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IMPROVED FIREMAN'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM

By

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IMPROVED FIREMAN'S COMPRESSED AIR BREATHING SYSTEM PRESSURE VESSEL DEVELOPMENT PROGRAM

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FORWARD

This report is submitted by Structural Composites Industries, Inc., in partial fulfillment of Contract NAS 9-12414. It covers all work on the program, which was conducted from January 1972 to August 1973.

The work was performed by Structural Composites Industries, Inc. Robert Gordon and Harry A. King were the Program Manager and Principal Investigator. Edgar E. Morris conducted the pressure vessel design analysis.

Fabrication of the metal liners was accomplished by Metallite Manufacturing Company, Glendale, California (cupping), Eagleware Manufacturing Company, Los Angeles, California (flow forming), and Martin-Marietta Aluminum, Torrance, California (boss end forming). Design and filament-winding was accomplished by Structural Composites Industries, Inc.

Testing of completed units was conducted by Approved Engineering Test Laboratories, Los Angeles, California, and Structural Composites Industries, Inc.

Guidance and direction were provided throughout the program by NASA Johnson Space Center Technical Monitor, Pat McLaughlin.

ABSTRACT

Prototype high-pressure glass filament-wound, aluminum-lined pressurant vessels suitable for use in a fireman's compressed air-breathing system were designed, fabricated, acceptance tested, successfully qualification tested, and delivered to demonstrate the feasibility of producing such high-performance, lightweight units. The resultant 60 standard cubic foot (SCF) air capacity 4000 psi tanks of 6.5-inch diameter, 19-inch length, and 415-inch volume, weigh empty only 13 pounds, approximately 75% as much as current 45 SCF (2250 psi) steel units, while containing 33% more air. Compared to current steel 60 SCF (3000 psi) tanks, the new units weigh empty approximately 50% as much. In addition to significantly lower weights, these units are two inches or 10% shorter in length than the steel units. They also have non-rusting aluminum interiors, removing the corrosion hazard, the need for internal coatings, and the possibility of rust particles clogging the breathing system present in current steel cylinders.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

APPENDICES

SUMMARY

Design, fabrication, testing, and small-scale production of high-pressure, lightweight, glass filament-wound air storage vessels for fireman's breathing systems were accomplished. The work demonstrated the required pressure vessel structural performance capabilities and the feasibility of fabricating such vessels in large-scale production.

The requirements for the pressure vessel, as specified by NASA, were some of the most difficult combined structural performance, test, and exposure conditions ever required of a production air tank. They included:

- Weight of 14 pounds while containing 60 standard cubic feet of air at 4000 psi operating pressure. (This can be compared to a current steel unit containing only 45 SCF, weighing 19 pounds or a 60 SCF unit weighing 26 pounds.)
- Proof pressure of 6750 psi and minimum burst pressure of 9000 psi
- Diameter of 6.5 inches and length of 20 inches.
- Service life of 15 years with water vapor containing air (therefore, the tank must be totally nonrusting)
- Working temperature between 60 and 200°F
- Failure mode such that should failure occur during use, the mode would be air leakage rather than by catastrophic rupture
- Capability of withstanding 12 drops from 10 feet onto a rigid steel plate, 6 drops at -60°F and 6 drops at 200°F, impacting on both ends and on side
- Capability of withstanding 5 drops at various angles from 16 feet onto a rigid steel plate with 200 pounds attached to the tank
- Capability of receiving a direct hit from a .30 caliber armor piercing bullet, while fully pressurized, to 4000 psi with air without a subsequent tank explosion or even a cut more than three inches long being formed
- Resistance to repeated temperature shock by plunging a tank heated to 200°F into a -60°F bath and a -60°F tank into a 200°F bath

- Capability of being placed in a 600°F oven while pressurized to 2000 psi (when already at 200°F) and held there for five minutes
- Capability of being repeatedly placed in a 400°F oven and held at this condition for 10 minutes while pressurized to 2000 psi
- Capability of being pressure-cycled 10,000 times to a service pressure of 4000 psi (equivalent to two use cycles every day for 15 years)
- Capability of being pressure-cycled 100 times to a proof pressure of 6750 psi (this is equivalent to one proof cycle every two months for 15 years; typically, proof cycles would be conducted once every one to three years or a maximum total of 15)
- Resistance to high humidity, salt atmosphere, and sand and dust

All of these requirements had to be fulfilled with a pressure vessel design and fabrication procedure suited to a large-scale manufacture at reasonable cost.

In order to achieve required performance under the combination of requirements, a highly specialized manufacturing technique called filament winding was selected and used in conjunction with very high-strength, lightweight glass fibers and a high-strength, tough and heat-resistant epoxy resin. These materials were further combined with a nonrusting, tough, high-strength and corrosion-resistant seamless aluminum alloy lining to seal in the air and provide the necessary connecting threads.

The pressure cylinder developed with these materials passed all the specified requirements and is being field tested. The program resulted in significant developments and advancements in producing high-performance metal-lined, filament-wound pressure containers, with ability to sustain operational requirements, severe environmental exposure, and significant damage and, at the same time, provide the required burst factor of safety. During testing of the composite pressure vessels, some rather interesting observations were made and a few of these are summarized here to indicate how the vessel might behave in unusual situations.

Test vessels shot with a .30 caliber armor-piercing bullets pressurized with both air and water showed no tearing or fragmentation of any kind. The only result was an entry hole about the size of the bullet. Because the bullet did not fully penetrate the tank in either case, there was no exit hole.

One vessel had its aluminum liner intentionally defected with a cut one-half way through its thickness. The unit, after 1,000 use pressure cycles to 4000 psi, finally began to leak at 8,450 psi and could not be pressurized to burst, dramatically demonstrating the leak before burst capability.

Another vessel was intentionally cut one-half way through its fiberglass hoop wraps and cycled 1,000 times to a use pressure of 4,000 psi. When no leak developed, the cut was deepened to three-fourths of the total hoop thickness and the vessel cycled another 100 times. Again with no leak, the cut was deepened to the full thickness of the hoop wrap and made about one inch long. When no leak developed after another 100 pressure cycles, the cut was widened to two inches long entirely through the hoop wrap. After another 100 use cycles to produce failure, the cut was finally lengthened to a massive four inches length. Failure finally occurred at 3,200 psi.

Another interesting test consisted of pressure cycling a vessel 10,000 times to 4000 psi service pressure and 100 times to 6750 psi proof pressure, while entirely submerged in sea water. This tank then was burst-tested at 9600 psi.

In conclusion, a rugged, durable vessel has been developed suitable for commercial service, as demonstrated by severe accelerated testing. Long-term performance is being verified by NASA field trails and extended pressure storage testing. Economic study results made clear that high manufacturing rates are required to significantly reduce product costs in commercial production.

I. INTRODUCTION

A. PROGRAM OBJECTIVE AND REQUIREMENTS

The objective of this program was to design, fabricate, test and deliver prototype pressure vessels which are suitable for use in a fireman's compressed air breathing system. These pressure vessels were to have a minimum weight consistent with reasonable production costs and adequate structural safety.

Basic design requirements were as follows:

- Nominal charge pressure of 4000 psig
- Minimum volume of 415 cubic inches (60 SCF of air at 4000 psi)
- A desired envelope not to exceed 6.5-inch-outside diameter and 18-inch in length
- Weight not to exceed 14 pounds
- Ability to demonstrate a 9000 psig minimum burst pressure after exposure to a rigorous sequence of qualification testing including extensive pressure cycling; repeated proof tests; impact and drop tests; and humidity, salt atmosphere, high and low temperature exposures.

All of the above were met with the exception of unit length which is approximately 19.2-inches.

B. BACKGROUND

1. Metal Vessels - Currently Used Technology and Technology Available

Amazing progess have been made in the development and application of high performance, low weight metallic materials for aerospace pressure vessels during the past 10 to 15 years. Although a wide variety of metallic materials are available and usually considered by the aerospace designer, commercial industry generally still uses the structural materials of the past with their substantially lower weight efficiency, primarily because of (1) economic consideration, (2) constraints of regulating agency codes, and (3) inertia to change.

As a point for reference, traditional ASME authorized steels for unfired pressure vessel use have typical yield strengths of 30,000 to 100,000 psi and ultimate strengths of 55,000 to 122,000 psi. During the 1960's, some increase in strength levels was permitted by code cases covering low alloy constructional steels (e.g., T-1, T-1A, SS-100, J Alloy S-110) supplied by the mills in a water quenched and tempered condition with 100,000 to 110,000 psi yield strength and 115,000 to 135,000 psi tensile strength. These materials do not require heat treatment after welding for vessel fabrication.

To achieve higher strength, the use of heat treated or cold worked materials is required. Department of Transportation (DOT) regulations set standards and practices for commercial seamless gas storage vessels such as fireman's breathing tanks. Specification DOT-3AA (for pressures over 500 psi and water capacity under 1000 pounds) specifies the ratio between proof and operating pressures (5/3), and between design burst and operating (20/9), with the design based on proof pressure. This code limits maximum stresses in pressure cylinders for commercial use to 42,000 psi at operating pressure, 70,000 psi at proof pressure, and 93,000 psi at design burst pressure, effectively dictating the wall thickness, requiring utilization of low strength metals, and resulting in heavy weight.

AISI 4130 steel is the material used in fireman's breathing tank manufacturing to meet these code requirements. Cylinders are fabricated by cold draw forming to make a cylinder with one closed end, followed by hot spinning to close the opposite end and form the port, threading, and heat treating. Fabricated 4130 steel fireman's breathing cylinders are usually given corrosion protective coatings of phosphitizing on the inside and paint on the outside, with epoxy interior coating and galvanized and vinyl exterior coating also being used for SCUBA breathing tanks. Bottles so produced weigh about 19 pounds for a 514 inch^3 water volume and 2250 psig operating pressure (45 SCF air capacity) and 26 pounds for a 514-inch^3 water volume and 3000 psig operating pressure (60 SCF).

Specification DOT-3HT is a more recent modification of DOT-3AA for lighter weight cylinders for aircraft use only. Maximum stresses allowed are 63,000 psi at operating pressure, 105,000 psi at proof pressure, and about 140,000 psi at design burst pressure.

Aluminum breathing tanks are produced by Luxfer USA Limited for SCUBA applications in various sizes. These seamless tanks are made from 6351-T6 aluminum. In 514-inch^3 volume size (45 SCF), diameter is 6.9 inches, length is 22.5 inches, and weight is 18 pounds for a 2250 psig operating pressure.

2. Glass Filament-Wound Composites

a. A Material With A Long History And Record Of Reliability

Interest in filament-wound tankage for aerospace applications has been constantly increasing because of the need for maximum weight-saving and because state-of-the-art advancements have demonstrated that the reliability level needed in specific applications can be attained in filament-wound structures. Since the early 1950's, when the first serious efforts were made to produce high-strength, light-weight glass filament-wound vessels and rocket motor cases, significant successes have been achieved in development of a technology base and reliable application of these composite structures to operational systems. Successes with early glass-filament rocket structures served to stimulate increased interest in composite materials. Then, based on the potential for weight-saving, a great deal of research was directed toward development of glass filament-wound motor cases for use in advanced designs of Polaris and Minuteman solid rocket propulsion systems. The emergence of filament-wound composites into operational military and aerospace systems occurred rapidly over the last ten years when rocket motor cases were developed and used in these missile systems. Attainment of the design objectives for the Polaris and Minuteman rocket cases and their reliable production made possible extremely important increases in overall system performance. Applications in sophisticated aircraft, undersea vehicles, and results from technology development by NASA for cryogenic tankage has further demonstrated successful use experience with this material and its high performance capabilities.

Filament-wound composite tankage structures now promise to extend this success to many other types of pressure vessels. The use of such structures for fireman's compressed air pressure vessels results in considerable weight savings because the winding material has a much higher strength for its weight than do all metal-tank materials.

b. Properties and Characteristics

Exact weight comparison are often made between filament-wound and homogeneous-metal pressure vessels for particular hardware requirements. However, the detailed approach is not convenient for obtaining a broad comparative view of the relative weight efficiences of various shape and material combinations. For this reason, Figure I is presented to provide a convenient comparison.

The Filament-Winding Principle - The filament-wound reinforced-plastic structure contains many continuous, small-diameter, high-strength fibers imbedded in a matrix of organic or inorganic material. Such composites are fabricated by winding a specifically oriented pattern of pretensioned, resin -impregnated, continuous filaments onto a mandrel and curing the resin. The fibers, which in most applications are glass, constitute the primary load-carrying element because of their relatively high modulus of elasticity compared with matrix materials. Maximum structural efficiency is obtained by orienting these fibers to provide the strength components needed to meet the applied loads. In pressure vessels and other structures where the directions and relative magnitudes of forces are fixed, the matrix resin has the secondary role of controlling fiber efficiency by transferring loads from broken fibers, hardening the structure in terms of shape and fiber orientation, and protecting fibers from each other and from degrading environments. Winding patterns are used that orient the filaments so that the principle forces load the glass as much as possible in pure tension along the filament axis. The materials of construction, winding pattern, and the shape all affect vessel burst strength and weight for a given pressure and volume. The relative weight chart (Figure 1) shows these relationships for filament-wound vessels and also includes comparative data for homogeneous constructions.

Cylinder Winding - A biaxial winding pattern is used to meet the orthotropic force field in the cylinder. Outer layers of hoop windings are balanced to inner longitudinal windings in a vessel axial-strength ratio of approximately 2:1. This ratio is adjusted somewhat so that the filaments will exactly meet all stresses within the structure to provide equal margins of safety in all directions.

The heads are integrally formed by extending the longitudinal wraps in the cylindrical portion continuously around the end closure using a wrapped-in-plane construction wherein the longitudinal stresses are balanced to the pressure loading and the hoop stresses approach zero. Each filament circuit describes a closed path lying in a plane, except for the small advancement necessary to lay successive applications by the proper adjustment of the circumferential and meridional radii in the head contour. This is based upon the relationship that, for a given point in the end closure, when the circumferential radius equals exactly twice the meridional radius there can be no circumferential force as a result of internal pressurization. The wound head (based on a uniform wall) weighs essentially the same as would a cylinder that has the same major diameter and encloses the same volume. This is because, when the fibers are located correctly, i.e, an ideal isotensoid prevails, load-carrying efficiencies will be the same and as a direct result the weights for a veriety of wound vessels will be the same for the same pressure volume product.

In the head, as in the cylinder, the filaments are primarily loaded in pure tension, with minimum shearing forces between filaments; the latter load is handled by the resin. A wall-thickness buildup occurs at the polar bosses as a result of the necessity for passing all the glass that forms the wall at the major diameter through the smaller diameter at the boss. This buildup more than compensates for the small hoop forces localized in the boss area.

The Material - The glass content of filament-wound tanks is generally about 67 volume percent, or 82 weight percent. This ratio, with a density of 0.088 pound/inch^3 for S-901 glass (Owens-Corning Fiberglass Corporation) and an epoxy-resin density of 0.042 pound/inch^3, results in a composite density of 0.073 pound/inch^3, which is about one-quarter the density of steel and less than one-half the density of titanium. The low weight and the high strength of the composite material (e.g., 150,000 psi wall-hoop stress for a pressure vessel cylinder), provide a highly efficient structural material. The commercial grade E-glass filament composite, with approximately the same density, provides a strength on the order of 120,000 psi wall-hoop stress at an even lower raw material cost while still providing a high strength-to-weight efficiency.

Homogeneous metals by comparison are generall nearly isotropic, with properties similar in all directions. Care must therefore be exercised in metallic materials selection to obtain high strength with sufficient fracture toughness, because when a metal vessel is loaded, the wall is subjected to stress concentrations in the vicinity of any flaw which can result in a self-propagating catastropic failure throughout the entire wall. The load sharing interdependence of adjacent elements for the metal wall exists to a much lesser degree in the filament-wound vessel. The greater number of individually loaded elements (the filament) and the tough resin matrix tend to both reduce and localize the effect of a given flaw.

Filament-wound vessels approach ideal isotensoidal construction; in this case the filaments are uniformly loaded in tension along their entire length. The continuity of filament path and stress, the accuracy of filament placement, and the stress concentrations induced by filament crossovers influence the proportion of basic glass strength achieved in the vessel.

The maximum ultimate glass composite strengths that can be obtained have previously been shown in Figure I for the different vessel shapes and glass compositions. These are total wall composite strengths (adjusted to vessel axis) that have been actually achieved as computed from room temperature burst tests on Structural Composites Industries, Inc. (SCI) built 4-inch balanced cylinders, 8-inch spheroids, and 17-inch spheres. These strengths will be somewhat different for other vessels according to their size and proportions. Scaling factors have been developed by SCI to accurately predict these strengths.

The use of empirical data from tests of actual pressure vessels is needed to estimate design allowable stresses for a "new" configuration because there is no other acceptable method of arriving at design strength. This is because the glass filament material strength is greatly influenced by the form of the structure, its size and geometry, and the loading conditions. This point is illustrated in Figure 2, where the strength of a single filament of S-glass is shown to be about 700,000 psi; when this material is combined into twenty-end roving (bundle of 4080 filaments), the strength decreases to about 450,000 psi. Then the twenty-end roving is used to make pressure vessels, further decreasing strength as size increases. The same trend holds true for the commercial E-glass, as shown in this figure.

Figure 3 summarizes typical strength levels obtained at SCI for E- and S-glass-filament-wound specimens and full scale structures compared with high strength metal vessel materials. The strength-to-density ratio comparisons between filament-wound composites (FWC) and high-strength metals given in Figure 4 indicate the weight savings inherent with glass-filament-wound composites. However, this figure does not include the weight disadvantage of the liner needed inside the wound vessel. It should also be noted that the strengths and strength-to-density ratio comparisons shown are for single-cycle burst tests of vessels. Glass-filament-wound composite vessels (as well as metal vessels) are subject to strength degradation by cyclic and sustained loads, and elevated temperature exposures (as will be subsequently discussed) resulting in reduced weight efficiency from the values shown in applications which such loading and environmental conditions are key design considerations.

c. Liners For Filament-Wound Vessels

Although the filament-wound material is light in weight, it is permeable to gases and liquids under pressure. Permeability is overcome in gàs storage vessels by using a liner to prevent or minimize fluid transmission through the composite. Because the performance of a pressure vessel is based on its total weight, operating pressure, and volume, a minimum-weight liner is desirable to make maximum use of the filament-wound composites high strength-to-density ratio.

The functional requirements for sealant liners include -

- Impermeability to gases and liquids under pressure
- Resistance to corrosion by contained or contacted fluids or gases
- Strain compatibility between the liner and the composite structure up to the FWC-failure stress
- Resistance to fatigue when subjected to repetitive loading to the operating-stress level
- Toleration of tank expansion and contraction during temperature cycling

Molded elastomers, polymeric films, metal coatings, metal foil, and metal sheet have been used by SCI for liners. When a polymeric liner is functionally adequate for a specific application, designing the liner and filament-wound vessel is relatively straight-forward. Metal lined tanks require more design analysis and understanding than elastomeric liners but work by personnel at SCI (largely supported by NASA) has now reduced this complex problem to one of fairly straight-forward design and elastomeric and metallic liners now compete with each other on the basis of final properties and cost. Both of these materials are applicable to the fireman's compressed air system.

d. Elastomer Lined Glass Filament-Wound Vessels

This class of high pressure gas storage vessel has been used for many years with high reliability in stringent applications. The linings developed have been extensively evaluated over a wide range of test conditions and minimize fluid leakage to very low levels (<5%/year) over the -65 to 200°F temperature range.

e. Metal-Lined and Glass-Filament Reinforced Metal Vessels

Although elastomeric linings are considered adequate for the fireman's breathing tanks, performance and cost trade-off studies sometimes indicate some specific advantages to the metal-lined filament-wound vessels.

Composite tankage designs developed and evaluated under NASA sponsorship have b een based on two different liner design approaches. In the first, filament overwindings are used to reinforce a high-strength metal shell which has a thickness about one-third to one-half of what a homogeneous vessel would need if not reinforced. Designs are established by using analyses which combine strength and strain characteristics of the filament and metal shells. Combining the filament-wound composite with a metal shell provides the necessary sealant liner and permits the strength potential of both the filament and metal shells to be exploited. With this approach, glass filaments with epoxy resins have been used exclusively for the high-strength metal shell reinforcement. Tanks using this design philosophy are called glass reinforced metal vessels.

In the second approach, filament windings are used to reinforce a very thin metal liner (e.g., 0.006-inch to 0.020-inch-thick) which has the minimum possible thickness required for impermeability and fabrication. The liner carries only a small share of the structural loads. For this approach, glass filaments with epoxy resins have received the most emphasis, and a limited amount of work has been conducted on boron and graphite filaments with epoxy resins. Liners used are low-strength ductile metals. This concept, with the non-load bearing liner, is referred to as a metal-lined glass filament-wound vessel.

f. Present Design Philosophy of Glass Reinforced Metal Tankage

The primary objectives of design of a glass filament composite shell with an inner load carrying metal shell is to obtain maximum operating performance at minimum weight and to provide comparable or improved safe-life design over basic metal tank construction. Thick liners that share loads with the filament-wound shell offer an excellent approach to workable, low-weight, fluid stroage vessels. The functions and interactions of the parameters of filament reinforced smooth metal shell cryogenic vessels have been evaluated in detail by NASA and by SCI in past programs to establish optimum stress/strain relationships between the metal and fiber shells from strength, load, and strain compatibility viewpoints.

Analytical work and test evaluations have established many of the methods needed for analysis and rating of designs, and have indicated the technical problems which will be encountered with filament reinforced spheres, spheroids, and cylinders. They are related to the following factors:

(1) Load and strain compatibility of the two types of materials

(2) Constrictive wrap buckling strength of the metal shell

(3) Prestress (filament tensioning) set up between the two materials during fabrication and proof testing (sizing)

(4) Effects of prestress into the plastic region of the metal shell

(5) Thermal contraction characteristics of the various construction materials

(6) Effects of cyclic and sustained loading

For a specific tank configuration and metal and filament shell materials, particular attention must be paid to relative shell thicknesses and winding tension prestress (during fabrication, or pressure-sizing past the metal shell yield point after fabrication) to obtain the following significant conditions:

Condition (1): Suitable compression strain in the metal and tension strain in the composite to provide for thermal contraction differences during tank exposure to extremes of cold or elevated temperatures.

Condition (2): Suitable stress/strain relationships between the filament and metal shells to permit achievement of specified (optimum design) allowable operating stresses in the filaments and metal shells, simultaneously, at the operating pressure.

Condition (3): Suitable stress/strain relationships between the shells to permit attainment of a high fraction of the filament ultimate strength

- prior to exceeding the metal shell biaxial ductility capability
- as the metal shell approaches its maximum strength capability

Condition (4): Preclude metal shell buckling due to constrictive wrap stresses

3. Pressure Vessel Considerations Pertaining To The Fireman's Breathing Tank

From the foregoing technology status review, it is clear that a variety of attractive high performance pressure vessel materials, design approaches, and performance capabilities have been developed for aerospace applications which are candidates for the fireman's breathing tank.

The filament-wound tanks, with metal liners or elastomer linings, are the leading candidates for the application due to their light weight and failure mode characteristics. Additionally, there is a growing acceptance of filament-wound vessels. For example, the ASME has issued Section X of the ASME Boiler and Pressure Vessel Code in 1969, which covers fiberglass-reinforced plastic pressure vessels for certain applications. This code enables the extension of use of the vessels for military and aerospace applications to commercial and industrial applications which require compliance with an ASME code. However, this code specifies a 6:1 factor-of-safety plus 100,000 pressure cycle fatigue to pass its requirements.

Concurrent with the issue of the new ASME Code, SCI conceived a unique set of design configurations, high rate commercial production manufacturing processes, and winding machinery which will allow the production of small-sized filament-wound life support tanks offering significant increases in capacity and reductions in weight at a price of interest to large commercial markets.

In aerospace applications, pressure vessel weight has usually been of first importance, followed by reliability and cost. For the commercial breathing tank application, reliability and safety must be the first consideration dictating materials, design, and process selection. Cost is the next key consideration; prices to the equipment manufacturer and user for the improved breathing tank must be within range of a large percentage of the market. Weight and/or capacity increase must be significantly improved over currently used pressure vessels to provide meaningful advantages and to fulfill the pressing needs of the potential user.

C. BASIC TECHNICAL PROGRAM

This program was conducted in three basic phases as follows:

1. Phase I - Design

Designing a pressure vessel which meets the broad and specific requirements of this program, and is suitable for wide acceptance by fire departments in terms of safety and low cost.

2. Phase II - Fabrication

Developing and fabricating pressure vessels as defined in the design phase. Pressure vessels produced in this phase served as test articles during the test phase to demonstrate their suitability for the intended use.

3. Phase III - Test

Testing pressure vessels produced in Phase II to demonstrate that they are capable of satisfying the general requirements, the specific qualification test plan and procedures requirements, and the general requirements of firefighting.

4. Deliverable Tanks

Following successful completion of Phase III, thirty-three units were produced and submitted to NASA.

D. NASA PROGRAM REQUIREMENTS

1. Design Phase

The program was directed to encompass the design and preparation of the detailed specification and test plan for a fireman's compressed air breathing system pressure vessel. This pressure vessel was not to be based on unknown materials or processes, but upon refinement and application of existing technology. It was expected that existing pressure vessel design and technology would be utilized. The required activity is defined in the following paragraphs.

a. Material Selection

A specific material composition and the specific material properties (tensile strength, heat treatment, elongation, etc.) shall be defined. The material selection shall be based on the design requirements and expected production fabrication costs. Material properties which shall be considered, in addition to ultimate and yield strengths, are fatigue, creep, impact, fracture toughness, stress-corrosion cracking, hydrogen stress-cracking, and corrosion rates. The material selection shall include specific examples of how the material has, in other applications, satisfied similar performance requirements. The selection rationale for the proposed material shall be presented.

b. Stress Analysis

A detailed stress analysis, based on the design requirements, shall be presented. The effects of strap mounting, mechanical impact, thermal cycling, pressure cycling, useful life, gunfire tests, and fracture mechanics analysis for a "leaking" mode of failure shall be given special attention. The stress analysis shall include the valve attachment port, threads, and boss.

c. Detail Design

Detail design drawings of the pressure vessel shall be prepared. These shall define all dimensions, materials and processing requirements.

d. Fabrication Method

The proposed fabrication method shall be defined in detail. All portions of the fabrication process shall be described. Alternate fabrication methods shall be discussed and the selected material for the proposed method presented. The fabrication method selection shall include specific examples of how the process has, in other applications, satisfied similar performance requirements.

e. Economic Analysis

A detailed economic analysis shall be presented for the material and fabrication methods. If alternate materials/processes are surveyed, they shall be ranked in order of economic acceptability. The cost per unit pressure vessel shall be estimated for production rates of 1,000, 5,000, and 25,000 units/year. The non-recurring and recurring cost shall be defined for the above production. The economic analysis shall be substantiated by presenting the cost of similar production items, material costs, and processing costs.

f. Recommendation

An optimum material/fabrication process shall be defined based on the preceding tasks. The recommendation shall include specific examples of how the material/process has, in other applications, satisfied similar performance requirements. Also, if alternate materials/ processes are surveyed, they shall be ranked in order of acceptability for this requirement. NASA concurrence shall be required prior to the fabrication process.

g. Specification, Detail

A detailed specification which is suitable to define the design, manufacture, and inspection of production vessels shall be prepared. This specification shall include basic structural design calculations, authorized materials, material processing requirements such as welding and heat treatment, design, environmental and structural requirements, quality assurance, surface protection, identification and markings, retest requirements and frequency.

h. Test Plan

A test plan shall be prepared to define a test program which will demonstrate that the pressure vessel satisfies the requirements of Table I. The test plan shall define the number of test articles, the sequence of tests for each test article, the test conditions, and the documentation and test report requirements.

i. Design Phase Reporting

A design phase report shall be prepared. The design phase report shall be contained as an Addendum to the Monthly Progress Report. This design phase report must be approved by NASA prior to starting the fabrication phase.

2. Fabrication Phase

a. Drawings/Process Requirements

The fabrication phase shall include the preparation of tooling drawings, process specifications, process procedures, and quality control requirements. These documents shall receive NASA concurrence prior to pressure vessel fabrication and shall be included in the program final report.

b. Fabrication Requirements

The fabrication shall be in accordance with the specification prepared in Section 1.g.

c. Fabrication Quantity

The contractor shall recommend to NASA the number of pressure vessels required to support the test plan defined in Section 1.h. The total number of pressure vessels fabricated shall, with NASA approval, be based on the preceding recommendation plus an additional fifteen pressure vessels for NASA demonstration and tests (subsequently increased to thirty-three).

d. Fabrication Phase Reporting

A fabrication phase report shall be prepared which addresses Paragraph 2.a through 2.c. This fabrication phase report must be approved by NASA before starting the test phase.

3. Test Phase

a. Test Procedure

A detailed test procedure shall be prepared based on the test plan described in Section 1.h. This test procedure shall be approved by NASA prior to the start of testing.

b. Test Program

A test program, as defined in the test plan and test procedure, shall be conducted by the contractor. The intent of the test program is to demonstrate the pressure vessel will satisfy "Product Requirements".

c. Failure Notification

The NASA Technical Monitor shall be notified within forty-eight (48) hours of any failure experienced during this test program.

d. Test Report

The test program interim results shall be presented as an Addendum to the Monthly Progress Report. The test program final results shall be presented as an Addendum to the Final Report. The results shall include a summary of test activities, a discussing of test results (including any failures), tabulated test data, and original test data sheets.

e. Final Report

A final report for the design, fabrication, and test phase shall be completed.

E. PRODUCT REQUIREMENTS

1. Scope

The compressed air 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 60 SCF of air when charged to 4000 psi at 70°F.

2. 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. Requirements

The following requirements were defined by NASA prior to the design phase; some detailed requirements were subsequently revised to better reflect overall program objectives, as described under the Design and Test phases. The resulting specific requirements are summarized in Appendix F.

a. General

(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.

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

(3) Material Selection

Material properties which shall be considered, in addition to ultimate and yield strengths, are fatigue, 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.

(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.

(5) Stressed Areas

Stress concentration shall be avoided or minimized.

(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.

(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 threaded connection shall be per AND 10050-12 (subsequently modified -- see detail drawing).

(8) Dissimilar Materials

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

(9) Service Life

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

b. Design Requirements

The pressure vessel shall be designed to satisfy the following requirements:

(1) Nominal Charge Pressure

The pressure vessel shall be designed for a nominal charge pressure of 4000 psig at 70°F.

(2) Maximum Working Pressure

The pressure vessel shall be designed to a maximum working pressure of 4500 psig.

(3) Envelope

The pressure vessel shall be sized for a minumum volume of 415 cubic inches. It is desired that the external envelope not exceed 6.5 inches outside diameter and 18 inches in length (including boss).

(4) Weight

Weight of the pressure vessel shall be a minimum consistent with reasonable production cost and adequate structural safety. A weight not exceeding 14 pounds is desired.

(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.

(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 4000 psig and back to 0 psig.

(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.

c. Structural Requirements

(1) Proof Pressure

Proof pressure for the unit shall be 6750 psig minumum. The unit shall be capable of operating within the requirements of this specification following 100 proof cycles (subsequently reduced to 30 cycles). One proof cycle shall be defined as a pressurization to 6750 psig for a five-minute period, followed by a return to zero psig.

(2) Burst Pressure

The pressure vessel shall not rupture but may permanently deform when pressurized to 9000 psig. The burst pressure requirement shall exist following exposure to all other design, structural, and environment requirements (except for the induced flaw described in the next paragraph).

(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.

(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 vessel in three different orientations. The three 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.

(5) Impact Test High and Low Temperature

The pressure vessel shall be capable of operating within the requirements of this specification after having dropped ten feet to impact on a rigid steel plate. The vessel shall be pressurized to 4000 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.

(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 4000 psi and shall be repeated five times at various drop angles.

(7) Fragmentation Resistance

The cylinder shall be resistant to fragmentation when penetrated by a projectile. The cylinder shall, when pressurizing to 4000 psig (subsequently 4500 psig), be subjected to gunfire of .30 caliber armor-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.

(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.

(9) Leakage

Leakage shall not exceed 5% per year of initial charge pressure.

d. Environmental Requirements

(1) Thermal Cycling

The vessel shall be capable of operating within 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 4000 psig at 70°F and closed. The time between high temperature and low temperature exposure shall not exceed three minutes.

(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 after the conclusion of the humidity test and prior to operation and unspection, the unit temperature shall be decreased to 0°F and remain exposed to 0°F for one hour period with a maximum humidity of 100% room humidity including the condensation of water and frost.

(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°F for a period of five minutes. The vessel shall be at a temperature of 200°F and a pressure of 2000 psi at the start of the 600°F exposure. The 600°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.

(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.

(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 90°F for a 48 hour period in accordance with MIL-STD-810A, Method 509.1.

e. Quality Assurance

(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.

(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. 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

(3) Production Acceptance Test

The design effort shall define the required production acceptance tests.

f. Summary

These requirements are summarized in Table I.

II. PHASE I - DESIGN

The design developed for the improved fireman's compressed air pressure vessel consisted of a seamless aluminum alloy load-bearing liner completely overwrapped with S-glass/epoxy filament-wound composite structure. The following sections present the rational and trade study results employed in final design development.

Traditionally the design of a pressure vessel is started with the selection of a particular metal of construction, followed by a stress analysis of it, as used in the projected design. The results of the stress analysis are then used to develop a final design capable of meeting the required test conditions and of being manufactured economically.

In this instance, the achievement of the desired weight and dimensional limits, while keeping potential costs as low as possible, was required and materials were not specified. Accordingly, the specific types of combination of materials could not be selected until a wide variety of basic design combinations had been examined. The first step in this program was therefore a broad look at many possible materials and combinations of materials to see which might result in an optimum or near optimum product. This and subsequent investigations are described in the following Sections.

A. BASIC DESIGN CONSIDERATIONS, CANDIDATE MATERIALS, REQUIREMENTS ANALYSIS AND PRESSURE VESSEL DESIGN

1. Candidate Approaches

Three basic types of materials (all metal, filament-wound rubber lined, and filament-wound metal lined) together with their associated designs and possible modifications, were considered as candidates for the fireman's breathing tank with the potential for achieving the required reliability, cost, and weight goals were investigated. Results of this study resulted in the following basic selections.

a. All Metal Vessel

For all metal construction to have a chance of meeting weight, internal volume, length, and diameter requirements, high strength alloys are required. For steel, ultimate strengths on the order of 200,000 psi must be attained. Aluminum was not considered during the initial analysis because of weight projections and because its lower strengths resulted in wall thickness which did not permit achievement of diameter, length, and volume goals. Titanium was ruled out because of cost. Accordingly, the candidates were narrowed to alloy steels and some nickel base alloys such as Inconel 718.

For purposes of establishing a base line with an all-metal tank design and for comparison with the alternate composite tank approaches, 18% nickel maraging steel of 200 ksi yield strength was evaluated, based on its high strength and excellent fracture toughness characteristics. In addition, HP-9-4-30 steel was evaluated, due to its high mechanical properties, and lower costs than 18% nickel maraging. HY-140 was also investigated, due to its low cost, moderate strength, high fracture toughness, and resistance to stress corrosion cracking. Finally, 4130 was evaluated in great detail because it could act as a firm base starting point due to the extensive manufacturing know-how and cost histroy which has been developed with it. As will be presented later, large volume manufacturing costs for the maraging and 4130 steel vessels were also developed.

b. Glass Filament-Wound Rubber-Lined Vessels

Two candidates were considered for this evaluation: S-glass and E-glass construction.

c. Glass Filament-Wound Metal-Lined Vessels

Metal liners of 4130 steel, HY-140, and maraging steel were designed with both S-glass and E-glass overwrapping for comparison with the other two groups.

2. Specific Requirements for Pressure Vessel

Design requirements for the fireman's breathing system pressure vessel has been delineated under Program Requirements. These requirements were expected to be very difficult to achieve considering the need to meet them with high reliability, low cost for broad commercial acceptance, and low weight for significant system performance increase. Previously presented Table I lists a summary of the specific requirements most important in selection of materials and designs for the vessel, and which form the basis for the following requirement analysis.

3. Requirements Analysis and Pressure Vessel Designs

a. All Metal Vessel

(1) Stress in Vessel Under Required Design Loadings

(a) Burst Pressure

Based on the 9000 psig burst pressure requirement, the wall thickness of the vessel must be the following to prevent plastic instability:

$$t = \frac{P_B R}{\sigma_\mu}$$

where R = 3.35 inch

P_B = 9000 psi

σ_μ = $F_{t\mu}$ (the uniaxial tensile ultimate strength of the material)

t = Wall Thickness, inch

To be conservative, the 11 - 15% increase in failure stress, due to the 1:2 biaxial stress state (Von Mises Criterion), has been neglected and the uniaxial ultimate strength value was used.

(b) Proof Pressure

The required proof pressure of 6750 psig produces the following hoop stress for various wall thicknesses.

$$\sigma_P = \frac{P_P R}{t}$$

where t = Wall Thickness

R = 3.25 inch

P_p = 6750 psig

σ_p = F_{ty} (the uniaxial yield strength of material), psi

See Figure 5 for a plot of this equation, and the equations associated with burst pressure and operating pressure.

(c) Operating Pressure

An operating pressure of 4000 psi produces the following hoop stress for various wall thicknesses.

$$t = \frac{P_o R}{\sigma_o}$$

where P_o = 4000 psi

R = 3.25 inch

t = Thickness, inch

σ_o = Chosen by fracture mechanics analysis, psi

(2) Tank Weight

The tank weight for a given constant wall thickness is approximated by the following equation, not including boss opening and thread provisions:

$$\text{Weight} = (\text{Volume})(\text{Metal Density}) = (Lt\pi d + \pi d^2 t)\,\rho$$

L = Length of cylindrical section, inch

d = 6.5 inch

ρ = 0.29 lbs/inch^3 (Average density for steels)

See Figure 6 for a plot of this equation.

(3) $K_{\text{Threshold}}$ Designing

To avoid any sustained flaw growth with time, the pressure vessel is operated at a stress intensity factor below K_{TH}. K_{TH} as used here is the stress intensity factor below which, in the anticipated service environment, no flaw growth occurs under sustained loading. To obtain the highest operating stress possible, while avoiding sustained crack growth, the pressure vessel is proofed at a stress of 90% F_{ty} which results in the assurance that flaws larger than a certain size are not present.

If this size flaw $\left(\frac{a}{Q}\right)$ and the operating stress level (σ_o) result in a stress intensity factor less than K_{TH}, no sustained flaw growth occurs, as shown in Figure 7. To design for this condition, the following equation is used:

$$\left(\frac{K_{TH}^{R.T.}}{K_{lc}^{P.T.}}\right)\frac{F_{ty}^{P.T.}}{F.S.} = \sigma_o^{R.T.} \qquad (1)$$

where $K_{TH}^{R.T.}$ = threshold stress intensity factor at service temperature (i.e. room temperature)

$K_{lc}^{P.T.}$ = plain strain fracture toughness value at the proof temperature

F_{ty} = yield strength

F.S. = factor-of-safety at proof pressure, selected as 1.10

$\sigma_o^{R.T.}$ = maximum safe operating stress for sustained loading at service temperature (i.e. room temperature)

A plot of this equation for various values of $\frac{K_{TH}}{K_{lc}}$ appears in Figure 8.

(4) Operating Stress Wall Thickness Requirement

To obtain an operating stress of σ_o, the wall thickness is determined by the equation

$$t = \frac{P_o R}{\sigma_o}$$

(see previous Figure 5).

(5) Leak Before Burst

To meet the requirement that the pressure vessel leaks before catastrophic burst, the critical crack size, as determined by the equation following, must be larger than the wall thickness

$$\left(\frac{a}{Q}\right)_c = \frac{1}{1.21\pi}\left(\frac{K_{1c}}{M_K\sigma}\right)^2 = 0.263\left(\frac{K_{1c}}{\sigma}\right)^2 = a_c$$

This assures that a subcritical crack has penetrated the wall and the vessel has leaked before any crack reaches critical size.

(6) Cyclic Flaw Growth During Repeated Proof Tests

For a service life of 10,000 cycles with 100 proof tests (assumed at the rate of one every 100 service cycles) the fracture mechanics design must include a consideration of the cyclic crack growth which can occur during the 100 proof cycles and during the 100 service cycles. This has previously been shown graphically in Figure 7. a_2 is the actual initial crack size. When the crack size becomes a_1, there is no more proof test cyclic life in the vessel. Δa_ρ is the flaw growth potential during the 100 proof tests. Some estimation of a_2 must be made to predict 100 cycles of proof test life in the vessel. a_1 is the maximum flaw size in the vessel after the proof test. The flaw growth potential of this size crack during the 100 service cycles before the next proof test is $\Delta a_o = (a_3 - a_1)$. Cyclic stress flaw growth data must be available to determine that in 100 service cycles the flaw growth potential is not exceeded by the cyclic flaw growth.

Flaw growth rate data in the range of stress intensity factors near a_1 and σ_p and a_1 to a_3 and σ_o should be obtained for the material chosen to assure that in 100 proof test cycles and 100 service cycles the initial cracks do not grow to critical size.

(7) Analysis of Some Candidate Materials

Table 2 presents some candidate materials, their mechanical properties, and their cost. Tensile yield and ultimate properties of the materials are well known and straight forward. K_{1c} values must be chosen carefully from the correct size and geometry of test specimen. K_{TH} or K_{1scc} values must be obtained in an environment similar to the service conditions. Most of the data in the table were reported for salt water. Actually a test program to determine K_{1scc} for candidate materials in in the particular service environment and with cracks of geometry and size similar to those expected in the pressure vessel is the most reliable design approach.

<u>18 Nickel Maraging Steel (200 ksi) Analysis</u>

Wall thickness required by burst and material strength

$$t = \frac{P_B R}{F_{tu}} = \frac{(9000)(3.25)}{2.07 \times 10^5} = 0.141 \text{ inch}$$

This results in a vessel weight of about 15.5 pounds plus boss weight.

The safe operating stress determined from K_{TH} fracture mechanics considerations for the 200 ksi yield strength maraging steel is from Equation (1) and the data on Table 2.

$$\sigma_o = (.4) \frac{(200)}{1.1} = 73 \text{ ksi}$$

Figure 8 gives the same result.

Wall thickness required to operate at this stress is

$t = .180$ inch

vessel weight = 20 pounds, which is too high

Another factor limiting the design is the fact that the steel is too tough at room temperature to allow a sufficiently small maximum initial crack size to be determined. (This situation makes the safe operating stress lower than it would need to be if smaller flaws were screened by the proof test). If the vessel were proof tested at lower temperatures, F_{ty} would increase and K_{1c} would decrease and a smaller maximum initial flaw size could be determined and thus the operating stress could be made higher resulting in a lower vessel weight.

For example, using Equation (1), and the data of Table 2, for a proof test at -320°F, the maximum allowable operating stress is σ_o = 195 ksi at room temperature. For -100°F proof test, σ_o = 110 ksi at room temperature

With an operating stress of 110,000 psi = σ_o, from Figure 5

$t = 0.119$ inch and vessel weight $\cong$ 11.5 pounds from Figure 6.

This wall thickness is less than that required to meet the burst pressure requirement with this material (i.e., 0.141 inch).

To guarantee leak before burst

$$a_c = .263 \left(\frac{K_{Ic} \; R.T.}{\sigma_o} \right)^2 = .263 \left(\frac{1.25 \times 10^5}{1.10 \times 10^5} \right)^2$$

$$a_c = .342 \text{ inch} > .141 \text{ inch so leak before burst}$$

The size flaw which must be present to cause proof test fatalities is

$$a = .263 \left(\frac{1.25 \times 10^5}{2.00 \times 10^5} \right)^2 = .103 \text{ inch}$$

a sizeable flaw indeed, compared to the wall thickness. Therefore, the material is probably safe from the standpoint of cylic flaw growth, although data was not available for checking.

HP-9-4-30 (9% Nickel Steel) Analysis

Wall thickness required by burst and material strength

$$t = \frac{P_B R}{F_{ty}} = \frac{(9000)\,(3.25)}{225,000} = 0.13\text{- inch}$$

vessel weight = 14.6 pounds

The operating stress is (with room temperature proof)

$$\sigma_o = (0.5) \; \frac{210,000}{1.1} = 95,500 \text{ psi}$$

Wall thickness required to operate at this stress is

$$t = 0.136 \text{ inch}$$

vessel weight = 13 pounds

This design is closer to optimum since the wall thickness required for burst and operating pressures is very similar.

To guarantee leak before burst

$$a = 0.263 \left(\frac{K_{1c}\ R.T.}{\sigma_o} \right)^2 = \left(\frac{1.00 \times 10^5}{9.55 \times 10^5} \right)^2 = 0.289 \text{ inch}$$

0.289 > 0.136 so leak before burst

Size flaw present to cause proof test fatality

$$a = 0.263 \left(\frac{1.00 \times 10^5}{2.10 \times 10^5} \right)^2 = 0.059 \text{ inch}$$

This material is also believed to be attractive from the standpoint of cyclic flaw growth characteristics, but this should be checked using actual test data and the procedure indicated above.

HY-140 Analysis

This material has high K_{Ic} and high K_{TH} values with $K_{TH}/K_{Ic} = .50$ and yield strength of 140,000 psi. However, because of its relatively low yield strength, use of HY-140 results in an excessive homogeneous metal vessel weight, about 22 pounds, when designed to meet burst pressure requirements. Because of this material's excellent resistance to moist environments, relatively low cost, and ease of forming into seamless closed-end cylinders, it appears to be an excellent candidate for glass filament overwrapping to produce a composite pressure vessel of attractive weight. Accordingly, it will be evaluated for this type of vessel in a following section.

(8) Comments on Fracture Mechanics Analysis and Data

The following comments are pertinent from our preliminary analysis of the all metal vessels.

(a) There are probably several materials that can be used for this application which will provide required vessel weight and have sufficient fracture toughness to meet requirements. The necessary fracture mechanics data required of these materials to carry out detailed design optimization and materials selection study do not appear to be generally available. For instance, K_{Ic} and K_{TH} data could not be found that were considered valid for most of the materials initially screened. Specimen data of thickness and crack geometry simulating the pressure vessel condition and,most importantly, sustained flaw growth and cyclic flaw growth data were generally not available.

(b) The 18% nickel maraging and HP-9-4-30 steels that were evaluated were promising from the technical design viewpoint. However, they have raw material and fabrication costs which were considered too high for this application, as will be subsequently discussed. Even here, however, only very limited usable fracture mechanics data exist.

(c) A dual standard of vessel design exists. Using weight and factor-of-safety for fixing burst, proof, and operating levels leads to a need for high yield strength/ultimate strength material with high fracture toughness. If fracture mechanics was used alone for design, a thinner walled, lower factor-of-safety design might result which would achieve service life requirements.

(d) The maraging and HP-9-4-30 steel K_{TH}/K_{Ic} ratios appear rather low. The high K_{Ic} value results in a low operating stress level and consequently a heavier vessel because of lack of ability to screen flaws with the proof test at room temperature. Low temperature proofing will improve this situation. Low temperature proofing is expensive and, if required, could considerably increase the costs of maintaining the tanks.

(e) Fracture mechanics data will vary from heat to heat and for a specific mills product, which further complicates the picture.

(f) Utilization of a metal with good fracture toughness properties, such as HY-140, as the metal liner of filament overwrapped tank provides a means for obtaining a light weight vessel of lower cost and good projected service life capability.

b. Glass Filament-Wound Vessel

This vessel consists of a glass fiber filament-wound composite structure to sustain the pressure vessel load, an elastomer sealant liner, and metal end bosses at the apex of each vessel dome to meet porting and filament-winding requirements. Each of these components is discussed separately below, followed by presentation of pressure vessel designs, trade-off study results, and a discussion of ability of the vessels to meet the specific performance requirements.

(1) Filament-Wound Composite

To arrive at vessel designs, the filament-wound composite material ultimate design strengths and safe proof and operating pressure stress levels meeting the pressure vessel service life requirements has to be established. A characterization analysis was performed for both E-glass/epoxy and higher cost, higher strength, S-glass/epoxy filament-wound composite vessel structural walls. Characteristics investigated included filament fraction in the composite structure, composite density, and the following properties at 200 to -60°F: Filament strength in wound pressure vessel, tensile modulus, tensile strain, and cyclic and sustained loading effects in strength.

The minimum basic filament strength of S-glass is 415,000 psi and as E-glass is 253,500 psi in thin-walled small diameter vessels at a confidence level of 0.997. This strength is reduced by effects of vessel diameter, of geometry (length-to-diameter ratio and boss size), of wall thickness, or temperature, and of cyclic and sustained loads.

(a) Ultimate Strength

For 4000 psig operating pressure, and the vessel single cycle burst pressure anticipated necessary to sustain 10,000 operating cycles and 100 proof cycles (approximately 13,000 psig), the design allowable single pressure cycle ultimate cylinder wall hoop stress* at room temperature for the E-glass/epoxy vessel is 91,000 psi,

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*The cylinder wall thickness is composed of longitudinal winding and circumferential windings to take the imposed pressure loadings. Allowable longitudinal and hoop stresses were computed, as were longitudinal and circumferential wound filament and composite thicknesses. The cylinder wall winding thickness is the sum of the two thicknesses, and this stress is the hoop stress caused by ultimate internal pressure averaged over the two wall thickness.

and for the S-glass/epoxy vessel is 140,000 psi, with failure occurring in the hoop wound filaments at burst pressure.

The design temperature extremes of 200 °F to -60°F do not present any problems, but must be considered in the design. Figure 9 presents the effect of steady-state temperature exposure on the strength of wound vessels. As will be noted, strength retention in the hoop windings is 95% of room temperature value for the hoop windings and 87% of the room temperature value for the longitudinal windings. Applying these factors individually to the hoop and longitudinal windings results in design allowable single pressure cycle ultimate cylinder wall hoop stresses at 200°F of 83,000 psi for E-glass/epoxy and 127,000 psi for S-glass/epoxy. These ultimate wall strengths do not fix the design, as the cyclic and static fatigue conditions predominate.

At -60°F, the filament-wound composite strength increases.

(b) Most Significant Factors Affecting Safe Operating Stress Levels

Cyclic Loading: Glass filament-wound/epoxy pressure vessel composites are subject to strength degradation due to cyclic loads, especially when the load levels are high compared to the single cycle strength.

Figure 10 shows SCI data for cyclic loading effects on glass filament-wound vessels where the cycling is from zero to various percentages of single cycle strength. Figure 11 presents SCI data on the strength retention of filament-wound vessels pressure cycled at a fixed load level of 100, 1,000, 10,000, and 20,000 cycles.

Sustained Loading: Although there is an effect of sustained loading on vessel strength if the load levels are high, the proof and fatigue cycling results are believed to predominate in the design, and sustained loading conditions are not anticipated to be of major concern for vessel design.

Other Environmental Exposure Data: The following summarizes some of the data available in SCI files on the effect of environmental exposure parameters on pressure-vessel strength.

Vessels Unpressurized

- Aging at 6, 60 and 150°F for 6 months and longer
- Salt spray, fungus, humidity cycling per MIL-E-5272C
- 120-day exposure to humidity/temperature combination as severe as 95% room humidity at 160°F
- Boiling water exposure
- Submergence in ocean for one year
- Exposure to 13,300 psi external water pressure for one year

Vessels Pressurized

- Long-term storage for over one year in ambient air
- Pressure cycling for over 20,000 cycles in ambient air, and 10,000 cycles underwater
- 30-day storage under pressure and underwater
- Elevated and low temperature effects on cyclic life and burst strength

Concerning glass filament-wound reinforced epoxy plastics, there is very little corrosive attack in the marine environment. Tests have been conducted which show little loss in strength in internal pressure vessels stored in water under moderate loads. Exposure of this material for one year at 13,000 psi (equivalent to 30,000 feet depth) resulted in retention of 90% of compressive and shear strengths. Water absorption was less than 0.1%.

Figures 12 and 13 present results from environmental tests of very thin walled glass filament-wound vessels. (An accelerated aging condition compared to the much thicker wall of the fireman's breathing tank). As will be noted, reduction in single cycle vessel strength on the order up to 20% must be made in thin walled vessels to account for the environmental effects.

(c) Safe Operating Stress Level

The preceding data were applied to the 200°F single pressure cycle design allowable strengths to arrive at safe operating stress levels in the tank wall to sustain 200°F maximum temperature pressure cycling and environment conditions of thermal cycling, humidity resistance, and sand and dust resistance. The resultant 4000 psig cylinder wall hoop stress operating levels at 200°F are 21,200 psi for E-glass/epoxy and 32,000 psi for S-glass/epoxy. It should be noted that these are conservative values, selected to insure reliability and a successful program. Using these operating stress values for design at 4000 psig internal pressure will result in a single-cycle vessel burst strength of over 15,000 psig at 200°F and over 17,000 psig at room temperature.

(2) Rubber Sealant Liner

The liner in a filament-wound pressure container is critical to the complete unit since the wound composite material is not gas tight following pressurization. Accordingly, some form of sealing material or method is required to contain the enclosed gas.

Leakage in a elastomer lined filament-wound pressure container is typically due to three factors - - leakage through the port opening, leakage around the metal boss, and gas permeation through the liner itself. Leakage at the entrance boss is typically controlled by the O-ring seal and seat and, if properly machined and seated, should be very low. Leakage around the boss is prevented by obtaining a strong, uniform sealing bond between the metal and the liner. This is obtained through careful cleaning of the metal, and the application of a primer-tie coat and elastomeric-type adhesive between the metal and lining material. This combination of methods has resulted in very high realibility in container sealing. Permeability through the lining on the other hand is the result of the basic physical and chemical characteristic of the material itself and may be high or low depending (1) on the gas contained, (2) on the material, (3) on the contained pressure, (4) on the thickness of the material, (5) on the area exposed to the gas, (6) on the time involved, and (7) on the temperature of the gas and liner. Experimental test data indicate that the unit involved will lose approximately 2% of the contained gas in one year - - well below the value desired of 5% per year.

(3) Metal Bosses

Two bosses are usually required in a filament-wound structure with elastomeric lining, the first to permit access to the enclosed gas, the second to balance the winding at the opposite end and fill in the opening in the winding that would result if nothing were used. High strength steel is the material normally used so that the supporting flange around the end opening can be as thin as possible and the unit will have a low weight. Aluminum is also used occasionally for its resistance to corrosion and low weight.

(4) Vessel Design Trade-Off Study Results

Pressure vessel design trade-off studies were conducted using the design allowable operating pressure stress levels for S-glass/epoxy and E-glass/epoxy filament-wound composite and the pressure vessel design requirements of this program. The rubber liner thickness used was 0.10-inch-thick, and a steel boss was used at one vessel end and an aluminum boss at the opposite end.

Wall thicknesses on all designs were increased by 5% to compensate for the intentionally induced flaws of the test program to meet program requirements.

Results for the E-glass filament-wound vessel are shown in Figure 14 where vessel envelope dimensions of length and outside diameter are shown for various internal volumes; vessel total cylinder wall thickness (filament-wound composite plus 0.10-inches-thick liner) is also shown as a function of vessel diameter. The safe operating stress level for E-glass/epoxy results in a relatively thick vessel wall which, although rugged and durable, does not permit achievement of the desired 414-inches^3 volume and 4000 psig operating pressure within the 6.5-inches outside diameter by 18-inches-long preferred vessel envelope. Assuming that (1) the design requirements of temperature and pressure cycling cannot be relaxed to permit a higher operating stress, and/or (2) the operating pressure cannot be reduced to result in a thinner tank wall, either the vessel internal volume must be reduced to meet the envelope objectives, or the envelope must be increased.

The situation is improved with S-glass filament-wound construction, as shown in Figure 15. This higher-strength, lighter weight, and higher-cost material has a higher allowable safe operating level and consequently thinner wall. As presented in Figure 15, a 350-inch^3 vessel can be provided within the desired envelope dimensions. A 414-inch^3 vessel would require some increase in vessel diameter and/or length.

Figure 16 presents the E-glass and S-glass filament-wound vessel weights as a function of volume (in the range of interest pV/W has a constant value for either E-glass or S-glass, and is not affected by diameter and length combinations required to achieve a specific volume). As was expected, the E-glass vessel is significantly heavier than the S-glass vessel, weighing a total of about 22 pounds for 414-inch^3 volume. The S-glass vessel weighs only 14.5 pounds, close to the 14-pound objective. Weight breakdowns for both types of vessels at 400 and 500 inches^3 volume are given in Table 3 to indicate the relative weight contributions of the constituent materials.

(5) Ability of Vessels to Meet External Loads and Impacts

(a) Fragmentation Resistance

Fragmentation resistance is a key safety requirement for the fireman's breathing tank which is assured in the proposed filament-wound rubber lined tank. SCI filament-wound vessels with elastomeric linings are non-shatterable when compared to high strength metal tanks or GFR metal tanks. Extensive gunfire tests have been conducted with glass filament-wound vessels . with and without metal liners.

In one evaluation, glass filament-wound vessels with load-bearing metal liners were compared against glass filament wound vessels with the conventional linings.

A load-bearing, non-buckling liner of 6061-T6 aluminum was chosen for the GFR metal vessel. Liner half-shells of 0.210-inch-thick with integral bosses machined from 7-inch bar stock were electron-beam welded together, post-weld heat-treated, and over-wound with approximately 0.25-inch thickness of glass filament. Following cure, the tanks were pressurized to 5000 psi and shot with a tumbling 0.50 caliber armor-piercing projectile. The three tanks fabricated failed the gunfire test, in that the liner fragmented as a result of the combined gun shot and pressure loading.

A filament-wound tank with the elastomeric liner was fabricated and subjected to the same gunfire test. The vessel easily passed the gunfire test requirements of MIL-T-25363B without fragmentation.

(b) Impact Resistance and Drop Test

Tests as severe as requested in impact and drop tests have not been conducted to our knowledge on filament-wound vessels. Six-foot drop tests onto a rigid steel plate of unpressurized SCI elastomer-lined glass filament-wound vessels of similar relative thicknesses have been conducted with no indication of damage in subsequent structural tests because the tank metal bosses are wedged into the winding and are hence resistant to impact loads on their ends. It is believed that the filament-wound vessels, by virtue of their thick walls, will be highly resistant to impact and drop testing.

(6) Effects of Flaws and Damage

The relatively thick-wall glass filament-wound vessels for 4000 psig operating pressure gas storage cylinders have high impact resistance and are not vulnerable to damage from normal handling and use environments.

The environment to which the fireman's breathing tanks are to be subjected is not controlled, and instances where sharp objects are contacted, or heavy objectes impacted, are to be expected. It is therefore possible that some damage will be inflicted on the tank during its normal life span. No effect on performance is induced until blows of high enough energy to break fibers occur. The effects of damage to the end closure and the cylindrical section of pressure vessels was investigated at Aerojet/SCI during the development of the Polaris Rocket Motor Case.

It must be emphasized that this work was conducted with relatively thin-wall vessels, and that damage was intentionally induced by inpacting the vessels with sharp objects or by actually cutting of a portion of the pressure vessel wall with drills or saws.

In general, the findings were that the strength lost as a result of damage percentagewise was significantly less than the percentage of the thickness damaged. For the breathing tanks, where an expected cut might be 5% of the composite thickness, a strength loss of only

2.3% would be expected. This still leaves a relatively large safety factor for the man-rated commercial pressure vessel.

Evaluations have not been conducted of the effect of induced flaw growth during pressure cycling. However, the flaw does not propagate through the thickness as might be the case in a metal pressure vessel. Instead, a band of windings as wide and deep as the gouge "pops" loose, and the layer peels loose. Accordingly, it is expected that the tanks could sustain the 5% flaw depth without increase of the flaw depth due to service loading conditions.

(7) High Temperature Resistance

As previously noted, no detrimental effect is anticipated from five minute exposure to 600°F. A sample glass filament-wound tank section was heated to 200°F, then placed in an oven at 600°F. The filament-wound composite was 0.25-inch-thick. As a result of the low composite conductivity, inside wall temperature increased to only 350°F. There was therefore no indication of problems from this elevated temperature exposure testing. The 600°F on the 0.25-inch-thick wall outside, and 350°F on the inside, shows a significant temperature gradient. This elevated temperature condition will, of course, decrease wall strength during the temperature exposure, but there would be expected to be adequate strength retention to sustain the pressure load. In fact, the low thermal conductivity will cause reduced internal tank pressure build up due to compressed air temperature increase compared with an all metal tank.

(8) Permanent Volumetric Expansion

Test results for typical glass filament-wound vessels have shown that permanent volumetric expansion is about 2 - 4% of the temporary expansion after the first proof test.

c. Glass Filament Overwrapped Metal Vessel

This vessel consists of a load-bearing, non-buckling, metal liner which carries a substantial fraction of the pressure load and also acts as a sealant liner. Design concepts and requirements for this style of composite tank have already been presented. Two configurations of this type tank were investigated - - (I) the circumferential filament reinforced closed-end metal cylinder, and (2) the longitudinal and circumferential filament reinforced (completely overwrapped except for boss extensions) closed-end metal cylinder. Candidate component materials are reviewed below, followed by presentation of designs, and discussion of the performance features of the vessels.

(I) Filament-Wound Composite

Much of the previous discussion related to E-glass/epoxy and S-glass/epoxy filament-wound composite is pertient to the GFR metal tanks; substantiating data, properties, and procedures used to establish design values are presented there, except as specifically noted below.

(a) Ultimate Strength

Since the metal liner of the tank captures a large fraction (30 - 50%) of the pressure load, the filament-wound composite is significantly less thick for the GFR metal vessel case than it is for the glass filament-wound/rubber-lined vessel. Accordingly, the design allowable single pressure cycle filament-wound composite strength level is higher for the thinner wall composite.

For GFR metal tank design at SCI, filament-wound composite strength is expressed in terms of filament strength in initial design efforts, which is then converted to composite stresses and composite thicknesses. This is done to permit taking into account filament wrap angles, layer orientation details, and cases where only circumferential windings are used as opposed to longitudinal and circumferential winding patterns.*

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*This approach was also used in design of the glass filament-wound rubber lined vessels as discussed there.

The design allowable single pressure cycle ultimate filament stress at room temperature was determined to be 200,000 psi for E-glass and 330,000 psi for S-glass. For the 200°F condition, these values were reduced to 182,000 psi for E-glass and 300,000 psi for S-glass.

As was the case for the rubber lined glass filament-wound vessels, the above strengths do not fix the designs, as the cyclic loading is the most severe condition.

(b) Most Significant Factors Affecting Safe Operating Stress Levels

Cyclic Loading: Cyclic fatigue data developed for glass filament-wound vessels without metal liners subjected to zero-stress/strain to operating-stress/strain cycling ($R = 0.0$) is not directly applicable to GFR metal tanks. Due to the preload condition existing between the winding and metal shell, at zero tank pressure, the filaments have an initial preload in them. Upon pressure cycling between zero and operating pressure, the filaments strain cycle over a lower strain (stress) range, and this amplitude is superimposed on the residual filament stress (resulting from filament pretension) at zero pressure. This reduced strain range during cycling significantly improves filament-wound composite fatigue characteristics.

Unfortunately, only very little data exist on the subject of glass filament-wound composite vessel fatigue where the stress range is not zero-tension-zero. Cumulative fatigue damage laws have been shown not to apply to filament-wound composites. Rather than make unconservative assumptions for vessel design relative to fatigue effects, it was elected to conservatively apply the data available for glass filament-wound vessels subjected to zero-stress to operating to zero-stress fatigue cycling to the filament-wound composite reinforcing the metal shell.

(c) Safe Operating Stress Level

The preceding approach was used to establish conservative safe operating stress levels in the filament winding of the tank wall to sustain 200°F maximum temperature pressure cycling and the other stated environmental conditions. The resultant design allowable safe operating filament stress levels are 52,000 psi for E-glass and 83,000 psi for S-glass.

(2) Metal Liner

The metal liner material for use in preliminary design was selected based on the metal shell requirements as contained in the previous discussion.

(a) Fracture Mechanics Considerations

Fracture mechanics methods have not yet been established for light-weight, high-strength composite metal/filament overwrapped tankage but such a technique must be used if the weight saving advantages of this construction concept are to be successfully applied in optimum performance systems. These GFR metal tanks offer some apparently unique advantages over the all metal tank from a fracture mechanics viewpoint. First of all, the sizing operation performed on a GFR metal tank is a significantly more effective proof test than is presently applied to metal tanks. The sizing stress usually exceeds the yield strength of the metal liner, thereby effectively screening a smaller flaw than possible in a comparable metal tank. The plastic deformation that takes place during the sizing operation may blunt the flaws and improve the subcritical flaw growth characteristics of the metal liner. Secondly, the metal liners of GFR metal tanks are about one-third to one-half the thickness of comparable all metal tanks and therefore are more prone to a leakage failure mode. Tests of GFR metal tanks conducted to date have shown that, during failure, the liner material can be contained by the overwrap resulting in a non-shatterable design. Damage containment in case of a malfunction or failure is very desirable feature for fireman's breathing pressure vessels. The filament overwrap, due to its restraining effect, might also offer some advantage in reducing crack growth.

Elastic-Plastic Considerations: In aerospace vessels of minimum weight, the sizing cycle of GFR metal tanks plastically strains the liner material and therefore any defects are subjected to a plastic stress field. Presently, no analytic elastic-plastic solutions are available for flawed specimens subjected to Mode I crack deformation loadings. Some analytic solutions are available for flawed structures subjected to Mode III crack deformation. Personnel at Boeing and SCI are presently working on a joint program for NASA, NAS 3-14380, "Composite Tanks With Load Sharing Liners", which is determining effect of elastic-plastic deformation of liners on subsequent toughness, critical and subcritical crack growth of several candidate liners and two designs of overwrapped cylindrical pressure vessels. The following comments are taken from the Boeing/SCI work related to this tank program.

Effect of Overload on Subsequent Crack Growth: The sizing proof test operation conducted on a GFR metal tank may be considered an overload condition. The effects of an overload cycle on subsequent flaw growth rates have largely been ignored to date in the fracture control of aerospace pressure vessels.

Effects of Tension-Compression Loading on Cyclic Flaw Growth: An inherent design feature of the GFR metal tank is to put residual compressive stresses in the metal liner due to wrapping tension and/or by first plastically deforming the liner during the sizing operation. The stress range over which the liner must operate is from compression to tension. In GFR metal tanks with thick liners, compressive stresses can approach the compressive yield strength. Most cyclic flaw growth data to date has been generated using zero-tension cyclic loading profile. Increased cyclic flaw growth rates may exist in the liners of GFR metal tanks since they do operate in the tension-compression stress range.

Effects of Filament Overwrapping: The filament overwrapping acts as a contraint on the metal liner and will, in general, reduce any deformations that might occur locally in the area of a flaw. Through cracks in metal tanks (without any filament overwrapping) experience an increase in stress intensity due to bulging.

With through cracks in the metal liner of a GFR metal tank, one would anticipate a significant reduction in the amount of bulging that was permitted to take place and thereby reduce the stress intensity. Consequently, this would result in reduced crack growth rates if the tank was cycled.

Although no theoretical studies have been conducted to date to determine the amount of bulging present in shells having surface flaws, one would anticipate the effect to be significantly smaller than with the through crack. The remaining ligament of material between the surface flaw crack tip and the back side of tank wall would offer significant restraint to flaw opening even if plastically strained. Deformations around the surface flaw would not be as great and therefore the reduction in stress intensity by being overwrapped will be less than with a through crack.

Fracture Mechanics of GFR Metal Tanks: Since no theoretical methods have been developed to handle flaws subjected to general plastic deformation, it becomes necessary to empirically evaluate data to better understand the mechanics of failure and subcritical flaw growth for these flaws. The work required is extensive, and was beyond the scope of this program. Some work is being done now however on the Boeing/SCI program. Liner materials being studied in uniaxial specimens are 2219-T62 aluminum, Inconel X-750, and cryoformed 301 stainless steel; biaxial pressure vessel specimens to be fabricated are GFR 2219-T62 and GFR Inconel X-750 (STA) closed-end cylinders of 6-inch to 7-inch diameter by about 25-inch length.

Static fracture data being developed probably will fall into two distinct cases as shown in Figure 17. First, where failure occurs between the ultimate stress and yield stress (Case I), and second, where failure occurs between the ultimate strength and stress level at which the flaw grows through the specimen thickness (Case II). In either case, if the sizing stress cycle does not cause failure or leakage, one can say that no initial flaw greater than $(a/Q)_1$, could have been present in the material. The failure locus at cryogenic temperature is also bening developed. If failures can occur at smaller flaw sizes than screened by the room temperature sizing cycle, a cryogenic proof (within the elastic range) might be required. Cyclic life curves are being developed as schematically illustrated in Figure 18. Using such data, one could determine the permissible operating stress to guarantee the required service life based on the maximum initial size flaw that could have existed prior to the sizing cycle.

(b) Candidate Liner Materials Selection

Three criteria were used in selecting candidate metal liners for comparative evaluation of GFR metal tank designs with each other, and with alternate constructions (all metal and glass filament-wound/rubber lined):

- Strength and fracture mechanics characteristics of the linings, to give light-weight and good anticipated service life in the vessel
- Cost - both of the raw material and fabrication process

- o Past use of similar or like metals in GFR metal tanks

As was the case for all metal tanks, titanium alloys were ruled out by program requirements and excessive costs. Inconel X-750 and Inconel 718, while both attractive from past SCI use experience (NAS 3-6292) and strength, were ruled out when cost evaluations were made. Steel linings of 200,000 psi yield strength (typified by 18% nickel maraging and HP-9-4-30 steels) and of 140,000 psi yield strength (typified by HY-140 and 4130 steels) were selected for comparative analysis as representing two categories of metal linings offering promise in meeting program objectives. In the 200 ksi yield strength range, both 18% nickel maraging and HP-9-4-30 display high K_{1c} and good K_{TH} values. The raw material cost of maraging steel is higher than HP-9-4-30 steel, but somewhat easier to form.' In the 140 ksi yield strength range, 4130 is of low material and fabrication cost, compared with HY-140, and also displays lower K_{TH} values in moist water/salt water environments. Precipitation hardening stainless steels were not considered at this time due to cost projections, and cold worked stainless steels were not considered because of cost projections.

Aluminum alloy linings were not considered for the initial phases of this study. However, since they may offer weight, cost, and/or performance advantages in this application, they were reconsidered during a later phase of this design effort. The 600°F exposure condition can be expected to weaken aluminum alloys substantially, and cause loss of temper, particularly in the metal boss, thus there is some initial concern over their use.

(c) Metal Liner Design Properties

Listed in Table IV are the properties for metal liners used in preliminary design of the GFR metal tanks for comparative analysis of weight, performance, envelope, and costs.

(3) Metal Bosses

For the circumferentially glass filament reinforced metal vessel, the metal bosses will be of the same material and formed integrally with the metal shell.

For the completely wrapped vessel, the threaded boss port will be of the same material as the basic sheel, but will be attached to the shell by bonding and an elastomeric shear deformation layer, as shown in Figure 19.

(4) Vessel Design Trade-Off Studies

Pressure vessel designs were established meeting the required criteria based on two basic GFR metal concepts - - the circumferentially filament overwrapped metal cylinder and the completely overwrapped metal cyclinder - - and combinations of the materials already described. The structural analysis for the design studies was done utilizing SCI's computer program (see Section II-D) for GFR metal tanks and hand calculations based on it.

This method is adaptable to tanks with either geodesic or in-plane winding patterns along the cylinder and over the end domes and complemented by circumferential windings in the cylinder. It treats the filament shell by means of a netting analysis, which assumes (a) constant stresses along the filament path, and (b) that the resin makes a negligible structural contribution. The filament shell and the constant thickness liner are combined by equating strains in the longitudinal and hoop directions and adjusting the raii of curvature to match the combined material strengths at the design pressure; both the elastic and plastic portions of the metal-liner stress-strain relationship are considered in the analysis.

Design and analysis calculations were made by inputting specific vessel dimensions criteria and materials properties. The program established optimum head contours and defined component thicknesses and other dimensional coordinates, as well as the shell stresses and strains resulting from various combinations of design pressures and temperatures, the filament path lengths, and the weights, volumes and surface areas of the components and complete vessels. To permit engineering analysis, it also determines shell stresses and strains during vessel service cycling from a series of input pressures, composite temperatures, and metal shell temperatures.

Wall thicknesses of all designs were increased by at least 5% to compensate for the intentionally induced flaws of the program. For hoop wrapped cylinders, the thickness of the metal head section was increased substantially by about 66 to 100% over that needed to take the pressure loading conditions to improve damage tolerance due to impact and drop test requirements.

From the many designs evaluated, summary results of the most interesting filament wound configurations are presented in Table V.

(a) Hoop Wrapped Cylinders

Figure 20 shows schematically this vessel configuration. Referring to Table V, both the S-glass and E-glass/200 ksi yield strength steel vessels meet envelope, volume, and weight objectives. The steel liners are 0.066/0.065-inch-thick in the cylinder, which increases to 0.132/0.150-inch-thick in the heads to increase damage and impact tolerance. The metal thickness in the cylinder was selected from burst pressure and strength analysis. Circumferential overwrap thickness is 0.111-inch for S-glass construction and 0.175-inch for E-glass.

Figure 21 presents the vessel constituent material stress-strain diagram in the hoop direction of the cylinder. Both vessels are designed using allowable filament stresses at operating pressure, and filament winding tensions during fabrication were optimized so that metal liner yield does not occur at the 6750 psig proof pressure. At operating pressure, stresses in the overwrap are at their design level, and stresses in the metal are about 93,000 psi, less than one-half of yield strength. At the 9000 psig burst pressure, metal shell stresses in the longitudinal direction of the cylinder reach ultimate capabilities. Note that in the hoop direction, the burst strength capability is 12,200 to 12,400 psi. Thus design redundancy exists in the windings at burst pressure.

For the S-glass and E-glass/140 ksi yield strength steel vessels, the situation is different. Although the vessels meet envelope and volume requirements, they are heavier than desired. The steel liners are 0.094-inch-thick in the cylinder which was increased to 0.156-inch in the heads. Overwrap thicknesses are 0.111-inch-thick for S-glass and 0.175-inch-thick for E-glass. Again, at proof pressure, the liners do not exceed yield. At burst pressure, the failure will occur due to longitudinal stress in the metal in the cylinder section.

At operating pressure, filament stresses are at their allowable operating, and metal liner stresses are at 64,500 psi, about 46% of yield strength.

(b) Completely Wrapped Cylinders

These vessels show great promise (see Figure 19 previously for a sketch of this design). As summarized in Table V, the S-glass/200 ksi yield strength steel vessel meets envelope and volume requirements, and is of very light weight (8.9 pounds). The liner thickness of 0.050-inch in the cylinder and of 0.060-inch in the heads was selected for this case based on manufacturing cost considerations (further thickness reduction in seamless liner fabrication would have increased costs significantly). The longituditional winding is 0.028-inch along the cylinder, which increases up the heads to about 0.140 at the boss; hoop wrap thickness is 0.130-inch. This tank design does not exceed yield in the liner at proof pressure, if suitable design and fabrication technique are utilized. At operating pressure, filament stresses are at their safe allowable and metal liner stresses are 100,000 psi in the longitudinal direction and 91,000 psi in the hoop direction, about half of yield.

For the E-glass/200 ksi yield strength steel vessel, length will be about 18.8-inches. Vessel diameter and volume are in accordance with requirements, and vessel weight would be about 10.9 pounds. Stress conditions are approximately described for the S-glass reinforced vessel.

The S-glass/140 ksi yield strength steel vessel with 0.102-inch-thick liner meets design envelope, volume, and weight objectives. It also has been designed not to exceed yield at proof. At operating conditions, filament stresses are at design levels, and metal stresses are at 70,000 psi in the hoop direction (one-half of yield) and 55,200 psi in the longitudinal direction. With the overwrap provided (0.015-inch longitudinal and 0.090-inch circumferentially) burst pressure is 11,900 psi.

The S-glass/140 ksi yield strength steel vessel with 0.050/0.060-inch-thick liner is slightly longer than desired, and weighs only 12.0 pounds. It also has stress conditions as described above, and a burst pressure over 12,000 psi.

(5) Ability of Vessels to Meet External Loads and Impacts

(a) Fragmentation Resistance

SCI gunfire tests of composite vessels with load sharing metal liners have shown the GFR metal tanks to be much more vulnerable to ballistic impact than glass filament-wound vessels with elastomeric linings, as already discussed. In the GFR metal tanks substantial fragmentation can occur, with large pieces of the fragmented liner not being contained by the overwindings. Apparently, there is a threshold value of metal liner-to-overwrap thickness at which non-shatterability of the vessel can be attained, which is a function of the thickness ratio, the stress level, strength level, and toughness of the metal, and the vessel pressure level. Certainly, a GFR metal tank with a thin, ductile liner will be more ballisticlly impact resistance than a vessel with thicker, lower ductility liner. The interactions are not clear, and no meaningful predictions can be made except on a qualitative basis. However, the completely overwrapped metal liner is much more fragmentation resistant than the circumferentially wrapped vessel, and hence is to be desired to meet this performance requirement. The unreinforced ends of the hoop only wrapped cylinder can be expected to behave like an all metal tank, and the cylinder section, due to absence of transverse strengthening of the pure circumferential windings, is not as effective in containment of the metal pieces, or in resisting ballistic damage itself.

(b) Impact Resistance and Drop Test

The comments given for glass filament-wound vessels with rubber linings are applicable to the completely wrapped metal vessels, with expected high resistance to impact and drop testing. The hoop wrapped cylinders are also expected to be relatively resistant to the loading condition, due to the thickening provided to the metal heads.

(6) Effects of Flaws and Damage

In the GFR metal tanks, high tolerance to flaws and damage are provided by the designs proposed. As previously noted, the effect of surface flaws in the filament winding is only minor, as the winding peels perpendicular to the flaw rather than propagating through the wall thickness (as occurs if a flaw grows in a metal vessel). For hoop wrapped metal cylinders flawed or damaged on the metal ends, the wall thickness here is extra heavy to reduce pressure stress in the end domes and to reduce the stress intensity. The metallic materials selected have high fracture toughness and high threshold values for flaw growth, and accordingly, flaw and damage problems are not in general anticipated for this design configuration assuming proper metallic material selection.

(7) High Temperature Resistance

As already indicated for the glass/epoxy filament-wound composite, the required five-minute-600° F exposure should not degrade the composite windings sufficiently to produce problems. For a completely overwrapped metal tank configuration, the filament-wound composite will significantly insulate the metal due to the low thermal conductivity* except at the metal bosses, where heat soak-through will be greater. For the metal bosses and exposed metal heads of circumferentially reinforced metal cylinders, metal temperature rise may be significant. For candidate steel, the effect will be to reduce strength somewhat but not to levels which are considered a problem for the short exposure.

(8) Metal Liner Corrosion Prevention

When discussing a high pressure metal container capable of operating in a salt fog environment for fifteen years, corrosion protection becomes of critical importance. Such resistance and protection becomes even more important when high strength materials are used because (1) they are usually thinner than the standard vessel and therefore a standard rate of corrosion (sea water will corrode most steels at a rate of approximately 3 to 5 mils/year) will penetrate their walls faster, and (2) as their strength increases the effect of corrosion on their strength is generally magnified. Accordingly, in the steel lined and all steel tanks, an internal and external corrosion protective coating is considered essential if such designs are to be practical. Aluminum liners would not be expected to require such protection.

It is, of course, understood that the unit will not necessarily be operated continuously in such an environment. However, once salt enters the interior of such a unit, moisture condensation from temperature variations will inevitably result in the initiation of corrosion which will continue at a slow or fast pace depending on (1) the availability of moisture, (2) the amount and distribution of salt, (3) the particular metal, (4) the ambient temperature, and (5) the gaseous environment. Other factors such as the metal crystalline structure and uniformity will also effect the rate. In any case, some very efficient methods of protecting the

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*Glass filament-wound composite thermal conductivity is about 2.2 BTU-inch /^{o}F hour feet^2, compared with about 100 - 200 BTU-inch/^{o}F hour feet^2 for steel and 1300 - 1500 BTU-inch/^{o}F hour feet^2 for aluminum.

steel, especially in the interior of the bottle where corrosion can't readily be detected, must be utilized if a steel liner is to remain safe for the fifteen-year period.

