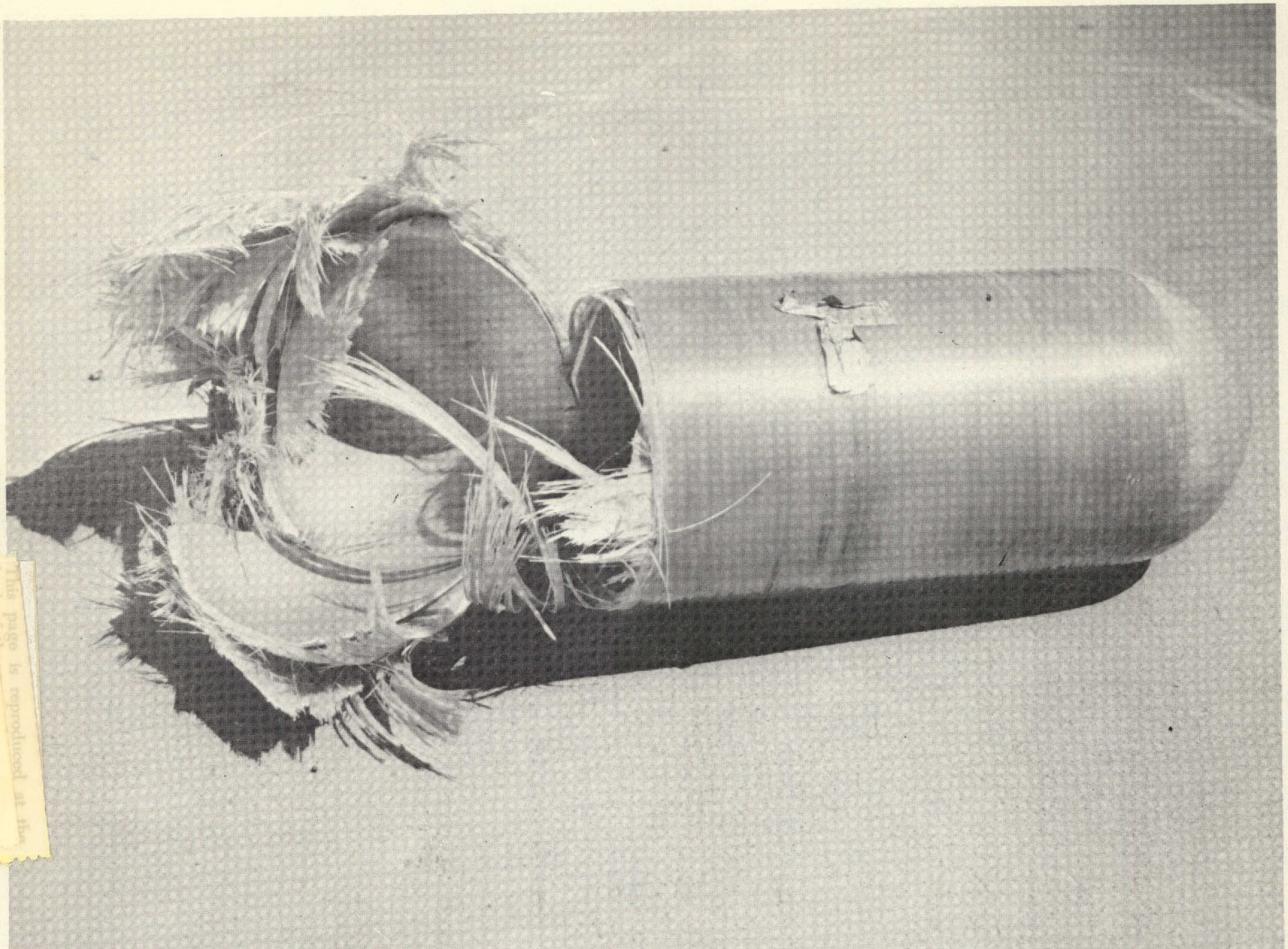


Figure B-8 Vessel S/N 14 After Failure

This page is reproduced at the

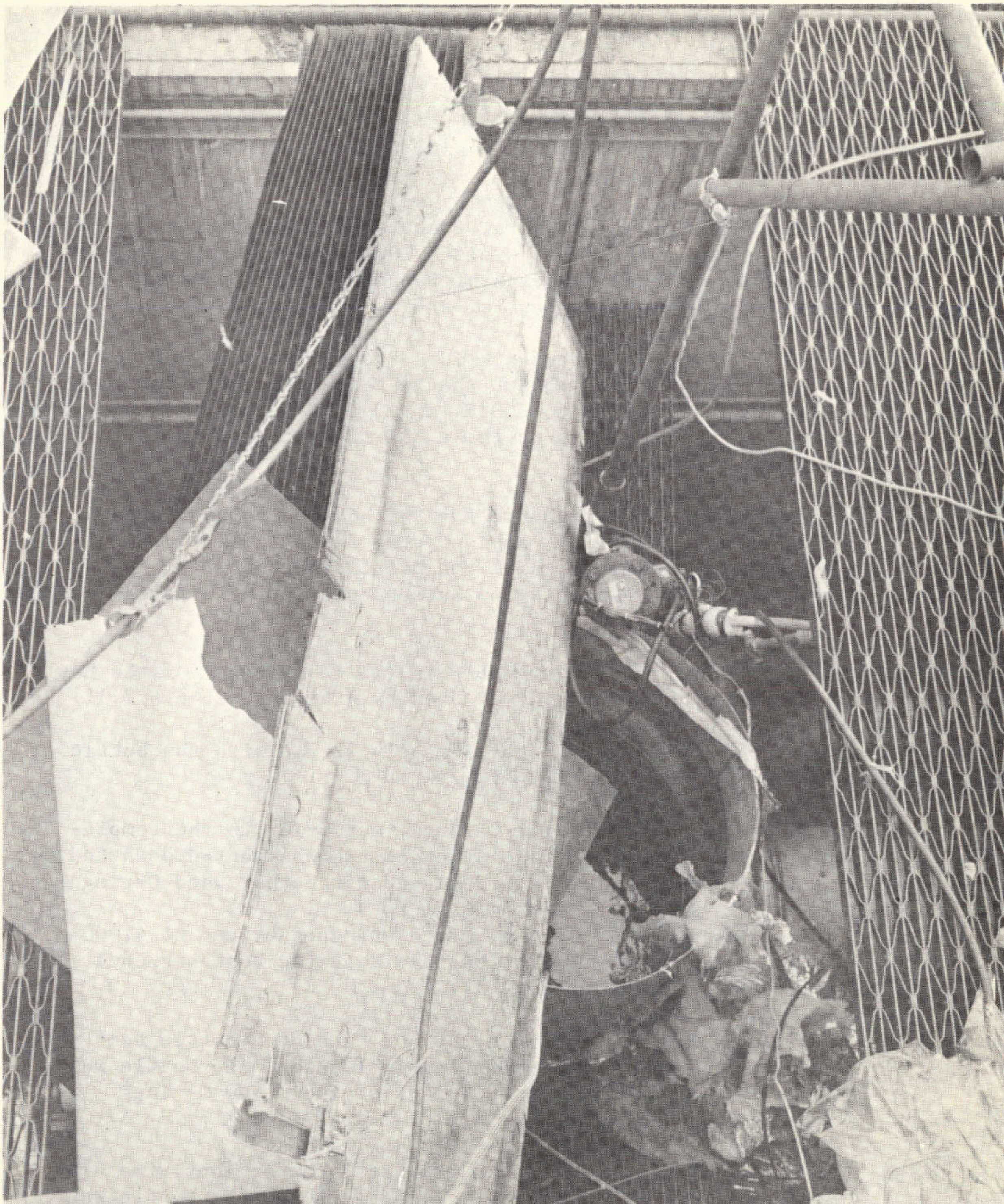


Figure B-9 Thermal Cycle Test Damage

This page is reproduced at the back of the report by a different reproduction method to provide better detail.

A more complete analysis of the vessel failure follows:

1) Test-item history: Test item 3 had previously been subjected to sizing and proof pressure; functional capability test; 10,000 operating pressure cycles; 100 proof pressure cycles and six impact tests at each of two temperatures and was in thermal cycle testing when failure occurred.

2) Normal thermal cycle sequence is: Pressurize to 4,000 psi at ambient temperature; subject the test item to -60°F for 10 min; subject the test item to 200°F for 10 min. The vessel successfully completed two of these thermal cycles when failure occurred.

3) The normal pressure sequence for the bottle included pressurizing to 4,000 psi at ambient temperature; disconnect pressurization source; chill the bottle and then warm the bottle per Step 2 without any subsequent venting or pressurization changes.

4) The first cold cycle lasted 60 min (while waiting for the hot bath to warm up). This is allowed by Procedure Step 6.7.11.

5) The first hot cycle was approximately 12 min with the bottle final temperature of 179.4°F.

6) Leakage was noted from the O-rings just prior to the completion of the first hot cycle. The bottle was vented down and the broken O-rings (2) were replaced with other used O-rings.

7) At the start of Cycle 2 the bottle was pressurized to 4,000 psi and inserted in the hot bath so that the test sequence would not be interrupted.

8) After approximately 2 min in the hot bath at a bottle temperature of 171°F, the O-rings again leaked. The bottle was removed and the O-rings were both replaced. New O-rings were used on this replacement.

9) The bottle was re-inserted in the hot bath for approximately 15 min (bottle temperature 180°F) after which the bottle was removed and inserted in the cold bath.

10) The bottle was soaked in the cold bath for 10 min with an almost immediate response of the thermocouple to the cold temperature. Final bottle temperature was -49.4°F.

11) Approximately 50 sec elapsed from the cold bath to the hot bath. The bottle had soaked in hot bath for 13 min when it failed at a temperature of 183.9°F.

12) Due to the rapid initial pressurization, some heat of compression would probably occur resulting in less pressure at ambient temperature than indicated.

13) When the bottle failed, it forced the hot bath tank and two major sections of grating into the lower cell area.

14) While pre-test safety precautions were adequate to protect personnel, if the bottle had failed during transfer, considerable damage might have occurred.

15) No procedure deviations occurred during any portion of the test.

16) The test requestor was notified of the failure and photographs were taken of both the test specimen and facility.

This vessel failure was attributed to an inadvertent omission of the final cure step (3 hrs at 320°F) during vessel manufacture. This vessel was unique in that it was hard carved from the overwrapping vendor in Salt Lake City to our Denver facility for testing. The vessel was staged or gelled prior to pick up but was not cured. The curing of the vessel was intended to be performed at Denver (all other vessels were cured prior to shipping to Denver) but did not occur due to an oversight and was placed in test.

Improperly cured resin has poor thermal and chemical resistance. The boiling water environment present during this test reduces the shear strength of uncured resin to nil. This factor plus the increased susceptability of exposed glass fiber to stress corrosion combined to cause pressature failure of this vessel.

4. Test Results - Vessel S/N 19

a. Operating Pressure Cycle - As required by paragraph 6.4 of the test procedure (Reference Section D of this appendix) the vessel pressure was changed hydrostatically from 0 psig to 4000 psig to 0 psig at approximately 4 cycles per min, for a total of 10,000 cycles.

There was no evidence of damage or physical degradation after the 10,000 cycles. The test data sheet is included as Table B-20.

b. Proof Pressure Cycle Test - As required by paragraph 6.5 of the test procedure, the vessel was pressurized hydrostatically to 6750 psig, maintained at 6750 psig for 30 sec, and then reduced to ambient for a total of 100 cycles. The test procedure and setup were modified slightly to allow use of a Haskel hydrostatic pump instead of a GN_2 source and the post-test functional test was not performed.

There was no evidence of damage or physical degradation after the 100 cycles. The test data sheet is included as Table B-20a.

c. Impact Test - As required by paragraph 6.6 of the test procedure, the vessel was pressurized to 4000 psig at ambient temperature and preconditioned to -60 ± 20°F or 180 ± 20°F while the gas volume of the vessel was isolated. The vessel pressure was then isolated and the vessel was removed from the bath and dropped 10 feet onto a 1/2-in. carbon steel plate. This sequence was repeated alternately at the cold then hot temperature for a total of 12 drops.

The vessel successfully completed the impact test as described. The test data sheet is included as Table B-21.

d. Thermal Cycle Test - As required by paragraph 6.7 of the test procedure, the vessel was pressurized to 4000 psig at ambient temperature, locked off, submerged in a -60 ± 20°F bath for 10 min and then submerged in a 180 ± 20°F bath for 10 min. The procedure required 200°F ± 10 but this reduced was allowed to preclude boiling. This sequence was repeated for a total of 20 cycles.

The vessel successfully completed the 20 thermal cycles with no evidence of damage or degradation. The test data sheet is included as Table B-22.

Table B-20 Test Data - S/N 19

Test: Operating Pressure Cycling Test

Vessel S/N: 19

Date: 6/27/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	10,000	10,000
Max Pressure	4000 ± 50 psig	4000 ± 50 psig
Min Pressure	0 to 100 psig	100 psig
Damage	None	None

Table B-20a - Test Data - S/N 19

Test: Proof Pressure Cycling Test

Vessel N/N: 19

Date: 6/28/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	100	100
Vessel Temperature	Ambient	86°F
Max Pressure	6750 ± 100 psig	6750 ± 100 psig
Min Pressure	0 to 100 psig	100 psig
Damage	None	None

Table B-21 Test Data - S/N 19

Test: Impact
Vessel S/N; 19
Date: 7/3/73 And 7/5/73
Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual	
		Sequence 1	Sequence 2
Valve End, -60°F	-60 ± 20°F		
Pretest Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 10°F	-52	-56
Predrop Temp	-60 ± 20°F	-46	-44
Damage	None	None	None
Valve End, +200°F	180 ± 20°F*		
Pretest Pressure	4000 ± 50 Psig	4000	4000
Temp In Bath	180 ± 10°F	178	184
Predrop Temp	180 ± 20°F	160	180
Damage	None	None	None
Opp End -60°F	-60 ± 20°F		
Pretest Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 20°F	-46	-72
Predrop Temp	-60 ± 20°F	-40	-56
Damage	None	None	None
Opp End,+200°F	180 ± 20°F*		
Pretest Pressure	4000 ± 50 Psig	4000	4000
Temp In Bath	180 ± 20°F	172	178
Predrop Temp	180 ± 20°F	168	165
Damage	None	None	None
Side, -60°F	-60 ± 20°F		
Pretest Pressure	3040-3950 Psig	3950	3950
Temp In Bath	-60 ± 20°F	-44	-60
Predrop Temp	-60 ± 20°F	-40	-40
Damage	None	None	None
Side, +200°F	180 ± 20°F*		
Pretest Pressure	4000 ± 50 Psig	4000	4000
Temp In Bath	180 ± 20°F	168	172
Predrop Temp	180 ± 20°F	162	160
Damage	None	None	None
Post-Test Functional			
Pressure	4000 ± 50 Psig		
Time At Pressure	30 Min	N/A	N/A
Leakage Rate	615 Scc/Hr Max.		
Damage	None		

*Reduced from 200°F ± 10 to preclude boiling.

Table B-22 Test Data-S/N 19

Test: Thermal Cycling

Vessel S/N: 19

Date: 7/10/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
No. of Cycles	20	20
Transfer Time	3 min max	30 sec
Cold Bath Temp	-60 ± 10°F	-50 to -70°F
Hot Bath Temp	180 ± 20°F	+160 to +180
Damage	None	None

Table B-23 Test Data-S/N 19

Test: Burst Pressure

Vessel S/N: 19

Date: 7/10/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Burst pressure	8900 psig min	9990 psig
Volume Increase Enter burette readings at pressure _____ prior to pressurization ____		
difference _____ (volume Increase)	N/A	N/A
Failure Mode	N/A	Glass Failure
Other Observations	N/A	Upper Dome No Fragments

e. *Burst Test* - The vessel was pressurized hydrostatically at a rate of 2000 to 3000 psi per min until rupture occurred. Rupture occurred at 9990 psig, originated in the upper dome, and was due to a glass failure.

The test data sheet is included as Table B-23 and the oscillograph recordings made during this test will be available at the Engineering Propulsion Laboratory for six months for further inspection and analysis. A photograph of the vessel after rupture is shown in Figure B-10.

Figure B-10 Vessel S/N 19 After Burst Test

5. Test Results - Vessel S/N 15

a. Examination of Product and Volume Determination - As required by paragraph 6.1 of the test procedure (Reference Section D of this appendix) the vessel was examined for evidence of damage, poor workmanship, and unintentional defects. The flaws were located and recorded. The vessel was weighed and measured and the volume was measured. Vessel weight was 8.09 pounds and the measured volume was 281.6 $in.^3$. The original test data is included as Table B-24.

b. Sizing, Expansion and Proof Test - As required by paragraph 6.2 of the test procedure, the vessel pressure was increased hydrostatically to 7600 psig at a rate not exceeding 500 psig per min and then was decreased to ambient. Next, the pressure was increased hydrostatically to 6750 psig at a rate not exceeding 500 psig per min, maintained for 5 min, and then decreased to ambient.

During the test the permanent volumetric expansion of the vessel was measured as 38% of the total change in volume during the sizing test and as 0% permanent expansion during the proof tests. There was no evidence of damage or physical degradation of the vessel. The test data is included as Table B-25 and a photograph of the test setup is shown in Figure B-2.

c. Functional Capability Test - As required by paragraph 6.3 of the test procedure, the vessel was submerged in water and pressurized with GN_2 to 4000 psig. This pressure was maintained for 30 min while the surface of the water was monitored for an indication of leakage. The vessel pressure was then reduced to ambient.

No gas bubbles were observed coming from the vessel. Had any bubbles been observed they would have been collected and measured with an inverted graduated cylinder. The test data sheet is included as Table B-26 and a photograph of the test setup is shown in Figure B-3.

d. Fragmentation Resistance Test - As required by paragraph 6.14 of the test procedure the vessel was strapped to the back pack and then to a sand bag. The vessel was struck with a 30-06 armour-piercing bullet fired from a distance of 100 yd at a muzzle velocity of 2800 ft/sec.

Table B-24 Examination of Product

Pressure Vessel S/N: 15

Test Date: 4/13/73

Test Engineer: J. LeBeau

Parameter	Allowable	Actual
Workmanship	Workmanlike	
Damage	None	
Defects	None	
Weight	9.0 lb max	8.09 lb
Diameter	5.0 in. max	5.57 in.
Length	18.7 in. max	18.58 in.
Volume	280 $in.^3$ min	281.62 $in.^3$
Deliberate Flaws (Overwrap)		
Flaw No. 1		
Location	(Record actual location)	Upper Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.
Flaw No. 2		
Location	(Record actual location)	Cylinder Section
Depth	Approx 0.002 in.	0.075
Length	Approx 1 in.	1.0 in.
Flaw No. 3		
Location	(Record actual location)	Lower Dome
Depth	Approx 0.002 in.	0.0035
Length	Approx 1 in.	1.0 in.