An investigation of current methods and materials indicates that a baked epoxy-phenolic coating designed for the corrosion protection of steel would probably be the most efficient product. Past tests by firms specializing in this area have indicated that with a 10 mil thick coating on cleaned steel, fifteen-year corrosion protection in a salt fog atmosphere is not considered difficult. An investigation of phosphatizing the surface - - the usual method of protection - - indicates that protection is achieved for only a few days and phosphatizing under an epoxy coating while satisfactory is often no better than putting the epoxy directly on the cleaned metal. However, since all corrosion methods behave differently on different steel alloys and since the final alloy has not yet been selected, testing would have to be performed with particular coatings and surface treatments to determine suitability for this particular requirement.

The baked epoxy-phenolic coating mentioned should not be compared to the typical "epoxy" coating used on such products as SCUBA tanks. The straight epoxy units usually end up as room temperature cured units without good thickness control, or pin hole checking and accordingly corrosion protection has been poor with them. The epoxy-phenolic coating discussed here is applied in a very closely controlled manner to achieve a minimum of 10 mils in final thickness. The product is baked at from 300 to 400°F and the product then inspected for pin holes with an electric probe. When such techniques and care have been utilized, fifteen-year corrosion protection of normal steel in a humid salt environment is typically achieved.

It should be noted here that the 48-hour salt atmosphere test specified is not considered nearly stringent enough for the fifteen-year required life expectancy. While there is not an exact correlation between salt fog tests (or any atmospheric tests, for that matter) and long time aging, industry experience here has indicated that a good 500-hour exposure to the standard MIL-STD-810A, Method 509.1 test gives good correlation with fifteen-year exposures.

In the use of a steel boss in conjunction with a rubber liner, no corrosion is expected between the two surfaces. However, when using the steel boss in conjunction with the steel liner, there might be the possibility of intermetallic corrosion should there be an electrically conductive path established between the two and should the materials be of a different alloy. This would be prevented by elastomer primer coats on each metallic surface plus an elastomeric adhesive used in between the two surfaces.

Intermetallic corrosion between the shut-off valve fitting (which may be of several different metals) and the boss is another matter and no completely satisfactory solution could be determined. Cadmium plating in the thread area may be satisfactory but is expensive. Many organic coatings are available but cannot be considered permanent. Accordingly, no final solution is proposed here and more evaluations will have to be conducted during the program. However, the obvious solution would simply be to specify a steel valve material which is compatible with the vessel.

4. Comparative Analysis of Results

The preceding analysis has indicated three practical design possibilities for the proposed fireman's breathing tank (1) all filament reinforced non-metallic lined tanks, (2) all metal tanks, and (3) filament reinforced plastic-metal combinations which are further subdivided into (a) completely filament overwrapped metal-lined tanks, and (b) metal tanks in which just the cylindrical section is filament reinforced. Because of the very large number of metal and metal-fiber combinations possible, an evaluation was undertaken which reduced each of these possibilities down to just two variations which hopefully would include one of the lowest cost, high strength products available and one of the highest strength (with toughness) products available regardless of cost. It was felt that with these basic boundaries set, other materials could be easily considered and their design possibilities evaluated without the difficult and extensive calculations needed for these basic initial designs. The results of this work is presented in the following Sections.

It is important to remember that while the dimensions and weight are of major importance, other inherent or design characteristics can also significantly alter the acceptability of the final product. To further illustrate this important area, Tables VI and VII were prepared. Table VI tries to numerically compare the four basic methods of construction with each other for each of the imposed requirements (other than dimensional, weight, and cost). While various weighing factors could likewise have been assigned to each of the considered requirements, this was not done because such weight may vary according to each evaluator. In any case, the purpose of the table is to point up that there are basic differences between the designs which must also be considered in selecting one or more designs for further development.

Table VII summarizes the results of the previous table in a more general way.

B. RESULTS OF BASIC DESIGN ANALYSIS

Following the basic analysis and considerations discussed in Section A, an initial detailed computer analysis of eleven candidate designs to meet the NASA requirements for a fireman's compressed air breathing system pressure vessel was undertaken. Included in this evaluation were designs based on (1) readily available fiber and metal commercial products and materials (including complete all filament-wound reinforced non-metallic lined and homogeneous metal vessels), (2) mixes of commercial and higher cost aerospace materials, and (3) all high-strength aerospace type products. Approximate manufacturing costs in large quantities, weights and dimensions, and expected capability to meet the NASA performance requirements, were all evaluated for each of the designs in order to provide a fuller understanding of both (1) the effects of the various requirements on the final design, and (2) the requisites for, and possibility of, providing a reasonably priced and sized unit. The results of this design are shown in Table VIII and clearly indicate the effect of high strength on bottle dimensions and weight. It is obvious that the 200, 000 psi yield strength of the maraging steel permits significant weight reductions over the 140, 000 yield strengths of 4130 and HY-140 steels. The weight reductions become even more significant when the metal units are wrapped with fiberglass, especially the S-glass. The difference in dimensions between all plastic E-glass and S-glass units, as well as the significant dimensional increase with the E-glass, was of greater proportion than expected and again points out the importance of high strength materials for these units.

These figures very clearly indicate that the basic parameters of 14 pounds maximum weight and 18-inches maximum length can be easily met and exceeded if cost is not a factor. While cost is discussed in detail in a following section and ends up ruling out many interesting possible designs, the data show the superiority of both the completely overwrapped (hoop and longitudinal wrappings) and partially overwrapped steel liner to the all metal and filament-wound non-metallic lined designs - if some of the test requirements - especially fragmentation resistance - are not required.

This data also generally rules out the E-glass/non-metallic lined and all metal (4130 and HY-140) designs because of excessive weight and/or dimensions. By arbitrarily stating that all vessels costing more than approximately $75.00 each in quantities of 25,000/year, or weighing more than approximately 17 pounds, or having a length greater than 21-inches would not be satisfactory, the number of basic potential designs is reduced to three, numbers 2, 5 and 9 (Table VIII).

Of the eleven designs examined in considerable detail, no one stood out as the outstanding choice, being superior to the others. However, one configuration (Design Number 5 - the hoop and longitudinally overwrapped steel liner) must be considered the number one contender with its very low-weight and low-costs, as well as good metal surface (thermal and impact) protection. Its deficiencies include borderline fragmentation resistance and the requirement for excellent interior corrosion control. A second front runner, Design Number 2, with no corrosion or fragmentation problems has only the limitations of being slightly more expensive, slightly heavier, and somewhat longer. A third design, Number 9, has the lowest costs but is borderline in weight, requires extensive corrosion control, and has no limited fragmentation resistance. All the other designs were either very expensive, too large, or too heavy.

While Designs 5 and 6 utilize 4130 steel heat treated to a 140,000 psi yield tensile strength, no final metal selection was made at this point, and as previously mentioned, aluminum alloys were not examined yet.

A final evaluation with NASA personnel resulted in the selection of Basic Design 5 as the path to be followed for definitive material and design work.

C. MATERIAL SELECTION

1. Metal Liner

With the above design parameters now selected, work was then concentrated on the final selection of the metal to be used as the liner. Aluminum alloy was introduced into the considerations because of its potential performance, fabrication, and cost advantages.

A large number of commercially available metals had been evaluated in the previous section as potential liner materials. The criteria employed in the initial screening phase were (a) mechanical properties including fracture toughness and subcritical flaw growth characteristics, (b) raw material costs, (c) cost of fabrication into seamless tanks, and (d) past experience with the materials in similar application.

It should be pointed out here that direct quantitative comparisons could not be made between many of the materials now considered due to lack of published data for the specific mechanical, metallurgical and environmental conditions involved. This problem is particularly evident in analyzing subcritical flaw growth under cyclic loading in the probable tank environment (i.e, humid air, water, salt water). However, some qualitative comparisons were made where there was reasonable support.

The evaluation of prospective metal liner material was based on a tank liner operating under tensile stresses although it is shown elsewhere that a unique feature of filament-overwrapped tanks is that the metal liner can be made to operate in the compressive region to some extent if desired. This is particularly important in reviewing cyclic life determinations presented in a following section. In general, glass filament reinforced metal tank designs have a significantly different stress-strain condition in the metal than experienced in homogeneous metal tanks as follows: (1) at proof pressure the metal is stressed near the yield strength, (2) at zero pressure, after proofing (or sizing), the metal is in compression, and (3) at operating pressure the metal is in tension or compression depending on design details and specific criteria used such as margin between proof and operating pressures. These stress conditions apply to the fireman's breathing tank, and design trade-off studies indicate that at the 6750 psi proof pressure the metal is near or slightly beyond the nominal yield stress. At zero pressure after proof the metal is in compression, and at operating pressure the metal is at about 25 to 44% of tensile yield stress. All static and cyclic fracture mechanics calculations that follow are based on proof stress equal to the yield strength and operating stress at 44% of yield.

It was immediately apparent that numerous materials have the necessary strength and static fracture toughness (K_{1c}) in air to provide the required leak-before-burst criterion and light-weight design. The titanium alloys and ultra high-strength steels were quickly eliminated due to excessive raw material and fabrication costs, leaving the low alloy high strength steels and age-hardenable aluminum alloys as prime candidates.

The most attractive grades of the above groups are 4130, 4340, D6AC and HY-140 steels and 6061-T6, 6351-T6, and 7075-T73 aluminum alloys. Typical mechanical properties for these materials are given in Table IX.

a. Threshold Design

The properties for 4130, 4340 and D6AC are given at the 140 ksi yield strength level after consideration of the threshold stress intensity K_{TH} or K_{1scc} in salt water. The relationship between K_{1scc} and yield stress has been determined for 4340 by Peterson, et al(3)*, as indicated in Figure 22, which shows the K_{1scc} versus yield strength relationship for critical stress intensities at the typical proof, and operating stress on the liner (100 amd 44% of yield strength respectively). It is not unreasonable to expect similar relationships for 4130 and D6AC. These alloys are only slight modifications of each other, and have similar tensile properties, corrosion resistance, and similar relationships between yield strength, and fracture toughness in air.(2, 5, 6) Also Benjamin and Steigerwald (5) have shown a remarkable similarity in K_{1scc} values for a number of low-alloy steels.

To obtain maximum assurance of safe operational performance, the tanks must be designed to operate below the threshold stress intensity (K_{1scc} or K_{TH}) at all times since the tanks would fail in a matter of hours in these steels above the threshold value.(2, 5, 7)

A tabulation of critical crack sizes at K_{1c} and K_{1scc} is given in Table X for the steels and aluminum alloys. The minimum yield strength is used for the standard tempers in the aluminum alloys. Initial estimates of metal liner thicknesses inthe cylinder section based on tank weight, raw material costs, and fabrication limitations placed the steels at 0.050-inch and the aluminum at 0.100-inch-thick. (While for these studies a uniform tank thickness is assumed, increased thicknesses at the boss end and the method of manufacture necessitate greater thicknesses in both heads than in the cylindrical section).

b. Fatigue Crack Growth Rates

Figure 23 is a plot of applied stress versus crack size for the aluminum alloys which illustrates the data from Table XI. Stress levels that intersect the critical stress intensity lines (K_{1c} and K_{1scc}) at a crack depth less than the liner thickness result in abrupt failure (i.e, burst rather than leakage). Stress levels intersecting at crack depths greater than the thickness would yield a leak-before-burst condition. It is understood that cracks cannot be greater than the thickness, however, the larger values are useful in comparing the margin of safety afforded by the different candidate materials.

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*Reference numbers - see end of text.

It can be readily seen that all materials except 7075-T73 provide leak-before-burst (i.e., $a_{cr}>t$) in an air environment at the designated proof stress. A flaw 0.066-inch deep or greater would cause a 7075-T73 tank to fail catastrophically. In salt water, all but 7075 again provides a leak-before-burst condition. Thus 7075-T73 must be eliminated from further consideration if used at the usual percentages of its minimum yield strength.

Another schematic display of the data in Table X is presented in Figure 24. The critical stress intensities at the proof and operating stresses are shown to be below the threshold for 6061 and 6351, while above threshold for 7075 at the proof stress.

There are no directly applicable crack growth rate data reported in the literature for the remaining candidate materials for the cyclic frequency and environment which concerns us. However, the published data on similar materials, including studies on the effects of frequency and environment can be used for relative comparisons. Johnson and Paris(8) have reviewed the subject of fatigue in great detail and report an astonishing similarity in growth rates for steels and aluminum alloys, which is apparently insensitive to composition, microstructive and strength levels in a given class of material. The same conclusion has been made by others from experiments on a wide range of steel alloys(6 & 9) and aluminum alloys(9, 10, 11, 12, 13 & 14). Fatigue crack growth rate plots (ΔK versus da/dN) are given for steels in Figure 25 and aluminum alloys in Figure 26. From discussions by Johnson and Paris(8), Crooker and Lange(9) and Gallagher(15), the combined influence of low cycling frequency and salt water environment is assessed at about an order of magnitude higher crack growth rate for stress intensities below the threshold. This phenomenon has been described as "environmentally-enhanced fatigue". A mean line has been drawn through the plots in Figures 25 and 26 and a parallel line at ten times the growth rate. The higher growth rate is used in calculating cyclic life expectancy for candidate liner materials because of the low cycling grequency (10,000 cycles in 15 years) and environmental conditions stipulated in the tank design requirements.

Cycles to failure have been calculated by a numerical integration process for the steels and two aluminum alloys. The procedure is as follows:

(1) Assume an initial flaw size, $(a/Q)_i$ (the proof and burst tests will not define a maximum initial flaw size).

(2) Compute ΔK (which equals K_I since we are considering only zero to tension loading for material evaluation).

(3) Determine da/dN from curve.

(4) Choose an incremental number of cycles, ΔN.

(5) Compute Δa and obtain new a_i, $2c_i$, and $(a/Q)_i$.

(6) Repeat the process until a_i equals the thickness, i.e. a through crack develops.

Table XI is a compilation of the calculations for determining the cyclic lifetime of the steels and aluminum alloys. The calculations indicate the aluminum alloys can tolerate a larger initial flaw, greater than 10% of the thickness, whereas a flaw less than about 8% would be required for the steels to survive a 10,000 cycle service life. The calculated cycles to leakage should not be interpreted as absolute values for predicting actual service life. As previously mentioned, such factors as overload during periodic proof tests and operating in compression to some extent should greatly improve the tolerance to flaws and cyclic lifetimes.

c. Corrosion Resistance

The corrosion resistance of the 6XXX series aluminum alloys is significantly superior to that of the low-alloy steels in salt water environments. The steels are also more susceptible to pitting attack than the aluminums, ranging from average depths of 10-50 mil after one year for steels, to 4-5 mils for aluminum (16). Also, the pit depth levels off after one-year exposure in aluminum, whereas the pitting in steels continue at a high rate of growth.

For complete resistance to corrosion, the liner material, whether a steel or aluminum alloy, should be protected against the environment because pits about 10% of thickness in depth can lead to corrosion-fatigue cracks and premature failure. However, experience to date with aluminum tanks indicates such coatings may not be necessary.

d. Comparison of Candidate Materials

(1) 4130, 4340, and D6AC Steels

There is little to choose between these three steels. All have been widely used in critical pressure-vessel applications and there is much fabrication know-how on these alloys. 4130 is the least expensive of the three, 10% less ($0.03/pound less) than 4340 or D6AC. The 4340 and D6AC are somewhat tougher materials providing an extra margin of safety. D6AC may have a higher $K_{I\,scc}$ than 4340 at the same strength level. Benjamin and Steigerwald (7) have determined a $K_{I\,scc}$ of 36 ksi$\sqrt{\text{inch}}$ for D6AC and 225 yield strength while for 4340 the value was 27 at 207 ksi yield strength. They also found at these strength levels, the D6AC steel had a slower crack velocity by a factor of ten. Jones (17) studies D6AC and 4330V (an improved version of 4340) and found that the former had a 30% longer fatigue life using mildly notched specimens. D6AC can be tempered at higher temperatures than 4130 or 4340 to achieve a given yield strength. This is desirable from a standpoint of residual stress relief. Distortion can be a problem in steels because of the austenite to martensite transformation and high temperature heat treatments required.

In addition to a stress corrosion cracking threshold in the steels there is a hydrogen cracking susceptibility which can further reduce their usefulness in a salt water environment. Corrosion of steel in water is accompanied by the liberation of atomic hydrogen which can enter the steel and cause hydrogen embrittlement and delayed failure.

(2) HY-140 Steel

HY-140 is a superior steel for this application from all aspects except the material and fabrication costs and availability which tend to exclude the alloy. It is not a truly commercial alloy. U. S. Steel, the only supplier, has made only small quantities of heavy plate for Naval applications. They have quoted 120-day delivery and 40,000 pound minimum mill run. In the starting material thickness required (.100 inch) the raw material cost would be about three times that of the other steels, (i.e. $1.00/pound). Fabrication difficulties are anticipated because of the high toughness, requiring several more passes and consequently significantly higher production costs.

(3) 6061-T6 and 6351-T6

These aluminums are completely acceptable from a fracture mechanics viewpoint. From Table XI, 6061 appears to be the best material when comparing cyclic life with 6351 for a given starting flaw size. Such conclusions are misleading in that the cycles to failure depend only upon stress, since the same crack growth rate was assumed for all the aluminum alloys. 6061 has a slightly lower yield strength than 6351 and, hence, a lower proof, and operating stress resulting in lower stress intensity and lower fatigue crack growth rate. If the two alloys were subjected to the same stress, it is quite probably that 6351 would outperform 6061. Likewise the environmental contribution to fatigue crack growth may vary among the different alloys in a family. The 6351 grade was developed in an effort to improve the corrosion resistance of 6061 by reducing the Cu, Mg, and Zn content, with a slight increase in Si to improve strength. Nordmark (18) of Alcoa has indicated that 6351 has a slightly better corrosion, fatigue and corrosion-fatigue resistance than 6061. Alcan Ltd., has sold 6351-T6 for use in SCUBA tanks for over ten years without a single reported tank failure. Also, the aluminums have much less complicated and less expensive heat treatments than do the steels. The effect of starting flaw size versus cycles to failure for both 6351 and the various steels is summarized in Figure 27.

(4) 7075-T73

This alloy does not have the sufficient toughness at the burst and proof stresses to assure leak-before-burst. Also, it is undesirable in terms of its anticipated fabrication difficulties, as well as being 10% more expensive than 6351 or 6061.

e. Selection of Metal Liner Material and Additional Comments

In summary, the aluminums are preferred over the steels because of the greater tolerance to flaws under environmentally-enhanced cyclic load conditions.

Of the two aluminum alloys, 6351 is favored over 6061 because of its slightly better fatigue and corrosion resistance, and higher strength. The results of this study are further summarized in Tables XII, XIII and XIV which indicate the reasons: (1) Aluminum is recommended over steel, (2) a liner thickness of about 0.1-inch-thick is recommended rather than one of about 0.05-inch, and (3) 6351 is recommended as the best potential alloy to be used.

Alloy 6351 is currently being produced by Alcan Aluminum Corp., Kaiser Aluminum and Alcoa, so while in limited general use, assurances have been received that this product can be made available as needed.

Of considerable concern in selecting aluminum as the material was (1) the possibility of obtaining thread galling and wear during application and removal of the regulator and (2) corrosive failure between the metal of the regulator and the aluminum.

Concerning both of these conditions personnel at Alcan Aluminum Corp., who have been associated with the development and use of aluminum SCUBA pressure tanks in England and the United States were contacted.

Results of work in England (where 6351 alloy is called HE 30) by Luxfer Limited indicate the following:

(1) Resistance to Corrosion

"HE30 alloy is free from corrosion problems and in particular is not susceptible to stress corrosion. In certain types of apparatus for analyzing gases, samples of high purity gas must be kept under pressure for reference purposes. It is essential to avoid contamination of these reference standards, and the excellent corrosion resistance of HE 30 aluminum alloy cylinders eliminates any risk. Moreover, Luxfer HE 30 cylinders are of one-piece seamless design, with a smooth interior, free from surface irregularities that could trap possible contaminants."

(2) Wear on Threads Due to Repeated Insertion and Removal of Valve

"During the life of a cylinder it is occasionally necessary to remove the value (e.g. for annual inspection). If the thread in the cylinder neck should be damaged when this is done, the cylinder would be rendered unserviceable. To establish that the expected service life of a cylinder is not shortened on this account, a cylinder neck was machined to a 1-inch Briggs thread. A dummy valve was machined from HE 30 TF extruded bar."

In a more recent report of Underwriters Laboratories, (File Ex 2790, January 5, 1972) in a series of tests for Alcan Co_2 fire extinguishers, valves were applied and removed from the test cylinders twenty-five times and examining after each removal to determine if any thread wear occurred. (No teflon tape was used for these tests.) Their results state there were no sign of thread wear on either of the test shells.

Thus, while certainly the aluminum threads will be more susceptible to damage than steel threads, it is believed that with reasonable care little or no damage will occur. Further, while it may be possible to use a steel thread insert to increase resistance to damage, it is believed that such a thread would set up galvanic corrosion which would be more undesirable than the slight thread wear which might occur. Anodizing the aluminum might be an alternate and more desirable approach if such protection appears necessary although it will be a fairly expensive process.

Concerning galvanic corrosion between the valve and the aluminum wall the Alcan Handbook of Aluminum, Third Addition, 1970, page 241 states "from the corrosion standpoint, aluminum can be safely coupled with zinc, cadmium, and chromium. Stainless steel and titanium can be coupled to aluminum in all but marine immersion conditions," thus it appears that any metal valve, well plated with zinc, cadmium, or chromium would be safe from galvanic corrosion. If steel threads turn out to be required, then, such plating on the inserts should make them acceptable.

In a test of Alcan 6351 alloy aluminum SCUBA tanks, United States Divers, the United States distributor, "subjected the valve and tank assembly to a series of tests which included immersion of the tank and valve assembly into a 180°F, oxygen rich, 10% salt water solution with no detrimental galvanic attack." While no times were listed for this test, verbal discussions indicated that it was for "several" days.

f. Design Strength

Additional characterization analysis of the 6351 Alloy was made to establish properties for use in vessel design. The results are summarized in Table XV. Minimum metal strengths have been determined with as much precision as can be obtained without actually conducting tests on coupons taken from an actual unit. This information has been obtained from Alcoa data on 6351 and 6061 alloys and from some 500 normal tensile tests carried out in England by Luxfer on actual 6351 Alloy (English HE 30) high-pressure-aluminum tanks, as well as other data in the literature. Vessel design was obtained using minimum values from this Table.

2. Glass Filament-Wound Composite

To arrive at vessel designs, the filament overwrap composite material ultimate design strengths and safe proof and operating pressure stress levels meeting the pressure vessel service life requirements must be established. A characterization analysis was performed for both E-glass/epoxy and higher cost, higher strength, S-glass/epoxy filament-wound composite vessel structural walls.

Design glass filament stress levels are given in Table XVI for the fireman's breathing tank geometry, 4000 psi operating pressure at 200°F., and the single cycle burst strength necessary to sustain 10,000 operating pressure cycles and 100 proof cycles with a residual burst strength greater than 9000 psig. These design values were used in subsequent vessel design calculations.

3. Matrix Systems

The resin system selected to bind the fibers together and protect them from the environment is as follows:

Resin - Essentially pure diglycidyl ether of Bisphenol A*
100 Parts by weight

Curing Agent - Hexahydrophthalic anhydride
84 parts by weight

Catalyst - Benzyl Dimethylamine
0.5 parts by weight

This formulation has been in use by SCI for filament winding for ten or more years and there is very extensive test data with it. In addition to high strength (typically 12,300 psi in RT tensile strength) and high elongation (typically 5.9%), it has very low water absorption (about 0.14% in 24 hours at RT) and good heat resistance (to about 300°F), relatively high intercaminal shear stress (10,000 psi), long pot life, and good viscosity characteristics for in-process impregnation winding. This resin was extensively evaluated under an Air Force Program "Development of Improved Processes for Filament-Wound Structures," AFML-TR-65-80, March 1965, and was found to be the best all-around filament-winding resin of those tested.

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*This product is represented by such commercial products as Dow Chemical Company's DER-332 or Celanese Epi-Rez 508.

D. DETAIL DESIGN

1. Overall Design

Based on previously presented data, a metal-lined tank with hoop and longitudinal glass-epoxy overwrap was selected as the optimum approach from a cost, size, weight, and resistance to environment standpoint.

A detailed look at the overall design was then made prior to initiation of the final design of the individual components. This evaluation resulted in two suggested basic design changes when compared to the earlier designs. These two changes may be seen in Figure 28 as compared to the original design shown previously in Figure 29 and were recommended for adoption because of (1) lower cost and/or (2) increased reliability. These changes shown in Figure 28, are (1) the removal of the aft or dead boss and (2) the making of the live or forward boss integral with the liner rather than as a separate unit bonded to it. The first change was recommended because of the high cost and weight of molding a special unit which performs no basic function other than to fill in space. It was felt that the second change increased the reliability of the part by (1) eliminating the potential leak path in the bonded joint between the boss and the liner, and (2) eliminating the possibility of breaking the adhesive bond between the two during a severe valve tightening operation.

2. Basic Design Parameters

A large number of tanks were designed on the computer for the configuration shown in Figure 28 with varying liner and fiber thicknesses for different strength metals and using "S" and "E" glass fibers for overwrap. The summarized results are presented in Figures 30 and 31. It can be seen from Figure 30 that for the particular liner thicknesses chosen, bottle weights for 40,000 psi aluminum are equivalent to 140,000 psi steel and result in a bottle weight of about twelve pounds using "S" glass and about 15-1/2 pounds using "E" glass. While weights may be similar for the two metals, resultant lengths would not be as shown in Figure 31. For instance, at a 140ksi metal yield strength, steel S-glass would have a length of about 16-3/4 inches, while the aluminum S-glass unit would be about 19-1/4 inches long. Obviously, the steel is more advantageous from this standpoint. However, the likelihood of steel corroding/oxidizing no matter how well protected, along with the necessary thinness of steel required, and the subsequent potential damage from impact are believed to be two important considerations to make this length differential an overriding design criterion.

3. Boss Design

a. Analysis Results

Preliminary liner dimensions required in the boss area for failure by shear, bending, tension, and in the threads were calculated for 10,000 psi and 16,000 psi failures for four metal strength levels as indicated in Figure 32, using conservative aluminum strength values because of the forming action in the area. These calculations tend to be on the conservative side since they exclude any help from the filament winding. However, stresses are very complex in this area and hence some conservatism is desirable here. It should be pointed out that while the unit wall is designed to fail "above" 9000 psi, the exact ultimate strength of the unit will obviously vary somewhat depending on the number of cycles and test conditions to which it has been exposed. Accordingly design proceeded on the basis of selecting numbers somewhere between the two extremes of 10,000 and 16,000 psi blow-out indicated in this Table. With metal forming in this area difficult because of the thin cylindrical wall and thick boss, exact final dimensions had to be determined by trial and error during metal forming. Accordingly, it was attempted to obtain as great a boss thickness as could be obtained with reasonable costs while maintaining a cylindrical wall thickness of about 0.10 inches.

b. Boss Analysis

(1) Configuration

The metal boss is fabricated from 6351-T6 Aluminum Alloy and is integral with the metal liner as previously discussed. It incorporates a 1.0625-12UN-2B thread, has a 1.66-inch-diameter body and a .350-inch-thick flange.

(2) Material Properties

Metal alloy properties were selected to determine the effect of their change on the final thickening rather than to be the precise numbers finally used.

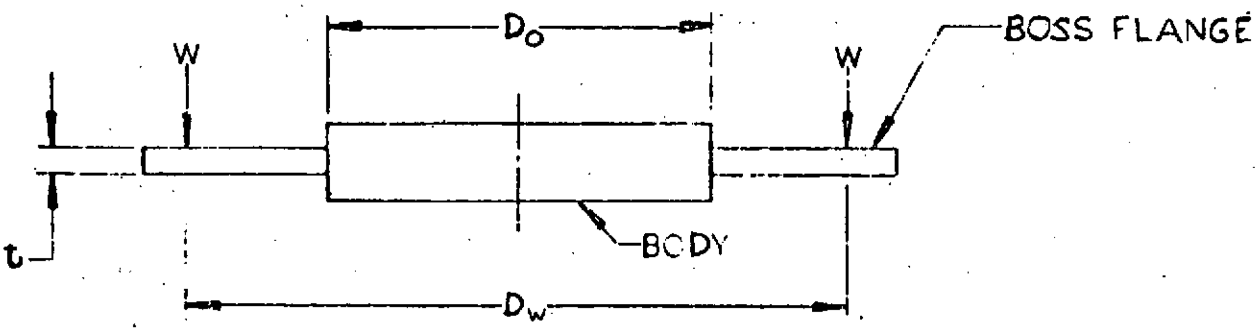
(3) Design Criteria

The metal boss is to be capable of sustaining the design single-cycle burst pressure of the Fireman's Breathing Tank, estimated to be 15,000 psig at 75°F.

(4) Analysis

(a) Bending Stress

The maximum stress in the flange is determined by using the conservative assumption that the flange is a flat plate with a concentrated annular load and a fixed inner edge (the body).



The end-for-end wrap pattern of the longitudinal filaments produces a rigid band around the boss that supports the flange. The load applied (W) is the reaction of the boss flange bearing against the composite structure. The total load is therefore equivalent to the pressure acting over the area within the reaction circle. The diameter at which the load is assumed to act (D_w) is:

$$D_W = (1+\epsilon_{f,1}) D_o + 2.0 W_L$$

where

$\epsilon_{f,1} = \frac{\sigma_{f,1}}{E_f} =$ Filament strain at ultimate stress, inch/inch

$\sigma_{f,1}$ = ultimate filament strength, psi = 250,000 psi at 75°F.

E_f = filament modulus, psi = 12.4×10^6 psi at 75°F.

W_L = filament-winding tape reaction point (0.08-inches).

The bending stress at the juncture of the flange and boss (σ_b) is calculated in accordance with formulas for loading on a flat plate (Reference 23, Case 22, Page 201):

$$\sigma_b = \frac{B_{22} W}{t^2}$$

where

$$W = \frac{\pi p_b D_w^2}{4}$$

$$\beta_{22} = \frac{D_w}{D_o} - 1$$

t = flange thickness, inch = 0.325 inches

$$\epsilon_{f,1} = \frac{\sigma_{f,1}}{E_f} = \frac{250,000}{12.4 \times 10^6} = 2.00 \times 10^{-2} \text{ inch/inch}$$

$$D_w = (1 + .02)\, 1.6 + 2.0\, (0.08) = 1.79 \text{ inch}$$

$$W = \frac{\pi(15,000)\ (1.79)^2}{4} = 37,800 \text{ pounds}$$

$$\beta_{22} = \frac{1.79}{1.60} - 1 = 0.12$$

The bending stress is

$$\sigma_b = \frac{(0.12)\ (37,800)}{(.325)^2} = 43,000 \text{ psi}$$

and, the margin of safety (M. S.) is given by

$$M.S. = \frac{F_{tu}}{\sigma_b} - 1$$

$$M.S. = \frac{47,000}{43,000} - 1 = \underline{\underline{+0.09}}$$

(b) Shear Stress

Shear Stress is given by

$$\sigma_s = \frac{P_b D_w}{4t} = \frac{(15,000)(1.79)}{(4)(0.325)}$$

$$= 20,600 \text{ psi}$$

$$M.S. = \frac{F_{t,s}}{\sigma_s} - 1 = \frac{25,000}{20,600} - 1 = 0.25$$

4. Final Unit Design

With the data supplied in the two previous sections, plus the data provided under metal liner material selection, the specific overall unit design began to take shape and it was now possible to begin the final computer runs to optimize the thickness interrelationships between the metal liner and the filament overwrap. This study included the determination of allowable strengths and operating stresses in the filament overwrap, optimization of the liner-fiber glass thicknesses, membrane analysis of the final design, and final drawings.

a. Glass Filament Composite Allowable Strengths and Operating Stresses.

(1) Introduction

To arrive at GFR aluminum fireman's breathing tank designs, the filament overwrap composite material ultimate design strengths and safe proof and operating pressure stress levels meeting pressure vessel service life requirements must be established. A characterization analysis was performed for S-glass/epoxy filament-wound composite vessel structural walls.

SCI has developed a systematic approach to the design of filament-wound vessels (References 24 to 26) and is using it in a number of applications. The method involves the use of pressure-vessel design factors, corresponding to a range of dimensional parameters to determine the allowable strength of each configuration. The factors are based on data covered in SCI tests of several thousand filament-wound vessels over a period of 16 years; these vessels had significant variations in their design parameters and ranged in diameter from 4 to 74 inches. Included as factors used for the selection of design allowable values are the strength of the glass roving, resin content, envelope dimensions (length and diameter), internal pressure level, axial port diameters, temperature, sustained loading requirements, and cylic loading requirements. The method was used in this analysis to establish realistic and conservative values for the allowable ultimate and safe operating stress levels for the 6.5-inch-diameter by 18-inch-long compressed air breathing tank.

(2) Determination of Allowable Ultimate Design Filament Strength

(a) Approach

From several prior SCI programs (e.g., References 27 and 28), designing of a S-glass filament wound vessel to sustain greater than 10,000 pressure cycles to operating pressure and show a residual burst pressure more than 2.2 times operating pressure is accomplished by designing the longitudinal filament burst strength capability to be 4.2 times operating pressure and the hoop filament burst strength capability to be 3.4 times operating pressure.

(b) Pressures

Design pressure for longitudinal filaments is 16,800 psig and for hoop filaments is 13,600 psig.

(c) Analysis

1. Longitudinal Filaments

The allowable longitudinal-filament strength is given by

$$F_{tu,f,l} = K_1 K_2 K_3 K_4 K_5 (\sec^2 \alpha) F_{tu,f}$$

The following design factors (Reference 26) are based on the specific vessel parameters

Parameter			Design Factor
Dc	=	6.5 inches	0.85 (K_1)
D_b/D_c	=	0.20	1.00 (K_2)
L/D_c	=	2.8	1.01 (K_3)
$t_{f,l}/D_c$	$\approx$	0.01895	0.75 (K_4)
T	=	$200^\circ F$	0.86 (K_5)

α = 4° (from geometry of vessel)

For S-901 glass filaments, the minimum tensile strength $F_{tu,f}$ is 415,000 psi at a confidence level of 0.997. Commerical grade S-glass has about 95% of S-901 glass strength, or a $F_{tu,f}$ of 394,000 psi. The ultimate longitudinal filament strength is

$$\begin{aligned} F_{tu,f,1} &= (0.85)(1.00)(1.01)(0.75)(.86)(1.00)\ 394,000 \\ &= 216,000 \text{ psi at } 200^{\circ}\text{F.} \end{aligned}$$

This is for a vessel with 16,800 psi single cycle burst strength, in which no metallic liner load carrying capacity is assumed, which is conservative.

2. Hoop Filaments

The allowable hoop filament is given by the relation

$$F_{tu,f,h} = K_1 K_4 K_5 \left(1 - \frac{\tan^2\alpha}{2}\right) F_{tu,f}$$

Design factors from Reference 26 are the following

Parameter	Design Factor
$D_c = 6.5$	0.92 (K_1)
$t_{f,h}/D_c = 0.0213$	0.89 (K_4)
$T = 200^{\circ}F$	0.95 (K_5)
$\alpha = 4^{\circ}$	

$$\begin{aligned} F_{tu,f,h} &= (0.92)(0.89)(0.95)(1.00)\ 394,000 \\ &= 307,000 \text{ psi at } 200^{\circ}\text{F} \end{aligned}$$

This is for a vessel with 13,600 psig single cycle burst strength without structural capability of the liner assumed in the design factor analysis, which is conservative.

(3) Safe Operating Stress Levels

The allowable ultimate design filament stresses were determined assuming a required "new vessel" burst strength of 16,800 psig longitudinally and 13,600 psi circumferentially in order to achieve pressure cycling requirements. Ratioing of the ultimate design stresses to the operating condition established the safe operating filament stress levels.

(a) Longitudinal Filaments

$$216,000 \text{ X} \frac{4,000}{16,800} = 49,000 \text{ psi}$$ safe operating filament stress level at 200°F.

(b) Hoop filaments

$$307,000 \text{ x} \frac{4000}{13,600} = 90,000 \text{ psi}$$ safe operating filament stress level at 200°F.

b. Optimization Study, Thickness and Stress Interrelationships

Configuration Definition

For the required 6750 psig proof pressure and 4000 psig operating pressure at a maximum temperature of 200°F, design optimization requires determining appropriate 6351-T6 aluminum thickness and overwrap thickness such that (1) the maximum metal shell compressive stress at zero pressure after proofing does not exceed the design allowable, (2) at 4000 psig and 200°F filament stresses do not exceed the safe operating stress levels, and (3) at 4000 psig and 200°F maximum 6351-T6 aluminum stress is less than its safe operating stress. Figure 33 presents study results as a function of liner thickness. The optimum weight design is for a 6351-T6 thickness of 0.140-inches, a longitudinal S-glass/epoxy wrap thickness of 0.113-inches, and a hoop wrap thickness of 0.190-inches. At these particular thicknesses, design allowables are reached and the metal shell operating stress is less than the 44% of yield stress desired.

Study results for vessel weight and length, for a constant outside diameter of 6.5-inches and an internal volume of 414-inches^3 showed that with a liner thinner or thicker than about 0.140-inches, vessel configurations deviate from "optimum" from the standpoint of weight based on the material variables used for design.

c. Membrane Analysis of the Final Design

Using Reference 29 and 30 analytical methods in conjunction with material properties of Tables XV and XVII for vessel membrane analysis, liner thicknesses of 0.140-inches, overwrapping with a longitudinal composite thickness (in the cylinder) of 0.113-inches and a hoop wrap thickness of 0.190-inches, results in stresses as listed in Table XVIII. (For a constant thickness liner and actual winding thicknesses). As noted from Figures 28 and 32, actual aluminum liner thickness increases from 0.140-inches at the cylinder ends and in the heads due to manufacturing, reducing stresses there significantly.

d. Final Unit Drawings

Figures 34 and 35 (prints 1269345 REVC and 1269367) show the detailed drawings for the final design of the 6351-T6 aluminum-lined and the completed NASA fireman's tank. It can be seen from these Figures that the outside diameter is 6.5 inches, overall length is 19.8 inches, and weight is approximately 13 pounds.

E. ECONOMIC ANALYSIS

1. Introduction

The selling price of any product is difficult to determine until a complete and final design has been agreed on and a production plant is set up and in production for a reasonable length of time. However, basic material and manufacturing costs are readily available and if these values can be combined with past experiences, available manufacturing techniques and speeds, reasonable estimates of total product costs and selling prices can usually be arrived at provided significant changes are not made in design. If somewhat similar products can be found which have been on the market for some time, reasonable cross checks can be obtained to determine if proper assumptions have been made. The following sections are based on this approach.

2. Rough Estimates of Eleven Potential Designs

Cost analysis of each of 11 basic systems first considered in this program were made at production rates of 10,000 and 25,000/year. It was originally requested that costs be determined at 1,000 and 5,000 units per year as well as 25,000/year. However, a detailed analysis showed that the minimum rate that a plant could operate on was between 10,000 and 15,000 units/year. Below this rate, costs rise so rapidly that the product costs quickly becomes unacceptable. If several similar units are made in the plant, then their combined production total can be at the minimum of 10,000 to 15,000/year, but there must be a production rate in this area for this or similar products to be produced on a practical and low cost basis.

With this point in mind, and with estimates made with current production methods, Table XIX was prepared. This Table, originally prepared in greater detail, was subsequently reduced in detail and the numbers rounded off because of the significant changes occuring manufacturing and materials costs taking place during the period of this contract.

Adding this data to the previously estimated data of weight and size results in the composite Table XX, which continues to show that the basic design number 5 with the metal liner (whether steel or aluminum) and with both hoop and longitudinal "S" glass overwraps is an optimum blend of small size, weight, and low cost.

3. Detailed Economic Analysis of Selected Design

A detailed economic analysis was then conducted for the materials and fabrication methods selected for the large-scale production of the fireman's breathing vessels. The results of this analysis are presented in Table XXI at production rates of 10,000 and 25,000 units per year.

4. Price Substantiation

The estimated selling price of about $49 at 2500 units/year for an aluminum-lined unit breaks down to a price per pound of approximately $3.70. Since the major raw material used in these units - the S-glass - sells for approximately $1.75/pound, and the formed liner is purchased for about $2.20/pound, the $3.70/pound price is considered extremely competitively priced, although attainable with careful attention to detail.

It is always difficult to obtain substantiation of a new item, especially when (1) it is advanced technically, (2) it utilizes new and expensive raw materials, and (3) there are no similar products currently on the market.

A pressure containing product which may be used for price comparison is fiberglass pipe used mainly in the chemical and oil industries. Six inch-diameter fiber-glass epoxy pipe in quantities of 240 feet or more sells for approximately $1.70/pound. This product, made by the A. O. Smith Company in random 30-foot-long sections and called Red-Thread fiberglass pipe, again uses low cost "E" glass fiber, and is for low pressure and temperature use.

A second price comparison product is fiberglass partially filament-wound gasoline storage tanks made by Owens-Corning Fiberglas Corporation. These units also use low cost "E" glass both as roving and in a low cost mat form and large amounds of very inexpensive polyester resin (about $0.20/pound versus about $0.60/pound for epoxy resin and curing agent). These individual units weigh between 1,200 and 3,300 pounds, so are hardly directly comparable. Their cost is about $0.64/pound.

As can be seen, neither of these comparison products are really comparable to the highly sophisticated design and construction of the NASA fireman's breathing tank with its 4,000 psi use and highly damage resistant structure. The only really similar units which might make a fair comparison would be filament-wound gas storage tanks for aircraft which use sophisticated rubber or metal liners and "S" glass fibers or are wire-wound. No meaningful prices could be obtained for such units because they are typically custom made in small quantities but prices of between $20.00/pound and $50.00/pound would not be unexpected.

Price variations within the individual comparison products are presented below:

Producing Firm: A. O. Smith
Product: Red Thread Fiberglass Pipe, Approximately 30 foot Random Lengths

Size and Characteristics:

Diameter Inches	Weight Pounds/ Feet	Use Pressure psi	Test Pressure psi	Maximum Use Temperature
2	0.4	300	1200	150°F
6	1.7	150	600	150°F

Cost:

Length, Foot	2-Inch Pipe Price/Foot	2-Inch Pipe Price/Pound	6-Inch Pipe Price/Foot/	6-Inch Pipe Price Pound
1-239	93¢	$2.33	$3.21	$1.88
240-2599	77¢	1.93	2.95	1.74
2600-7999	73¢	1.83	2.85	1.68
8000 and Over	See Manufacturer		See Manufacturer	

Producing Firm: Owens-Corning Fiberglas Corporation
Product: Glass-polyester Gasoline Storage Tanks

Size Gallon	Cost (FOB Houston)	Weight Pounds	Cost Per Pound
4,000	$ 831.	1,200	$0.693
6,000	1,028.	1,500	0.685
8,000	1,333.	2,000	0.667
10,000	1,575.	2,600	0.606
12,000	2,050.	3,300	0.621

III. PHASE II - FABRICATION

A. FABRICATION PROCESS DEVELOPMENT

1. Liner

The liner proved to be the major developmental task in this program. Once the basic design, alloy, and thicknesses was selected in Phase I, work began in trying to locate a fabricator and to define an optimum method of manufacture.

The original concept was to deep draw a closed-end cylinder from a flat plate followed by swagging in the boss end. The swagging operation was to be performed cold if possible but hot if not. Of major concern was the build-up of the metal at the boss area from the cylinder thickness of 0.14 inches to a minimum boss thickness of 0.350 inches. A firm specializing in the manufacture of high pressure containers was selected as the liner manufacturer. While their experience had been primarily in steel cylinders, they were also working with aluminum cylinders. After studying the final drawings (after participating in the proposal effort and early contract period) however, they declined to bid because of the required boss build-up and the tolerances necessary.

Alternate forms and methods of manufacture were immediately investigated. A firm who is currently making aluminum SCUBA tanks was contacted but wall thickness tolerances were again considered too tight for their impact extrusion process. Eagleware Manufacturing Company, Los Angeles, California was finally selected to use their hydro-mechanical drawing process to form the cylinder and automatic spinning equipment to form the boss.

Because of expressed concern by several firms in forming the liner, an alternate plan for liner development and manufacture was undertaken. This plan was designed to reduce the risk in dollars and time of building expensive forming dies, then finding out that they needed modification or redesign (since there was little history on such thin wall units to draw on). This plan utilized existing tooling modifying them as needed to obtain a unit as close to the print as possible and available aluminum alloy 6061, then developing the process and making subscale units for examination and study.

Work with 6061 alloy was initiated because it was readily available while 6351 alloy required that a special batch be made at the aluminum mill and would not be available for at least twelve weeks. Since 6061 alloy is so close to 6351, it was felt that all processes developed with it would be very similar to that required for 6351 alloy.

Starting with 5/16 inches thick 6061-0 plate, cups were successfully formed by Eagleware as shown in Figure 36. These units were then flow-formed to the required diameter and thicknesses by Eagleware. Atlas Manufacturing Company in South San Francisco, a user of one of the automatic spinning machines handled by Eagleware was then sent the parts to form the boss area by spinning. Results were successful and after some development in shaping, contours very close to those required were obtained. These completed parts were then used for filament winding process development and design testing.

Results of tests run on liners which were filament wound are described in the first section of this report and indicated that the design was sound and reasonable and no changes were required before lengthening the unit.

Unfortunately, with the process development now completed and the majority of unknowns now known, the bid price received for the full scale units was now beyond both the original estimate and the scope of the program. Alternate sources and manufacturing techniques were then examined and two new vendors located. The final liner manufacturing process then became as follows:

Traditional Deep Forming, 4 Draws	Metalite Manufacturing Company Glendale, California
Flow Forming	Eagleware Manufacturing Company Los Angeles, California
Swage Forming, Hot	Martin Marietta Aluminum Company Torrance, California

Prior to going to this modified process, however, some of the original short length units had their bosses swage formed by Martin-Marietta Aluminum Company, were filament-wound, and tested. While some difficulty was encountered in taking these units to burst as discussed in the test phase section, these units proved themselves to be at least equal to the spun boss units both in virgin burst strength and after cycling 10,000 use cycles at 4,000 psi and 100 proof cycles at 6,750 psi. Accordingly the full-scale liners were ordered into production.

Few problems were encountered during the manufacture of these liners and after cyclic testing of initial units to prove out the process, a total of about 80 completed liners were delivered for filament winding.

Figures 37 and 38 show two views of the liners in initial forming stages while Figure 39 shows the final product. A print of these completed final units is presented in Section C as Figure 34 (Drawing 1269345, C Revision).

Data on the strength of test coupons run alongside actual liners during their heat treat are presented in Table XXII. It can be seen from this data that the strengths are not quite as high as expected. However, these coupons were made from plate rather than formed like the bottles were and accordingly the data is not directly comparable.

2. Filament-Winding

Compared to the special attention areas encountered in liner development, there were relatively few problems encountered in the filament-winding operation. With the roving and matrix (resin) selected during the design phase, only the method of application of the resin and development of the specific winding pattern to achieve the necessary composite thicknesses was required.

a. Impregnation Technique

Because this product was to be developed as a low cost commercial item, component cost was important. Accordingly, the wet impregnation (as opposted to the preimpregnation) technique was selected for applying the resin to the roving.

b. Roving

The original roving selected was 60-end commercial "S" glass from Ferro Corporation. Unfortunately, Ferro found that they could not consistently produce the 60-end product. The order was then switched to Owens-Corning Fiberglas Corporation for their similar product and the order was switched to 20-end S-2. Little or no change was expected in product from such a switch except that since it was desirable to be able to apply as much glass as quickly as possible to the liner to keep costs down, the number of packages of roving being used increased from 3 for 60-end roving to 9 for 20-end roving. Fewer packages could have been used, but this would have necessitated a different winding pattern and the final unit would have been longer since the fewer ends of input would have produced a narrower band of glass fiber being applied, and hence more glass would have built up around the boss. For instance, the current fiber build up of the boss is approximately one-inch. Should only 4-20-ends have been used, the build up would approximately double, lengthening the bottle by almost two inches.

c. Winding Pattern Development

In order to reduce costs to an absolute minimum in production units, it was decided to dispense with a boss at the aft end (or closed end) of the unit. Normally in filament winding, a uniform pattern of glass and resin is applied over both ends of a structure and a boss or port whether used or not, is put on both ends. In this case, since only one port was required, it was felt that anything other than glass fiber put on the opposite end to protect the metal would add both weight and dollars. Accordingly, it was decided to attempt to wind this structure without a boss of any kind in this location. This decision directlv affected the winding pattern to be used and a hoop and modified longitudinal pattern (i.e., fibers placed approximately 90° to each other to resist the hoop and longitudinal forces) was, accordingly, selected instead of a true helical pattern complemented with hoop wrap. Some difficulties were encountered initially in developing a stable winding pattern for the longitudinal filaments at the closed vessel end. Minor modification of the longitudinal wrap angle permitted successful longitudinal winding of the vessels.

The port size dictated the angle that the fibers were actually placed on the bottle (pure longitudinal winding would be at 0° to the cylinder axis; in actual practice, this angle varys from about 5° to perhaps 15° or more depending on the length to width of the container, the port sizes, and the width of the winding tapes) because the fibers, in addition to going from end to end of the liner, had to stay in place after application while under high tension. With two curved heads to pull over, this can present some difficulty expecially with the wide band width here dictated by the low build up and the speed of application desired. A series of experiments resulted in the fibers being applied in the longitudinal direction in four layers with 46 turns per layer or a total of 184 turns.

Hoop fiber winding was not of such concern since they are placed essentially parallel to each other just over the cylindrical section. The only place for them to slip to therefore was at the edges of the cylindrical section where the head joins the cylinder. Because it was desired to apply the hoop fibers slightly over this tangent point between the cylinder and the heads and onto the heads to be sure that all of the cylinder was covered (placing the fibers not quite to the edge of the cylindrical section can reduce the units strength) end dams were placed at each desired hoop stopping point to prevent the fibers from slipping down on the heads. This safety precaution was used in spite of the added complexity because it was felt that in production it would be more difficult to determine exact tangent points (since the liners vary slightly) and it was desired that the hoop wraps always go at least to this tangent point.

The hoop pattern selected was five layers of approximately 97 turns per layer or a total of about 485 turns, using the same 9-20 end package of S-2 glass. The approximate numbers are required because each bottle is slightly different in length.

Photographs of both the longitudinal and hoop winding operations are shown in Figures 41, 42 and 43.

d. Gel and Cure Cycle

No development was required for these areas since they are dependent on the resin selected and the resin has been very well characterized in the past. The units were gelled on the winding machine using hot air guns to provide the heat. Gel occurred in about one hour. Final cure took place in a controlled temperature over and consisted of 16 hours at 300^{o}F.

B. SUMMARY OF FABRICATION PROCEDURES

Figure 44 presents a summary chart of the fabrication procedure used throughout production of the fireman's tank, together with the testing occurring at particular steps.

Figure 45 shows the final filament-wound fireman's tank .

Fabrication specifications are presented as Appendices A to D.

IV. PHASE III - TESTING

A. TEST REQUIREMENTS

As previously summarized in Table I, and repeated in Table XXIII, the basic requirements for the pressure container for the fireman's compressed air breathing system can be seen to be very comprehensive and, in fact, to contain several tests - such as the drop and impact tests, the flaw growth test, and the high heat resistance test - which to our knowledge have never been conducted before on fiberglass or fiberglass reinforced metal pressure containers.

In this summary - requirements table are listed 23 specific or general requirements. Each of these requirements is addressed in the following sections, together with a discussion of the particular test used and the results of those tests to determine how well the unit being evaluated met these conditions.

B. TEST DATA

Vessel test data are given in Table XXIV, and the detailed test report is presented as Appendix E. Summary information is presented below.

C. TEST METHODS AND RESULTS SUMMARY

1. Tank Capacity

a. Requirement is 60 SCF of air at 4000 psig and 70°F. To achieve this, an internal volume of the tank was specified as 414 inch^3.

b. Tank capacity was measured by weighing the tank empty and dry, filling it with tap water at approximately 70°F to the bottom of the threads in the boss, re-weighing the tank, and from the difference between the two weights determining the volume contained.

c. Volume measurements were made at three different stages of each units manufacture - 1) prior to proof or manufacturing pressurization (i.e., as manufactured), 2) after manufacturing pressurization (to 6750 psig) during which the metal liner stretches as described in Section II of this report, and 3) after acceptance testing during which the unit is again pressurized to 6750 psig. Units as manufactured showed an average volume of 405 inches^3 and varied from about 404 inches^3 to about 409 inches^3. After manufacturing sizing, volume increased to an average of 412 inches^3 and varied from about 411 inches^3 to about 413 inches^3. There was no, or essentially no, change from these values following the acceptance test. At a use pressure of 4000 psi, this volume increases approximately 5 inches^3, giving a use volume in each tank of approximately 415 inches^3 or exactly as required. This results in a contained volume of about 60 SCF at 4000 psi and 70° F.

2. Tank Envelope

a. Target requirement for the vessel outside envelope is 6.5-inch-outside-diameter by 18-inch-long including the boss.

b. Length measurements were made from the closed-end to the boss surface. Diameter measurements were made at four points on the cylindrical section with steel "pi" tapes which read directly in diameter rather than as circumference.

c. Total unit length averaged 19.2 inches with only slight variation from unit to unit. Unit diameter after acceptance testing averaged about 6.55 inches with individual readings going from about 6.50 to 6.60 inches.

3. Target Weight

a. Target weight is 14 pounds.

b. Weight measurements were made with completed units empty and dry on a kilogram balance.

c. Weights averaged 12.8 pounds with some variation between 12.6 and 13.5 pounds on earlier units. This value is approximately 10% below the target value of 14.0 pounds.

4. Service Life

a. Service life is specified to be 15 years with water vapor containing air as the working fluid.

b. There was no satisfactory way to accelerate service life aging. Accordingly, no specific tests could be run here. The effect of cyclic fatigue gives some indication of how the unit will fatigue after a specific number of cycles which might be encountered during a 15 year period, but does not give the effect of long term storage at pressure or mishandling. Reinforced plastic pressure containers have been in use for almost 20 years, and in general do not show any deteriorating effects from just aging unless they are under stress. Very little engineering design data exist for combined cyclic and static loading. However, as noted from the vessel design data, stresses at operating pressure in the filaments are less than 30% of the 200°F allowable ultimate. Experience in military aircraft applications (e.g., F-111) indicate no problem after many years of continuous static pressure loading (> 8 years) at comparable filament stress levels. NASA has initiated a long-term static pressure test program on the SCI fireman's breathing tank to obtain additional data.

c. No tests could be run to meet this condition.

5. Working Pressure

Working pressure is defined as 4000 psig nominal at 70°F and 4500 psig maximum.

Results of these tests are indicated in Table XXIV and show compliance with this requirement.

6. Operating Pressurization Cycle

a. Requirement is for the vessel to resist 10,000 cycles between working pressure of 0 and 4000 psig.

b. Cyclic fatigue was obtained by pressurizing the unit to 4000 psig, holding the unit at pressure for a few seconds, then releasing the pressure back to 0 psig, and repeating this procedure until 10,000 cycles had been applied. The test setups used are shown in Figures 46 and 47.

c. Results of this test have previously been indicated in Table XXIV and show that the unit successfully passed this test. Both subscale (full diameter, short length) and full-scale units were cycled from 0 psig to 4000 psig through 10,000 such cycles. These units were also typically cycled 100 times (except 6b and 9) to proof pressure of 6750 psig and then burst, in some instances, after other tests. The 10,000 cycle testing is approximately equivalent to two cycles per day every day of the year for fifteen years. One hundred proof cycles are approximately equivalent to one proof cycle every two months for fifteen years. (The DOT special permit for these units requires a proof test every three years or a maximum of six tests during the fifteen-year life.)

7. Working Temperature

a. The working temperature for this unit is to be from (-) 60°F to (+) 200°F.

b. An indication of whether the product will pass this condition was obtained in the following three tests:

(1) Thermal cycling where a pressurized unit is cycled from a 200°F chamber to a (-) 60°F chamber and back again through severl cycles (20 cycles used here).

(2) Actually pressure cycling the unit at the two extremes of temperature.

(3) Hot and cold drop tests.

While test (1) may be encountered in actual service, test (2) would probably not be so encountered, since it is highly unlikely that a unit would be filled to pressure while at either a (-) 60°F or at 200°F. It might be discharged at these conditions, but this is a considerably less difficult situation than the pressurization where the resin and glass are actually put under strain while at temperature rather than just have their strain relieved as occurs on use or release of pressure.

The test setup used for test (1), together with a time-temperature curve, are shown in Figures 49 and 50.

c. Results of these tests are presented as vessel 6 (Qualification Test 3 (QT-3)) and vessel 12 (QT-6A) in Table XXIV, previously shown. Vessel 6 was tested as Test (2) above and burst at 8300 psig, rather than at greater than 9000 psig, as predicted. This lower-than-expected burst is believed due to two factors. First, as mentioned above, actually being pressure cycled up and down at 200°F, 5000 times is a severe fatigue condition. As stated above, such a situation should not be encountered in actual service. Second, the (-) 60°F cooling bath was made up of a water-glycol mixture to prevent freezing. Glycol has a very low evaporation rate and it is believed that its introduction to the unit, while being pressure cycled, forced this lubricating compound throughout the structure, adding a strength-reducing factor to the unit which could not be easily removed. This second problem was resolved by using a water-alcohol mixture on subsequent testing (Vessel 27 or QT-6B) to prevent the introduction of glycol to the unit while it is being cycled. As indicated in Table XXIV, this vessel successfully passed its testing sequence, which included 20 thermal cycles -60 to 200°F.

8. Proof Pressure

a. Requirements are for a proof pressure of 100 cycles between 0 and 6750 psig. This requirement was reduced to 30 proof cycles for test units 6b and 9.

b. This test was measured with a pressure gauge and the test apparatus indicated in Figure 48.

c. Results of this test have previously been indicated in Table XXIV and show that the unit successfully passes this test. Note also the comments under 6c previously on this test.

9. Burst Pressure

a. Requirements are for a burst pressure greater than 9,000 psig.

b. This test is performed in a special test chamber as indicated in Figure 51.

c. Results of this test have previously been indicated in Table XXIV and show that the unit successfully passes this test. One low value (QT-3) has been discussed in 7.c previously. A second low value (QT-6A) will be discussed in Section 10.c.

10. Failure Mode

a. The failure mode shall be by leak failure rather than catastrophic rupture during working pressure cycling.

b. Mode of failure was determined by visual examination of the tank after burst test. If the vessel failed by leak during the test, there was typically no obvious visual failure of the unit, except that the test system was unable to keep the unit pressurized. Leakage was noticed as water or gas seeping through the outer wall of the unit. Figure 52 shows the set-up for flaw growth resistance which partly checked this feature.

c. Two test units where the leakage type failure was most noticeable were QT-5 and QT-6A. QT-5 was a test in which the metal liner was purposely defected on its outside surface (0.070 deep x .35" wide) 50% of the liner thickness prior to filament winding. This unit, after cycling, when attempting to burst it with gaseous nitrogen began to leak at 8,450 psi and could not be further pressurized due to the excessive leakage rate. There was no burst of any kind and the unit looked undamaged.

The QT-6A vessel began to leak on between its first to eighteenth proof cycle after 6,637 prior cycles at use pressure (4,000 psi). NASA-JSC performed a detailed failure analysis of this vessel, presented as Appendix G. This evaluation indicated that the failure actually occurred on the first proof cycle, although leakage was so slow as to be unnoticed during subsequent pressurization until the eighteenth cycle, when significant leakage began. There was no visually noticeable damage to the unit. However, the NASA failure analysis revealed that the liner failure initiated from a manufacturing flaw on the inside surface of the aluminum liner.

The following conclusions were made from the Appendix G failure analysis:

- The aluminum liners have shallow forming tears that act as stress concentrations for initiation of fatigue cracks.
- Manufacturing flaws are probably unavoidable and cannot be treated or detected inside the vessel where the flaw growth occurs.
- The flaw growth failure probably resulted from (1) stresses, which were higher than predicted, or (2) a cyclic flaw growth rate which was higher than predicted.
- The failure mode was leakage rather than catastrophic mode.

With the exception of (1) QT-3, which was believed to have been damaged by exposure to glycol and cycling at 200°F and subsequently burst at 8,300 psi, and (2) QT-4, which had its hoop wraps completely cut through for a distance of 4-inches, and burst at 3,100 psi, all other test units subject to burst test (QT-2, -6, -6B, -7, -8 and -10) actually burst in the hoop section as designed above the minimum burst pressure of 9,000 psi. This was approximately as predicted by fracture mechanics which indicated that leak before burst should occur up to proof pressure of 6,750 psig. Beyond this, burst before leak might occur due to using up the ultimate tensile strength capability of the materials of construction.

11. Surface Flaws

a. All testing was to be performed with surface flaws of 5%.

b. Measurement of depth of surface flaws was obtained by inserting a stiff, thin, markable material into the flaw, marking its depth of penetration, then measuring it. No device could be found which was thin and narrow enough to permit direct reading of the natural or induced flaw.

c. Flaws were purposely induced in the surface of each QT unit to a depth somewhat greater than the required 5% (0.190 depth fiberglass x 5% = 0.010 inch) because of the difficulty in measuring such a small depth of cut. Three flaws were placed in the overwrap of each unit, each flaw typically one-inch long, about 0.015 inch deep, and located one in the forward head, one in the aft head, and one in the cylindrical section, in all cases, approximately perpendicular to the applied fibers. Flaws 0.14 x 5% = 0.007-inch deep (with the exception of QT-5) were not placed in the metal liner, because each liner already had many such flaws as manufactured, all in the neighborhood of of .004 to .010 deep and some running the entire length of the liner.

In no case, with the exception of QT-4 and QT-5 where massive flaws were induced [in QT-4, the flaw was 4-inch-long and cut entirely through the hoop windings or 0.19-inch deep; in QT-5, the flaw was placed in the liner and was approximately 0.070-inch-deep (50% of the total liner thickness) and 0.35-inch-long as required by the formula $a/2C = 0.2$ (where 2c = flaw width and a = flaw depth)] did failure, when it occurred, appear to be related to the intentionally introduced flaws. Failure of 6a was an unintentional flaw.

12. Impact Resistance

a. The unit is required to resist a 10-foot drop onto its boss end, closed end, and side at a temperature of (-)60°F and of 200°F, for two cycles of each condition, or a total of 12 drops.

b. A schematic diagram of the test set up used for this requirement is given in Figure 57.

c. Vessel QT-6 was originally intended to be subjected to the impact resistance test, as well as several further tests. However, the simulated valve used for this test failed on impact during two of the required twelve drops. During the last of these failures, the escaping gas propelled the unit into a pile of steel beams and concrete blocks, resulting in severe surface damage. This unit was therefore burst tested as is without further testing and burst at 9,900 psi. Other than the surface cuts from impact on sharp surfaces, there was little indication of damage to the unit from dropping.

Vessel QT-6B was also subjected to the drop tests, as well as other tests and cycling and burst at 12,300 psig, passing the test with ease.

13. Drop Test

a. The unit is required to withstand a drop from a height of 16-feet with 200 pounds attached onto a rigid steel plate. There were five repetitions of this drop at various angles.

b. A schematic diagram of the test set up used for this test is given in Figure 54.

c. Vessel QT-2 was subjected to this test. Even though the unit broke away from the restraining tether three out of the five drops when the steel pressurization tube broke off at the simulated valve, and the vessel was significantly damaged among the steel beams and concrete blocks, its burst strength was still 9,300 psig, passing the test.

14. Fragmentation Resistance

a. With 4,000 psig internal pneumatic pressure in the test unit, when impaced by a .30 caliber AP projectile at 2,800 fps, the result was to be that the maximum opening or cut in the tank was three inches and the tank remain in one piece.

b. Testing was conducted as indicated in Figure 55. The test unit was set so the impact point was in the cylindrical section and the exit point in the end section, in an attempt to see how the two different sections behaved under such conditions.

c. Vessel QT-I was subjected to this test, but inadvertently was pressurized hydrostatically instead of pneumatically. The results indicated no tear at all, only frayed fibers at the point of impact or entry. The projectile did not exit through the head, but did break a few fibers on the exit side before comint to a stop.

Vessel QT-IA was a repeat of QT-I above except that it was pressurized penumatically as required. Results were identical to test QT-I.

15. Permanent Volumetric Expansion

a. The unit was to have a permanent volumetric expansion of 1% of the temporary expansion.

b. Temporary volumetric expansion of the pressurized vessel was measured at SCI by pressurizing the unit to proof pressure, then on release of pressure, capturing and measuring the water which is released by the unit. This procedure does not take into account the compressibility of the water and accordingly, this correcting factor must be multiplied into any SCI data. This correcting factor and the compressibility of water at 6,750 psi is about 2%.

Approved Engineering Test Laboratories (AETL), the firm performing the major portion of the testing for SCI for this program, obtained their temporary expansion values by measuring the amount of water pumped into the tank during pressurization. Their data, therefore, also contains this built in error which must be corrected for.

Permanent expansion was measured by both firms by weighing a unit full of water before and after the sizing and acceptance test.

c. This requirement is based on traditional values from the metal tank industry and is considered of little value to a fiberglass tank where considerably larger expansions are normal. Also, the ability to measure the permanent expansion within 1 cc accurately is somewhat open to question both from a balance standpoint (while measuring 12,500 gms) and from a filling to the threads standpoint. Yet a ± 1 cc or 1 gram variation = ± 0.4% of such a value.

Values recorded for the permanent expansion during acceptance testing showed a variation of from 0% to greater than 4%, or an actual permanent deformation measurement of from 0 to 11 cc's. Accordingly, the target value of 1% is considered of little significance for this type of tank which during its sizing operation at proof pressure typically has a permanent expansion of about 100 cc's and a temporary uncorrected expansion of about 250 cc's. In general, however, units have 0% permanent expansion after the first pressure sizing operation.

16. Leakage

a. Leakage shall not be more than 5% per year.

b. The leakage test was conducted as indicated in schematic diagram, Figure 56. In this arrangement, the vessel when pressurized to 4,000 psig with air, was submerged for 10 minutes in the water bath. If there was no noticeable leakage, the test was to be discontinued. If bubbles appeared, the test was to be extended to 30 minutes. Leakage was not to be greater than 10 cc's per hour.

c. Vessel QT-3 was measured in this fashion and exhibited no leakage during the 10 minute time period. Measurement was accordingly discontinued and the test was considered passed.

17. Thermal Cycling

a. The vessel is to be capable of being cycled twenty times between water at 200°F and water-glycol at (-)60°F while charged to 4,000 psig. Time between high and low temperature was not to exceed 3 minutes and time in both baths shall be 10 minutes.

b. This test was conducted in the apparatus previously shown in Figure 49, while data on the cycle used was shown in Figure 50.

c. Thermal cycling was conducted on QT Units Number 6A and 6B.

In Unit 6B, there appeared to be no degradation from temperature cycling and the unit burst as expected. Accordingly, the temperature cycling itself is considered not to significantly degrade the vessel.

18. Humidity Resistance

a. The vessel is to be capable of resisting the humidity environment imposed by MIL-STD-810A, Method 507.1 plus 0°F and 100% RH for one hour.

b. This test is an accelerated environment test and consists of exposure to a warm humid atmosphere cycling between 28 and 71°C at a humidity of between 85 and 95% for 10 days.

c. This test was waived and tank QT-7 subjected instead to a full 10,000 use pressure cycles and 100 proof pressure cycles while completely submerged in room-temperature seawater. Its burst at 9,600 psig indicated satisfactory compliance and resistance to moisture even though such a test would typically be considered much more difficult to pass than the non-pressure cycling humidity test.

19. High Temperature Resistance

a. The vessel is to withstand exposure to 600°F for five minutes while at a pressure of 2,000 psi.

b. This test requires theplacing of the test unit into a 600°F oven and monitoring temperature and pressure for the five minute period as indicated in Figure 57.

c. Tank QT-6A was subjected to this test. Temperature and pressure readings are shown graphically in Figure 58. Because vessel 6A leaked at a lower than expected number of pressure cycles after other tests were performed on it, there was some concern that the high temperature exposure may have affected the heat treat of the aluminum or properties of the overwrap. With respect to the aluminum liner, this seems unlikely in view of the very short time that the aluminum was above 300°F (about 40 seconds above 300°F). During the repeat testing of Unit QT 6B, contained volume of the tank was precisely measured before and after thermal exposure to determine if some prestress relaxation might have occurred, allowing the liner to lose its compressive load and therefore change in domensions. Volume measurement before exposure was 415.0 inch^3, while after exposure it was 415.6 inch^3. Such a small change is not considered significant, and it is believed that the test condition did not affect the test unit.

To further check this characteristic, Unit QT-8 was tested. This unit was subjected to twelve cycles of 10-minute exposures to 400°F before burst testing. Burst at 13,200 psig indicated essentially no degradation from such multiple exposures.

20. Sand and Dust Resistance

a. The vessel is to resist exposure to sand and dust as specified in MIL-STD-810A, Method 510.1 .

b. This test evaluates the vessels ability to resist the effects of dry dust (typically 140 mesh silica flour) when blown at the unit at 1,750 feet/minute for 6 hours at room temperature and 6 hours at 145°F.

c. This test was waived by NASA personnel.

21. Salt Atmosphere Resistance

a. The vessel is to resist salt atmosphere exposure as specified in MIL-STD-810A, Method 509.1 .

b. This test is of limited use without significant correlation to actual use conditions, but gives some indication of corrosion possibilities in a particular system. The exposure is for 48 hours at 95°F.

c. This test was conducted on Unit QT-6A. No corrosive attack was noticed following this exposure.

22. Product Manufacturing Production Evaluation

a. Production quantities to be considered shall be 1,000, 5,000 and 25,000 units/year.

b. A typical production line should be designed to determine probable production rates and costs.

c. The results of this exercise indicated that about 15,000 units must be produced per year to be able to have a viable plant.

Such units need not all be identical, but must all be compatible with the specific machinery and equipment selected. Below about 15,000 units per year, the selling price quickly rises above $100 per tank and, thus, is economically unsound in the present market.

23. Cost

a. Units produced for Fireman's Breathing System Application should be as inexpensive as possible.

b. Current steel tanks are sold by the manufacturer for about $25 each.

c. As previously indicated in Table XXI, it is believed in quantities of about 25,000 per year the improved Fireman's Breathing System pressure vessel can be manufactured and sold for about $49 each.

D. SPECIAL EVALUATION

Subsequent to the qualification test program conducted as described above, a special test series was conducted on vessels selected from the production run of vessels delivered to NASA-JSC under this contract. The purpose of the testing was to verify the performance of the fabrication lot (following a change in glass-fiber finish by Owens Corning, the fiberglass manufacturer) and to demonstrate ability to withstand a higher 4500 psi cyclic operating pressure level. Data are given in Table XXIV, tests 9 and 10, and summarized as follows:

1. Virgin Burst Test

Vessel S/N 74 was returned to SCI by NASA-JSC for this test. The vessel was inspected, and subjected to the hydrostatic burst test. Fracture occurred at 13,650 psi in the hoop-wound filaments at one end of the cylinder.

2. Cycle Plus Burst Test

Vessel S/N 61 was returned to SCI by NASA-JSC for this test. The vessel was inspected, and then subjected to a hydrostatic test sequence consisting of (1) 5000 operating pressure cycles 0 to 4500 psi, (2) 30 proof pressure cycles 0 to 7500 psi, (3) 5000 operating pressure cycles 0 to 4500 psi, and (4) burst testing. The vessel sustained the cycling pressure testing [(1) to (3)] without any noticeable degradation. In the burst test, pressure was increased to 9000 psi, at which time liner leakage failure occurred, demonstrating leak before burst capability.

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TABLE I

FIREMAN'S COMPRESSED AIR BREATHING SYSTEM REQUIREMENTS SUMMARY

1. Capacity: 60 SCF of air at 4000 psig and 70°F
   Internal volume of tank = 414 $in.^3$
2. Target Envelope: 6.5-in.-dia by 18-in.-long, including boss
3. Target Weight: 14 lbs.
4. Service Life: 15 years with water vapor containing air as the working fluid
5. Working Pressure: 4000 psig nominal at 70°F
   4500 psig maximum
6. Operating Pressurization Cycle: 10,000 cycles between 0 and 4000 psig
7. Working Temperature: (-)60°F to (+)200°F
8. Proof Pressure: 100 cycles between 0 and 6750 psig (subsequently reduced to 30 cycles)
9. Burst Pressure: Greater than 9000 psig
10. Failure Mode: Leak failure mode rather than catastrophic rupture for flaw growth during operating pressure cycling.
11. Surface Flaws: 5% of structural depth
12. Impact Resistance: 10 foot drop, boss end, non-boss end, and vessel side at (-)60°F and 200°F, 12 cycles
13. Drop Test: With 200 lbs attached, height of 16 ft, 5 repetitions at various angles.
14. Fragmentation Resistance: At 4500 psig, impact with .30 cal AP projectile at 2800 fps, 3-in. max opening cut in tank, tank to remain in one piece
15. Permanent Volumetric Expansion: 1% of temporary expansion
16. Leakage: 5%/year
17. Thermal Cycling: 20 Cycles (-)60°F to 200°F
18. Humidity Resistance: MIL-STD-810A, Method 507.1 plus 0°and 100% RH for 1 hr
19. High Temperature Resistance: 600°F(5 minutes with 2000 psig initial gas pressure
20. Sand and Dust Resistance:(1) MIL-STD 810A, Method 510.1
21. Salt Atmosphere Resistance:(1) MIL-STD-810A, Method 509.1
22. Production Quantities: 1000, 5000, and 25,000 units/yr
23. Cost: As low as possible.

(1) These tests were deleted (except for single salt fog test on SCI Unit 6A) in favor of additional water and high temperature exposure (see test summaries

TABLE II

SOME CANDIDATE STEELS AND TYPICAL PROPERTIES FOR FIREMAN'S BREATHING PRESSURE VESSEL

Material	Yield Strength ksi	Tensile Strength ksi	Fracture Toughness, Kic, Ksi $\sqrt{\text{in}}$	Threshold Fracture Toughness, Kth Ksi $\sqrt{\text{in}}$	Raw Material Cost Range $/Lb
5Ni-Cr-Mo-V HY 140	140-150(1),(2)	155-160	279(1), 200(2)	100(2)	0.50-0.60
12 Ni-5Cr- 3 Mo	186-194(1)(4)		133-233(1)(4)		
T-1	110(1)		177(1)		
18 Ni(200) Maraging	190-200	205-210	107(1), 125(2)	50(2)	2.75-3.20 (Vacuum remelt)
18 Ni(250) Maraging	246(1)		87(1)		2.75-3.20 (Vacuum remelt)
H-11	215-220(2)(3)	255-260(2)(3)	40-60(2)(3)		1.50-1.75
D6AC	210	225	70-90	25	1.20 (Vacuum remelt)

TABLE II (contd)

SOME CANDIDATE STEELS AND TYPICAL PROPERTIES FOR FIREMAN'S BREATHING PRESSURE VESSEL

Material	Yield Strength ksi	Tensile Strength ksi	Fracture Toughness, Kic, Ksi √in	Threshold Fracture Toughness, Kth Ksi √in	Raw Material Cost Range $/Lb
4340	215(4)	-	55(4)		1.20 (Vacuum remelt)
	220(5)	263(5)	53(5)(6)		
	190(6)		82-105(6)		
	155(6)		102(6)		
4130	158(5)		100(5)		0.25-0.30
HP-9-4	180	200	135	60-80	1.75
AM 355	200(4)	43-76(4)			

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TABLE III

TYPICAL WEIGHT BREAKDOWN GLASS-FILAMENT-WOUND VESSELS WITH NON-METALLIC LINERS

Operating Pressure = 4000 psig
Maximum Operating Temperature - 200°F

	Volume, $in.^3$	
	400	500
S-Glass/Epoxy		
Filament-Wound Composite, lbs	10.93	13.43
(Hoop Windings), lbs	(4.90)	(6.30)
(Longitudinal Windings) lbs	(6.03)	(7.13)
Liner (0.10-in.-thk), lbs	1.40	1.66
Metal Bosses, lbs	1.79	1.79
TOTAL, lbs	14.12	16.88
E-Glass/Epoxy		
Filament-Wound Composite, lbs	19.64	22.88
(Hoop Windings), lbs	(8.60)	(10.81)
(Longitudinal Windings), lbs	(11.04)	(12.07)
Liner (0.10-in.-thk), lbs	1.30	1.57
Metal Bosses, lbs	1.79	1.79
TOTAL, lbs	22.73	26.24

TABLE IV

STEEL LINER PRELIMINARY DESIGN PROPERTIES FOR GFR METAL VESSELS

Property	18% Nickel Maraging	HP-9-4	4130	HY 140
Yield Strength, psi	200,000	200,000	140,000	140,000
Ultimate Tensile Strength, psi	210,000	210,000	160,000	160,000
Elastic Modulus, psi	26×10^6	28×10^6	29×10^6	28×10^6
Plastic Modulus, psi	170,000	170,000	200,000	200,000
Poisson's Ratio				
Below Yield	0.3	0.3	0.3	0.3
Past Yield	0.5	0.5	0.5	0.5
Density, lb/in^3	0.283	0.283	0.283	0.283
Coefficient of Thermal Expansion, in/in°F	6.3×10^{-6}	6.3×10^{-6}	6.3×10^{-6}	6.3×10^{-6}

TABLE V

SUMMARY OF RESULTS

PRELIMINARY DESIGNS OF GFR STEEL FIREMAN'S BREATHING PRESSURE VESSELS

	Vessel Overall Length (in)		Cylinder Outside Diameter (in)	Liner Thickness (in)		Hoop Composite Thickness (in)	Longo Composite Thickness (in)	Vessel Internal Volume (in^3)	Vessel Weight (lbs)	(1) Failure Mode at 9000 ps Burst Pressur
				Heads	Cylinder					
Hoop Wrapped Cylindrical Vessels										
S-Glass/200 Ksi Yield Steel	17.2		6.500	0.132	0.066	0.111	-	414	10.6	M
E-Glass/200 Ksi Yield Steel	17.8		6.500	0.130	0.065	0.173	-	414	11.5	M
S-Glass/140 Ksi Yield Steel	17.5		6.500	0.156	0.094	0.111	-	414	17.2	M
E-Glass/140 Ksi Yield Steel	18.2		6.500	0.156	0.094	0.173	-	414	18.1	M
Complete Overwrapped Cylindrical Vessels										
S-Glass/200 Ksi Yield Steel	17.6		6.500	0.060	0.050	0.130	0.028	414	8.9	F
E-Glass/200 Ksi Yield Steel	18.8		6.500	0.060	0.050	0.208	0.045	414	10.9	F
S-Glass/140 Ksi Yield Steel	18.5		6.500	0.102	0.102	0.090	0.015	414	12.0	F
E-Glass/140 Ksi Yield Steel	18.5		6.500	0.060	0.050	0.180	0.045	414	12.2	F

Notes (1) Failure Modes M = Metal longitudinal direction in cylinder; F = filament overwrap

(2) Includes 1.81 lbs for bosses

(3) 200 Ksi yield strength steel typified by 18% nickel managing and HP-9-4-30; 140 Ksi yield strength steel typified by HY 140 and 4130

(4) All vessels have 4000 psi operating pressure 6750 psi proof pressure and burst pressure $\leq$ 9000 psig

TABLE VI

ESTIMATED BASIC CHARACTERISTICS OF POTENTIAL FIREMAN'S BREATHING SYSTEM PRESSURE VESSELS (1)

	Container Construction			
Requirements	Non-Metallic Lined Complete Overwrap	Metal Lining, Complete Glass Overwrap	Metal Lining, Hoop Overwrap Only	All Metal
Service Life - (15 years)	3	2	2	2
Weight - 15 lbs for volume and size	2	4	4	3
Working Temp (-60-+200°F)	4	4	4	4
Cyclic Fatigue (10,000 cycles)	4	3	3	4
Proof Cycles (100 cycles)	4	4	4	4
Burst (after all testing)	4	3	3	4
Flaw Growth (50% thick)	4	3	3	3
Impact (-60 to + 200°F)	3	2	2	3
Drop (5 cycles)	3	3	2	2
Fragmentation (ballistic)	4	2	1	1
Volumetric Expansion	4	4	4	4
Leakage	4	4	4	4
Thermal Cycling	4	4	4	4
Humidity	4	4	4	4
High Temp (600°F)	4	4	4	4
Sand and Dust	4	4	4	4
Salt	4	3	2	2
TOTAL	63	57	54	56

Notes
(1) Rating System
4 - No problem expected
3 - Probably OK but requires specific test
2 - Expected difficulty but may be correctable
1 - Not believed to be compatible with requirements

TABLE VII

CHARACTERISTICS SUMMARY

Options	Filament-Wound/ Non-Metallic Lined	All Filament-Wound/ Metal Lined	Hoop Filament-Wound/Metal Lining	All Metal
Major Advantages	Excellent fragmentation or other failure protection.	Improved fragmentation protection compared to hoop wrapped and all metal units	Low Cost	Low Cost
	Intermediate weight			
	Excellent corrosion protection	Lowest weight		
	Very safe design	Intermediate cost		
Major Disadvantages	Higher cost than other composite tanks, and increased length	Reduced ballistic protection compared to filament-wound plastic unit	No ballistic or other failure protection	No ballistic or other failure protection
			Requires careful corrosion protection	Requires careful corrosion protection
			Highest weight of composite tank	High weight

TABLE VIII

A COMPARATIVE PHYSICAL EVALUATION OF VARIOUS DESIGNS FOR THE FIREMAN'S BREATHING PRESSURE VESSEL

Number:	1	2	3	4	5	6	7	8	9	10	11
Type Liner:	Non-Metallic	Non-Metallic	Maraging	Maraging	4130	Maraging	Maraging	4130	4130	4130	Maraging
Type Filament Winding:	H & L	H & L	H & L	H & L	H & L	H	H	H	H	None	None
Type Fiber:	E	S	E	S	S	E	S	E	S	None	None
Est. Wt. Lbs	21.6	13.9	10.9	8.9	12.0	11.5	10.6	18.1	17.2	21.9	17.2
Est. Length, In.	22.7	21.3	18.8	17.6	18.5	17.8	17.2	18.2	17.5	18.2	17.2
Design O.D. In.	7.0	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Liner Thickness, Inc.											
Head	0.100	0.100	0.060	0.060	0.060	0.132	0.132	0.156	0.156	-	-
Cylinder	0.100	0.100	0.050	0.050	0.050	0.065	0.066	0.094	0.094	-	-
Winding Thickness											
Hoop, In.	0.382	0.235	0.208	0.130	0.180	0.173	0.111	0.173	0.111	-	-
Long. In.	0.312	0.192	0.045	0.028	0.045	-	-	-	-	-	-

H = Hoop Winding.

L = Longitudinal Winding.

4130 or HY-140 steels, 140,000 psi yield strength.

Maraging steel at 200,000 psi yield strength.

TABLE IX

TYPICAL MECHANICAL PROPERTIES OF CANDIDATE MATERIALS AT OPTIMUM STRENGTH LEVELS

	Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation %	K_{Ic}, ksi $\sqrt{in.}$	K_{Iscc} (Salt Water), ksi $\sqrt{in.}$
Steels					
4130	140	160	15	120(a)(1)(2)	65(b)
4340	140	155	15	150(a)(1)(2)	65(3)
D6AC	140	149	20	150(a)(1)(2)	65(b)
HY140	142	149	20	250(4)	>100(c)
Aluminum					
6061-T6	40(33min.)	45	12	26(5)	>26(e)
6351-T6	45(35min.)	48	11	26(d)(6)	>26(e)
7075-T73	63(56min)	73	10	28(7)	>28(e)

Notes: (a) K_{Ic} values based on extrapolation of data presented in Refs. (1, 2) to lower yield strengths.

(b) K_{Iscc} based on data given in Ref (3) for 4340. Similar values were assumed for 4130 and D6AC.

(c) Estimated by Boeing Airplane Co., and U. S. Steel.

(d) Estimated from Ref. (4), comparing unit propagation energy of 6351-T6 versus 6061-T6.

(e) Estimated by Alcoa, i.e. no susceptibility to stress corrosion cracking salt water.

TABLE X

CRITICAL FLAW SIZES AT PROOF AND OPERATING STRESS FOR K_{Ic} AND K_{Iscc} IN THE STEEL AND ALUMINUM ALLOYS

Steels	K_{Ic}, ksi$\sqrt{\text{in.}}$	$a_{cr} = .263\left(\frac{K_{Ic}}{\sigma}\right)^2$		K_{Iscc} ksi$\sqrt{\text{in.}}$	$a_{cr} = .263\left(\frac{K_{Iscc}}{\sigma}\right)^2$	
		a_{cr}(p)in.	a_{cr}(o)in.		a_{cr}(p)in.	a_{cr}(o) in.
4130 (σ_{ys}= 140 ksi) (proof)σ_p =140 ksi (operating)σ_o=62 ksi	120	.193	.98	65	.057	.29
4340 (σ_{ys}=140) σ_p=140 σ_o=62	150	.229	1.54	65	.057	.29
D6AC (σ_{ys}=140) σ_p=140 σ_o=62	150	.229	1.54	65	.057	.29
HY 140 (σ_{ys}=140) σ_p=140 σ_o=62	250	.84	4.2	100	.134	700
Aluminum Alloys						
6061-T6 (σ_{ys}=33) σ_p=33 σ_o=14.5	26	.163	.82	26	.163	.82
6351-T6 (σ_{ys}=35) σ_p=35 σ_o=15.4	26	.145	.74	26	.145	.74
7075-T73 (σ_{ys}=56) σ_p=56 σ_o=24.5	28	.066	.34	28	.066	.34

(p) refers to proof condition
(o) refers to operating condition

TABLE XI

COMPUTATION OF CYCLIC LIFE FOR STEELS AND ALUMINUM ALLOYS

I. Steels (4130, 4340, D6AC, HY140) (a)

(a) Assume starting flaw size a_o=.010 in., 2 C_o=.100 in., $(a/Q)_o$=.0091 in.

a/Q	Ki ksi$\sqrt{in}$	da/dN x 10^{-5} in/cycle	N	Δa, in	a_i, in	2 C_i, in	$(a/2C)_i$	$(a/Q)_i$
.0091	11.1	4.5	1000	.0045	.0145	.109	.133	.0128
.0128	13.7	9.5	1000	.009	.0235	.127	.185	.0187
.0187	16.7	14	1000	.014	.0375	.155	.241	.0268
.-268	19.8	22	570	.0125	.050	(through crack in 3570 cycles).		

(b) Assume starting flaw size a_o=.005 in., 2 C_o=.050 in. $(a/Q)_o$=.0045 in.

.0045	6.8	1.5	5000	.0075	.0125	.065	.191	.0098
.0098	12.4	7	3000	.021	.0335	.107	.314	.0199
.0199	17.1	18	920	.0165	.050	(through crack in 8920 cycles)		

(c) Assume starting flaw size a_o=.0025 in., 2 C_o=025 in., $(a/Q)_o$ =.0023 in.

.0023	6.0	1	5000	.005	.0075	.030	.250	.0052
.0052	9.3	3.5	5000	.0165	.024	.063	.380	.0126
.0126	1.37	9.5	3650	.0260	.050	(through crack in 13650 cycles)		

II. 6061-T6 Aluminum (b)

(a) Assume starting flaw size a_o=.010 min., 2 C_o=.100 in. $(a/Q)_o$ = .0091 in.

.0091	2.5	2	5000	.010	.020	.120	.166	.0166
.0166	3.4	5	5000	.025	.045	.170	.265	.0305
.0305	4.6	12	3000	.036	.081	.242	.335	.0477
.0477	5.7	19	1000	.019	.100	(through crack in 14000 cycles)		

(b) Assume starting flaw size a_o=.005", 2 C_o=.050", $(a/Q)_o$=.0047 in.

.0047	1.9	1	5000	.005	.010	.060	.167	.0083
.0083	2.4	2	5000	.010	.020	.080	.250	.014
.014	3.1	4.5	5000	.0225	.0425	.125	.34	.025
.025	4.1	9	5000	.045	.0875	.215	.41	.044
.044	5.6	21	600	.0125	.100	(through crack in 20,600 cycles)		

TABLE XI (con't)

III. 6351-T6 Aluminum (c)

(a) Assume starting flaw size a_o=.010 in., 2 C_o=.100 in., $(a/Q)_o$=.0091 in

a/Q	K_t ksi$\sqrt{in}$	$da/dN \times 10^{-5}$ in/cycle	N	Δa, in	a_i, in		$(a/2C)_i$	$(a/Q)_i$
.0091	2.9	3	5000	.015	.025	.130	.191	.0198
.0198	4.2	11	5000	.055	.080	.240	.333	.0470
.0470	6.6	32	620	.020	.100	(through crack in 10,620 cycles)		

(b) Assume starting flaw size a_o=.005 in., 2 C_o=.050 in., $(a/Q)_o$ = .0047 in.

.0047	2.2	1.5	5000	.0075	.0125	.065	.193	.0098
.0098	2.9	3.5	5000	.0165	.029	.098	.296	.0184
.0184	4.1	9.5	5000	.0475	.0765	.193	.396	.0393
.0393	5.9	23	1020	.0235	.100	(through crack in 16,020 cycles)		

(c) Assume starting flaw size a_o=.0025, 2 C_o=.025, $(a/Q)_o$=.0023 in.

.0023	1.46	0.6	10,000	.006	.0085	.037	.230	.0062
.0062	2.3	2.0	10,000	.020	.0285	.077	.372	.0150
.0150	3.7	7	5,000	.035	.062	.147	.421	.0302
.0302	5.2	17	1,000	.017	.079	.181	.434	.0372
.0372	5.8	23	910	.021	.100	(through crack in 26,910 cycles)		

NOTES:

(a) Yield Strength = 140 ksi; Operating Stress = 62 ksi
(b) Yield Strength = 33 ksi; Operating Stress = 13.6 ksi
(c) Yield Strength = 35 ksi; Operating Stress = 15.4 ksi

TABLE XII

METAL LINER SELECTION

Aluminum vs Steel

	Aluminum	Steel
ADVANTAGES	1. High resistance to general and pitting corrosion. 2. Low weight sensitivity to metal thickness variation due to metal forming. 3. Long history of success in severe SCUBA use. 4. Greater tolerance to flaws in preventing leakage. 5. Slightly lower initial cost.	1. High strength to weight ratio. 2. Decreased OD per ID. 3. Much history and capability to form into required shape. 4. High heat resistance. 5. Highly durable threads.
DISADVANTAGES	1. Low strength/density (except 7075 alloy). 2. More difficult forming technology. 3. Longer per constant OD. 4. Threads subject to some wear during use.	1. Very subject to corrosion especially pitting: requires perfect coating. 2. Unit weight very sensitive to forming thickness variation. 3. High density requires thin case wall: a) more subject to impact damage. b) less to corrode if initiated. c) less crack growth to leakage.

TABLE XIII

METAL LINER SELECTION

Aluminum Thickness

	0.05" Thick Cylinder Section	0.10" Thick Cylinder Section
ADVANTAGES	1. Slightly lower final unit weight. 2. Slightly decreased OD per ID	1. Higher resistance to penetration by: a) corrosion b) crack growth 2. Higher resistance to damage by impact. 3. Less critical in forming operation.
DISADVANTAGES	1. Very difficult to obtain required build up at boss area for threads. 2. More expensive final unit.	1. Less fiberglass protection to resist impact and heat.

TABLE XIV

METAL LINER SELECTION

1. Aluminum Alloy

	7075 T-73	6351 T-6	6061 T-6	5083 H321–H343
Typ. F_{tu}*	73,000 psi	48,000	45,000	46-52,000 (?)
Typ. F_{ty}*	63,000	45,000	40,000	33-41,000 (?)
Typ. Elong.*	13%	11%	12%	16%-10%
Min. F_{tu}*	68,000	37,000	35,000	44-50,000
Min. F_{ty}*	56,000	35,000	33,000	31-39,000
Min. Elong.	8%	8%	8%	12%-6%
ADVANTAGES	1. Very strong.	1. Readily formed. 2. Slightly higher strength than 6061 3. Slightly higher corrosion resistance than 6061. 4. 10 years history in SCUBA use. 5. Currently in production for this use.	1. Readily formed. 2. Readily available.	1. Highest resistanc to corrosion. 2. Readily formed.
DISADVANTAGES	1. More difficult to form. 2. More forming steps required. 3. Subject to "lube bursts" and surface ruptures. 4. High loss factor during mfg. 5. 10% more expensive base price. 6. Significantly lower corrosion resistance than 5 or 6000 series	1. Limited availability. 2. Limited forming knowledge available.	1. Slightly lower strength and corrosion resistance than 6351.	1. Because of non-uniform stretching during forming, expect non-uniform propertie throughout unit.
Choice	4	1	2	3

* Extruded shape values for 6061 and 6351, sheet values for 7075 and 5083

TABLE XV

ALUMINUM ALLOY 6351-T6 PHYSICAL AND MECHANICAL PROPERTIES BASED ON DATA FROM EXTRUDED SHAPES MATERIAL PROPERTIES USED FOR VESSEL DESIGN

	Value	
Property	75°F	200°F
Density, lb/in^3	0.098	
Coefficient of Thermal Expansion in/in -F°	8.915×10^{-6}	
Tensile Yield Strength, psi		
Typical	43,000	41,000
Minimum	41,000	39,000
Tensile Ultimate Strength, psi		
Typical	50,000	47,000
Minimum	47,000	44,000
Elongation, %		
Typical	15	18
Minimum	12	-
Elastic Modulus, psi	10×10^6	
Plastic Modulus, psi	1×10^5	
Shear Strength, psi		
Typical	30,000	
Minimum	25,000	
Poisson's Ratio	0.325	
Maximum Attainable Operating Compressive Stress (90% of yield)	-36,800	

TABLE XVI

FIREMAN'S BREATHING TANK PROGRAM

DESIGN GLASS FILAMENT STRESS LEVELS

Vessel Designed For 12,000 psig Single-Cycle Burst	E-Glass		S-Glass	
	75°F	200°F	75°F	200°F
Hoop filament Ultimate Strength, psi	206,000	195,000	307,000	293,000
Longitudinal Filament Ultimate Strength, psi	167,000	144,000	251,000	216,000
Vessel Designed For 4000 psig Operating Pressure, 10,000 Cycle Requirement With 9000 psig Minimum Residual Strength				
Hoop Filament Safe Operating Stress, psi		59,000		90,000
Longitudinal Filament Safe Operating Stress, psi		34,400		49,000

TABLE XVII

S-GLASS/EPOXY FILAMENT-WOUND COMPOSITE PHYSICAL AND MECHANICAL PROPERTIES MATERIAL PROPERTIES USED FOR VESSEL DESIGN

Property	Value	
	75°F	200°F
Density, lb/in^3	0.073	
Fraction of Filament in Composite	0.67	
Cooficent of Thermal Expansion in/in - °F	2.0×10^{-6}	
Elastic Modulus (Filament), psi	12.4×10^6	
Safe Operating Filament Stress Level, psi		
Longitudinal Filaments		49,000
Hoop Filaments		90,000

TABLE XVIII

DESIGN STRESS AND PRESSURES
GFR 6351-T6 FIREMAN'S BREATHING TANK

	Pressure and Stress, psi				
Constituent	Proof 6750 psig	Zero Pressure After Proof	Operating 4000 psig at 75°F	Operating 4000 psig at 200°F	Minimum Burst 9000 psig at 75°F
Aluminum Shell					
• Cylinder					
- Hoop Direction	41,967	-35,218	10,521	6,167	42,761
- Longitduinal Direction	41,669	-11,838	19,869	16,072	42,418
• Head (Point 1)					
- Hoop Direction	38,096	- 70	22,547	22,550	50,712
- Longitudinal Direction	41,184	- 7,268	21,444	21,856	46,324
• Head (Point 81)					
- Hoop Direction	40,851	- 165	17,463	11,715	43,836
- Longitudinal Direction	41,231	-18,834	16,760	10,220	42,879
Glass Filament-Wound Composite Shell					
• Cylinder					
- Hoop Filaments	112,752	38,606	82,544	87,293	164,709
- Longitudinal Filaments	57,336	22,092	42,977	50,064	100,971
• Head (Point 1)					
- Longitudinal Filaments	58,269	13,570	40,059	39,289	93,725
• Head (Point 81)					
- Longitudinal Filaments	63,027	11,680	42,108	46,163	91,537

TABLE XIX

ESTIMATED SELLING PRICE OF VARIOUS DESIGNS FOR THREE PRODUCTION RATES

Number:	1	2	3	4	5	6	7	8	9	10	11
Type Liner:	Non-Metallic	Non-Metallic	Maraging	Maraging	4130*	Maraging	Maraging	4130*	4130*	4130*	Maraging
Type Filament Winding:	H & L	H & L	H & L	H & L	H & L	H	H	H	H	None	None
Type Fiber:	E	S	E	S	S	E	S	E	S	None	None
Est. Selling Price $											
10,000/year	75.00	90.00	160.00	165.00	65.00	195.00	200.00	50.00	55.00	35.00	190.00
25,000/year	50.00	60.00	110.00	115.00	50.00	140.00	140.00	35.00	40.00	25.00	130.00
$/Lb Approx. (25,000 Unit Rate)	2.30	4.30	10.00	12.90	4.15	12.15	13.20	1.95	2.35	1.15	7.55
Order of Economic Acceptability	5	6	7	8	4	10	11	2	3	1	9

* Similar costs (within ±5%) whether 6351 aluminum or 4130 steel is used as the liner.

TABLE XX

SUMMARY OF THE EFFECT OF THREE BASIC DESIGN VARIATIONS FOR THE FIREMAN'S BREATHING TANK ON WEIGHT, LENGTH, AND ESTIMATED COSTS

No.	Type Liner	Type * Filament Winding	Type Glass Fiber	Est. Wt. lbs.	Est. Length Inches	Outside Diameter Inches	Est. Selling Price 25,000/Year
1	Non-Metallic	H & L	E	21.6	23.3	7.0	50.00
3	Maraging Steel	H & L	E	10.9	18.8	6.5	110.00
8	4130 Steel (or Aluminum)	H	E	18.1	18.2	6.5	35.00
6	Maraging Steel	H	E	11.5	17.8	6.5	140.00
2	Non-Metallic	H & L	S	13.9	18.8	6.5	60.00
5	4130 Steel (or Aluminum)	H & L	S	12.0	18.5	6.5	50.00
4	Maraging Steel	H & L	S	8.9	17.6	6.5	115.00
9	4130 Steel (or Aluminum)	H	S	17.2	17.5	6.5	40.00
7	Maraging Steel	H	S	10.6	17.2	6.5	140.00
10	4130 Steel (or Aluminum)	-	-	21.9	18.2	6.5	25.00
11	Maraging Steel (200 ksi YS)			17.2	17.2	6.5	130.00

* H = Hoop
L = Longitudinal

TABLE XXI

ECONOMIC ANALYSIS

GFR FIREMAN'S BREATHING TANK

		Estimated Costs, Dollars	
	Item	10,000 Units/Yr.	25,000 Units/Yr.
1.	Liner, Subcontract, 6351T-6, Complete	14.00	12.50
2.	Glass Fiber, "S" Glass	11.20	11.20
3.	Resin-Curative	1.90	1.90
4.	Exterior Coating	.20	.20
5.	Miscellaneous	.20	.20
6.	Total Material	27.50	26.00
7.	Labor, Manufacturing	3.00	2.50
8.	QC, Materials and Product	.75	.70
9.	Factory Overhead	20.00	8.00
10.	G&A and Selling Expense	4.50	4.00
11.	Total Costs	55.75	41.20
12.	Profit, 10% After Taxes	11.15	8.04
13.	Probable Selling Price	66.90	49.24

MARTIN MARIETTA
ALUMINUM

CERTIFIED REPORT OF CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES

WROUGHT ALUMINUM PRODUCTS

TABLE XXII

CUSTOMER **Structural Composite Industries** DATE **8 March 73**

ORDER NO. ______ ALLOY & TEMPER **6351-T6**

SPECIFICATIONS ______ PART NO. ______

MECHANICAL PROPERTIES

PRODUCTION LOT NO.	TENSILE STRENGTH PSI		YIELD STRENGTH PSI		ELONG. %-IN 2" OR 4 D		MINIMUM BRINELL HARD NO. FOR FORGINGS	CONDUCTIVITY % I.A.C.S.
65-809013								
		Average		Average		Average		
3	**44,000**		**39,300**		**10.0**			
3	**43,500**	43,867	**39,100**	39,767	**12.0**	11.33		
3	**44,100**		**40,900**		**12.0**			
4	**42,700**		**39,800**		**11.0**			
4	**43,800**	43,533	**39,800**	39,200	**13.0**	11.67		
4	**44,100**		**38,000**		**11.0**			
5	**45,400**		**42,100**		**13.0**			
5	**45,600**	45,467	**40,700**	41,633	**12.0**	12.33		
[illegible]	**45,400**		**42,100**		**12.0**			

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SEE REVERSE SIDE FOR CHEMICAL COMPOSITION OF ALLOY LISTED

NUMBER OF PIECES COVERED BY THE ABOVE LOT ______

THIS IS TO CERTIFY THAT THE MATERIAL APPLIED TO THE ABOVE ORDER AND COVERED BY THIS REPORT HAS BEEN INSPECTED IN ACCORDANCE WITH APPLICABLE SPECIFICATIONS DESCRIBED FORMING A PART OF THIS ORDER, AND THAT REPRESENTATIVE MATERIAL HAS BEEN TESTED AND WAS FOUND TO MEET THE REQUIREMENTS. SHOWN ARE THE RESULTS FOR ALLOY COMPOSITION LIMITS AND MECHANICAL PROPERTIES.

MARTIN MARIETTA ALUMINUM INC.

Metallurgical Department

HA-1628 REV. 8/72

TABLE XXIII

FIREMAN'S COMPRESSED AIR BREATHING SYSTEM REQUIREMENTS SUMMARY

1. Capacity: 60 SCF of air at 4000 psig and 70°F
   Internal volume of tank = 414 in.^{3}
2. Target Envelope: 6.5-in.-dia by 18-in.-long, including boss
3. Target Weight: 14 lbs.
4. Service Life: 15 years with water vapor containing air as the working fluid
5. Working Pressure: 4000 psig nominal at 70°F
   4500 psig maximum
6. Operating Pressurization Cycle: 10,000 cycles between 0 and 4000 psig
7. Working Temperature: (-)60°F to (+)200°F
8. Proof Pressure: 100 cycles between 0 and 6750 psig
9. Burst Pressure: Greater than 9000 psig
10. Failure Mode: Leak failure mode rather than catastrophic rupture for flaw growth during operating pressure cycling.
11. Surface Flaws: 5% of structural depth
12. Impact Resistance: 10 foot drop, boss end, non-boss end, and vessel side at (-)60°F and 200°F, 2 cycles
13. Drop Test: With 200 lbs attached, height of 16 ft, 5 repetitions at various angles.
14. Fragmentation Resistance: At 4000 psig, impact with .30 cal AP projectile at 2800 fps, 3-in. max opening cut in tank, tank to remain in one piece
15. Permanent Volumetric Expansion: 1% of temporary expansion
16. Leakage: 5%/year
17. Thermal Cycling: 20 Cycles (-)60°F to 200°F
18. Humidity Resistance: MIL-STD-810A, Method 507.1 plus 0°and 100% RH for 1 hr
19. High Temperature Resistance: 600°F(5 minutes while at 2000 psi)
20. Sand and Dust Resistance: MIL-STD 810A, Method 510.1
21. Salt Atmosphere Resistance: MIL-STD-810A, Method 509.1
22. Production Quantities: 1000, 5000, and 25,000 units/yr
23. Cost: As low as possible.

TABLE XXIV

TESTING CONDUCTED ON FIREMAN'S TANKS DESIGN VERIFICATION TESTING

Test Number	Vessel Serial Number	Configuration	Liner	Wrap	Operating Cycles	Proof Cycles	Maximum Pressure, psi	Burst Pressure, psi	Failure Mode
1	SL-1	Subscale	6061 T6 - Spun Head and Boss	S-Glass	120	50	13,900	13,900 (1)	Hoop Glass
2	SL-2	Subscale	6061 T6 - Spun Head and Boss	S-Glass	10,000	100	11,800	11,800	Hoop Glass
3	SL-3	Subscale	6061 T6 - Spun Head and Boss	S-Glass	None	1	14,000	14,000	Hoop Glass
4	SL-4	Subscale	6061 T6 - Forged Head and Boss	S-Glass	None	1	12,500	None (3 Attempts)	Seal Failure
5	SL-5	Subscale	6061 T6 - Forged Head and Boss	S-Glass	10,000	100	12,000	None (4 Attempts)	Seal Failure
6	1	Fullscale	6351 T6 - Forged Head and Boss	S-Glass	10,000	100	11,800	11,800	Liner Crack at Head-to-Cylinder Juncture
7	2	Fullscale	6351 T6 - Forged Head and Boss	S-Glass	None	1	12,200	12,200 (2 Attempts)	Seal Failure

TABLE XXIV

TESTING CONDUCTED ON FIREMAN'S TANKS QUALIFICATION TESTING

Test Number	Vessel Serial Number	Test	Result	Comment	Failure Mode
QT-1	9	Gunfire	° No fragmentation ° 3/4-in. liner tear ° vessel retained slug	QT-1 Pressurized hydraulically to 4500 psi	Leak through bullet hole.
QT-1A	11			QT-1A Pressurized pneumatically to 4500 psi	Leak through bullet hole
QT-2	5	16-ft. Drop Test (16-ft. drop with 200 lb. load onto rigid steel plate, 5 times @ 4500 psig)	Subsequent burst 9300 psig	Unit had surface damage caused by "pinwheeling" around test cell after test fitting failure. Vessel broke away 3 times out of 5 drops.	Cylinder, Hoop Fibers
QT-3	6	Pressure Cycling Hi/Low Temp. ° 5000 @ -60°F ° 5000 @ +200°F ° 100 Proof @ 70°F	Subsequent burst 8300 psig	Test does not reflect actual conditions and should be considered as off design. Pressure Cycling 0-4000 psi (operating) and 0-6750 psi (proof)	Cylinder, Hoop Fibers
QT-4	8	Flaw-Growth in Wrap (1300 pneumatic cycles with intentional flaw in wrap)	No flaw growth Ultimate gailure at 3100 psig after 4-in.-long cut introduced through full hoop-wrap thickness	Wrap initially cut to 50% of hoop wrap depth 1-in. long. No flaw growth in wrap after 1000 cycles to 4000 psi; flaw size was increased 3 times following 100 pressurization cycles until failure occurred.	Cylinder, Hoop Fibers
QT-5	10	Flaw Growth in Liner (1000 pneumatic cycles with intentional flaw in liner)	No failure during cycling. Subsequent liner leak failure at 8450 psig during pneumatic burst test.	Intentional liner flaw was 0.070-in. deep by .350-in. long. Pressure cycling 0-4000 psi.	Leak, unable to burst
QT-6	17	10-ft. Drop Test Hi/Low Temp. ° 6 drops -60°F ° 6 drops +200°F	Subsequent burst 9900 psig.	Unit was scheduled for full-qual. sequence but outer wrap was severely damaged following failure of the test fitting. (Comment continued on Page 3)	

TABLE XXIV

TESTING CONDUCTED ON FIREMAN'S TANKS
QUALIFICATION TESTING (Cont'd.)

Test Number	Vessel Serial Number	Test	Result	Comment	Failure Mode
QT-6 (Continued)				Unit was pressurized to 3500 psi at -60° F drop and to 4500 psi at +200° F drop. Drop orientations equally distributed between each end and side.	Cylinder, Hoop Fibers
QT-6A	12	Full Qual Sequence ° High temp. exposure (600° F for 5 min.) ° Thermal cycling -60° F to +200° F (20 times by bath emersion) ° Salt fog exposure ° Pressure cycling	Liner leak after 6633 operating and 18 proof cycles.	Unit was added to replace No. 6 Pressures - High Temp. Exposure: 2000 psi - Thermal Cycling: 4000 psi - Operating Cycles: 0 to 4000 to 0 psi - Proof Cycles: 0 to 6750 to 0 psi	Liner Leakage
QT-6B	27	Full Qual Sequence ° Pressure cycling (10,000 operating and 30 proof cycles) ° Thermal cycles -60° F to +200° F (20 times by bath emersion) ° 10-ft. Drop Test ° High temp. exposure (600° F for 5 minutes)	Subsequent burst 12,300 psig	Unit was added to replace No. 6A. Proof cycle requirement was reduced from 100 to 30. High temperature test was moved to last in sequence. Salt fog deleted and underwater cycling added on subsequent test. Pressures: Same as QT-6A and QT-6. 12,300 psi burst exceeded 9000 psi min. requirement following qual. sequence.	Cylinder, Hoop Fibers
QT-7	4	Pressure Cycling (under water) ° 10,000 operating ° 100 proof cycles	Subsequent burst 9600 psig	Test was added to demonstrate water exposure capability. Pressure Cycling: 0-4000 psi (operating) and 0-6750 psi (proof)	Cylinder, Hoop Fibers
QT-8	3	Thermal exposure ° 12 exposures (400° F 10 minutes)	Subsequent burst 13,200 psig	Test was added to further demonstrate high-temperature exposure capability	Cylinder, Hoop Fibers
9	61	Press Cycling 10,000 cycles to 4500 psig and 30 proof cycles to 7500 psig	Subsequent burst 9000 psig (liner leak failure)	Tests QT-9 and QT-10 were added as lot verification following change in fiberglass finish made by Owens Corning. Increased cyclic pressure (4500 psig) was also demonstrated.	
10	74	Single Cycle Burst	Burst at 12,300 psig		Cylinder, Hoop Fibers

RELATIVE WEIGHTS FOR UNLINED PRESSURE VESSELS AT CONSTANT PRESSURE X VOLUME

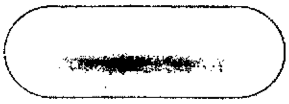
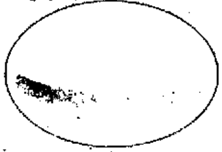
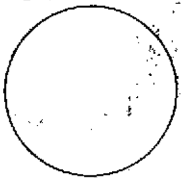
VESSEL SHAPE **MATERIAL**	**CYLINDER**  $W = 2\left(\frac{\rho}{\sigma_H}\right) PV$	**OBLATE SPHEROID**  $W = 3\left(\frac{\rho}{\sigma_L}\right) PV$	**SPHERE**  $W = 1.5\left(\frac{\rho}{\sigma}\right) PV$
S FIBERGLASS 20 END - HTS FINISH EPOXY-ANHYDRIDE RESIN	1.0 $\frac{\sigma_H}{\rho} = \frac{170,000}{.073} = 2.33 \times 10^6$	1.0 $\frac{\sigma_L}{\rho} = \frac{245,000}{.073} = 3.36 \times 10^6$	1.5 $\frac{\sigma}{\rho} = \frac{85,000}{.073} = 1.16 \times 10^6$
E FIBERGLASS 20 END-HTS FINISH EPOXY-ANHYDRIDE RESIN	1.4 $\frac{\sigma_H}{\rho} = \frac{125,000}{.075} = 1.67 \times 10^6$	1.4 $\frac{\sigma_L}{\rho} = \frac{185,000}{.075} = 2.47 \times 10^6$	2.1 $\frac{\sigma}{\rho} = \frac{65,000}{.075} = .87 \times 10^6$
TITANIUM ALLOY 6 AL - 4 V FORGED & HEAT TREATED	2.3 $\frac{\sigma}{\rho} = \frac{165,000}{.160} = 1.03 \times 10^6$		1.7 $\frac{\sigma}{\rho} = \frac{165,000}{.160} = 1.03 \times 10^6$
ALUMINUM ALLOY 7075 - T6	2.9 $\frac{\sigma}{\rho} = \frac{78,000}{.097} = .80 \times 10^6$		2.2 $\frac{\sigma}{\rho} = \frac{78,000}{.097} = .80 \times 10^6$
HI STRENGTH STEEL LADISH $D6_AC$ HEAT TREATED	3.0 $\frac{\sigma}{\rho} = \frac{220,000}{.283} = .78 \times 10^6$		2.2 $\frac{\sigma}{\rho} = \frac{220,000}{.283} = .78 \times 10^6$

Figure 1

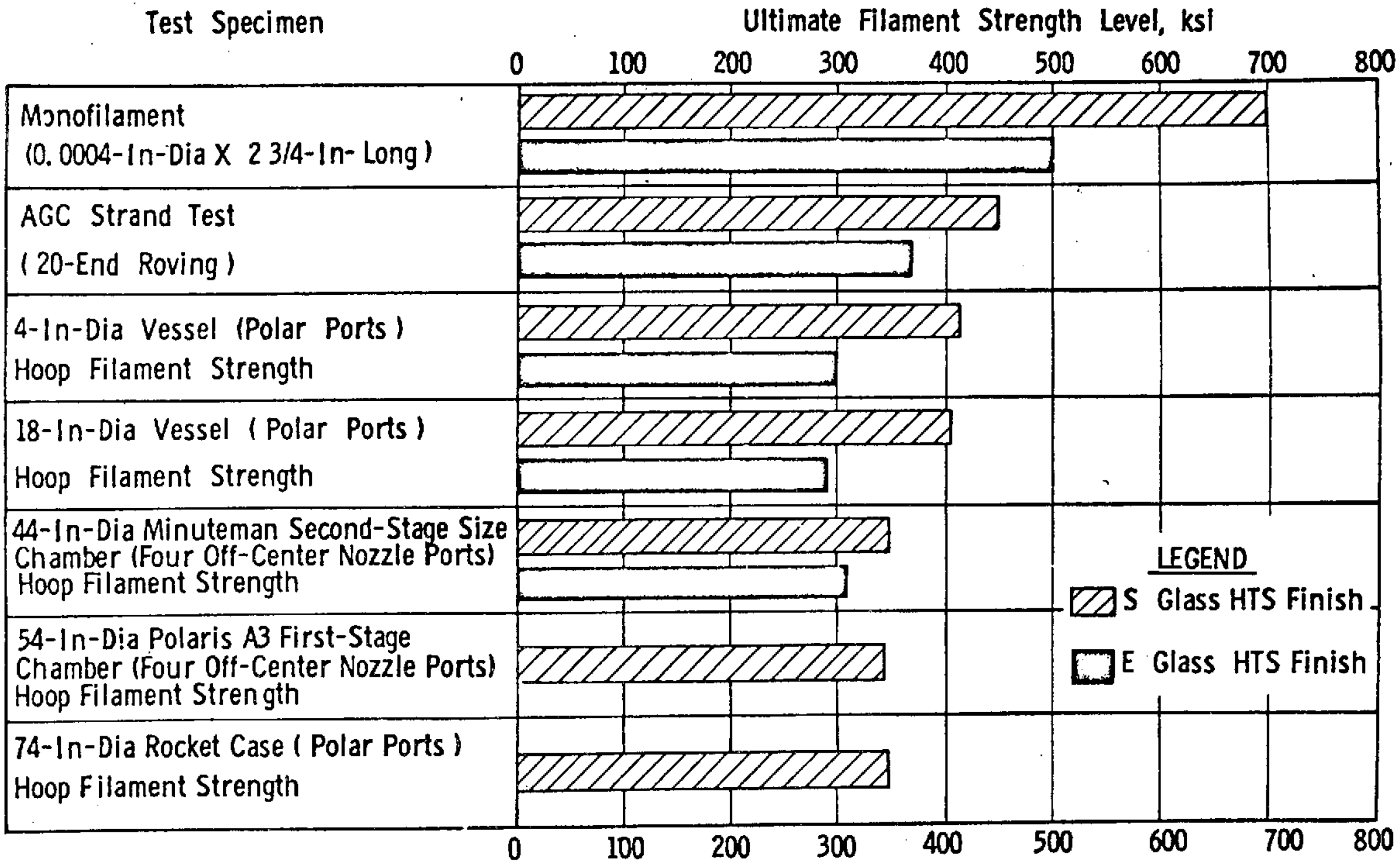
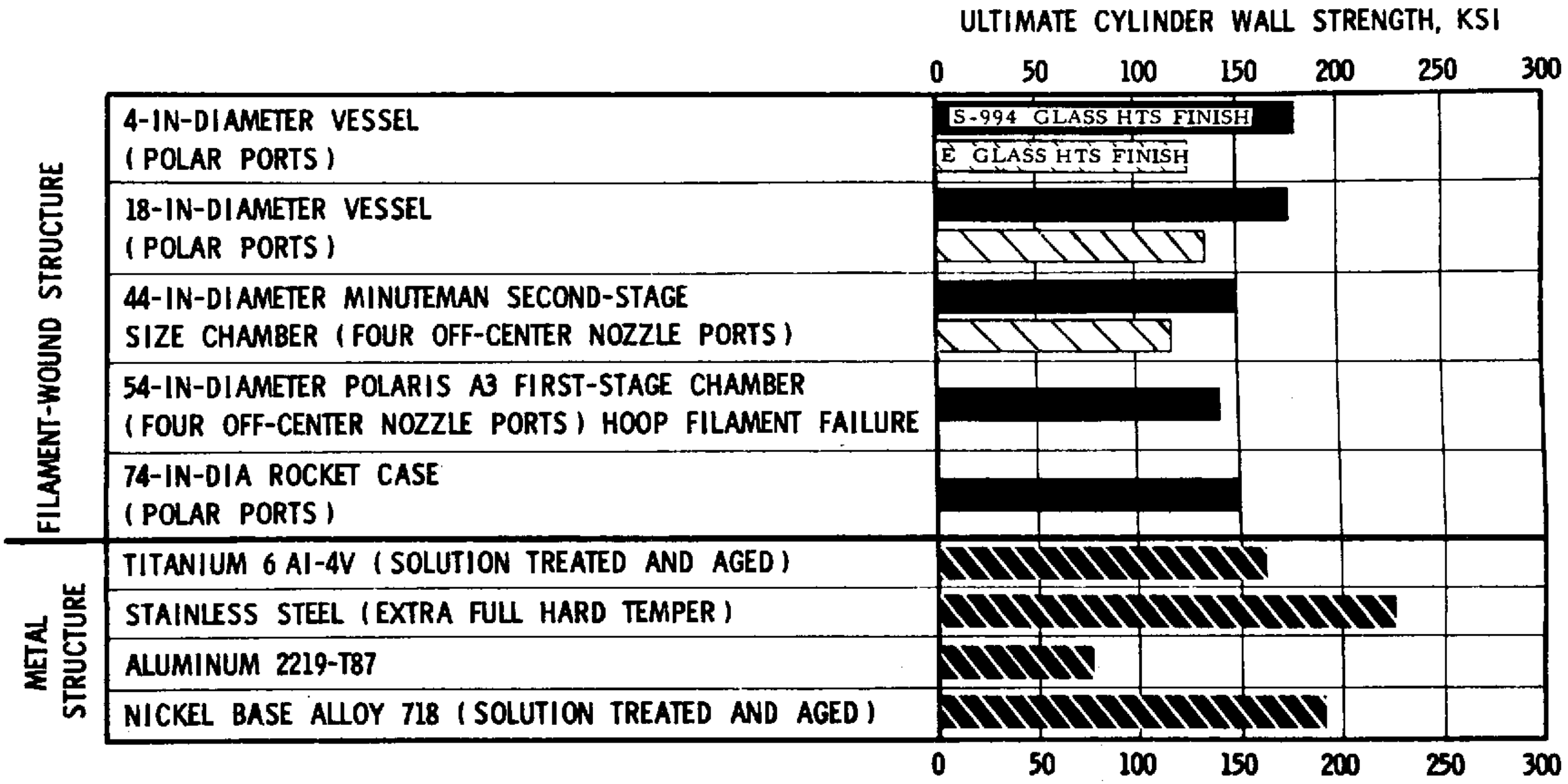


Figure 2

Demonstrated Average Tensile Strength of S and E Glass Filaments

Figure 3



Demonstrated Average Tensile Strengths of Glass Filament-Wound Composite and Homogeneous Metal Pressure Vessels

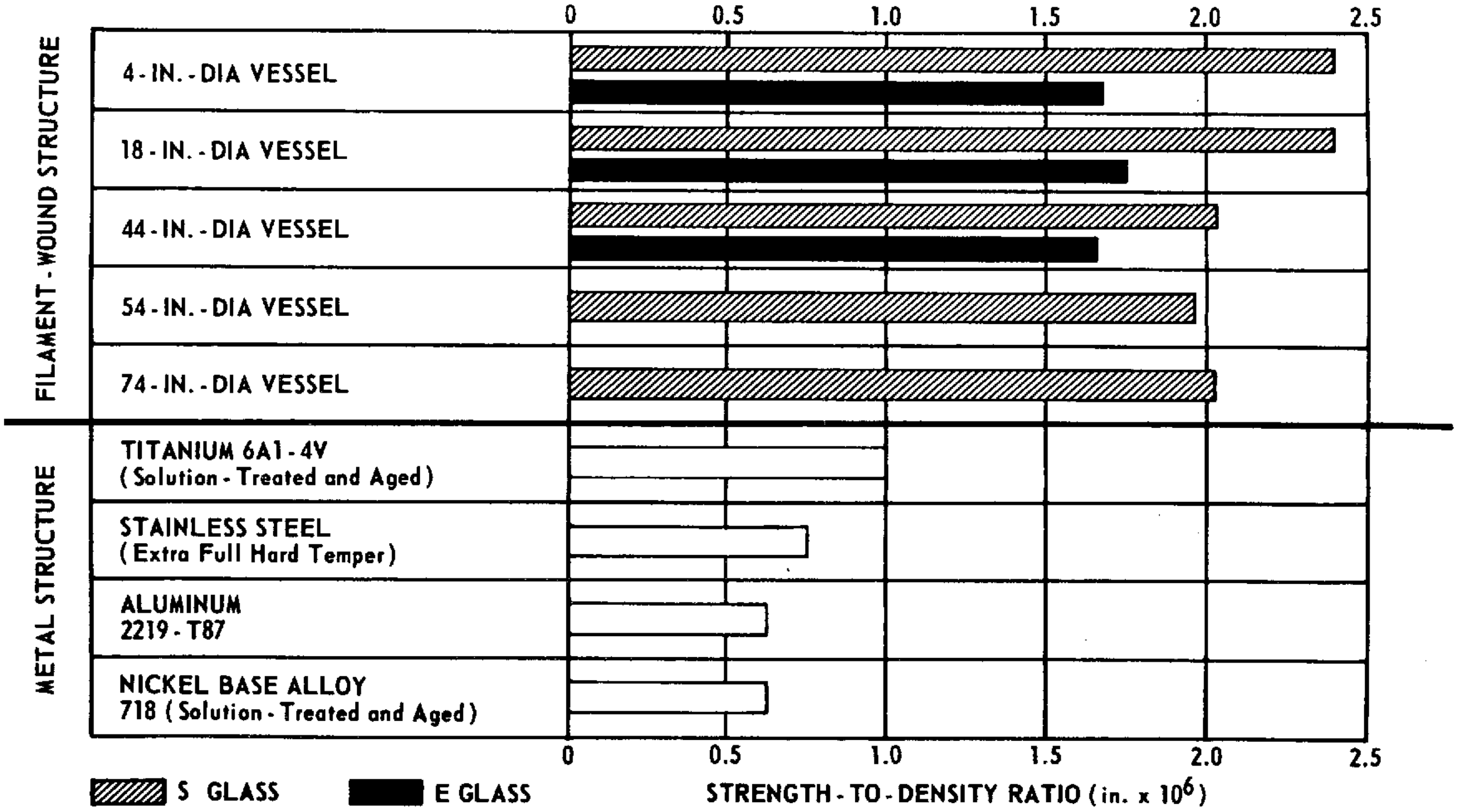


Figure 4

Strength-to-Density Ratio Comparison

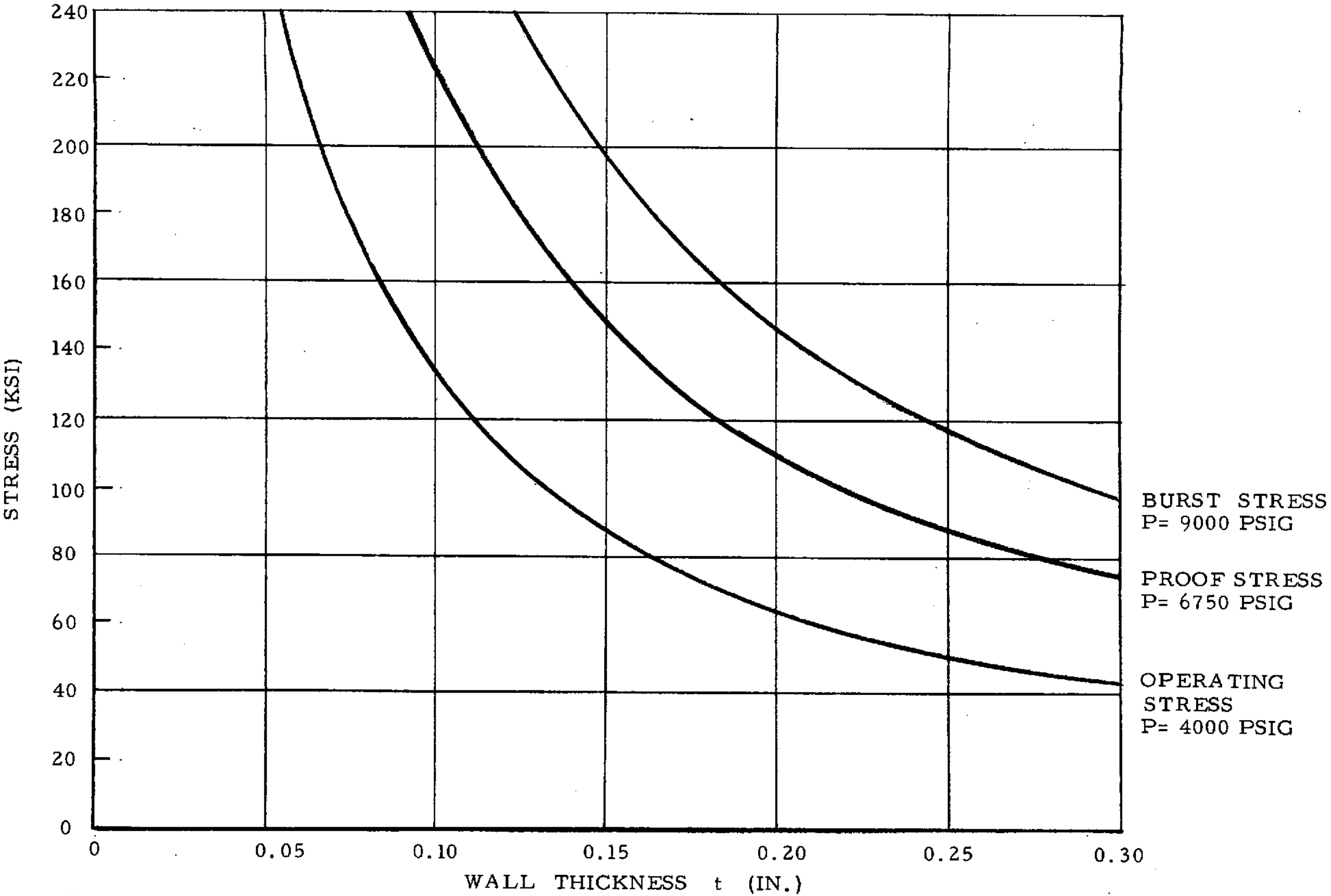


Figure 5

METAL VESSEL HOOP STRESSES AS A FUNCTION OF WALL THICKNESS FOR OPERATING, PROOF, AND BURST PRESSURES

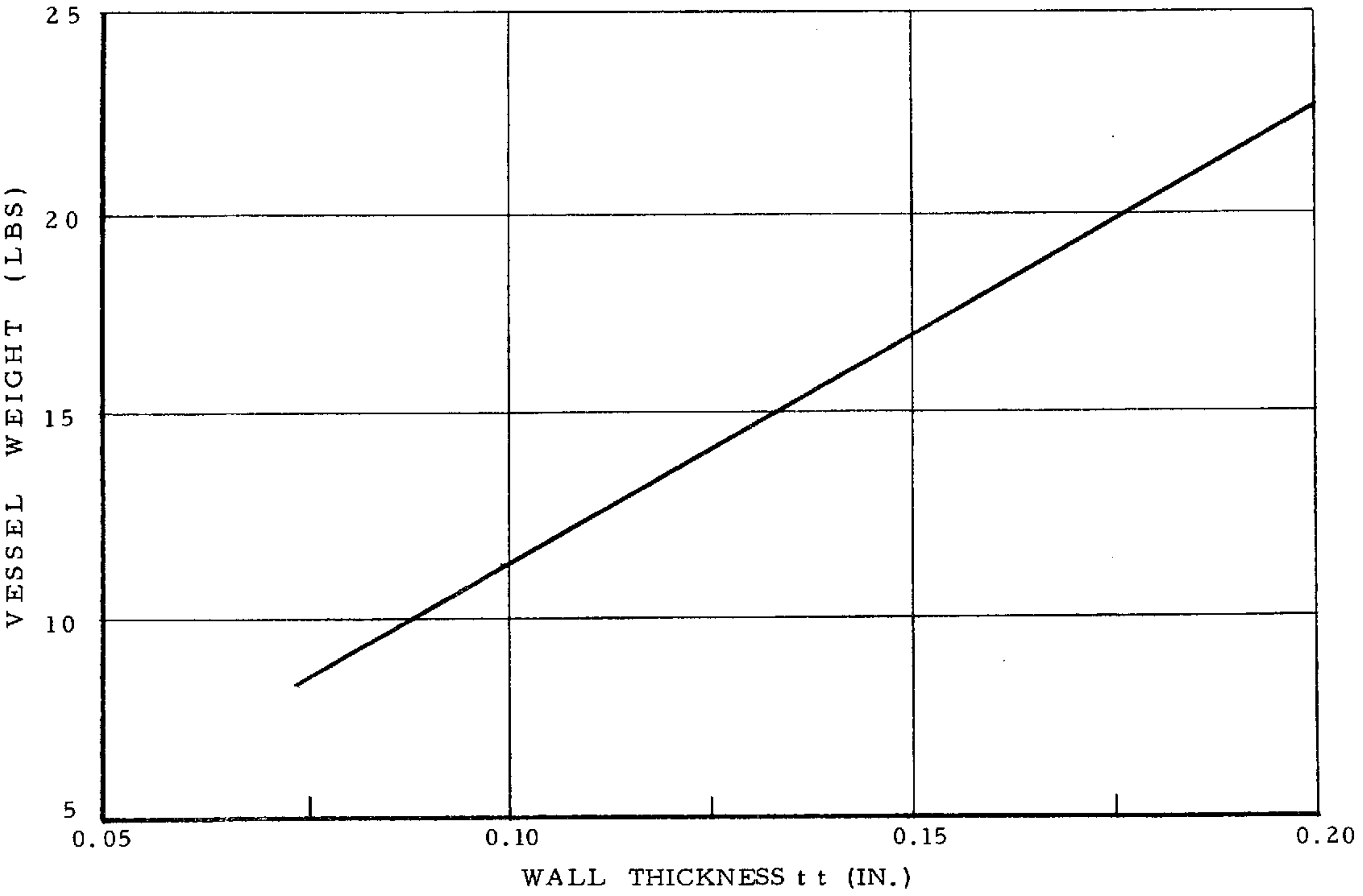
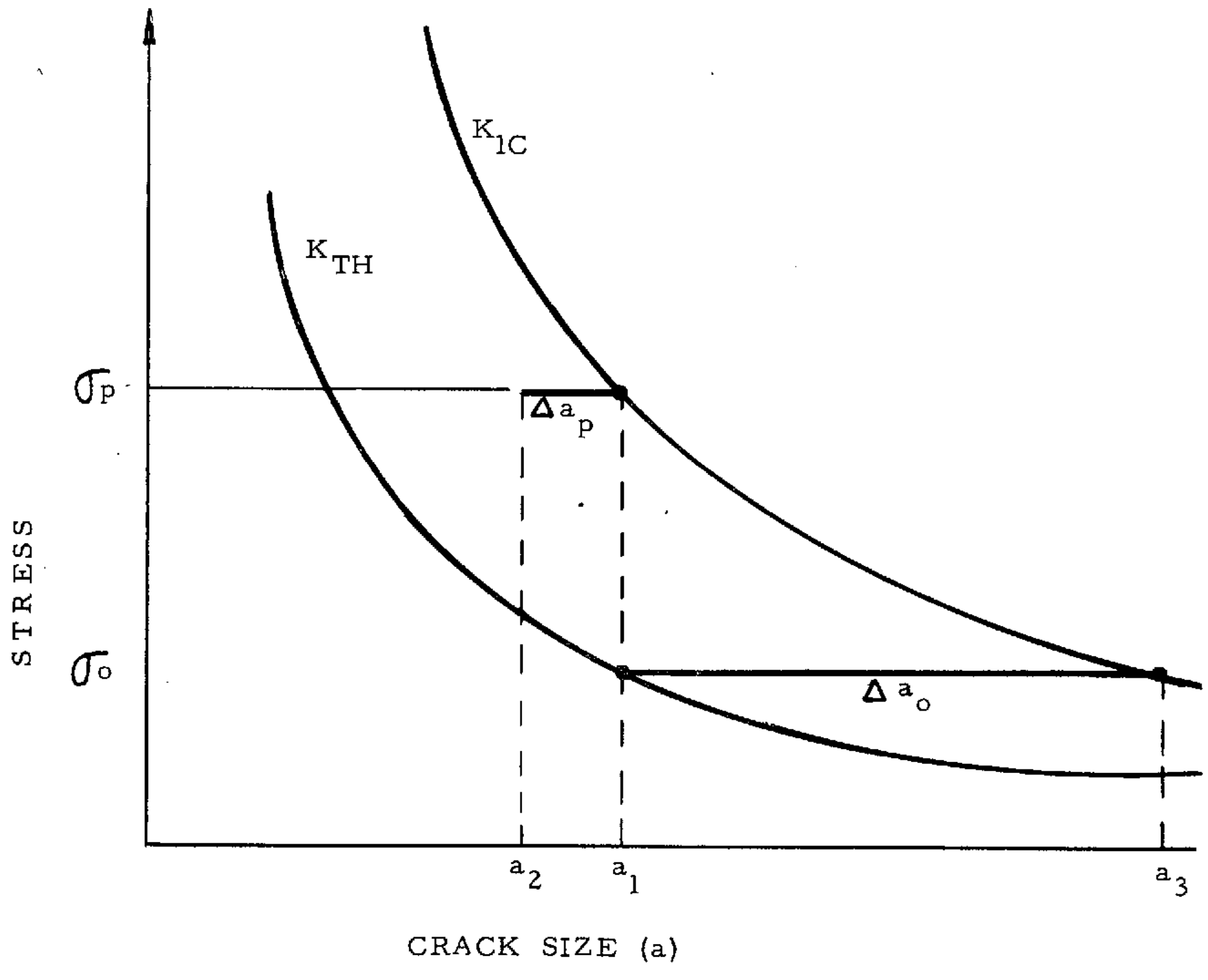


Figure 6

STEEL VESSEL WEIGHT VS WALL THICKNESS

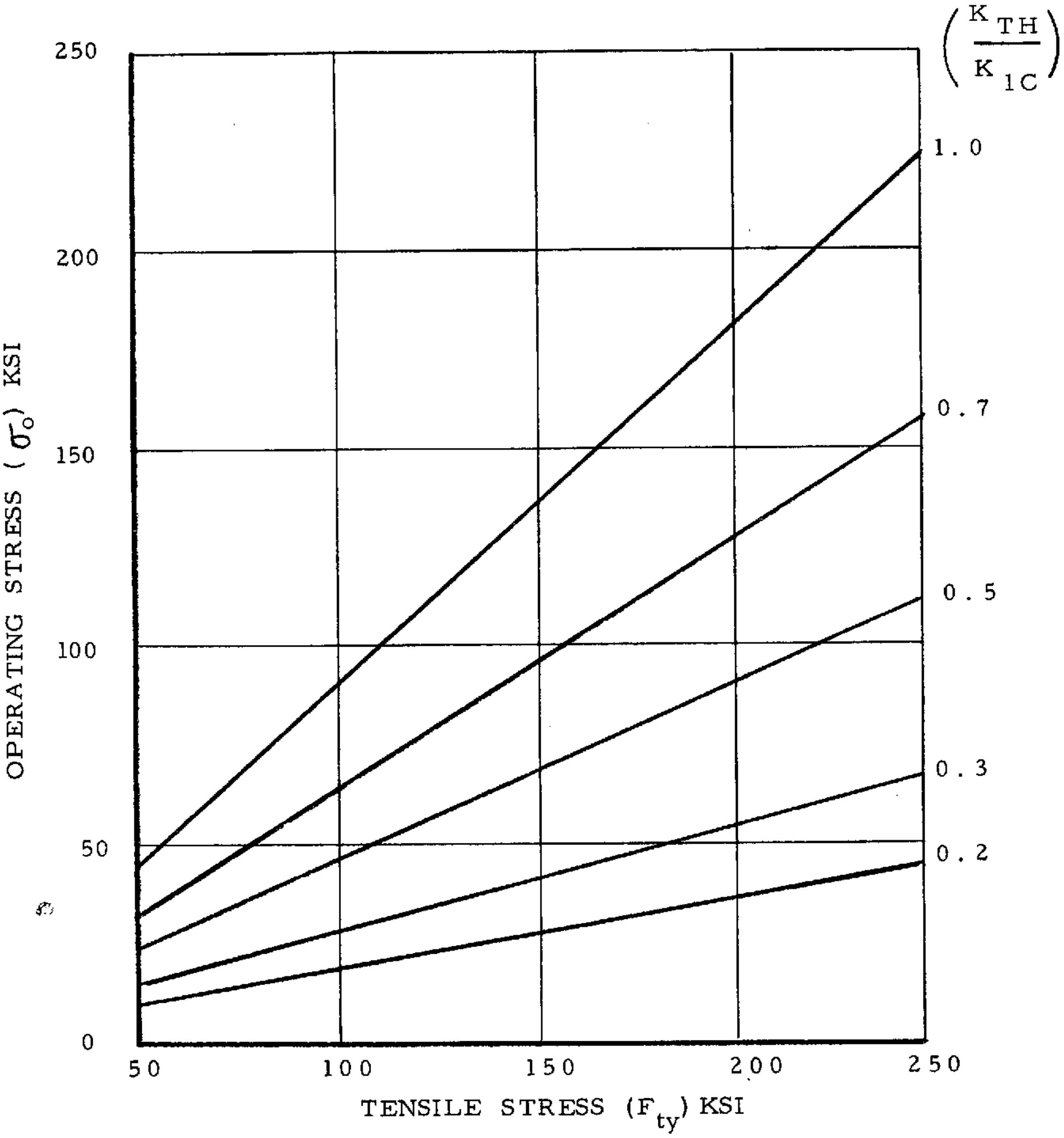
(p_b = 4000 psi, V = 500 in^3, D ≃ 6.5-in, L ≃ 21-in.)



$(a_1 - a_2) = \Delta a_p$ = Flaw growth potential under proof test conditions.

$(a_3 - a_1) = \Delta a_o$ = Flaw growth potential under operating conditions.

Figure 7



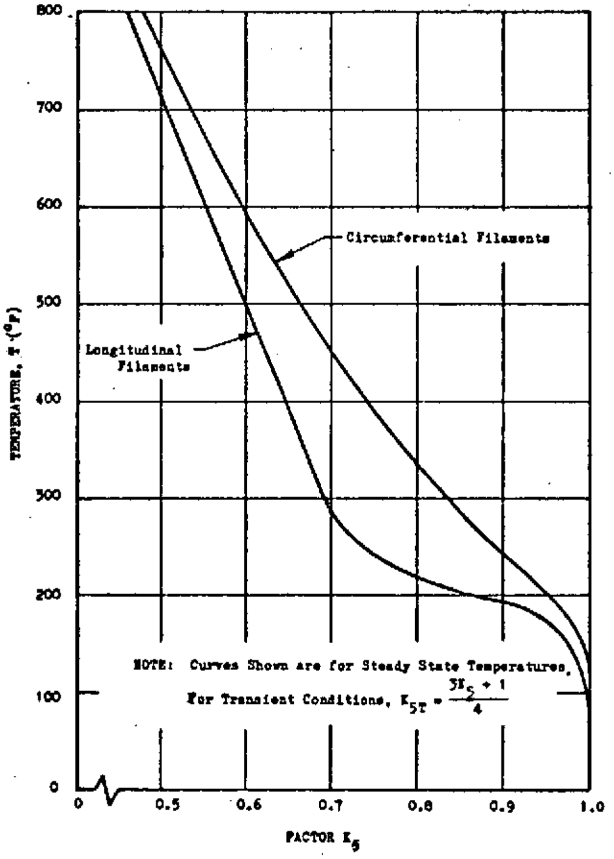
OPERATING STRESS VS TENSILE YIELD STRESS FOR VARIOUS K_{TH}/K_{1C} RATIOS

Figure 8

STRUCTURAL MATERIALS HANDBOOK

DESIGN PROCEDURES			6-20

DESIGN FACTOR K_5
FOR VARIATION OF ALLOWABLE FILAMENT STRESS
AS A FUNCTION OF TEMPERATURE



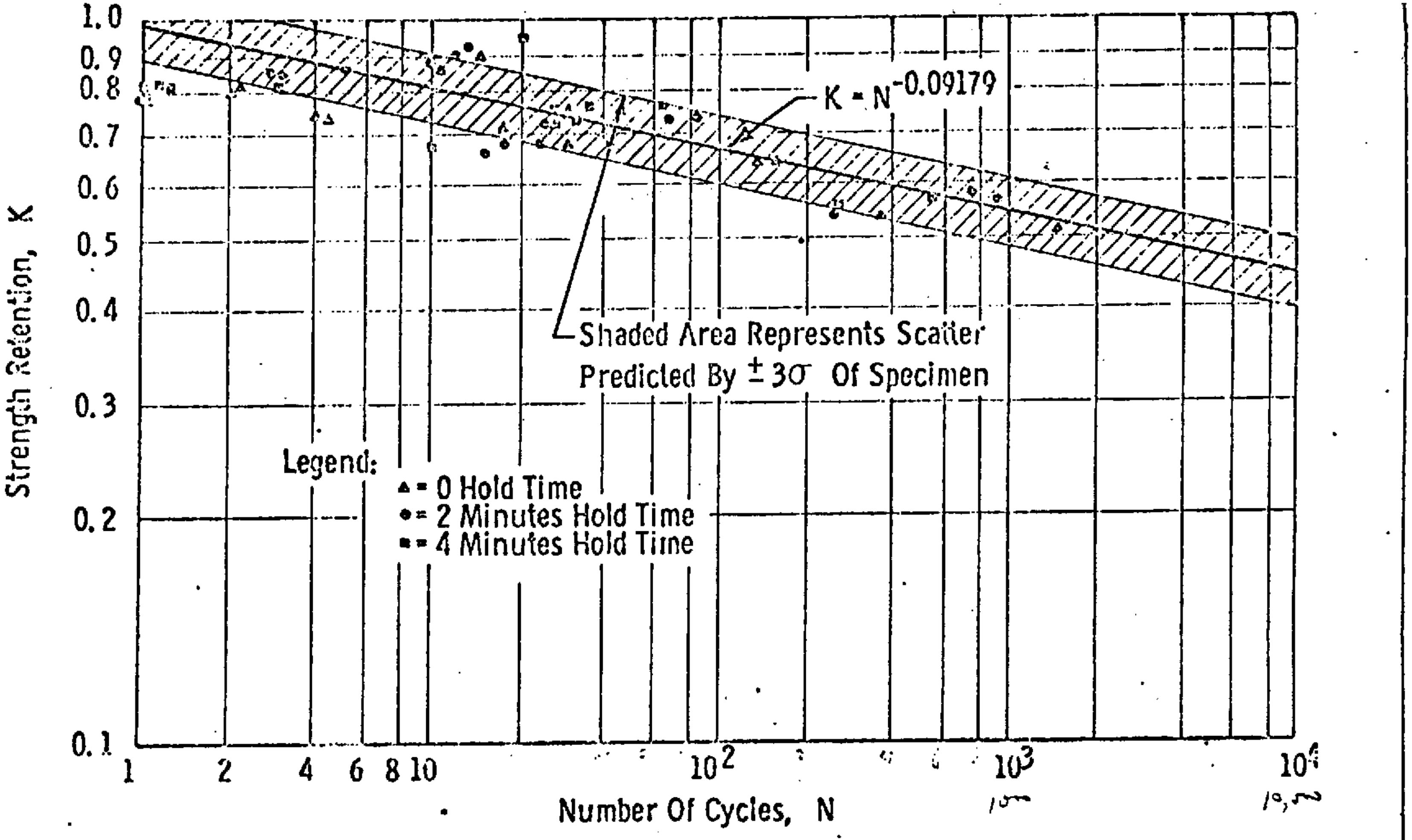
NOTE: Curves Shown are for Steady State Temperatures.
For Transient Conditions, $K_{5T} = \frac{3K_5 + 1}{4}$

AEROJET GENERAL

STRUCTURAL MATERIALS DIVISION
VON KARMAN CENTER
AZUSA CALIFORNIA

Effect of Temperature on Strength of Glass Filament-Wound Vessels

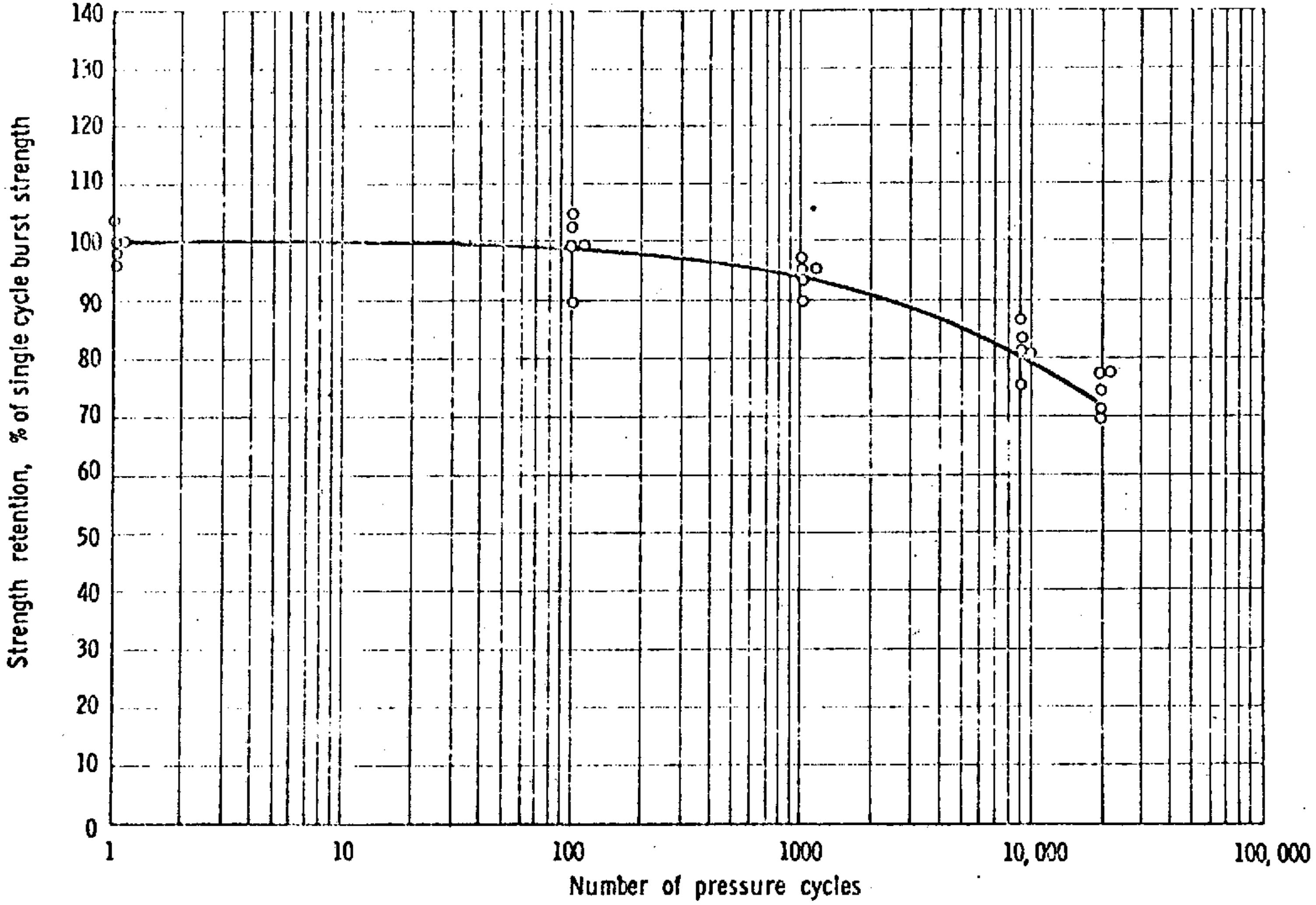
Figure 9



EFFECT OF CYCLIC LOADS ON HOOP STRENGTH OF 4-IN-DIA CYLINDERS

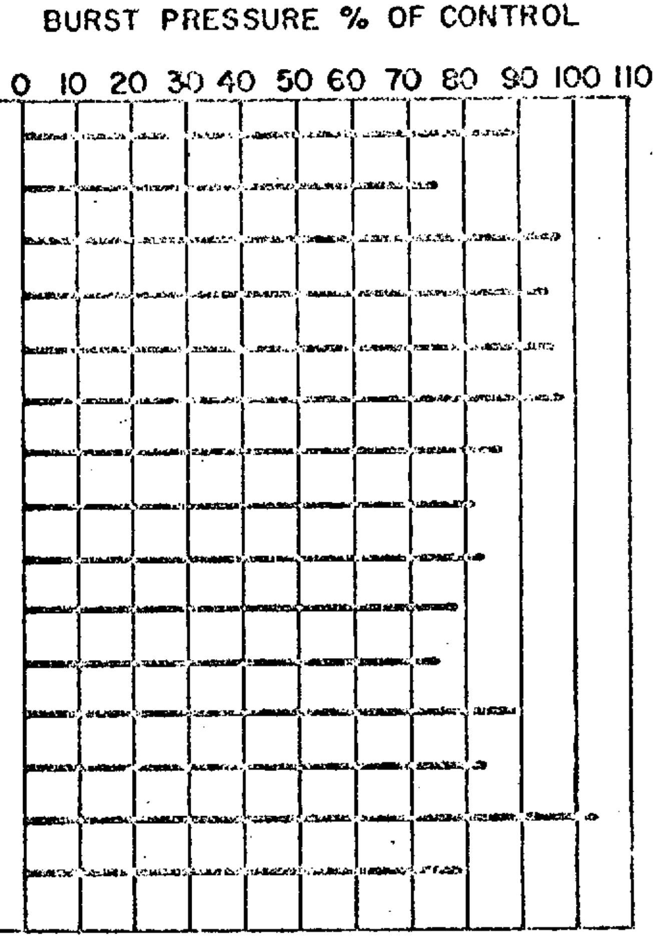
Figure 10

Figure 11



STRENGTH RETENTION OF 4-IN-DIA FILAMENT-WOUND VESSELS PRESSURE CYCLED AT 25% OF ORIGINAL STRENGTH
(0.86 LONGITUDINAL-TO-HOOP FILAMENT STRESS BALANCE)

PAINT APPLIED	% PRESTRESS	RESIN SYSTEM	TREATMENT
NO	80	58-68/R PRE PREG.	2 HOUR WATER BOIL
NO	80		24 HOUR WATER BOIL
YES	80		HUMIDITY CYCLED
YES	0		HUMIDITY CYCLED
NO	0		HUMIDITY CYCLED
NO	80		CONTROL 5% STRESS
NO	80		CONTROL 25% STRESS
NO	80		HUMIDITY CYCLED 5% STRESS
NO	80	58-68/R PRE PREG.	HUMIDITY CYCLED 25% STRESS
NO	0	58-68/R IN-PROCESS	HUMIDITY CYCLED
NO	80	58-68/R IN-PROCESS	
NO	0	826-MPDA IN-PROCESS	
NO	80	826-MPDA IN-PROCESS	
NO	0	828/MNA/ BDMA/LP-3	
NO	80	8[illegible] BDMA/LP-3	HUMIDITY CYCLED



LEGEND

PAINT APPLIED-YES SAMPLES HAD MAGNA X-500 POLARIS WHITE COATING APPLIED.
HUMIDITY CYCLED PER MIL-E-5272C.