Table B25 Test Data - S/N 15

Test: Sizing, Volumetric Expansion, and Proof Pressure

Vessel S/N: 15

Date: 4/23/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Sizing Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 137 Prior To Pressurization 0 At Pressure 137 After Pressurization 52 Difference (A) 137 Difference (B) 85 $\% \text{ Increase} = \frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}} (100)$ $\frac{(137) - (85)}{(137)} (100) = 38\%$	7600 ± 50 N. R.	7600 38%
Vessel Damage	None	None
Proof Pressure Time At Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 118 Prior To Pressurization 0 At Pressure 118 After Pressurization 0 Difference (A) 118 Difference (B) 118 $\% \text{ Increase} = \frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}} (100)$ $\frac{(118) - (118)}{(118)} (100) = 0$	6750 ± 50 5 Min 1%	6750 5 Min 0%
Vessel Damage	None	None

Table B-26 Test Data-S/N 15

Test: Functional Capability

Vessel S/N: 15

Date: 4/23/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure	4000 ± 50 psig	4000 psig
Time at Pressure	30 min	30 min
Leakage rate	6.5 scc/hr max	0
Damage	None	None

Table B-27 Test Data-S/N 15

Parameter	Allowable	Actual
Pressure	4500 ± 50 psig	4500 psig
Distance	Approximately 100 yd	100 yd
No. of hits required to rupture	N/A	1
Length of rupture	3-in. + 1 hole dia	No Tear
Travel of fragments*	None	No Fragments

Note: This test is for information only and there is no failure criteria.

*No fragments left the vessel. The vessel remained attached to the backpack which remained attached to the sandbag.

One hit was required to rupture the vessel and the bullet entered the vessel in the cylindrical section slightly below center and exited directly opposite (see Figures B-11, 12, and 13). The entry and exit holes did not cause any liner tear and no fragments left the glass wrap. Upon rupture, the vessel remained attached to the back pack which remained attached to the sand bag. The test data sheet is included as Table B-27.

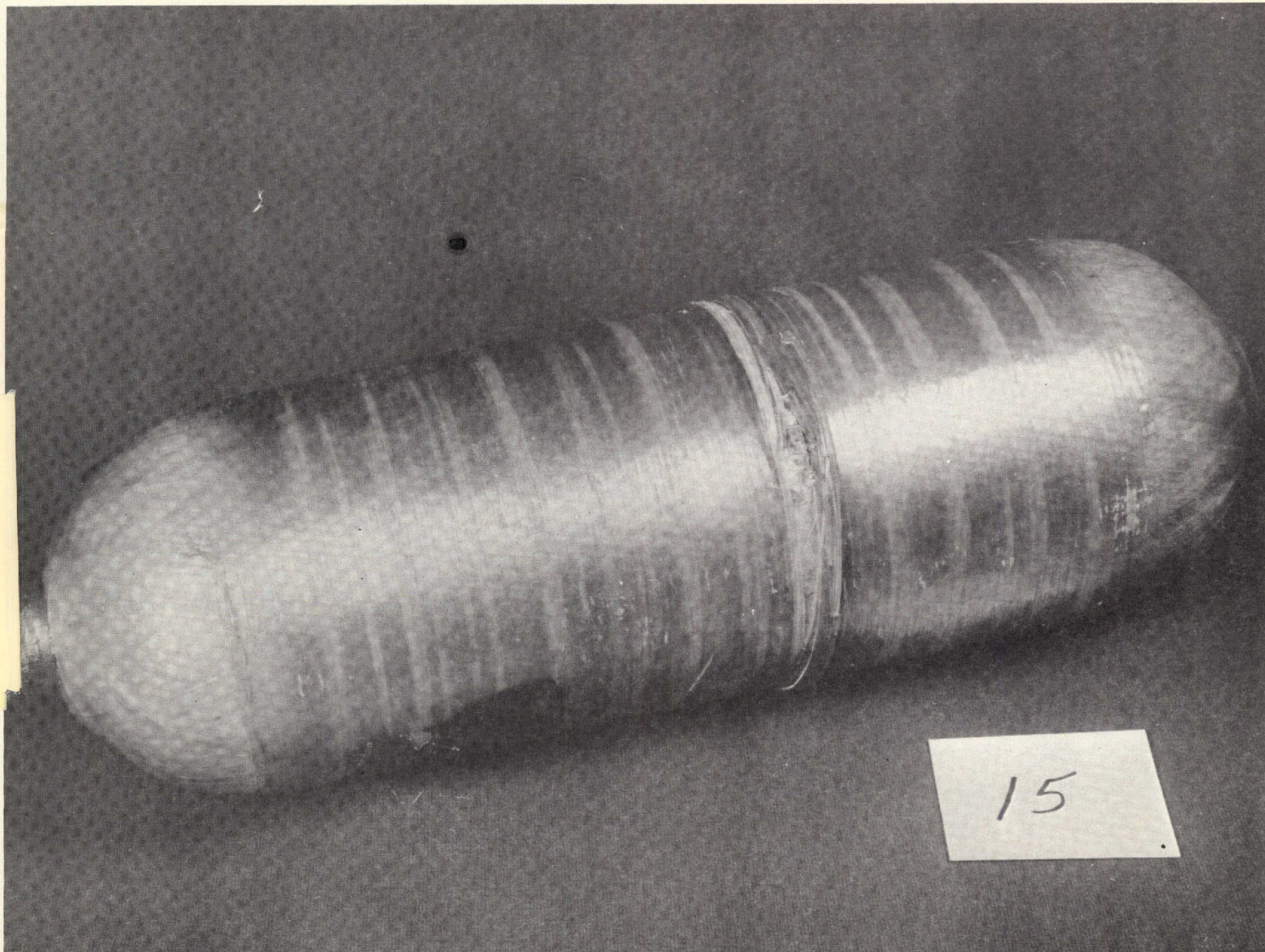


Figure B-11 Drop Test Setup

better detail.

Figure B-12 Vessel S/N 15 Bullet Entry Hole

Figure B-13 Vessel S/N 15 Bullet Exit Hole

6. Test Results - Vessel S/N 34

a. Examination of Product and Volume Determination - As required by paragraph 6.1 of the test procedure (Reference Section D of this appendix) the vessel was examined for evidence of damage, poor workmanship, and unintentional defects. The flaws were located and recorded. The vessel was weighed and measured and the volume was measured. Vessel weight was 8.54 pounds and the measured volume was 281.2 $in.^3$. The original test data is included as Table B-28.

b. Sizing, Expansion and Proof Test - As required by paragraph 6.2 of the test procedure the vessel pressure was increased hydrostatically to 7600 psig at a rate not exceeding 500 psig per min and then was decreased to ambient. Next the pressure was increased hydrostatically to 6750 psig at a rate not exceeding 500 psig per min, maintained for 5 min, and then decreased to ambient.

During the test the volumetric expansion of the vessel was measured as 0% permanent expansion during the proof test. Volumetric expansion data during the sizing test was lost due to a test facility leakage problem. There was no evidence of damage or physical degradation of the vessel. The test data is included as Table B-29 and a photograph of the test setup is shown in Figure B-2.

c. Functional Capability Test - As required by paragraph 6.3 of the test procedure, the vessel was submerged in water and pressurized with GN_2 to 4000 psig. This pressure was maintained for 30 min while the surface of the water was monitored for an indication of leakage. The vessel pressure was then reduced to ambient.

No gas bubbles were observed coming from the vessel. Had any bubbles been observed they would have been collected and measured with an inverted graduated cylinder. The test data sheet is included as Table B-30 and a photograph of the test setup is shown in Figure B-3.

d. Flaw Growth Test - As required by paragraph 6.12 of the test procedure, the vessel pressure was cycled pneumatically from 0 psig to 4000 psig to 0 psig for a total of 1000 cycles and then was increased hydrostatically at a rate of 2000 to 3000 psig per min until rupture occurred at 12,200 psig. The 4000 psig pressure was maintained for 10 sec each cycle and the water spray was not necessary to control vessel temperature. The flaw growth test setup is shown in Figures B-14 and B-15.

Table B-28 Examination of Product

Pressure Vessel S/N: 34

Test Date: 4/13/73

Test Engineer: J. LeBeau

Parameter	Allowable	Actual
Workmanship	Workmanlike	
Damage	None	
Defects	None	
Weight	9.0 lb max	8.54 lb
Diameter	5.6 in. max	5.62 in.
Length	18.7 in. max	18.59 in.
Volume	280 $in.^3$ min	281.2 $in.^3$
Deliberate Flaws (Overwrap)		
Flaw No. 1		
Location	(Record actual location)	Upper Dome
Depth	Approx 0.002 in.	0.0035 in.
Length	Approx 1 in.	1.0 in.
Flaw No. 2		
Location	(Record actual location)	Cylinder Section
Depth	Approx 0.002 in.	0.075 in.
Length	Approx 1 in.	1.0 in.
Flaw No. 3		
Location	(Record actual location)	Lower Dome
Depth	Approx 0.002 in.	0.0035 in.
Length	Approx 1 in.	1.0 in.

Table B-29 Test Data - S/N 34

Test: Sizing, Volumetric Expansion, and Proof Pressure

Vessel S/N: 34

Date: 4/19/73

Test Engineer: D. E. Dulaigh

Paremeter	Allowable	Actual
Sizing Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure ___ At Pressure ___ Prior To Pressurization ___ After Pressurization ___ Difference (A) ___ Difference (B) ___ % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(\quad) - (\quad)}{(\quad)}$ (100) = _____ Vessel Damage	7600 ± 50 1% None	7600 Psig Data Lost Due To System Leak None
Proof Pressure Time At Pressure Percent Permanent Volume Increase (Calculate As Follows) Enter Burette Readings: At Pressure 68 At Pressure 68 Prior To Pressurization 0 After Pressurization 0 Difference (A) 68 Difference (B) 68 % Increase = $\frac{\text{Permanent Volume Increase (A-B)}}{\text{Temporary Volume Increase (A)}}$ (100) $\frac{(68) - (68)}{(68)}$ (100) = 0 Vessel Damage	6750 ± 50 5 Min 1% None	6750 Psig 5 Min 0% None

Table B-30 Test Data-S/N 34

Test: Functional Capability

Vessel S/N: 34

Date: 4/24/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure	4000 ± 50 psig	4000 psig
Time at Pressure	30 min	30 min
Leakage rate	6.5 scc/hr max	0
Damage	None	None

Table B-31 Test Data-S/N 34

Test: Flaw Growth

Vessel S/N: 34

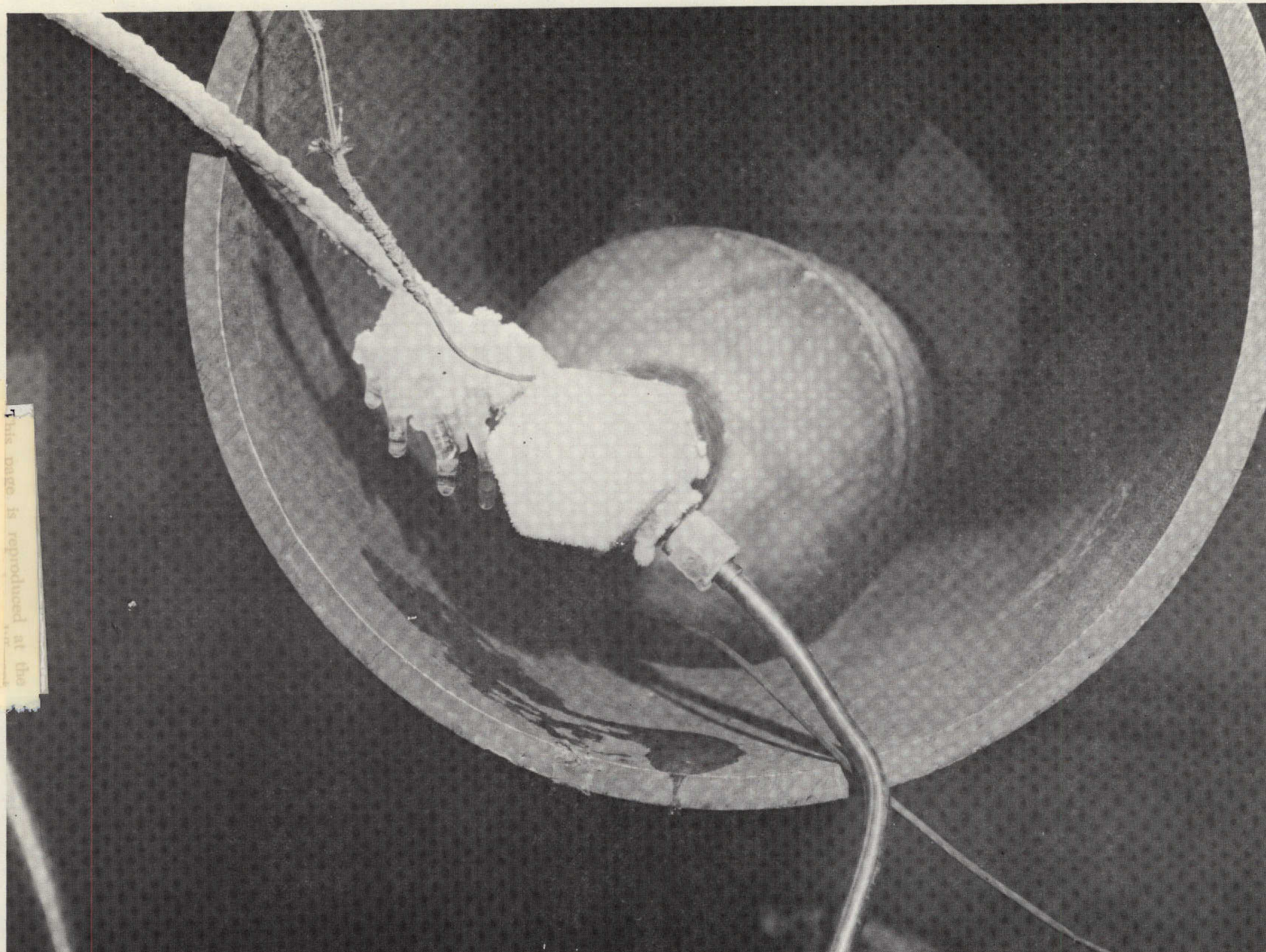
Date: 5/31/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure, Max	4000 ± 50 psig	400 ± 50 psig
Pressure, Min	100 psig max	0 to 100 psig
Vessel Temp	200°F max	Approx 80°F
No. of Cycles	N/A	1000
Failure Mode	Non-Hazardous	No Cycle Failure*
Failure Pressure/Cycle		12,000 psig during Burst*

Note: This test is for information only and there is no failure criteria.

*The vessel satisfactorily completed 1000 cycles and had glass failure in upper dome at 12,200 psig during hydrostatic burst. One piece = 6 in.^{2} and one piece = 3 in.^{2} left the wrap and were not contained.



This page is reproduced at the
better detail.

Figure B-14 Flaw Growth Test Setup

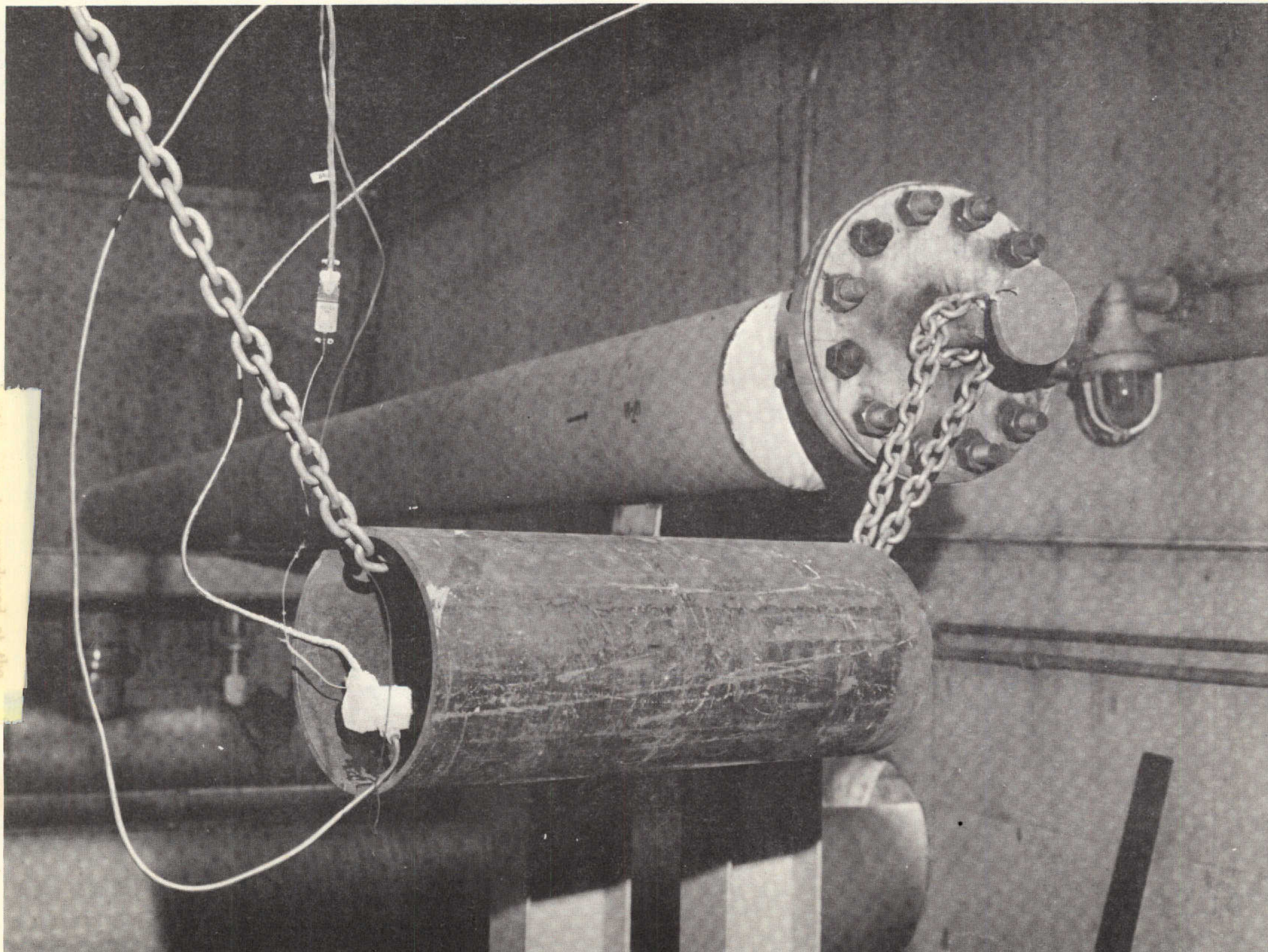


Figure B-15 Flaw Growth Test Setup

The vessel successfully completed the 1000 pneumatic operating cycles with no evidence of damage or degradation. The major induced flaw after cycling is shown in Figure B-16. During the burst test the vessel ruptured in the upper dome at 12,200 psig due to a glass failure and two liner pieces (6-in.^{2} and 3-in.^{2}) were not contained by the glass wrap. The test data is included in Table B-31. Photographs of the test setup are shown in Figures B-5 and B-6, and a photograph of the ruptured vessel is shown in Figure B-17.