HUMIDITY CYCLED 4-IN-DIA TEST SPECIMENS
TEST RESULTS SUMMARY

10-027-116

Figure 12

Environmental Tests on Filament Wound GRP Cylinders

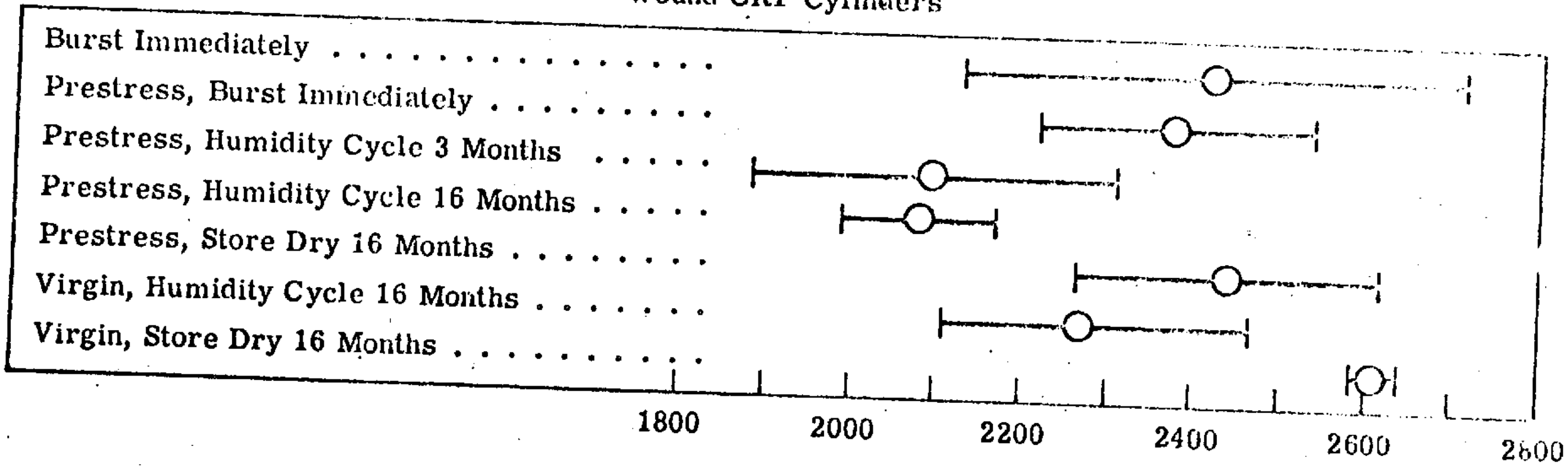


Figure 1

Figure 13

E GLASS / EPOXY FILAMENT WOUND
VESSEL DIAMETER, LENGTH, AND
VOLUME RELATIONSHIPS

OPERATING PRESSURE = 4000 PSIG
MAXIMUM DESIGN TEMP. = 200 °F
ABS LINER

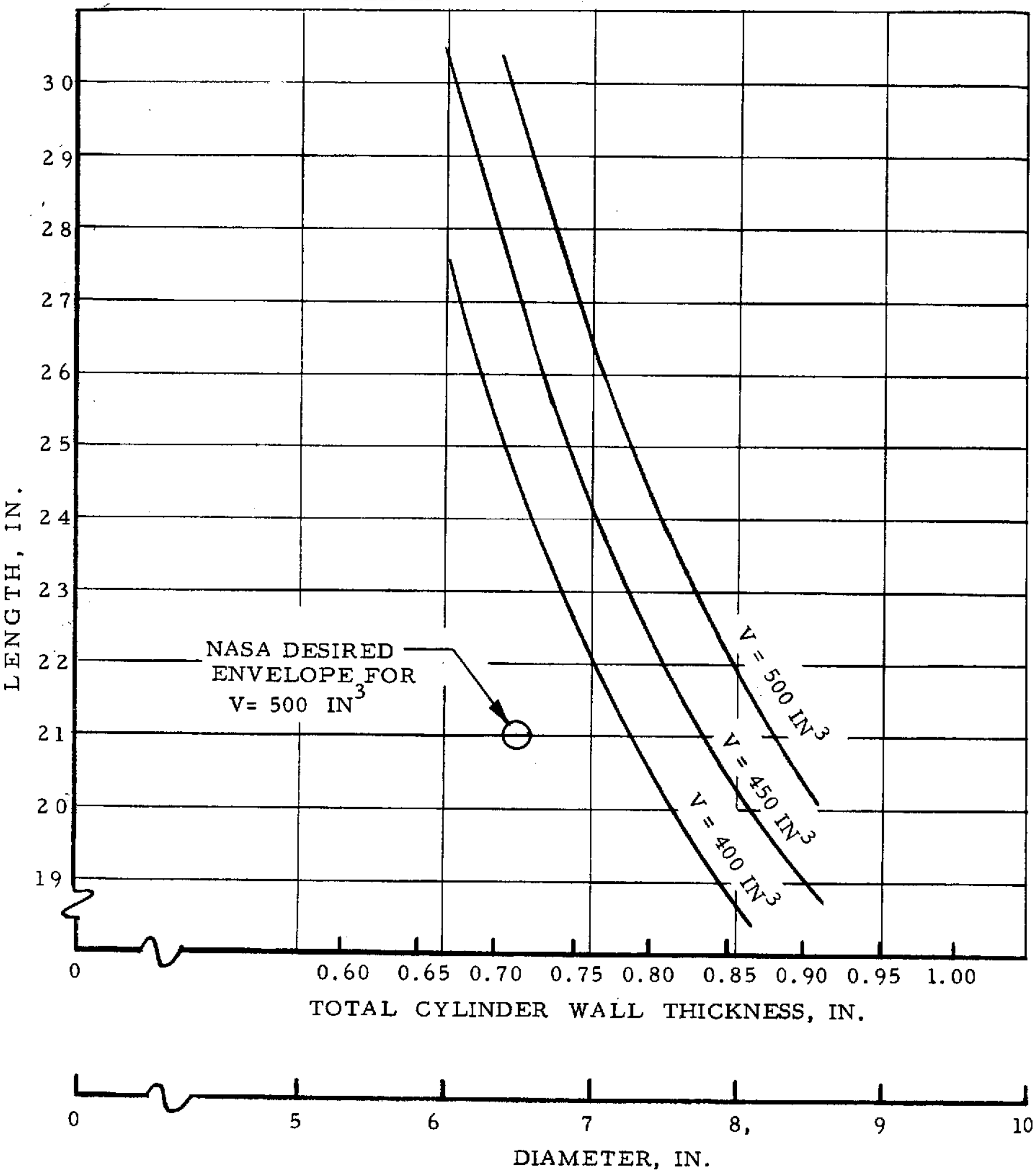


Figure 14

S GLASS / EPOXY FILAMENT WOUND VESSEL DIAMETER, LENGTH, AND VOLUME RELATIONSHIPS

OPERATING PRESSURE = 4000 PSIG
MAXIMUM DESIGN TEMP. = 200 °F
ABS LINER

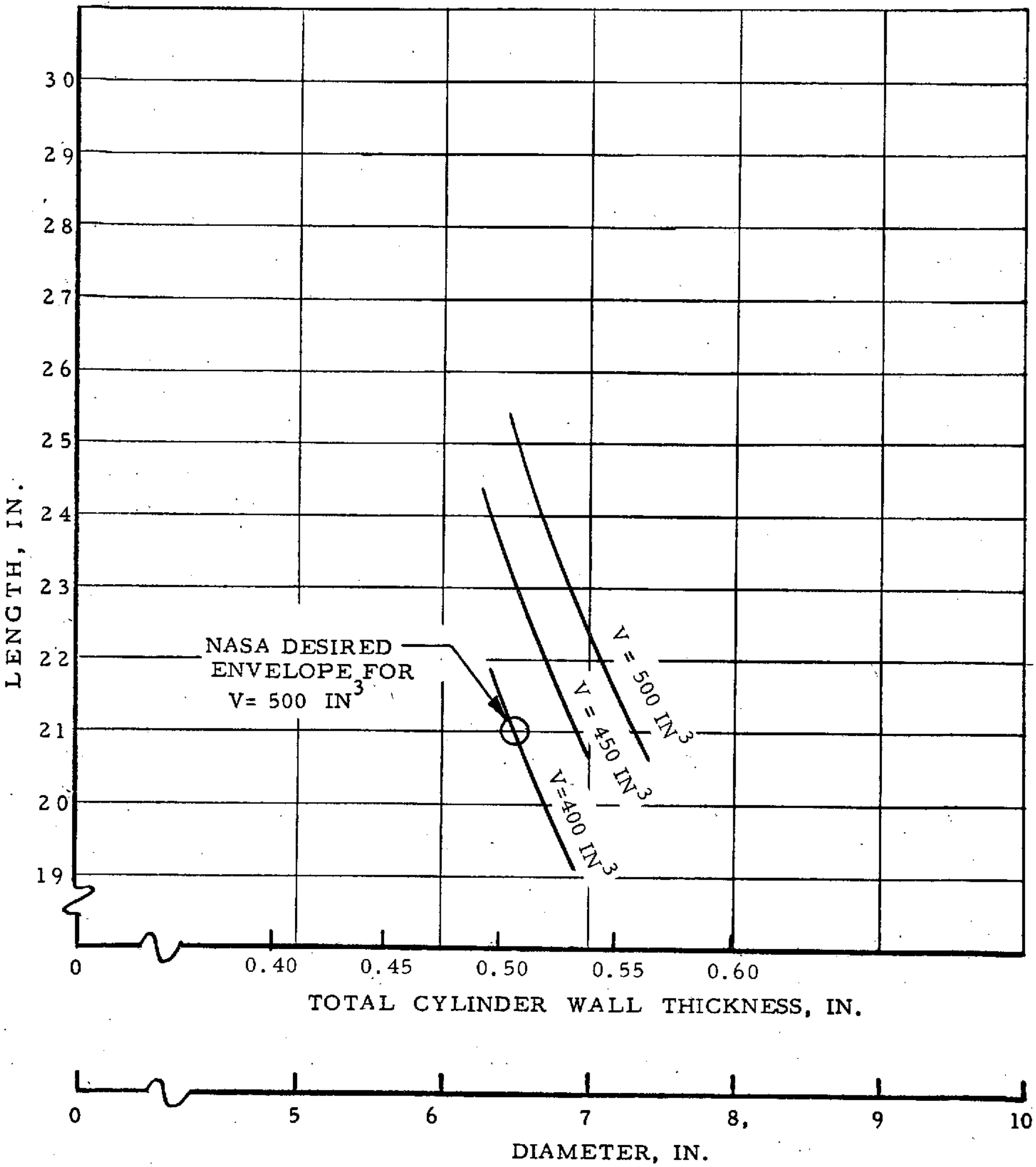


Figure 15

E GLASS / EPOXY AND
S GLASS / EPOXY FILAMENT - WOUND
VESSEL WEIGHTS VS VOLUME

OPERATING PRESSURE = 4000 PSIG
MAXIMUM DESIGN TEMP. = 200 °F
ABS LINER

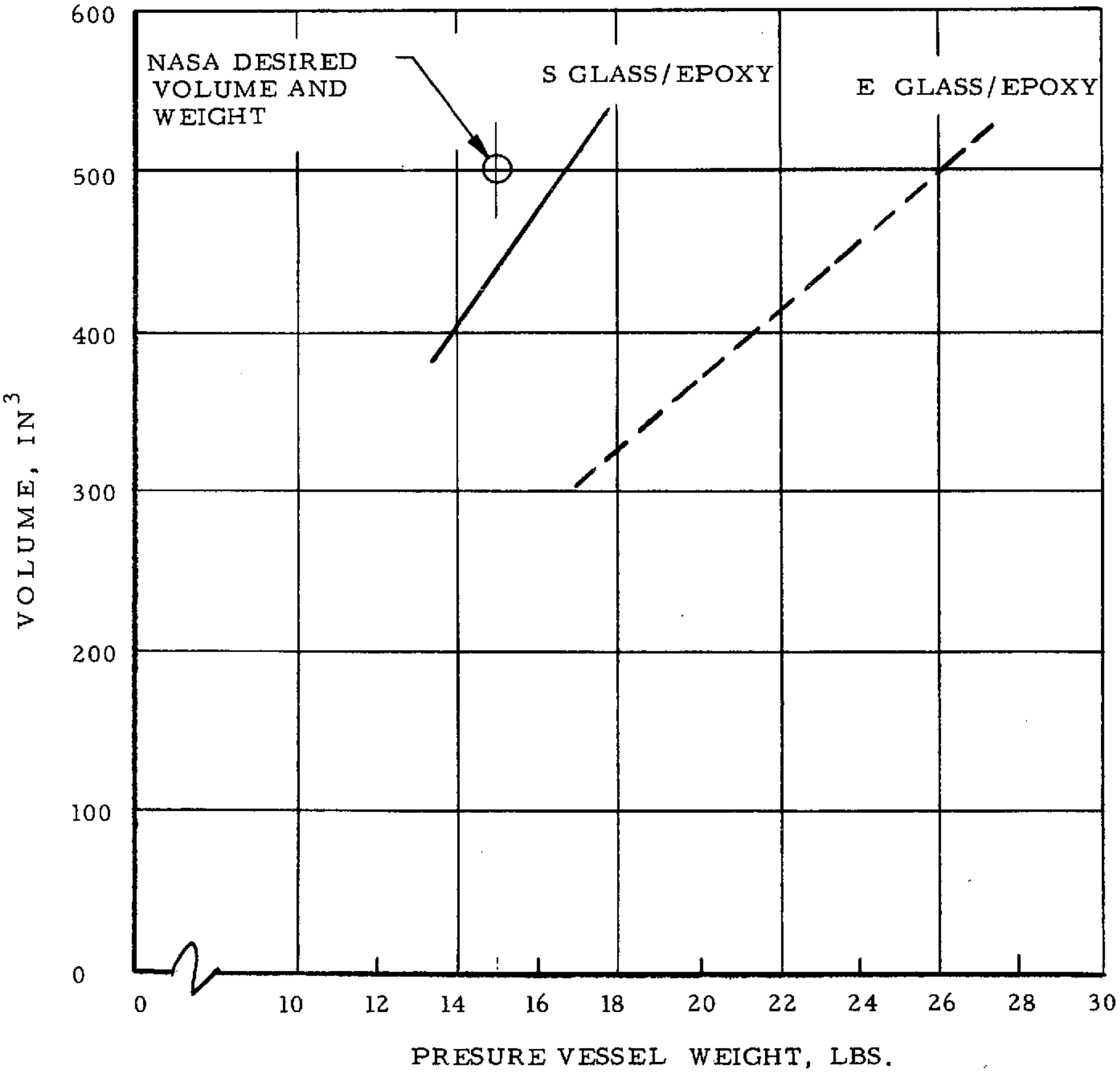
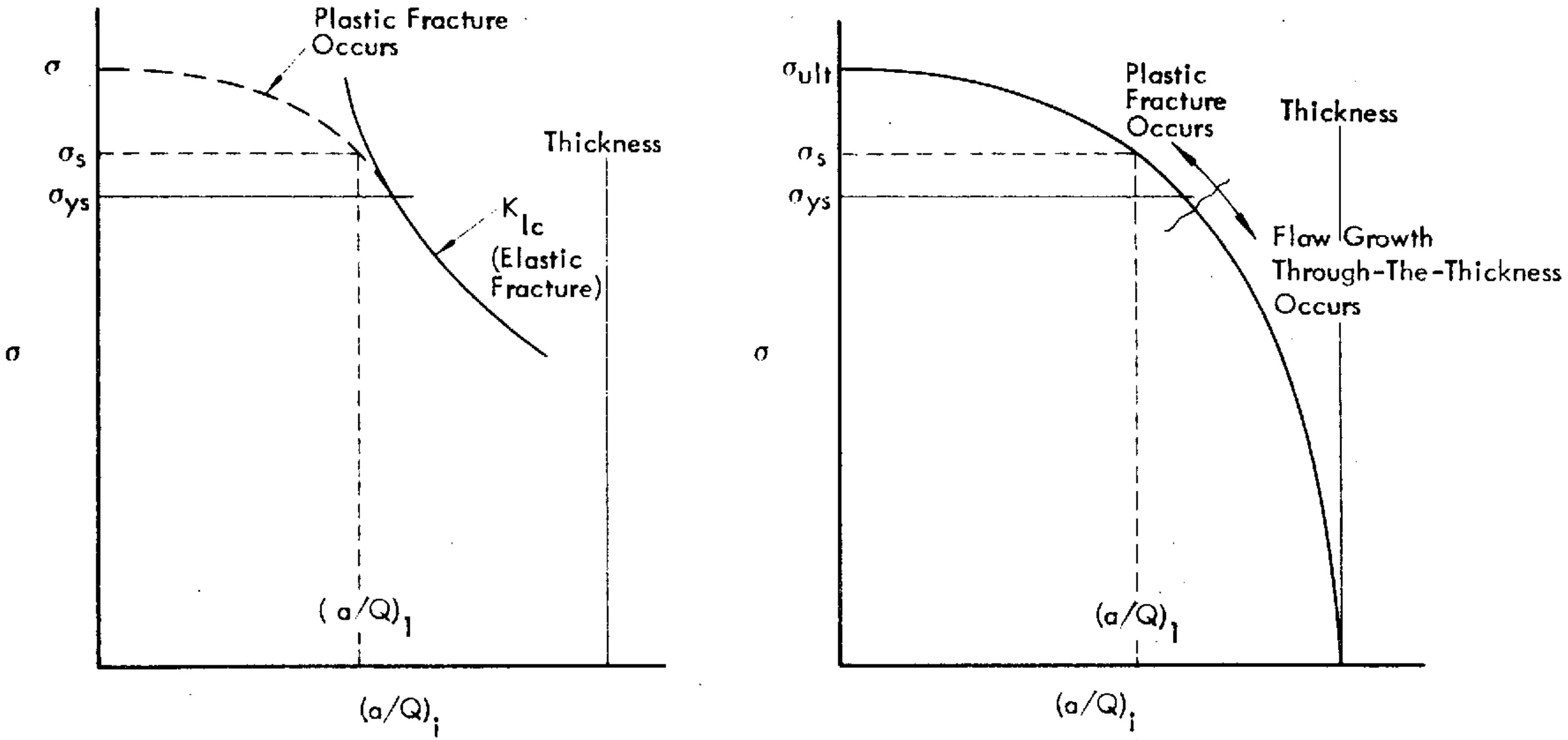


Figure 16



CASE I - LOW TOUGHNESS AND/OR THICK MATERIALS

CASE II - HIGH TOUGHNESS AND/OR THIN MATERIALS

Figure 17

TYPICAL FAILURE MODES

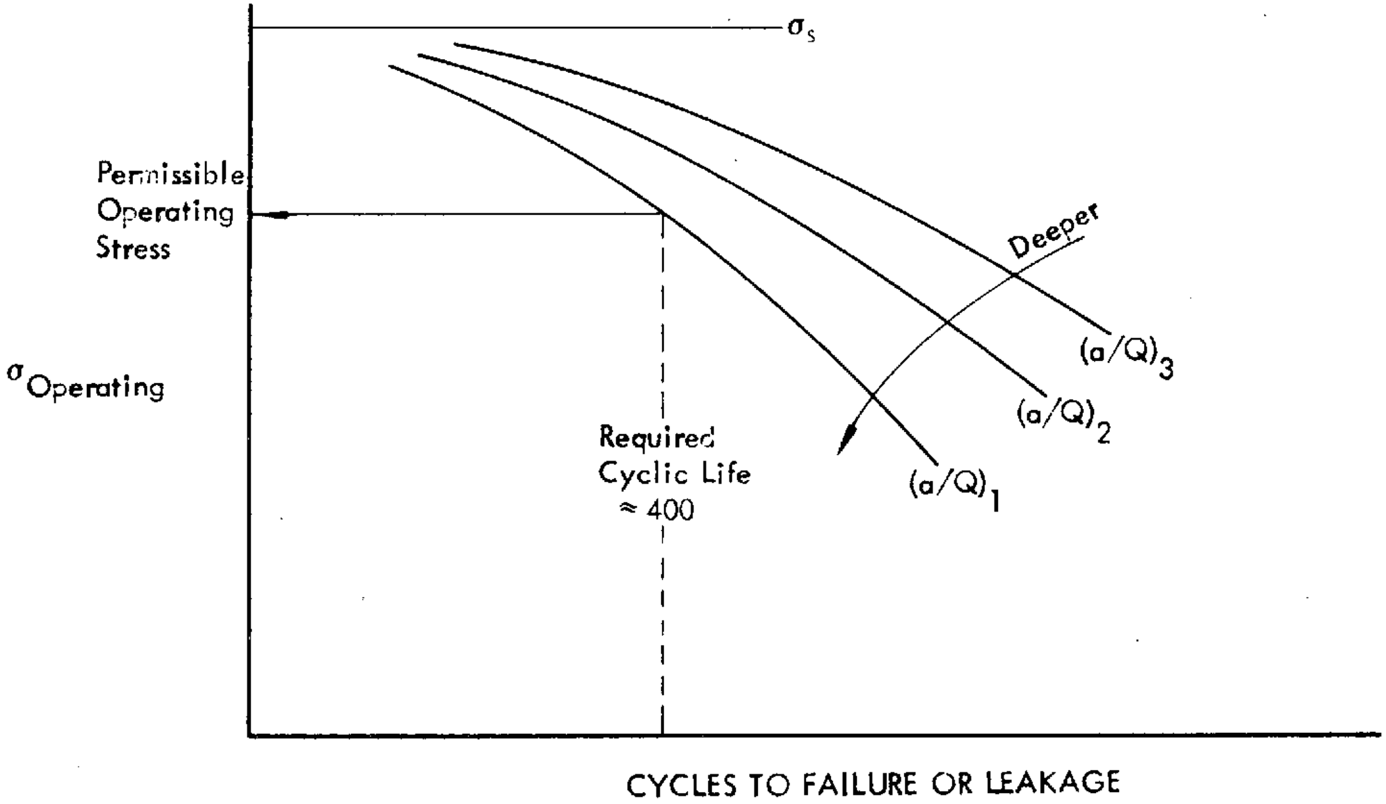
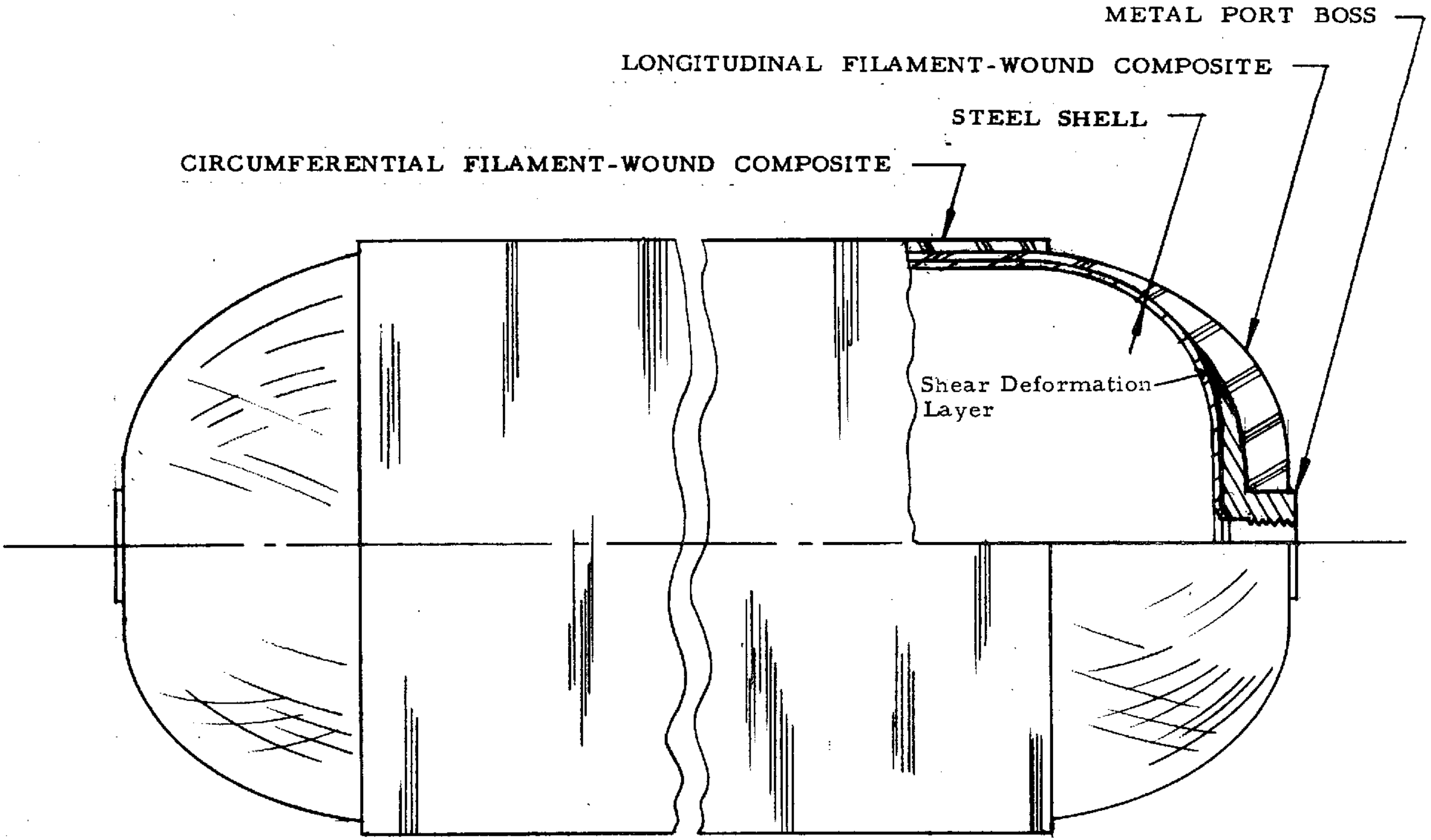


Figure 18

CYCLIC LIFE DATA PRESENTATION



FEATURES OF GFR METAL PRESSURE VESSEL COMPLETELY FILAMENT REINFORCED

Figure 19.

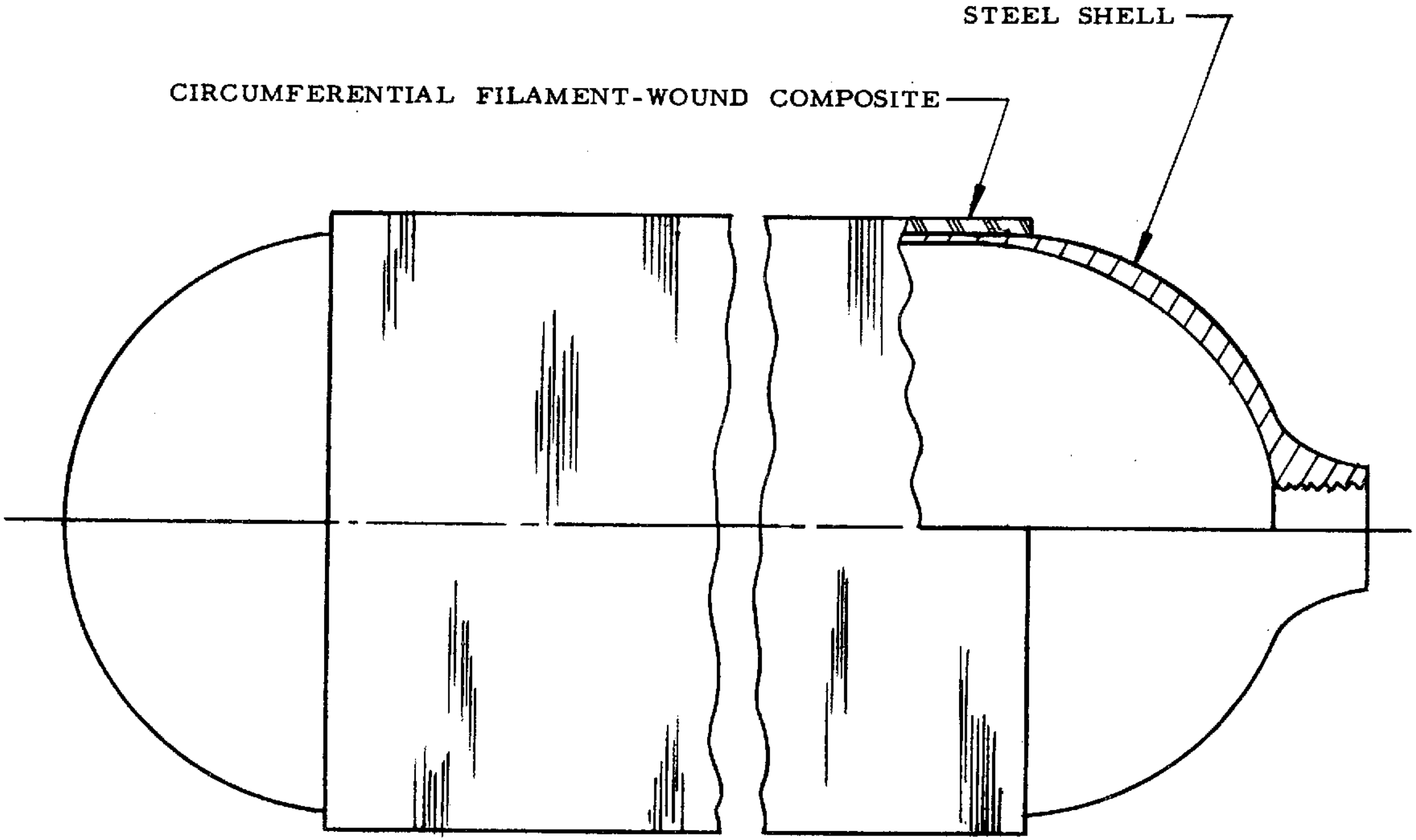
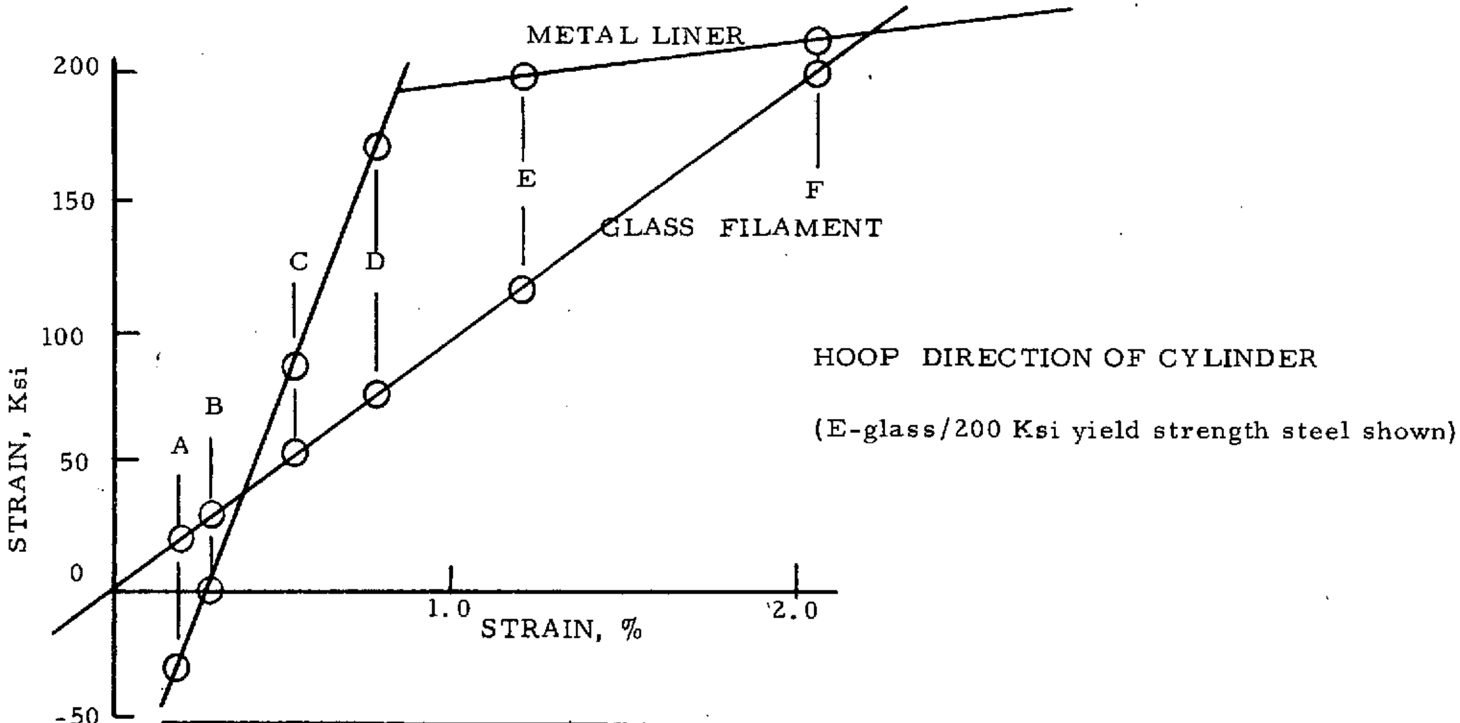


Figure 20

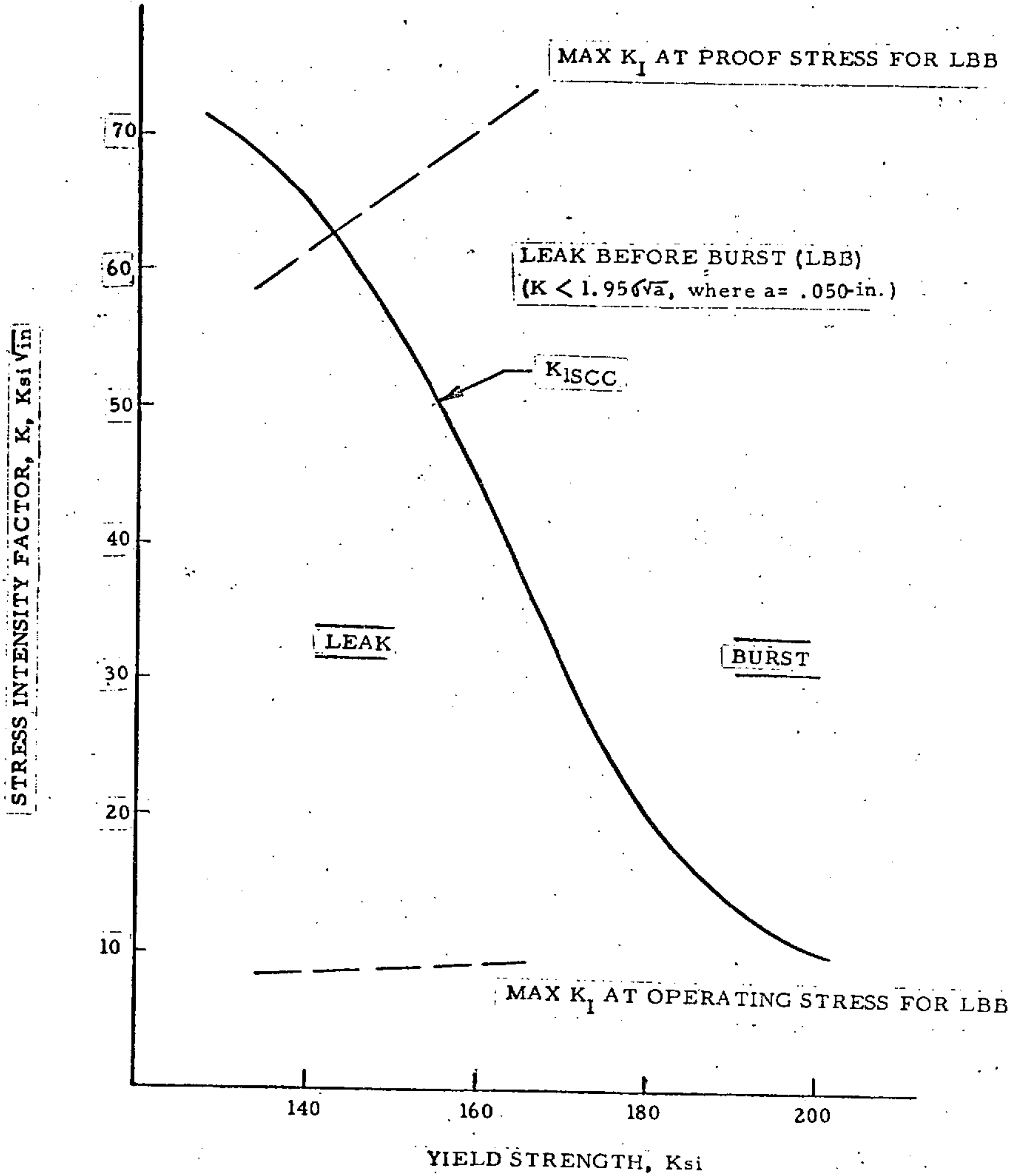
FEATURES OF GFR METAL PRESSURE VESSEL
CIRCUMFERENTIALLY FILAMENT REINFORCED



	Condition	After Proof	Winding	Operating	Proof	Burst	
						Longitudinal Metal	Hoop Overwrap
Constituent	Pressure, psig	0	0	4000	6750	9000	12,200 & 12,500
	Point	A	B	C	D	E	F
E glass/200 Ksi yield strength steel							
Hoop filaments		17,900	29,100	52,000	75,500	115,000	200,000
Hoop metal		-32,100	0	93,300	179,500	203,000	210,000
Longitudinal metal		0	0	93,300	157,400	210,000	285,000
S glass/ 200 Ksi yield strength steel							
Hoop filaments		38,200	56,000	83,000	113,800	185,400	330,000
Hoop metal		-43,100	0	93,300	187,100	203,000	210,000
Longitudinal metal		0	0	93,300	157,400	210,000	292,000

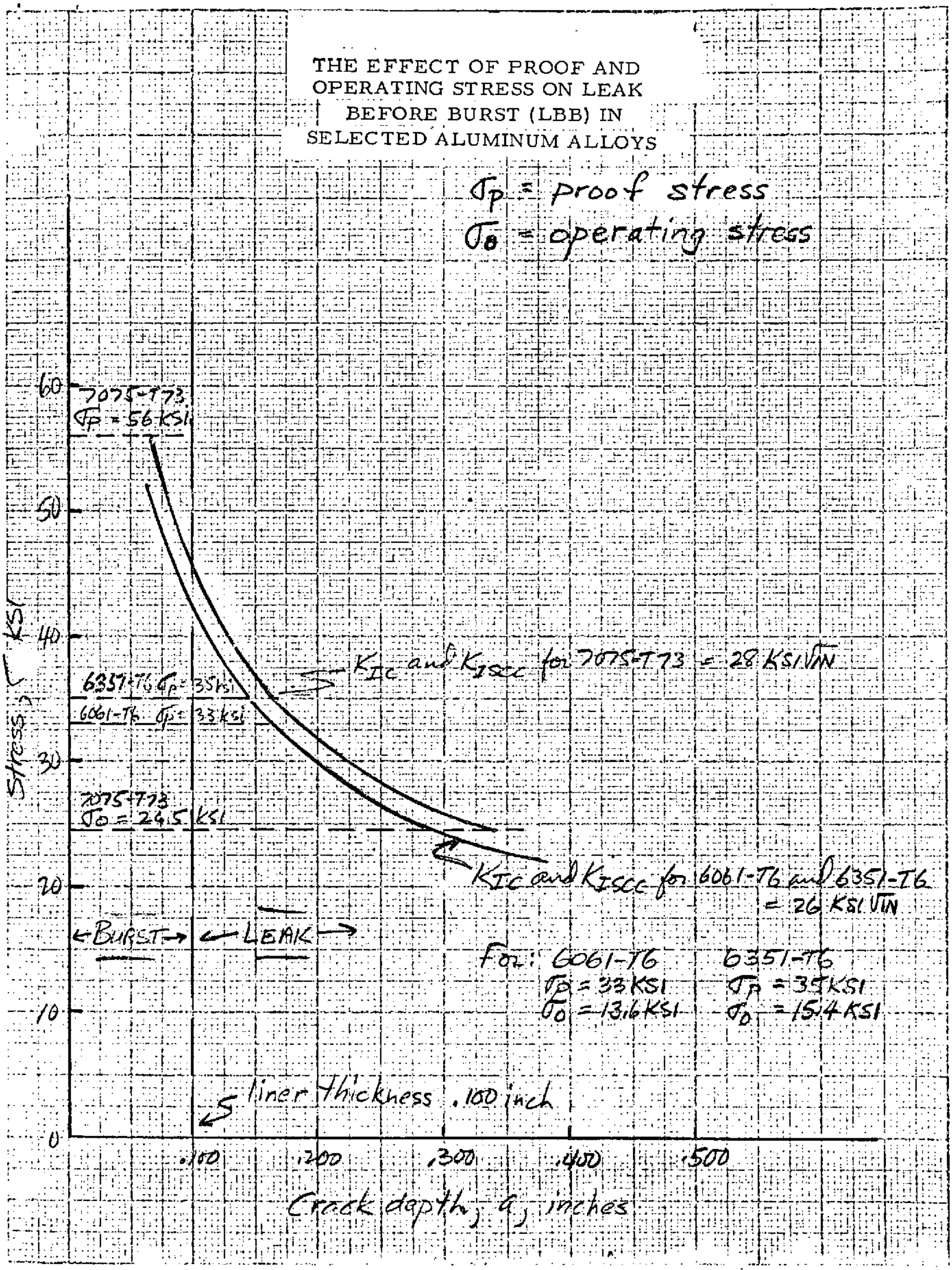
TYPICAL HOOP WRAPPED STEEL VESSEL STRESS STRAIN DIAGRAMS, AND STRESS STATES IN CONSTITUENT MATERIALS AT VARIOUS CONDITIONS

Figure 21



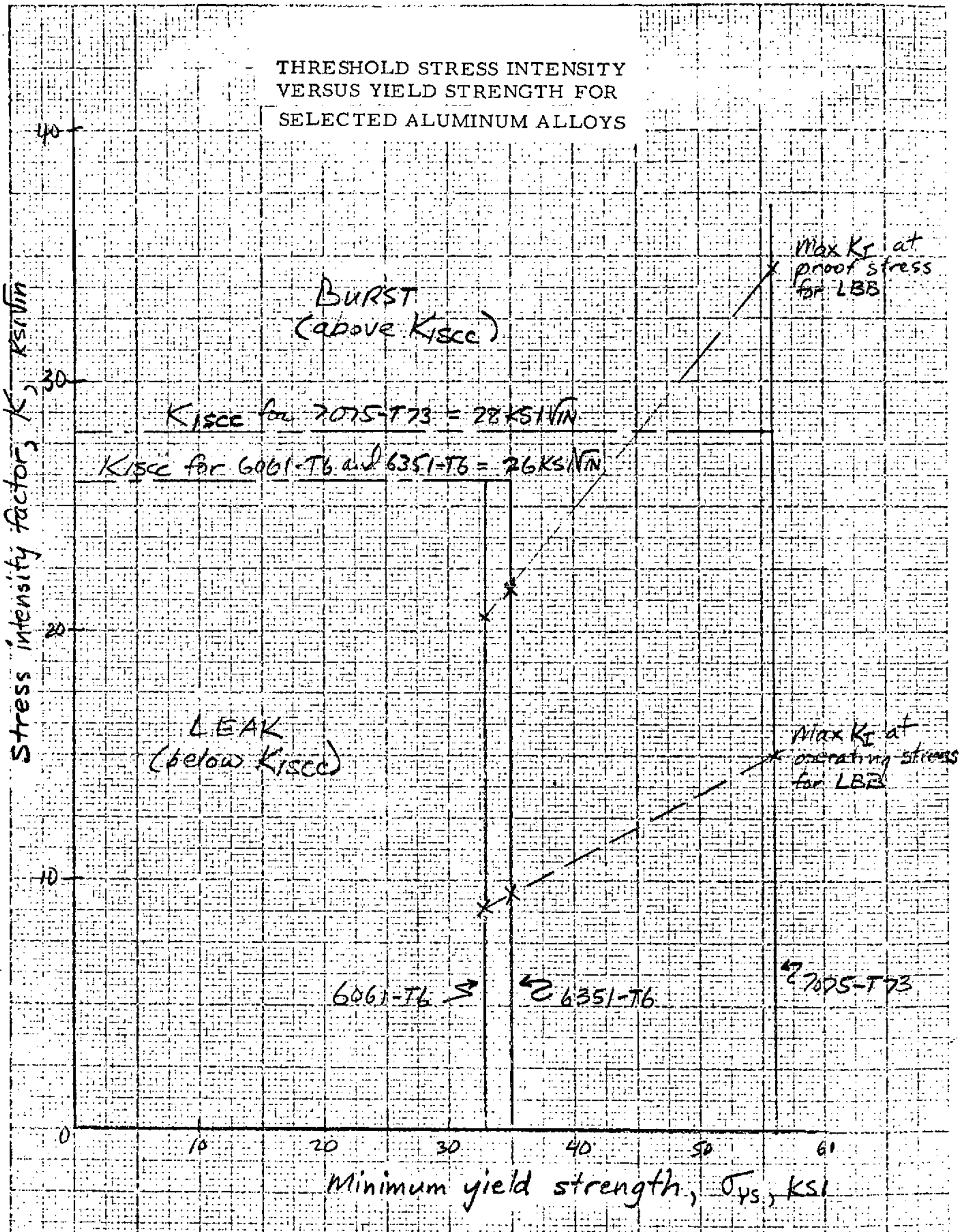
THRESHOLD STRESS INTENSITY VS YIELD STRENGTH
FOR 4340 STEEL
(It is assumed 4130 and D6AC behave similarily)

Figure 22



THE EFFECT OF PROOF AND OPERATING STRESS ON LEAK BEFORE BURST (LBB) IN SELECTED ALUMINUM ALLOYS

Figure 23



THRESHOLD STRESS INTENSITY
VERSUS YIELD STRENGTH FOR
SELECTED ALUMINUM ALLOYS

Figure 24

FATIGUE CRACK GROWTH RATES FOR STEELS IN AIR AND SALT WATER ENVIRONMENTS

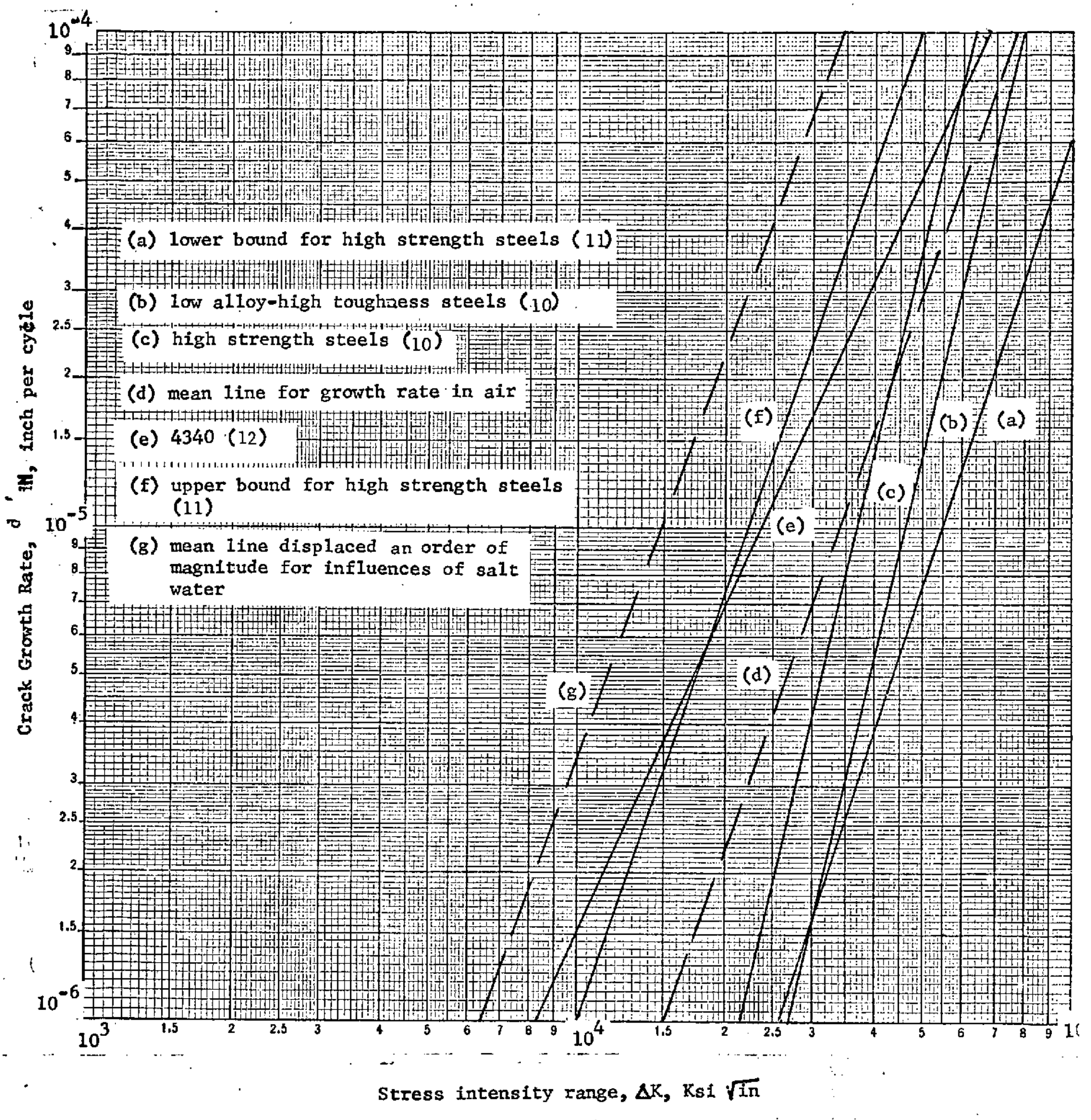


Figure 25

FATIGUE CRACK GROWTH RATES FOR ALUMINUM IN AIR AND SALT WATER ENVIRONMENTS

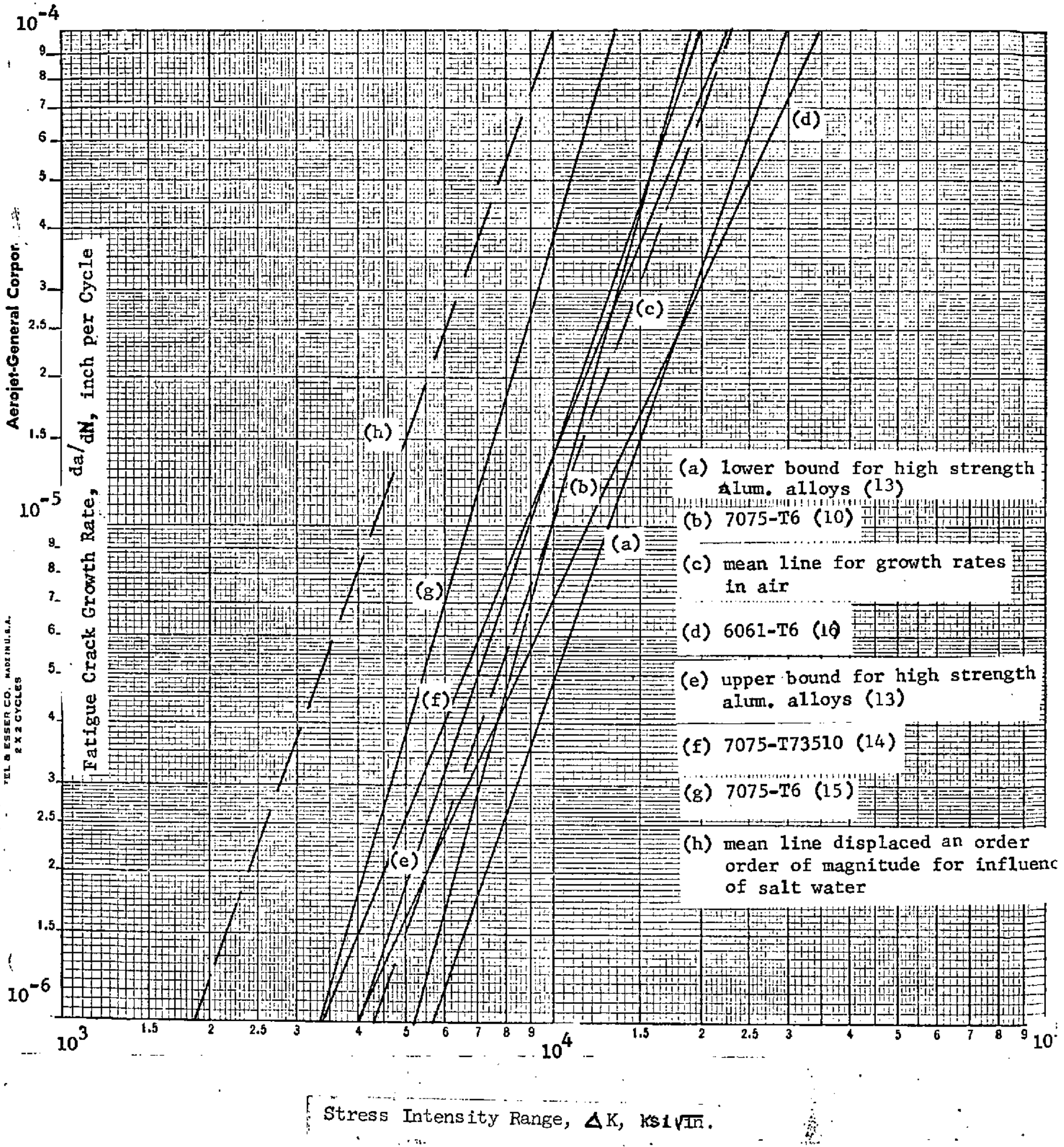
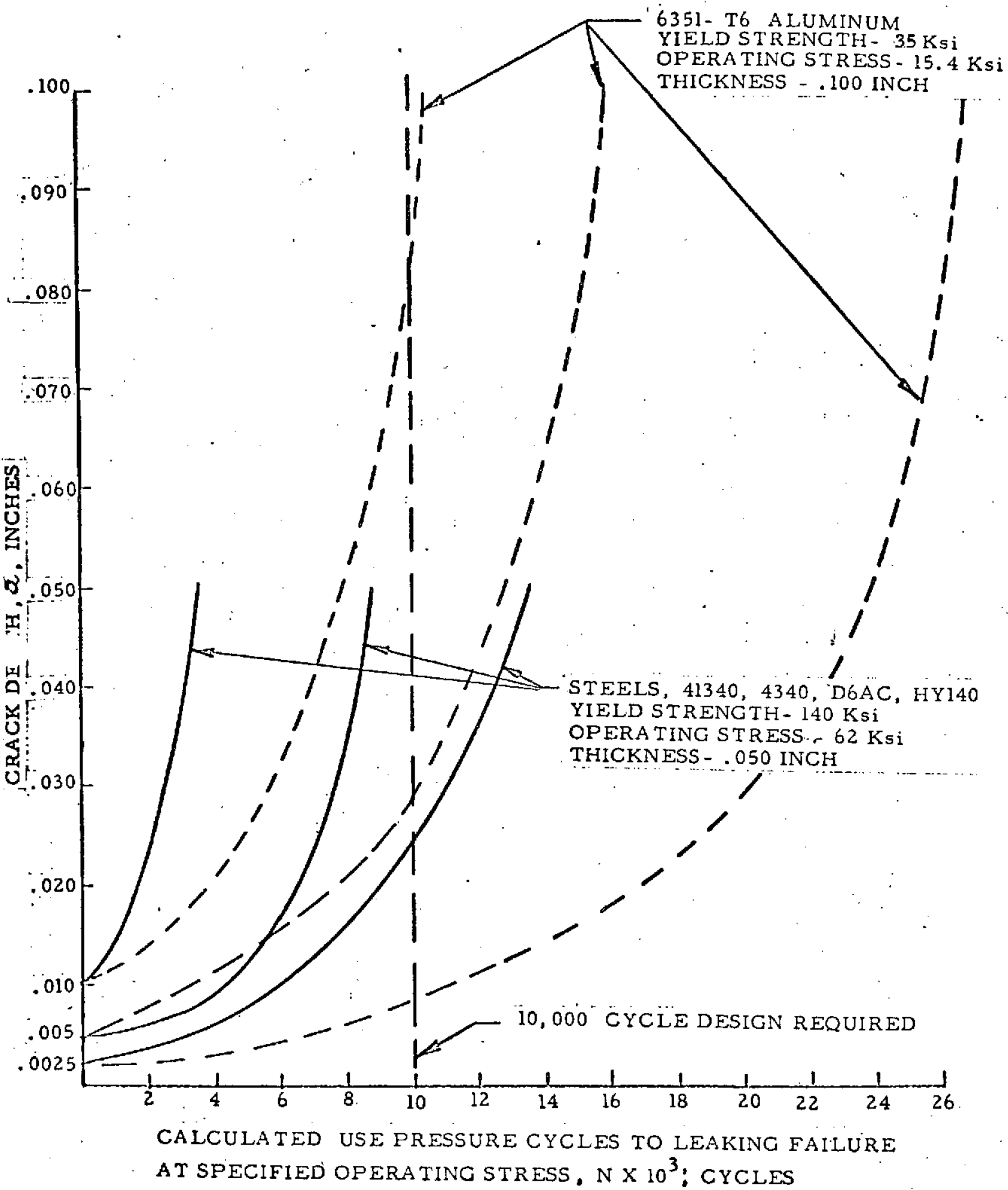


Figure 26



STARTING FLAW SIZE VERSUS CYCLES TO FAILURE FOR
6351-T6 ALUMINUM AND SPEGIFIED STEELS.

Figure 27

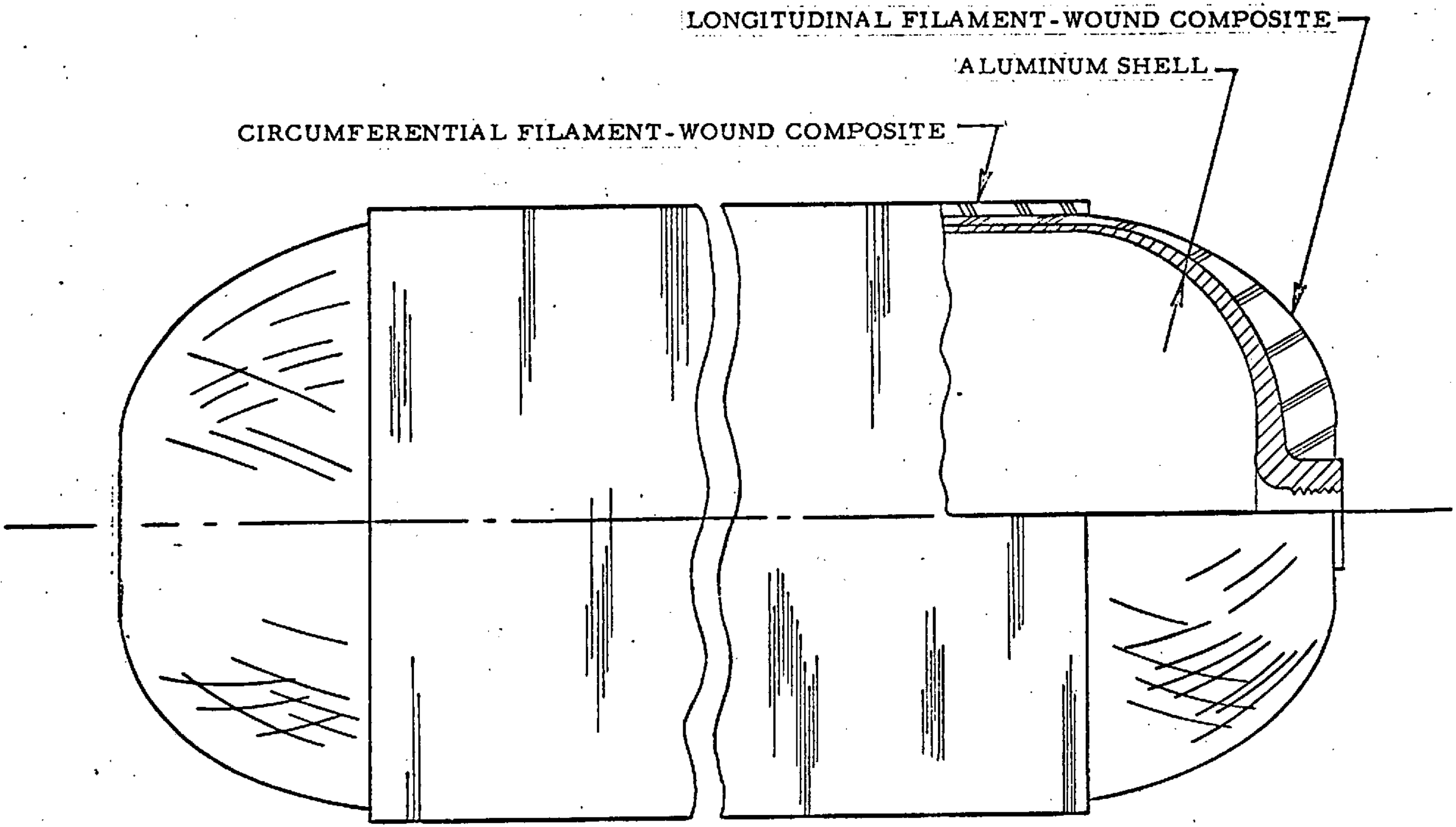


Figure 28

FEATURES OF GFR METAL PRESSURE VESSEL COMPLETELY FILAMENT REINFORCED

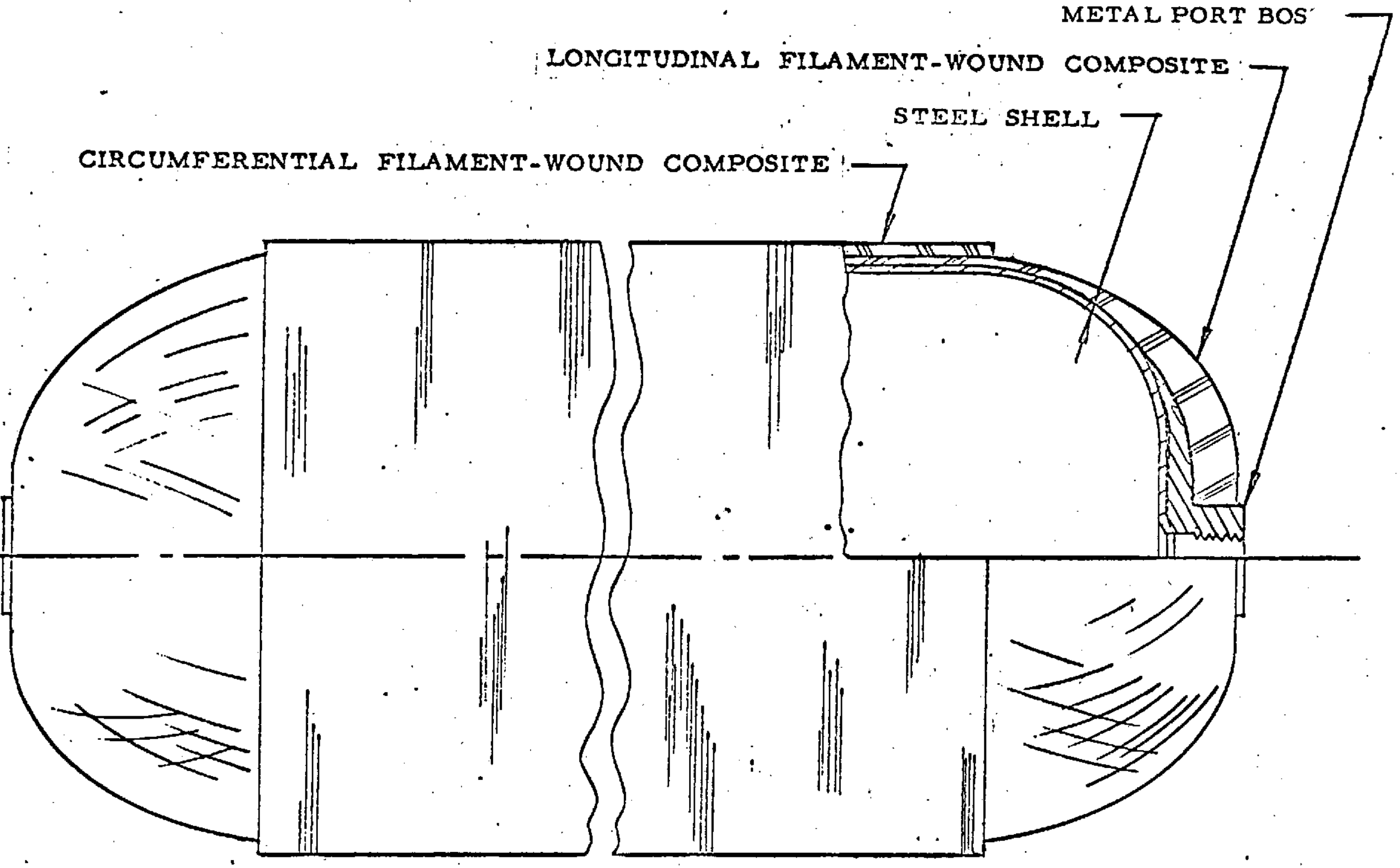


Figure 2

FEATURES OF GFR METAL PRESSURE VESSEL COMPLETELY FILAMENT REINFORCED

The Effect of Type and Strength of Metal and Fiber on the Weight of the Fireman's Breathing Tank for 0.10-in. Thick Aluminum and 0.05-in. Thick Steel Liners

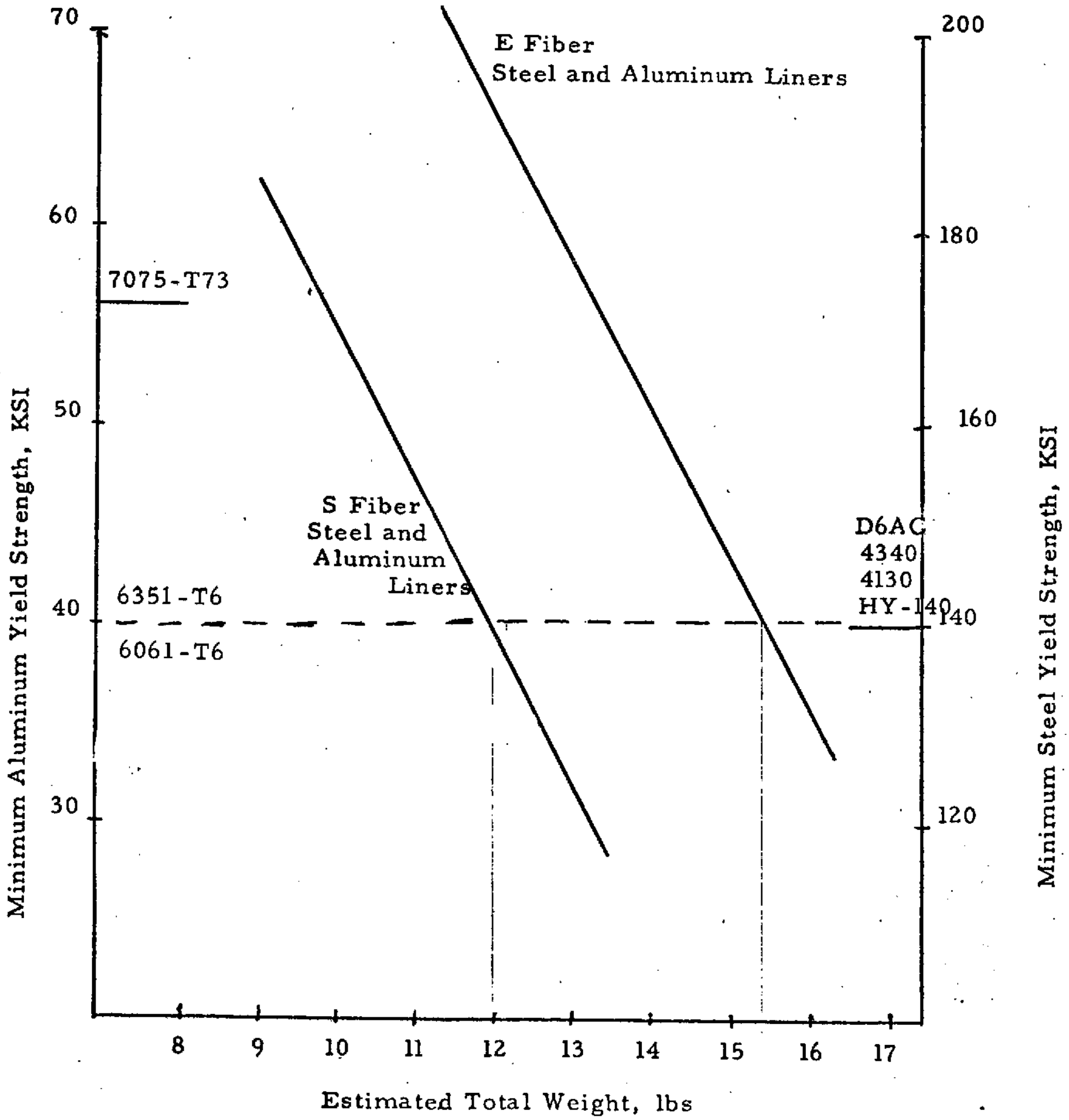


Figure 30

The Effect of Type and Strength of Metal and Fiber on the Length of the Fireman's Breathing Tank using 0.05-in. Thick Steel and 0.10-in. Thick Aluminum Liners

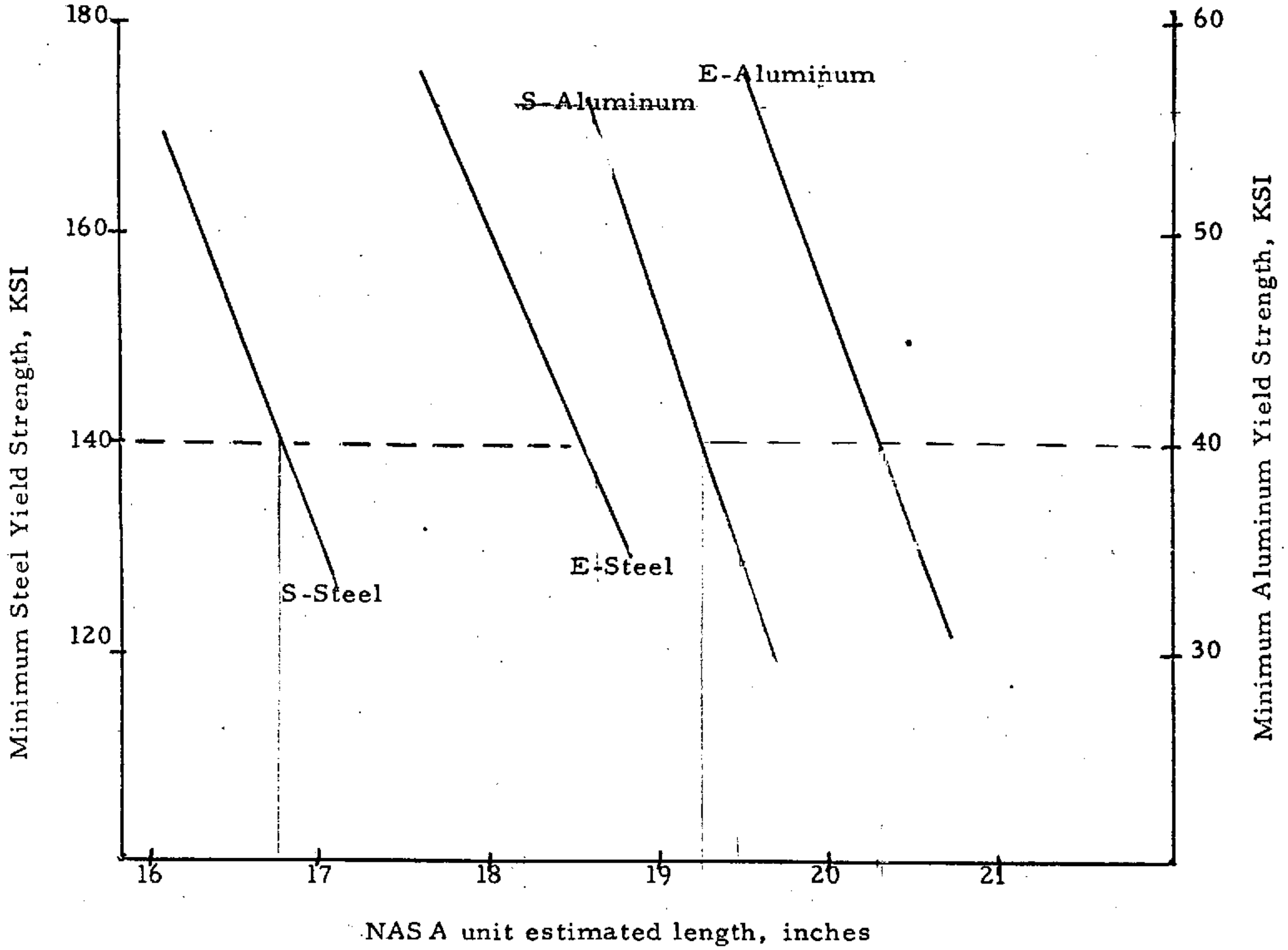
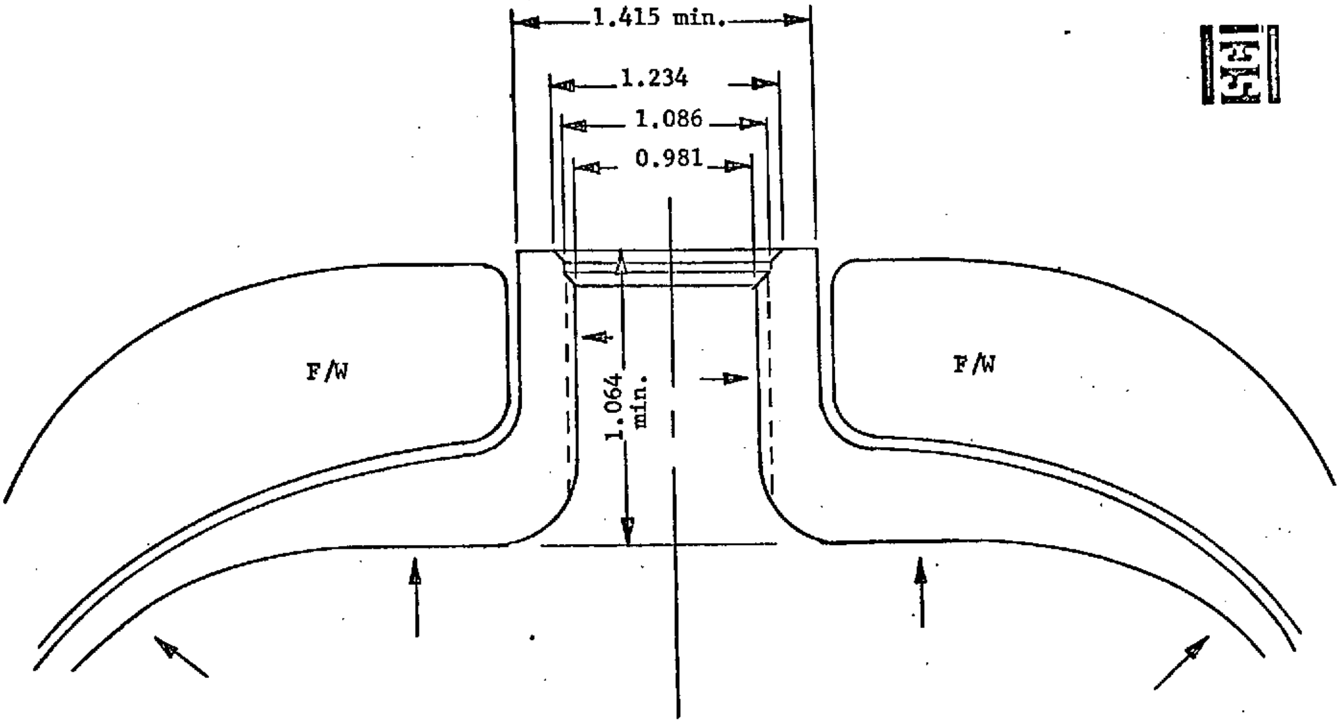


Figure 31



Minimum Boss Dimension Thicknesses, Inches

	Aluminum				Steel			
	6351 -T6		7075 - T73		D6AC - 4340		HY-140 - 4130	
F_{tu}	41,000 (min)		67,000 (min)		175,000 (min)		152,000 (min)	
F_{ty}	35,000 (min)		56,000 (min)		160,000 (min)		140,000 (min)	
Est.Failure Pressure	10,000 psi	16,000 psi	10,000 psi	16,000 psi	10,000 psi	16,000 psi	10,000 psi	16,000 psi
Shear Failure	0.173	0.276	0.106	0.169	0.040	0.064	0.047	0.074
Bending Failure	0.293	0.371	0.229	0.290	0.142	0.179	0.152	0.193
Tension Failure	0.065	0.104	0.040	0.065	0.015	0.024	0.018	0.028
Thread Length	0.26	0.42	0.16	0.26	0.061	0.098	0.070	0.112
Min. AND Thread Requirement	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217

Figure 32

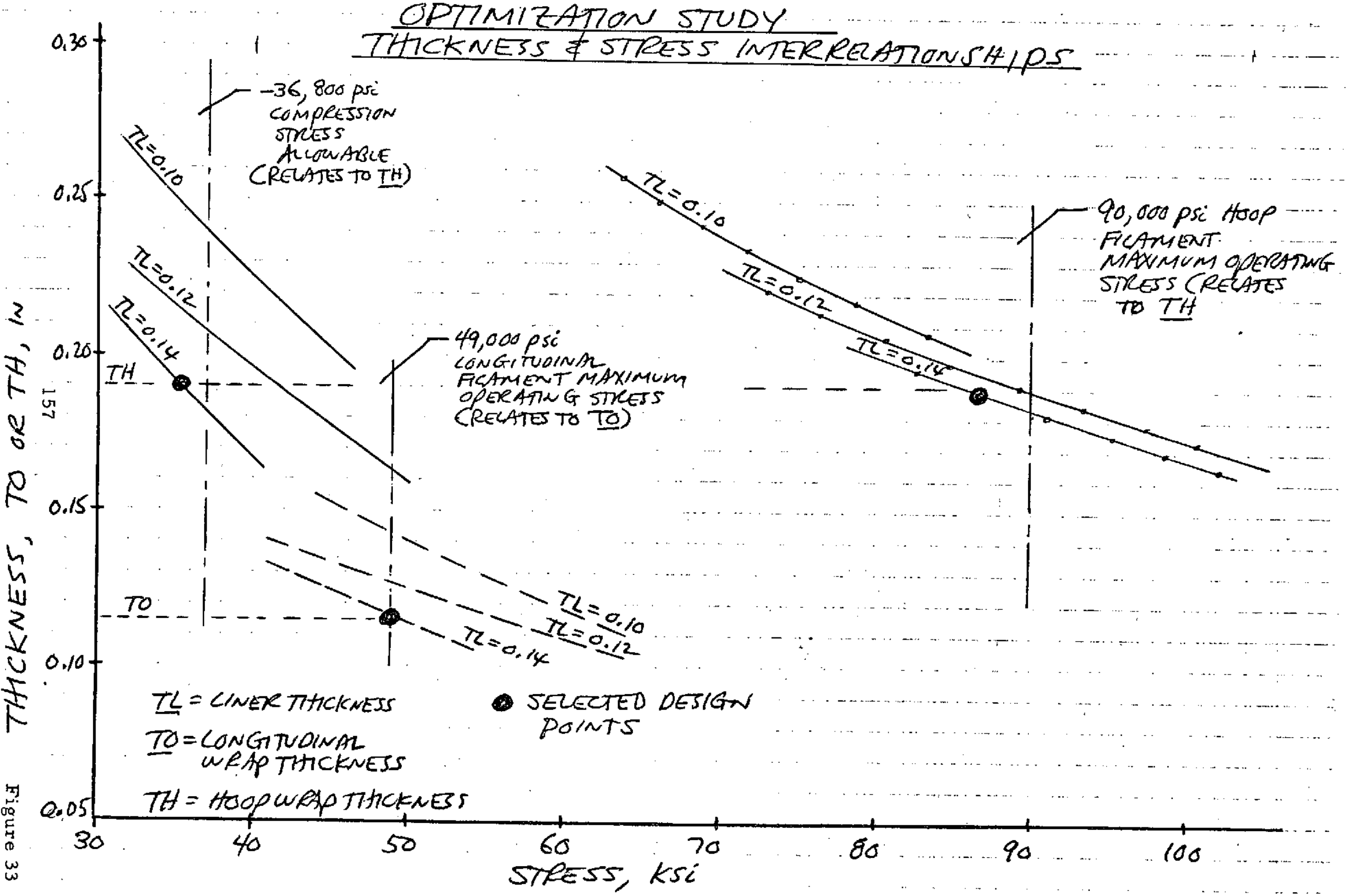
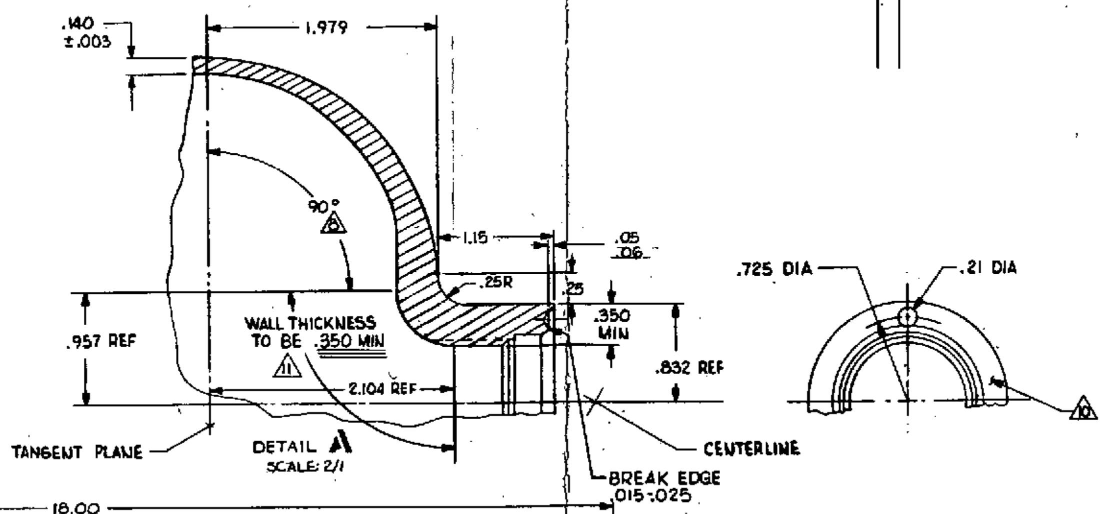

OPTIMIZATION STUDY
THICKNESS & STRESS INTERRELATIONSHIPS
THICKNESS, TO or TH, IN
STRESS, ksi
0.30
0.25
0.20
0.15
0.10
0.05
30
40
50
60
70
80
90
100
TL=0.10
TL=0.12
TL=0.14
TH
TO
-36,800 psi COMPRESSION STRESS ALLOWABLE (RELATES TO TH)
49,000 psi LONGITUDINAL FILAMENT MAXIMUM OPERATING STRESS (RELATES TO TO)
90,000 psi HOOP FILAMENT MAXIMUM OPERATING STRESS (RELATES TO TH)
TL=0.10
TL=0.12
TL=0.14
TL=0.10
TL=0.12
TL=0.14
TL = LINER THICKNESS
TO = LONGITUDINAL WRAP THICKNESS
TH = HOOP WRAP THICKNESS
● SELECTED DESIGN POINTS

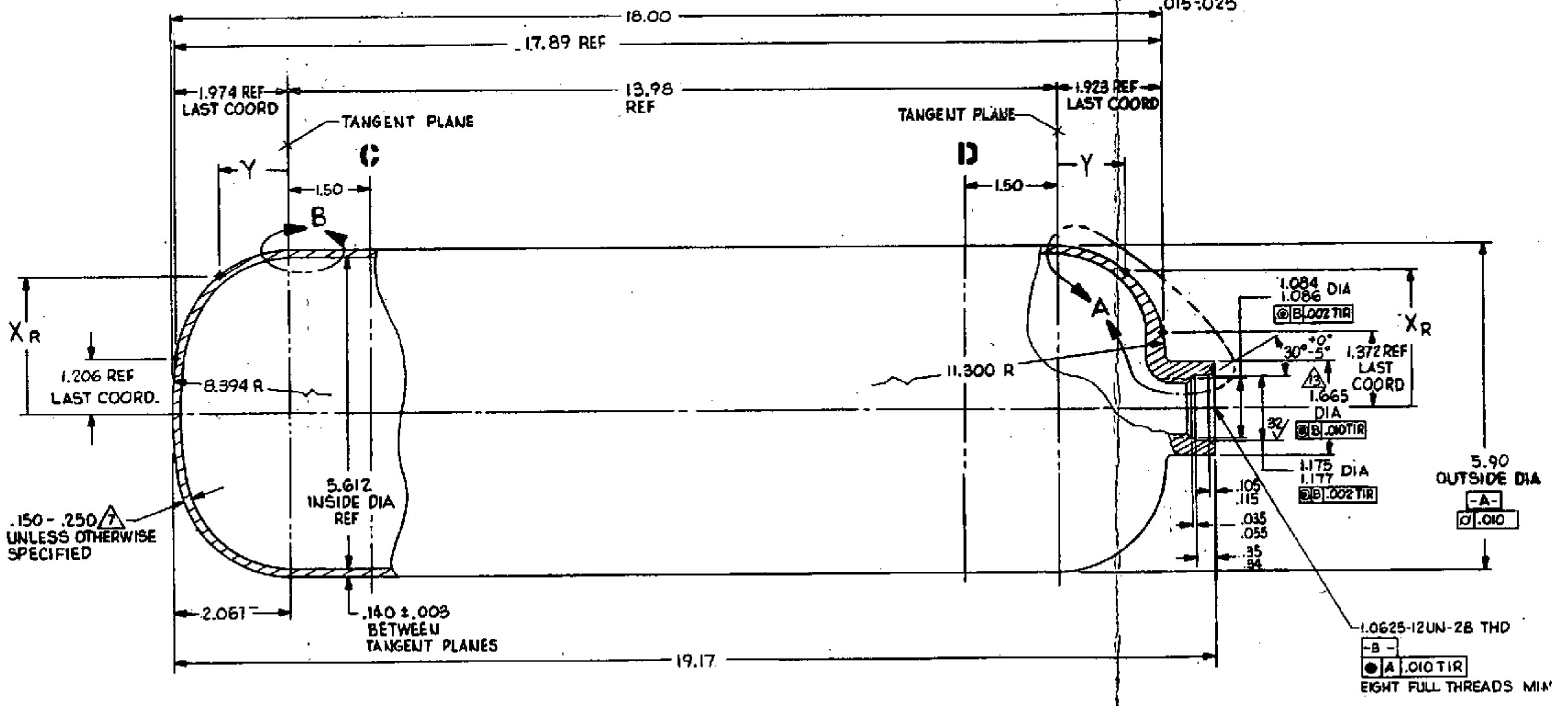
Figure 33

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	SEE DCN	12/6/72	
	B	OU F/D, ZONE D-2, ◎ B .002 TIR OU 1.175 DIA WAS ◎ A .002 TIR	1/12/73	M. CASTILLO
	C	SEE DCN	4/9/73	

NOTES:

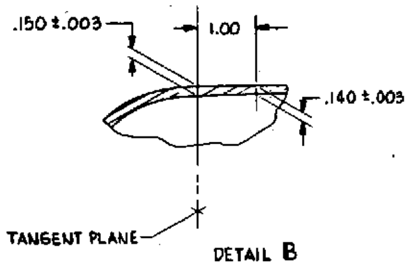
1. REMOVE ALL BURRS AND SHARP EDGES
2. INTERPRET DRAWING PER MIL-D-1000.
3. MATERIAL: 6351-0 ALUMINUM ALLOY SHEET CIRCLE, 0.250 IN. THICK X 18.5 IN. DIAMETER.
4. FABRICATE AND PROCESS IN ACCORDANCE WITH SCI 72-1. .
5. NO SURFACE DEFECTS GREATER THAN 0.005 DEEP PERMITTED. INSPECT EXTERIOR AND INTERIOR SURFACE OF LINER JUST PRIOR TO NECKING OPERATION. INSPECT EXTERIOR SURFACE AFTER FINAL FORMING AND HEAT TREATMENT.
6. SURFACE FINISH TO BE 250 RMS OR BETTER.
7. WALL THICKNESS IN AFT HEAD MAY VARY UNIFORMLY IN THICKNESS FROM .150 AT TANGENT PLANE TO .250 AT THE CENTERLINE.
8. WALL THICKNESS IN BOSS END MAY VARY SMOOTHLY IN THICKNESS FROM .140 AT TANGENT PLANE TO .350 MIN AT .957 FROM CENTERLINE WITH NO UNDERCUT ALLOWED.
9. LINER WEIGHT 5.7 ± 0.2 LBS (REF ONLY).
10. PERMANENTLY APPLY MANUFACTURER'S SERIAL NO.
11. GENTLE FORMING FOLDS PERMITTED ON INTERIOR SURFACE OF BOSS END.
12. PLANES C & D IN A RESTRAINED POSITION DEFINES -A- .
13. MACHINING DISCONTINUITY SHALL NOT EXCEED .060.





OUTSIDE CONTOUR FOR AFT END	
Y	X_R
0.029	2.946
0.263	2.929
0.496	2.882
0.758	2.793
1.019	2.660
1.250	2.496
1.506	2.245
1.754	1.882
1.882	1.591
1.958	1.309
1.974	1.206

OUTSIDE CONTOUR OF BOSS END	
Y	X_R
0.029	2.946
0.263	2.928
0.496	2.882
0.758	2.793
1.018	2.660
1.248	2.498
1.502	2.251
1.612	2.112
1.745	1.904
1.864	1.642
1.901	1.516
1.923	1.372



QTY REQD	SYM	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	UNIT WT.	ZONE	ITEM NO.
			-1	LINER	6351-T6 AL ALY	AA6351			

LIST OF MATERIALS

PART DASH NO.	NEXT QTY	FINAL REQD	NEXT ASSY	USED ON
-1	1	1	1269367-2	1269343
-1	1	1	1269367-1	1269343

APPLICATION

DRAWING LEVEL 0

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE ON DECIMALS ANGULAR
.XX ± .03 ± 2°
.XXX ± .010
DO NOT SCALE DRAWING

TREATMENT

FINISH

SIMILAR TO 1269302

ACT. WT. CALC WT

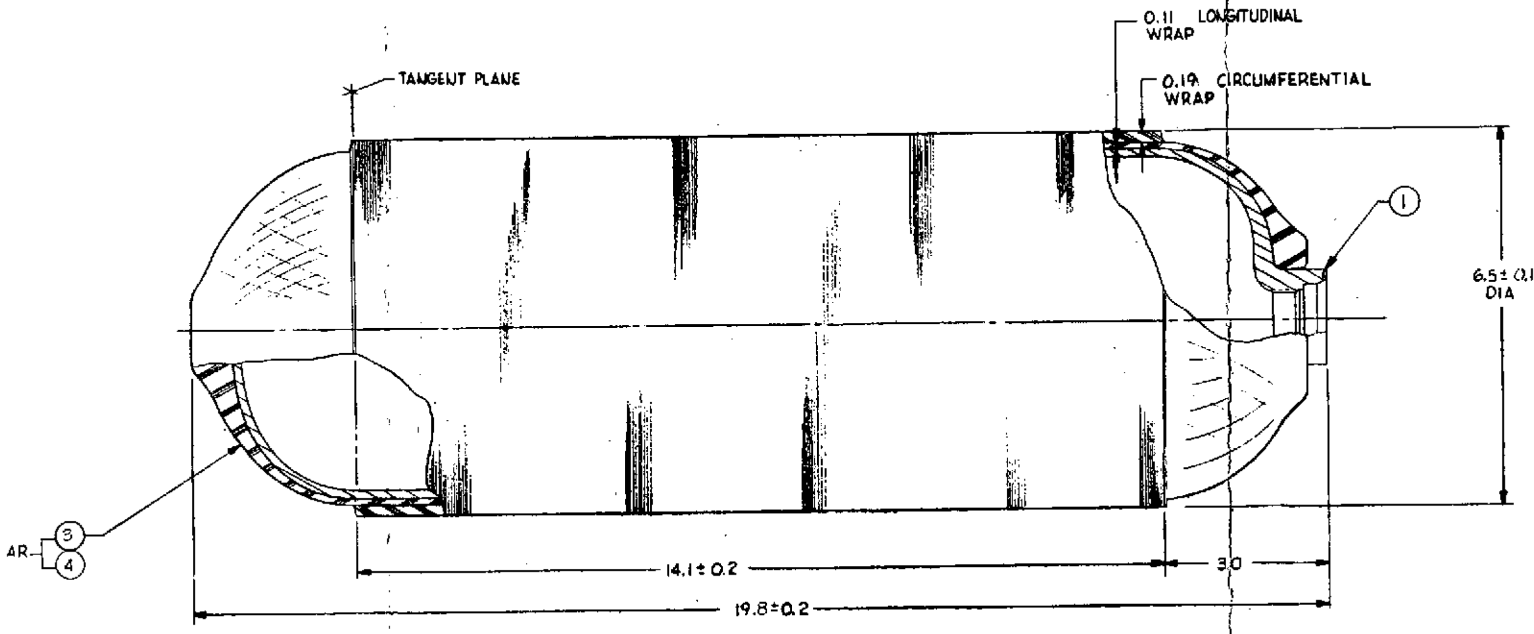
CONTRACT NO. 2001
DRAWN M.R. CASTILLO 11-15-72

TITLE
LINER, SWAGED BOSS,
ALUMINUM ALLOY -
GFR TANK

DWG SIZE E
CODE IDENT NO. 3
DWG NO. 1269345
SCALE 1/1
REL DATE 11-15-72

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	SEE DCN	[illegible]	[illegible]

NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. INTERPRET DRAWING PER MIL-D-1000.
3. APPLY WINDINGS AND PROCESS PER SPECIFICATION SCI 73-13.
4. ACCEPTANCE TEST COMPLETED TANK PER SPECIFICATION SCI 73-13
5. INTERNAL VOLUME (UNPRESSURIZED): 408 ± 5 CU. IN.
6. WEIGHT: 13.4 ± 0.6 LBS.



QTY REQD -1	SYM	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL
AR				RESIN	EPOXY
AR				GLASS ROVING	
1			1269345-1	LINER	

LIST OF MATERIALS

-1			1269543-3	—
			NEXT ASSY	USED ON
			APPLICATION	

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE ON DECIMALS ANGULAR ± 2°
.XX ± .03
.XXX ± .010
DO NOT SCALE DRAWING
TREATMENT
FINISH
SIMILAR TO 1269303

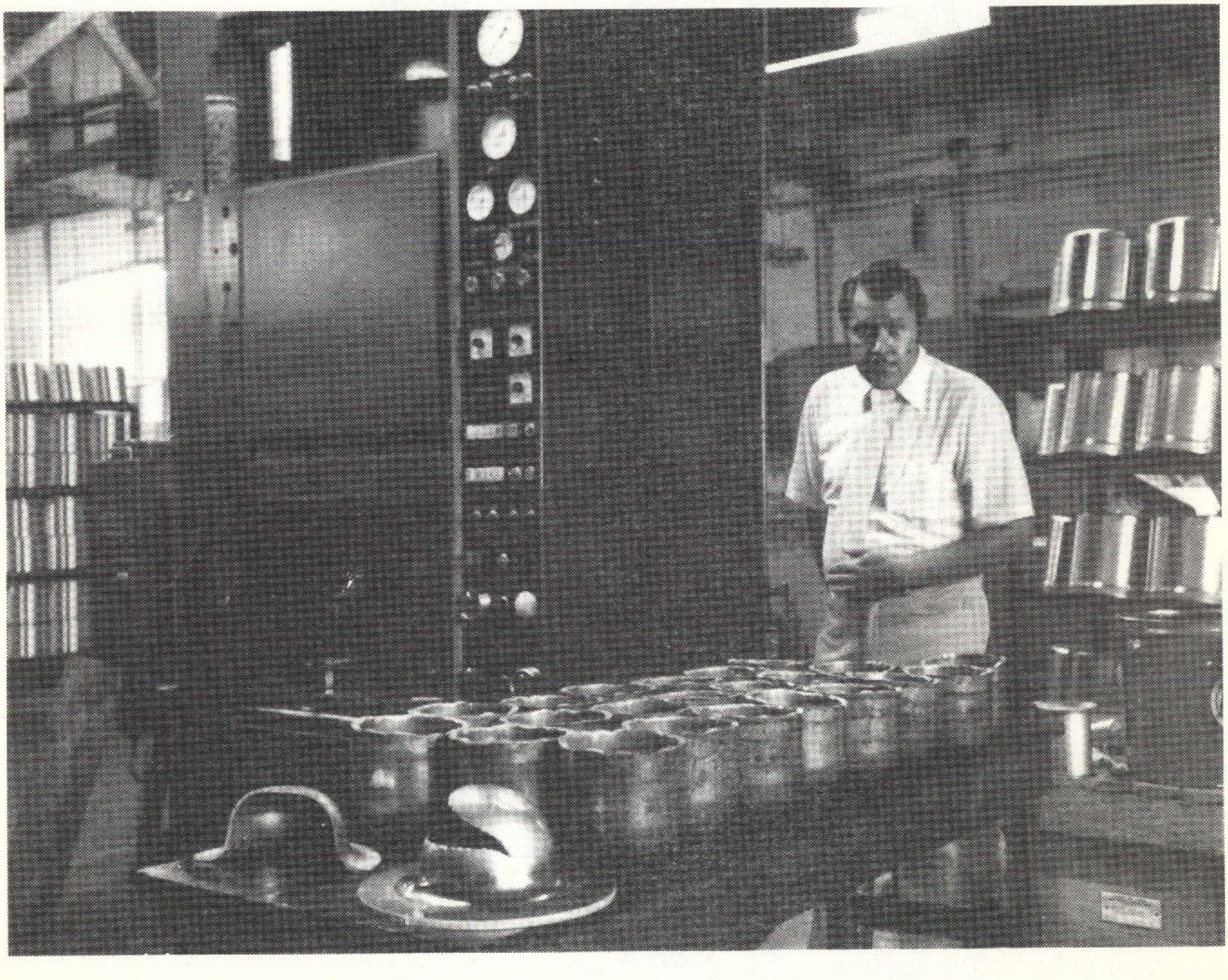
CONTRACT NO. 2001
DRAWN M.R. CASTILLO 4-17-73
4-17-73
EEMORRIS 4-17-73

TITLE IMPROVED FIRE[illegible]
TANK, GLASS-[illegible]
ALUMINUM ALLOY-SWAGED BOSS
SIZE E
367
SCALE 4-17-73

FOLDOUT FRAME 2

FOLDOUT FRAME

A



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

HYDRO FORMED PARTS AND PRESS

Figure 36

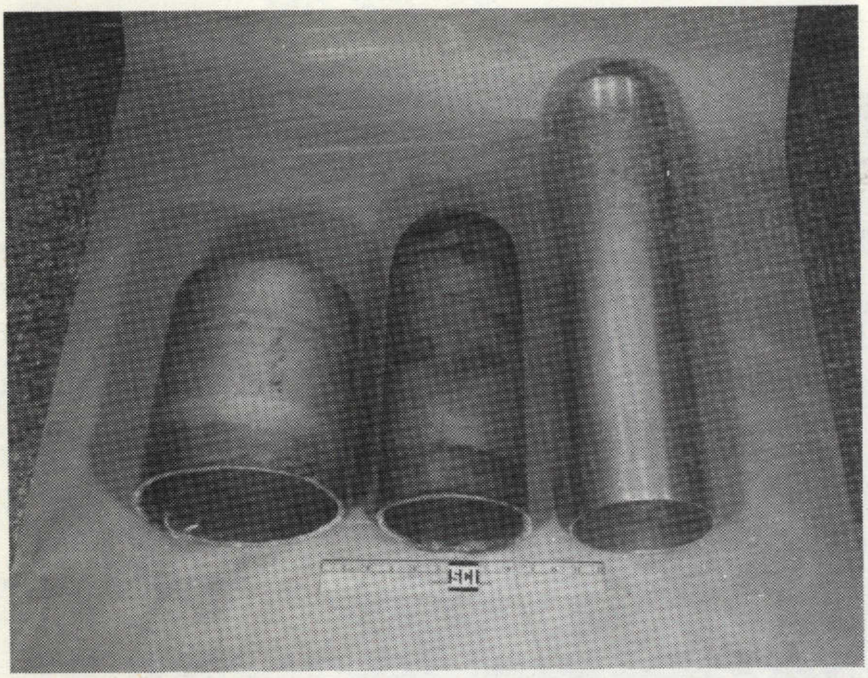
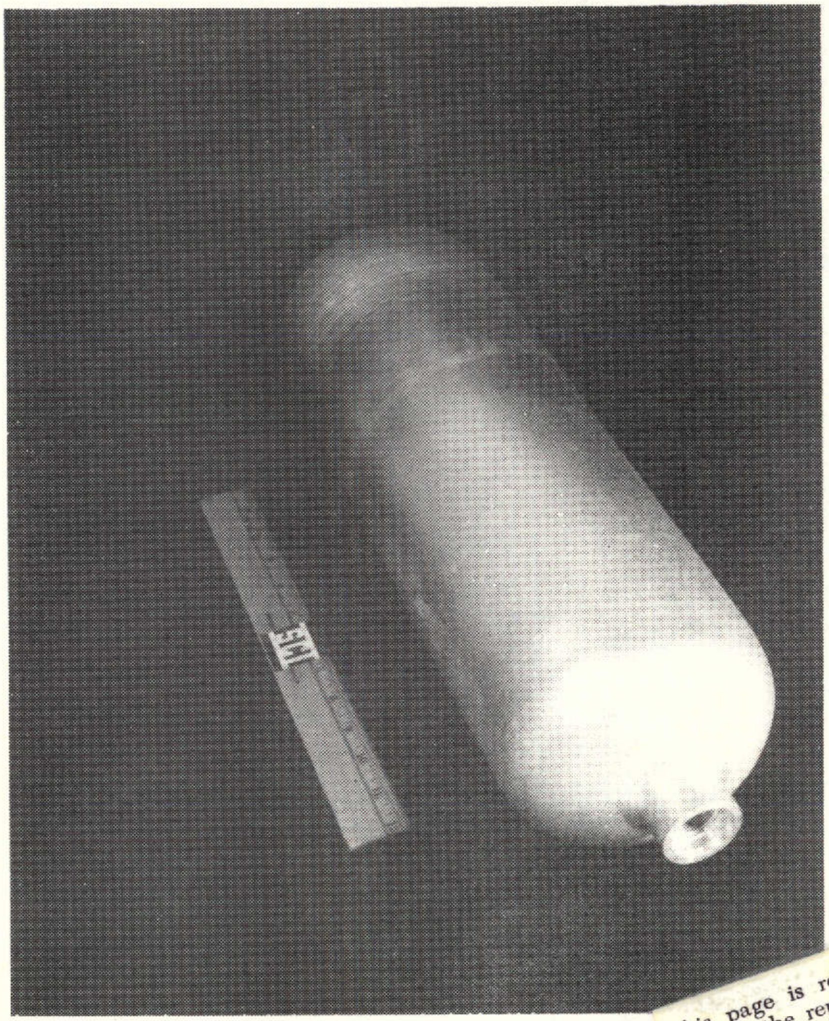


Figure 37 - Aluminum Liner Forming Stages

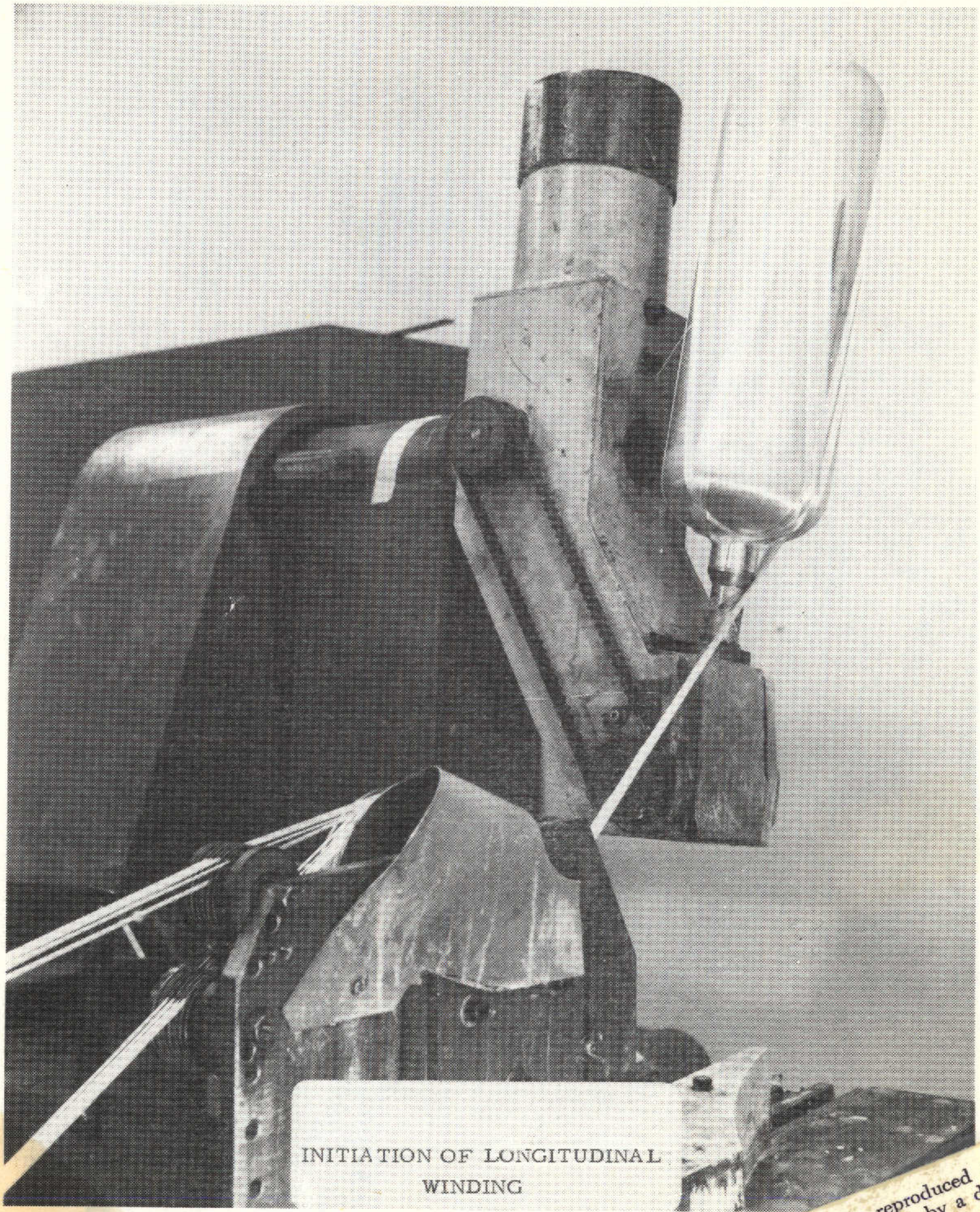
Figure 38 - Aluminum Liner Forming Stages

Figures 37 and 38



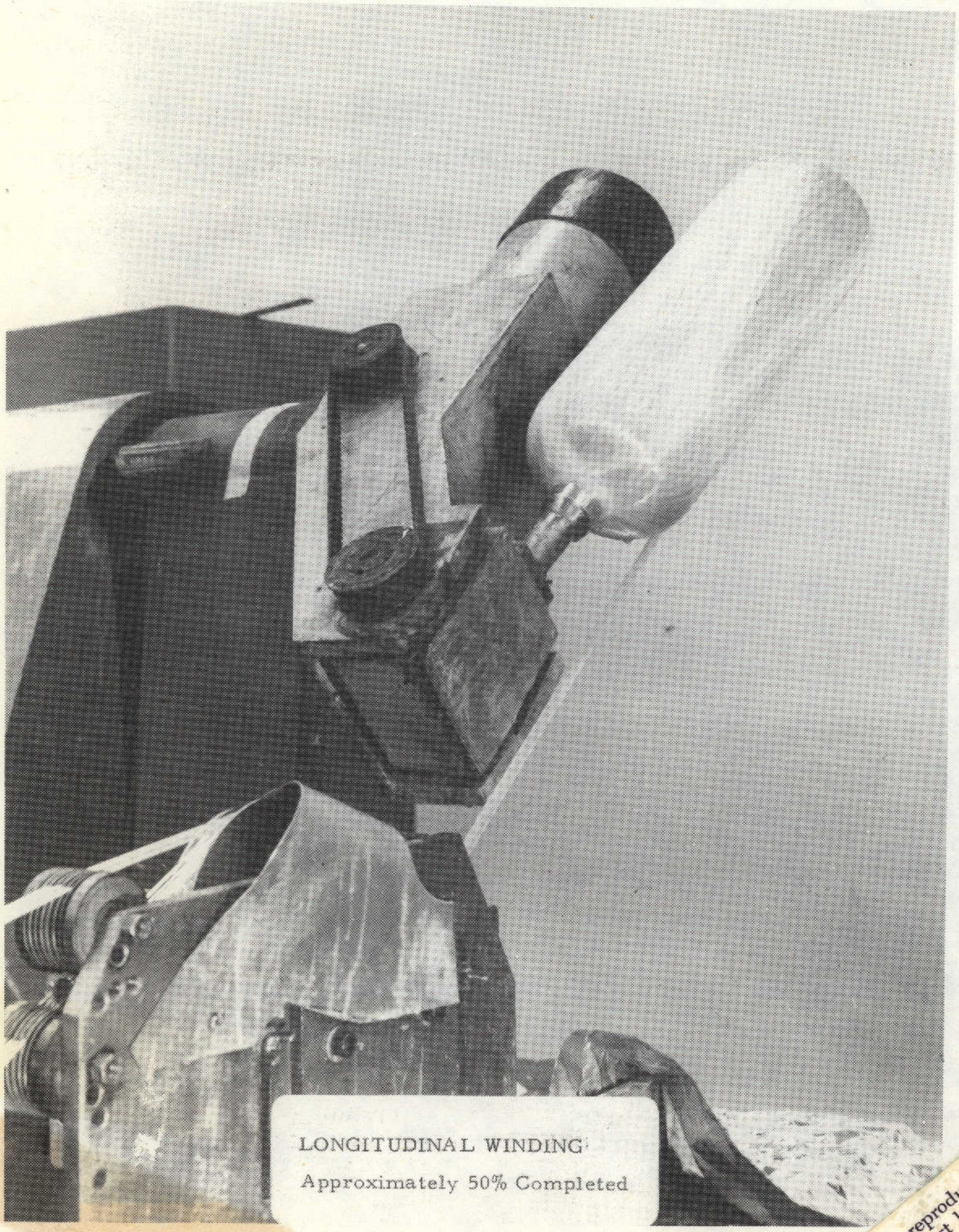
Final Liner Shape - Boss End

Figure 39



INITIATION OF LONGITUDINAL WINDING

Figure 41

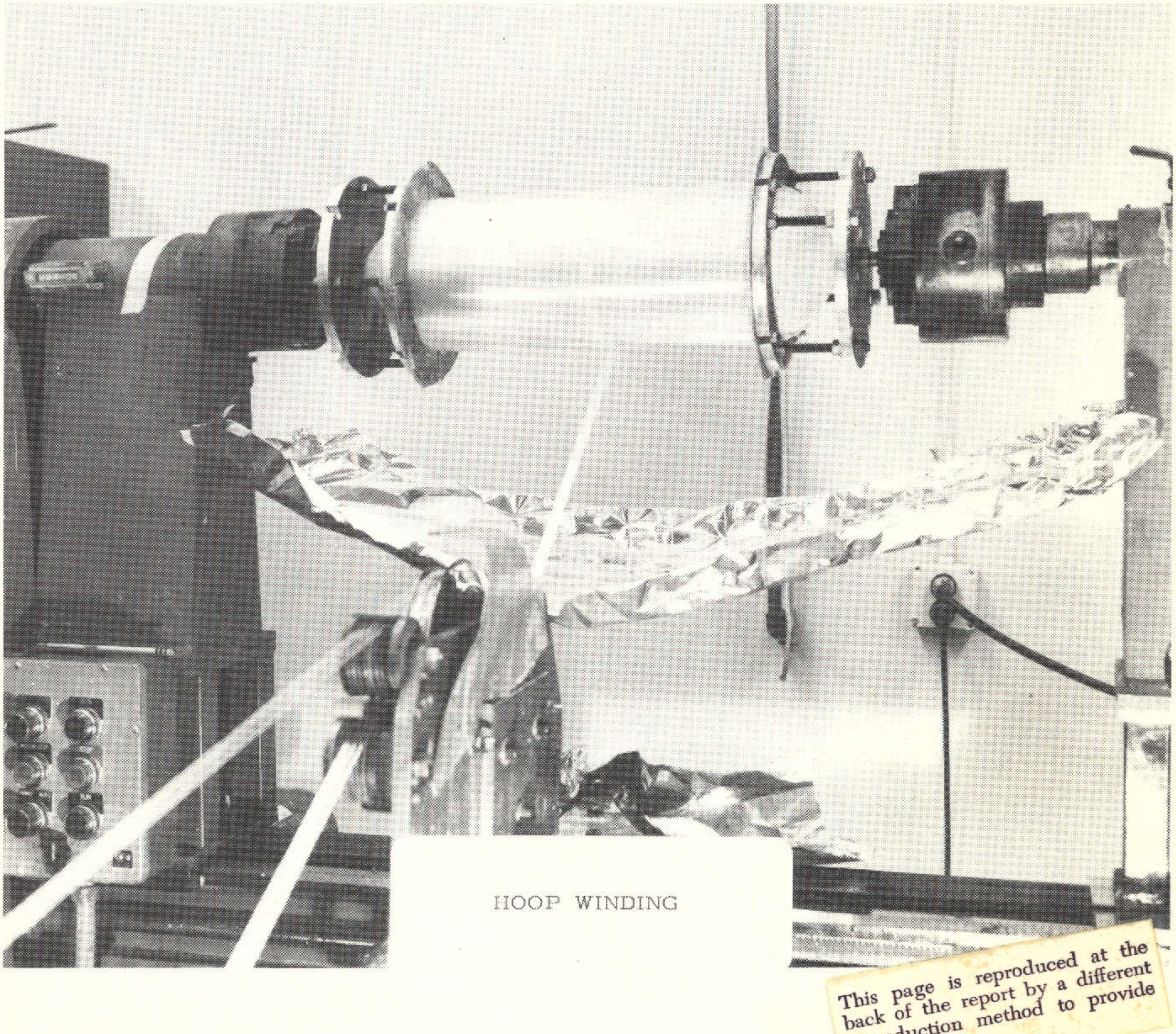


LONGITUDINAL WINDING

Approximately 50% Completed

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

Figure 42



HOOP WINDING

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

Figure 43

FABRICATION METHOD FOR NASA FIREMAN'S BREATHING TANK

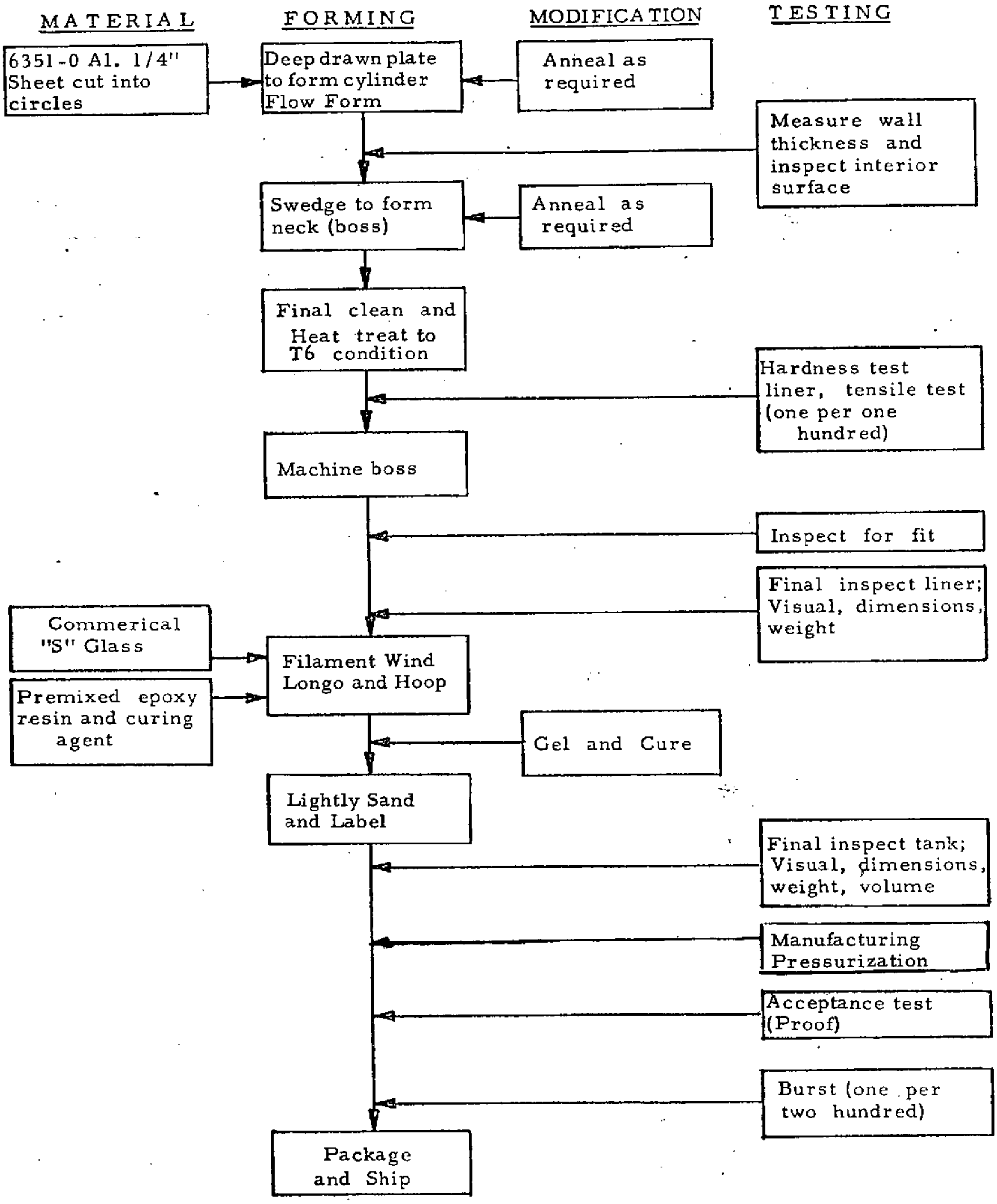
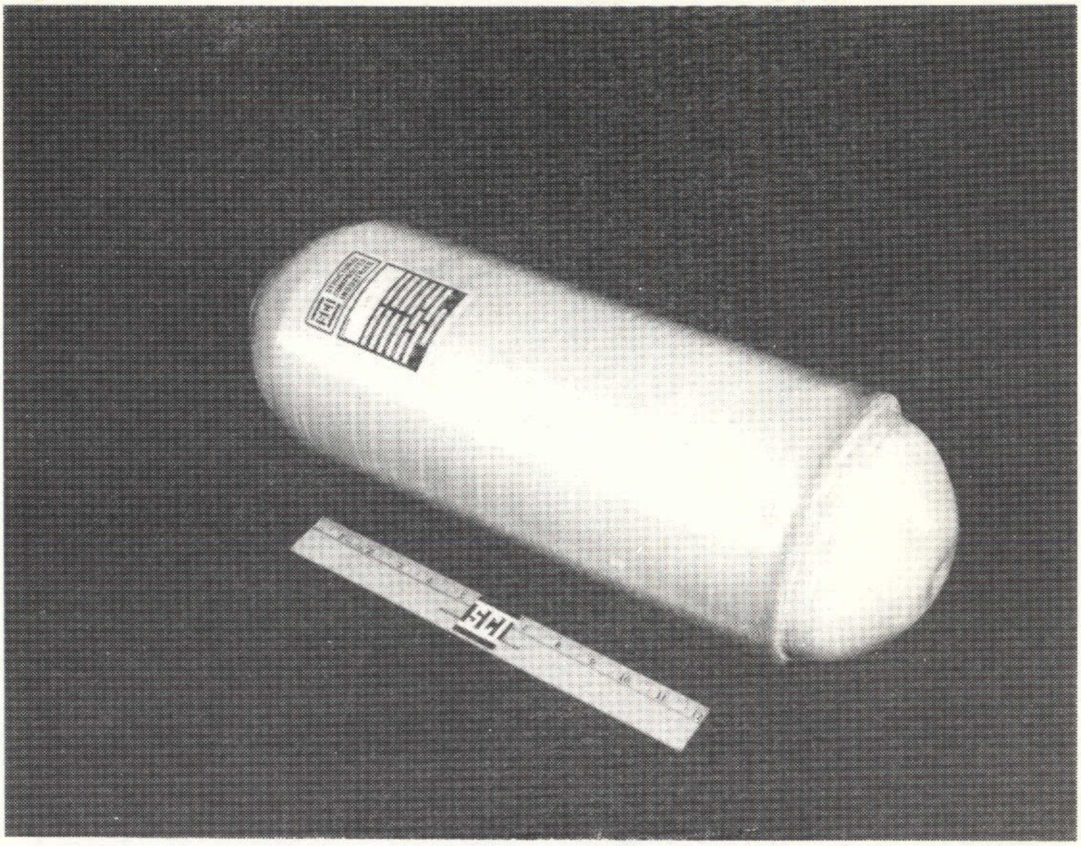
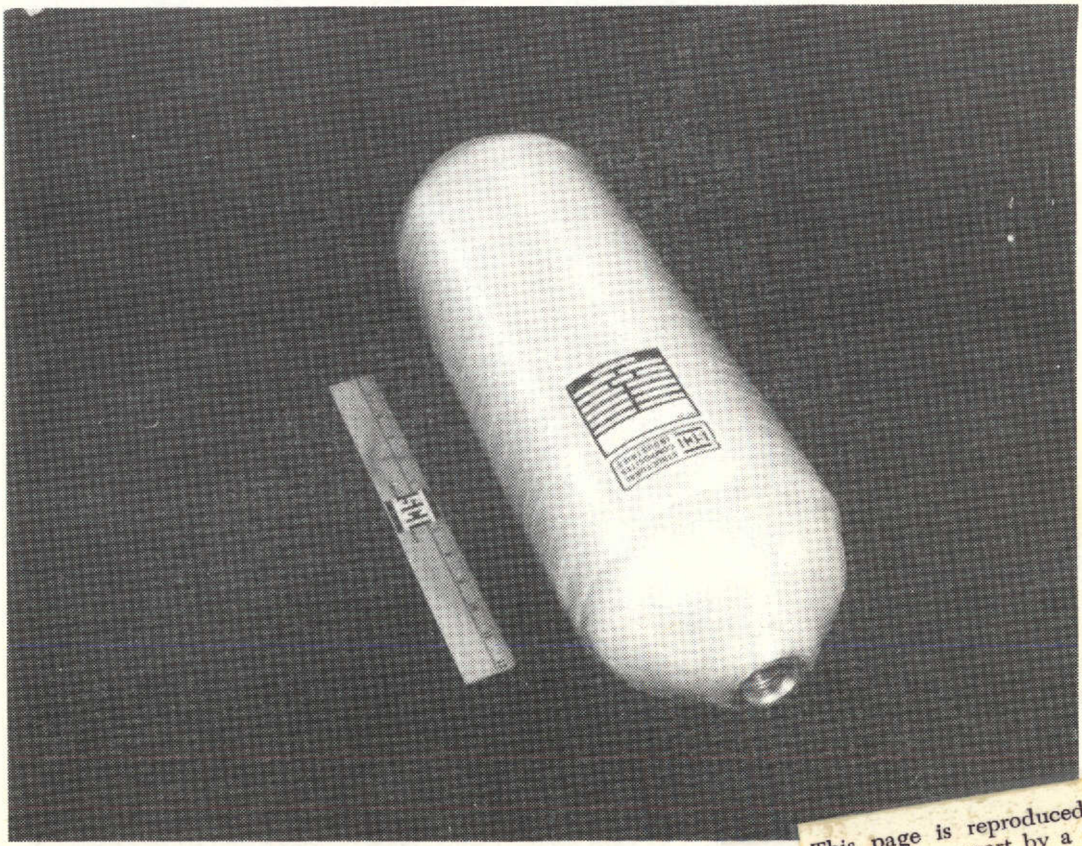


Figure 44



Full Scale Tank



Full Scale Tank - Boss End

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

Figure 45

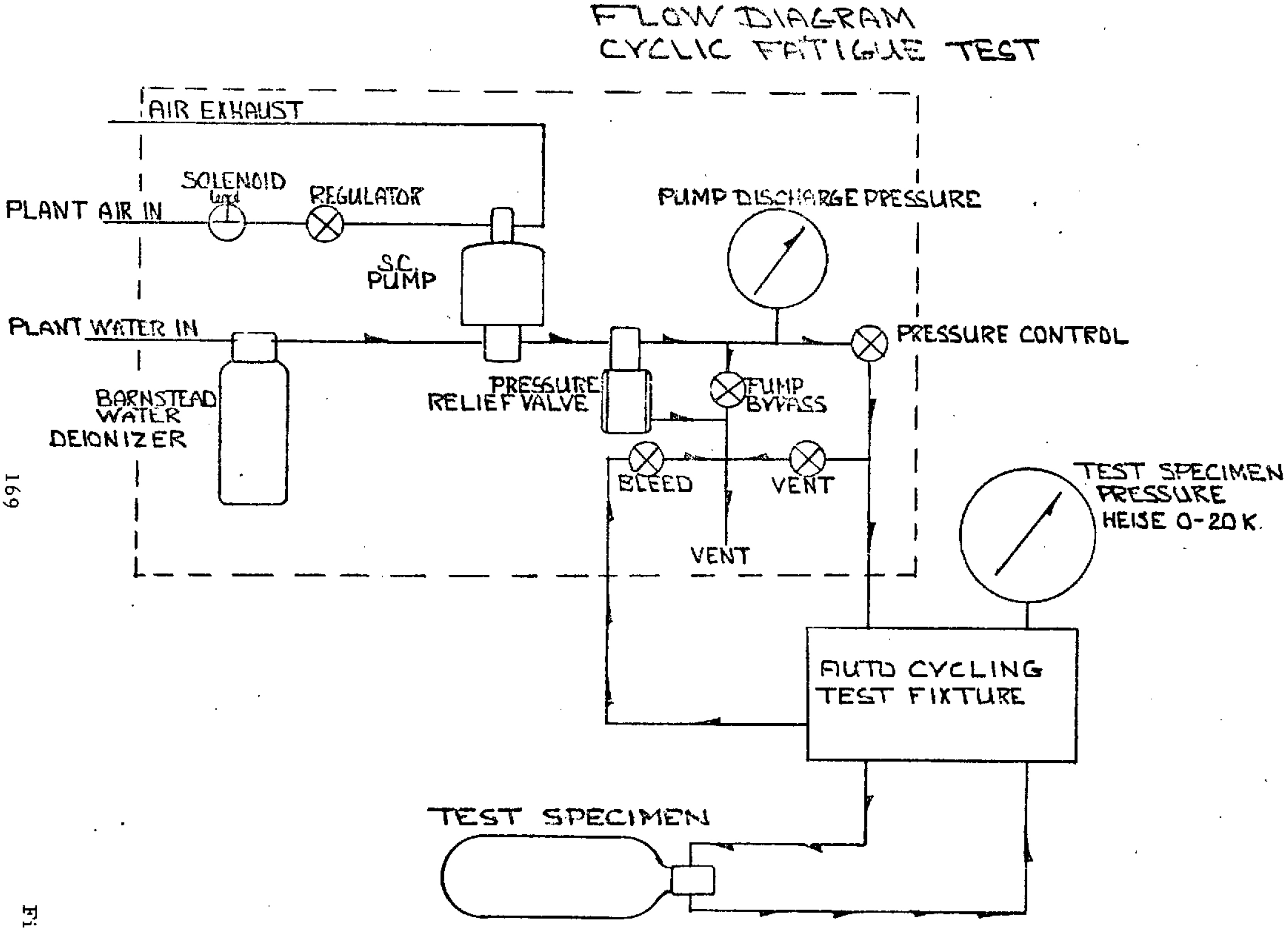
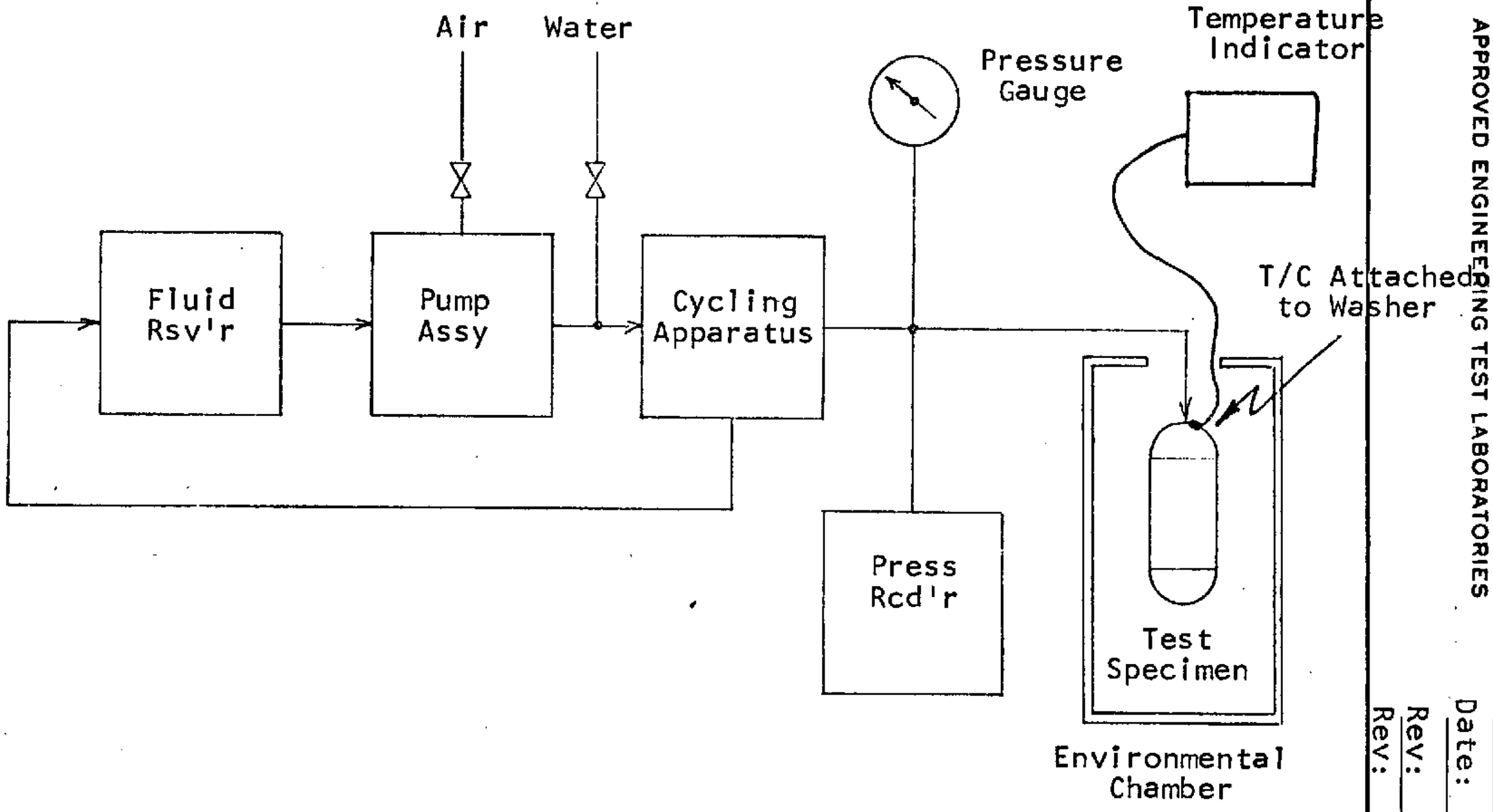


Figure 46

5/4/73



SCI CYCLIC FATIGUE TEST SYSTEM

Figure 47

STRUCTURAL COMPOSITES INDUSTRIES, INC.

PRESSURE VESSEL
ACCEPTANCE TEST PROCEDURE DATA SHEET

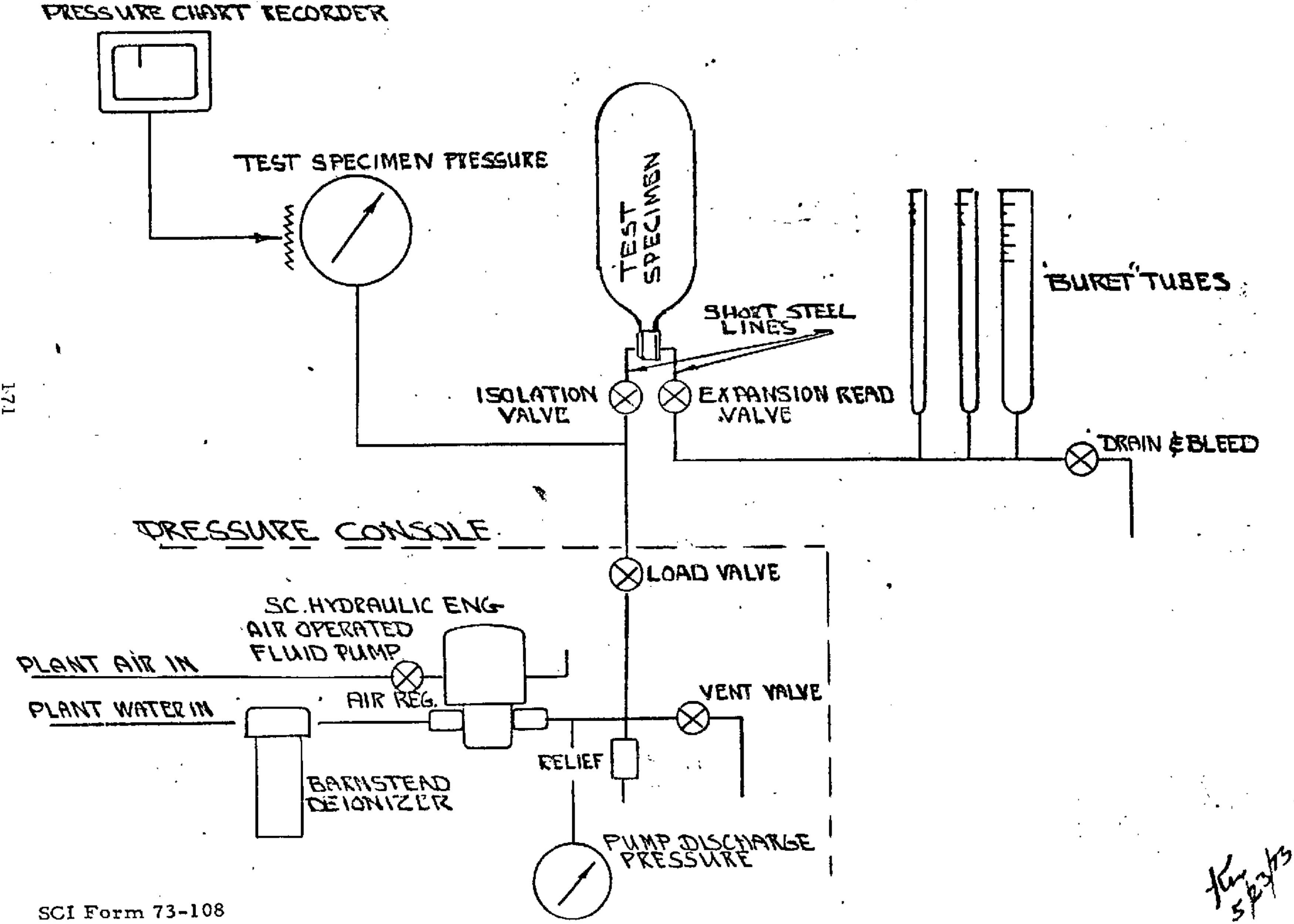
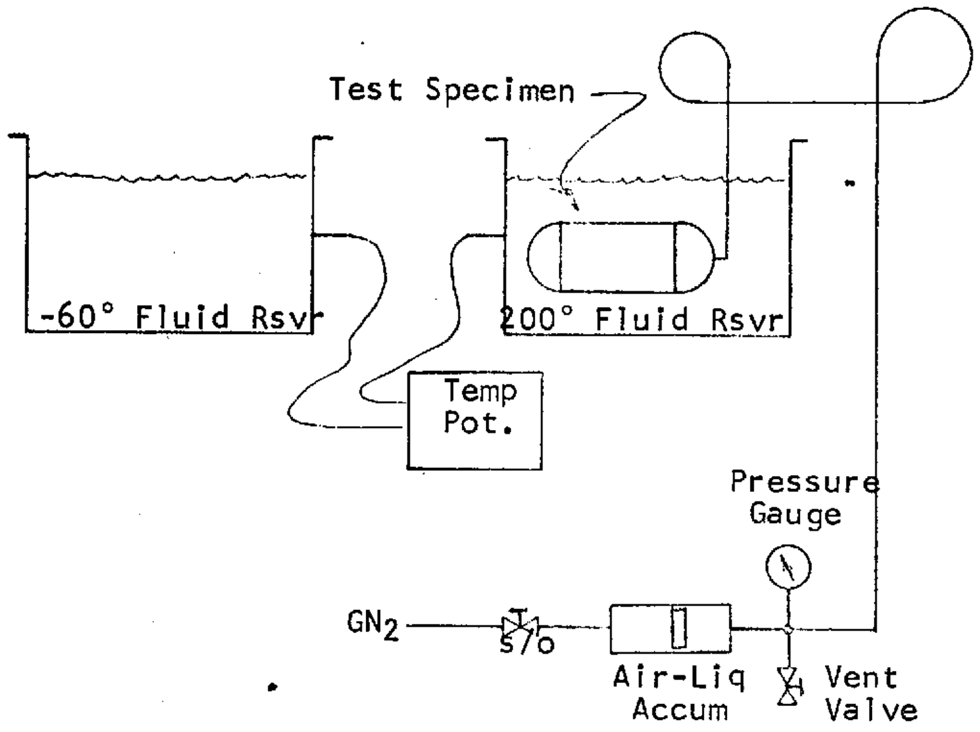


Figure 48

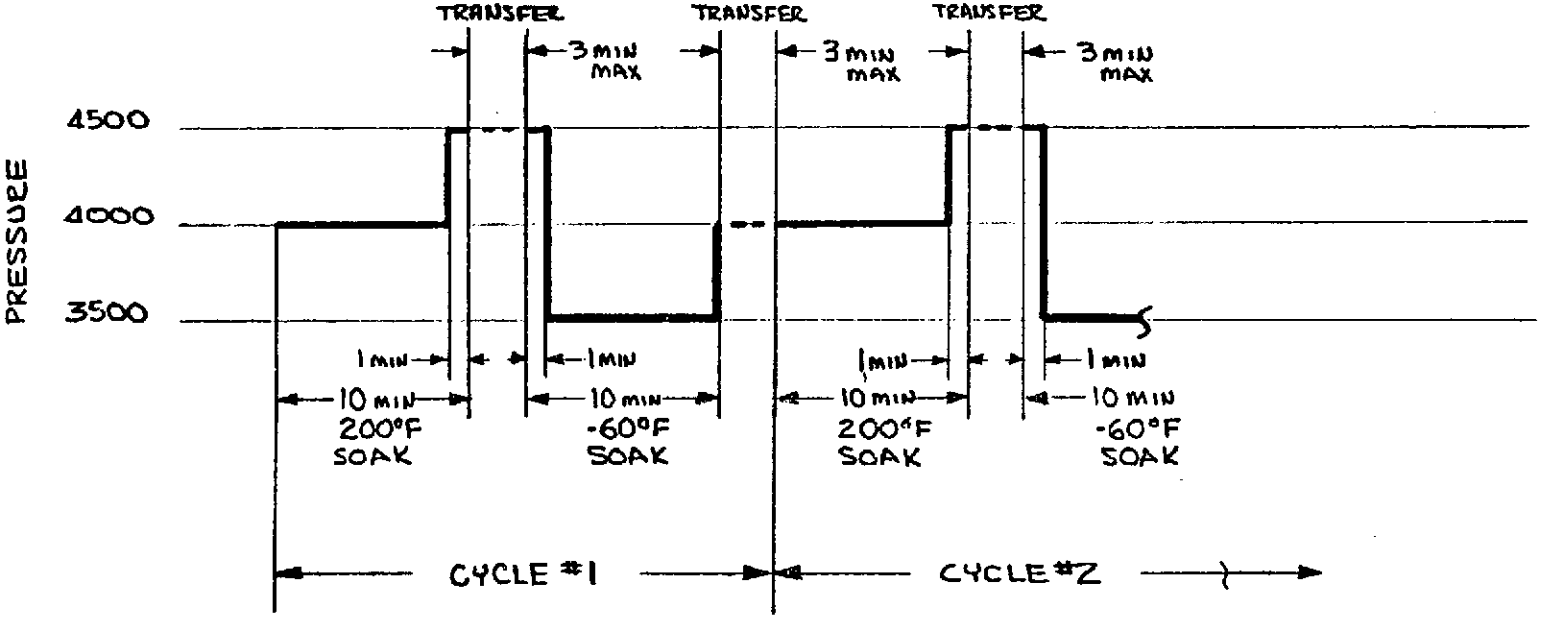
5/23/73

SCI Form 73-108



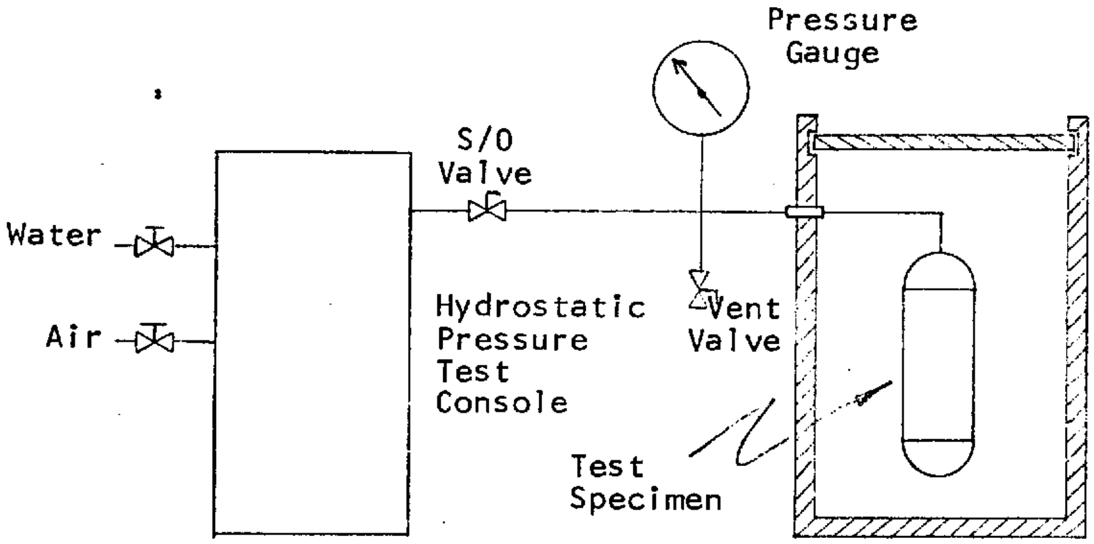
THERMAL CYCLING TEST

Figure 49



PRESSURE versus TIME CURVE

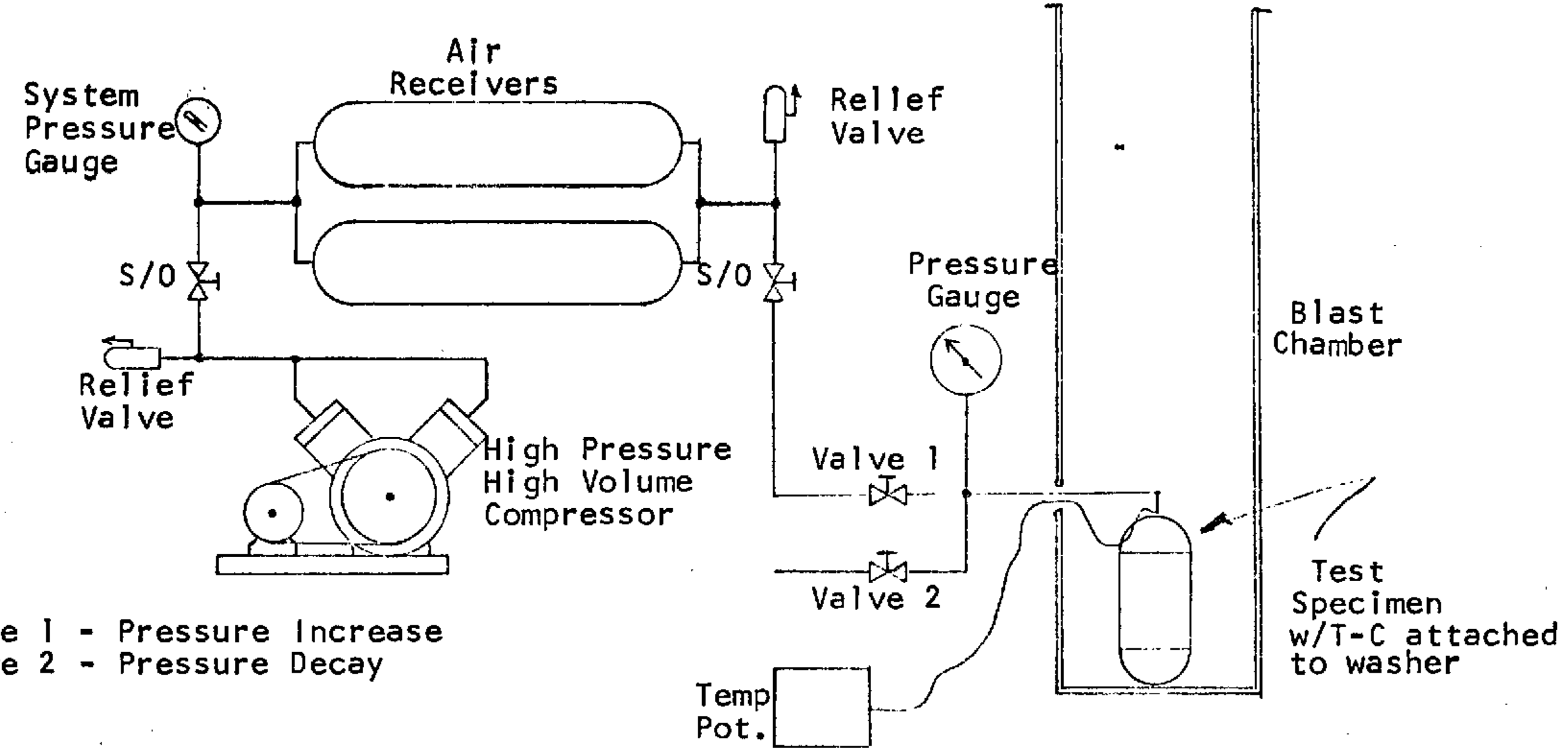
Figure 50



BURST TEST

C-3

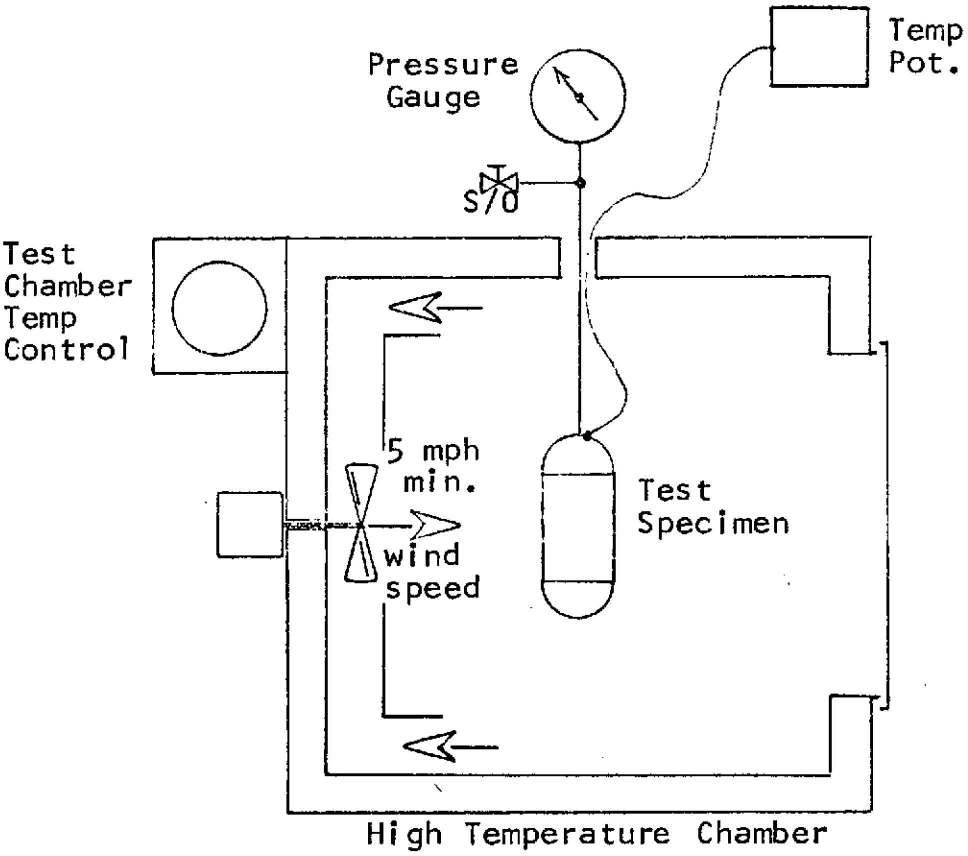
Figure 51



Valve 1 - Pressure Increase
Valve 2 - Pressure Decay

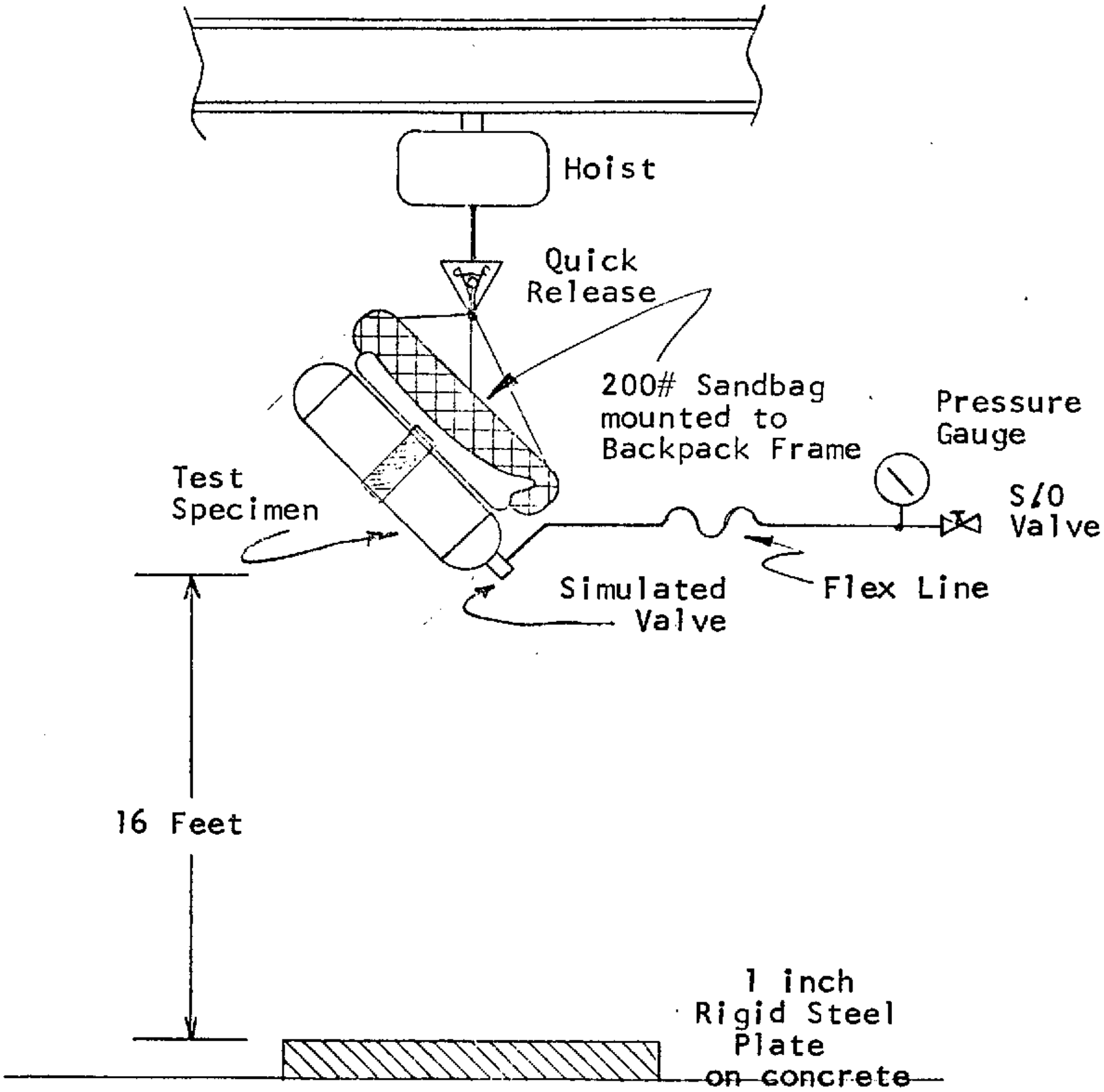
FLAW GROWTH RESISTANCE TEST

Figure 52



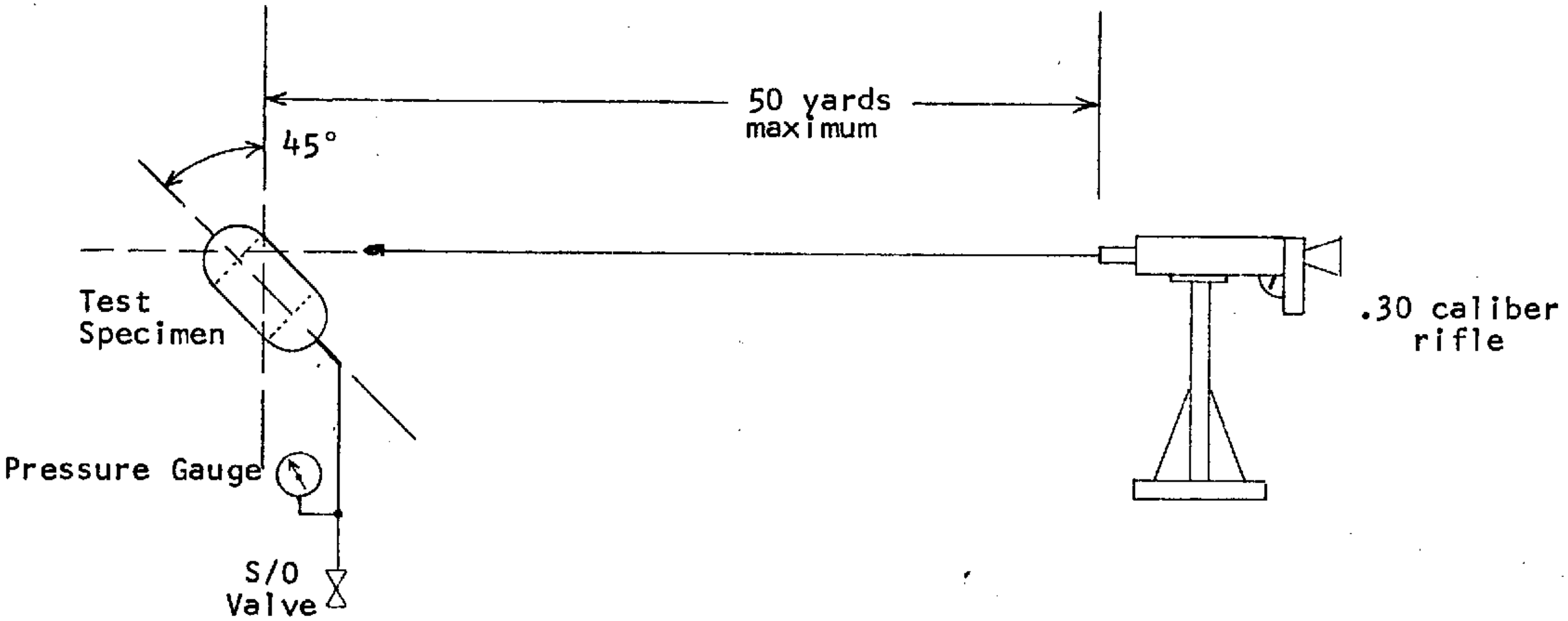
HIGH TEMPERATURE EXPOSURE TEST

Figure 53



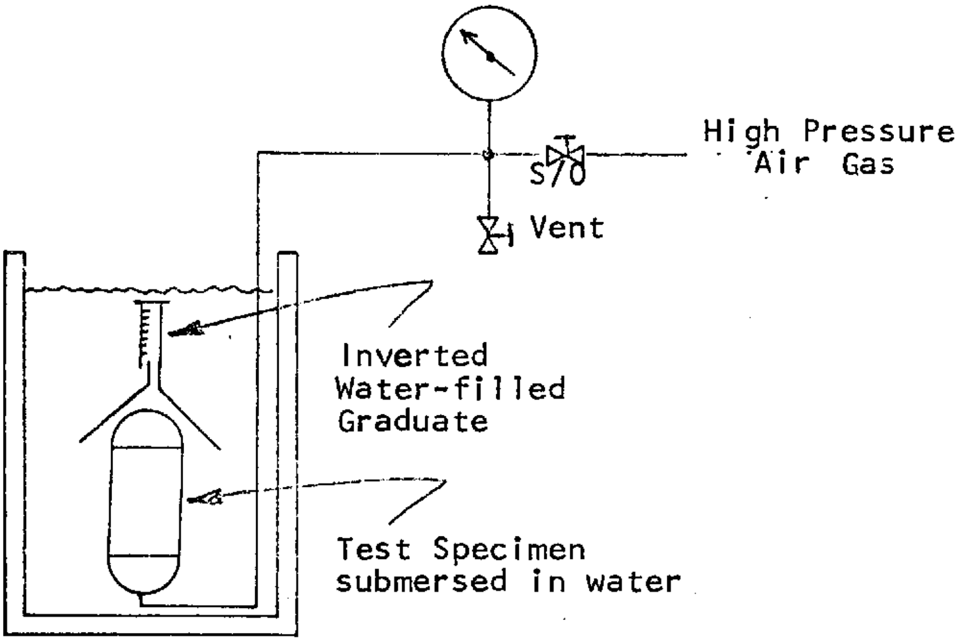
DROP TEST

Figure 54



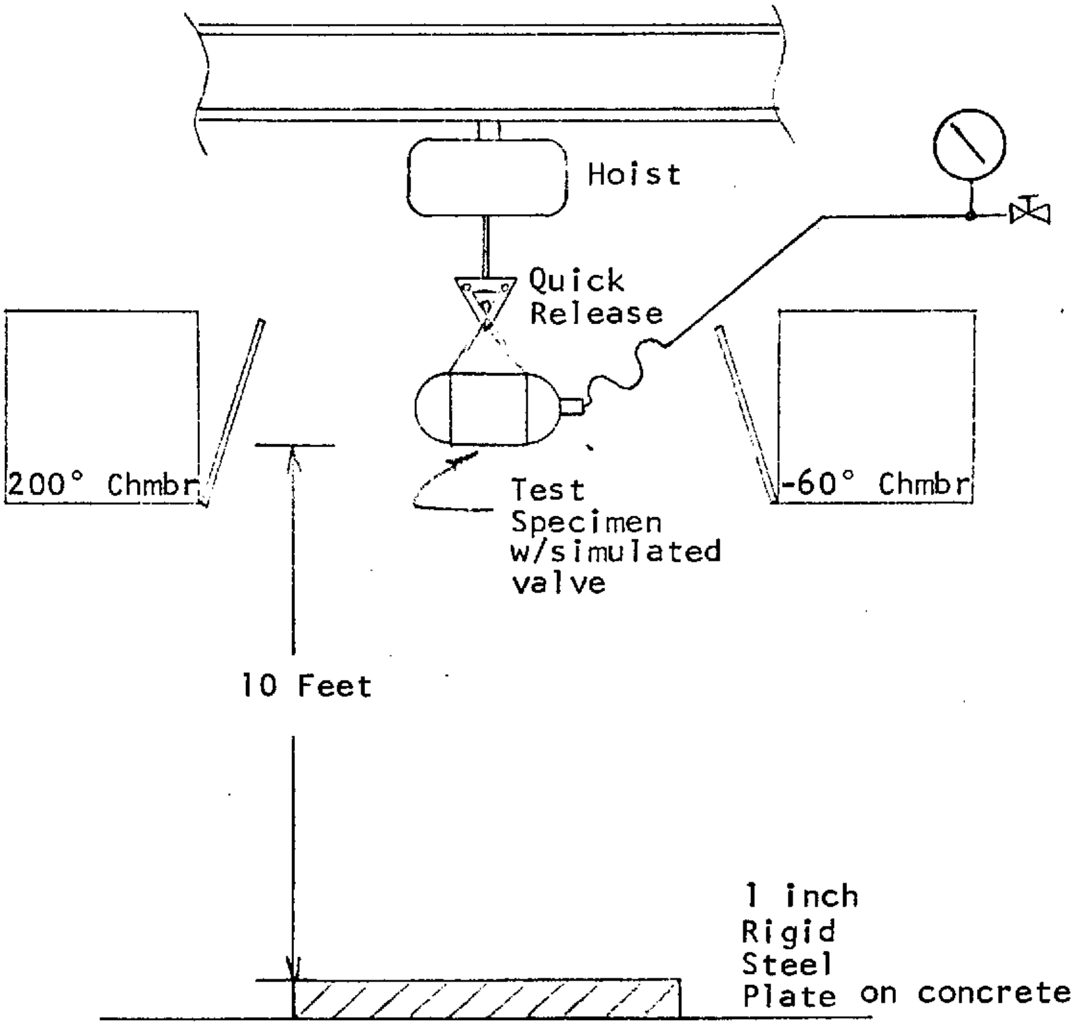
FRAGMENTATION RESISTANCE TEST

Figure 55



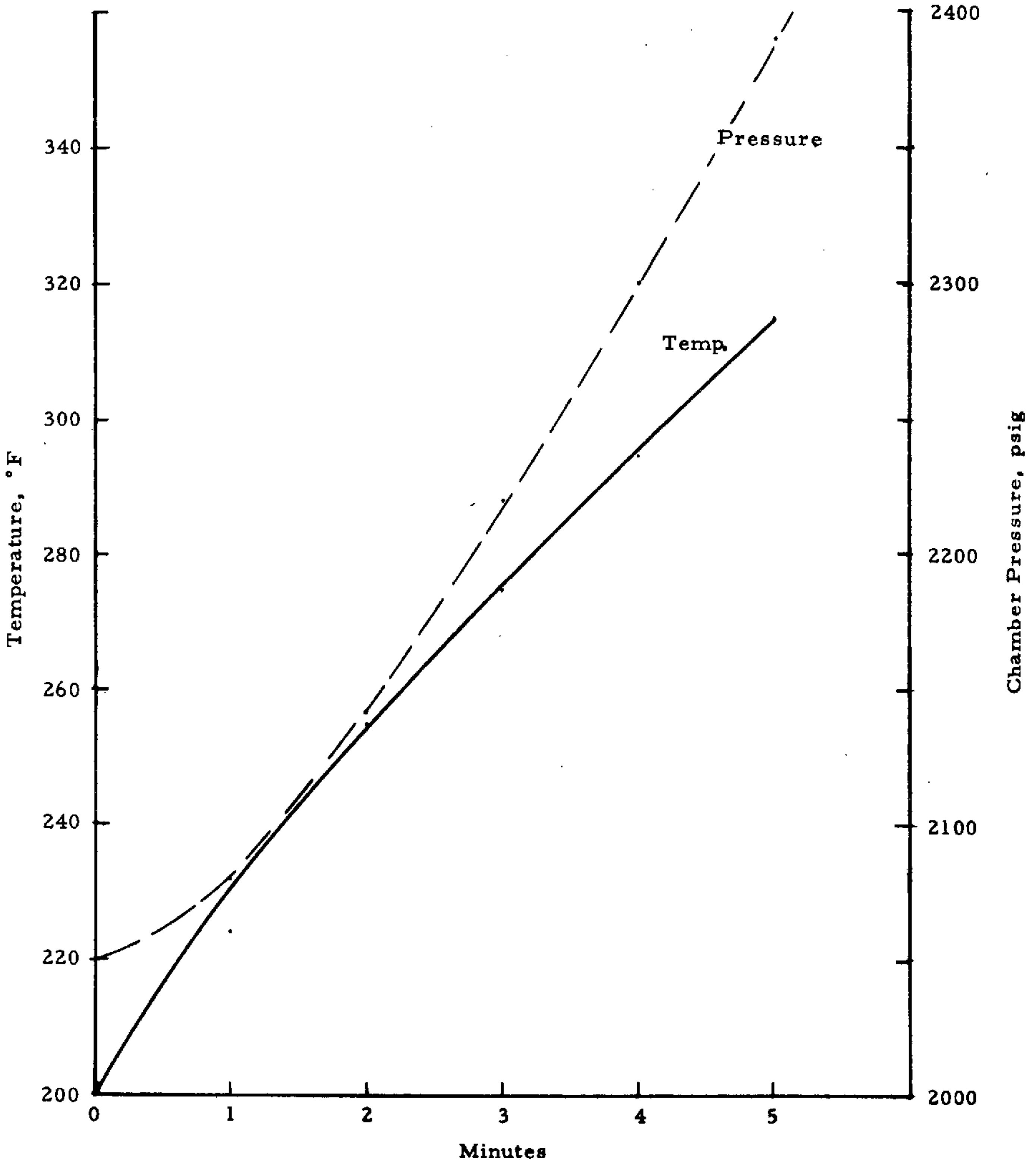
LEAKAGE TEST

Figure 56



IMPACT RESISTANCE TEST

TEST TANK Q/T 6A
600°F EXPOSURE TEST
THERMOCOUPLE ATTACHED TO WASHER AT BOSS



Time of exposure to 600°F

Figure 58

APPENDIX A

6351-T6 ALUMINUM SEAMLESS LINER FABRICATION SPECIFICATION

(SWAGED BOSS)

STRUCTURAL COMPOSITES INDUSTRIES INC.
6344 NORTH IRWINDALE AVENUE AZUSA, CALIFORNIA 91702 (213) 334-8221

6351-T6 ALUMINUM SEAMLESS LINER FABRICATION SPECIFICATION

(SWAGED BOSS)

SPECIFICATION NUMBER 72-1, REVISION B

APRIL 1973

(REPLACES SPECIFICATION NUMBER 72-1, REVISION A, MARCH 1973)

G F R TANK

WORK ORDER 2001

1.0 SCOPE

This specification establishes the requirements for fabricating seamless 6351-T6 aluminum liners for glass filament reinforced (GFR) tanks.