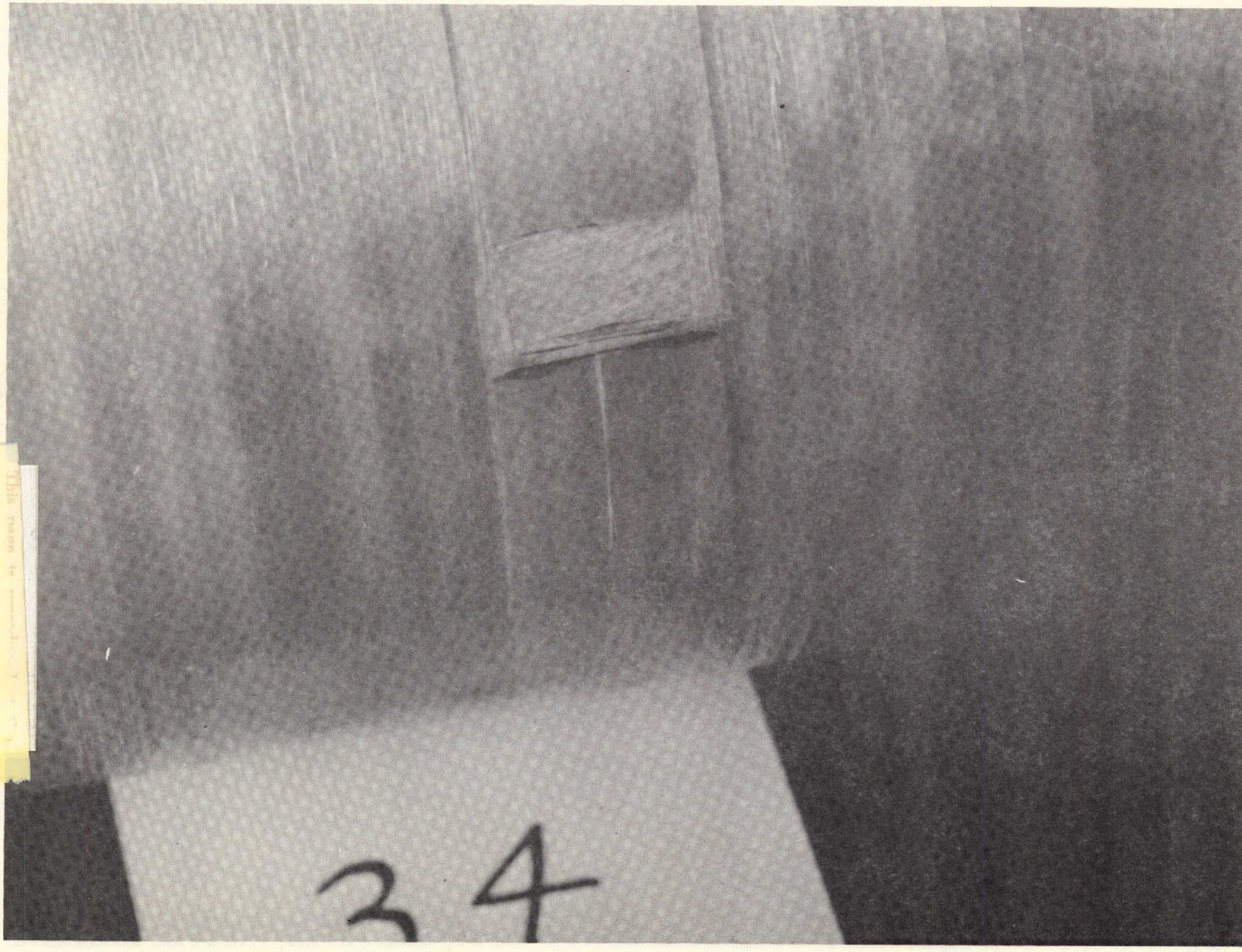


Figure B-16 Vessel S/N 34 Induced Flaw After Cycling

This page is reproduced at the

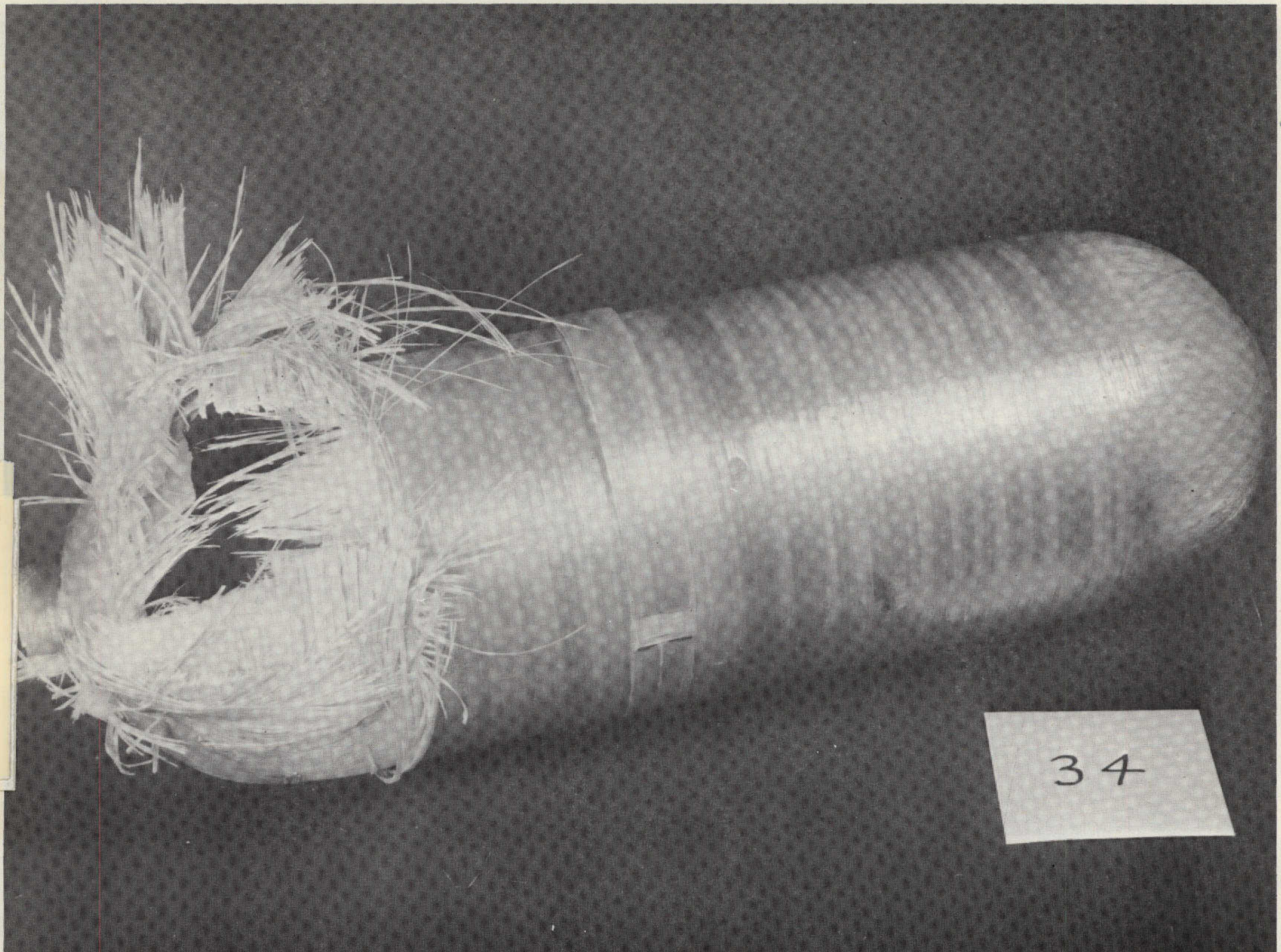


Figure B-17 Vessel S/N 34 After Burst Test

7. <u>Test Results - Vessel S/N 47</u>

a. Drop Test - As required by paragraph 6.13 of the test procedure, the vessel was strapped to a backpack and a 200-lb bag of lead shot as shown in Figures B-18, 19, and 20. The vessel was pressurized to 4500 psig and then dropped from a height of 16 ft onto a 1/2-in. carbon steel plate. The drop was repeated for a total of five drops and each drop was such that the vessel impacted first.

The vessel outer wrap sustained severe damage due to the backpack gussets (Figures B-21 and B-22) but these gussets probably had sharper edges than a typical production backpack. No other damage or degradation was found. The test data sheet is included as Table B-32.

b. Burst Test - The vessel was pressurized hydrostatically at a rate of 2000 to 3000 psig per min until rupture occurred.

Rupture occurred at 10,200 psig, originated at the intersection of the cylinder section and the lower dome where severe glass damage had been sustained during drop test (Figures B-19 and B-20). There were no fragments and all portions of the liner were contained by the glass. The volumetric expansion at 9000 psig was measured as 148 cc.

The test data sheet is included as Table B-33. A photograph of the vessel after rupture is shown in Figure B-23.

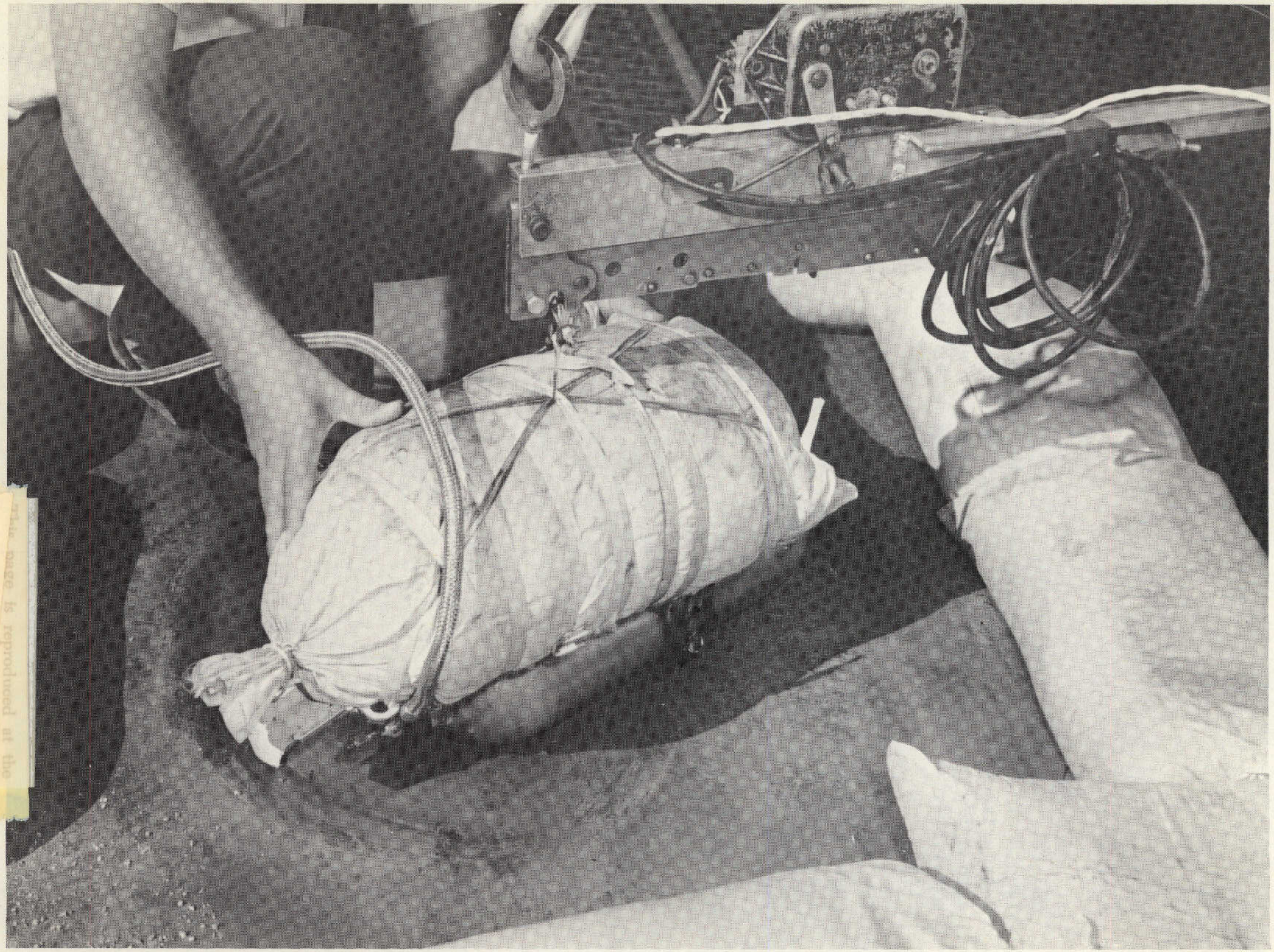


Figure B-18 Drop Test Setup

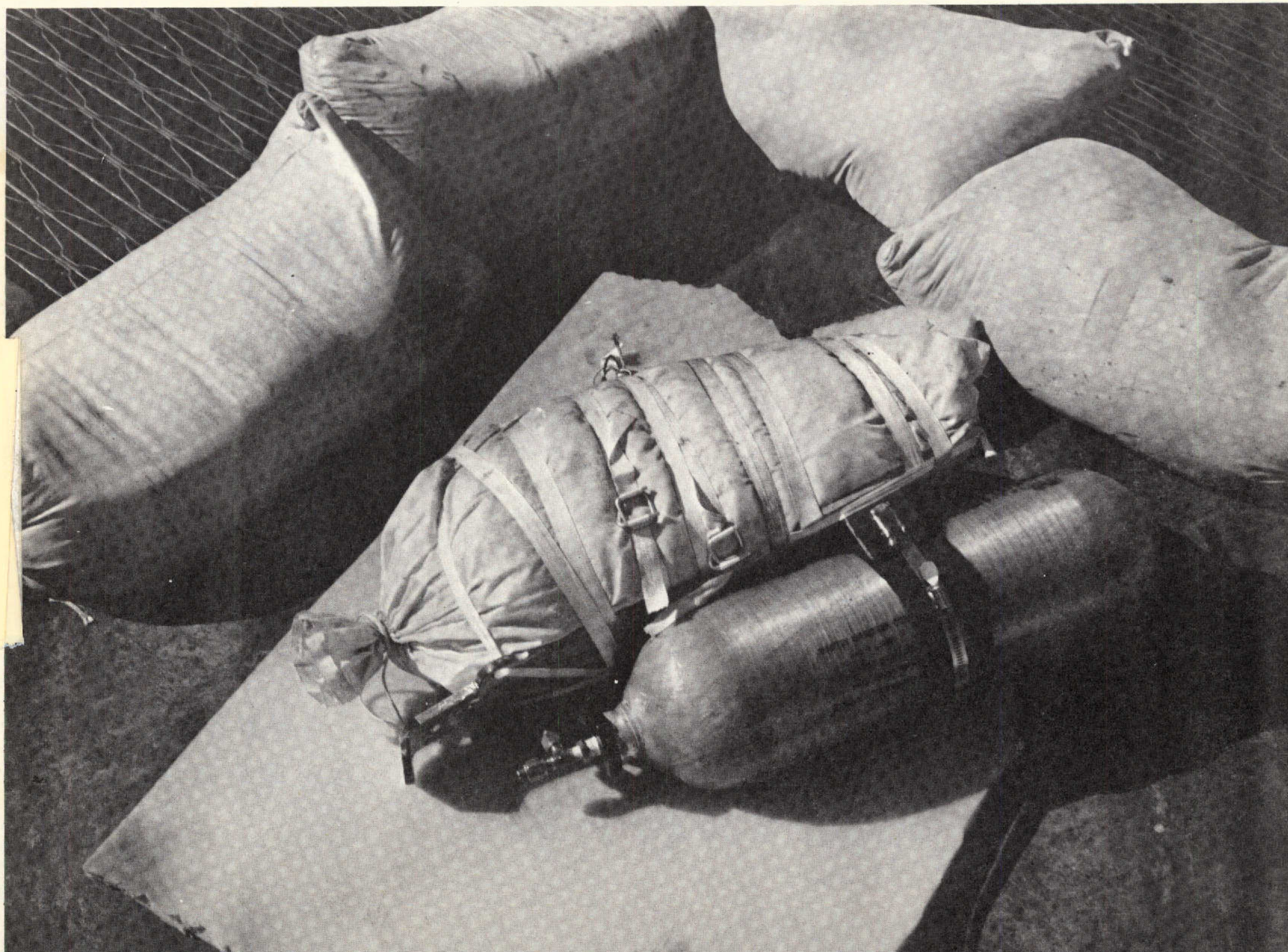


Figure B-19 Drop Test Setup

This page is reproduced at the
back of the report by a dif
reproduction

Figure B-20 Drop Test Backpack

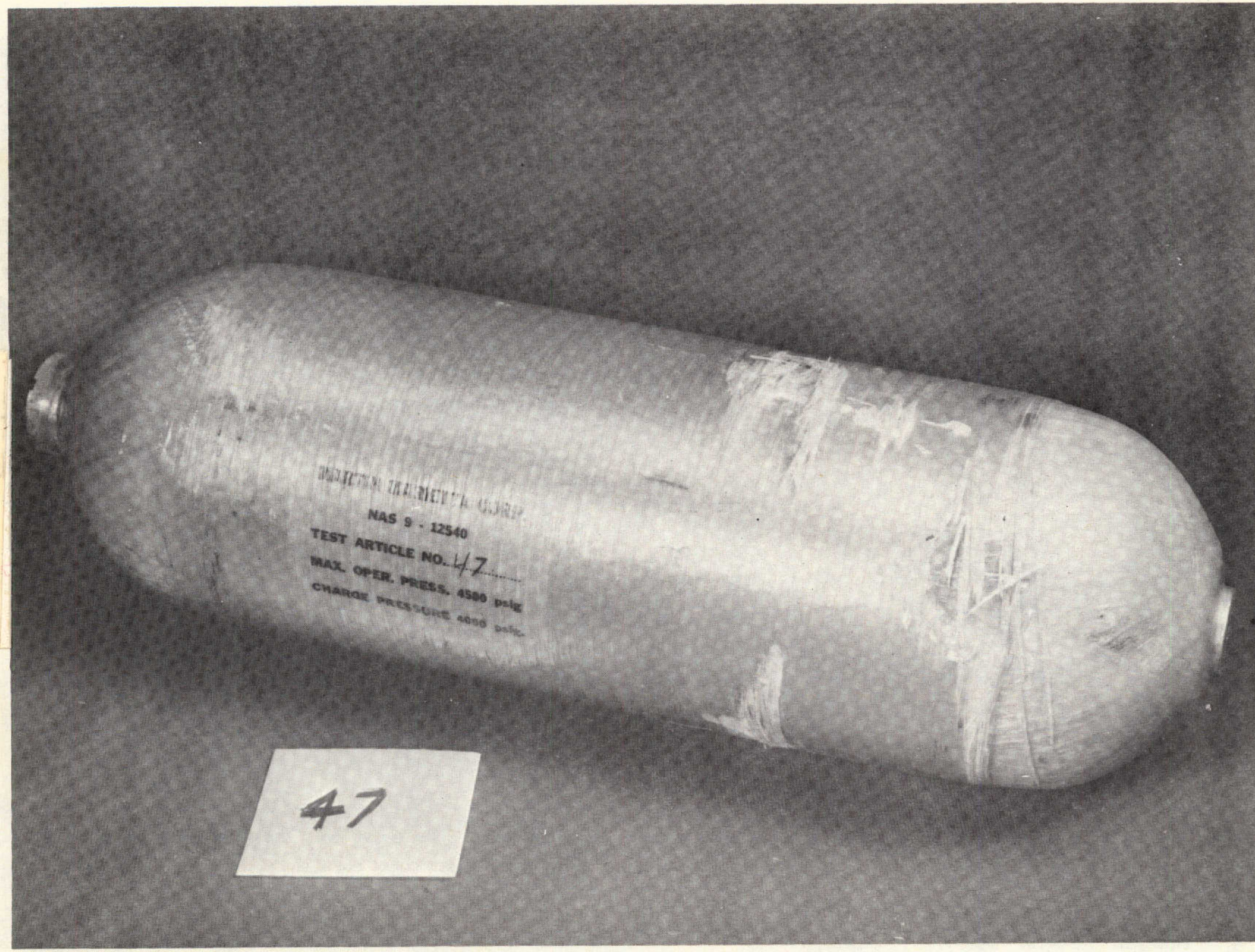


Figure B-21 Vessel S/N 47 After Drop Test

This page is reproduced at the
back of the report by a different
better detail.