2.0 APPLICABLE DOCUMENTS

Unless otherwise specified, the following documents of issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein.

2.1 STANDARDS

Federal Test Method Standard Number 151, Metals, Test Methods

2.2 SPECIFICATIONS

Military

MIL-H-6088E - Heat Treatment of Aluminum Alloys

Aluminum Association

AA6351 - Aluminum Alloy 6351, Chemical Composition

Structural Composites Industries, Inc. - Specification 72-2

Heat Treatment of 6351 Aluminum Sheet

2.3 DRAWINGS

Structural Composites Industries, Inc.

SCI 1269345 . - Seamless Liner, Swaged Boss, Aluminum Alloy 6351-T6 (Released 12 January 1973)

SCI Sketch 73-014 - Cup Operation, Deep Draw

SCI Sketch 73-016 - Flow Form

3.0 REQUIREMENTS

3.1 MATERIALS

The material used shall be aluminum alloy 6351-0 in accordance with the chemistry limits of Aluminum Association Specification AA6351.

3.1.1 Starting Blanks

Each blank shall be circular and have thickness and diameter gauge limits as specified on SCI Drawing 1269345. The blanks shall be in the mill-annealed condition (0 temper) and shall have the following mechanical properties:

Ultimate tensile strength	-	18,000 psi minimum
Tensile yield strength (.2 offset)	-	5,000 psi minimum
Elongation in 2 inch	-	25 percent minimum

Prior to forming, the blanks shall be degreased and cleaned to remove all mill grease, inks, and foreign matter that could be damaging to the blank during the forming operations.

3.2 FORMING PROCEDURE

The blanks shall be fabricated into seamless liners in accordance with SCI Drawing 1269345 and in three operations as follows:

1.	Cup operation (deep draw)	SCI Sketch 73-014
2.	Flow form	SCI Sketch 73-016
3.	Swage	SCI Drawing 1269345

3.2.1 Lubrication

Sufficient lubrication shall be applied to the part during forming to prevent scratching, galling, seizing, or burnishing of the surfaces.

3.2.2 Process Anneals

Process anneals may be employed during forming as required to prevent tearing, cracking, etc., as a result of work hardening and residual stress buildup in the parts from previous operations. The parts shall be degreased and cleaned of all lubricant, shop oils, and dirt prior to process annealing operations. The annealing operation shall be selected in accordance with SCI Specification 72-2 and MIL-H-6088E as applicable.

3.2.3 In-Process Inspection

After each forming operation, the parts shall be visually inspected for surface damage on all interior and exterior surfaces. Surface defects shall be ground and blended out to smooth contour. Depth of grind shall not exceed .008-inch. The wall thicknesses shall be measured and recorded at three equally spaced locations along the cylinder at 90° stations, as well as three readings up the head portions of the part - also at 90° stations. Records of these inspections shall be maintained.

3.2.4 Final Heat Treatment

After the tanks have been formed, they shall be degreased and cleaned of all foreign matter, on interior and exterior surfaces. The tanks shall be solution heat treated and aged (T6 condition) per SCI Specification Number 72-2 and MIL-H-6088E, where applicable, and physical properties as indicated.

3.2.4.1 Distortion

Quench distortion after solution treating shall be minimized by using water spray. Suitable fixturing shall be employed to ensure uniform quenching of all parts in a furnace load. If distortion exceeds the dimensions and tolerances given in SCI Drawing 1269345 , a final sizing pass will be performed prior to the aging treatment.

3.2.5 Threading

After final heat treatment, the neck of the liner shall be machine threaded per SCI Drawing 1269345 . Care must be exercised in fixturing to avoid damaging the liner. Threads are required to be clean, even, without cracks, and to gauge. The liner interior and exterior shall be degreased and cleaned of all shop oils, dirt, and machine cuttings prior to delivery to SCI.

3.3 FINAL INSPECTION

Each finished liner shall meet the dimensional and tolerance requirements of SCI Drawing 1269345 . External surfaces shall be uniformly smooth and free of visible scratches, tears, cracks, and indentations. The removal of surface defects is permitted provided the thickness of the metal is not reduced below the minimum specified on the drawing. Inspection shall be per Table 3.3 attached.

3.4 WORKMANSHIP

The workmanship shall be of sufficient high grade to ensure uniform quality of parts produced.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 SUPPLIERS' RESPONSIBILITIES

The supplier (s) shall be responsible for fabrication, heat treatment, inspection, and identification of the part s in accordance with all of the requirements and procedures of this specification.

No deviation from this specification shall be allowed except with the approval, in writing, of the cognizant SCI Project Engineer. This approval shall be in the form of an amendment or revision to this specification. The supplier(s) shall maintain records of material heat numbers, production lot numbers, and heat treat log numbers, test and inspection data and dates of each operation. These records, letters of conformance, and other pertinent information affecting liner fabrication shall be forwarded without delay to the cognizant SCI Project Engineer and SCI Inspection Department.

4.1.1 Acceptance Criteria

Acceptance of the parts shall be based upon compliance with the requirements herein as verified by in-process testing and inspection and final inspection of the finished part. Noncomformance shall be cause for rejection.

4.2 COGNIZANT SCI PERSONNEL

As required, SCI personnel, such as project engineer, metallurgical engineer, etc., shall be permitted to observe those phases of work as is necessary.

5.0 PREPARATION FOR DELIVERY

5.1 IDENTIFICATION

Each finished liner shall be assigned a serial number which is permanently stamped on the top of the neck as shown in SCI Drawing 1269345. The serial number shall relate to the contractor's records per Paragraph 4.1.

5.2 PACKAGING

The finished liners shall be packed in suitable containers to prevent damage during shipping to SCI Receiving Inspection Department, and between suppliers as applicable.

DOCUMENT APPROVAL SIGNATURE SHEET

Type of Document:

Fabrication Specification

Document Number:

SCI Specification 72-1,
Revision A

Title:

6351-T6 Aluminum Seamless Liner Fabrication Specification (Swaged Boss)

Prepared By:

E. C. Hart

Date:

April 1973

Approval Signature	Title	Date
[illegible] King	Project Manager	5/7/73
Earle C Hart per [illegible]	Metallurgist	
	Engineering Manager	
C.P. Dolphin	Quality Control Manager	5-2-73

Authorized For Release By:

C. P. Dolphin

Quality Control Documentation
Structural Composites Industries, Inc.

APPENDIX B

6351-T6 ALUMINUM SEAMLESS LINER FABRICATION SPECIFICATION

(SPUN BOSS)

STRUCTURAL COMPOSITES INDUSTRIES INC.
6344 NORTH IRWINDALE AVENUE AZUSA, CALIFORNIA 91702 (213) 334-8221

6351-T6 ALUMINUM SEAMLESS LINER FABRICATION SPECIFICATION

(SPUN BOSS)

SPECIFICATION NUMBER 73-15, REVISION A

APRIL 1973

(REPLACES SPECIFICATION NUMBER 73-15 MARCH 1973)

G F R TANK

WORK ORDER 2001

1.0 SCOPE

This specification establishes the requirements for fabricating seamless 6351-T6 aluminum liners for glass filament reinforced (GFR) tanks.

2.0 APPLICABLE DOCUMENTS

Unless otherwise specified, the following documents of issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein.

2.1 STANDARDS

Federal Test Method Standard Number 151, Metals, Test Methods.

2.2 SPECIFICATIONS

Military

MIL-H-6088E - Heat Treatment of Aluminum Alloys

Aluminum Association

AA6351 - Aluminum Alloy 6351, Chemical Composition

Structural Composites Industries, Inc. - Specification 72-2

Heat Treatment of 6351 Aluminum Sheet

2.3 DRAWINGS

SCI 1269302 - Seamless Liner, Spun Boss, Aluminum Alloy 6351-T6

SCI Sketch 73-014 - Cup Operation, Deep Draw

SCI Sketch 73-015 - Flow Form

3.0 REQUIREMENTS

3.1 MATERIALS

The material used shall be aluminum alloy 6351-0 in accordance with the chemistry limits of Aluminum Association Specification AA6351.

3.1.1 Starting Blanks

Each blank shall be circular and have thickness and diameter gauge limits as specified on SCI Drawing 1269302 . The blanks shall be in the mill-annealed condition (0 temper) and shall have the following mechanical properties:

Ultimate tensile strength - 18,000 psi minimum

Tensile yield strength (.2% offset) - 5,000 psi minimum

Elongation in 2 inch - 25 percent, minimum

Prior to forming the blanks shall be degreased and cleaned to remove all mill grease, inks, and foreign matter that could be damaging to the blank during the forming operation.

3.2 FORMING PROCEDURE

The blanks shall be fabricated into seamless liners in accordance with SCI Drawing 1269302. and in three operations as follows:

1.	Cup operation (deep draw)	SCI Sketch 73-014
2.	Flow form	SCI Sketch 73-015
3.	Spinning	SCI Drawing 1269302

3.2.1 Lubrication

Sufficient lubrication shall be applied to the part during forming to prevent scratching, galling, seizing, or burnishing of the surfaces.

3.2.2 Process Anneals

Process anneals may be employed during forming as required to prevent tearing, cracking, etc., as a result of work hardening and residual stress buildup in the parts from previous operations. The parts shall be degreased and cleaned of all lubricant, shop oils, and dirt prior to process annealing operations. The annealing operation shall be selected in accordance with SCI Specification 72-2 and MIL-H-6988E as applicable.

3.2.3 In-Process Inspection

After each forming operation, the parts shall be visually inspected for surface damage on all interior and exterior surfaces. Surface defects shall be ground and blended out to smooth contour. Depth of grind shall not exceed .008-inch. The wall thicknesses shall be measured and recorded at three equally spaced locations along the cylinder at 90° stations, as well as three readings up the head portions of the part - also at 90° stations. Records of these inspections shall be maintained.

3.2.4 Final Heat Treatment

After the tanks have been formed, they shall be degreased and cleaned of all foreign matter, on interior and exterior surfaces. The tanks shall be solution heat treated and aged (T6 condition) per SCI Specification Number 72-2 and MIL-H-6088E, where applicable, and physical properties as indicated.

3.2.4.1 Distortion

Quench distortion after solution treating shall be minimized by using water spray. Suitable fixturing shall be employed to ensure uniform quenching of all parts in a furnace load. If distortion exceeds the dimensions and tolerances given in SCI Drawing 1269302. , a final sizing pass will be performed prior to ageing treatment.

3.2.5 Threading

After final heat treatment, the neck of the liner shall be machine threaded per SCI Drawing 1269302 . Care must be exercised in fixturing to avoid damaging the liner. Threads are required to be clean, even, without cracks, and to gauge. The liner interior and exterior shall be degreased and cleaned of all shop oils, dirt, and machine cuttings prior to delivery to SCI.

3.3 FINAL INSPECTION

Each finished liner shall meet the dimensional and tolerance requirements of SCI Drawing 1269302 . External surfaces shall be uniformly smooth and free of visible scratches, tears, cracks, and indentations. The removal of surface defects is permitted provided the thickness of the metal is not reduced below the minimum specified on the drawing.

3.4 WORKMANSHIP

The workmanship shall be of sufficient high grade to ensure uniform quality of parts produced.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 SUPPLIERS' RESPONSIBILITIES

The supplier(s) shall be responsible for fabrication, heat treatment, inspection, and identification of the parts in accordance with all of the requirements and procedures of this specification.

No deviation from this specification shall be allowed except with the approval, in writing, of the cognizant SCI Project Engineer. This approval shall be in the form of an amendment or revision to this specification. The supplier(s) shall maintain records of material heat numbers, production lot numbers, and heat treat log numbers, test and inspection data, and dates of each operation. These records, letters of conformance, and other pertinent information affecting liner fabrication shall be forwarded without delay to the cognizant SCI Project Engineer and SCI Inspection Department.

4.1.1 Acceptance Criteria

Acceptance of the parts shall be based upon compliance with the requirements herein as verified by in-process testing and inspection, and final inspection of the finished part. Non-conformance shall be cause for rejection.

4.2 COGNIZANT SCI PERSONNEL

As required, SCI personnel, such as Project Engineer, Metallurgical Engineer, etc., shall be permitted to observe those phases of work as is necessary.

5.0 PREPARATION FOR DELIVERY

5.1 IDENTIFICATION

Each finished liner shall be assigned a serial number which is permanently stamped on the top of the neck as shown in SCI Drawing 1269302 . The serial number shall relate to the contractor's records per Paragraph 4.1.

5.2 PACKAGING

The finished liners shall be packed in suitable containers to prevent damage during shipping to SCI Receiving Inspection Department, and between suppliers as applicable.

DOCUMENT APPROVAL SIGNATURE SHEET

Type of Document:

Fabrication Specification

Document Number:

SCI Specification 73-15
Revision A

Title:

6351-T6 Aluminum Seamless Liner Fabrication Specification (Spun Boss)

Prepared By:

R. Gordon

Date:

April 1973

Approval Signature	Title	Date
[illegible] C. King	Project Manager	5/7/73
Earle C Hart per (PD)	Metallurgist	
	Engineering Manager	
C.P. Dolgokin	Quality Control Manager	5-2-73

Authorized For Release By:

C.P. Dolgokin

Quality Control Documentation
Structural Composites Industries, Inc.

APPENDIX C

6351-T6 ALUMINUM SHEET
HEAT TREAT SPECIFICATION
FIREMAN'S BOTTLE

STRUCTURAL COMPOSITES INDUSTRIES INC.
6344 NORTH IRWINDALE AVENUE AZUSA, CALIFORNIA 91702 (213) 334-8221

6351-T6 ALUMINUM SHEET
HEAT TREAT SPECIFICATION
FIREMAN'S BOTTLE

PRINT NUMBER 1269345 AND 1269302

SPECIFICATION NUMBER 72-2, REVISION B

APRIL 1973

WORK ORDER 2001

1.0 SOLUTION HEAT TREATMENT IN FURNACE (T-6 CONDITION)

1.1 Soak at 940°F ± 5°F for 30 minutes, followed by rapid quench and total immersion in cold water (75°F or less). During removal of parts from furnace, the metal temperature should not get below 800°F before immersion in the quench water. Water volume should be sufficient to keep final temperature below 100°F during quench cycle.

2.0 AGING

2.1 Soak for 8 hours at 340°F ± 5°F for optimum physical values.

2.2 Alternative: Soak time for 5 hours at 365°F ± 5° may be used for high production volume, but produces slightly lower strength and ductility values. (Reference only - Applicable only if specified on Purchase Order).

3.0 ANNEALING

3.1 Soak at 775°F, 2-3 hours. Cool slowly at rate not exceeding 50°F drop per hour to 500°F below removal.

4.0 ACCEPTANCE TEST

4.1 Test coupons should have the minimum physical properties indicated below

Tensile Strength (ultimate), psi	45,000
Yield Strength, psi	38,000
Elongation, %	8 -- 10

4.2 The liner should have a hardness greater than Rockwell B60

5.0 PROCESS ANNEALING

5.1 Annealing to eliminate work-harden conditions during processing may be accomplished by heating to 650°F or above (not exceeding 775°F) and holding until uniform temperature has been established throughout the furnace load. Cooling in air or in the furnace are acceptable.

DOCUMENT APPROVAL SIGNATURE SHEET

Type of Document:

Heat Treat Fabrication

Document Number:

SCI Specification 72-2, Revision B

Title:

Heat Treat Specification For 3651-T6 Aluminum Sheet
Fireman's Bottle - Drawing Number 1269345 and 1269302

Prepared By:

E. C. Hart

Date:

April 1973

Approval Signature	Title	Date
	Project Manager	
Earl C Hart by	Metallurgist	5-1-73
	Engineering Manager	
C.P. Dolphin	Quality Control Manager	5-2-73

Authorized For Release By:

C.P. Dolphin

Quality Control Documentation
Structural Composites Industries, Inc.

APPENDIX D

GLASS FILAMENT OVERWRAP FOR FIREMAN'S BREATHING TANK

(SWAGED BOSS)

STRUCTURAL COMPOSITES INDUSTRIES INC.

6344 NORTH IRWINDALE AVENUE AZUSA, CALIFORNIA 91702 (213) 334-8221

GLASS FILAMENT OVERWRAP FOR
FIREMAN'S BREATHING TANK
(SWAGED BOSS)

SPECIFICATION NUMBER 73-13, REVISION C

AUGUST 1973

(REPLACES SCI SPECIFICATION NUMBER 73-13-B, JULY 1973)

WORK ORDER 2001

1.0 SCOPE

1.1 This document describes the procedures for fabricating a glass fiber reinforced (GFR) metal liner pressure vessel (tank).

1.2 This document includes surface preparation of the metal liner, filament winding, cure procedures, and final inspection of the tank. The metal liner fabrication and inspection are described in SCI Specification 72-1 (supercedes SCI Specification 9141-12).

2.0 APPLICABLE DOCUMENTS

2.1 DRAWINGS

SCI Drawing 1269345 - Liners, Swaged Boss, Aluminum Alloy

SCI Drawing 1269367 - Improved Fireman's Breathing Tank

2.2 SPECIFICATIONS

SCI Specification 72-1A 6351-T6 Aluminum Seamless Liner Fabrication (Swaged Boss) and Figure 3.3 thereof *

MIL-R-60346A Type III Class I Glass Roving, S2, Type 456 x 31 750 yield 20 end

3.0 REQUIREMENTS

3.1 GENERAL INSTRUCTIONS

3.1.1 The vessel fabrication instructions shall be followed carefully and completely.

3.1.2 Any deviations from the specifications for fabrication shall be noted on the fabrication record (Figure 3.1) in order that all factors may be taken into account when analysis of the vessel is made after test.

3.2 FABRICATION PROCEDURE

3.2.1 Liner Surface Preparation **

Visual inspection is required. If the unit looks dirty -

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*Figure 3.3 of SCI Specification 72-1A is attached hereto for reference only

**A liner fabricated in accordance with Specification 72-1A shall be used.

then it may be cleaned by solvent wiping using a clean rag moistened with MEK or toluene.

3.2.2 Glass Roving

The glass roving is procured from OCF Corporation in approximately 15 pound spools and designated as Continuous Strand Roving 470 X31-750, S-2 Glass.

3.2.3 Resin Formulation and Mix Procedure

3.2.3.1 Formulation

Formulation	Parts by Weight
Resin: DER 332	100
Curing Agent: HHPA	84
Catalyst: BDMA	0.5

3.2.3.2 Suppliers

DER 332:	Dow Chemical Company
HHPA:	Plastics Division, Allied Chemical Company New York or other suitable sources
BDMA:	Naumee Chemical Co., St. Bernard, Michigan or other suitable sources

3.2.3.3 Mixing Instructions

(a) The curing agent shall be heated to 135 ± 5°F approximately 4 hours just prior to winding. All crystals shall be completely melted.

(b) The resin shall be heated to

105 ± 5°F and the melted curing agent added. This mixture shall be thoroughly agitated until the mixture is clear.

(c) The catalyst shall then be added to the resin/curing agent mixture and agitated for a minimum of five minutes until the resinous mixture is thoroughly blended.

(d) The catalyzed resin shall be placed in the impregnation tank of the winding machine.

3.2.4 Winding Machine Set-Up and Calibration

3.2.4.1 Set the winding gear trains to give the required number of longitudinal winding for one complete revolution of the mandrel and the required lead per turn of hoop winding. The ratio is .4:1 on Lathe Number E101518-901.

3.2.4.2 Install the prepared liner and shaf assembly in the winding machine.

3.2.4.3 Install nine rolls of 20-end roving in the tension devices for longitudinal and hoop winding. Thread roving through control rollers and resin impregnating bath to liner.

3.2.4.4 Calibrate the tension devices to provide static tension of two pounds for 20-end roving for longitudinal winding and five pounds for 20-end roving for hoop winding.

3.2.5 Winding Operation

3.2.5.1 Proceed to wind the roving in the longitudinal orientation. A total of 185 turns ± 1 turn is to be used.

3.2.5.2 Select a winding speed of approximately 7RPM (a machine setting of 1.0) to prevent roving slipping, and hold the roving if necessary to prevent slippage.

3.2.5.3 Change the set up for hoop winding. Add roving spacing racks (SK 72-013) on each end to prevent roving from slipping down the shoulder. Wind roving along the cylindrical section. Apply a total of 485± 10 turns uniformly spaced along the cylinder. Speed following direction change over should be approximately 7 RPM (set 1.0) for the first layer, 12 RPM (set 2.0) for the second layer, 17 RPM (set 3.0) for the third, fourth, and fifth layers.

3.2.6 Cure and Post Cure

3.2.6.1 Place the wound vessel horizontally on a rotating rack with heat in place to gel the unit. Gelling will take one to two hours.

3.2.6.2 Following gel, cure the vessel in an air-circulating oven. Set at 335°F for four hours or 300°F for 16± 3 hours.

3.2.7 Sand the completed vessel lightly to remove surface roughness and wipe lightly with an epoxy or urethane coating (not to be used on Q/T vessels) to reseal the sanded surface. Attach the label and overcoat with the sealing resin.

3.2.8 Sizing Pressurization

3.2.8.1 Each tank shall be weighed dry to get its tare weight.

3.2.8.2 The tank shall then be filled with clean water up to the bottom thread and then weighed again in order to get its initial volume.

3.2.8.3 The tank shall then be pressurized to 6750 psig ± .5% and held for five minutes and released, making the measurements required below.

3.2.8.4 The effluent water during depressurization shall be measured. The reading in the burette when the tank is at 6750 psig shall be the tare value.

3.2.8.5 The burette reading at ambient pressure pressure shall be recorded.

3.2.8.6 The tank and the fittings shall then be removed. The tank shall then be weighed with the water remaining inside after filling or removing water so it just touches the bottom thread.

3.2.8.7 All the data shall be recorded in Figure 3.2.8 attached. The computations indicated shall be made.

3.3 FINAL INSPECTION - QUALIFICATION TEST UNITS

3.3.1 Each finished tank shall be weighed dry to get its tare weight.

3.3.2 The tank shall then be filled with clean water up to the bottom thread and weighed in order to get its capacity in grams (pounds) of water.

3.3.3 Each finished tank shall be tested by hydrostatic pressurization of 6750 psig ± 0.5% and held for five minutes and released.

3.3.4 The tank total volume shall be determined at 6750 psig and after pressure release. The total and permanent volumetric expansion shall be computed.

3.3.5 The final length and diameter of the tank shall be determined and recorded.

3.3.6 All data shall be recorded in Figure 3.3 attached.

3.4 FINAL INSPECTION - PRODUCTION

3.4.1 Production acceptance testing criteria shall be determined from tank and qualification test results, the requirements of the DOT Special Permit and incorporated into this specification by formal revision.

3.4.2 Subsequent to qualification test and prior to production, a limited number of tanks will be fabricated and field evaluated. Acceptance of these tests will be based on a proof pressure test in accordance with Paragraph 3.3 but the data are to be recorded on Figure 3.4.2 attached hereto.

3.4.3 A Barcol hardness test of the liner is optional. If taken, however, it shall be on the open ended boss opposite the serial number. The data so taken shall be listed on the vessel liner check out sheet, Figure 3.3, of the SCI Specification 72-1-A, as Test Number 8.

4.0 PREPARATION FOR DELIVERY

4.1 Each finished and accepted tank shall be identified by serial number relating to the manufacturer's production, inspection, and test records. The identification shall be applied to the tank by glued label on the cylindrical portion of the tank during the overcoating (Paragraph 3.2.7).

4.2 The label to be applied shall be as shown in Figure 4.2 attached. The blocks in the label shall be filled out as follows:

4.2.1 In the upper block where it says "Mfg. For" - type "NASA - JSC".

4.2.2 In the lower part of the same upper block add in capital letters "NOMINAL CHARGE PRESSURE 4000 psig AIR".

4.2.3 Above Part Number put in "1269367-1".

4.2.4 Serial Number is assigned in order of fabrication.

4.2.5 Stock Number - leave blank.

4.2.6 Specification Number is "SCI 73-13C".

4.2.7 Empty Weight - give this to the nearest tenth of a pound.

4.2.8 Charged Weight - leave blank.

4.2.9 Maximum Operating Pressure - put in "4500 psig".

4.2.10 Test Data - put in month and year of test (will typically be 1-3 days after manufacture).

4.2.11 Type - leave blank.

4.2.12 Class - leave blank.

4.2.13 Size - put in "60 SCF".

4.2.14 Manufacturing Date - date of gel, month, and year only.

4.2.15 Contract Number- put in "NAS 9-12414".

4.2.16 Manufacturer's Code Number - leave blank.

Labels and NASA decals are located on the tank as shown in Drawing 1269343 (a copy of which will be posted in the Inspection Department).

4.3 Each tank shall be washed on the inside with approximately 400 cc's of Freon TF. A washing and soaking time of about 20 minutes is required. Following spinning and tumbling, and while the solvent is still in the tank, the tank boss area shall be wiped and/or brushed to remove any contaminants. Following washing, the tank shall be emptied and the solvent inspected. If it appears fairly dirty, a second wash is to be performed. If the solvent looks clean, the bottle shall be drained of all solvent and solvent vapor and a plastic sealing plug installed in the boss.

FIREMAN'S TANK
F/W FABRICATION LOG
FIGURE 3.1

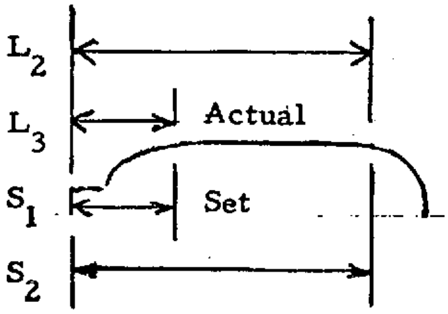
Work Order Number ____________ Drawing Number ______________

Tank Serial Number __________ Date Started _________ Date Completed _______

A. Materials

1. Liner: Serial Number _______

(Take "L" dimensions from figure 3.3 of SCI Specification 72.-1A)



L_2 ______ in

L_3 ______ in

S_1 ______ in

S_2 ______ in

Actual From Liner L_2 (-) L_3 ________ in

Set From Dams S_2 (-) S_1 ________ in

2. Roving: Longo: No. Ends ___________ Type ______________

Batch ______________ Mfg. ______________

Hoop: No. Ends ____________ Type ______________

Batch ______________ Mfg. ______________

3. Matrix:

	Material	Ratio	Batch No.	Amount, gms	Vendor/P.O. No.
1.	332	100			
2.	HHPA	84			
3.	BDMA	0.5			

Dates Mixed: (1, 2) ______________ (1, 2, & 3) ___________

B. Winding Data

1. Longo: No. of Spools _____________ Total Turns __________

Tension ________________ Comment ___________

____

Date Completed _________________________________

FIREMAN'S TANK
F/W FABRICATION LOG
FIGURE 3.1

Work Order Number ________________ Drawing Number ____________

2. Hoop: No. of Spools ____________ No. Layers __________

Tension ________________ No. Turns __________

C. Thermal Data

1. Gel: Time of Start ________ Finish ________________

Comments ______________________________________

____

2. Cure: Date and Time In ________ ________ Temperature ______ °F

Date and Time Out ________ ________ Temperature ______ °F

Comments ______________________________________

____

D. Operator ____

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number ____________ Tank Serial Number ____________

Date ____________ Observer ____________

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight		
2	3.2.8.2	Filled Weight		
3		Capacity $\left[(2) - (1)\right]$		
4	3.2.8.3	Sizing Operation	psig	minutes
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure		psig
6	3.2.8.5	Burette Reading at Ambient Pressure		psig
7	3.2.8.6	Filled Weight		
8		Permanent ΔV $\left[(7) - (2)\right]$		
9		Elastic ΔV $\left[(6) - (5)\right]$		
10		Total V $\left[(9) + (7)\right]$		
11		Total ΔV $\left[(9) + (8)\right]$		
12		Permanent ΔV $\left[(8) / (10)\right]$	%	
13		$\frac{\text{Permanent } \Delta V}{\text{Total } \Delta V}$ $\left[\frac{(8)}{(11)}\right]$	%	

SCI SPECIFICATION 73-13 REVISION A (APRIL 1973)

FIGURE 3.3
QUALIFICATION TEST TANKS ACCEPTANCE TEST PROCEDURE DATA SHEET

Tank Q/T Number

Tank Serial Number

Date(a)

Observer

Item	Paragraph	Procedure		cc or Grams(b)	Pounds
1.	3.3.1	Tank Dry Weight (Must be less than 14 lbs) (same as 3.2.8.1)			
2.	3.3.2	Tank Filled Weight (same as 3.2.8.6)			
3.		Tank Water Capacity [(2) - (1)]			
4.	3.3.3	Hydrostatic Proof Pressure			psig
5.		Duration of Pressure			minutes
6.		Comments:			
7.	3.3.4	Tank Volume at Pressure (c)			
8.		Tare Reading before Proof			cc
9.		Reading at Proof Pressure			cc
10.		ΔV-Total [(9) - (8)]			cc
11.		Tare Reading after Proof			cc
12.		ΔV - Permanent [(11) - (8)]			cc
13.		ΔV - Permanent [(12)/ (10)] x 100			%
14.		Total Volume at Proof Pressure [(3) + (10)] Must be greater than 6923 cc			cc
15.		Tank Overall Length, (d) Inches Must be less than 20.0 inches			
16.		Tank Diameter (d), Cylindrical	D_1		
		Average of 4 readings	D_2		
		Must be less than 6.60 inches	D_3		
			D_4		
		Average			
17.		Total Volume at Operating Pressure (4000)(e)			in^3

SCI SPECIFICATION 73-13, REVISION A (APRIL 1973)

FIGURE 3.3 (continued)

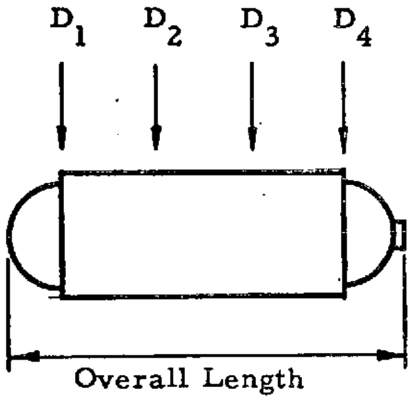
QUALIFICATION TEST TANKS ACCEPTANCE TEST PROCEDURE DATA SHEET

(a) If different dates and observers are involved, insert dates and initials near record of specific tests.

(b) Measure in cc of water - assume 1 cc = 1 gram

(c) Volumetric expansions are determined by pumping from a full burette into the prefilled and bleed tank. Burette readings are taken at ambient pressure (tare), at proof pressure (reading), and after pressure release to ambient (second tare reading). A trial run on the test system without the tank provides the measure of the test system expansion.

(d) Location of Measurements



(e) Total volume at operating pressure, 4000 psi

(1) $\text{Volume } (4000) = \frac{4000}{6750}\left[(14)\right] + \frac{2750}{6750}\left[(3) + (12)\right]$, cc

(2) $\text{Volume } (4000) = \left[(e)(1)\right] \times .0610$, inches^3

Enter (e) (2) into Item 17 on previous sheet

SCI SPECIFICATION 73-13-B, REVISION C (JULY 1973)

DOCUMENT APPROVAL SIGNATURE SHEET

Type of Document:

Fabrication Specification

Document Number:

Specification 73-13-B
Revision C

Title:

Glass Filament Overwrap for Fireman's Breathing Tank

Prepared By:

H. A. King

Date:

July 1973

Approval Signature	Title	Date
	Project Manager	8/1/73
	Metallurgist	
Edgar T Maris	Engineering Manager	8/1/73
	Quality Control Manager	
Robert Gordon	Program Manager	8/1/73

Authorized for Release by:

Quality Control Documentation
Structural Composites Industries, Inc.

Work Order 2001
H. A. King
4/24/73

SCI SPECIFICATION 72-1A

FIGURE 3.3

FIREMAN'S COMPRESSED AIR BREATHING SYSTEM VESSEL LINER CHECK-OUT

Liner Number ______________ Date ________________

Test No.	Feature	Desig-nation	Dimension	Toler-ance	Actual Reading	Comment
1	Overall Length	L1	19.17	0.03		
2	Boss End to Aft Tangent Point	L2	(Calc. Dim) 17.11	0.03		
3	Boss End to Forward Tangent Point	L3	(Calc. Dim) 3.13	0.03		
4	OD, Middle		5.90	0.03		
5	Number of Threads		>7	-		
6	"O" Ring Diameter		1.176	0.001		
7	Weight, lbs.		5.7	0.2		
	Weight, grams		2590	90		

STRUCTURAL COMPOSITES INDUSTRIES, INC.

PRESSURE VESSEL
ACCEPTANCE TEST PROCEDURE DATA SHEET

Type Vessel ____________________

Work Order Number ______________ Vessel Serial Number ____________

Date __________ Test Engineer ______________ Witness ______________

Specification __________________

1. Empty Weight ______________ Grams = ______________ Pounds
2. Pretest Filled Weight __________ Grams
3. Capacity [2 - 1] ______________ cc

Proof and Volumetric Expansion Test:

Proof __________ psig ______________ Seconds

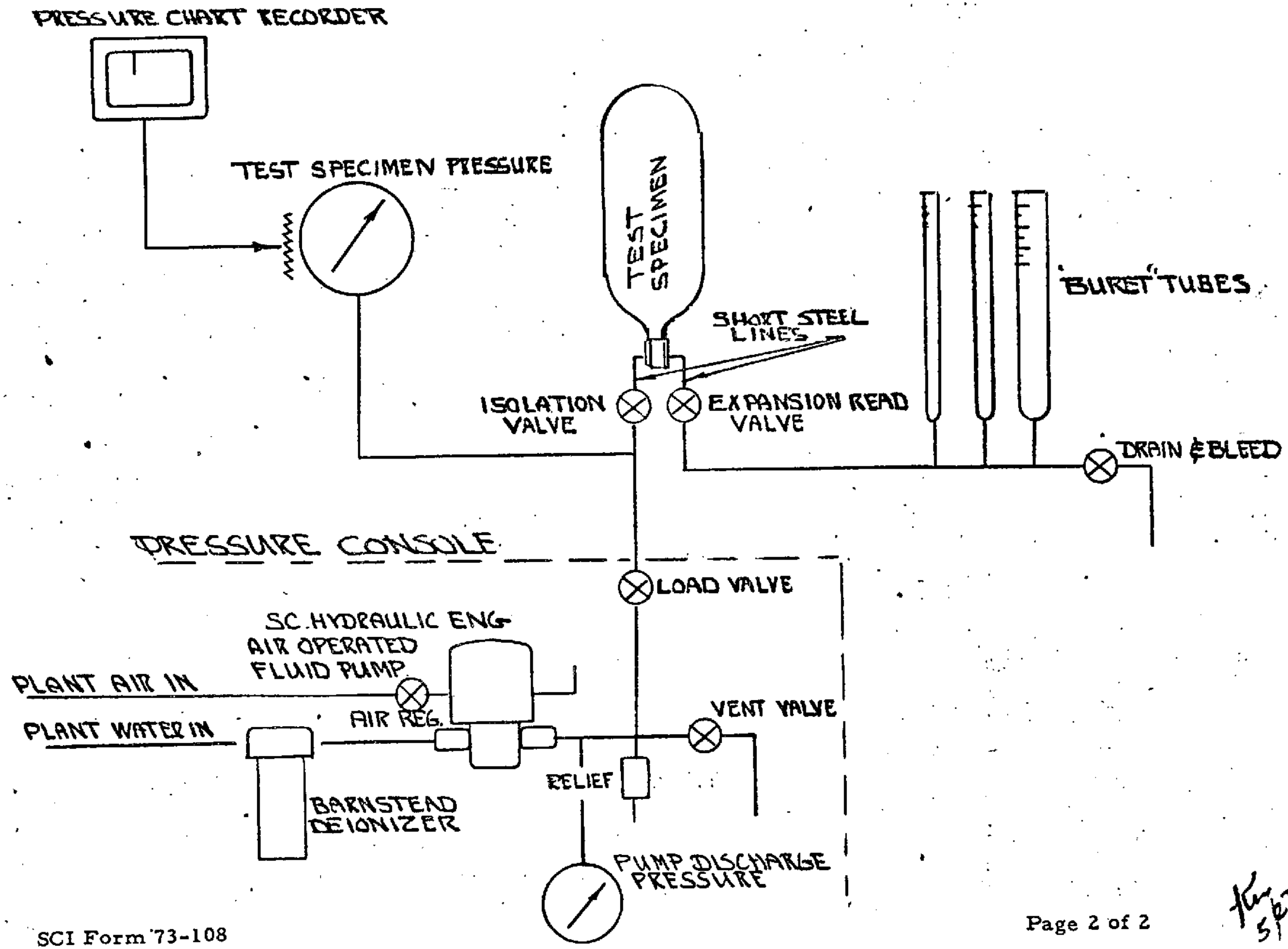
4. Burette Reading at Proof Pressure ________ cc at ______________ psig
5. Burette Reading at Working Pressure ______ cc at ______________ psig
6. Burette Reading at Ambient Pressure ______ cc at ______________ psig

---

7. Post Test Filled Weight ______________ Grams
8. New Capacity [7 - 1] ______________ cc
9. Permanet Set [8 - 3] ______________ cc
10. Elastic Expansion at Working Pressur [5 - 6] ______________ cc
11. Elastic Expansion at Proof Pressure [4 - 6] ______________ cc
12. Final Length, inches ______________
13. Final Middle Diameter, inches ______________

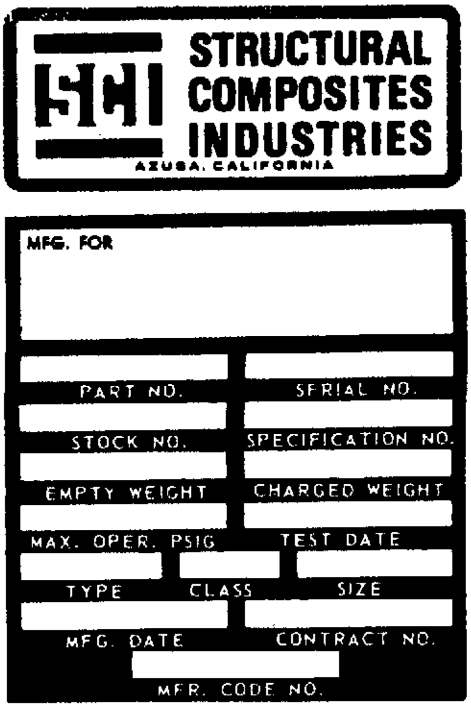
STRUCTURAL COMPOSITES INDUSTRIES, INC.

PRESSURE VESSEL
ACCEPTANCE TEST PROCEDURE DATA SHEET



SCI Form 73-108

5/23/73



STRUCTURAL
COMPOSITES
INDUSTRIES
AZUSA, CALIFORNIA

MFG. FOR

PART NO.
SERIAL NO.
STOCK NO.
SPECIFICATION NO.
EMPTY WEIGHT
CHARGED WEIGHT
MAX. OPER. PSIG
TEST DATE
TYPE
CLASS
SIZE
MFG. DATE
CONTRACT NO.
MFR. CODE NO.

Figure 4.2

UNIT PRODUCTION RECORD FOR

SPECIFICATION NUMBER_______________

Revision No.	Production Start Date	Production Completion Date	Total Units Producted	Unit No. Start	Unit No. Complete
No Spec.	1-31-73	4-17-73	13	1	13
A	4-73	7-24-73	36	14	49*
B	No change in manufacturing procedure		-	-	-
C	7-25-73			50	

* Some deviation from specification regarding winding speeds occured during No. 20-49 as new operators were broken in and as we tried to determine cause of wrinkle.

APPENDIX E

TEST REPORT

APPROVED ENGINEERING TEST LABORATORIES

Report No. 565-1180
P. O. No. 9290
Date: 9 August 1973
136 Page Report

RECEIVED
AUG 20 1973

Test Report No. 565-1180
Qualification Test Report
on
Fireman's Breathing Tanks
P/N 1269367-1, S/N's QT-1A, QT-2 thru QT-6, QT-6A, QT-6B, QT-7 & QT-8

TESTED FOR:

STRUCTURAL COMPOSITES INDUSTRIES, INC.
6344 North Irwindale Avenue
Azusa, California 91702

TESTED BY:

CEL, INC.
A Subsidiary of Approved Engineering
Test Labs
1431 Potrero Avenue
South El Monte, California 91733

STATE OF CALIFORNIA
COUNTY OF LOS ANGELES } ss

IRV WILLIAMS, Division Manager being duly sworn, deposes and says: That the information contained in this report is the result of complete and carefully conducted tests and is to the best of his knowledge true and correct in all respects.

William J. Aron for

SUBSCRIBED and sworn to before me this 9 day of August, 1973

Karl G. Schmidt
Notary Public in and for the County of Los Angeles, State of California.

OFFICIAL SEAL
KARL G. SCHMIDT
NOTARY PUBLIC - CALIFORNIA
LOS ANGELES COUNTY
My Commission Expires Sept. 22, 1973

SIGNATURES

Written By: Karl G. Schmidt Date: 8-9-73
PUBLICATIONS MANAGER, Karl G. Schmidt

Approved By: Ron Ellis For R.A. LOIBL Date: 8-15-73
PROJECT MANAGER, Robert Anthony Loibl

Approved By: Robert Roma for Date: 8/15/73
QUALITY CONTROL MANAGER, L. LaPan

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

1.0 PURPOSE

The purpose of this report is to present the test procedures used and the test results obtained during the performance of a test program. The test program was conducted to determine conformance of ten Fireman's Breathing Tanks, Part Number 1269367-1, Serial Numbers QT-1A, QT-2 through QT-6, QT-6A, QT-6B, QT-7 and QT-8, to the Qualification Test requirements specified in Reference 2.1 in accordance with Reference 2.2.

2.0 REFERENCES

2.1 Approved Engineering Test Laboratories Qualification Test Program Procedure Number 565-1180 "B", dated 30 April 1973, for Improved Fireman's Breathing Tank Assemblies, Part Number 1269367-1.

2.2 Structural Composites Industries, Inc. Purchase Order Number 9290.

3.0 SUMMARY AND CONCLUSIONS

3.1 Ten Fireman's Breathing Tank Assemblies, Part Number 1269367-1, Serial Numbers as noted in Paragraph 1.0, were submitted to this laboratory for a Qualification Test Program described in this report. The test specimens were manufactured by Structural Composites Industries, Inc., 6344 North Irwindale Avenue, Azusa, California 91702.

3.2 All test specimens prior to test were deliberately flawed as follows:

a - Liner Flaw: Depth = 5% of 0.113" = 0.006"
Length = 5 X Depth = 0.030"
Liner flaw on QT-5 was .350 Length x 50% (.070) Depth.

All liners had manufacturing marks larger than the required flaws and did not require deliberate flawing.

b - Hoopwrap: Depth = 5% of 0.140" = 0.007"
Length = 5 X Depth = 0.035"
(Length was equal to 1.0" on QT-6A, QT-6B, QT-7 and QT-8)

Hoopwrap flaw was one axial flaw in the middle of the cylindrical section.

c- Longitudinal Wrap: Depth = 5% of 0.190" = 0.010"
Length = 5 X Depth = 0.050"
(Length was equal to 1.0" on QT-6A, QT-6B, QT-7 and QT-8)

One circumferential flaw as in the boss head to the cylinder plane.

One 45° flaw was in the closed head halfway between the bottom of the head and the hoopwrap.

3.3 During the test program the following anomalies were noted:

a - As noted in Notice of Deviation Number 101, during Burst Testing of Serial Number QT-3, the specimen burst at 8300 psig when pressurized at an average rise rate of 4500 psig per minute. The minimum allowable burst pressure is 9000 psig. The specimen was returned to the customer.

b - During the Impact Resistance Test on Serial Number QT-6, extreme damage to the tank resulted due to the specimen breaking loose from restraining straps and bouncing off sharp rocks, steel and concrete. The specimen was burst for information only and was replaced in the test program by Serial Number QT-6A.

c - During the Cyclic Fatigue testing on Serial Number QT-6A, the specimen exhibited leakage on the 18th proof cycle after 6633 pressure cycles. The specimen was replaced with Serial Number QT-6B.

All test results are presented for evaluation.

4.0 TEST CONDITIONS

Unless otherwise specified in this report all tests were performed at room ambient conditions consisting of a temperature of 75 ± 15° F., a relative humidity of less than 95 percent and a barometric pressure of 29.92 ± 2.0 inches of mercury absolute.

5.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-1A

5.1 Sizing Test

5.1.1 The specimen was weighed. The specimen was then filled with water and the filled weight was obtained. The difference between the filled weight and the tare weight was the capacity of the specimen.

5.1.2 The specimen was pressurized to 6750 psig using water as a test medium. The amount of increase in volume was measured using a buret. The customer representative obtained all data noted above, and the customer-furnished data sheet is presented in Appendix 1.

5.2 Fragmentation Resistance Test

5.2.1 The specimen was pressurized to 4500 psig using gaseous nitrogen per MIL-P-27401 as the test medium. The pressurization rate did not exceed 1,000 psi per minute.

5.2.2 The test specimen was subjected to a single gunfire of .30 caliber armor piercing ammunition from a distance of 50 yards maximum. The specimen was restrained in such a manner as to allow the projectile to enter at a 45-degree angle through the cylinder section and, exited through the head. The muzzle velocity of the .30 caliber projectile was approximately 2800 feet per second.

5.2.3 The condition of the specimen following the test is illustrated in Photographs 1 and 2. The metal liner remained in one piece, and the maximum tear did not exceed three inches maximum. All data are presented in the data sheet in Appendix 1.

6.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-2

6.1 Sizing Test

The test described in Paragraph 5.1 was performed. The test data sheet is presented in Appendix 2.

6.2 Drop Test

6.2.1 The specimen, with a simulated valve installed, was pneumatically pressurized to 4500 psig using gaseous nitrogen per MIL-P-27401 as the test medium. The rate of pressurization did not exceed 1000 psi per minute.

6.2.2 The test specimen was attached to a backpack frame to which a 200-pound sandbag was secured.

6.2.3 The specimen was dropped from a height of 16 feet, impacting on a rigid steel plate. A total of five drops was performed with impacts at the following drop angles:

a - Simulated Valve Up
b - Simulated Valve Down
c - Horizontal
d - Simulated Valve 45 degrees Up
e - Simulated Valve 45 degrees Down

All drops resulted in initial impact on either the tank or simulated valve.

6.2.4 The specimen was visually examined at the completion of each impact. Minor surface damage was noted on the closed end when the 1/4 inch threads stripped from the simulated valve on Drop Number 5 and the tank ricocheted against the concrete.

6.2.5 The test data are presented in the data sheet in Appendix 2.

6.3 Burst Test

6.3.1 The specimen, filled with water and bled of all entrapped air, was installed in a hydrostatic test system.

6.3.2 The hydrostatic pressure was increased at a rate of 3000 to 5000 psi per minute until burst occurred.

6.3.3 Burst pressure of 9300 psig was noted. The minimum allowable burst pressure was 9000 psig. Rupture occurred in the hoopwrap section of the tank. An axial tear approximately five inches long was noted near the closed end. The condition of the specimen following testing is illustrated in Photograph 3.

7.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-3

7.1 Sizing Test

The testing performed in Paragraph 5.1 was performed. The data sheet is presented in Appendix 3.

7.2 Temperature Cyclic Fatigue Resistance Test

7.2.1 The test specimen, filled with a water-glycol mixture, was bled of all entrapped air, and was installed in the test system.

7.2.2 The test specimen temperature was increased to, and maintained at, 200°F. The specimen was subjected to 5000 hydrostatic pressure cycles of 4000 psig. (Each cycle consisted of increasing the test specimen pressure from 0 psig to 4000 psig to 0 psig at a cyclic rate of two to four cycles per minute.)

7.2.3 Following 5000 cycles at a temperature of 200°F, 100 cycles were performed at room ambient temperature at the proof pressure of 6750 psig for a period of 30 seconds per cycle.

7.2.4 The specimen temperature was then decreased to, and maintained at, -60°F. The test specimen was then subjected to 5000 hydrostatic pressure cycles of 4000 psig pressure. Each cycle was performed as described in Paragraph 7.2.2.

7.2.5 Visual examination at the completion of the 10,000 pressure cycles revealed no leakage, rupture, or other adverse effects. The specimen was then subjected to the Sizing Test described in Paragraph 5.1. All test data are presented in the data sheets in Appendix 3.

7.3 Leakage Test

7.3.1 The test specimen was immersed in water and was pressurized to 4000 psig using gaseous air as the test medium.

7.3.2 The specimen was monitored for evidence of external leakage for a period of ten minutes. The ambient temperature was maintained at 80°F. No leakage was noted. The data sheets are presented in Appendix 3.

7.4 Burst Test

The test described in Paragraph 6.3 was performed. Rupture occurred at 8300 psig which is lower than the minimum required of 9000 psig. Burst occurred in the hoopwrap section. The tear of approximately three inches, axially, was noted in the middle of the cylinder in the cylindrical area. The condition of the specimen following testing is illustrated in Photograph 4. The failure is further described in Notice of Deviation Number 101 presented in Appendix 3 along with the data sheets.

8.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-4

8.1 Sizing Test

The test described in Paragraph 5.1 was performed. The test data are presented in the data sheet in Appendix 4.

8.2 Flaw Growth Resistance Test Number 1

8.2.1 Following acceptance test by the customer, the specimen was preflawed on the exterior surface at the midpoint of the cylindrical section. The flaw was as described in Paragraph 3.2 of this report, with the exception of the length of the deliberate was increased to 1.0 inches.

8.2.2 The specimen was installed in the test system. The specimen was pressurized to 6750 psig for a period of five minutes using gaseous nitrogen per MIL-P-27401 as the test medium.

8.2.3 The specimen was subjected to 1,000 pneumatic pressure cycles of 4000 psig using air as the test medium. The specimen was visually examined at the completion of each 100 cycles for structural degradation. At the completion of 600 cycles, it was noted that lamination separation on the hoopwrap at the point of flawing had occurred. (Reference Photograph 5)

8.2.4 At the completion of 1000 cycles, the customer representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1100 cycles.

8.2.5 At the completion of 1100 cycles, the customer representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1200 cycles.

8.2.6 At the completion of 1200 cycles, the customer representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1300 cycles.

8.2.7 At the completion of 1300 cycles, the customer representative increased the depth of the deliberate flaw. As the pressure was being increased from zero psig, the test specimen ruptured at 3100 psig in a catastrophic manner. The flaw growth resistance test setup is illustrated in Photographs 5 and 6. The condition of the specimen following rupture is illustrated in Photograph 7.

8.2.8 The data sheets are presented in Appendix 4.

9.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-5

9.1 Sizing Test

The test described in Paragraph 5.1 was performed. The data sheet is presented in Appendix 5.

9.2 Flaw Growth Resistance Test Number 2

9.2.1 Prior to testing, the specimen was preflawed on the exterior surface of the metal liner at the midpoint of the cylindrical section. The flaw was as described in Paragraph 3.2 of this report, with the exception of the length of the deliberate flaw was increased to 1.0 inches.

9.2.2 The specimen was installed in the test system. The specimen was pressurized to 4000 psig and was subjected to 1,000 pneumatic pressure cycles using gaseous air as the test medium. Each pressure cycle consisted of increasing the specimen pressure of 4000±50 psig and maintained the pressure for a period of ten seconds. The test specimen pressure was then decreased to 100 psig or less.

9.2.3 The cyclic rate was 2.8 cycles per minute in order to maintain the specimen temperature below 200°F. The specimen temperature was maintained at 194°F.

9.2.4 Visual examination at the completion of the 1000 cycles revealed no damage or other adverse effects. The test setup is illustrated in Photograph 8. The data sheet is presented in Appendix 5.

9.3 Burst Test

9.3.1 The specimen was pressurized with gaseous nitrogen per MIL-P-27401. The pressure was increased at a rate of 3100 psi per minute. At a pressure of 8500 psig, excessive leakage through the windings was noted. No visible evidence of damage was noted. Testing was discontinued at this point. The data sheet is presented in Appendix 5.

10.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-6

10.1 Sizing Test

The test described in Paragraph 5.1 was performed. The data are presented in Appendix 6.

10.2 Impact Resistance Test

10.2.1 The specimen, with a simulated valve installed, was pneumatically pressurized to 4000 psig at room ambient temperature using gaseous nitrogen per MIL-P-27401 as the test medium. The pressurization rate did not exceed 1000 psig per minute.

10.2.2 The specimen was dropped from a height of ten feet impacting on a rigid steel plate. The impacts were performed at the following drop angles:

a - Simulated Valve Down
b - Simulated Valve Up
c - Horizontal

10.2.3 A total of six impacts was performed. Three impacts per Paragraph 10.2.2 were performed at a temperature of -60°F and then three impacts were performed at a temperature of +200°F.

10.2.4 The tests of Paragraphs 10.2.2 and 10.2.3 were repeated.

10.2.5 During the cooldown to -60°F and the heatup to +200°F, the specimen's pressure decreased or increased with temperature. The pressure was not allowed to decrease below 3500 psig at -60°F or increase above 4500 psig at +200°F.

10.2.6 During the 12th drop, the threads stripped from the 1/4 inch facility port on the simulated valve. Rapid exhaust of gases broke the tank from the bonding straps and caused severe damage to the test item as it rocketed against concrete abutments and gravel. The condition of the specimen is illustrated in Photographs 9 and 10. The data are presented in Appendix 6.

10.3 Burst Test

10.3.1 The specimen, filled with water and bled of all entrapped air, was installed in a hydrostatic test system.

10.3.2 The hydrostatic pressure was increased at a rate of 3000 to 5000 psi per minute until rupture occurred.

10.3.3 Burst pressure of 9900 psig was noted. As this burst test was for information only, no minimum burst was applicable. The condition of the specimen following testing is illustrated in Photograph 11.

11.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-6A

11.1 Sizing Test

The test described in Paragraph 5.1 was performed. The data are presented in the data sheets in Appendix 7.

11.2 High Temperature Exposure Test

11.2.1 The specimen was installed in a temperature chamber and pressurized to 2000 psig using gaseous nitrogen per MIL-P-27401 as the test medium. The temperature of the test specimen was increased to, and maintained at, 200°F, for a period of 30 minutes while the pressure level was maintained at 2000 psig.

11.2.2 The specimen was then transferred to the high temperature chamber which was previously heated to, and stabilized at, 600°F. The specimen was maintained in the high temperature chamber for a period of five minutes. During the five-minute period, the specimen pressure and temperature were measured at one-minute intervals. The test data are presented in Appendix 7.

11.2.3 Visual examination at the completion of testing revealed that the hoopwrap, depth and width of the cut, started to separate circumferentially from the body. This condition is illustrated in Photograph 12.

11.3 Thermal Cycling Test

11.3.1 The specimen, filled with a water/glycol mixture, and bled of all entrapped air, was installed in a test system. The specimen's pressure was increased to 4000 psig. Pressure was controlled during the test as shown in Appendix 7, Figure 9A.

11.3.2 The specimen was alternately immersed in water at 200°F and water/glycol mixture at -60°F for a total of 20 cycles in each bath with a ten-minute exposure at each temperature extreme. The transfer time from bath to bath was 2.5 minutes.

11.3.3 During cycling, the specimen was visually examined for evidences of cracking or rupturing of material. No adverse effects were noted. At the conclusion of the 20 cycles, the specimen was then depressurized and the length and diameter were measured. The measurements are presented in the data sheets in Appendix 7.

11.4 Salt Fog Resistance Test

11.4.1 The specimen, with simulated valve installed, was suspended in the fog chamber in such a manner as to prevent condensate dripping on the exterior surfaces. The specimen was subjected to a salt fog concentration of 5.0 percent, by weight, for a period of 48 hours. During the 48-hour period, the temperature was maintained at 97°F, the salt solution pH was 6.8, and the salt fog fallout was 1.76 ml per hour per 80 square centimeters of horizontal collecting area.

11.4.2 Visual examination at the completion of testing revealed no corrosion or material deterioration as a result of testing.

11.4.3 The data sheets are presented in Appendix 7.

11.5 Cyclic Fatigue Test

11.5.1 The specimen, filled with water and bled of all entrapped air, was installed in a test system.

11.5.2 The test specimen was subjected to 10,000 hydrostatic pressure cycles of 4000 psig at room ambient conditions. (Each cycle consisted of varying the specimen pressure from zero to 4000 to zero psig at a cyclic rate of two to four cycles per minute. Actual cyclic rate was 2.5 cycles per minute.)

11.5.3 Following completion of 6633 cycles, 100 cycles of proof pressure of 6750 psig for a period of 30 seconds per cycle were to be applied to the specimen,

11.5.4 During the eighteenth proof cycle at a pressure of 3000 psig, water seepage through the hoop wrap was noted. Testing was discontinued at this point. The data sheets are presented in Appendix 7.

12.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-6B

12.1 Sizing Test

The test described in Paragraph 5.1 was performed. The test data are presented in the data sheet in Appendix 8.

12.2 Cyclic Fatique Test

12.2.1 The test described in Paragraph 11.5, except that proof cycles were reduced to 30, was performed. A total of 10,000 cycles was performed. Visual examination at the completion of testing revealed no damage or other adverse effects.

12.2.2 Following the 10,000 cycles of testing, the specimen was subjected to a Sizing Test as described in Paragraph 5.1. The data are presented in the data sheet in this report in Appendix 8.

12.3 Thermal Cycling Test

The test described in Paragraph 11.3 was performed. No damage was noted. The dimensions following 20 cycles of testing in each of the temperature extremes are presented in the data sheet in Appendix 8. (The fluid in the specimen and the -60° bath was isopropyl alcohol during the test per instructions of SCI engineering.)

12.4 Impact Resistance Test

The test described in Paragraph 10.2 was performed. Visual examination at the completion of testing revealed no damage other than a flattening of the closed end after impact. The data are presented in the data sheets in Appendix 8.

12.5 High Temperature Exposure Test

The specimen was subjected to the test described in Paragraph 11.2. Visual examination at the completion of testing revealed approximately six filament strands of the outer winding started to separate from the hoopwrap in the area shown on the sketch in the data sheet in Appendix 8.

12.6 Burst Test

12.6.1 The specimen was subjected to the test described in Paragraph 7.4. Burst occurred at a pressure of 12,300 psig. The condition of the specimen following burst testing is illustrated in Photograph 13. The data are presented in Appendix 8.

13.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-7

13.1 Sizing Test

The test described in Paragraph 5.1 was performed. The data are presented in the data sheet in Appendix 9.

13.2 Cyclic Fatigue Test (Room Ambient Temperature)

13.2.1 The specimen, filled with water and bled of entrapped air, was immersed in room ambient temperature water and was connected to a test system.

13.2.2 The specimen was subjected to 10,000 hydrostatic pressure cycles at a pressure of 4000 psig. Each cycle consisted of varying the pressure from zero to 4000 to zero psig at a cyclic rate of two to four cycles per minute. Actual cyclic rate varied between 2.5 and 3 cycles per minute.

13.2.3 At the completion of 5,000 cycles, 100 cycles of proof pressure at a pressure of 6750 psig were performed for a duration of 30 seconds per cycle.

13.2.4 At the completion of the 10,000 cycles of testing, visual examination revealed no damage or other adverse effects. The specimen was then subjected to a proof cycle test by the customer representative. The customer-furnished data sheet is presented in Appendix 9.

13.3 Burst Test

13.3.1 The specimen, filled with water and bled of all entrapped air, was installed in a pressure test system. The hydrostatic pressure was increased at a rate of 4850 psi per minute until rupture occurred at 9600 psig.

13.3.2 Failure occurred in the hoop cylindrical section area. A 3-1/2 inch axial tear was noted near the closed end. The condition of the specimen following testing is illustrated in Photograph 14. The data sheets are presented in Appendix 9.

14.0 TEST PROCEDURES AND TEST RESULTS, Serial Number QT-8

14.1 Sizing Test

The testing described in Paragraph 5.1 was performed. The test data are presented in the data sheet in Appendix 10.

14.2 High Temperature Exposure Test Number 2

14.2.1 The specimen was installed in a test chamber and was pressurized to 2000 psig using gaseous nitrogen per MIL-P-27401 as the test medium. The temperature of the test specimen was maintained at room ambient conditions for a period of 30 minutes while the pressure was maintained at 2000 psig.

14.2.2 The specimen was then transferred to the high temperature test chamber which was previously heated to, and maintained at, 400°F. The test specimen was maintained in the high temperature chamber for a period of ten minutes. During the High Temperature Exposure, the following parameters applied:

a - The minimum wind velocity in the chamber was five miles per hour.

b - The test specimen internal pressure was allowed to seek its own level.

c - The pressure level and temperature of the test specimen was measured and documented at one-minute intervals.

14.2.3 The test specimen was then removed from the high temperature chamber until the specimen's temperature was 100°F maximum.

14.2.4 The tests described in Paragraphs 14.2.2 and 14.2.3 were repeated for a total of 12 cycles of high temperature exposure. All data are presented in the data sheets in Appendix 10. Visual examination at the completion of testing revealed no damage or other adverse effects. The test setup is illustrated in Photograph 15.

14.3 Burst Test

14.3.1 The specimen was pressurized using gaseous nitrogen per MIL-P-27401 as the test medium. The pressure was increased at approximately 3000 psi per minute until rupture occurred.

14.3.2 Rupture occurred at 13,200 psig. Visual examination revealed hoop failure in the cylindrical section. The data are presented in the data sheets in Appendix 10.

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REPORT NO. 565-1180
PHOTOGRAPH 1
GUNFIRE TEST RESULTS
SERIAL NO. QT-1A
(ENTRY)

REPORT NO. 565-1180
PHOTOGRAPH 2
GUNFIRE TEST RESULTS
SERIAL NO. QT-1A
(EXIT)

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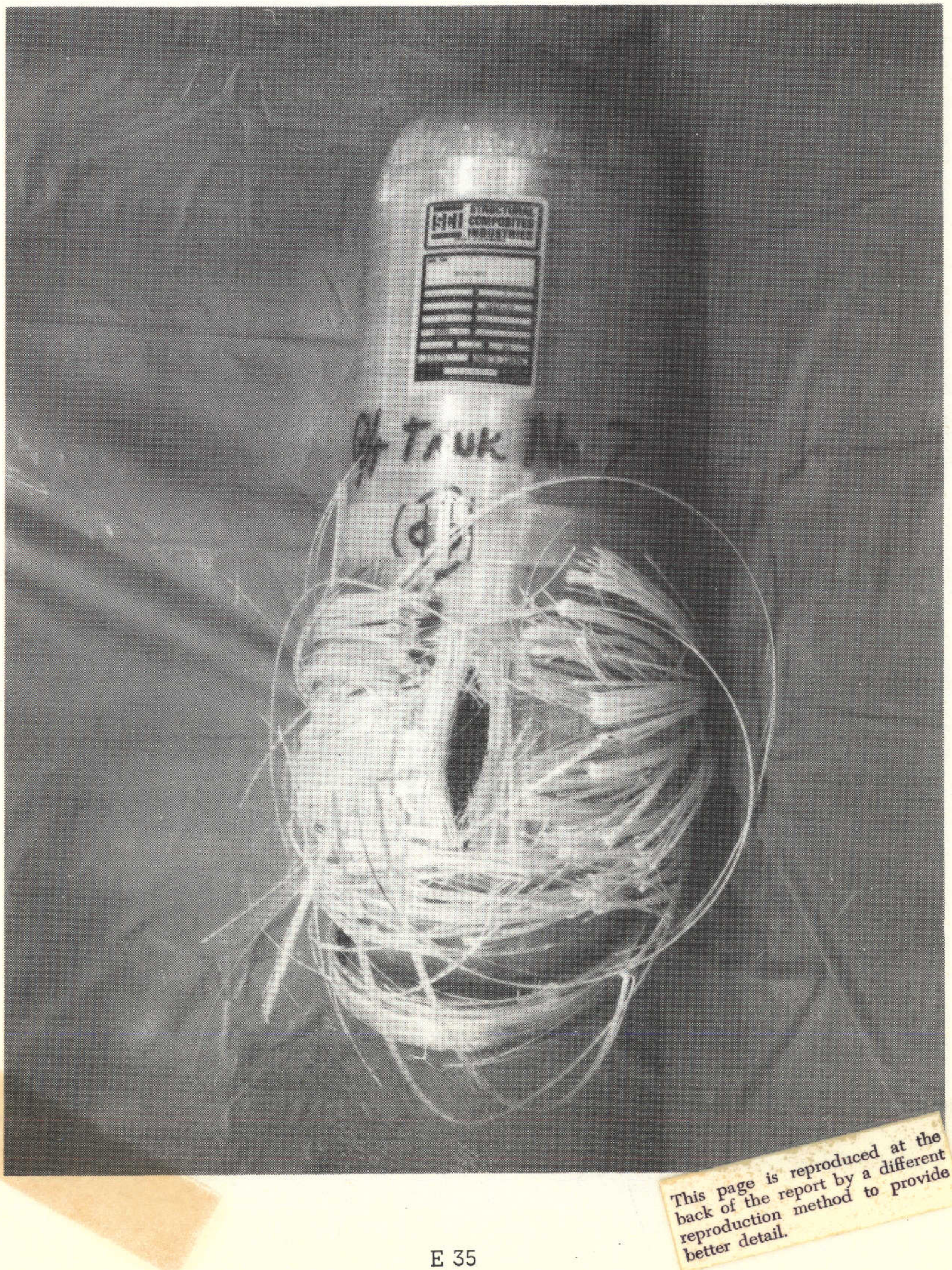
REPORT NO. 565-1180
PHOTOGRAPH 3
CONDITION OF SPECIMEN
FOLLOWING BURST TEST
SERIAL NO. QT-2



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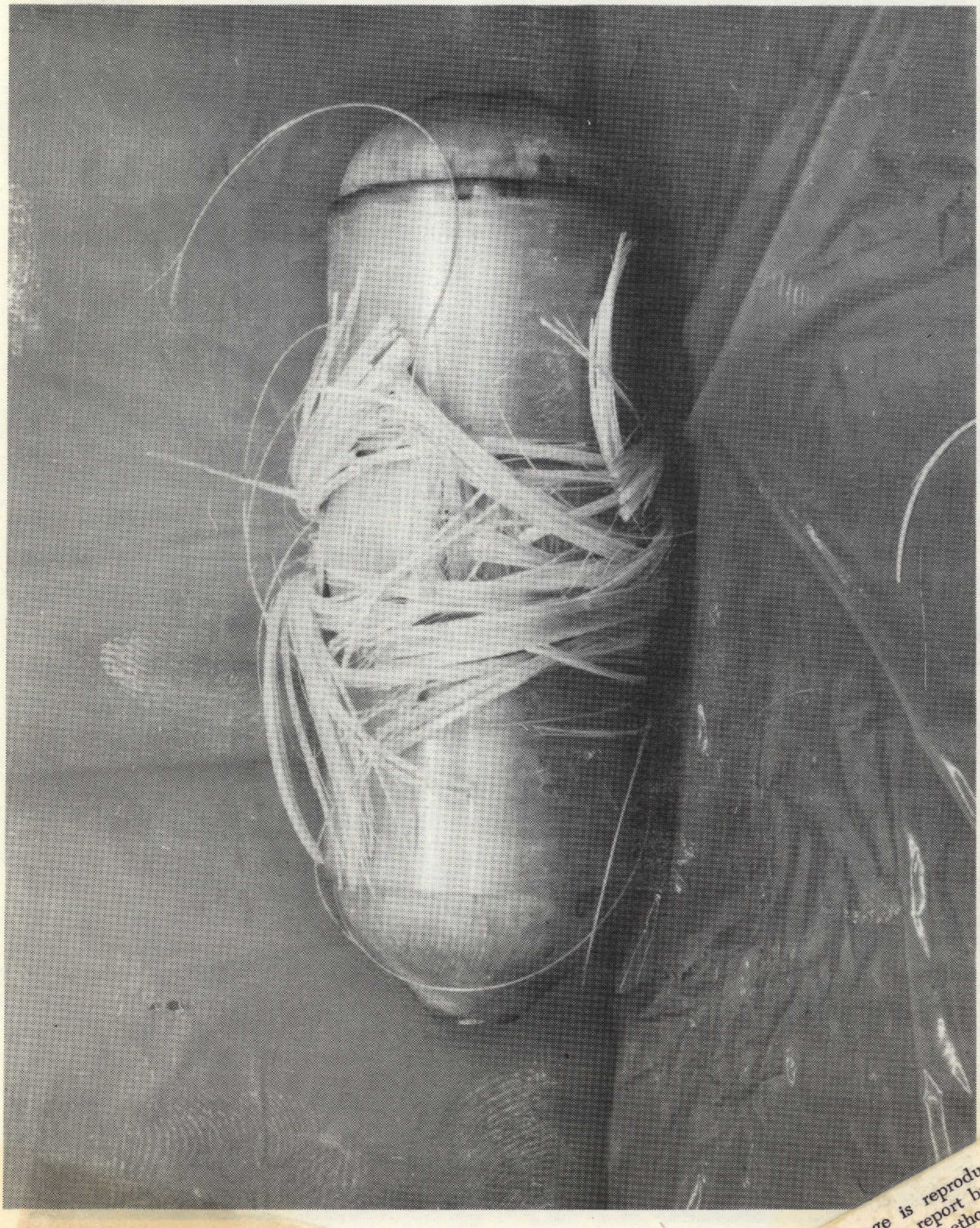
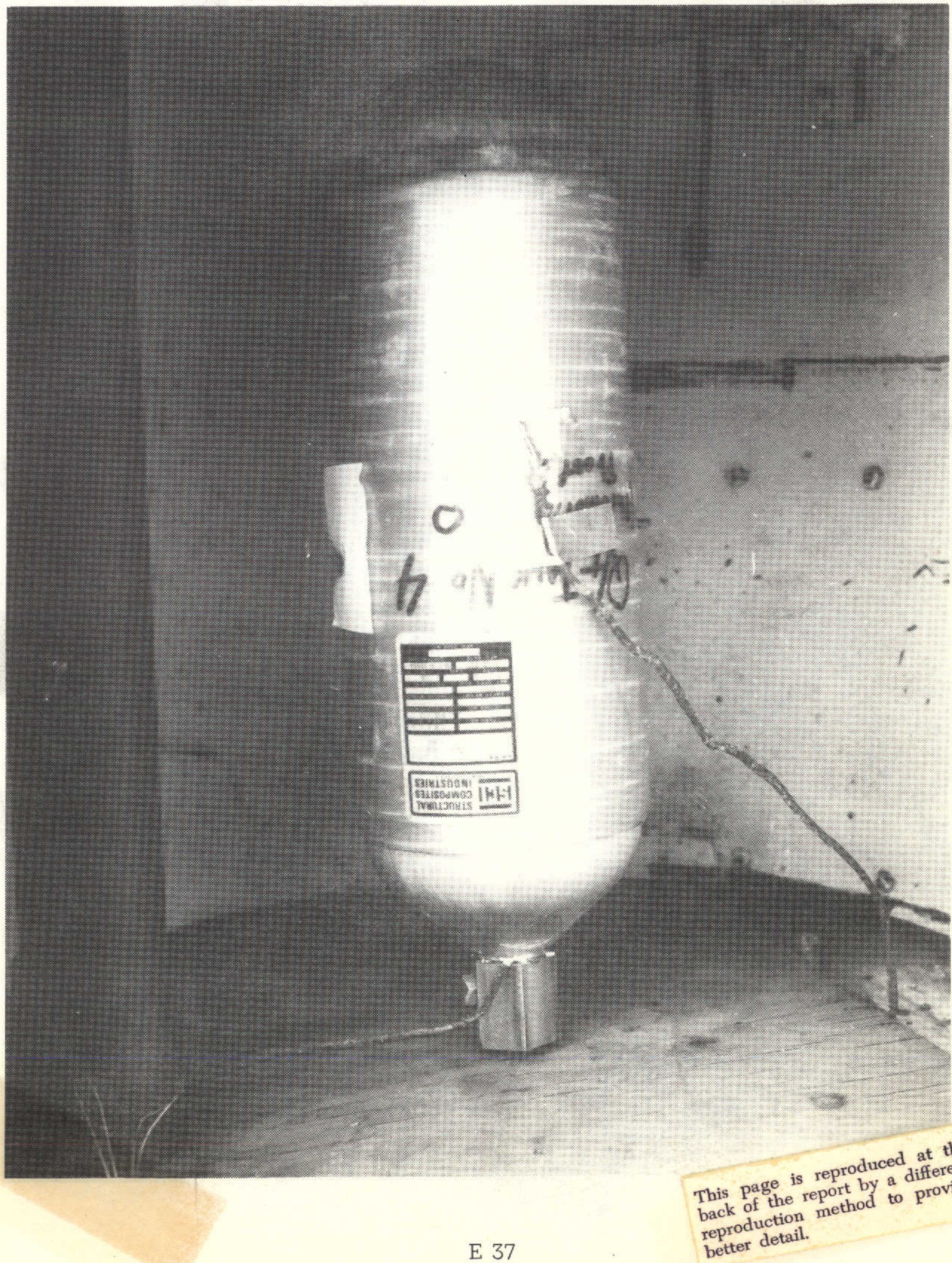
REPORT NO. 565-1180
PHOTOGRAPH 4
CONDITION OF SPECIMEN
FOLLOWING BURST TEST
SERIAL NO. QT-3)



REPORT NO. 565-1180
PHOTOGRAPH 5
CONDITION OF SPECIMEN
FOLLOWING 600 CYCLES OF
FLOW GROWTH RESISTANCE TEST
SERIAL NO. QT-4



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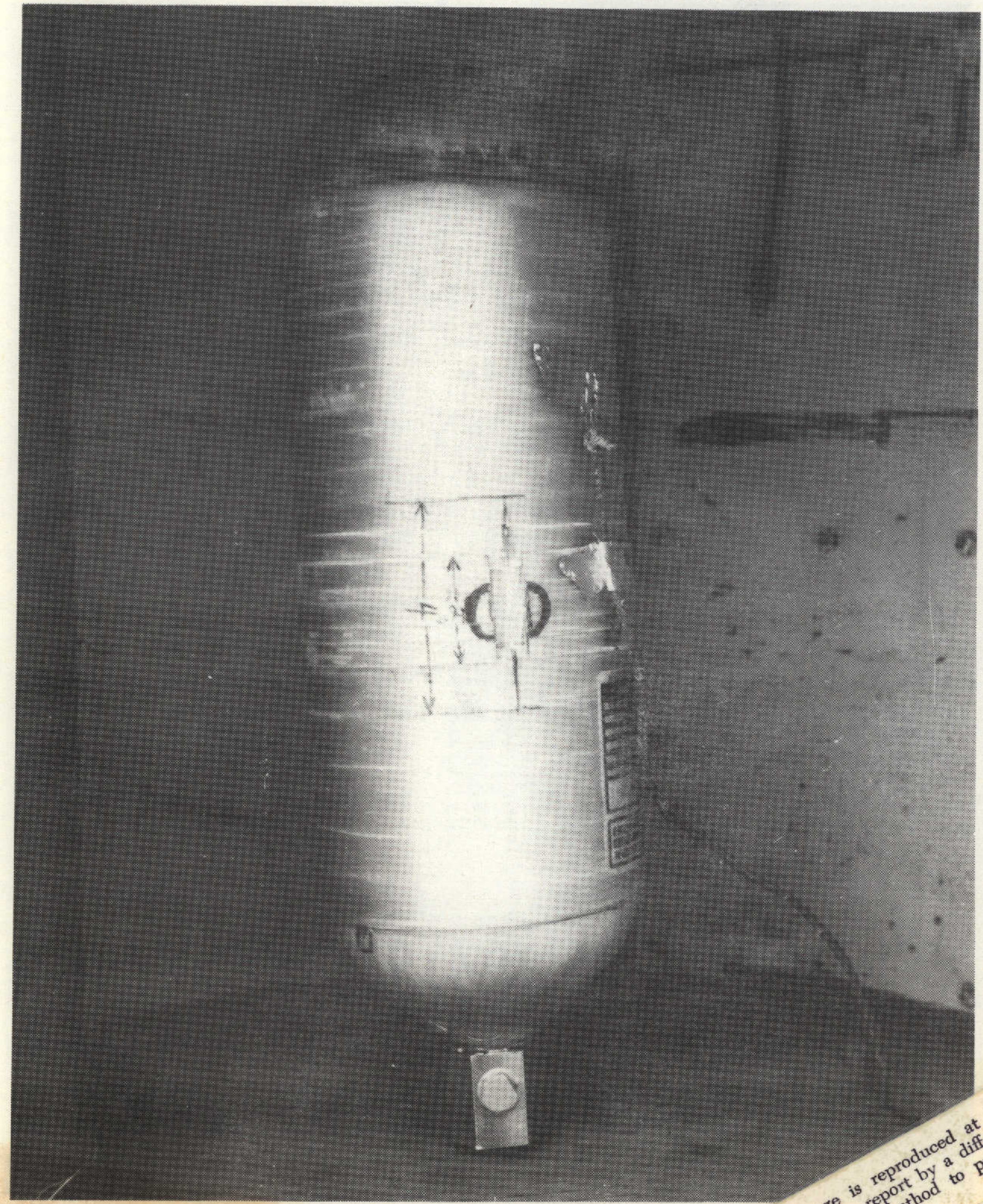
APPROVED ENGINEERING TEST LABORATORIES

REPORT NO. 565-1180
PHOTOGRAPH 6
CONDITION OF SPECIMEN
FOLLOWING FOURTH CUT, FLOW
GROWTH RESISTANCE TEST
SERIAL NO. QT-4



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REPORT NO. 565-1180
PHOTOGRAPH 7
BURST TEST RESULTS
SERIAL NO. QT-4

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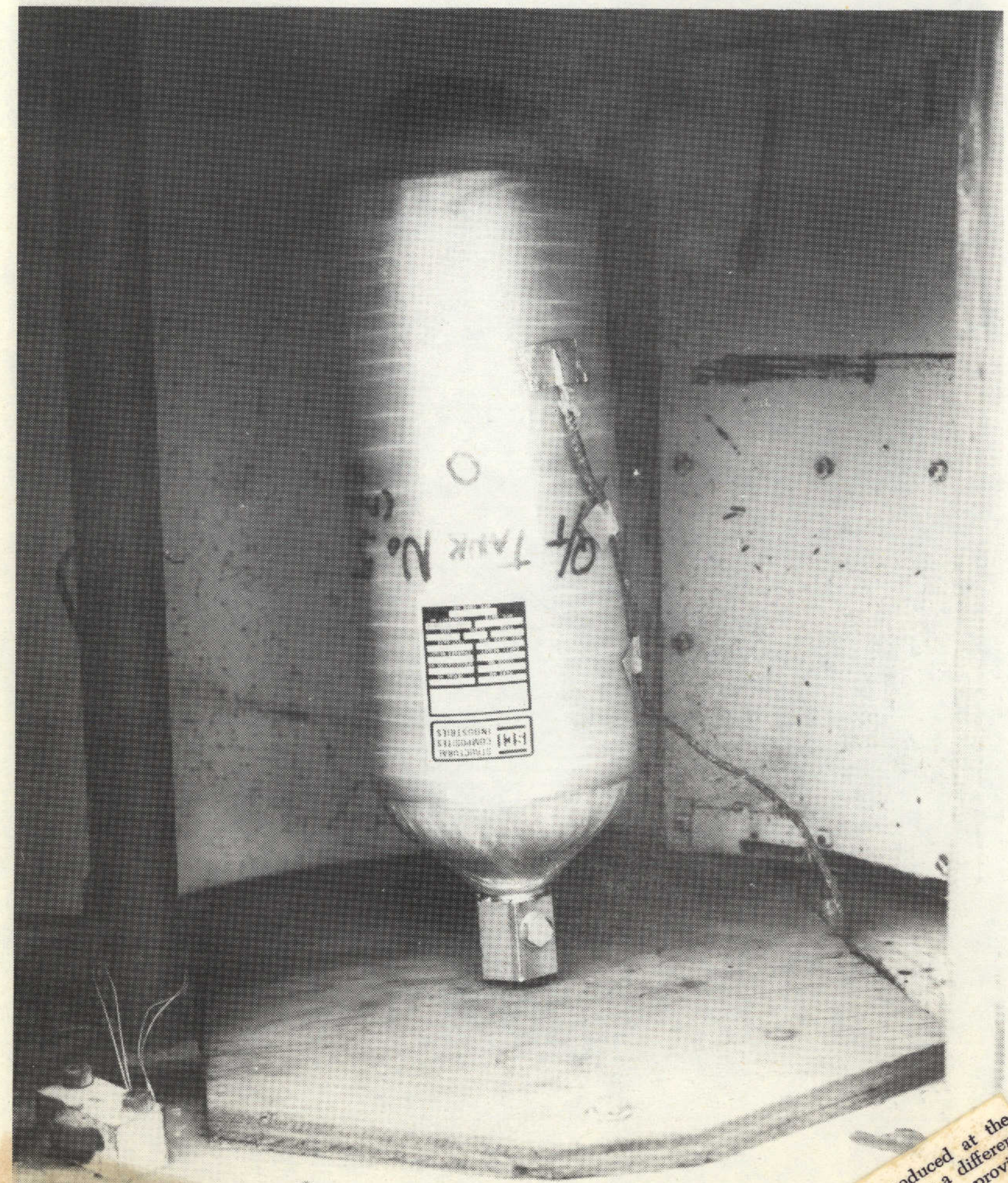
REPORT NO. 565-1180
PHOTOGRAPH 8
FLOW GROWTH RESISTANCE
TEST NUMBER 2
SERIAL NO. QT-5