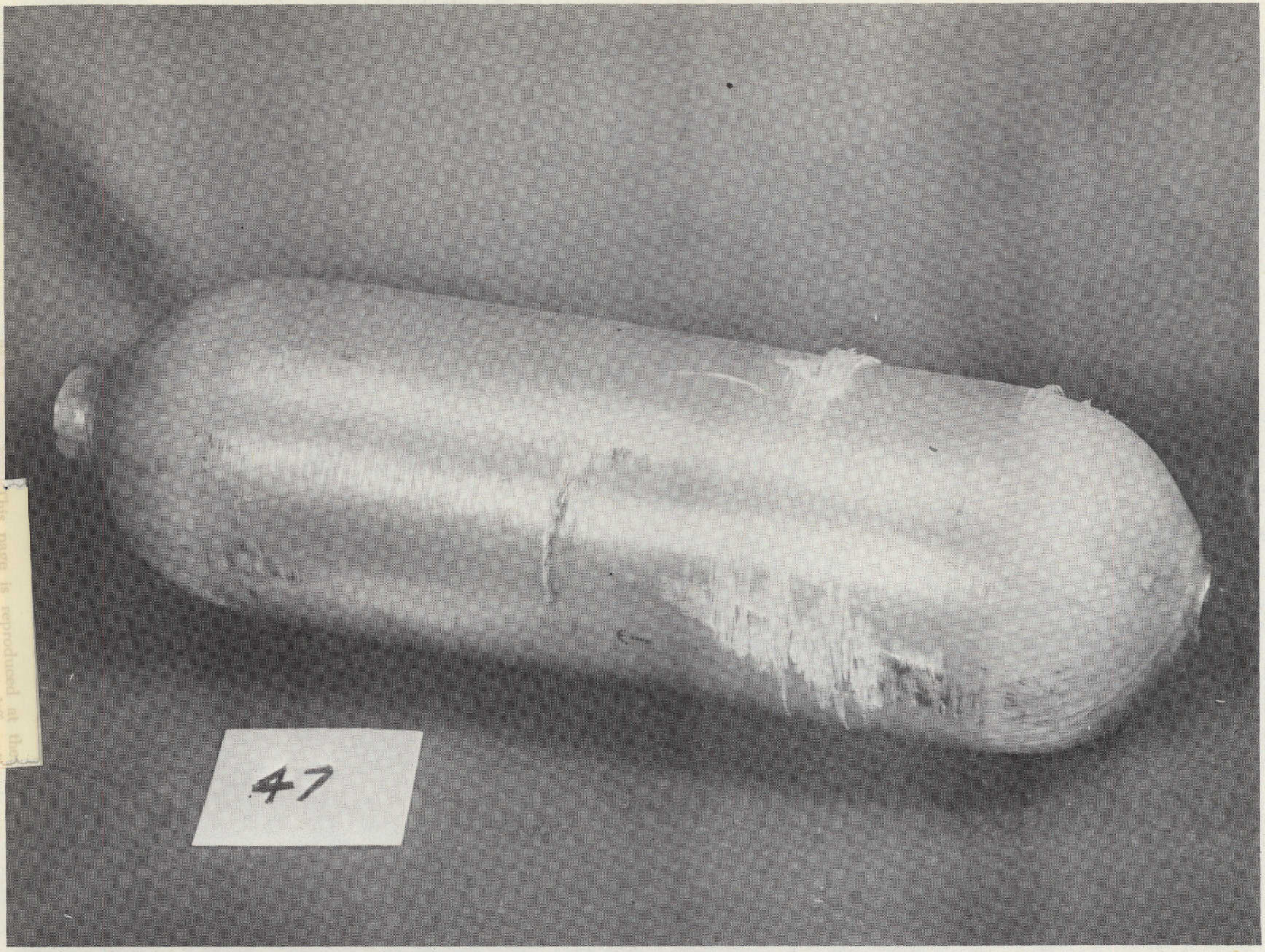


Figure B-22 Vessel S/N 47 After Drop Test

Table B-32 Test Data-S/N 47

Test: Drop Test

Vessel S/N: 47

Date: 6/15/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Pressure	4500 ± 50 psig	4500 psig
No. of Drops	5 min	5
Drop No. 1	Side, Parallel to Axis	6/15/73 Ok 1
Drop No. 2	Side, Parallel to Axis	6/15/73 Ok 2
Drop No. 3	Closed End, 45° to Axis	6/18/73 Ok 1
Drop No. 4	Closed End, 45° to Axis	6/18/73 Ok
Drop No. 5	Valve End, 45° to Axis	6/18/73 Ok
Sandbag Weight	200 ± 5 lb	200 lb
Ambient Temperature	N/A	85°F
Damage	N/A	*

Note: This test is for information only and there is no failure criteria.

1 Minor gouge due to backpack gussett.

2 Major gouges in vessel due to backpack gussett. Gouge is thru outer layer of hoop overwrap.

*Outer hoop wrap was damaged as noted in photographs (Figures VII-5 and VII-6).

Table B-33 Test Data-S/N 47

Test: Burst Pressure

Vessel S/N: 47

Date: 6/19/73

Test Engineer: D. E. Dulaigh

Parameter	Allowable	Actual
Burst Pressure	8900 psig min	10,200
Volume Increase Enter Burette readings at pressure 100 prior to pressurization 248		
difference 148 cc (volume increase)	N/A	148 cc
Failure Mode	N/A	(All of liner contained within glass.
Other Observations	N/A	Failure origin was at point of severe glass damage at intersection of barrel and lower dome.

Figure B-23 Vessel S/N 47 After Burst Test

APPENDIX C

REFERENCE TEST PROCEDURE

APPENDIX C - REFERENCE TEST PROCEDURE

The following test procedure was typical of the methodology used to conduct the tests described in Appendix B when so referenced by the test results data. Some additions or deviations to this procedure were made during the course of testing as previously described.

6.0 TEST PROCEDURE

6.1 Examination of Product and Volume Determination

6.1.1 Visually examine the pressure vessel for evidence of damage, poor workmanship or unintentional defects. Record existing vessel identification or identify as required.

6.1.2 Locate the three deliberate overwrap flaws. Record their dimensions and locations.

6.1.3 Photograph the pressure vessel.

6.1.4 Weigh the pressure vessel.

6.1.5 Measure the diameter and the length of the pressure vessel.

6.1.6 Measure the volume of the pressure vessel by filling it with water from a graduated cylinder. There shall be no external tube or pipe fittings attached to the vessel during the test.

6.1.7 Verify that the data obtained in steps 6.1.1 through 6.1.5 are recorded on the data sheet (Figure C-1). There is no failure criteria for this test.

6.2 Sizing, Volumetric Expansion and Proof Pressure Test

Note: *Volumetric expansion determination is required during proof pressure testing. It will also be accomplished during vessel sizing for information only.*

6.2.1 Install the vessel in the test setup of Figure C-2.

6.2.2 Close VPR, VPV, and VVV.

Pressure Vessel S/N:

Test Date:

Test Engineer:

Parameter	Allowable	Actual
Workmanship Damage Defects	Workmanlike None None	
Weight Diameter Length Volume	9.0 lbs max. 5.5 in. max. 18.7 in. max. 280 $in.^3$ min.	
Deliberate Flaws Flaw #1 Location Depth Length Flaw #2 Location Depth Length Flaw #3 Location Depth Length	 (Record actual location) Approx. 0.002 in. Approx. 1 in. (Record actual location) Approx. 0.002 in. Approx. 1 in. (Record actual location) Approx. 0.002 in. Approx. 1 in.	

Figure C-1 Test Data Sheet Examination of Product

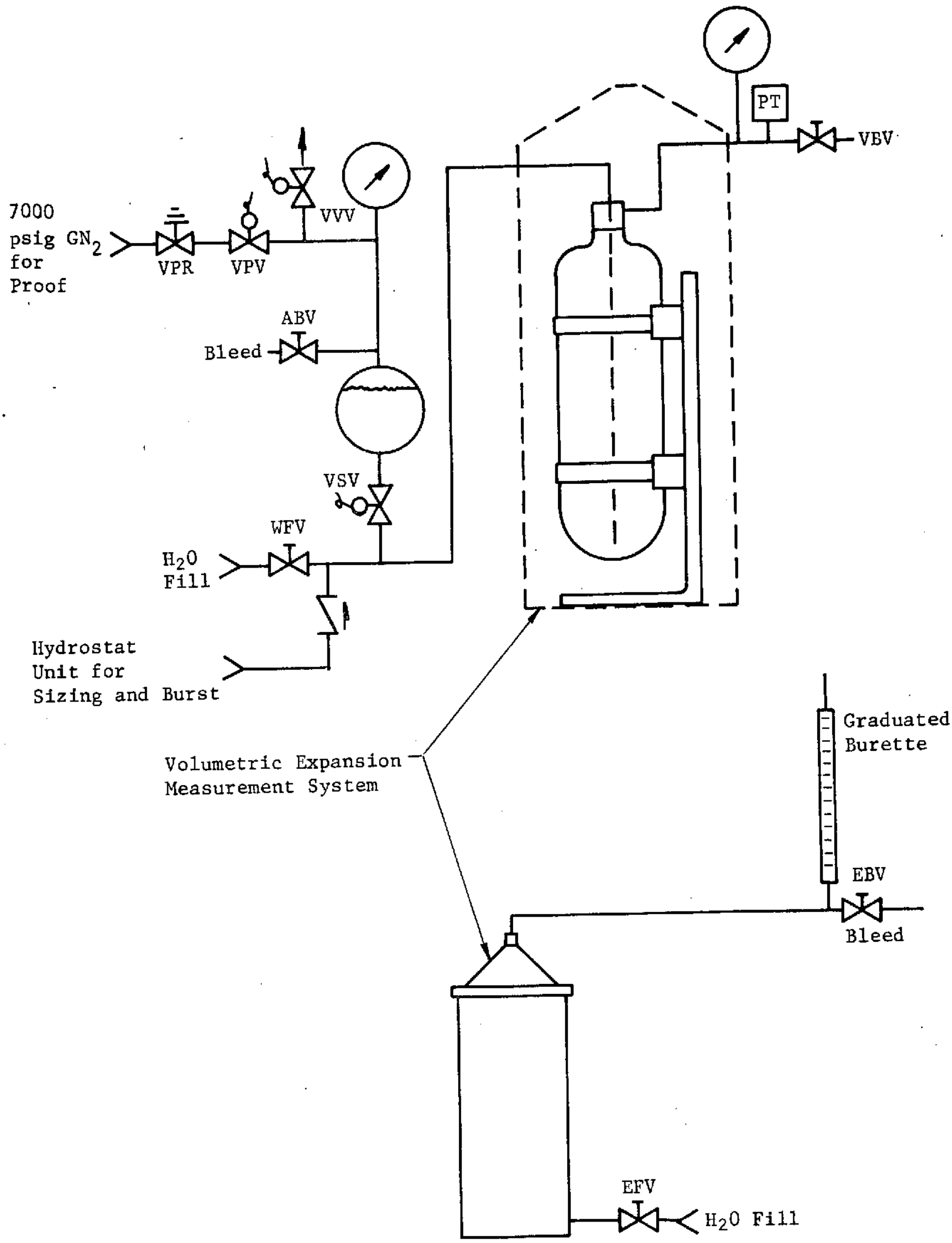


Figure C-2 Pressurization Fixture

6.2.3 Open WFV, VSV and ABV and fill the accumulator with water. Also bleed water through the hydrostat unit. Close ABV and VSV.

6.2.4 Open VBV and fill the vessel with water. Close VBV while flowing water through it. Then close WFV.

6.2.5 Open EBV and EFV and fill the volumetric fixture with water. Adjust the water level in the graduated burette to the lower part of the scale. Close EFV and EBV.

6.2.6 Verify no leakage through EFV or EBV by verifying no perceptible change in the water level during a 5-minute period.

6.2.7 Place the test area in RED condition and make an appropriate P.A. announcement. Verify that no personnel are in the vicinity of the vessel.

Note: *Vessel sizing will be accomplished first.*

6.2.8 Read and record the water level in the burette.

6.2.9 Start the recorders.

6.2.10 Operate the hydrostat unit to increase the vessel pressure to 7600 ± 50 psig at a rate not to exceed 500 psi per min.

6.2.11 Read and record the water level in the burette.

6.2.12 Open VFV to reduce vessel pressure to ambient. Stop the recorders. Close VFV.

6.2.13 Read and record the water level in the burette.

Note: *The proof pressure test will now be accomplished.*

6.2.14 Open VSV and VPV. Start the recorders.

6.2.15 Open handloader VPR as required to increase the vessel pressure to 6750 ± 50 psig at a rate not to exceed 500 psi per minute.

6.2.16 Use VPR as required to maintain vessel pressure at 6750 ± 50 psig for 5 min. Read and record the water level in the graduated burette at the end of the 5-min. period.

Test: Sizing, Volumetric Expansion, and Proof Pressure

Vessel S/N:

Date:

Test Engineer:

Parameter	Allowable	Actual
Sizing Pressure Percent permanent volume increase (Calculate as follows) Enter burette readings: at pressure ____ at pressure ____ prior to pressurization ____ after pressurization ____ difference (A) ____ difference (B) ____ $\% \text{ Increase} = \frac{\text{Permanent volume increase (A-B)}}{\text{Temporary volume increase (A)}} (100)$ $\frac{(\quad) - (\quad)}{(\quad)} (100) =$ ______ Vessel Damage	7600 ± 50 1% None	
Proof Pressure Time at Pressure Percent permanent volume increase (Calculate as follows) Enter burette readings: at pressure ____ at pressure ____ prior to pressurization ____ after pressurization ____ difference (A) ____ difference (B) ____ $\% \text{ Increase} = \frac{\text{Permanent volume increase (A-B)}}{\text{Temporary volume increase (A)}} (100)$ $\frac{(\quad) - (\quad)}{(\quad)} (100) =$ ______ Vessel Damage	6750 ± 50 5 min. 1% None	

Figure C-3 Test Data Sheet

6.2.17 Close VPR and VPV.

6.2.18 Open VVV and reduce vessel pressure to ambient. Stop the recorders.

6.2.19 Read and record the water level in the burette.

6.2.20 Remove the vessel from the test fixture and examine for damage, or other evidence of permanent deformation. Any of the above or any performance degradation during the test will constitute a vessel failure.

6.3 Functional Capability Test

6.3.1 Install the vessel in the test setup of Figure C-4.

6.3.2 Fill the water bath to a level above the top of the vessel.

6.3.3 Adjust and fill the funnel and inverted graduate such that all leakage will be collected in the graduate.

6.3.4 Close VVV and VPR.

6.3.5 Open VPV and start recorders. Place the area in RED and make an appropriate announcement.

6.3.6 Operate regulator VPR as required to increase vessel pressure to 4000 ± 50 psig.

6.3.7 Maintain 4000 ± 50 psig for 30 min. Collect all leakage of the vessel during this time.

6.3.8 Close VPV and VPR and open VVV to reduce vessel pressure to ambient. Stop the recorders and place the area in GREEN.

6.3.9 Measure and record the vessel leakage, actual pressure of step 6.3.6 and any vessel damage or deterioration. Any damage or deterioration or leakage in excess of 6.5 scc/hour will constitute a vessel failure.

6.4 Operating Pressure Cycle Test

6.4.1 Install the vessel in the test setup of Figure C-2 except that the volumetric expansion fixture is not required. Two vessels may be tested in parallel if desired.

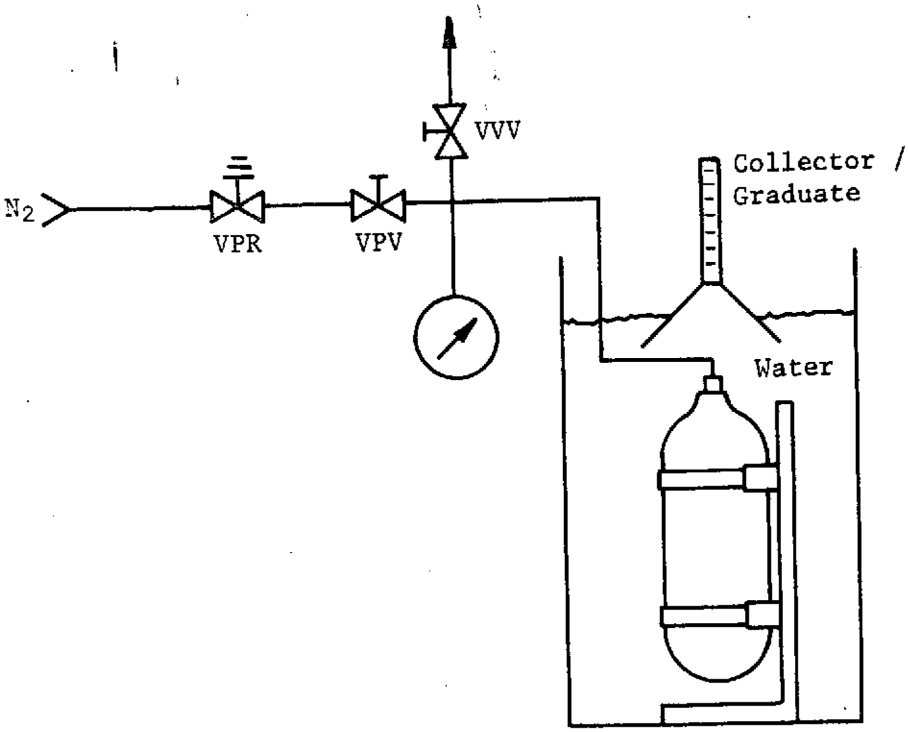


Figure C-4 Functional Capability Setup

Test: Functional Capability

Vessel S/N:

Date:

Test Engineer:

Parameter	Allowable	Actual
Pressure	4000 ± 50 psig	
Time at pressure	30 min.	
Leakage rate	6.5 scc/hr. max.	
Damage	None	

Figure C-5 Test Data Sheet

6.4.2 Close VPR and VVV.

6.4.3 Open WFV, VSV and ABV and fill the accumulator with water. Close ABV and VSV.

6.4.4 Open VBV and fill the vessel with water. Close VBV while flowing water through it. Then close WFV. Place the area in RED and make an appropriate announcement.

6.4.5 Open VSV and VPV and start the recorders.

6.4.6 Open VPR as required to increase vessel pressure to 4000 ± 50 psig.

6.4.7 Close VPV and open VVV.

6.4.8 When vessel pressure is 100 psig or less close VVV and open VPV.

6.4.9 When vessel pressure is 4000 ± 50 psig close VPV. Open VVV.

6.4.10 Repeat steps 6.4.8 and 6.4.9 for a total of 10,000 cycles. The cycles need not be continuous, but should be approximately 2-4 cycle/min. Refill the accumulator by opening WFV and ABV each 100 cycles or as required by the test engineer. Recalibrate the recorders each 100 cycles minimum. Recorders shall be on during each cycle. Cycling may be automated as desired. Any pressure cycle which does not meet the pressure criteria will be disregarded.

6.4.11 At the completion of 10,000 cycles or at vessel failure, place the area in GREEN and close VPR and VPV. Open VVV and remove the vessel from the test setup.

6.4.12 Inspect the vessel for damage or deterioration. Any damage, deterioration or failure during the subsequent functional test will constitute a vessel failure.

Test: Operating Pressure Cycling Test

Vessel S/N:

Date:

Test Engineer:

Parameter	Allowable	Actual
No. of Cycles	10,000	
Max Pressure	4000 ± 50 psig	
Min Pressure	0-100 psig	
Damage	None	
Post Functional		
Pressure	4000 ± 50 psig	
Time	30 min.	
Leakage	6.5 scc/hr. max.	
Damage	None	

Figure C-6 Test Data Sheet

6.5 Proof Pressure Cycle Test

6.5.1 Install the vessel in the test setup of Figure C-2 except that the volumetric expansion fixture is not required. Two vessels may be tested in parallel if desired.

6.5.2 Close VPR, VPV, and VVV.

6.5.3 Open WFV, VSV and ABV and fill the accumulator with water. Close ABV and VSV.

6.5.4 Open VBV and fill the vessel with water. Close VBV while flowing water through it. Then close WFV. Place the area in RED and make an appropriate announcement.

6.5.5 Open VSV and VPV and start the recorders.

6.5.6 Open VPR as required to increase vessel pressure to 6750 ± 100 psig and maintain for approximately 30 sec.

6.5.7 Close VPV and open VVV.

6.5.8 When vessel pressure is 100 psig or less, close VVV and open VPV.

6.5.9 When vessel pressure is 6750 ± 100 psig maintain it using VPR for 30 sec. and then close VPV and open VVV.

6.5.10 Repeat steps 6.5.8 and 6.5.9 for a total of 100 cycles. The cycles need not be continuous. Recorders shall be on during each cycle. Cycling may be automated with pressure switches or micro switches as desired. Any pressure cycle which does not meet the pressure criteria will be disregarded.

6.5.11 At the completion of 100 cycles or at vessel failure, place the area in GREEN and close VPR and VPV. Open VVV and VBV and remove the vessel from the test setup.

6.5.12 Inspect the vessel for damage or deterioration. Any damage, deterioration or failure during the subsequent functional test will constitute a vessel failure.

Test: Proof Pressure Cycling Test

Vessel S/N:

Date:

Test Engineer:

Parameter	Allowable	Actual
No. of Cycles	100	
Vessel Temperature	Ambient	
Max Pressure	6750 ± 100 psig	
Min Pressure	0-100 psig	
Damage	None	
Post Functional		
Pressure	4000 ± 50 psig	
Time	30 min.	
Leakage	6.5 scc/hr. max.	
Damage	None	

Figure C-7 Test Data Sheet

6.6 Impact Test

Warning: *Since the vessel has not been qualified, no personnel are allowed in the area of the vessel when pressurized.*

6.6.1 Install the vessel in the test setup of Figure C-8. Drop height is 10 ft.

6.6.2 Precondition the bath to -60 ± 10°F, and the hot bath to 200 ± 10°F.

6.6.3 Place at least 6 in. of foam rubber over the steel plate and perform "practice drops" until it is reasonably certain that the vessel will impact at the desired attitude. Remove the foam rubber.

6.6.4 With the vessel at ambient conditions, close VVV and open VPV as required to increase vessel pressure to 4000 ± 50 psig. Close VPV.

6.6.5 Lower the vessel into the appropriate bath and allow the vessel temperature to achieve -60 ± 20°F or 200 ± 20°F. Record this temperature on the data sheet (Figure C-9). When in the hot bath, vent bottle as necessary to keep pressure at 4500 ± 50 psig. Maintain a log of test operations on Data Sheet 2 (Figure C-10), including temperature stabilization times.

6.6.6 Raise the vessel to the release point at the release attitude determined in step 6.6.3.

6.6.7 Verify all personnel are clear, place the area in RED and make an appropriate announcement.

6.6.8 Read and record the vessel temperature and pressure.

6.6.9 Release the vessel support tie cord remotely and allow the vessel to drop to the steel plate.

6.6.10 Open Valve VVV and depressurize the vessel.

6.6.11 Place the area in GREEN. Inspect the vessel and record any damage on the test data sheet. This test is for information only and there is no failure criteria.

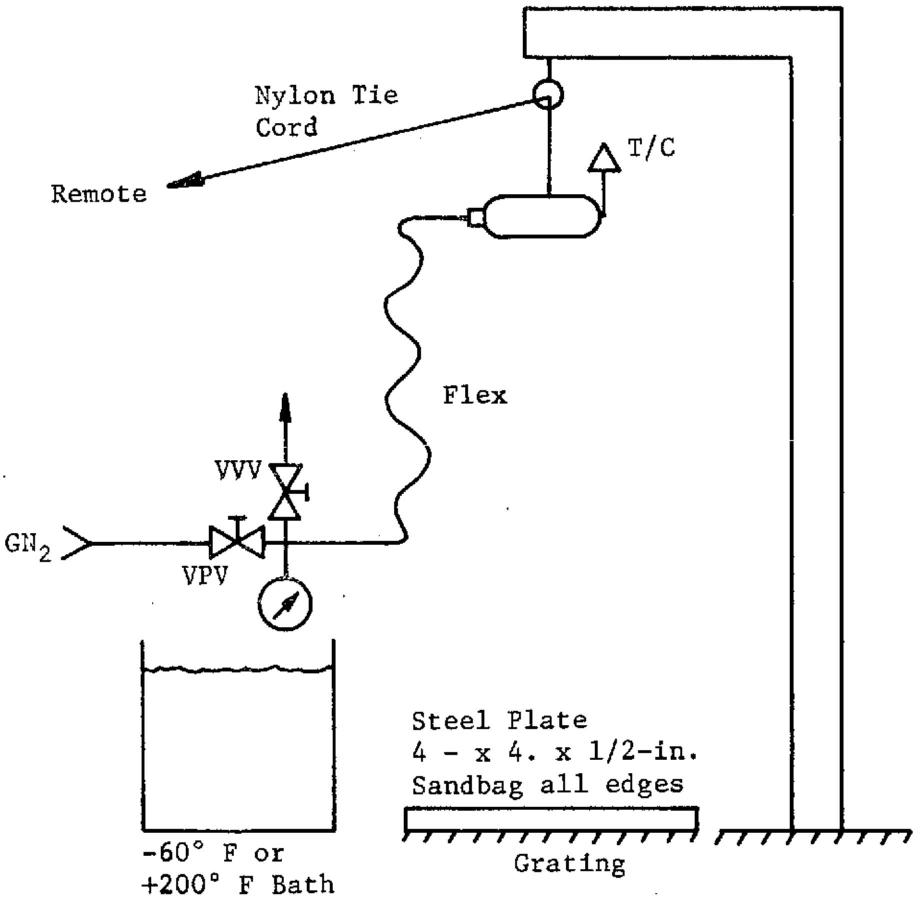


Figure C-8 Impact and Shock Setups

(Sheet 1 of 2)

Test: Impact
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual	
		Sequence 1	Sequence 2
Valve End, -60°F			
Pretest pressure	-60 ± 20°F		
Temp in bath	3040-3950 psig		
Predrop temp	-60 ± 10°F		
Damage	-60 ± 20°F		
	None		
Valve End, +200°F			
Pretest pressure	200 ± 20°F		
Temp in bath	4500 ± 50 psig		
Predrop temp	200 ± 10°F		
Damage	200 ± 20°F		
	None		
Opp. End. -60°F			
Pretest pressure	-60 ± 20°F		
Temp in bath	3040-3950 psig		
Predrop temp	-60 ± 20°F		
Damage	-60 ± 20°F		
	None		
Opp. End, +200°F			
Pretest pressure	200 ± 20°F		
Temp in bath	4500 ± 50 psig		
Predrop Temp	200 ± 20°F		
Damage	200 ± 20°F		
	None		
Side, -60°F			
Pretest pressure	-60 ± 20°F		
Temp in bath	3040-3950 psig		
Predrop temp	-60 ± 20°F		
Damage	-60 ± 20°F		
	None		
Side, +200°F			
Pretest pressure	200 ± 20°F		
Temp in bath	4500 ± 50 psig		
Predrop temp	200 ± 20°F		
Damage	200 ± 20°F		
	None		

Figure C-9 Test Data Sheet

(Sheet 2 of 2)

Parameter	Allowable	Actual	
		Sequence 1	Sequence 2
Post-Test Functional			
Pressure	4000 ± 50 psig		
Time at pressure	30 min.		
Leakage rate	6.5 scc/hr. max.		
Damage	None		

Note: This test is for information only and there is no failure criteria.

Figure C-9 Test Data Sheet (Concl)

Test: Impact
Vessel S/N:
Date:
Test Engineer:

Figure C-10 Test Data Sheet

6.6.12 Repeat steps 6.6.1 thru 6.6.11 until the bath temperature and impact points tabulated below have been tested. Repeat the sequence shown for a total of two times.

Vessel Predrop Temp	Vessel Impact Point
- 60 ± 20°F	Valve End
+200 ± 20°F	Valve End
- 60 ± 20°F	End Opposite Valve
+200 ± 20°F	End Opposite Valve
- 60 ± 20°F	Side
+200 ± 20°F	Side

6.6.13 Subject the vessel to the functional test of Paragraph 6.3. There is no failure criteria for this test.

6.7 Thermal Cycling Test

6.7.1 Install the vessel in the setup of Figure C-11. Attach approximately 8 lb. of ballast to the vessel using the backpack or other convenient means. Thermocouples will be located in each bath and attached to the vessel liner. A shutoff valve will be connected to the vessel.

6.7.2 Condition the hot bath to 200 ± 10°F and the cold bath to -60 ± 10°F. These temperatures shall be maintained throughout the test.

6.7.3 With the vessel at ambient temperature, connect a GN_2 pressurization system to the vessel valve.

6.7.4 Pressurize the vessel to 4000 ± 50 psig and close the vessel valve to lockup the vessel pressure. Disconnect the pressurization system.

6.7.5 Start the temperature recorders. Maintain a log of test operations, including vessel temperature, on the data sheet (Figure C-12).

Warning: *No personnel shall be in line of sight of the vessel as it is lowered into either bath.*

6.7.6 Lower the vessel into the cold bath.

6.7.7 Remove the vessel from the cold bath after 10 min.

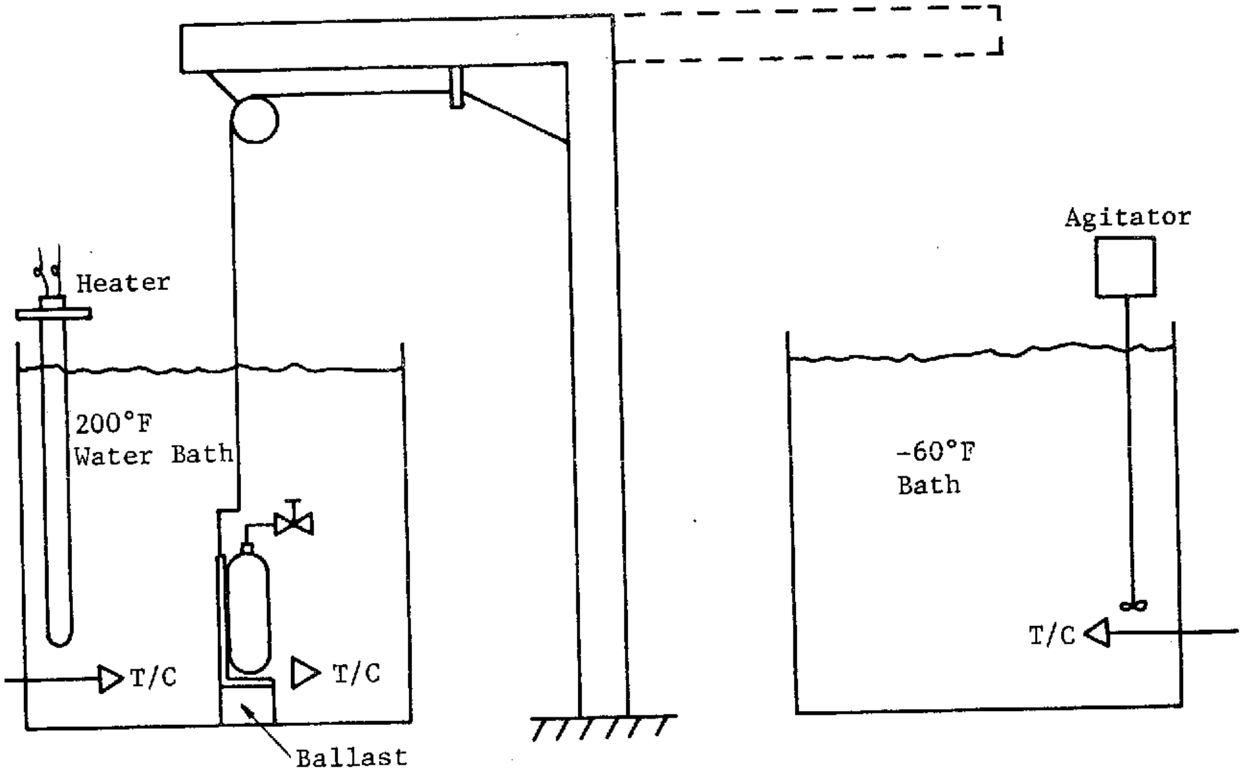


Figure C-11 Thermal Cycling Setup

Test: Thermal Cycling
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
No. of Cycles	20	
Transfer time	3 min. max.	
Cold bath temp	-60 ± 10°F	
Hot bath temp	200 ± 10°F	
Damage	None	
Post Functional		
Pressure	4000 ± 50 psig	
Time	30 min.	
Leakage	6.5 scc/hour max.	
Damage	None	

Figure C-12 Test Data Sheet

6.7.8 Lower the vessel into the hot bath within 3 min. after removal from the cold bath.

6.7.9 Remove the vessel from the hot bath after 10 min.

6.7.10 Lower the vessel into the cold bath within 3 min. after removal from the hot bath.

6.7.11 Repeat steps 6.7.7 through 6.7.10 for a total of 20 exposures to each bath. Testing need not be continuous, but the 3-min. maximum trasfer time must not be violated. The recorders shall be on whenever the test is in progress. If a delay in cycling is required, the vessel should remain in one of the baths during the delay.

6.7.12 Remove the vessel from the baths and open the vessel valve to reduce vessel pressure to ambient.

6.7.13 Inspect the vessel for evidence of damage or deterioration. Any damage or deterioration or failure during the subsequent fuctional capability test will constitute a vessel failure.

6.7.14 Subject the vessel to a functional capability test per paragraph 6.3.

6.8 <u>Humidity Test</u>

6.8.1 Connect a vessel valve to the vessel.

6.8.2 Connect a GN_2 pressurization system to the vessel valve and increase the vessel pressure to 120 $\pm$ 10 psig. Close the vessel valve to lockup the pressure and disconnect the pressurization system.

6.8.3 Subject the vessel to a 10-day humidity test per MIL-STD-810A, method 507.1. The post-thermal cycle functional will serve as baseline data.

6.8.4 Within 5 min. after completion of the humidity test, place the vessel in a chamber that has been preconditioned to 0 $\pm$ 5°F at less than 100% relative humidity.

6.8.5 Maintain 0 $\pm$ 5°F and less than 100% R.H. for a period of 1 hr.

6.8.6 Remove the vessel and inspect it. Any damage or structural degradation will constitute a vessel failure.

Test: Humidity
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure	120 ± 10 psig	
Humidity Test	per MIL-STD-810A, 507.1	
Post Humidity Soak		
Temperature	0 ± 5°F	
Humidity	100% max.	
Time	1 hr	
Damage	None	

Figure C-13 Test Data Sheet

6.9 High Temperature Exposure

Note: *Steps 6.9.7 thru 6.9.9 should be practiced in advance with a dummy vessel.*

6.9.1 Verify that the test setup is complete per Figure C-14.

6.9.2 Attach the vessel and vessel valve to the backpack and to the high temperature handling fixture.

6.9.3 Connect a GN_2 pressurization system to the vessel valve.

6.9.4 Open the vessel valve and submerge the vessel in the 200 ± 20°F bath.

6.9.5 Pressurize the vessel to 2000 ± 20 psig.

6.9.6 After vessel temperature stabilizes, close the pressurization valve.

Warning: *Care should be taken to prevent burns to personnel during this test. Asbestos gloves should be worn.*

Warning: *The burner is propane fired and appropriate precautions should be taken.*

6.9.7 Place the burner in operation and establish a temperature of 600 ± 50°F at the temperature sensor.

6.9.8 Verify flow of air through the chamber is greater than 5 mph, by using the "Anamatherm" unit in chamber outlet.

6.9.9 Using the high temperature handling fixture, place the vessel in the chamber. Record pressure and temperature on the data sheet at 30-sec. intervals. Secure the burner after 5 ± .5 min.