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REPORT NO. 565-1180
PHOTOGRAPH 9
CONDITION OF SPECIMEN
FOLLOWING IMPACT TEST
SERIAL NO. QT-6 (BOSS END)

REPORT NO. 565-1180
PHOTOGRAPH 10
CONDITION OF SPECIMEN
FOLLOWING IMPACT TEST
SERIAL NO. QT-6 (CENTER HOOP)

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REPORT NO. 565-1180
PHOTOGRAPH 11
BURST TEST RESULTS
SERIAL NO. QT-6

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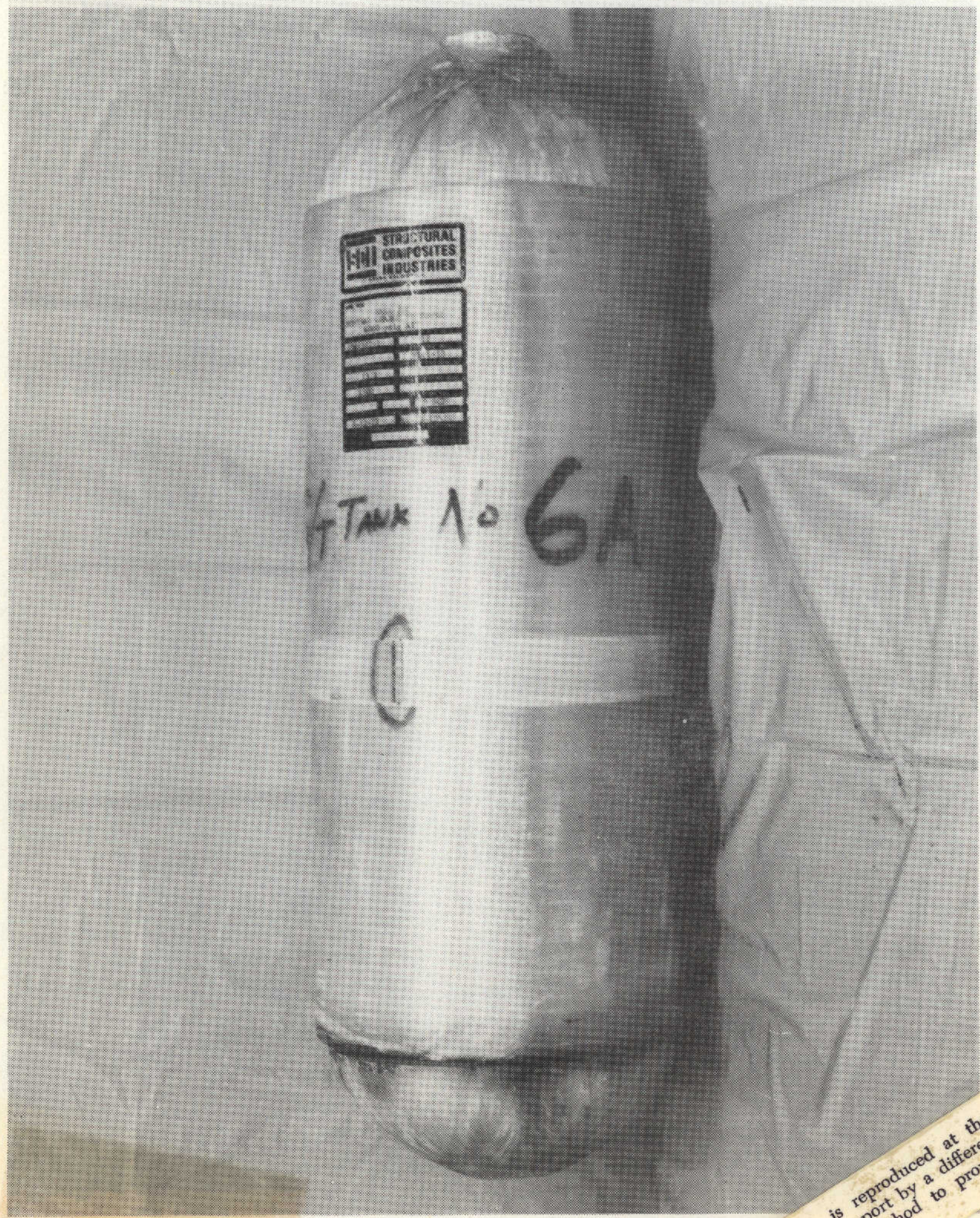
REPORT NO. 565-1180
PHOTOGRAPH 12
CONDITION OF SPECIMEN
FOLLOWING EXTREME TEMPERATURE
TEST - SERIAL NO. QT-6A



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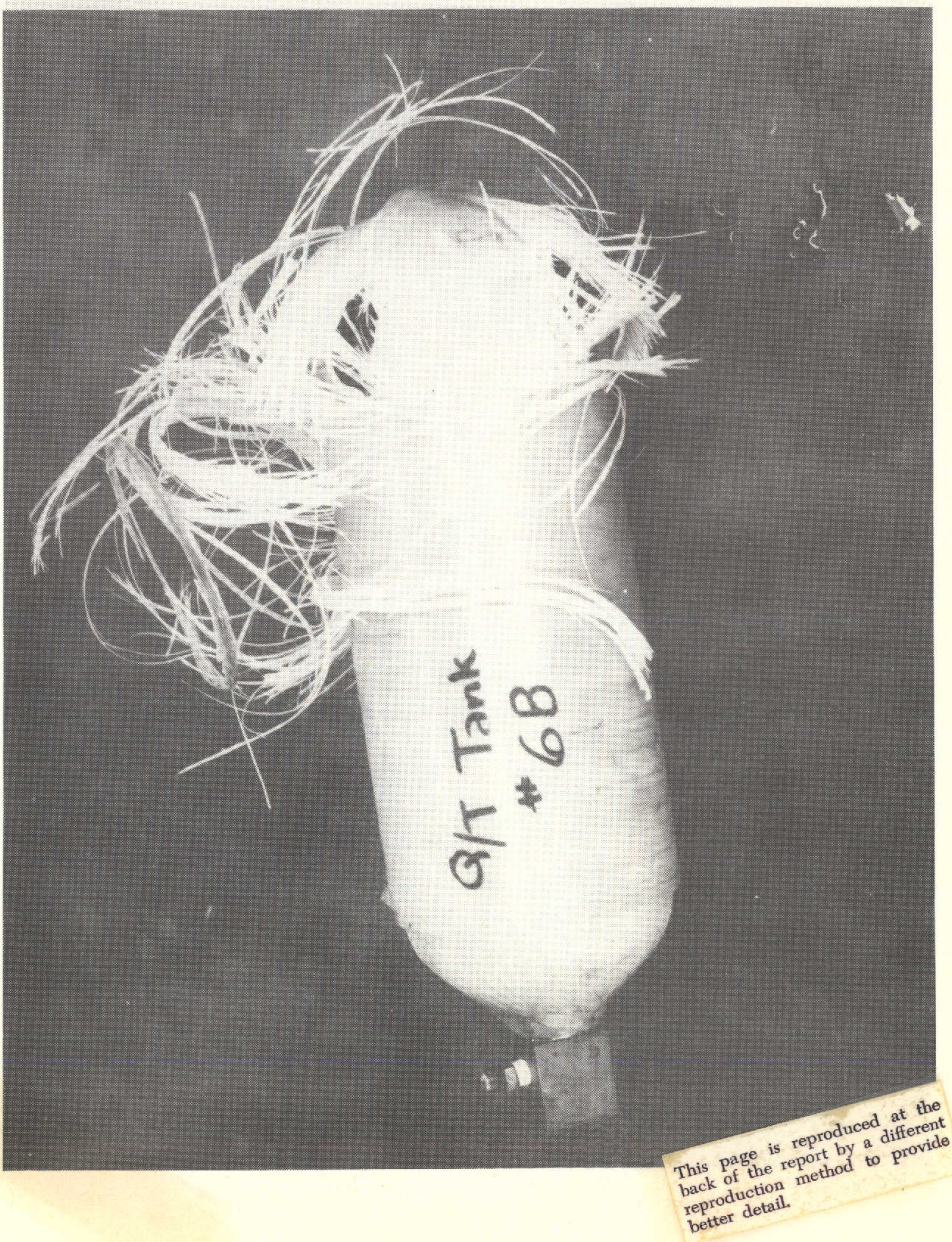
REPORT NO. 565-1180
PHOTOGRAPH 13
BURST TEST RESULTS
SERIAL NO. QT-6B



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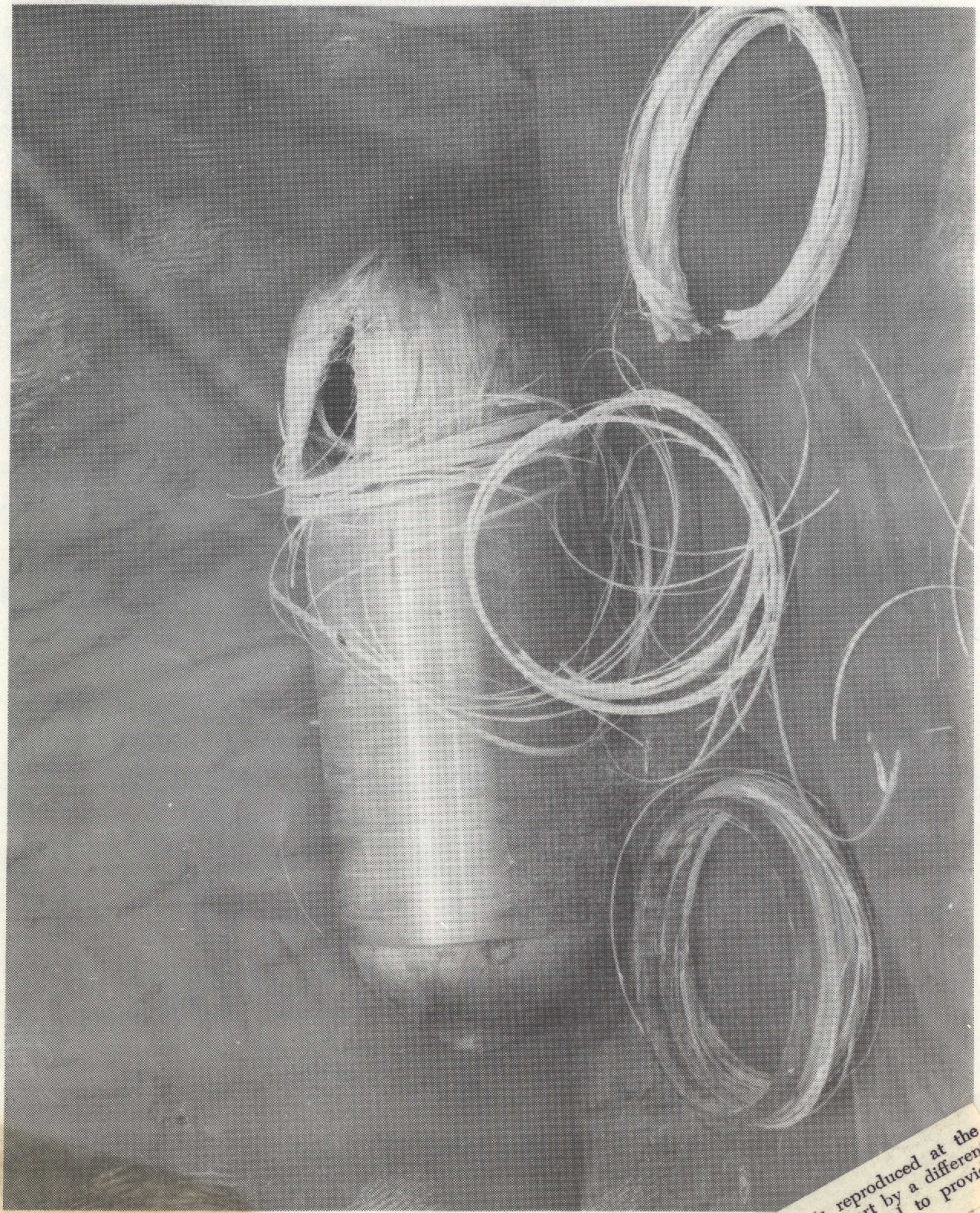
REPORT NO. 565-1180
PHOTOGRAPH 14
BURST TEST RESULTS
SERIAL NO. QT-7



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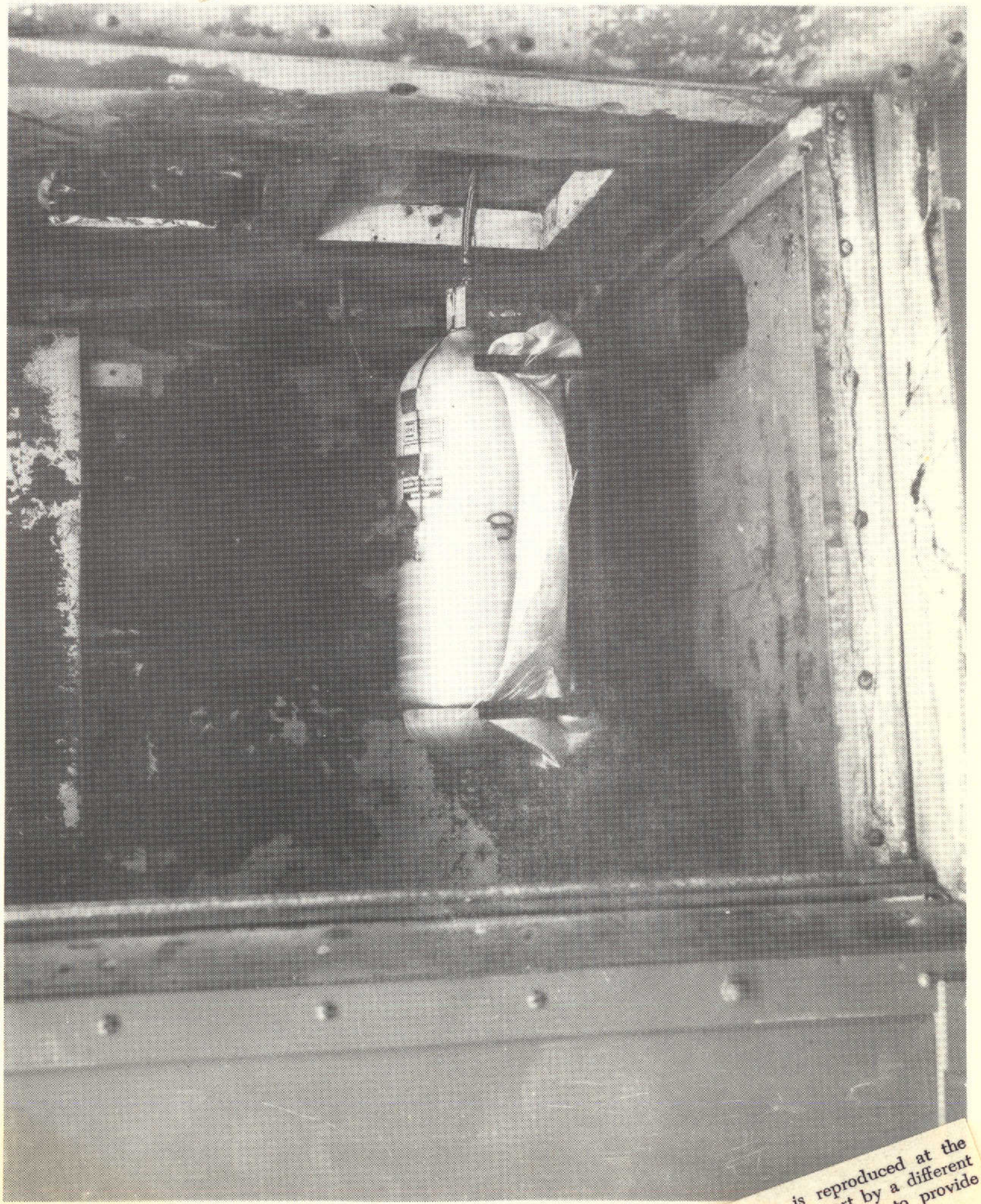
REPORT NO. 565-1180
PHOTOGRAPH 15
HIGH TEMPERATURE EXPOSURE
TEST SETUP - SERIAL NO. QT-8



APPENDIX I

Data Sheets

S/N QT-1A

SCI SPECIFICATION 73-13 (ARRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 1-A

Tank Serial Number QT 1A 11

Date: 4/12/73

Observer K. Hansen

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	SCI 2 6,083	13.44
2	3.2.8.2	Filled Weight	SCI 2 12,749	28.17
3		Capacity [(2) - (1)]	SCI 2 6,666	14.73
4	3.2.8.3	Sizing Operation	SCI 2 406,759 6,750 psig	5 minutes
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure	SCI 2 400	6750 psig
6	3.2.8.5	Burette Reading at Ambient Pressure	SCI 2 141	0 psig
7	3.2.8.6	Filled Weight	SCI 2 12,826	28.34 LBS.
7A.	WATER capacity Post TEST - 6,743			
8		Permanent ΔV [(7) - (2)]	SCI 2 77	
9		Elastic ΔV [(6) - (5)]	SCI 2 259	
10		Total V [(9) + (7A)]	SCI 2 7002	
11		Total ΔV [(9) + (8)]	SCI 2 336	
12		Permanent ΔV [(8) / (10)]	SCI 2 1.09 %	
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	SCI 2 22.91 %	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV: B 30 APR 73

DATA SHEET NUMBER 1

PART NUMBER 1269367-1, TANK NUMBER QT1A

FRAGMENTATION RESISTANCE TEST, Paragraph 7.1

Parameter	Required	Actual
Pressure	4500±80 psig GN_2	4500 psig
Temperature	Ambient	72 ° F.
Muzzle Velocity	Approx. 2800 fps	

Mode of Failure ENTRY APPROX 1/2" DIAM – NO TEAR EXIT OF ENTIRE BULLET DID NOT OCCUR – MOST OF PROJECTILE WAS STILL IN TANK AFTER TEST

Tested By LOIBL & HARKINK CEL 10 TEST Date 4-14-72
Witness ______ Date ______

Note; A weighted charge projectile was used.
SEE TEST EQUIPMENT LOG

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV: B 30 MAR 73

TEST EQUIPMENT LOG

TEST FRAGMENTATION RESISTANCE M/O 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT 1A
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.1

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
4/14	1	TAPE MEASURE	NONE	LUFKIN	0-100 FT	± 1 IN	N/R
	2	30 CAL RIFLE	NONE	WINCHESTER	N/A	N/A	N/A
	3	30 AP Ammo	NONE	UTAH	APPROX 2800 FPS	N/A	N/A
	4	PRESS CONSOLE	P-3104	CEL	8000 PSI	N/A	N/A
	5	PRESS GAUGE	P-300L	ASHCROFT	5000 PSIG	±0.5%	5-2-73
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
	20						

GENERAL TEST NOTES:

ITEM #3: ARMOR PIERCING - CALIBER .30 M2
UTAH ORDNANCE PLANT

PAGE ____ OF ____
TEST BY LOIBL CEL 10 TEST DATE 4-14-73
ENGR. ____ GOV'T QAR ____

AAB PTG 215

70

APPENDIX 2

Data Sheets

S/N QT-2

SCI SPECIFICATION 73-13 (ARRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17 Tank Serial Number QTZ 5

Date: Observer K.A., HK.

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	6120	13.52
2	3.2.8.2	Filled Weight	12,795	28.27
3		Capacity [(2) - (1)]	6675 407.308	14.73
4	3.2.8.3	Sizing Operation	6750 psig	5 minu
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure @ USE PRES:	500 395	6750 psig 4,000 "
6	3.2.8.5	Burette Reading at Ambient Pressure	209	0 psig
7	3.2.8.6	Filled Weight	13,868	
7A. water capacity		Post test: 6748		
8		Permanent ΔV [(7) - (2)]	73	
9		Elastic ΔV [(6) - (5)]	292	
10		Total V [(9) + (7A)]	7090	
11		Total ΔV [(9) + (8)]	365	
12		Permanent ΔV [(8) / (10)]	1.03 %	
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	20.0 %	

DATA SHEET NUMBER 2

PART NUMBER 1269367-1, TANK NUMBER QT2

DROP TEST, Paragraph 7.2.1

Parameter	Required	Actual
Pressure	4500±90 psig GN_2	4550 psig
Temperature	Ambient	76 ° F.
Weight Sandbag	200#	206 #
Drop Height	16 feet	15 5/6 feet
Drop #1	Valve Up	NO DAMAGE
Drop #2	Valve Down	NO DAMAGE
Drop #3	Horizontal	NO DAMAGE
Drop #4	Valve 45° Up	NO DAMAGE
Drop #5	Valve 45° Down	NO DAMAGE

Vessel Examination MINOR SURFACE DAMAGE ON CLOSED END WHEN 1/4" THREADS STRIPPED FROM SIMULATED VALUE ON DROP #5 & TANK RICOCHETED AGAINST CONCRETE

Tested by LOIBL Date 4-11/13-73

Witness ______ Date ______

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 3

PART NUMBER 1269367-1, TANK NUMBER QT2

BURST TEST, Paragraph 7.2.2

Parameter	Required	Actual
Burst Pressure	9000 psig min.	9300 psig
Pressure Rise Rate	3000/5000 psi/min	5314 psi/min AVERAGE

Mode of Failure RUPTURE IN HOOPWRAP SECTION OF TANK AXIAL TEAR APPROX 5 INCHES LONG NEAR CLOSED END REF PHOTOGRAPH

Tested By LOIBL CEL 1J TEST Date 4-19-73

Witness __________ Date __________

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV: B 30 Apr 73

TEST EQUIPMENT LOG

TEST DROP TEST & BURST TEST MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT 2
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.2

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
4/12	1	PRESS GAUGE	P-300L	ASHCROFT	5,000 PSIG	±0.5%	5-2-73
	2	BOOST PUMP	NONE	SPRAGUE	10,000 PSIG	N/A	N/A
	3	SCALE	G-304$	HOBART	1000#	± 1/2#	9-13-73
	4	TAPE MEASURE	NONE	LUFKIN	20 FT	N/A	N/A
4/19	5	PRESS GAUGE	P-3033	MARSH	30,000 PSIG	±0.5%	5-19-73
	6	PRESS CONSOLE	P-3036	CEL	15,000 PSIG	N/A	N/A
	7	STOPWATCH	G-3142	SECURITY	30 MIN	±0.07%	6-8-73
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
	20						

GENERAL TEST NOTES:

PAGE ____ OF ____
TEST BY LOIBL CEL TEST DATE 4-19-73
ENGR. ____ GOV'T QAR ____

APPENDIX 3

Data Sheets

S/N QT-3

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17 Tank Serial Number QT-3 SCI 2 6 (qt-3)

Date: Observer KH, HK.

Item	Paragraph	Procedure		cc or grams		Pounds	
1	3.2.8.1	Tare Weight	SCI 2	6151		1359	
2	3.2.8.2	Filled Weight	SCI 2	12,835		2836	
3		Capacity [(2) - (1)]	SCI 2	6684		1477	
4	3.2.8.3	Sizing Operation	SCI 2	407,857 6,750	psig	5	minu
		Comments:					
5	3.2.8.4	Tare Volume at Sizing Pressure @ use pressure	SCI 2 SCI 2	500 393		6750 4,000	psi
6	3.2.8.5	Burette Reading at Ambient Pressure		205		0	psi
7	3.2.8.6	Filled Weight	SCI 2	12,905		28.52	
7a.		WATER CApacity Post TEST: 6,754					
8		Permanent ΔV [(7) - (2)]	SCI 2	70			
9		Elastic ΔV [(6) - (5)]	SCI 2	295			
10		Total V [(9) + (7)]	SCI 2	7049			
11		Total ΔV [(9) + (8)]	SCI 2	365			
12		Permanent ΔV [(8) / (10)]	SCI 2	.99	%		
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	SCI 2	19.1	%		

DATA SHEET NUMBER 17

PART NUMBER 1269367-1, TANK NUMBER QT3 WO# 1040-10-1

TEMPERATURE CYCLIC FATIGUE RESISTANCE TEST, Paragraph 7.13

Parameter	Required	Actual
Pressure	4000 psig Liq.	4000 psig
Temperature	200° F.	200 ° F.
Cycles	5000	5000
Cyclic Rate	2/4 cpm	2.5 cpm
Pressure	6750 psig Liq.	6750 psig
Cycles	100	100
Hold	30 sec	30 sec
Pressure	4000 psig Liq.	4000 psig
Temperature	-60° F.	-60 ° F.
Cycles	5000	5000
Cyclic Rate	2/4 cpm	2.5 cpm

Vessel Examination COMPLETED

Tested By KEN HANSEN SCI Date 5-1-73

Witness ______ Date ______

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

POST CYCLIC FATIGUE TEST FOLLOWING PARA 7.13.3 OF T.P.

Work Order Number 1040-10

Tank Serial Number 6 (qual #3)

Date 4/30/73

Observer K. Hanson

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	6151	
2	3.2.8.2	Filled Weight	12905	
3		Capacity [(2) - (1)]	6754	
4	3.2.8.3	Sizing Operation	6750 psig	5 minute
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure	500	6750 psig
6	3.2.8.5	@ use pressure Burette Reading at Ambient Pressure	210	psig
7	3.2.8.6	Filled Weight	12,927	cc.
7.A	Post Proof capacity = 6776			
8		Permanent ΔV [(7) - (2)]	22	cc.
9		Elastic ΔV [(6) - (5)]	290	
10		Total V [(9) + (7A)]	7066 x .06102	431.16"^{3}
11		Total ΔV [(9) + (8)]	312	
12		Permanent ΔV [(8) / (10)]	.990 %	
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	7.05 %	

Temperature Fatigue Resistance test.

Notes!

5,000 cycles adv: 3/min.

@ 3,000 cycles: "O" Ring @ Boss Blew out.

@ 4,760 cycles: "O" Ring & or Back up ring Failure.

30 SEC. HOLD. EACH cycle.

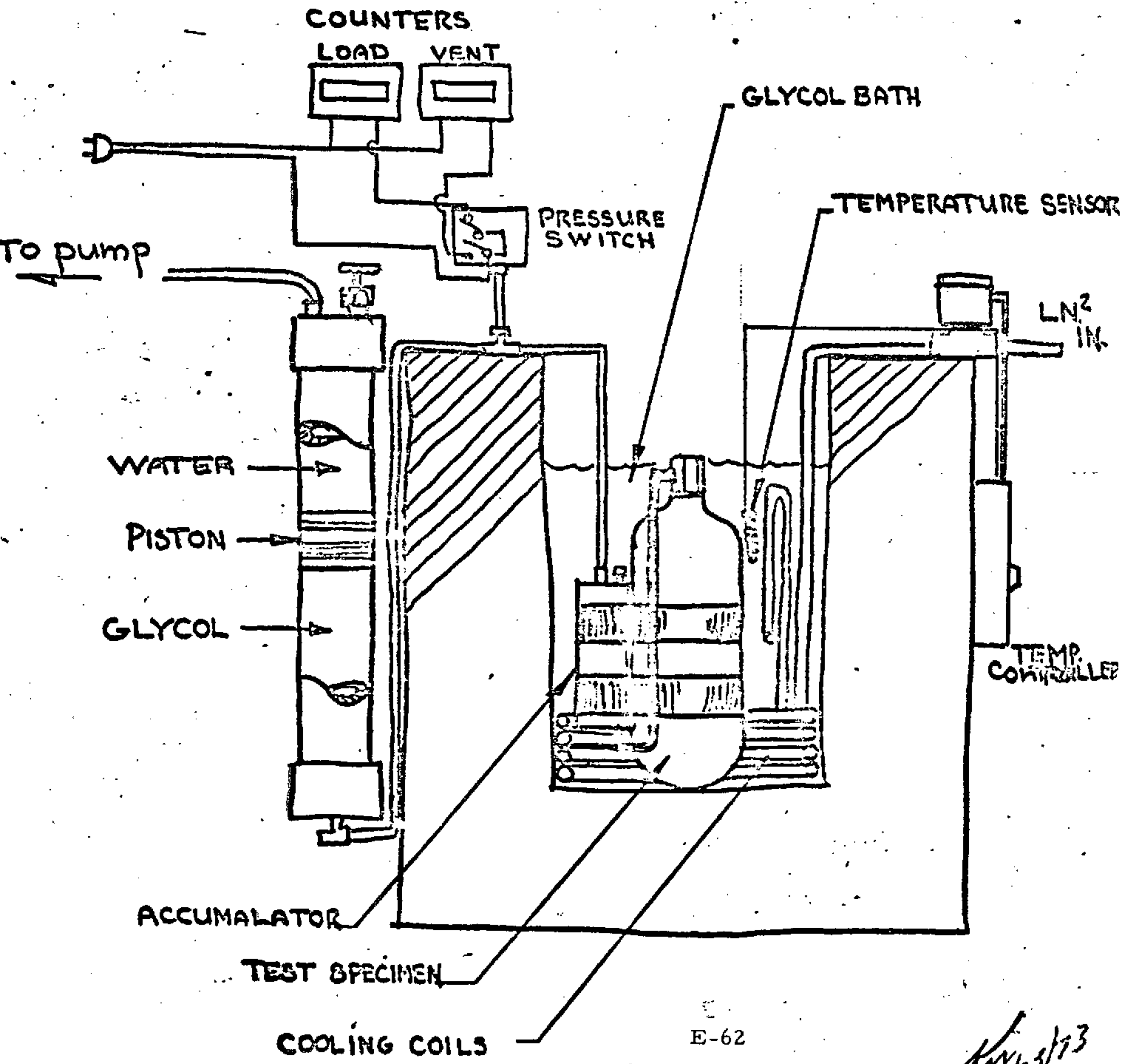
6,750 100 cycles @ Ambient 4/19/73

Proof Test: ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~
7.13.2.1
~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~

Pumping speed:
Time 0-To 6,750 approx: 50 Sec:

This Portion of TEST completed 4/20/73 K

W.O. 1040-10-1


COUNTERS
LOAD
VENT
GLYCOL BATH
TEMPERATURE SENSOR
PRESSURE SWITCH
To pump
LN2 IN.
WATER
PISTON
GLYCOL
TEMP. CONTROLLER
ACCUMALATOR
TEST SPECIMEN
COOLING COILS

4/23/73

S.C.I.

[redacted] TEST LABORATORIES

TEST EQUIPMENT LOG

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

ST Temperature Cyclic Fatigue Resistance M/O
STOMER Structural Composites Industries
ST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N Qual. 3
ECIFICATION CEL/AETL QTP 565-1180 PAR 7.13.2

DATE	Item	Description	SCI. No.	Mfgr.	Range	Acc'y	Calib Due
4/16/73	1	Millivolt Potentiometer	1615901	L&N.	- to + 100mv.	.1%	4/19/73
"	2	Temp chart recorder.	56C006A	B.C.	0-500°f.	3%	8/26/73
"	3	Test pressure gauge:	L604404	HEISE.	0-20K PSI.	1%	10/24/73
"	4	Auto cycle test fixture	A-1	SCI.	0-7,000 PSI	N.A.	N.A.
"	5	Environmental chamber	A-2	SCI.	-95°f+240°f.	± 2%	4/3/74
" SCI 2	6	Pressure chart Recorder.	P00130	L&N	0-10	——	*
"	7						
	8						
	9						
	10						
	11						
	12						
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GENERAL TEST NOTES:

* Item #3 contains a pressure transducer.
Item 6 is calibrated with Item #3 upon use. SCI 2

PAGE ___ OF ___

TEST BY ___ DATE ___

ENGR. R. GORDON · H. King GOV'T QAR ___

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

ST Temperature cyclic fatigue resistance MJO W.O. 1040-10-1
STOMER Structural Composites Industries
ST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N 3
ECIFICATION CEL/AETL QTP 565-1180 PAR 7.13.3

DATE	Item	Description	SCI. No.	Mfgr.	Range	Acc'y	Calib Due
4/24/73	1	Cryostat: IA Test fix:	1-A	S.C.I.	-90° to +240°f.	± 3°f.	N.A.
"	2	Millivolt Potentiometer	1632418	L&N.	-10 to +100mv.	.03%.	4/13/74
"	3	Test Pressure Gauge:	L-604404	HEISE	0 to 20K.	1%.	10/24/73
"	4	Auto cycle test fixture	A-1	S.C.I.	0-7000 PSI	N.E 20psi	NA.
"	5	Pressure chart Recorder:	P-00130	L&N	-0-10mv.	—	*
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
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GENERAL TEST NOTES: * Item #3 contains a pressure transducer.
Item #5 is calibrated with Item #3 upon use. K. SCI 2

PAGE ____ OF ____

TEST BY K. Hansen. SCI 2 DATE ____
ENGR. H.K. & R.G. GOV'T QAR ____

E-64

A&B PTG. — 215

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 16

PART NUMBER 1269367-1, TANK NUMBER QT3

LEAKAGE TEST, Paragraph 7.12

Parameter	Required	Actual
Pressure	4000 psig Air	4000 psig
Temperature	Ambient	80 ° F.
Duration	10 minutes	10 min.
Leakage	10 cc/hr. maximum	0 cc
Duration	30 minutes, total	SEE NOTE min.
Leakage	10 cc/hr. maximum	SEE NOTE cc

Tested By LOIBL Date 5-8-73

Witness ______________________ Date __________

NOTE: If no leakage is observed in ten minutes duration the fact shall be noted in the ACTUAL column and the 30 minute test may be omitted. B

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST LEAKAGE MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-3
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.12

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P-3011E	HEISE	0-10K PSI	±0.1%	23 JUL 73
	2	PRESS CONSOLE	P-3104E	CEL	8000 PSI	N/A	N/A
	3	STOPWATCH	G-3142E	SECURITY	30 MIN	±0.07%	6-8-73
	4						
	5						
	6						
	7						
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	9						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY LOIBL CEL 10 DATE 5-8-73
ENGR. ____ GOV'T QAR ____

AEB PTG — 21

DATA SHEET NUMBER 18

PART NUMBER 1269367-1, TANK NUMBER QT3

BURST TEST, Paragraph 7.14

Parameter	Required	Actual
Temperature	Ambient	85 ° F.
Burst Pressure	9000 psig minimum	8300 psig
Pressure Rise Rate	3000/5000 psi/min	4500 psi/min AVERAGE

Mode of Failure HOOPWRAP SECTION - CYLINDRICAL AREA
TEAR OF APPROX 3 INCHES, AXIAL,
IN MIDDLE OF CYLINDER

Tested By LOIBL CEL 10 TEST Date 5-8-73

Witness ______ Date ______

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST Burst MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-3
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.14

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P-3033E	MARSH	0-30KPSI	±0.5%	5-19-73
	2	PRESS CONSOLE	P-3036E	CEL	15,000 PSI	N/A	N/A
	3	STOPWATCH	G-3142E	SECURITY	30 MIN	±0.07%	6-8-73
	4						
	5						
	6						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY Loibl CEL 10 TEST DATE 5-8-73
ENGR. ____ GOV'T QAR ____

AAB FTG 215

NOTICE OF DEVIATION

AETL

APPROVED ENGINEERING TEST LABORATORIES

DATE: 5-8-73

☐ LOS ANGELES DIVISION / 5320 WEST 104TH STREET / LOS ANGELES, CALIFORNIA 90045 / (213) 776-3202
☐ VALLEY DIVISION / 9551 CANOGA AVENUE / CHATSWORTH, CALIFORNIA 91311 / (213) 341-0830
☐ SAUGUS DIVISION / 20744 SOLEDAD CANYON ROAD / SAUGUS, CALIFORNIA 91350 / (805) 259-8184
☐ CALIFORNIA TEST LABS DIV. / 619 E. WASHINGTON BLVD. / LOS ANGELES, CALIF. 90015 / (213) 747-4235
CEL SUBSIDIARY

CUSTOMER: STRUCTURAL COMPOSITES
MJO NO.: 565-1180
PART NO.: 1269367-1
N.O.D. NO.: #101
SERIAL NO.: QT-3
P.O. NO.: 9290
TEST PROCEDURE: CEL QTP 565-1180
PARAGRAPH: 7.14

REQUIREMENT: THE TEST SPECIMEN, FILLED WITH WATER, SHALL BE PRESSURIZED TO RUPTURE AT A RATE OF 3000 TO 5000 PSI/MINUTE. MINIMUM BURST PRESSURE TO BE 9000 PSIG.

DEVIATION: THE TEST SPECIMEN BURST AT 8300 PSIG WHEN PRESSURIZED AT AN AVERAGE RISE RATE OF 4500 PSI/MIN.

DISPOSITION: RETURN TO SCI

APPROVAL: BOB GORDON RAS
(Customer Representative)

CUSTOMER NOTIFICATION:

Made to: DR. BOB GORDON
How: TELECON
Date & Time: 5-8-73 PM
By: BOB LOIBL
DCAS Notified: ☐ YES ☐ NO NOT RQ'D
DATE
A.E.T.L. Dept. Supervisor

CEL 10 TEST

A&B PTG. — 231

APPENDIX 4

Data Sheets

S/N QT-4

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17 Tank Serial Number SCI 2 82 (QT-4)

Date: ______ Observer H.K., K.H.

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	SCI 2 6,100	1348
2	3.2.8.2	Filled Weight	SCI 2 12,787	2825
3		Capacity [(2) - (1)]	SCI 2 6687	1477
4	3.2.8.3	Sizing Operation	SCI 2 408.040 6,750 psig	5 min
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure	SCI 2 500	6,750 psi
		@ USB PRESSURE:	397	4,000
6	3.2.8.5	Burette Reading at Ambient Pressure	SCI 2 213	0 psi
7	3.2.8.6	Filled Weight	SCI 2 12,862	2842 LBS.
7A	WATER capacity	POST TEST. 6,762		
8		Permanent ΔV [(7) - (2)]	SCI 2 75	cc.
9		Elastic ΔV [(6) - (5)]	SCI 2 287	cc.
10		Total V [(9) + (7A)]	SCI 2 7049	
11		Total ΔV [(9) + (8)]	SCI 2 362	
12		Permanent ΔV [(8) / (10)]	SCI 2 1.06 %	
13		$\frac{\text{Permanent } \Delta V}{\text{Total } \Delta V}$ $\left[\frac{(8)}{(11)}\right]$	SCI 2 20.7 %	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 6

PART NUMBER 1269367-1, TANK NUMBER QT4

FLAW GROWTH RESISTANCE TEST NUMBER 1, Paragraph 7.4

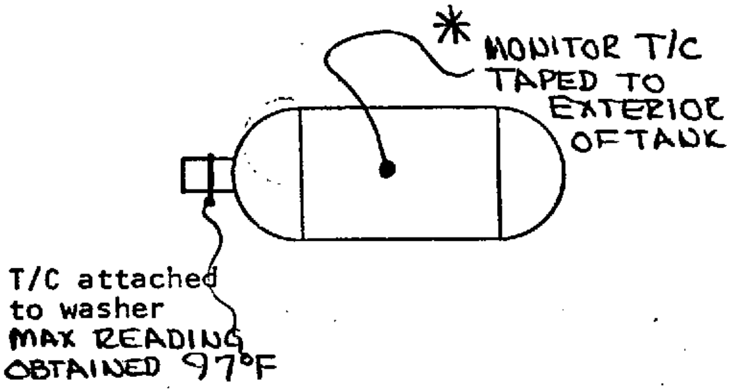
Parameter	Required	Actual
Pressure	4000 psig Air	4000 psig
Temperature	200° F. maximum	196 ° F.*
Cycles	1000	1000
Cyclic Rate	2/4 cpm desired	2.8 cpm

Remarks SEE DATA SHEET NO 7 FOR COMMENTS

NOTE: A GASEOUS NITROGEN PROOF, 6750 PSIG - 5 MINUTES, WAS PERFORMED DURING ATP

Tested By M.D. CONNELL CEL 10 TEST Date 4-13-73

Witness ____________ Date, ____________



DATA SHEET NUMBER 7

PART NUMBER 1269303-1, TANK NUMBER QT4

- -

Flaw Growth Resistance Test Number 1

General Notes:

Flaw Growth Resistance test started in late afternoon and was shutdown for evening after completion of 475 cycles. Test was restarted next day and 1000 total cycles completed.

The test specimen was examined at the completion of each 100 cycles for structural degradation. At the completion of 600 cycles it was noticed that lamination separation on the hoop-wrap at the point of flawing had occurred.

At the completion of 1000 cycles, a SCI representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1100 cycles.

At the completion of 1100 cycles, a SCI representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1200 cycles.

At the completion of 1200 cycles, a SCI representative increased the depth of the deliberate flaw. An additional 100 cycles were performed for a total of 1300 cycles.

At the completion of 1300 cycles, a SCI representative increased the depth of the deliberate flaw. As the pressure was increased from 0 psig, the test specimen ruptured at 3100 psig in a catastrophic manner. Reference photograph.

RAS CEL 10 TEST

APPROVED ENGINEERING TEST LABORATORIES

TEST EQUIPMENT LOG

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST FLAW GROWTH RESISTANCE & BURST #1 MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-4
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.4

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P-832V	HELICOID	16,000 PSIG	±0.5%	5-23-73
	2	PRESS PUMP					
	3	STOPWATCH	G-3142E	SECURITY	30min	±0.07%	6-8-73
	4						
	5						
	6						
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ______ OF ______

TEST BY M. CONNELL CEL 10 TEST DATE 4-13-73
ENGR. ______ GOV'T QAR ______

A&B PTG. -- 215

APPENDIX 5

Data Sheets

S/N QT-5

SCI SPECIFICATION 73-13 (MARCH 1973)

FIGURE 1

QUALIFICATION TEST TANKS
ACCEPTANCE TEST PROCEDURE DATA SHEET

Tank Q/T No. 5

Tank S/N 10 (QT5)

Date(a) ______

Observer ______

Item			**cc or Grams**(b)	**Pounds**	
1.	3.3.1	Tank Dry Weight (Must be less than 14 lbs)	5985	13.18	
2.	3.3.2	Tank Filled Weight	12630		
3.	HAK 3/28/3	Tank Water Capacity [(2) - (1)]	6645 405.477	14.64	
4.	3.3.3	PNEUMATIC ~~Hydrostatic~~ Proof Pressure (GN2)		6750 psig	
5.	RAS 4-4-73	Duration of Pressure		5 minutes	
6.		Comments: COMPLIED - 1000 PSIG GN2 UNDER WATER AFTER TEST REVEALED NO LEAKAGE			
7.	3.3.4	Tank Volume at Pressure (c)			
8.		Tare Reading before Proof		______ cc	
9.		Reading at Proof Pressure		______ cc	
10.		ΔV-Total [(9) - (8)]		______ cc	
11.		Tare Reading after Proof		______ cc	
12.		ΔV - Permanent [(11) - (8)]		______ cc	
13.		ΔV - Permanent [(12)/(10)] x 100		______ %	
14.		Total Volume at Proof Pressure [(3) + (10)] Must be greater than 6923 cc		______ cc	SCI 1
15.		Tank Overall Length,(d) Inches Must be less than 20.0 inches		19.739	SCI 1
16.		Tank Diameter(d), Cylindrical	D_1	6.550	SCI 1
		Average of 4 readings	D_2	6.595	SCI 1
		Must be less than 6.60 inches	D_3	6.605	SCI 1
			D_4	6.566	
		Average		6.579	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No.		565-1180
Date:		3 Mar 73
Rev:	A	28 Mar 73
Rev:	B	30 Apr 73

DATA SHEET NUMBER 8

PART NUMBER 1269367-1, TANK NUMBER QT 5

- -

FLAW GROWTH RESISTANCE TEST NUMBER 2, Paragraph 7.5

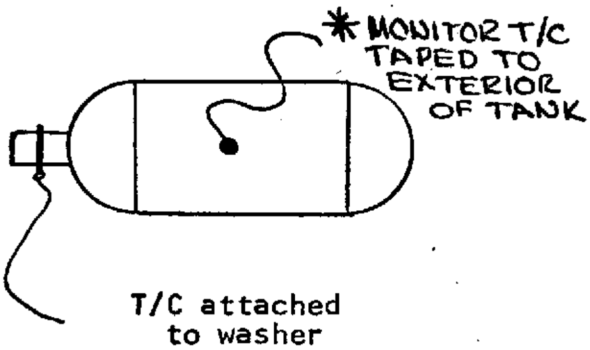
Parameter	Required	Actual
Pressure	4000 psig Air	4000 psig
Temperature	200° F.	194 ° F *
Cycles	1000	1000
Cyclic Rate	2/4 cpm desired	2.8 cpm

Remarks NO VISUAL EVIDENCE OF DAMAGE NOTED

NOTE: A GASEOUS NITROGEN PROOF, 6750 PSIG - 5 MIN, WAS PERFORMED DURING ATP CEL 13 TEST

Tested By M.D. CONNELL CEL 13 TEST Date 4-13-73

Witness ______________________ Date __________



* MONITOR T/C TAPED TO EXTERIOR OF TANK

T/C attached to washer
MAX READING OBTAINED 98°F

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 9

PART NUMBER 1269367-1, TANK NUMBER QT5

- -

BURST TEST, Paragraph 7.5.7

Parameter	Required	Actual
Test Media	Gaseous Nitrogen	
Temperature	Ambient	76 ° F.
Burst Pressure	As observed	8500 psig
Pressure Rise Rate	3000/5000 psi/min	3100 psi/min

Mode Of Failure EXCESSIVE LEAKAGE THRU WINDINGS - NO VISUAL EVIDENCE OF DAMAGE WAS NOTED

Tested By M. CONNELL CEL 10 TST Date 4-13-73

Witness ________ Date ________

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST FLAWGROWTH RESISTANCE & BURST #2 MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-5
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.5

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	R-832V	HELICOID	16,000 PSIG	±0.5%	5-23-73
	2	PRESS PUMP					
	3	STOPWATCH	G-3142E	SECURITY	30 MIN	±0.07%	6-8-73
	4						
	5						
	6						
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY M. CONNELL CEL 10 183 DATE 4-13-73
ENGR. ____ GOV'T QAR ____

A&B PTG. -- 215

APPENDIX 6

Data Sheets

S/N QT-6

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17 Tank Serial Number QT6 7

Date: Observer K.H. H.K.

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	SCI 2 6150	13.59
2	3.2.8.2	Filled Weight	SCI 2 12825	28.34
3		Capacity [(2) - (1)]	SCI 2 6675	14.75
4	3.2.8.3	Sizing Operation	1/67.308 SCI 2 6750 psig	5. minu
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure @ USE =	SCI 2 500 396	6750 psig — 4,000 PSIG.
6	3.2.8.5	Burette Reading at Ambient Pressure	SCI 2 205 —	0 psig
7	3.2.8.6	Filled Weight	SCI 2 12,905	28.52
7A:	WATER capacity Post TEST: 6755			
8		Permanent ΔV [(7) - (2)]	SCI 2 80 cc.	
9		Elastic ΔV [(6) - (5)]	SCI 2 295 cc.	
10		Total V [(9) + (7A)]	SCI 2 7050	
11		Total ΔV [(9) + (8)]	SCI 2 375	
12		Permanent ΔV [(8) / (10)]	SCI 2 1.13 %	
13		$\frac{\text{Permanent } \Delta V}{\text{Total } \Delta V}$ $\left[\frac{(8)}{(11)}\right]$	SCI 2 21.3 %	

DATA SHEET NUMBER 10

PART NUMBER 1269367-1, TANK NUMBER 6

IMPACT RESISTANCE TEST, Paragraph 7.6

Parameter	Required	Actual
Pressure	4000 psig GN_2	
Drop Height	10 feet	10 feet
Temperature	-60° F.	
Drop #1	Valve Down	3500 psig -65 °F
Drop #2	Valve Up	3500 psig -63 °F
Drop #3	Horizontal	3510 psig -60 °F
Temperature	200° F.	
Drop #4	Valve Down	4500 psig 200 °F
Drop #5	Valve Up	4500 psig 200 °F
Drop #6	Horizontal	4490 psig 195 °F
Temperature	-60° F.	
Drop #7	Valve Down	3500 psig -63 °F
Drop #8	Valve Up	3510 psig -60 °F
Drop #9	Horizontal	3510 psig -59 °F
Temperature	200° F.	
Drop #10	Valve Down	4500 psig 200 °F
Drop #11	Valve Up	4490 psig 198 °F
Drop #12	Horizontal	4490 psig 195 °F

NOTE: The pressures at -60°F shall not be permitted to be less than 3500 psig. The pressures at 2000°F shall not be permitted to be greater than 4500 psig. B

Data Sheet No. 10 con't

Tank Number QT6

- -

Vessel Examination ON 12TH DROP THREADS STRIPPED FROM 1/4" FACILITY PORT ON SIMULATED VALVE - RAPID EXHAUST OF GASSES BROKE TANK FROM BONDING STRAPS (SEE BELOW)

Tested By LOIBL CEL 10 TEST Date 4-12-73

Witness ________ Date ________

AND CAUSED SEVERE DAMAGE TO TEST ITEM AS IT ROCKETED AGAINST CONCRETE ABUTMENTS AND GRAVEL - REFERENCE PHOTOS

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

TEST EQUIPMENT LOG

TEST IMPACT RESISTANCE MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT6
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.6

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
4/12	1	TEMP CONDITIONER	ENV-840S	THERMOTRON	-100°/+400°F	N/A	N/A
	2	TEMP POT	—	—	—	—	—
	3	TEMP POT	ENV-566V	M-H	-100°/+300°F	±0.5%	5-8-73
	4	GAUGE, PRESS	P-300L	ASHCROFT	5,000	±0.5%	5-2-73
	5	BOOST PUMP	NONE	SPRAGUE	10,000	N/A	N/A
	6	TAPE MEASURE	NONE	LUFKIN	20 FOOT	N/A	N/A
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ___ OF ___
TEST BY Loibl
ENGR. E-84 CEL
DATE 4-12-73
GOV'T QAR

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 18

PART NUMBER 1269367-1, TANK NUMBER QT6

- -

BURST TEST, Paragraph 7.14

Parameter	Required	Actual
Temperature	Ambient	70 ° F.
Burst Pressure	9000 PSIG MINIMUM	9900 psig
Pressure Rise Rate	3000/5000 psi/min	4200 psi/min AVERAGE

Mode of Failure AXIAL TEARS IN HOOP AREA ABOUT 1/3 WAY FROM CLOSED END

TWO TEARS – EACH ABOUT 3" LONG

Tested By LOIBU CEL 10 TEST Date 4-27-73

Witness ________ Date ________

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST Burst MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-6
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.14

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P-3033E	MARSH	30000 PSIG	±0.5%	5-19-73
	2	PRESS CONSOLE	P-3036E	CEL	15000 PSI	N/A	N/A
	3	STOPWATCH	G-3142E	SECURITY	30 MIN	±0.07%	6-8-73
	4						
	5						
	6						
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ____ OF ____
TEST BY Loibl DATE 4-27-73
CEL 10 104
ENGR. ____ GOV'T QAR ____

APPENDIX 7

Data Sheets

S/N QT-6A

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001

Tank Serial Number 12 (GT 6A)

Date: 4/17/73

Observer K Hansen

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	13.04 5,900	130
2	3.2.8.2	Filled Weight	27.75 12 558	27.75
3		Capacity [(2) - (1)]	14.71 6,658	14.7
4	3.2.8.3	Sizing Operation	6,750 psig	5 minu
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure	450	6,750 psig
		VOL @ USE pressure.	354	4,000 "
6	3.2.8.5	Burette Reading at Ambient Pressure	189	0 psig
7	3.2.8.6	Filled Weight	27.97 12660	27.97 LBS.
7A.		water capacity after Proof.	6760 —	412.5^{43}
8		Permanent ΔV [(7) - (2)]	102	
9		Elastic ΔV [(6) - (5)]	261	
10		Total V [(9) + (7A)]	15.51 7021	
11		Total ΔV [(9) + (8)]	363	
12		Permanent ΔV [(8) / (10)]	1.45 %	
13		$\frac{\text{Permanent } \Delta V}{\text{Total } \Delta V}$ $\left[\frac{(8)}{(11)}\right]$	28. %	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 11

PART NUMBER 1269367-1, TANK NUMBER QT6A

HIGH TEMPERATURE EXPOSURE No.1, Paragraph 7.7

Parameter	Required	Actual
Temperature	200° F.	200 ° F.
Pressure	2000 psig GN_2	2050 psig
Duration	30 minutes	45 min.
Transfer Time	Minimum Time	30 sec.
Temperature, Chamber	600° F.	608 ° F.
After 1 minute		
Specimen Pressure	As measured	2060 psig
Specimen Temperature	As measured	232 ° F.
After 2 minutes		
Specimen Pressure	As measured	2140 psig
Specimen Temperature	As measured	255 ° F.
After 3 minutes		
Specimen Pressure	As measured	2220 psig
Specimen Temperature	As measured	275 ° F.
After 4 minutes		
Specimen Pressure	As measured	2300 psig
Specimen Temperature	As measured	295 ° F.
After 5 minutes		
Specimen Pressure	As measured	2390 psig
Specimen Temperature	As measured	317 ° F.

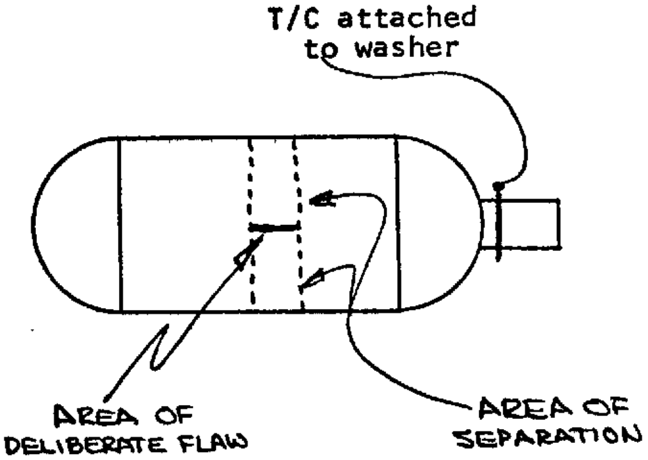
Data Sheet No. 11 con't

Tank Number QT6A

Vessel Examination HOOPWRAP, DEPTH & WIDTH OF CUT, START TO SEPARATE CIRCUMFERENTIALLY FROM BODY – REF DRAWING & PHOTOGRAPH

Tested By LOIBL Date 4-19-73

Witness ______ Date ______



APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV: B 30 APR 73

TEST EQUIPMENT LOG

TEST HIGH TEMPERATURE EXPOSURE #1 MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT6A
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.7

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
4/19	1	PRESS GAUGE	P-300L	ASHCROFT	5000 PSIG	±0.5%	5-2-73
	2	PRESS CONSOLE	P-3104	CEL	8000 PSI	N/A	N/A
	3	STOPWATCH	G-3142	SECURITY	30 MIN	±0.07%	6-8-73
	4	TEMP CHAMBER	ENV-56	BEMCO	0-350°F	±1%	N/A
	5	TEMP RECORDER	"	"	"	"	7-13-73
	6	T/C BRIDGE	ENV-3039	M-H	-100/+600°F	±0.1%	5-10-73
	7	TEMP CHAMBER	ENV-3103	NAA	0-1000°F	N/A	N/A
	8	TEMP CONTROLLER	ENV-3061	HONEYWELL	0-1200°F	±2°F	5-3-73
	9	PRESS GAUGE	P-3027	ASHCROFT	3000 PSIG	±0.5%	4-22-73
	10						
	11						
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GENERAL TEST NOTES:

TEST BY LOIBL DATE 4-19-73
ENGR. GOV'T QAR
PAGE OF

AAB PTG J15

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 12

PART NUMBER 1269367-1, TANK NUMBER QT6A

- -

THERMAL CYCLING TEST, Paragraph 7.8

Parameter	Required	Actual
Pressure	4000 psig Initial	4025 psig
Temperature, Bath 1	200° F.	210 ° F. min.
Temperature, Bath 2	-60° F.	-65 ° F. max.
Cycles	20, Bath 1	20 cycles
	20, Bath 2	20 cycles
Duration per Cycle	10 minutes, Bath 1	10 min.
	10 minutes, Bath 2	10 min.
Transfer Time	3 minutes maximum	2.5 min.
Dimension, Length	20 in. maximum	19.81 inches
Dimensions, Diameter	6.6 in. maximum Pos 1	6.509 inches B
	Pos 2	6.538 inches
	Pos 3	6.521 inches
	Pos 4	6.511 inches C

Vessel Examination NO VISUAL EVIDENCE OF DAMAGE NOTED

Note: Pressure versus Temperature Figure 9a

Tested By LOIBL CEL 30 Date 4-30 & 5-1-73

Witness ______ Date ______

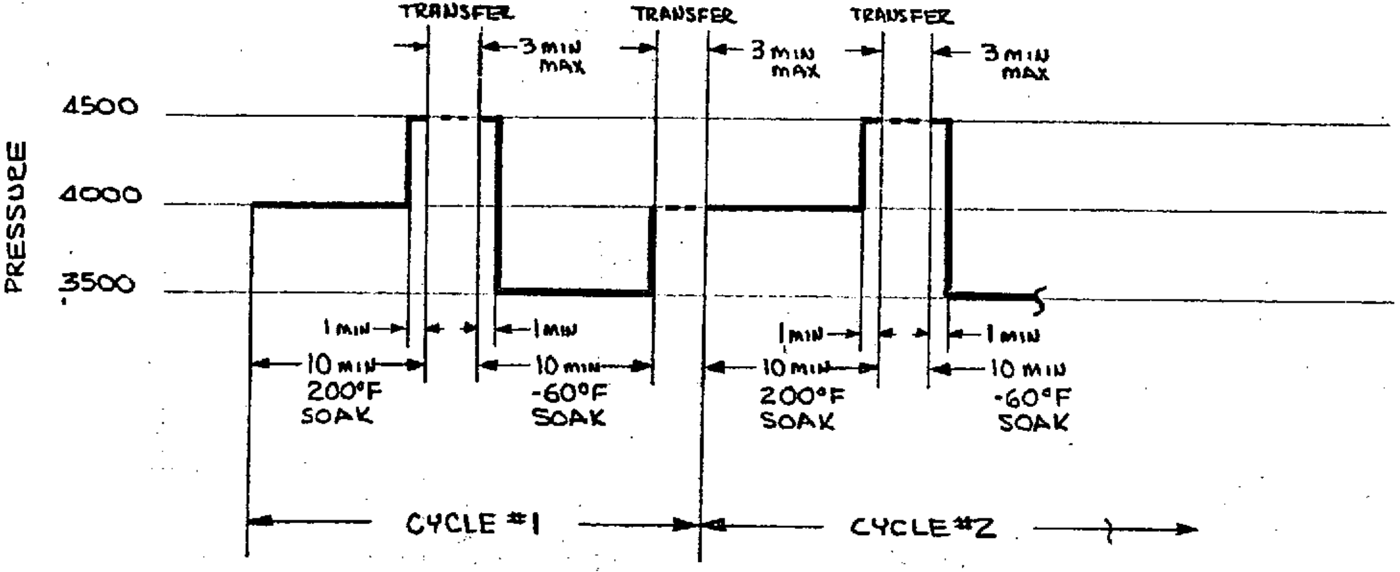

FIGURE 9a

PRESSURE versus TIME CURVE

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV B 30 APR 73

TEST EQUIPMENT LOG

TEST THERMAL CYCLING MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 126936-1 S/N QT-6A
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.8

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESSURE GAUGE	P-300L	ASHCROFT	0-5000 PSI	±0.5%	5-2-73
	2	BOOST PUMP	NONE	SPRAGUE	10,000 PSIG	N/A	N/A
	3	STOPWATCH	G-3142	SECURITY	0-30 MIN	±0.07%	6-8-73
	4	TEMP BRIDGE	ENV-3039	M-H	-100°/600°F	±0.1%	5-10-73
	5	HOT PLATE	G-3167		AMB/600°F	±20°F	N/A
	6	VERNIER CALIPERS	G-3125	MODERN TOOLS	0-24 IN	±0.001 IN	9-5-73
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY LQBL CEL 10 TEST DATE 5-1-73
ENGR. ____ GOV'T QAR ____

AAB PTC 215

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 15

PART NUMBER 1269367-1, TANK NUMBER QT6A

SALT FOG RESISTANCE TEST, Paragraph 7.11

Parameter	Required	Actual
Temperature	95 ° F.	97 ° F.
Duration	48 hours	48 hours
Salt Solution Concentration	5% by weight	5 %
Salt Solution pH	6.5 to 7.2	6.8 pH
Salt Fog Fallout	0.5 to 3 ml/80 cm²/HR over 16 hours	1.76 ml/HR

Vessel Examination Tank Number 6

NO VISUAL EVIDENCE OF CORROSION OR MATERIAL DETERIORATION AS A RESULT OF THE SALT FOG TEST

Tested By Loibl CEL 13 TEST Date 5-4-73

Witness ______ Date ______

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV B 30 APR 73

TEST EQUIPMENT LOG

T ST SALT FOG RESISTANCE TEST MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT6A
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.11

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	SALT FOG CHAMBER	ENV-3050	1 P&F	FED-STD	-151	7-14-73
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						
	11						
	12						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY LOIBL CEL 12 TEST DATE 5-4-73
ENGR. ____ GOV'T QAR ____

A&B PTG --- 215

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 4

PART NUMBER 1269367-1, TANK NUMBER QT6A

CYCLIC FATIGUE TEST, Paragraph 7.3.1

Parameter	Required	Actual
Pressure	4000 psig H_2O	4000 psig
Temperature	Room Ambient	RAT ° F.
Cycles	5000	6633
Cyclic Rate	2/4 cpm	2.5 cpm
Pressure	6750 psig H_2O	6750 psig
Temperature	Room Ambient	RAT ° F.
Cycles	100	17 *
Hold	30 sec	30 sec
Pressure	4000 psig H_2O	psig
Temperature	Room Ambient	° F.
Cycles	5000	
Cyclic Rate	2/4 cpm	cpm

Remarks *ON 18TH CYCLE @ 3000 PSIG WATER SEEPAGE THRU THE HOOPWRAP WAS NOTICED - SEE SCI DATA SHEET

Tested By SCI RAf Date 5-8-73 5-9-73

Witness ______ Date ______

NOTES:

Firemans Breathing TANK & Q.T. 6A

2:15 pm 5/7/73 Established test set up & Began cyclic fatigue test.
Event counter = 0 min. of operation = 0

5/8/73 8:45
Event counter. 2,815 Min. of Operation. 1118. = 2.517/m
" 151.07/HR

5/8/73 2:30 pm counter: 3,660 Min = 1451 = 2.522 n/mi
" 151.34/HR

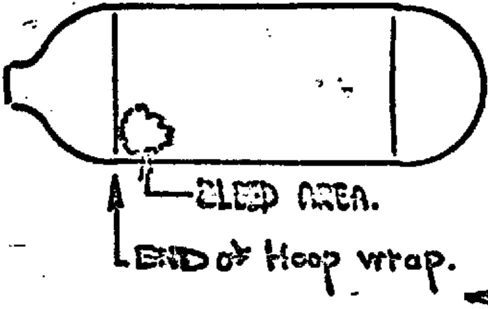
Estimated time to complete 5000 n = 8.85 HRS: = 11:30 pm:
" " " " 10,000 41.8 HRS =

Should have. 6,303 n @ 8:00 am 5/9/73. (17.5 HRS)

5/9/73 8:30 am counter 6,633 min. 2537 = 2.614/min.
" 156.8/HR

proof tests: ~~||||~~ ~~||||~~ ~~||||~~ |||

On the 18th proof cycle, tank began bleeding water through side: @ 3000 p.s.i.g. @ approx: 3" DIA. Area. (SEE sketch)



cut unit open & Dye-checked for Flaws & Cr

Small crack approx 3/8" Long also in this Area.

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPEENT LOG

TEST Cyclic fatigue test MJO 1010-10-1
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N (QT-GA) 12
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.15

DATE	Item	Description	S.C.I. No.	Mfgr.	Range	Acc'y	Calib Due
5/3/73	1	Portable pumping sta.	2	S.C.I.	0-20K	——	N.A.
	2	Auto cycle T.F.	N.A.	S.C.I.	0-6K.	±20PSI.	"
	3	Test Pressure (gauge)	1:604104	Heise	0-20K:	±.5% F.S.	Oct. 73
	4	Pressure Chart Recorder	R00131	L&N.	0-10mv.	±50PSI.	"
	5						
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
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	20						

GENERAL TEST NOTES: Auto cycle test fixture (Item #2) & chart recorder (Item #4) contain pressure transducers & are calibrated upon use with Item #3

SCI 2

TEST BY SCI 2 DATE 5/8/73
ENGR. RG / H.K. GOV'T QAR

PAGE ____ OF ____

AAO PTG

70

APPENDIX 8

Data Sheets

S/N QT-6B

①

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001 Tank Serial Number QT6B 27 SCI 2

Date: 5/9/73 Observer K. Haman

Item	Paragraph	Procedure		cc or grams	Pounds	
1	3.2.8.1	Tare Weight		SCI 2 12.87 5,827	12.87	
2	3.2.8.2	Filled Weight		27.57 12,979	27.57	
3		Capacity	[(2) - (1)]	SCI 2 14.70 6,652	14.7	
4	3.2.8.3	Sizing Operation		405,905 6,750 psig	5	minutes
		Comments:				
5	3.2.8.4	Tare Volume at Sizing Pressure		SCI 2 400	6750	psig
6	3.2.8.5	Burette Reading at Ambient Pressure		SCI 2 153	0	psig
7	3.2.8.6	Filled Weight		SCI 2 12558	27.75 Lb.	
7A •	Post sizing water capacity			6731		
8		Permanent ΔV	[(7) - (2)]	SCI 2 79	cc.	
9		Elastic ΔV	[(6) - (5)]	SCI 2 247		
10	perm + Elastic	Total V	[(9) + (7)]	SCI 2 6978		
11		Total ΔV	[(9) + (8)]	SCI 2 326		
12		Permanent ΔV	[(8) / (10)]	SCI 2 1.13 %		
13		Permanent ΔV / Total ΔV	$\left[\frac{(8)}{(11)}\right]$	SCI 2 24.2 %		

CYCLIC FATIGUE TEST

W.O. NUMBER

DATE. 5/10/73

S.N. SCI. #27 & Martin M. #64

SPEC Qual test/565-1180

CONDITIONS. LAB Ambient temp: 0000 ~ to 4,000 psIG: + 30 proofs to 6750

CYCLE NUMBER	MIN OF OPERATION	COMMENTS.	DATE-TIME
217	68	approx 2 ~/min:	6/10/73
535	145	Refilled oiler on Hydro pump	" 3:40 pm
650	193		" 4:30pm
781	262	4 on on nose	" 5:40 "
5,254	2,090	Midnight Sunday: 2.51/min	12:04 6/10/73
6,438	2,578	= 2.49/min	815 6/11/73
6700	2693	Shut down to perform Proofs:	10:35 am "
Proof to 6,752 PSIG. 30 times @ 30 sec. Hold:		Completed: 12	
Resume cycling			
		Cleaned Air filter & Refilled pump oiler:	
6,875	2,752		6/11/73: 1:45pm
Shut down test "Arnel" working on plant air compressor:			
Restart @ 4:45pm:			
8,122 -	3,766 : Temporary Shut down due to Loss of Plant Air:		
unit did not shut down. Min. Meter Faulty contacts?.			
8124	3768:	Resume test.	6/12/73 9:25am
compressor inoperative again. @ 10:45 am.			
Restart @ 11:00 am.			
8980	4200	off for evening	6/12/73 5:55 P
8980	4200	On	6/13 9:20 A
SCI 2 12000-	9593 SCI 2		4:00 pm 6/13/73
		SCI 2 Post TEST Filled weight =	12,579 GRm
		SCI 2 Empty " =	5,827
		SCI 2 water capacity =	6,752 gm.

COMPLETED

SCI SPECIFICATION 73-13 (ARRIL 1973)

FIGURE 3.2.8

2ND SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001

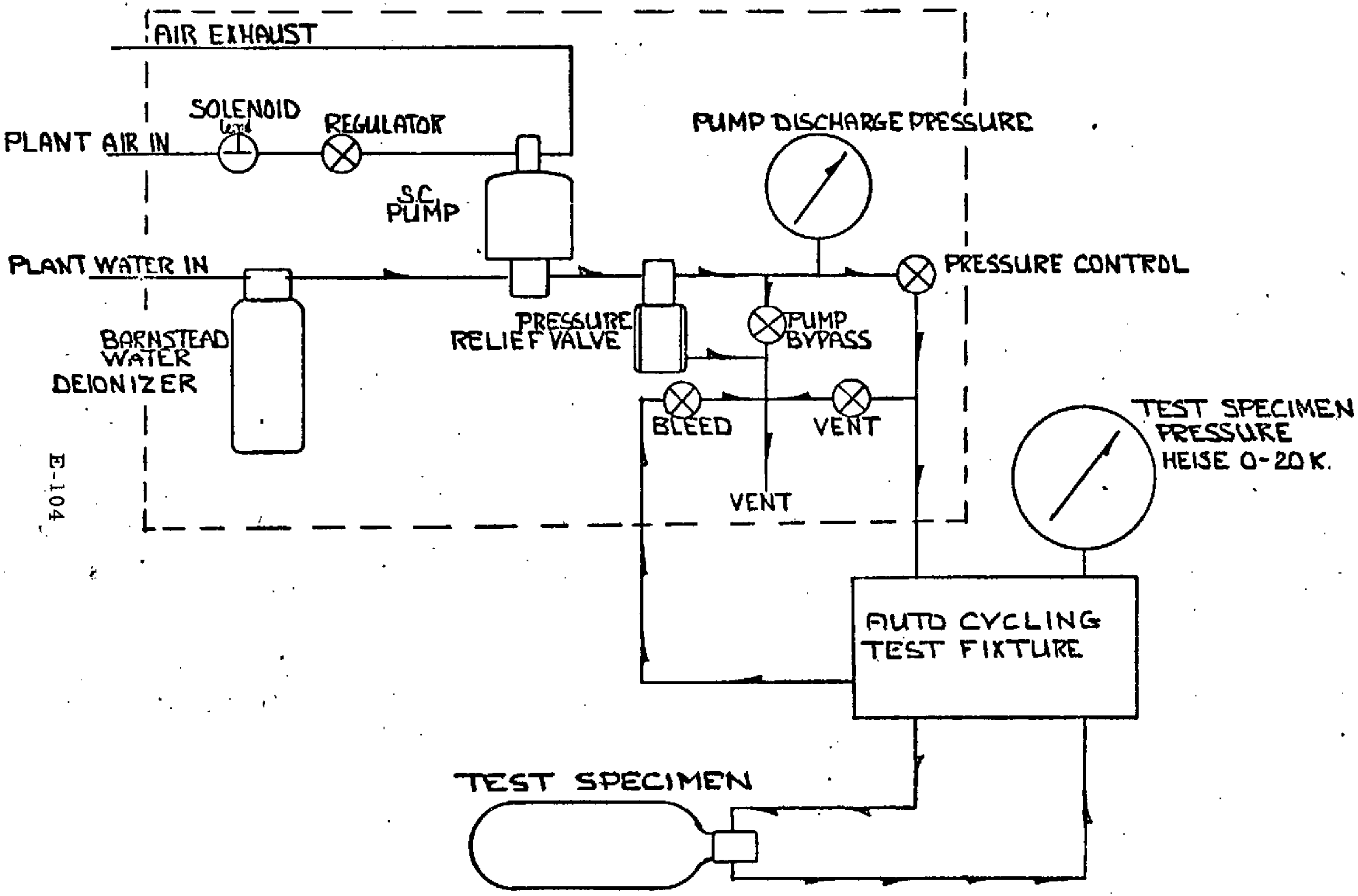
Tank Serial Number 27

Date: 5/10/73

Observer K. Hanson

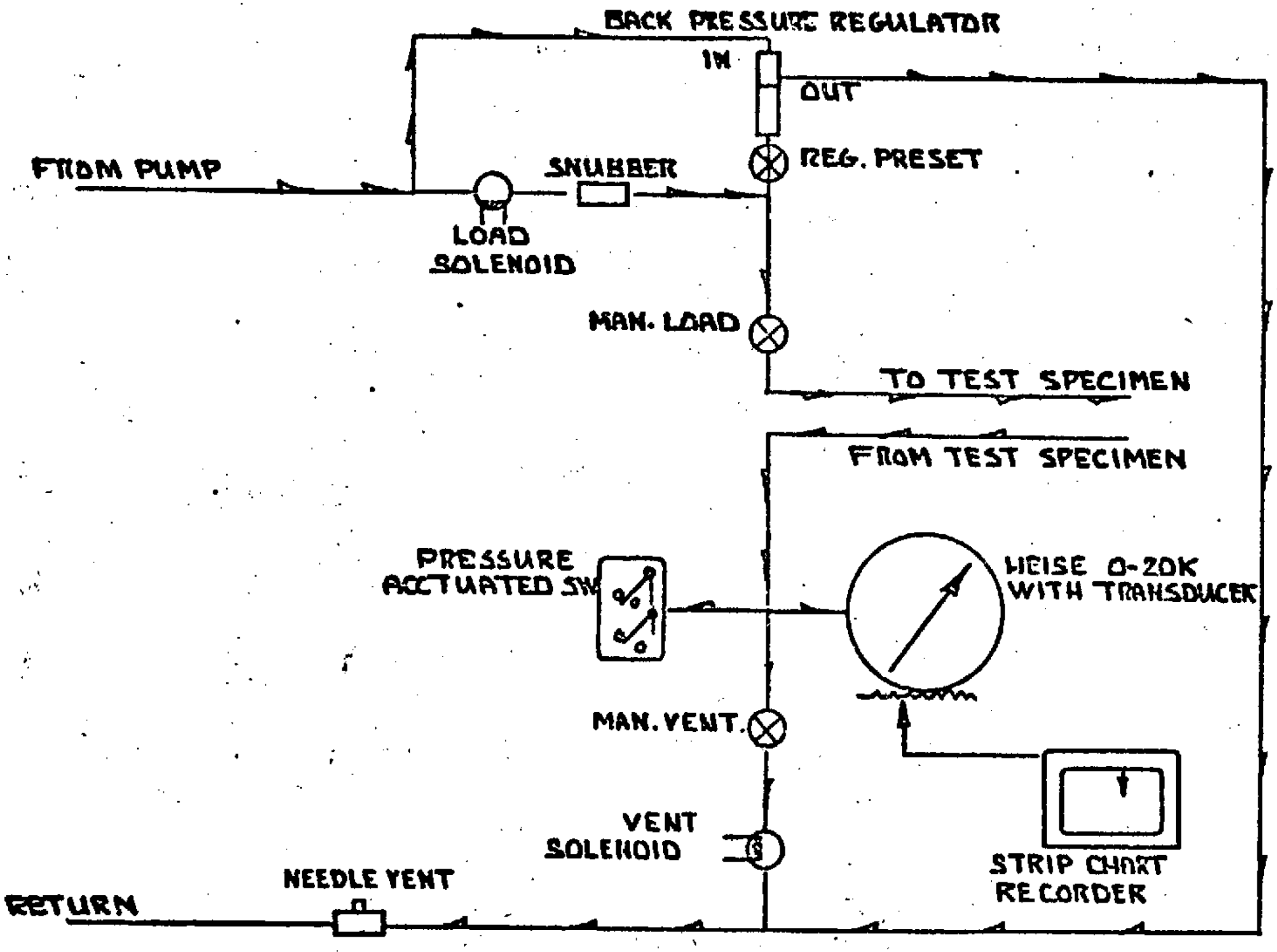
Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	SCI 2 5,827	
2	3.2.8.2	Filled Weight (7A)	12,558	
3		Capacity [(2) - (1)]	6731	
4	3.2.8.3	Sizing Operation Comments:	SCI 2 6,750 psig	5 min
5	3.2.8.4	Tare Volume at Sizing Pressure	SCI 2 400	6,750 psi
6	3.2.8.5	Burette Reading at Ambient Pressure	SCI 2 155	0 psi
7	3.2.8.6	Filled Weight	12561	
7A -	Post 2nd sizing WATER capacity:		6,734	
8		Permanent ΔV [(7) - (2)]	3.	
9		Elastic ΔV [(6) - (5)]	245	
10		Total V [(9) + (7A)]	6979	
11		Total ΔV [(9) + (8)]	248	
12		Permanent ΔV [(8) / (10)]	.043 %	
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	1.20 %	

FLOW DIAGRAM
CYCLIC FATIGUE TEST



5/4/73

AUTO-CYCLE TEST FIXTURE



5/2/73

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 12

PART NUMBER 1269367-1, TANK NUMBER QT6B

THERMAL CYCLING TEST, Paragraph 7.8

Parameter	Required	Actual
Pressure	4000 psig initial	4000 psig
Temperature, Bath 1	200° F.	+201 ° F. min
Temperature, Bath 2	-60° F.	-65 ° F. max
Cycles	20, Bath 1	20 cycles
	20, Bath 2	20 cycles
Duration per Cycle	10 minutes, Bath 1	10 min.
	10 minutes, Bath 2	10 min.
Transfer Time	3 minutes maximum	2 min.
Dimension, Length	20 in. maximum	19.922 inches
Dimensions, Diameter	6.6 in. maximum Pos 1	6.460 inches
	Pos 2	6.576 inches
	Pos 3	6.563 inches
	Pos 4	6.547 inches

Vessel Examination NO DAMAGE NOTED

Note: Pressure versus Temperature Figure 9a

Tested By JERRY GREENBERG Date 6-20-73

Witness ______ Date ______

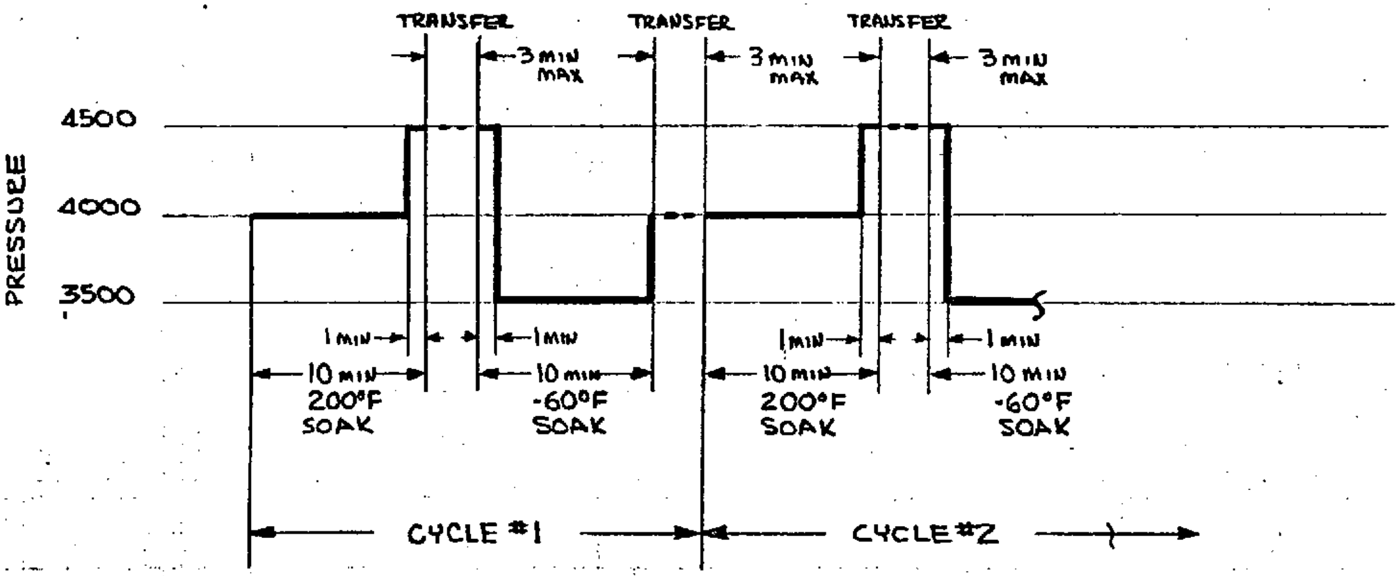


FIGURE 9a

PRESSURE versus TIME CURVE

APPROVED ENGINEERING TEST LABORATORIES

TEST EQUIPMENT LOG

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST THERMAL CYCLING MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT 6B
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.8

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
6-20	1	PRESS GAUGE	P-300L	ASHCROFT	0-5000PSI	±0.5%	8-7-73
	2	TEMP BRIDGE	ENV-3039	M-H	-100°/600°F	±0.2%	9-12-73
	3	TEMP CTRLR	NONE	HONEYWELL	-300°/300°F	±0.1%	NOT RQ'D
	4	TEMP PLATE	G-3167		AMB/600°F	±20°F	NOT RQ'D
	5	STOPWATCH	G-3142	SECURITY	0-30 MIN	±0.07%	
	6	VERNIER CALIPERS	G-3125	MODERN TOOLS	0-24 IN	±0.001"	9-5-73
	7						
	8						
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	19						
	20						

GENERAL TEST NOTES:

PAGE 1 OF 1
TEST BY Loibl CEL 10 TAI DATE 6-20-73
ENGR. GOV'T QAR

ABB PTG --- 215

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 10

PART NUMBER 1269367-1, TANK NUMBER 6B

IMPACT RESISTANCE TEST, Paragraph 7.6

Parameter	Required	Actual
Pressure	4000 psig GN_2	
Drop Height	10 feet	10 feet
Temperature	-60° F.	
Drop #1	Valve Down	3600 psig -60 °F
Drop #2	Valve Up	3600 psig -60 °F
Drop #3	Horizontal	3600 psig -60 °F
Temperature	200° F.	
Drop #4	Valve Down	4400 psig 200 °F
Drop #5	Valve Up	4400 psig 200 °F
Drop #6	Horizontal	4400 psig 200 °F
Temperature	-60° F.	
Drop #7	Valve Down	3600 psig -63 °F
Drop #8	Valve Up	3600 psig -63 °F
Drop #9	Horizontal	3600 psig -63 °F
Temperature	200° F.	
Drop #10	Valve Down	4400 psig 200 °F
Drop #11	Valve Up	4400 psig 200 °F
Drop #12	Horizontal	4450 psig 205 °F

NOTE: The pressures at -60°F shall not be permitted to be less than 3500 psig. The pressures at 2000°F shall not be permitted to be greater than 4500 psig. B

Data Sheet No. 10 con't

Tank Number QT6B

Vessel Examination NO VISIBLE EVIDENCE OF DAMAGE OTHER THAN A FLATTENING OF THE CLOSED END AFTER IMPACT

Tested By GERRY GREENBERG CEL 10 Date 6-28-73

Witness ____________________ Date ________

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST IMPACT RESISTANCE MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT 6B
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.6

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
6-28	1	PRESS GAUGE	P-300L	ASHCROFT	0-5000 PSI	±0.5%	8-7-73
	2	TEMP CONDITIONER	ENV-840 $	THERMOTRON	-100°/400°F	N/A	N/A
	3	TEMP BRIDGE	ENV566V	M-H	-100°/300°F	±0.5%	8-15-73
	4	BOOST PUMP	NONE	SPRAGUE	10,000 PSI	N/A	N/A
	5	TAPE MEASURE	NONE	LUFKIN	20 FT	N/A	N/A
	6						
	7						
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GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY WOIBL CEL 10 TEST DATE 6-28-73
ENGR. ____ GOV'T QAR ____

DATA SHEET NUMBER 11

PART NUMBER 1269367-1, TANK NUMBER QT6B

HIGH TEMPERATURE EXPOSURE No.1, Paragraph 7.7

Parameter	Required	Actual
Temperature	200° F.	205 ° F.
Pressure	2000 psig GN_2	2025 psig
Duration	30 minutes	60 min.
Transfer Time	Minimum Time	30 sec.
Temperature, Chamber	600° F.	604 ° F.
After 1 minute		
Specimen Pressure	As measured	2035 psig
Specimen Temperature	As measured	261 ° F.
After 2 minutes		
Specimen Pressure	As measured	2115 psig
Specimen Temperature	As measured	304 ° F.
After 3 minutes		
Specimen Pressure	As measured	2200 psig
Specimen Temperature	As measured	333 ° F.
After 4 minutes		
Specimen Pressure	As measured	2280 psig
Specimen Temperature	As measured	352 ° F.
After 5 minutes		
Specimen Pressure	As measured	2375 psig
Specimen Temperature	As measured	369 ° F.