6.9.10 Remove the vessel from the chamber and open the valve to reduce the vessel pressure to ambient.

6.9.11 Inspect the vessel for evidence of structural degradation. Perform a Functional Capability Test per 6.3. Any evidence of structural degradation or failure is for information only. There is no failure criteria for this test.

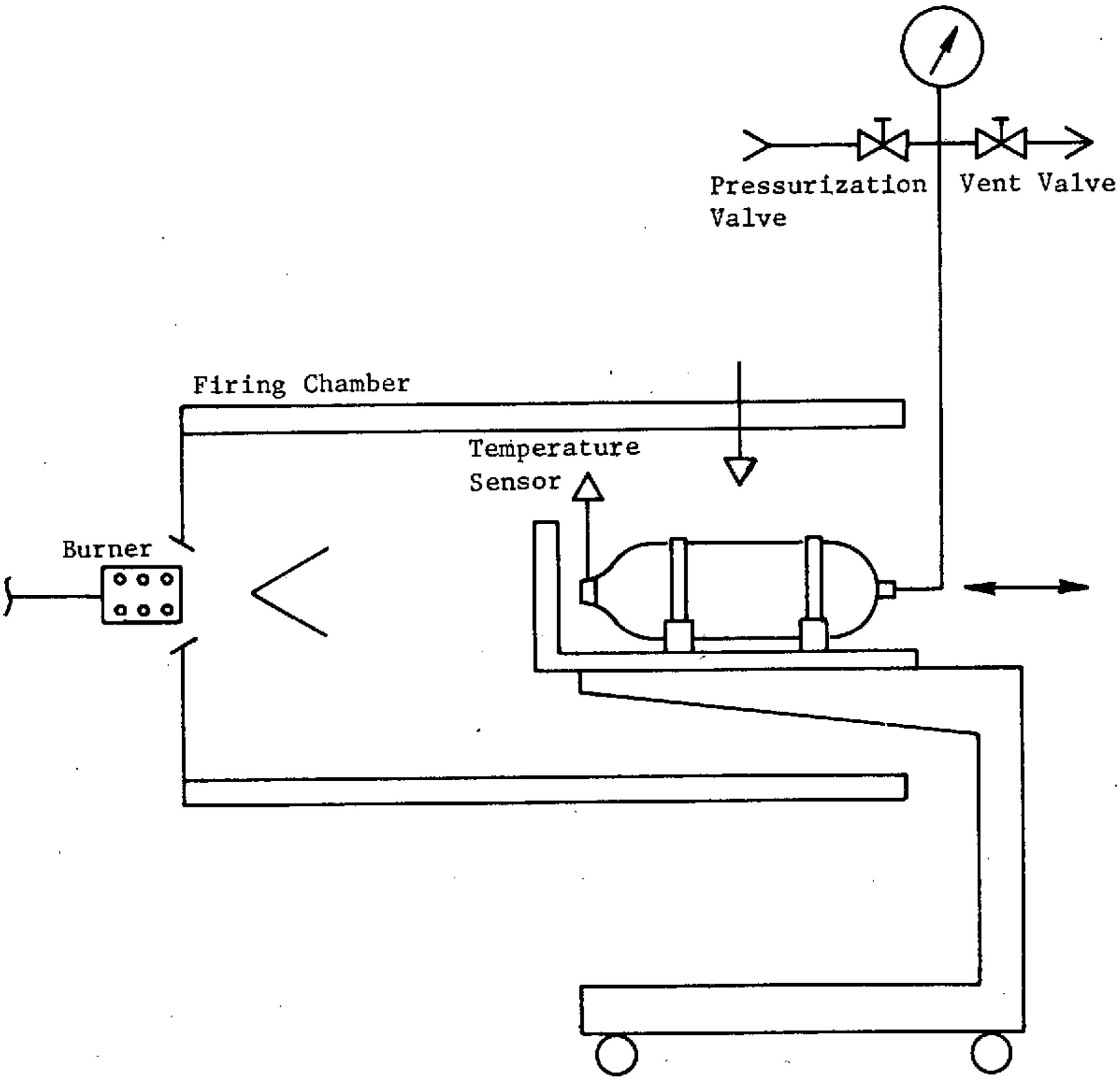


Figure C-14 High Temperature Exposure

Test: High Temperature Exposure
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Bath temperature	200 ± 10°F	
Chamber velocity	5 mph min.	
Chamber temperature	600 ± 50°F	
		Min. Press. Temp.
Vessel Pressure and Temperature (record at 30 sec. intervals)		0
		.5
		1.0
		1.5
		2.0
		2.5
		3.0
		3.5
		4.0
		4.5
		5.0
Damage	None	
Post-functional		
Pressure	4000 ± 50 psig	
Time at pressure	30 min.	
Leakage rate	6.5 scc/hr max.	
Damage	None	

Note: This test is for information only and there is no failure criteria.

Figure C-15 Test Data Sheet

6.10 Sand and Dust Test

6.10.1 Connect a vessel valve to the vessel.

6.10.2 Connect a GN_2 pressurization system to the vessel valve and increase the vessel pressure to 120 ± 10 psig. Close the vessel valve to lockup the pressure and disconnect the pressurization system.

6.10.3 Subject the vessel to a Sand and Dust Test per MIL-STD-810A, Method 510.1, which includes a post-environment functional capability test (which is not required for this test item). The second 6-hr. test (Ref. MIL-STD-810A, Method 510.1, paragraph 4.d) need not be performed immediately.

6.10.4 Any damage or structural degradation during this test will constitute a vessel failure.

6.11 Salt Atmosphere Test

6.11.1 Connect a vessel valve to the vessel.

6.11.2 Connect a GN_2 pressurization system to the vessel valve and increase the vessel pressure to 120 ± 10 psig. Close the vessel valve to lockup the pressure and disconnect the pressurization system.

6.11.3 Subject the vessel to a Salt Fog test per MIL-STD-810A, Method 509.1, which includes 2 post-environment functional capability tests which are not required for this test item. A 1% salt solution will be used.

6.11.4 Any damage or structural degradation during this test will constitute a vessel failure.

6.12 Flaw Growth

6.12.1 Verify that the major flaw (1-in. x 50% thick) has been made in the vessel overwrap. The location will be determined and documented by the program manager.

Test: Sand and Dust
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure Sand and Dust Test Damage	120 $\pm$ 10 psig Per MIL-STD-810A, 510.1 None	

Figure C-16 Test Data Sheet

Test: Salt Fog
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure Salt Fog Test Damage	120 $\pm$ 10 psig Per MIL-STD-810A, 509.1 None	

Figure C-17 Test Data Sheet

6.12.2 Install the vessel in the test setup of Figure 1 except that the volumetric expansion measurement system is not to be used. Arrange water spray nozzles for tank cooling. A thermocouple shall be attached to the vessel and recorded continuously throughout the test.

Note: Do not fill the pressurization system with water.

6.12.3 Close VPR, VPV,WFV, ABV, and VVV.

6.12.4 Open VSV and VPV.

6.12.5 Place the area in a RED conditon and make an appropriate announcement. Verify no personnel are in the test area. THIS IS A HAZARDOUS TEST. Start the recorder.

6.12.6 Open VPR as required to increase vessel pressure to 4000 $\pm$ 50 psig at a rate such that vessel temperature does not exceed 200°F. Use water spray as necessary to limit vessel temperature.

6.12.7 Close VPV.

6.12.8 Wait for 10 sec minimum then open VVV.

6.12.9 When vessel pressure is 100 psig or less, close VVV and open VPV.

6.12.10 When vessel pressure is 4000 $\pm$ 50 psig, close VPV.

6.12.11 Wait 10 sec and then open VVV.

6.12.12 Repeat steps 6.12.9 through 6.12.11 until vessel leakage, structural degradation or 1,000 cycles occurs. VPR may be adjusted to obtain the desired pressurization rate. Vessel temperature will be limited to 200°F maximum by use of cooling water spray and control of cycle rate. Pressure cycling need not be continuous. If the vessel survives 1,000 cycles, pressurize the vessel until failure occurs.

6.12.13 Close all valves, stop the recorders, place the area in a GREEN condition, photograph the vessel and remove it from the test setup.

Test: Flaw Growth
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure, Max	4000 ± 50 psig	
Pressure, Min	100 psig max.	
Vessel temp	200°F max.	
No. of cycles	N/A	
Failure Mode	Non-hazardous	
Failure Pressure/Cycle	______________	

Note: This test is for information only and there is no failure criteria.

Figure C-18 Test Data Sheet

6.13 <u>Drop Test</u>

6.13.1 Install the vessel equipped with the simulated valve in the test setup of Figure C-8 except that a 200 ± 5 lb bag of sand or lead shot or other material will be strapped to the backpack and vessel. The environmental bath is not required for this test. The drop will be accomplished with a remotely operated release mechanism. The vessel thermocouple is not required.

6.13.2 Position the vessel and sandbag 16 ft above the steel plate and ready the release mechanism. Assure that orientation is such that the vessel will impact in the attitude specified in the data sheet. Drops are to be made in the order specified.

6.13.3 Close VVV and open VPV to increase vessel pressure to 4500 ± 50 psig. Close VPV.

6.13.4 Place the area in a RED condition, make an appropriate announcement, and verify no personnel in the test area.

6.13.5 Activate the release mechanism and verify that vessel has dropped.

6.13.6 Open VVV and place the area in GREEN.

6.13.7 Inspect the vessel for damage or structural degradation. This test is for information only and there is no failure criteria.

6.13.8 If the vessel held pressure throughout the previous drop, repeat steps 6.13.2 through 6.13.7 at different impact attitudes for a total of five drops. Photograph will be taken of the vessel in the "as failed" condition, if failure occurs.

6.13.9 If the vessel held pressure throughout the last drop, remove the vessel from the backpack and subject it to a functional capability test per paragraph 6.3.

6.14 <u>Fragmentation Resistance Test</u>

6.14.1 Install the vessel on the backpack and attach the back to a 200-lb bag similar to that used for the Drop Test.

6.14.2 Connect a vessel valve to the vessel and a GN_2 pressurization system to the vessel valve.

Test: Drop Test
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure	4500 ± 50 psig	
No. of drops	5 minimum	
Drop #1	Side, parallel to axis	
Drop #2	Side, parallel to axis	
Drop #3	Closed end, 45° to axis	
Drop #4	Closed end, 45° to axis	
Drop #5	Valve end, 45° to axis	
Sandbag weight	200 ± 5 pounds	
Ambient Temperature	N/A	
Damage	N/A	

NOTE: This test is for information only and there is no failure criteria.

Figure C-19 Test Data Sheet

Figure C-20 Test Data Sheet

Test: Fragmentation Resistance
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Pressure	4500 ± 50 psig	
Distance	Approximately 100 yds	
No. of hits required to rupture	N/A	
Length of rupture	3-in. + 1 hole dia.	
Travel of fragments	None	

NOTE: This test is for information only and there is no failure criteria.

Figure C-20 Test Data Sheet

6.14.3 Open the vessel valve and increase the vessel pressure to 4500 ± 50 psig. Close the vessel valve and disconnect the pressurization system.

6.14.4 Transport the pressurized vessel and sandbag to a remote area.

6.14.5 Obtain a 30-06 rifle cartridge having an approximate muzzle velocity of 2800 fps using an armour piercing bullet. The muzzle velocity will not be measured during test.

6.14.6 Load the cartridge into a 30-06 rifle and verify that no personnel are within 100 yds of the vessel.

6.14.7 Fire the rifle such that the bullet strikes the cylindrical portion of the vessel.

6.14.8 Use a hunters spotting scope if necessary to verify vessel rupture.

6.14.9 If vessel rupture did not occur, repeat steps 6.14.5 through 6.14.8 until rupture occurs.

6.14.10 Inspect the vessel and photograph it in the as-is condition. Photograph the rupture and measure its length. Measure the distance of travel of any fragments. This test is for information only and there is no failure criteria.

6.15 Burst

6.15.1 Install the vessel in the test setup of Figure C-2.

6.15.2 Close VPV and VVV.

6.15.3 Open WFV, VSV, and ABV and flow adequate water to bleed in VSV. Bleed water through the hydrostat unit. Close ABV and VSV.

6.15.4 Open VBV and fill the vessel with water. Close VBV while flowing water through it. Then close WFV.

6.15.5 Open EBV and EFV and fill the volumetric fixture with water. Adjust the water level in the graduated burette to the lower part of the scale. Close EFV and EBV.

6.15.6 Verify no leakage through EFV or EBV by verifying no perceptable change in the water level during a 5 minute period.

6.15.7 Place the test area in RED condition and make an appropriate P.A. announcement. Verify that no personnel are in the vicinity of the vessel.

Note: *A volumetric expansion reading will be obtained at 9000 psig prior to bursting the vessel.*

6.15.8 Read and record the water level in the burette.

6.15.9 Start the recorders.

6.15.10 Operate the hydrostat unit as required to increase the vessel pressure to 9000 $\pm$ 100 psig at a rate 3000-5000 psi/min.

6.15.11 Read and record the water level in the burette.

6.15.12 Open EBV.

6.15.13 Increase the vessel pressure to failure. Stop the recorders.

6.15.14 Remove the vessel from the test fixture. Photograph the vessel and examine the damage. Record observations on the data sheet (Figure C-21).

Test: Burst pressure
Vessel S/N:
Date:
Test Engineer:

Parameter	Allowable	Actual
Burst pressure	8900 psig Minimum	
Volume increase Enter burette readings at pressure ____ prior to pressurization ____		
difference ____ (volume increase)	N/A	
Failure mode	N/A	
Other Observations	N/A	

Figure C-21 Test Data Sheet

APPENDIX D

ALCOA GREEN LETTER

ALCOA ALUMINUM ALLOYS
6070 AND 6071

ALCOA ALUMINUM ALLOYS
6070 (Extrusions) - 6071 (Sheet and Plate)

by

H. H. NUERNBERGER

SALES DEVELOPMENT DIVISION

NEW KENSINGTON, PA.

JUNE 15, 1962

Not Released For Publication

ALUMINUM COMPANY OF AMERICA

SALES DEVELOPMENT DIVISION

ALCOA ALUMINUM ALLOYS 6070 AND 6071

TABLE OF CONTENTS

Page No.

LIST OF TABLES AND FIGURES

ALCOA ALUMINUM ALLOYS
6070 (Extrusions) - 6071 (Sheet and Plate)

INTRODUCTION

The Alcoa Research Laboratories and the Metallurgical Division have developed alloys 6070 and 6071 to fill a demand for a structural alloy having substantially higher mechanical properties than 6061 while retaining similar weldability and corrosion resistance characteristics.

Both are heat-treatable, aluminum-silicon-magnesium-manganese alloys. Alloy 6070 is available in the form of extrusions and 6071 is available in the form of sheet and plate.

COMPOSITION

The nominal composition and limits of 6070 and 6071 are shown in Table I.

PHYSICAL PROPERTIES

The physical properties of 6070 and 6071 are shown in Table II.

MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Table III shows the typical mechanical properties of the -0, -T4, and -T6 tempers of alloys 6070 and 6071 in comparison with those of other structural aluminum alloys, viz., 6061, 2014, 6351, and 6066.

Table IV shows the minimum (design) mechanical properties of 6070-T6, 6071-T6, and 6061-T6 alloys.

BUCKLING CONSTANTS

The buckling constants, corresponding to those of other structural aluminum alloys shown in Table 4 of the "Alcoa Structural Handbook", are shown in Table IV.

FATIGUE

The results of rotating-beam fatigue tests (smooth and notched specimens) of 6070-T6 and 6071-T6 are shown in Figure 1. The corresponding bands data for alloy 6061-T6 are also shown. It will be noted that the endurance limits of 6070-T6 and 6071-T6 are about the same as those of 6061-T6.

MECHANICAL PROPERTIES AT ELEVATED AND LOW TEMPERATURES

The tensile properties of 6070-T6 and 6071-T6 alloys at low temperatures and after prolonged exposure at elevated temperatures will be available in the future. It is anticipated that the effects of temperature on these properties will be about the same as those for 6061-T6 through 400°F. Above 400°F, their mechanical properties will be the same as shown for 6061-T6 in Table 2(a) of the "Alcoa Aluminum Handbook".

CORROSION

An over-all appraisal of the corrosion tests made by Alcoa Research Laboratories indicates that the corrosion resistance of alloys 6070 and 6071 is very good and is comparable with that of 6061, in atmospheric exposures. Differences in weathering of these alloys are not discernible in industrial atmospheres such as New Kensington, Pa., or even the seacoast environment such as Point Judith, R.I. The basis for this comparison includes groove-welded and riveted assemblies. These alloys are sufficiently corrosion resistant that they do not require a paint coating in normal atmospheric exposure.

In severe corrosion exposure, such as immersion in sea water, alloys 6070 and 6071 were not equal to 6061 in resistance to corrosion. However, in this type of exposures, all of these alloys should be protected by a good paint coating.

STRESS CORROSION

The tests at A.R.L. on alloys 6070-T6 and 6071-T6 have revealed a high resistance to stress-corrosion cracking. When products of these alloys are stressed in the longitudinal and in the long-transverse directions, the resistance is very similar to that of 6061-T6. Groove-welded joints in 1/4" thick 6071-T6 plate have also shown a high resistance to stress-corrosion cracking.

SOLUTION HEAT TREATMENT

The recommended temperature range for solution heat treatment of products of alloys 6070 and 6071 is 1025°F, plus or minus 10° F. After holding at temperature, the material is quenched in cold (room-temperature) water. The temper designation for this condition is -T4.

NATURAL AGING

One difference of alloys 6070 and 6071 in comparison with alloy 6061 is the faster rate of natural aging in the first few hours after solution heat treatment and quenching. If any forming work is planned after quenching, it should be done within the first hour or the aging should be prevented by refrigeration, in order to take advantage of the more workable condition.

Natural aging curves for alloys 6070, 6071, and 6061 are shown in Figure 2.

PRECIPITATION HEAT TREATMENT

To achieve the optimum strengths, products of these alloys are artificially aged, after solution heat treatment, at 320° F for 18 hours (plus or minus 2 hours) or 350° F for 8 hours (plus or minus 1 hour). The temper designation for this condition is -T6.

ANNEALING

The annealing practice for alloys 6070 and 6071 in a heat treated condition involves holding at a temperature of 775° F for 2 hours, followed by cooling at a rate of 50° F per hour until a temperature of 500° F is reached. The rate of subsequent cooling is unimportant.

To substantially soften strain-hardened material or to only partially remove the effects of heat treatment, the material could be heated to 650° F. The rate of cooling is unimportant.

REHEATING

At present, test data are not available to establish the maximum reheating time and temperature for hot forming of 6070-T6 and 6071-T6. However, preliminary data indicate that these alloys will have the same response to reheating as alloy 6061-T6. The maximum reheat times suggested for hot forming are: 300° F – 200 hrs.; 325° F – 100 hrs.; 350° F – 10 hrs.; 375° F – 2 hrs.; 400° F – 30 min.; 425° F – 15 min.; 450° F – 5 min.; 500° F – should not be used. These times and temperatures are based on a 5% maximum decrease in mechanical properties.

FORMING RECOMMENDATIONS

Alcoa Research Laboratories' and Alcoa Process Development Laboratories' tests indicate that alloy 6071-T6 is slightly more difficult to form than 6061-T6 and requires larger bend radii. The suggested bend radii for various thicknesses of alloy 6071-T6 sheet and plate are given in Table V.

ARC WELDING

The general fusion-welding characteristics of alloys 6070 and 6071 have been evaluated by A.R.L. and A.P.D.L. using gas-tungsten arc (tig) and gas-metal arc (mig) welding processes, and found to be similar to those of 6061 alloy, with either 4043 or 5556 filler wire. The strengths of as-welded panels were the same or slightly higher than those of 6061. Reheat treatment and aging after welding improves the strengths of the welds.

The comprehensive weld data necessary to establish joint ultimate and yield-strength qualification (design) values for 6070 and 6071 alloys are not available at this time.

RESISTANCE WELDING

Alloys 6070 and 6071 can be successfully spot and seam welded using machine schedules similar to those established for 6061.

Flash weld data appear to be consistent in indicating average strengths of 50,000 psi in the as-welded condition and 55,000 psi after reheat treatment and aging.

BRAZING AND SOLDERING

The low solidus temperatures of alloys 6070 and 6071 require special brazing techniques. Soldering is satisfactory, with the same fluxes and fillers as are used with 6061.

FINISHING

The same techniques used for anodizing, hard coating, and producing conversion coatings on 6061 can be used on 6070 and 6071.

TABLE I

CHEMICAL COMPOSITIONS

ALLOY 6070
(Extrusions)

	Nominal %	Limits % (Max. Unless Shown as a Range)
Si	1.3	1.0 – 1.7
Fe	–	0.50
Cu	0.25	0.15 – 0.4
Mn	0.7	0.40 – 1.0
Mg	0.8	0.50 – 1.2
Cr	–	0.10
Zn	–	0.25
Ti	–	0.15
Others, Each	–	0.05
Others, Total	–	0.15
Aluminum	Remainder	Remainder

ALLOY 6071
(Sheet and Plate)

	Nominal %	Limits % (Max. Unless Shown as a Range)
Si	1.5	1.1 – 1.9
Fe	–	0.50
Cu	0.25	0.15 – 0.4
Mn	0.70	0.40 – 1.0
Mg	1.10	0.80 – 1.4
Cr	–	0.10
Zn	–	0.25
Ti	–	0.15
Others, Each	–	0.05
Others, Total	–	0.15
Aluminum	Remainder	Remainder

TABLE II

ALLOYS 6070 AND 6071

PHYSICAL PROPERTIES

	6070	6071	6061
Specific Gravity	2.71	2.71	2.70
Density, lb/in^3	0.098	0.098	0.098
Melting Range, °F	1070-1200	1055-1195	1100-1205
Electrical Conductivity at 20°C, IACS			
-0 Temper	52	51	47
-T4 Temper	40	39	40
-T6 Temper	44	43	43
Thermal Conductivity at 25°C, CGS Units			
-0 Temper	0.47	0.47	0.43
-T4 Temper	0.37	0.36	0.37
-T6 Temper	0.41	0.40	0.40
Average Coefficient of Thermal Expansion, $°F \times 10^{-6}$			
68°F – 212°F	12.7	12.6	13.0
68°F – 292°F	13.3	13.2	13.5
68°F – 572°F	13.8	13.7	14.1
Modulus of Elasticity psi			
$E, 10^6$	9.9	9.9	9.9
$E_c, 10^6$	10.1	10.1	10.1
$G, 10^6$	3.8	3.8	3.8

Table II Physical Properties

Alloy and Temper	Tensile Strength, Ultimate psi	Tensile Strength, Yield psi	Elongation in 2 in., Percent (1)	Elongation in 2 in., Percent (2)	Brinell Hardness (3)	Shear Strength, psi	Endurance Limit, psi
*6070-0	21,000	10,000	20	--	35	14,000	9,000
*6070-T4	49,000	30,000	20	--	90	30,000	13,000
*6070-T6	57,000	52,000	12	--	120	34,000	14,000
*6071-0	21,000	10,000	20	--	35	14,000	9,000
*6071-T4	49,000	30,000	20	--	90	30,000	13,000
*6071-T6	57,000	52,000	10	--	120	34,000	14,000
6061-0	18,000	8,000	25	30	30	12,000	9,000
6061-T4	35,000	21,000	22	25	65	24,000	13,000
6061-T6	45,000	40,000	12	17	95	30,000	14,000
2014-0	27,000	14,000	--	18	45	18,000	13,000
2014-T4	62,000	42,000	--	20	105	38,000	20,000
2014-T6	70,000	60,000	--	13	135	42,000	18,000
6351-T4	42,000	27,000	--	20	60	22,500	13,500
6351-T6	47,000	43,000	--	13	95	29,000	13,500
6066-0	22,000	12,000	--	18	43	14,500	--
6066-T4	52,000	30,000	--	18	90	29,500	--
6066-T6	57,000	52,000	--	12	120	34,000	16,000

* Tentative Values
(1) 1/16 in. thick specimen
(2) 1/2 in. diameter specimen
(3) 500 KG Load - 10mm Ball

TABLE IV

DESIGN (EXPECTED MINIMUM) MECHANICAL PROPERTIES FOR 6070-T6 EXTRUSIONS, 6071-T6 SHEET AND PLATE COMPARED WITH THOSE OF 6061-T6 EXTRUSIONS, SHEET AND PLATE

Alloy Form		6070-T6 (1) Extrusions (2)	6061-T6 Extrusions (2)	6071-T6 (1) Sheet & Plate (3)	6061-T6 Sheet & Plate (3)
F_{tu}, ksi	L	50	38	50	42
	T	47	36	50	42
F_{ty}, ksi	L	45	35	48	36
	T	42	33	47	35
F_{cy}, ksi	L	45	35	47	35
	T	45	35	48	36
F_{su}, ksi		29	24	32	27
F_{bru}, ksi	e/D=1.5	75	61	80	67
	e/D=2.0	95	80	105	88
F_{bry}, ksi	e/D=1.5	63	49	66	50
	e/D=2.0	72	56	75	58
Elongation in 2 in. or 4D, %		8	10	6	8-10
Buckling Constants, KSI					
B		49.8	38.3	52.2	38.3
D		0.299	0.202	0.394	0.202
C		55	63	60	63
B_1		29.9	23.0	31.3	23.0
D_1		0.139	0.094	0.183	0.094
C_1		72	82	77	82

(1) Tentative Values

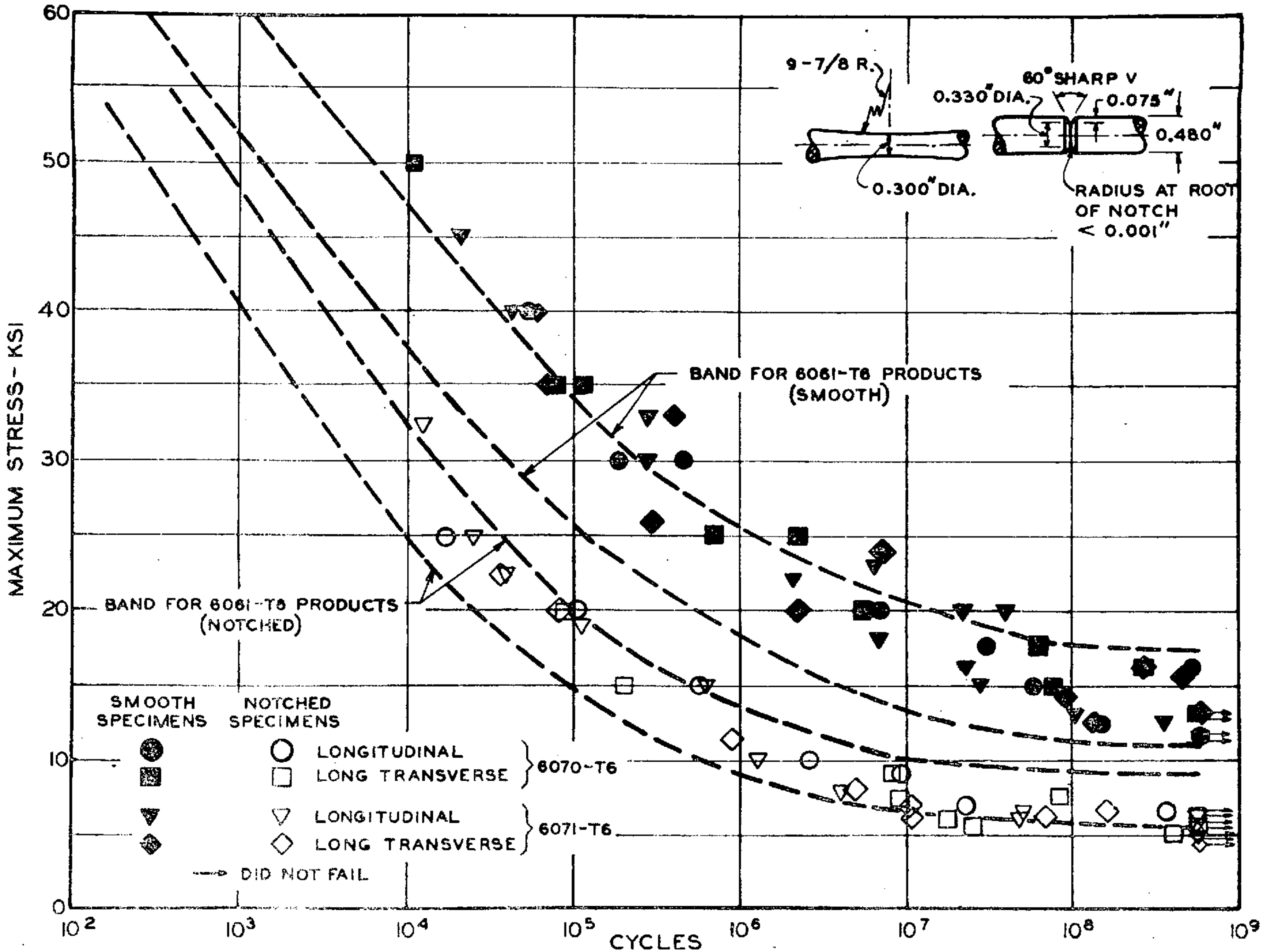
(2) Thickness equal to or less than 3"; cross sectional area equal to or less than 32".

(3) Thickness 0.010" to 2.000".

TABLE V

Approximate Radii for 90° Cold Bend

SHEET & PLATE	RADII EXPRESSED IN TERMS OF THICKNESS "t"		
Thickness, in.	6071-0	6071-T4	6071-T6
0.064	0 – 1t	1-1/2 – 2 t	2-1/2 – 3t
0.125	1/2 – 1-1/2t	1-1/2 – 2-1/2t	2-1/2 – 3-1/2t
0.187	1/2 – 1-1/2t	1-1/2 – 2-1/2t	3 – 4t
0.250	1/2 – 1-1/2t	2 – 3t	4 – 5t
0.375	1 – 2t	2 – 3t	4 – 6t
0.500	1 – 2t	2-1/2 – 3-1/2t	5 – 7t



ALCOA RESEARCH LABORATORIES

ROTATING FATIGUE CURVES - ALLOYS 6070-T6 AND 6071-T6

FIGURE I

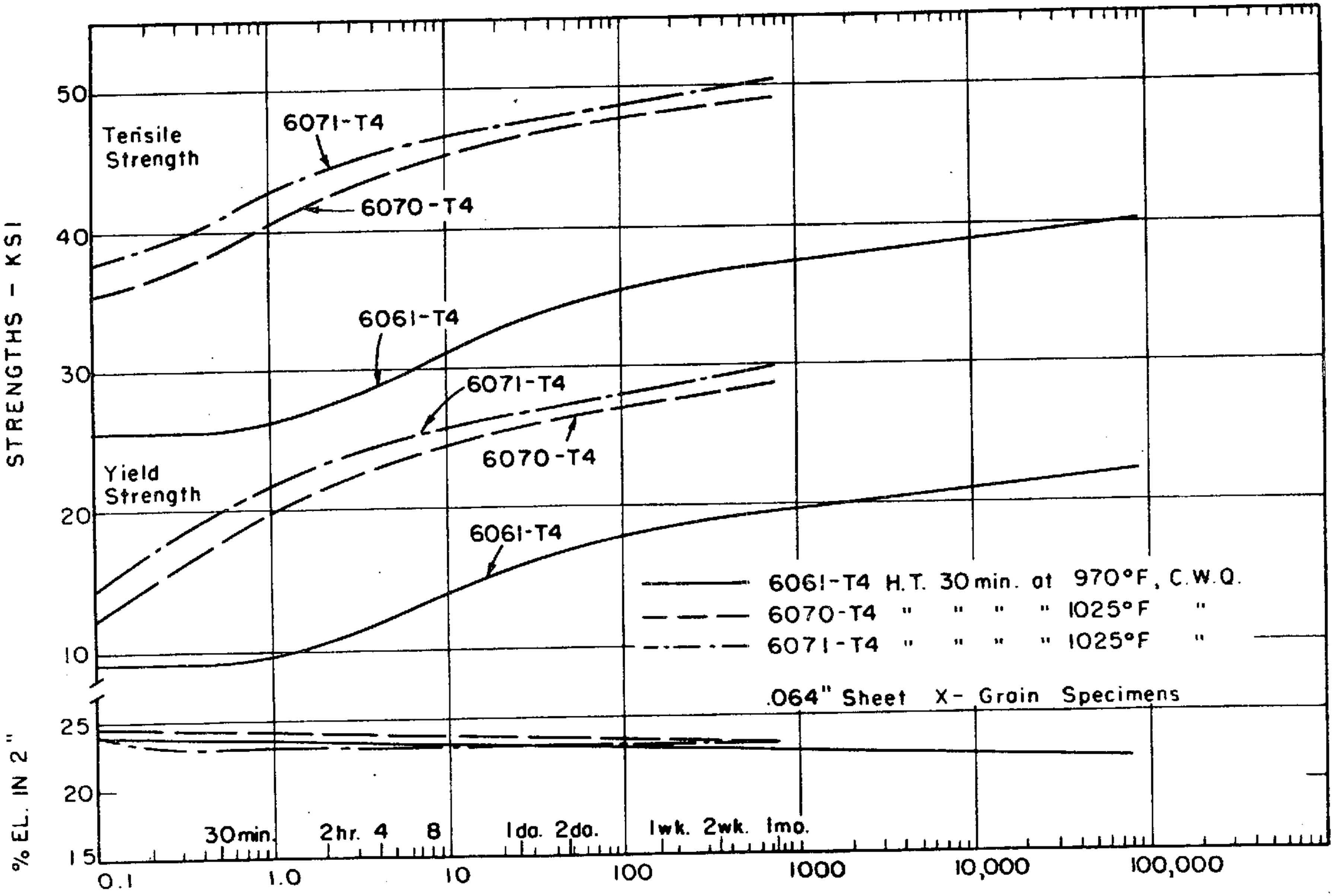

STRENGTHS - KSI
% EL. IN 2"
Tensile Strength
Yield Strength
6071-T4
6070-T4
6061-T4
6061-T4 H.T. 30 min. at 970°F, C.W.Q.
6070-T4 " " " " 1025°F "
6071-T4 " " " " 1025°F "
.064" Sheet X- Grain Specimens
50
40
30
20
10
25
20
15
30min. 2hr. 4 8 1da. 2da. 1wk. 2wk. 1mo.
0.1
1.0
10
100
1000
10,000
100,000
AGING TIME - HOURS

FIG. 2

APPENDIX E

WINDING PROCEDURE
FOR
FIREFIGHTER'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM

APPENDIX E--WINDING PROCEDURE FOR FIREFIGHTER'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM

The following procedure was used to glass overwrap 6070-T6 aluminum liners, reference Drawing 1630-72-014-001.

1.0 SCOPE

1.1 This procedure describes the overwrapping requirements for fabrication of an epoxy-glass overwrapped Firefighter's Compressed Air Breathing System pressure vessel to meet the design requirements of NASA Contract NAS9-21540.

2.0 MATERIALS

2.1 Roving - "S" glass, Owens Corning type S-2 with 470 sizing, 250 yds per lb (approximately 60 end).

2.2 Resin - Epoxy consisting of 50 pbw Epon 828, 50 pbw Epon 1031, 90 pbw Nadic Methyl Anhydride (NMA), 0.5 pphw Benzyldimethylamine (BDMA).

2.3 Curing Agent - NMA

2.4 Accelerator - BDMA

2.5 Solvent - Methyl-Ethyl-Ketone (MEK), acetone, or equivalent.

2.6 Kimwipe or cheesecloth

2.7 Liner (1630-72-014-001)

2.8 Identification labels which state: Manufacturer, part number, serial number, contract number, permit number, date manufactured, inspector's mark, charge pressure, and the statement "Warning--Charge with Air Only", to be printed on label prior to overwrapping.

3.0 EQUIPMENT

3.1 Entec - Model 424 Filament Winding Machine, capable of winding in both helical and hoop (circ.) modes.

3.2 Oven - air circulating, temperature range to 350°F.

3.3 Radiant heating rotating stand for jelling resin after winding.

3.4 Shop Aids - as required to mix and weigh resin components and for removing excess resin during winding, etc.

4.0 GENERAL REQUIREMENTS

4.1 All overwrapping shall be accomplished using the materials and equipment specified in 2.0 and 3.0 of this document.

4.2 The winding sequence shall be comprised of an alternating polar and hoop wrap orientation. The following sequence and amount of fiber ends to be applied in each step is given below. All winding is to be done in the wet state.

1) Apply polar oriented material, i.e., 125 circuits with a 60-end roving delivery system,

2) Apply 826-854 circuits with a 60-end roving delivery system and a hoop wrap setting of 10 revolutions per inch,

3) Apply polar oriented material, i.e., 192 circuits with a 60-end roving delivery system,

4) Apply 228-240 circuits (as in item 2) above.

4.3 All overwrap material shall be uniformly distributed over the winding surface. The polar wrap material must lay against liner boss and plug while winding. The total number of ends in each winding orientation shall be approximately: 38,000 - polar and 65,000 - hoop.

4.4 Hoop-oriented material, step 2 above, shall be placed over the complete cylindrical area of the liner and extended into dome areas at each end of the liner (as shown on Sheet 1, LAB 1630-72-014). Step 4, hoop-wrap material shall be placed primarily in the cylinder portion of the liner to prevent sluffing or slipping of glass off the ends of the vessel. Some sluffing and slipping is permitted in first circ. wrap.

4.5 A label shall be applied to each vessel.

4.6 A quality control inspection shall be performed on each vessel.

4.7 Cure temperature shall not exceed 350°F.

4.8 The liner shall be cleaned before winding with Kimwipes or cheesecloth moistened with MEK or equivalent.

4.9 Foreign Materials: The finished part shall be free of foreign material such as dirt, etc.

4.10 Gaps: There shall be no visible gaps exposing an over-wrapped metal surface. The overwrap shall be applied such that a relatively smooth surface is produced which has no gaps deeper than a single overwrap thickness.

4.11 Resin Starved Areas: There shall be no resin starved areas in the liner overwrap. Resin starved areas are those areas that are not uniformly coated with resin.

4.12 Surface Irregularities: The outer surface of the cured overwrap shall be uniform and free of excessive resin globs, frayed fibers, or loose ends.

4.13 Maintain a current traveler sheet for each vessel (example - pg. 6).

4.14 Do not use abrasives on external surface of finished part except to remove hazardous protruding fibers.

4.15 After part is finished, store vessel in safe place and tape open end of vessel closed to prevent threat damage and contamination.

5.0 <u>WINDING PROCEDURE</u>

5.1 Weigh liner and glass roving spools to nearest 0.1 lb.

5.2 Clean liner with MEK and Kimwipes or equivalent until all visible contamination is removed.

5.3 Weigh out resin components.

5.3.1 Heat 828 to 200 $\pm$ 20°F and stir slowly if necessary to dissolve 1031 particles. Cool solution to 120 $\pm$ 10°F. Mix with NMA and BDMA.

5.4 Load liner in winding machine by inserting a threaded rod in boss end of liner and establish center in other end of liner for tailstock. Center part with respect to helical winding stroke.

5.5 Set tension spring to 16 lbs on each roving.

5.6 Set hoop wrap lead dial to 5.66.

5.7 Set helical band advance dial to 2.0.

5.8 Set helical circuit counter to 125.

5.9 Fill the resin bath reservoir with the warm resin mixture. Maintain warm workable resin mixture ($120 \pm 15^{\circ}F$).

5.10 Tie on wrapping material for first helical wrap at boss end and helically wrap until the circuit counter number has reached 125. Helical wrap shall be applied at a rate of 5 - 10 circuits per minute.

5.11 Screed excess resin from liner while wrapping. Collect and pour back into reservoir.

5.12 Tie off helical wrap so that cut end lies approximately at midcylinder and change machine to hoop winding mode.

5.13 Tie on wrapping material in cylindrical area of liner and put on 826-854 circuits of hoop oriented wrap beyond hoop offset dimensions of 2.6 and 1.9 in. The liner is rotated at a speed up to 60 rpm.

5.14 Screed excess resin as in 5.11 above.

5.15 Switch machine to helical winding mode and set helical circuit counter to 192. Apply helical circuits in the manner used in 5.10, 5.11 and 5.12 above.

5.16 Note new hoop offset dimensions, i.e., 3.7 in. from boss end of liner and 3.1 in. from plug end of liner, and change machine to hoop winding mode.

5.17 Tie on wrapping material in cylindrical area of liner and apply 114-120 circuits of hoop oriented material uniformly between the new hoop offset dimensions. Screed excess resin. Do not tie off.

5.18 Place numbered (from liner) identification label in hoop wrap area and wrap 114-120 circuits of hoop oriented material over label and uniformly between offset dimensions as in 5.18. Label should be placed toward threaded end of vessel.

5.19 Wipe excess resin from surfaces of vessel.

5.20 Remove vessel from winding machine and place in heating stand.

5.21 Turn on heat stand and establish that part is rotating (about 2 - 10 rpm). Keep in stand for a minimum of 2 hours.

5.22 Weigh glass spools. Record weight.

5.23 Remove from heat stand and place vessel in hot, $320 {}^{+30}_{-10}$ °F, air circulating oven for 3 hours.

5.24 Remove vessel from oven, allow to cool, and weigh. Record weight and tape end shut.

5.25 Maintain traveler sheets current with appropriate QC coverage during various stages of overwrapping.

VESSEL FABRICATION TRAVELER

Job (Contract) NAS9-12540

Liner Mtl (lot & type)________
____
Liner S/M________
Liner Wt (gms)________
Liner Vol ($in.^3$)________
Liner Length (in.)________
Liner Diameter (in.)________
Visual Inspection Comments
____
____
____

Fiberglass Roving Type & Lot
____
____
Wt Spls before (gms)________
Wt Spls after (gms)________
Net Fiber Wt (gms)________
Resin Type________
____
Net Resin Wt (gms)________

Overwrap Inspection Date*________
Cure Vessel (date)*________
Size Vessel (date)*________
Permanent Vol Change (cm^3)
____
Plastic Vol Change (cm^3)
____
Final Vessel Wt (gms)________
Final Vessel Vol ($in.^3$)________
Final Vessel OD (in.)________

Operation	Description	Operator	Date
1) Records	Complete left column of this form before winding; keep form current as operations are completed.	________	________
2) Machine Setup	a) Polar gear ratio 90/64 dial setting 2.0	________	________
	b) Circ gear ratio 120/75 dial setting 5.66	________	________
	c) Winding tension: polar 16 lb, circ 16 lb	________	________
3) Resin Preparation	Formula: Epon 828 - 50 pbw, Epon 1031 - 50 pbw, NMA - 90 pbw, BDMA - .5 pphw Melt 1031 @ 200 ± 20°F, cool 1031 to 140 ± 20°F and add NMA and BDMA. Heat resin bath to 120 ± 10°F.	________	________
4) Liner Preparation	Wipe with MEK or acetone.		
5) Winding Procedure (60 end roving)	a) Apply polar wrap, 125 circuits	________	________
	b) Apply circ wraps, 826-854 liner revs	________	________
	c) Apply polar wrap, 192 circuits	________	________
	d) Apply circ wraps, 228-240 liner revs	________	________
	NOTE: Screed excess resin with a teflon paddle		
6) Label	Record S/N on label, date, QC stamp, and place label under last circ wraps of vessel (it is permissible to bond label after curing vessel).	________	________
7) Gel Resin	Place overwrapped liner in rotating gel fixture, apply heat, screed excess resin from winding surface as liner rotates; gel for 2 hours minimum.	________	________
8) Resin	Place gelled overwrapped liner in oven and cure: 3 hr @ 320 +30°/-10°F. QC check here.	________	________
9) Weights	Weigh cured vessel & roving spools, record above.	________	________
10) Vessel Test	Size vessel, pressurize to 7600 psig, record volume change, QC check, complete and sign this traveler.	________	________

*Quality inspection required, affix stamp on this form

____
Supervisor

APPENDIX F

TASK REPORT -

FABRICATION OF ADDITIONAL TEST PRESSURE VESSELS

APPENDIX F--TASK REPORT--FABRICATION OF ADDITIONAL TEST PRESSURE VESSELS

REQUIREMENTS

It was required that 55 additional Firefighter's Breathing System vessels be fabricated to support additional long-term exposure tests (to be performed at LeRC, NASA Lewis Research Center, Cleveland, Ohio) and to support field test evaluation by selected firefighting organizations in several large cities in the United States. These additional vessels were to be manufactured in a manner identical to the original vessels evaluated earlier in this contract, i.e., using the same materials and amounts of materials and manufacturing procedure with allowances made only for the use of different manufacturing equipment.

It was also required that two randomly selected manufactured vessels be subjected to cyclic tests. Each vessel was pressurized from zero to 4500 psig 10,000 times and then subjected to 30 proof cycles (0 to 6750 psig). Residual burst strength was then obtained from the cycled vessels.

It was also required that each vessel be quality inspected at various stages in the manufacturing process.

PROCEDURE

Liners were manufactured as in the previous program by Martin Marietta Aluminum using essentially the techniques described in Chapter V and conforming to the liner design shown in Figure IV-6.

These liners were then overwrapped using the procedure given in Appendix E and sized at a pressure of 7600 psig. Strength and quality of the overwrap material was confirmed by physical testing.

The S-2 fiberglass manufactured by Owens Corning was purchased with type 470 finish and in 250 yd/lb yield.

Retention of strength after sustained-load water-boil exposure was good (89 percent) and was in excellent agreement with earlier data.

The physical characteristics of 57 vessels manufactured for this task are shown in Table F-2. Twenty of these vessels were delivered to NASA-Lewis and the remaining untested vessels were shipped to NASA-JSC as indicated in the Table.

Four vessels listed in Table F-2 were tested. Vessel number 4-75 was tested for virgin burst strength; it failed at 14,600 psig.

Another vessel S/N 11, not shown in the table, failed in virgin burst at 13,920 psig. This vessel was wound prior to all task vessels using a liner rejected from the earlier liner lots and was considered to be preliminary.

Three task vessels (S/N's 3-5, 3-7, 4-43) were subjected to cyclic pressure testing, i.e., 10,000 cycles of 0-4500 psig plus 30 cycles of 0-6750 psig. The first vessel tested, S/N 3-5, failed after 7800, 0-4500 psig cycles. The mode of failure was not catastrophic, i.e., the liner leaked. No glass was displaced as a result of this failure and the external appearance of the vessel was unchanged.

Failure analysis indicated that cracks had propagated from folds created during forming for boss end closure. These folds are so tight that they appear as cracks and are excellent crack starters which grow during pressure or fatigue cycling.

Fold-cracks, i.e., those deep enough to produce crack like defects, were not exhibited on all liners. There was also a large size range of fold-cracks noticed. Vessel 3-5 was considered to have large or deep fold-cracks, some extending across (perpendicular to) three threads.

A close visual examination of the 15 liners in the three-series lot revealed that seven of the 15 had deep fold-cracks extending more than one thread up into the threaded boss toward the sealed end of the vessel. Those seven liners were rejected from this task.

Quality inspections were performed at the following positions in the manufacturing sequence:

a) Visual liner inspection prior to overwrapping,

b) Hardness check of each liner,

c) Overwrap quantities verified,

d) Curing cycle checked--permanent record retained,

e) Monitor of sizing cycle by quality personnel.

Pertinent information and quality approval stamps were retained on traveler sheets maintained for each vessel (example shown in Appendix E). A quality stamp was affixed to the label of each vessel to certify overwrapping date and procedure.

C. PHYSICAL AND TEST DATA

Chemical analysis and mechanical properties were obtained on each lot of liners. Both evaluations showed the material to conform to the requirements for 6070-T6 aluminum per Alcoa, Appendix D.

The average hardness readings taken from all liners was Rockwell "F" 89. The range of hardness was quite small, i.e., all readings were between 84 and 94. The hardness was slightly lower than typical (about F99) probably due to lack of support in the neck where the readings were taken.

Several liners were rejected during visual examination. The primary reasons for rejection were eccentricity of the boss end threads, i.e., threads were not placed in the center of the boss, or excessive folding which caused crack like fold lines to be visually observable in the threaded neck area.

These fold-cracks were found to be sites for crack growth during fatigue cycling tests of test article vessels as discussed later.

NOL rings were fabricated from the S-2 fiberglass and Epon 828/1031/NMA/BDMA epoxy resin system selected earlier in this program. Tensile, shear and accelerated stress corrosion tests (sustained-load water boil) were performed on this new lot of glass and resin from which all task vessels were fabricated. The data from these tests are shown in Table F-1. These data show good agreement with that obtained earlier and presented in Chapter III of this report.

Table F-1
NOL Ring Test Data (per ASTM D-2290 & 2344) - S-2 Fiberglass With Epoxy Resin

Ultimate Tensile Strength (Fiber Stress, ksi)	+Ultimate Shear Strength (ksi)	*Residual-Ultimate Tensile (Fiber Stress, ksi)
297.5		
332.3	9.2	272.8
297.9	9.3	283.4
322.3	8.6	267.9
	9.4	288.1
	9.2	
312.5 AVG.	9.1 AVG.	278.0 AVG.

*NOL ring samples exposed to operating stress level for 4-hr in Boiling Water (200°F) before tensile testing

+NOL ring segment

TABLE F-2

PHYSICAL CHARACTERISTICS OF TASK VESSELS

Serial Number	Liner Weight (lb)	Vessel Weight (lb)	Final Volume** (in.^{3})	Final Dia.** (in.)	Permanent Volume Change During Sizing (in.^{3})
3-1+	3.89	8.36	282.0	5.65	2.44
3-5*	3.91	8.69	282.6	5.66	3.11
3-6+	3.93	8.72	282.1	5.70	2.50
3-7*	3.95	8.56	282.7	5.66	2.50
3-8+	3.88	8.57	282.7	5.67	2.50
3-9+	3.93	8.57	282.1	5.69	2.50
3-10+	3.87	8.46	282.8	5.66	2.50
3-16+	3.91	8.43	282.0	5.66	2.59
4-1+	3.94	8.74	283.9	5.68	2.44
4-2+	3.95	9.11	282.7	5.69	1.71
4-3°	3.99	8.72	284.4	5.65	2.38
4-4+	3.93	8.79	283.2	5.67	2.56
4-6°	3.96	8.65	284.3	5.64	2.81
4-7°	3.96	8.76	283.2	5.67	2.32
4-9+	3.93	8.75	283.4	5.67	2.38
4-10°	3.97	8.95	283.6	5.68	2.44
4-11°	3.91	8.61	283.2	5.64	2.69
4-12°	3.94	8.71	282.4	5.65	2.44
4-13+	3.99	8.62	283.8	5.63	2.38
4-14°	3.94	8.69	283.0	5.66	2.69
4-15+	3.92	8.78	282.7	5.66	2.75
4-16°	3.95	8.93	280.2	5.70	2.20
4-17+	3.95	8.64	283.3	5.64	2.56
4-18+	3.99	8.52	283.2	5.61	2.44
4-20°	3.94	8.64	283.6	5.65	2.44
4-21+	4.07	8.70	284.0	5.63	2.26
4-22°	3.90	8.75	284.1	5.64	2.69
4-23°	3.94	8.81	283.6	5.66	2.75
4-24+	3.94	8.86	284.5	5.67	2.50
4-25+	3.94	8.65	284.0	5.65	2.26
4-27+	3.95	8.78	283.2	5.66	2.44
4-30°	4.00	8.96	282.8	5.68	2.32
4-31°	3.96	8.73	283.8	5.65	2.75
4-32°	4.01	8.85	282.8	5.67	2.50
4-33°	4.03	8.77	282.2	5.65	2.38
4-34+	3.92	8.73	284.0	5.67	2.81
4-36+	3.96	8.90	283.2	5.67	2.50
4-37°	3.98	8.47	282.1	5.61	2.69
4-39°	3.98	8.65	284.1	5.65	2.69
4-40°	4.00	8.77	282.4	5.65	2.60
4-42°	3.95	8.75	282.9	5.64	2.20
4-43*	3.98	8.54	285.5	5.66	3.66
4-44+	3.94	8.54	283.5	5.63	2.38
4-45°	3.98	8.62	283.1	5.64	2.69
4-46+	3.94	8.48	283.2	5.61	1.95
4-47+	4.04	8.84	282.8	5.67	2.32
4-48+	3.95	8.70	284.2	5.64	2.44
4-50+	3.98	8.78	284.6	5.68	2.50
4-51+	3.94	8.79	282.4	5.67	2.50
4-60+	3.94	8.45	283.5	5.61	2.87
4-62+	3.86	8.28	282.1	5.59	2.69
4-65+	3.86	8.55	283.5	5.64	2.81
4-67+	3.91	8.48	282.1	5.63	3.17
4-68+	3.86	8.79	283.5	5.68	3.05
4-70+	3.98	8.81	282.8	5.68	2.87
4-75*	3.92	8.87	281.7	5.67	2.69
4-77+	3.92	8.69	282.4	5.64	2.20
	3.95 AVG.	8.69 AVG.	283.1 AVG.	5.65 AVG.	2.56 AVG.

+Delivered to NASA-JSC

°Delivered to NAS-LeRC

*Test Article

**Volume and diameter after sizing

From the remaining eight liners of this lot, 3-7 was selected as bieng typical with respect to degree of fold-cracking exhibited and was subjected to the pressure cycling sequence. 3-7 survived pressure cycling and had a residual burst pressure of 8300 psig. The mode of failure exhibited by 3-7 was quite typical, i.e., a glass failure originating in the open end dome allowing liner fragments to be expelled. A small degree of crack growth had occurred in fold-cracks but failure could not be attributed to liner fatigue. Sectioning revealed that this vessel had an unusually small amount of hoop overwrap material at the at the dome-cylinder junction; the prime causal suspect for the lower residual burst value.

Test article 4-43 was produced from a liner exhibiting no visual fold-cracks and a minimum of puckering in the neck-closure area. This vessel survived the pressure cycling sequence and had a residual burst pressure of 9750 psig. This failure was unique in that it was a leaking mode failure exhibiting no glass damage or fragmentation. Examiniation showed that fold-initiated cracking had still occurred but to a small degree. The cracks had opened during burst and allowed safe release of the pressurant (water) without other structural damage.

4-75 was tested as a virgin burst strength vessel. This vessel exhibited some visual fold-cracking, about 1 thread long or 0.07 in. into the boss threaded area, at three locations around the periphery of the opening. This vessel was chamfered at a 32° angle to a depth sufficient to remove the last complete threat at the bottom of the boss and thus all visual evidence of fold-cracks. This vessel had a virgin burst strength of 14,600 psig. The failure was not attributed to any liner weakness and represents the highest burst strength attained with this design.

D. CONCLUSIONS

Although difficulties were encountered with liner defects, all failures resulting from liner defects were not catastrophic thus proving the fail-safe feature of this design. The pressure sequence applied to these vessels was more severe than in the earlier program, i.e., pressure was applied to 4500 psig (maximum operating pressure) instead of 4000 psig (charge pressure). This seemingly modest change in pressure actually raises the liner hoop stress from 14.5 to 19.9 ksi which is significant in terms of fatigue life. The 10,000 cycle requirement is also quite stringent considering in service this represents two complete pressure cycles a day, 365 days per year for about 14 years.

Even though test conditions were rigorous, vessels 3-7 and 4-43 survived the cycling sequence and showed residual burst strengths twice the operating design pressure of the vessels. Those vessels delivered under this task are considered to have properties typical of those exhibited by these two test vessels and are in no way considered to be inferior to those produced during the initial portion of this program.