Data Sheet No. 11 con't

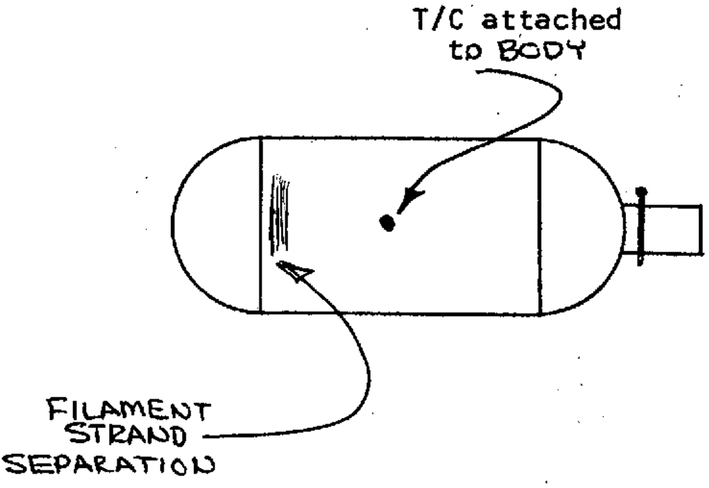
Tank Number QT6B

Vessel Examination APPROX 6 FILAMENT STRANDS OF THE OUTER WINDING STARTED TO SEPARATE FROM THE HOOPWRAP IN THE AREA SHOWN ON SKETCH BELOW

Tested By Loibl CEL 10 TEST Date 6-30-73

Witness ____________ Date ________

VOLUME PRIOR TO TEST 415 IN^3
VOLUME AFTER TEST 415.6 IN^3



APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST HIGH TEMP EXPOSURE MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-6B
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.7

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
6-30	1	PRESS GAUGE	P-300L	ASHCROFT	0-5000 PSI	±0.5%	8-7-73
	2	PRESS CONSOLE	P-3104	CEL	8000 PSI	N/A	N/A
	3	STOPWATCH	G-3142	SECURITY	0-30 MIN	±0.07%	9-12-73
	4	TEMP CHAMBER	ENV-56	Bemco	0-350°F	±1%	N/A
	5	TEMP RECORDER	"	"	"	"	7-13-73
	6	T/C BRIGDE	ENV-3039	M-H	-100°/600°F	±0.2%	9-12-73
	7	TEMP CHAMBER	ENV-3103	NAA	0-1000°F	N/A	N/A
	8	TEMP CONTROLLER	ENV-3061	HONEYWELL	0-1200°F	±2°F	7-22-73
	9						
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GENERAL TEST NOTES:

PAGE 1 OF 1

TEST BY LOIBL CEL 10 TEST DATE 6-30-73
ENGR. GOV'T QAR

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 18A

PART NUMBER 1269367-1, TANK NUMBER QT6B

BURST TEST, Paragraph 7.14

Parameter	Required	Actual
Temperature	Ambient	82 ° F.
Burst Pressure		12,300 psig
Pressure Rise Rate	3000/5000 psi/min	5200 psi/min AVERAGE

Mode of Failure AXIAL TEAR APPROX 3" LONG IN
HOOP SECTION AT CLOSED END
3 PLACES

Tested By WOIBL CEL 10 TEST Date 6-30-73
Witness Date

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST BURST TEST MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT 6B
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.14

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
6-30	1	PRESS GAUGE	P-3033	MARSH	0-30K PSI	±0.5%	8-7-73
	2	PRESS CONSOLE	P-3036	CEL	15000 PSIG	N/A	N/A
	3	STOPWATCH	G-3142	SECURITY	0-30 MIN	±0.07%	9-12-73
	4						
	5						
	6						
	7						
	8						
	9						
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GENERAL TEST NOTES:

PAGE ____ OF ____
TEST BY LOIBL CEL 10 TEST DATE 6-30-73
ENGR. ____ GOV'T QAR ____

AAB PTG 215

7C

APPENDIX 9

Data Sheets

S/N QT-7

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17

Tank Serial Number QT7 4 SCI 2

Date:

Observer K.H., H.K.

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	SCI 2 6105	13.49
2	3.2.8.2	Filled Weight	SCI 2 12,795	28.27
3		Capacity [(2) - (1)]	SCI 2 6,690 408,223	14.78
4	3.2.8.3	Sizing Operation	SCI 2 6,750 psig	5 minut
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure @ use press:	SCI 2 500 395	6,750 psig 4,000 psig
6	3.2.8.5	Burette Reading at Ambient Pressure	SCI 2 203	0 psig
7	3.2.8.6	Filled Weight	SCI 2 2,868	28.43
7A.	Water capacity: 6763			
8		Permanent ΔV [(7) - (2)]	SCI 2 73	
9		Elastic ΔV [(6) - (5)]	SCI 2 297	
10		Total V [(9) + (7A)]	SCI 2 7060	
11		Total ΔV [(9) + (8)]	SCI 2 370	
12		Permanent ΔV [(8) / (10)]	SCI 2 1.03 %	
13		$\frac{\text{Permanent } \Delta V}{\text{Total } \Delta V}$ $\left[\frac{(8)}{(11)}\right]$	SCI 2 19.72 %	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 4A

PART NUMBER 1269367-1, TANK NUMBER QT 7

CYCLIC FATIGUE TEST, Paragraph 7.15 Water .

Parameter	Required	Actual
Pressure	4000 psig H_2O	4000 psig
Temperature	Room Ambient Water	75 ° F.
Cycles	5000	5000
Cyclic Rate	2/4 cpm	2.5/3 cpm
Pressure	6750 psig H_2O	6750 psig
Temperature	Room Ambient Water	75 ° F.
Cycles	100	100
Hold	30 sec.	30 sec
Pressure	4000 psig H_2O	4000 psig
Temperature	Room Ambient Water	75 ° F.
Cycles	5000	5000
Cyclic Rate	2/4 cpm	2.5 cpm

Remarks COMPLETED 5/6/73

Tested by KEN HANSEN SCI Date 5/6/73

Witness Date

SCI SPECIFICATION 73-13 REVISION A (APRIL 1973)

FIGURE 3.3

QUALIFICATION TEST TANKS
ACCEPTANCE TEST PROCEDURE DATA SHEET
POST CYCLIC FATIGUE TEST FINAL PROOF.

Tank Q/T Number 7 Tank Serial Number 4

Date[a] 5/7/73 Observer K. Hanson

Item	Paragraph	Procedure	cc or Grams[b]	Pounds
1.	3.3.1	Tank Dry Weight (Must be less than 14 lbs) (same as 3.2.8.1)	6105	
2.	3.3.2	Tank Filled Weight ([redacted])	12,898	
3.		Tank Water Capacity [(2) - (1)]	6793	
4.	3.3.3	Hydrostatic Proof Pressure		6750 psig
5.		Duration of Pressure		5 minutes
6.		Comments:		
7.	3.3.4	Tank Volume at Pressure (c)		
8.		Tare Reading before Proof		500 cc
		@ use Pressure:		410
9.		Reading at Proof Pressure		210 cc
10.		ΔV-Total [(9) - (8)]		290 cc
11.		Tare Reading after Proof		500 cc
12.		ΔV - Permanent [(11) - (8)]		0 cc
13.		ΔV - Permanent [(12) / (10)] x 100		0 %
14.		Total Volume at Proof Pressure [(3) + (10)] Must be greater than 6923 cc		7,083 cc
15.		Tank Overall Length,(d) Inches Must be less than 20.0 inches		
16.		Tank Diameter (d), Cylindrical	D_1	
		Average of 4 readings	D_2	
		Must be less than 6.60 inches	D_3	
			D_4	
		Average		
17.		Total Volume at Operating Pressure (4000)(e)		419 in^3

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST Cyclic fatigue test W/O 1040-10-1
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N Q.T. 7
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.15

DATE	Item	Description	SCI. No.	Mfgr.	Range	Acc'y	Calib Due
5/3/73	1	Portable pumping Sta	2	SCI.	0-20K.	——	N.A.
	2	Auto cycle T.F.	1A.	SCI.	0-6K.	±20PSI.	*
	3	Test Pressure Gauge	L:609404	HEISE	0-20K.	± .5% F.S.	Oct. 73
	4	Pressure Chart Recorder	P.00131	L&N.	0-10mv.	± 50PSI.	*
	5						
	6						
	7						
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	19						
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GENERAL TEST NOTES: Auto cycle test fixture (Item * 2) & chart recorder (Item * 4) contain pressure transducers & are calibrated upon use with Item * 3

SCI 2

PAGE ____ OF ____

TEST BY K. Hamann DATE 5 3

SCI 2

ENGR. ____ GOV'T QAR ____

E-121

Firemans Breathing tank #7 Cyclic fatigue test:

0-To 4000 P.S.I.G. 10,000 cycles: in salt water environment.
LAB. Ambient temp:

5/3/73 Established test set up: & began cycling @ 1:00 pm:
per PARA: 7.15.1.

4:35 pm. # of cycks = 308 Min = 115.
Now operating on plant air compressor: Have installed
Sprague pressure relief valve: Set @ 10,000 to protect system:

8:30 am: 5/4/73
Number of cycles = 2629 Min = 1066
SHut Down to fill oiler for pump:
11:15 am - Number of cycks = 2901 Min = 1180:

2:25 pm. Nuber of cycks = 3376 Min of operation: 1365
cycling rate @ this time = 2.4 ~/min. = 144/HR.

Approx time to complete 1st 5,000 ~ = 11 HRS: = 1:25 pm Sat.
5/5/73

34 HRS/ 5,000 ~
4:10 pm: No. of cycles = 3640 Min of operation = 1468 O.K.

2:00pm Sat: 5/5/73 Nuber of ~ = 6,964 Min. of operation=2,763

Start 100 proof cycles. 0-to 6,750 Hold for 30 SEC. 2.5/min.
150/HR.

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3:40 pm: 7093 cycles: Min of Operation. 2814.

10,000 ~ completed Sunday 5/6/73 10:25 Am:

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 5A

PART NUMBER 1269367-1, TANK NUMBER QT 7

BURST TEST, Paragraph 7.15.5

Parameter	Required	Actual
Temperature	Room Ambient	82 ° F.
Burst Pressure	As Observed	9600 psig
Pressure Rise Rate	3000/5000 psi/min	4850 psi/min AVERAGE

Mode of Failure HOOP FAILURE - CYLINDRICAL SECTION
3 1/2 INCH AXIAL TEAR NEAR
CLOSED END
REF: PHOTOGRAPH

Tested By LOIBL (CEL 10 TEST) Date 5-8-73
Witness Date

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST Burst Test MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-7
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.15.5

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P-3033E	MARSH	0-30K PSIG	±0.5%	5-19-73
	2	PRESS CONSOLE	P-3036E	CEL	15,000 PSI	N/A	N/A
	3	STOPWATCH	G-3142E	SECURITY	30 MIN	±0.01%	6-8-73
	4						
	5						
	6						
	7						
	8						
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GENERAL TEST NOTES:

TEST BY Loibl DATE 5-8-73
ENGR. GOV'T QAR

PAGE OF

AAB PTG. — 215

APPENDIX 10

Data Sheets

S/N QT-8

Enclosure (1)

SCI SPECIFICATION 73-13 (APRIL 1973)

FIGURE 3.2.8

SIZING PRESSURIZATION PROCEDURE DATA SHEET

Work Order Number 2001-17 Tank Serial Number QT8 3

Date: 3/26/73 Observer H.K., K.H.

Item	Paragraph	Procedure	cc or grams	Pounds
1	3.2.8.1	Tare Weight	6065	13.40
2	3.2.8.2	Filled Weight	12,682	28.02
3		Capacity [(2) - (1)]	6,617	14.62
4	3.2.8.3	Sizing Operation	403,769 6750 psig	5 minutes
		Comments:		
5	3.2.8.4	Tare Volume at Sizing Pressure	500	6,750 psig
6	3.2.8.5	Burette Reading at Ambient Pressure	215	0 psig
7	3.2.8.6	Filled Weight	12,762	28.20 LBS.
7A:-WATER capacity: 6697.				
8		Permanent ΔV [(7) - (2)]	80	
9		Elastic ΔV [(6) - (5)]	285	
10		Total V [(9) + (7A)]	6982	
11		Total ΔV [(9) + (8)]	365	
12		Permanent ΔV [(8) / (10)]	1.14 %	
13		Permanent ΔV / Total ΔV $\left[\frac{(8)}{(11)}\right]$	21.9 %	

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 19

PART NUMBER 1269367-1, TANK NUMBER QT8

- -

HIGH TEMPERATURE EXPOSURE NO. 2, Paragraph 7.16

Parameter	Required	Actual
Temperature	100° F, Max	70 - 100° F. STARTING
Pressure	2000 psig	1950-2100 psig STARTING
Cycles, High Temperature	See attached data sheet	

After Test:

Vessel Examination NO VISUAL EVIDENCE OF DAMAGE NOTED TO TANK AS A RESULT OF HIGH TEMP EXPOSURE

Tested By LOIBL CEL 12 TEST Date 5-3-73

Witness ______ Date ______

Note: High Temperature chamber to be at 400°, +10°, -0° F.

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV B 30 Apr 73

GENERAL DATA SHEET

TEST High Temperature Exposure No. 2 MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Breathing Tank P/N 1269367-1 S/N QT8
SPECIFICATION AETL QTP 565-1180 PAR 7.16

		4-26	4-27	4-27	4-27	4-30	4-30	5-1
Cycle No.		1	2	3	. 4	5	6	7
Time	Item*	2025 90°	1975 70°	2025 90°	2100 100°	2000 80°	1975 75°	1950 72°
1 m.	Press	2040	1990	2040	2115	2000	1990	1960
	Temp	100 / 125	83 / 112	95 / 125	113 / 137	89 / 118	85 / 115	83 / 112
2 m.	Press	2090	2025	2080	2150	2050	2025	2000
	Temp	115 / 142	100 / 130	109 / 135	125 / 150	100 / 133	100 / 130	93 / 129
3 m.	Press	2150	2090	2150	2210	2110	2100	2060
	Temp	128 / 152	112 / 142	122 / 150	138 / 160	112 / 145	114 / 140	107 / 140
4 m.	Press	2210	2150	2210	2280	2175	2160	2140
	Temp	140 / 165	125 / 155	135 / 163	150 / 172	126 / 159	128 / 154	120 / 155
5 m.	Press	2275	2225	2280	2340	2240	2225	2200
	Temp	152 / 175	138 / 167	148 / 172	162 / 183	139 / 170	142 / 165	133 / 163
6 m.	Press	2330	2290	2340	2390	2300	2275	2250
	Temp	167 / 187	154 / 180	162 / 183	174 / 195	150 / 181	155 / 175	146 / 177
7 m.	Press	2375	2340	2380	2440	2350	2340	2310
	Temp	178 / 200	165 / 190	174 / 194	184 / 201	162 / 192	168 / 188	157 / 185
8 m.	Press	2440	2400	2440	2490	2400	2400	2360
	Temp	188 / 207	176 / 200	185 / 202	196 / 211	174 / 200	177 / 197	169 / 196
9 m.	Press	2490	2450	2490	2540	2450	2440	2410
	Temp	200 / 220	187 / 209	195 / 211	205 / 220	182 / 212	190 / 207	181 / 206
10 m	Press	2525	2500	2535	2580	2500	2500	2460
	Temp	207 / 225	198 / 220	205 / 222	213 / 230	195 / 220	200 / 220	192 / 215

GENERAL TEST NOTES:

*Press in psig
Temp in ° F. Washer / Hoopwrap

PAGE 2 OF 3

TEST BY LOIDL DATE 5-3-73
ENGR. GOV'T QAR
CEL 10

E-129

APPROVED ENGINEERING TEST LABORATORIES

GENERAL DATA SHEET

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV: B 30 APR 73

TEST High Temperature Exposure No. 2 M/O 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Breathing Tank P/N 1269367-1 S/N QT 8
SPECIFICATION AETL QTP 565-1180 PAR 7.16

		5-1	5-2	5-2	5-3	5-3		
Cycle No.		8	9	10	11	12		
Time	Item*	2000 82°	2025 87°	2100 100°	2000 82°	2025 88°		
1 m	Press	2010	2040	2100	2010	2040		
	Temp	94 / 121	95 / 123	107 / 135	92 / 122	98 / 126		
2 m	Press	2050	2080	2150	2060	2090		
	Temp	109 / 134	105 / 138	122 / 152	105 / 136	110 / 140		
3 m	Press	2120	2150	2200	2120	2150		
	Temp	124 / 146	117 / 150	135 / 162	118 / 148	124 / 151		
4 m	Press	2180	2210	2250	2180	2210		
	Temp	135 / 156	130 / 162	147 / 173	129 / 158	137 / 164		
5 m	Press	2240	2260	2310	2240	2275		
	Temp	149 / 169	141 / 172	157 / 184	142 / 168	148 / 175		
6 m	Press	2300	2325	2360	2300	2325		
	Temp	160 / 180	153 / 182	169 / 194	155 / 180	158 / 183		
7 m	Press	2350	2375	2410	2350	2375		
	Temp	172 / 189	166 / 194	181 / 205	165 / 190	170 / 194		
8 m	Press	2400	2425	2460	2400	2425		
	Temp	182 / 200	177 / 205	192 / 215	176 / 260	182 / 203		
9 m	Press	2450	2475	2510	2450	2475		
	Temp	194 / 210	186 / 212	202 / 224	187 / 208	192 / 212		
10 m	Press	2500	2525	2560	2500	2425		
	Temp	204 / 220	196 / 220	210 / 234	196 / 217	201 / 221		

GENERAL TEST NOTES:

* Press in psig

Temp in ° F. Washer / Hoopwrap

PAGE 3 OF 3

TEST BY Loibl

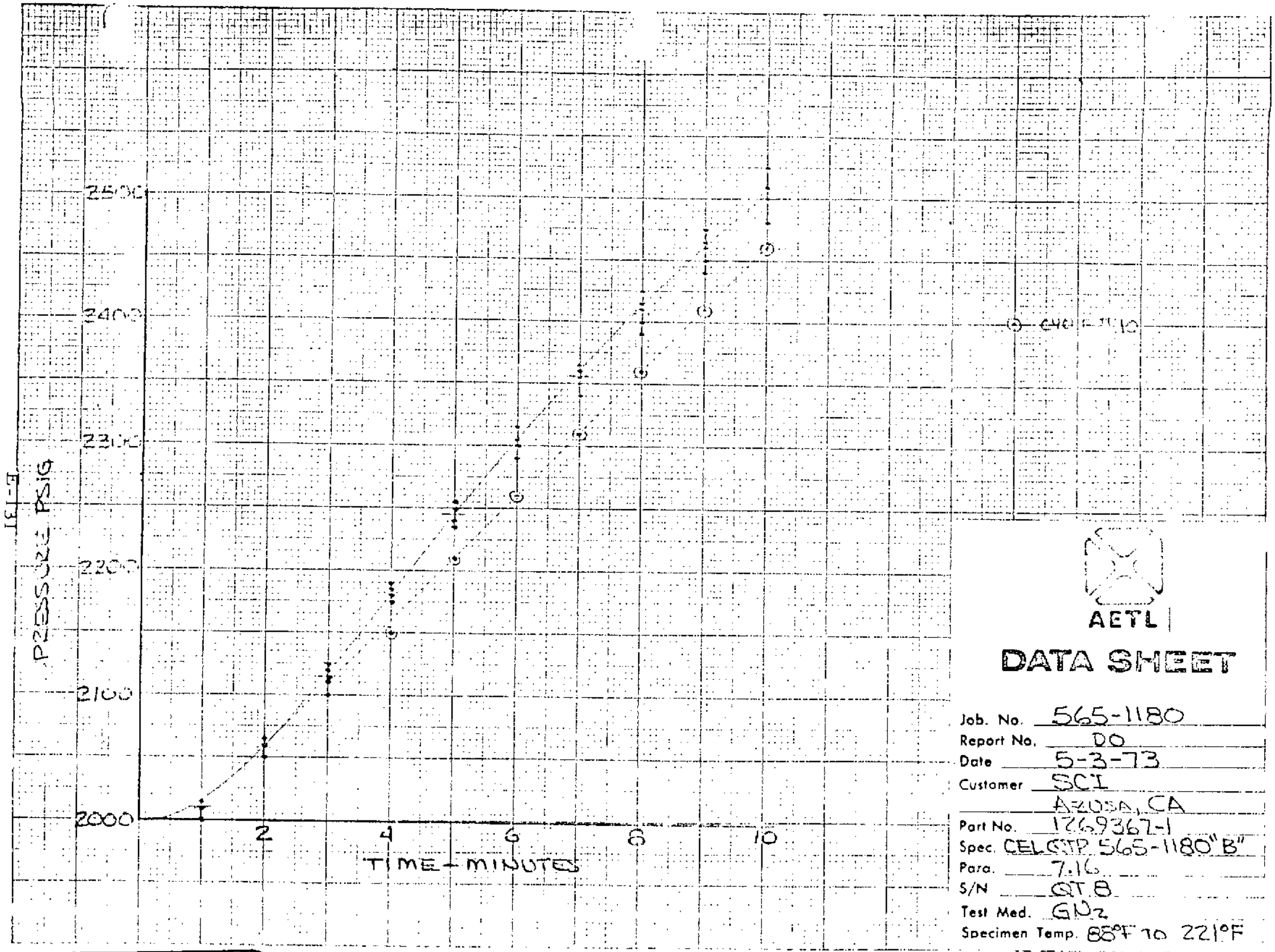
DATE 5-3-73

ENGR.

GOV'T QAR

E-130

E-131

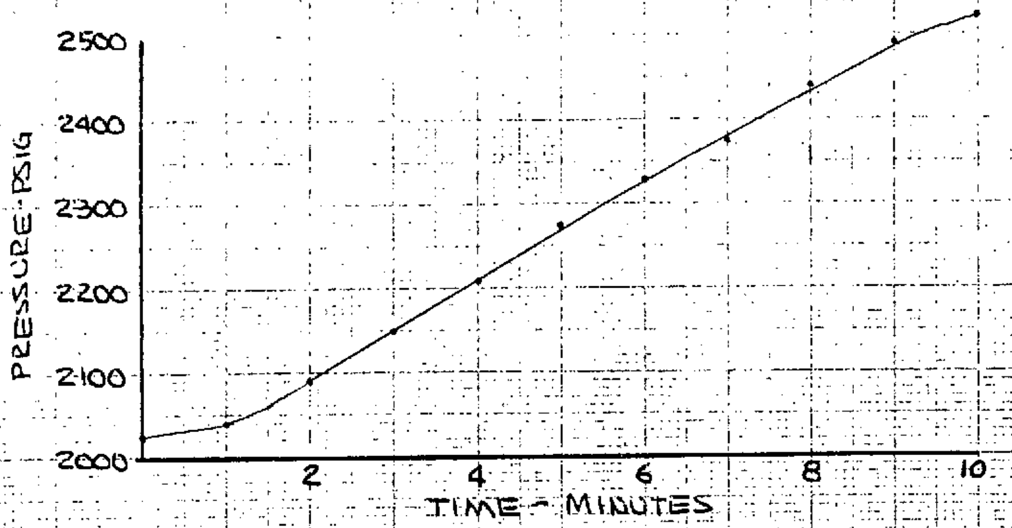


AETL

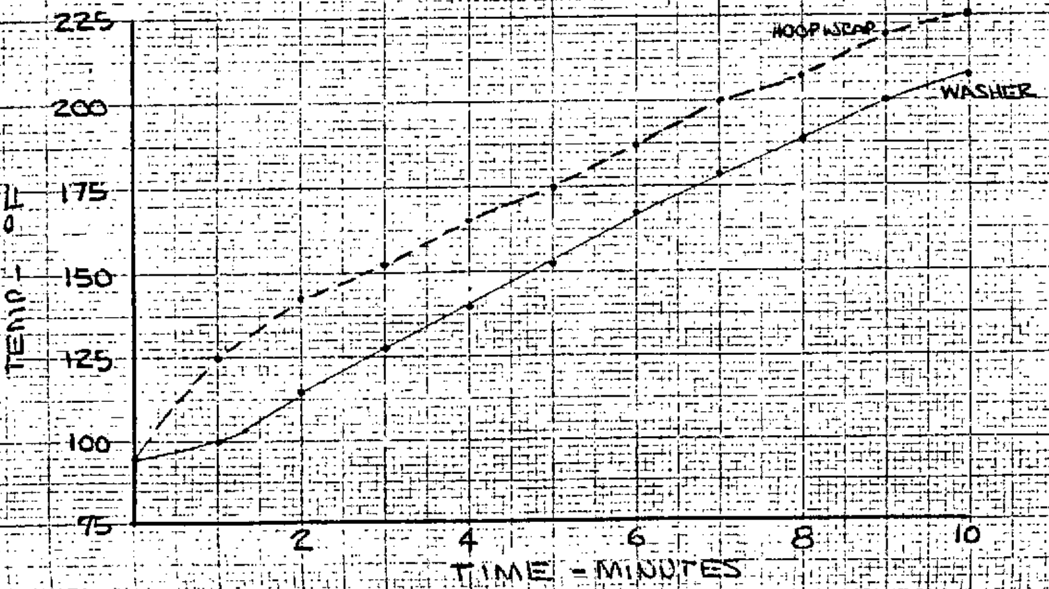
DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-3-73
Customer SCI
AZUSA, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180"B"
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. 88°F TO 221°F

COMPOSITE OF 12 CYCLES
START PRESS ADJUSTED
TO 2000 PSIG



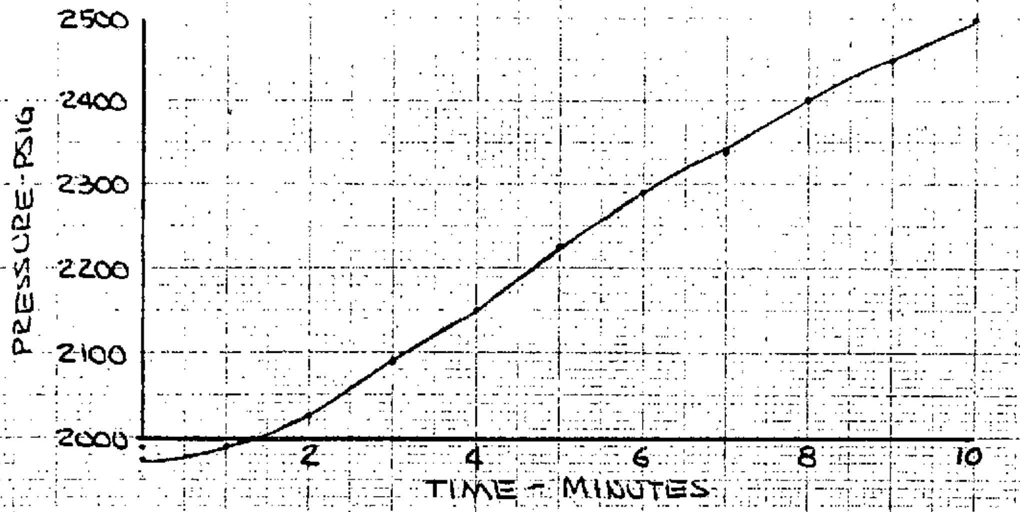
TANK QT 8
CYCLE # 1
START PRESS 2025 PSIG
START TEMP 90°F



AETL

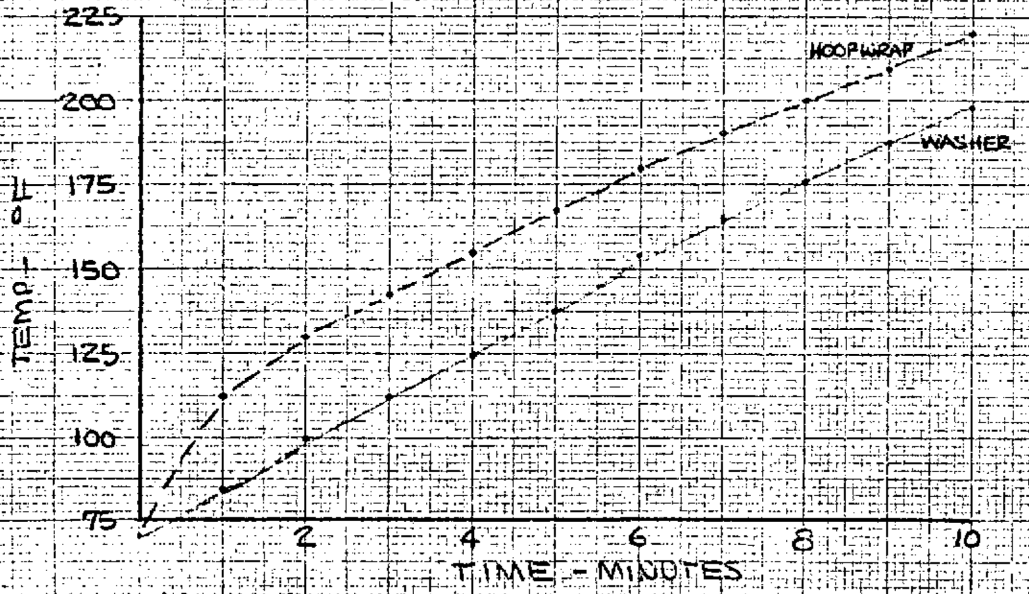
DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-26-73
Customer SCI
Azusa, CA
Part No. 1269367-1
Spec. CEL QTP 565-118CB
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. As Noted



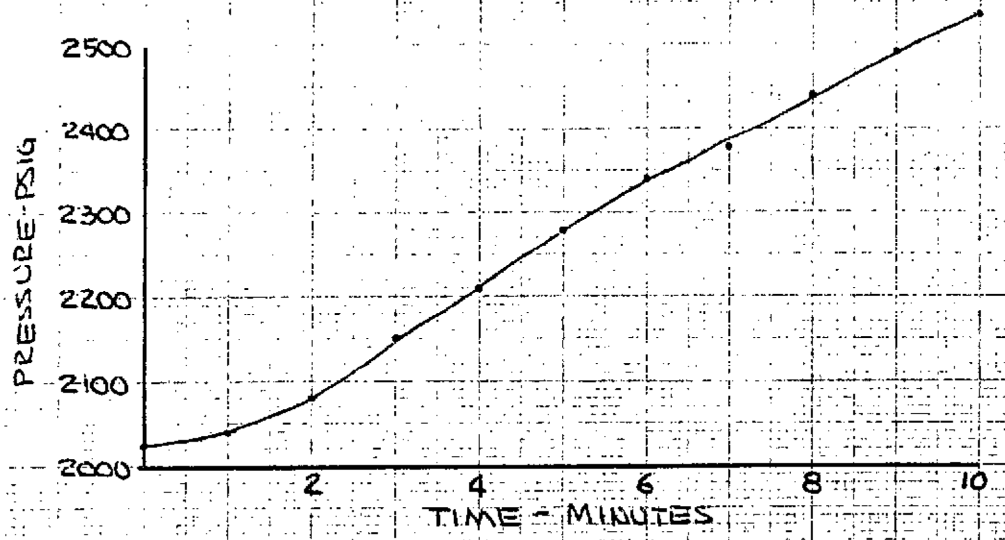
TANK QT 8
CYCLE # 2

START PRESS 1975 PSIG
START TEMP 70°F



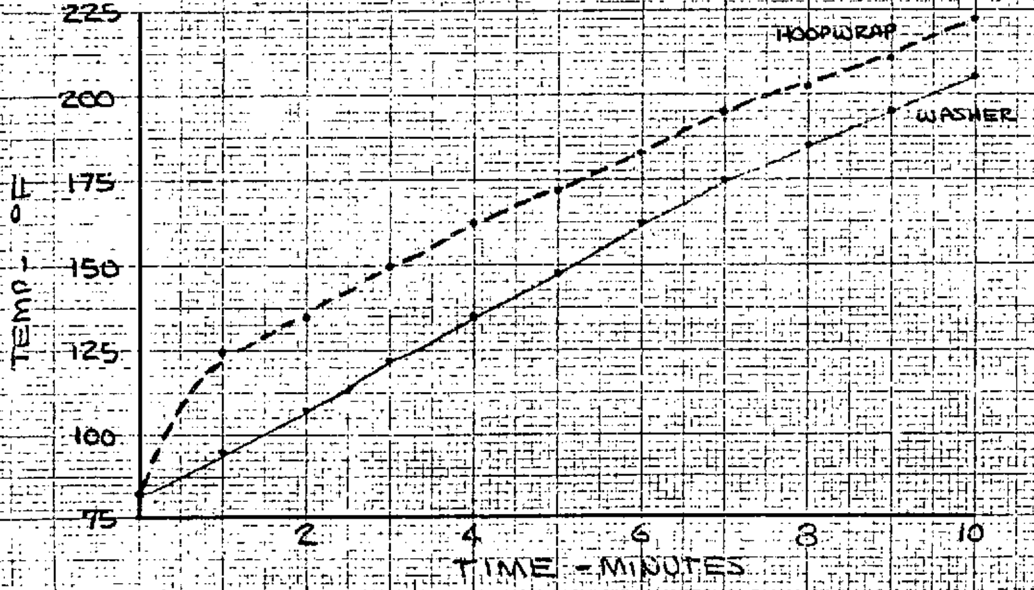
AETL
DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-27-73
Customer SCI
AZUSA, CA
Part No. 1267367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. AS NOTED



TANK QT 8
CYCLE # 3

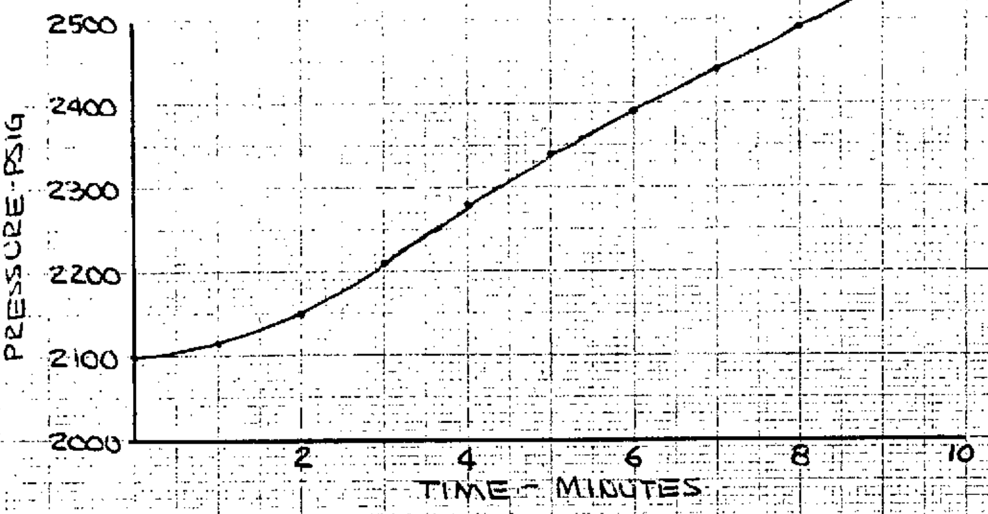
START PRESS 2025 PSIG
START TEMP 82°F



AETL

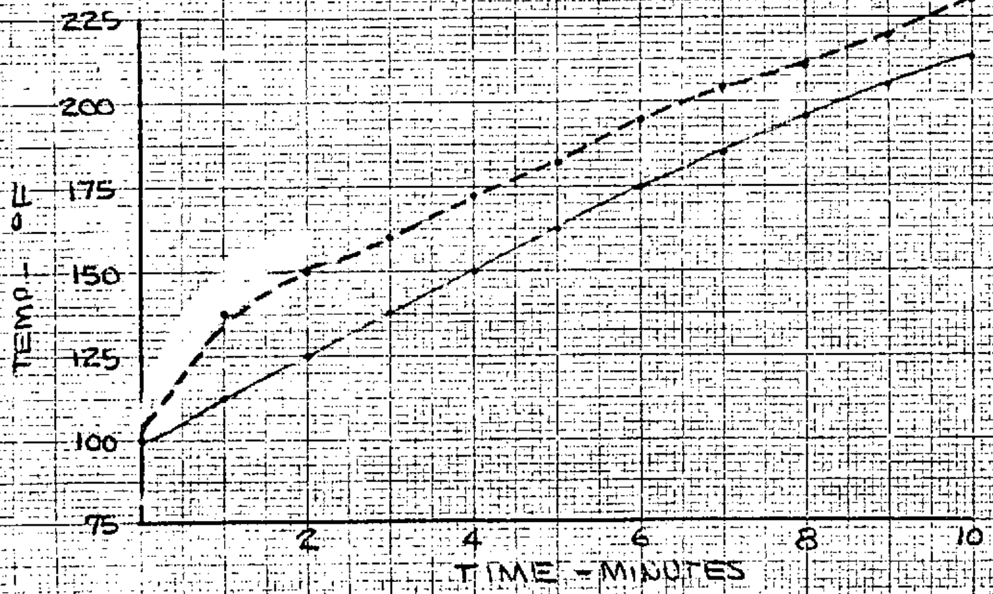
DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-27-73
Customer SCI
AZUSA, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180 B
Para. 7.16
S/N QT 8
Test Med. GN_2
Specimen Temp. AS NOTED



TANK QT 8
CYCLE # 4

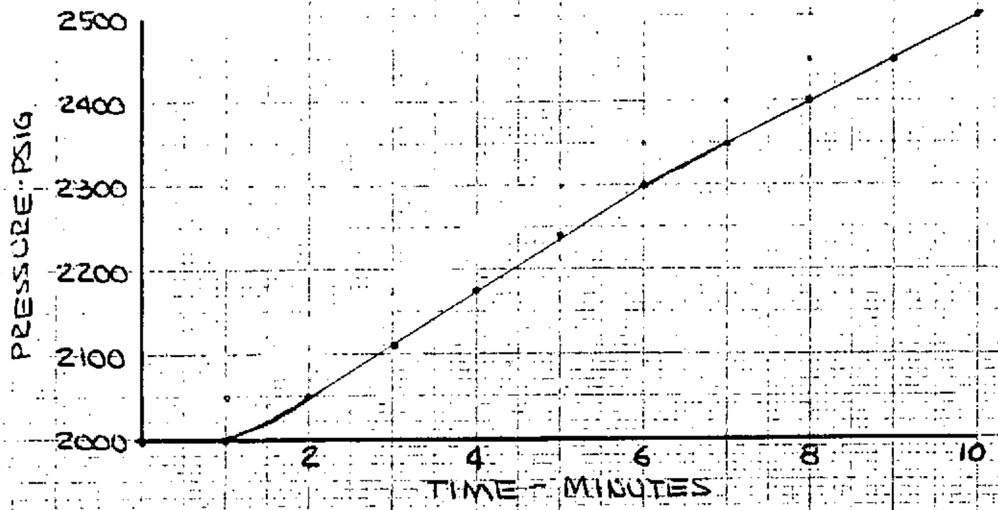
START PRESS 2100 PSIG
START TEMP 100°F



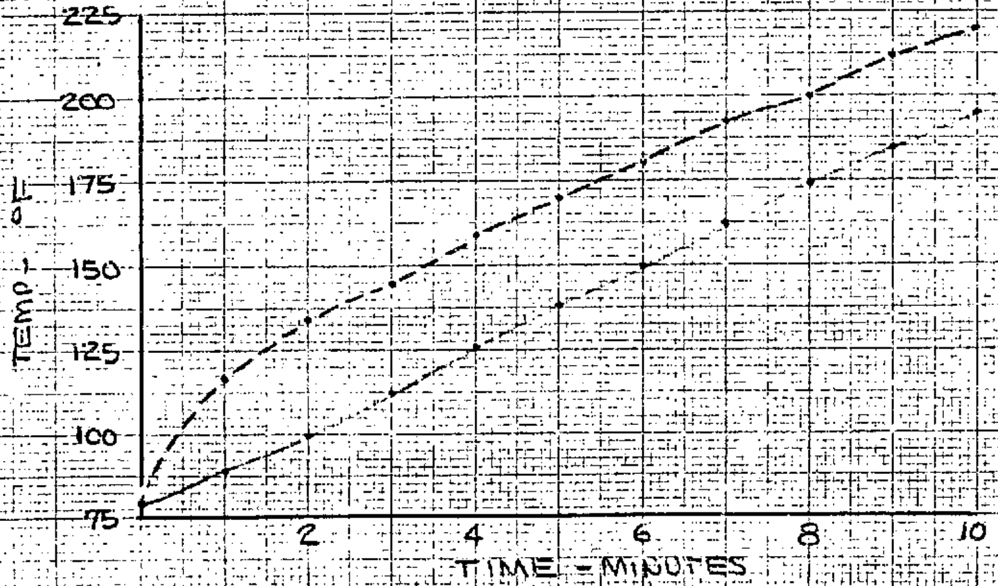
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-27-73
Customer SCI
AZUSA, CA
Part No. 1267367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. AS NOTED



TANK QT 8
CYCLE # 5
START PRESS 2000 PSIG
START TEMP 80°F



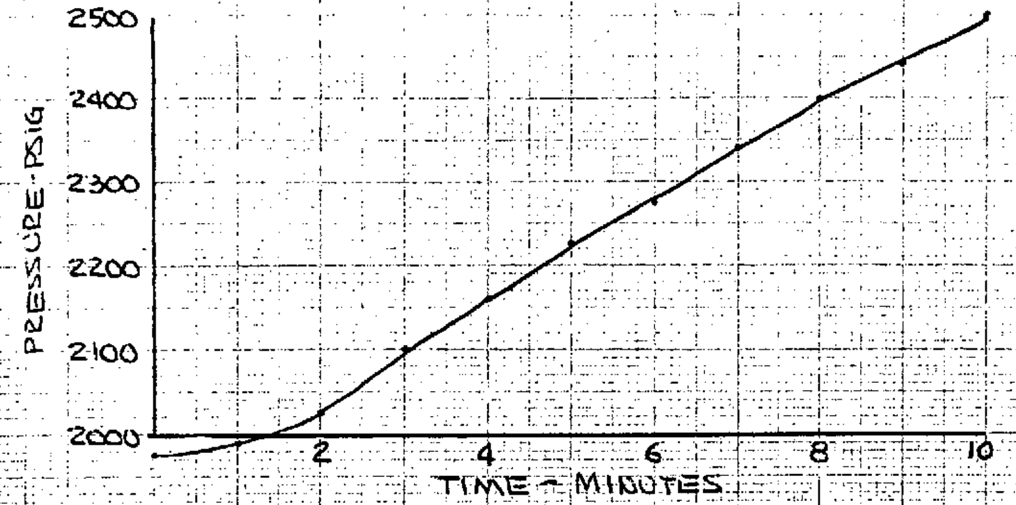
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-30-73
Customer SCI
AZUSA, CA
Part No. 1267367-1
Spec. CEL QTP 565-1180 B
Para. 7.16
S/N QT 8
Test Med. GN$_2$
Specimen Temp. AS NOTED

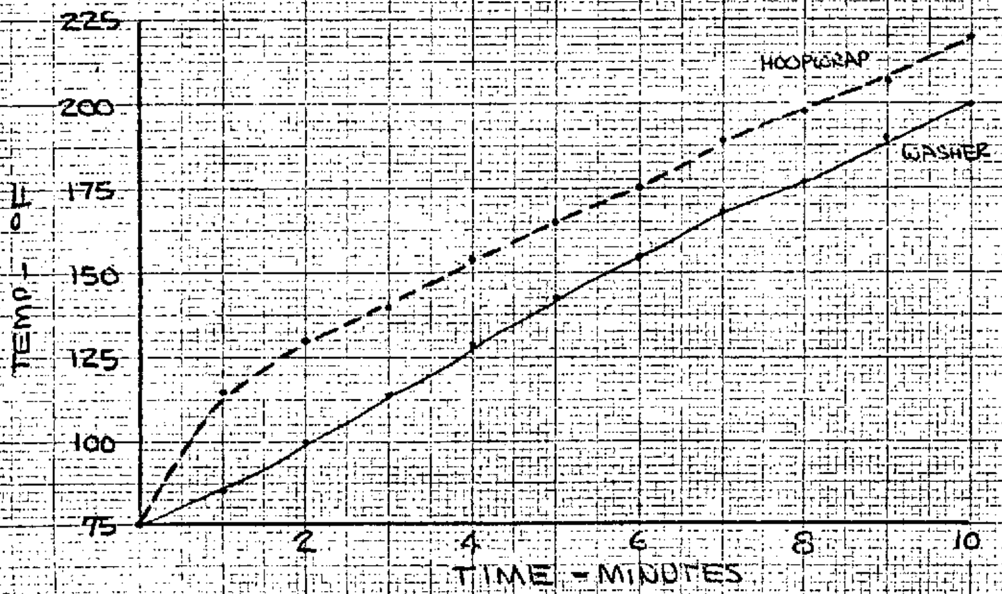
E 137

E-187



TANK QT8
CYCLE # 6

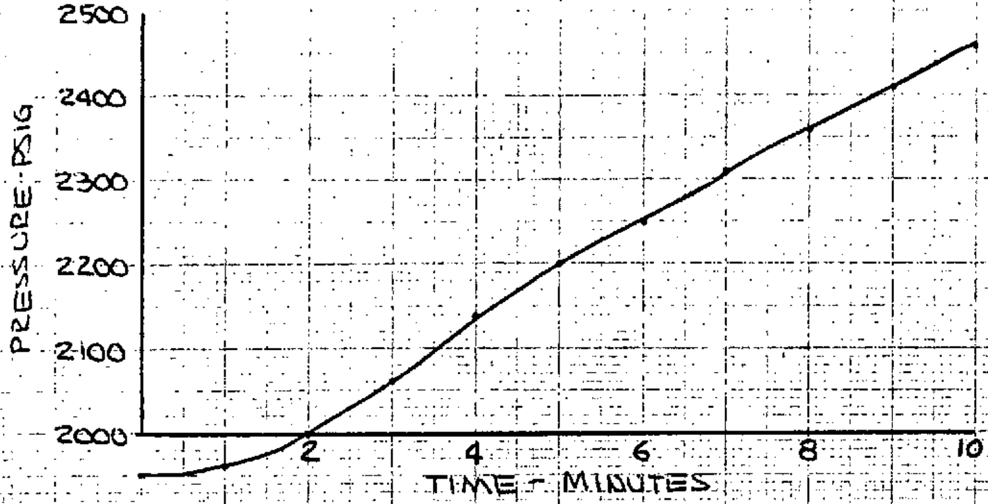
START PRESS 1975 PSIG
START TEMP 75°F



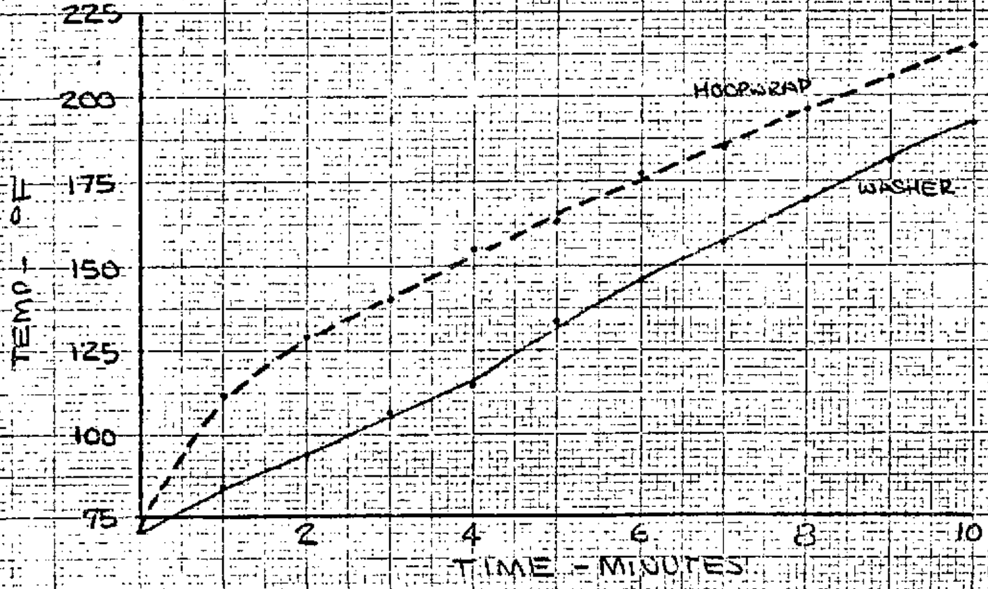
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 4-30-73
Customer SCI
Azusa, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT8
Test Mod. GN_2
Specimen Temp. AS NOTED



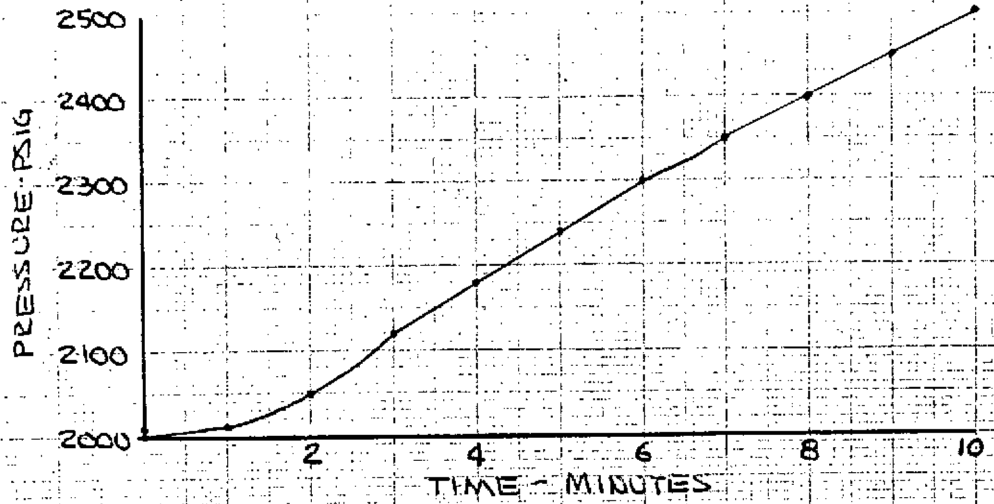
TANK QT 8
CYCLE # 7
START PRESS 1950 PSIG
START TEMP 72°F



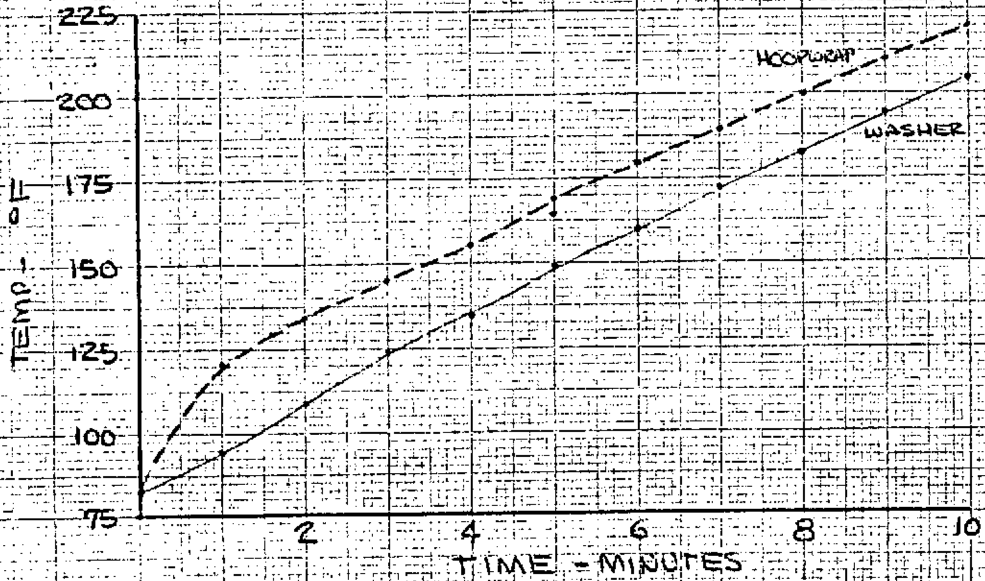
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-1-73
Customer SCI
AZUSA, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN_2
Specimen Temp. AS NOTED



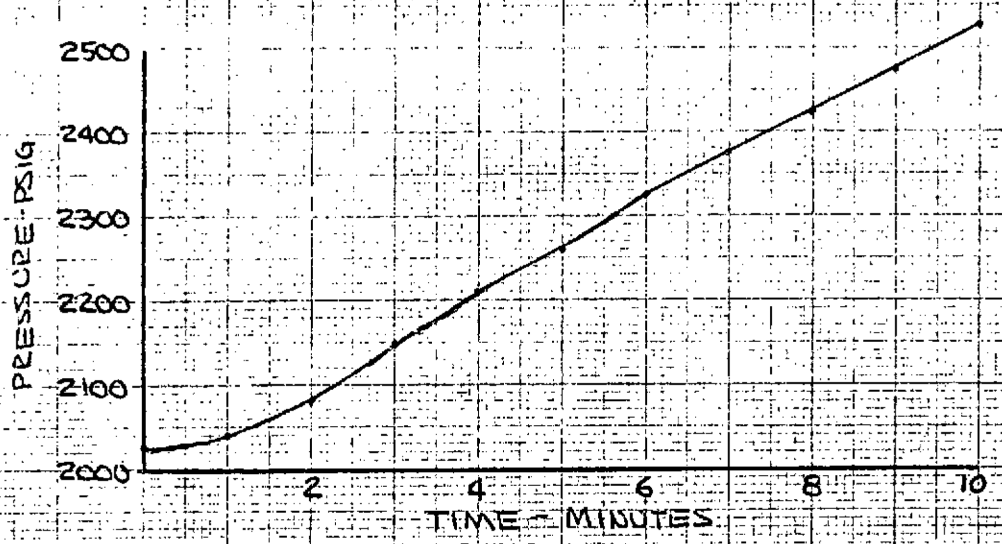
TANK QT 8
CYCLE # 8
START PRESS 2000 PSIG
START TEMP 82°F



AETL

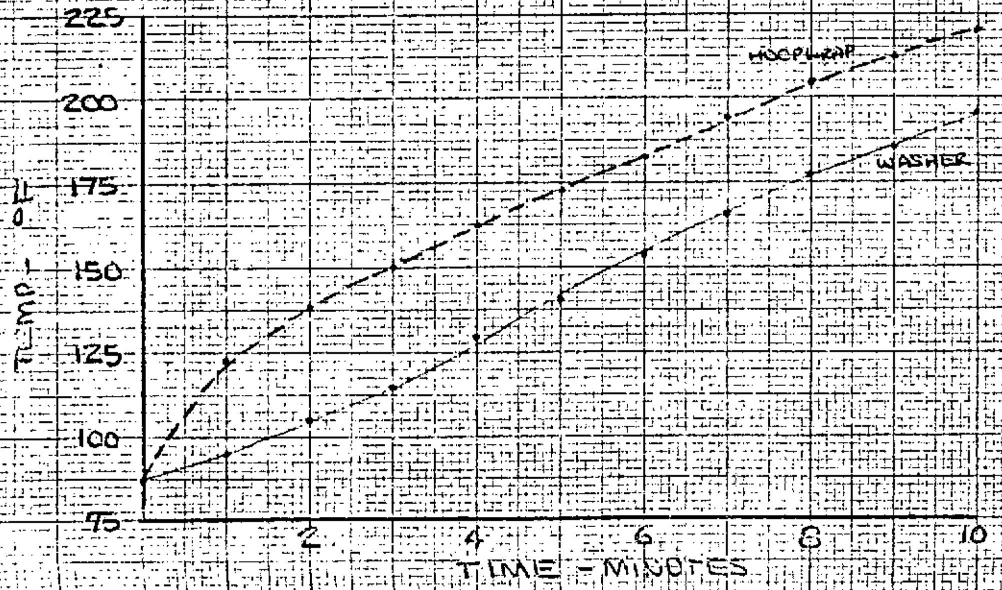
DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-1-73
Customer SCI
Azusa, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. AS NOTED



TANK QT8
CYCLE # 9

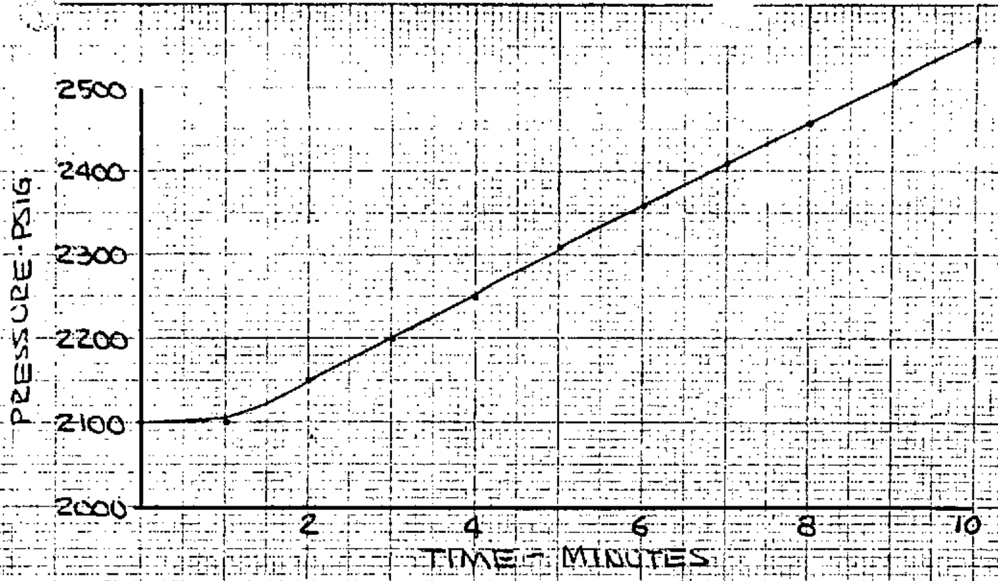
START PRESS 2025
START TEMP 87°F



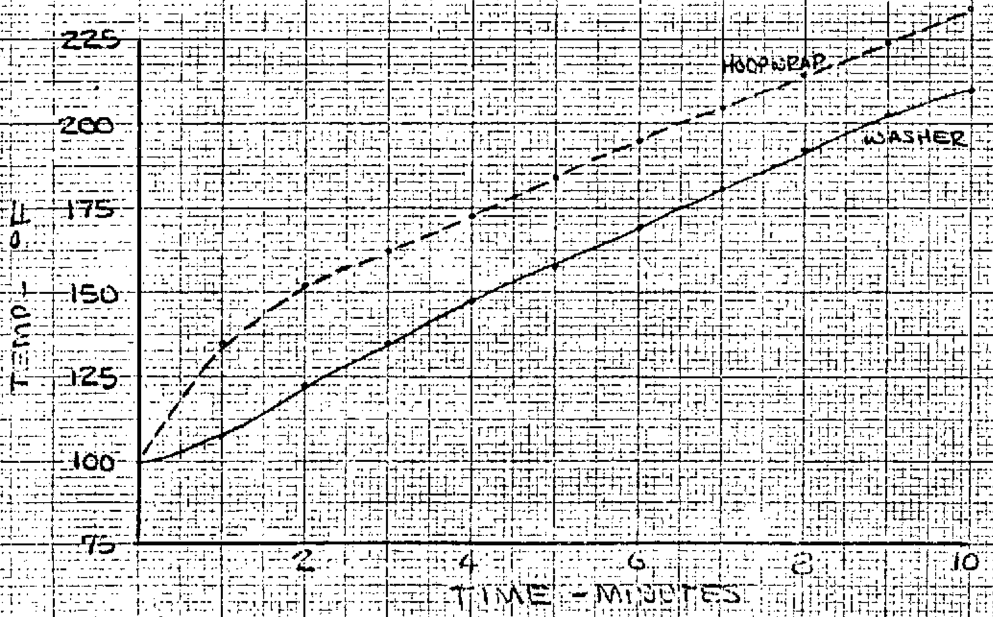
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-2-73
Customer SCI
AZUSA, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN2
Specimen Temp. AS NOTED



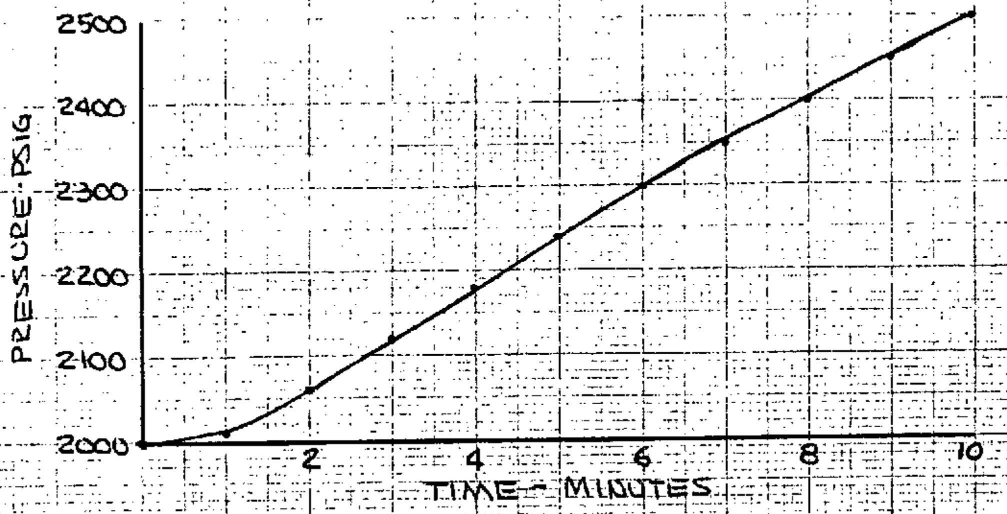
TANK QT 8
CYCLE # 10
START PRESS 2100 PSIG
START TEMP 100°F



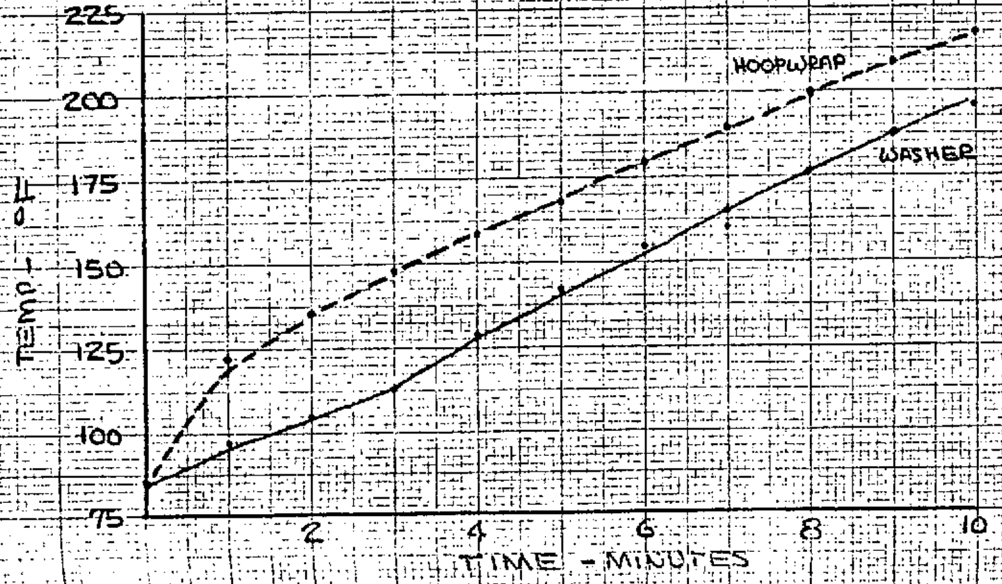
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-2-73
Customer SCI
Azusa, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Med. GN_2
Specimen Temp. AS NOTED



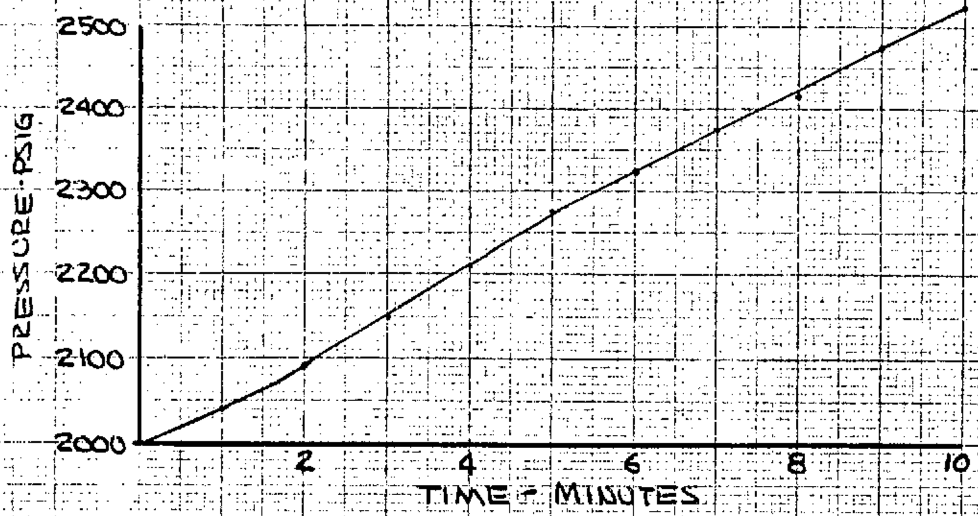
TANK QT 8
CYCLE # 11
START PRESS 2000 PSIG
START TEMP 85°



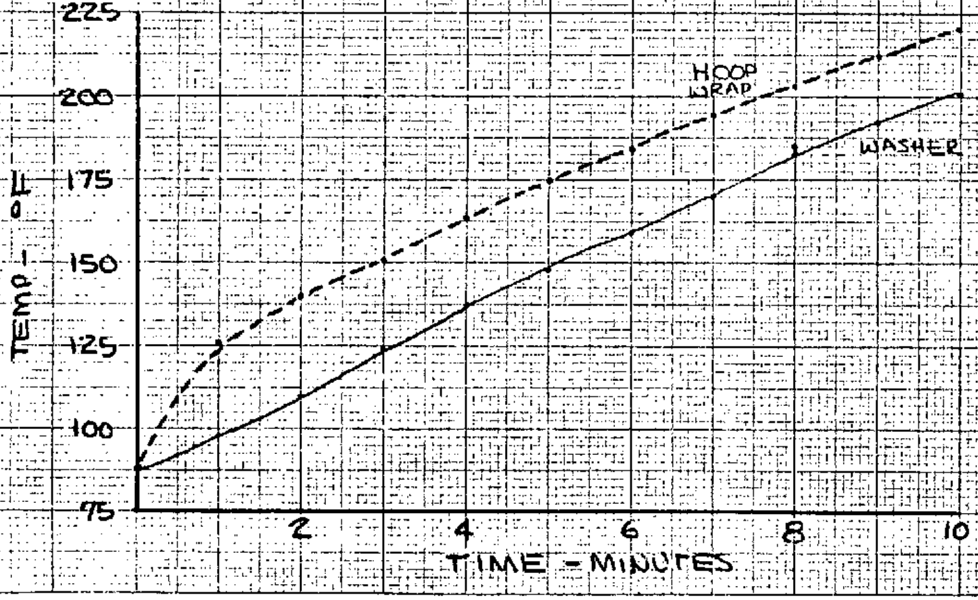
AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-3-73
Customer SCI
Azusa, CA
Part No. 1269367-1
Spec. CEL QTP 565-1180 B
Para. 7.16
S/N QT 8
Test Med. GN_2
Specimen Temp. AS NOTED



TANK QT 8
CYCLE # 12
START PRESS 2025 PSIG
START TEMP 88°F



AETL

DATA SHEET

Job. No. 565-1180
Report No. DO
Date 5-3-73
Customer SCI
AZUSA, CA
Part No. 1267367-1
Spec. CEL QTP 565-1180B
Para. 7.16
S/N QT 8
Test Mod. GN2
Specimen Temp. AS NOTED

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
REV B 30 APR 73

TEST EQUIPMENT LOG

TEST HIGH TEMPERATURE EXPOSURE #2 MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269367-1 S/N QT-8
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.16

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
4-26	1	PRESS GAUGE	P-300L	ASHCROFT	5000 PSIG	±0.5%	5-2-73
	2	PRESS CONSOLE	P-3104	CEL	8000 PSI	N/A	N/A
	3	PRESS GAUGE	P-3027	ASHCROFT	3000 PSIG	±0.5%	7-24-73
	4	STOPWATCH	G-3142	SECURITY	30 MIN	±0.07%	6-8-73
	5	TEMP CHAMBER	ENV-3103	NAA	0°-1000°F	N/A	N/A
	6	TEMP POT	ENV-3039	M-H	-100°/+600°F	±0.1%	5-10-73
	7	TEMP CONTROLLER	ENV-3061	HONEYWELL	0-1200°F	±2°F	5-3-73
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
	20						

GENERAL TEST NOTES:

PAGE ____ OF ____

TEST BY LOIBL DATE 5-3-73

CEL 10 TEST

ENGR. ____ GOV'T QAR ____

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73
Rev: B 30 Apr 73

DATA SHEET NUMBER 9A

PART NUMBER 1269367-1, TANK NUMBER QT8

- -

BURST TEST, Paragraph 7.16.7

Parameter	Required	Actual
Test Media	Gaseous Nitrogen	
Temperature	Ambient	81 °F.
Burst Pressure	As observed	13,200 psig
Pressure Rise Rate	3000/5000 psi/min	APPROX 3000 psi/min

Mode of Failure HOOP FAILURE - CYLINDRICAL SECTION

Tested By M. CONNELL CEL 13 Date 5-4-73

Witness BOB GORDON Date

APPROVED ENGINEERING TEST LABORATORIES

Procedure No. 565-1180
Date: 3 Mar 73
Rev: A 28 Mar 73

TEST EQUIPMENT LOG

TEST Burst Test MJO 565-1180
CUSTOMER Structural Composites Industries
TEST ITEM Fireman's Breathing Tank P/N 1269303-1 S/N QT-8
SPECIFICATION CEL/AETL QTP 565-1180 PAR 7.16.7

DATE	Item	Description	CEL No.	Mfgr.	Range	Acc'y	Calib Due
	1	PRESS GAUGE	P832V	HELICOID	16,000 PSIG	±0.5%	2-23-73
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						
	14						
	15						
	16						
	17						
	18						
	19						
	20						

GENERAL TEST NOTES:

PAGE ______ OF ______

TEST BY M. CONNELL DATE 5-4-73
ENGR. CEL 10 TEST GOV'T QAR ______

A&B PTG -- 215

APPENDIX F

SPECIFICATION, DETAIL

SPECIFICATION, DETAIL

The following is a proposed SCI draft for a general DOT permit covering glass-filament-overwrapped-aluminum-construction pressurized cylinders.

178. SPECIFICATION

Compressed gas pressure cylinder, seamless aluminum cylinder liners made of definitely prescribed aluminum, filament overwrapped with definitely prescribed fibrous-glass roving and epoxy matrix materials.

178.__-1 COMPLIANCE

Required in all details.

178.__-2 TYPE, SIZE AND SERVICE PRESSURE

Filament-wound over seamless liner not over 1,000 pounds water capacity (nominal) and service pressure at least 150 pounds per square inch.

178.__-3 INSPECTION BY WHOM AND WHERE

(a) By competent and disinterested inspector acceptable to the Bureau of Explosives; chemical analyses and tests, as specified, to be made within limits of the USA.

178.__-4 DUTIES OF INSPECTOR

(a) Inspect all material and reject any not complying with requirements.

(b) Verify chemical analysis of each heat of liner material by analysis or by obtaining producer's certificate of analysis. When verified by check analysis, one sample is to be taken from each cast lot or from one cylinder liner out of each inspection lot of 200 or less.

(c) Verify compliance of cylinders with all requirements, including markings; inspect inside before closing; verify proper heat treatment; witness all tests; obtain copies of all test results and certifications; verify threads by gage; report volumetric capacity, tare weight and minimum thickness of wall noted (see report form).

(d) Render complete report (178.__-19) to purchaser, cylinder, maker, and the Bureau of Explosives.

178.__-5 AUTHORIZED HEAT-TREATABLE ALUMINUM ALLOYS

(a) The following primary metal aluminum alloys are permitted:

CHEMICAL COMPOSITION LIMITS(2)

Aluminum Alloy Designation(1)									Others(3)		
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Total	Al
6351	0.7- 1.3	0.50 Max.	0.10 Max.	0.40- 0.8	0.40- 0.8		0.20 Max.	0.20 Max.	0.05 Max.	0.15 Max.	Remainder

MECHANICAL PROPERTY LIMITS(2)

Alloy and Temper	Tensile Strength - Ksi		Elongation Percent Minimum in 2" or 4D(4)	Minimum Hardness(5)
	Ultimate-Minimum	Yield-Minimum		
6351-T6	42	38	10	85

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(1) Aluminum Association Alloy designation number.

(2) ASTM B 221-72 Standard Specification for Aluminum-Alloy Extruded Bars, Rods, Shapes, and Tubes, Table 1 Chemical Composition Limits.

(3) Analysis is regularly made only for the elements for which specific limits are shown, except for unalloyed aluminum. If, however, the presence of other elements is suspected to be, or in the course of routine analysis is indicated to be in excess of specified limits, further analysis is made to determine that these other elements are in excess of the amount specified. (Aluminum Association Standards and Data - Third Edition - 1972-73)

(4) "D" represents specimen diameter.

(5) Brinell hardness using 500-kg load on a 10-mm ball, or equivalent. (Aluminum Association Standards and Data - Third Edition - 1972-73)

(b) The following fibrous-glass, commerical "S" composition is permitted:

Fibrous-Glass, Commercial "S" Glass Composition, %

$Si O_2$	Al_2O_3	MgO
65%	25%	10%

Tensile Strength: 450,000 psi minimum

Specific Gravity: 2.52

(c) The following epoxy resin matrix is permitted:

DER-332 (Dow Chemical) or equivalent - 100 parts by weight.

Hexahydrophthalic Anhydride - 84 parts by weight.

Benzyl Dimethylamine - 0.5 parts by weight.

178.__-6 IDENTIFICATION OF MATERIALS

Required; any suitable method that identifies materials and compositions, manufacturer's cast, melt, or lot number, solution heat treat batch number, and inspection lot number.

178.

178.__-7 DEFECTS

Aluminum material with seams, cracks, laminations, or other injurious defects not authorized.

178.__-8 MANUFACTURE

(a) The composite cylinder must be constructed of the authorized materials of (1) aluminum seamless liner, (2) fully overwrapped with continuous glass-filament windings applied in "in-plane," modified-in-plane," or "helical" patterns complemented with circumferential windings along the cylinder section.

(b) Cylinder shells must be manufactured by appropriate commercial methods and at a cleanliness level to ensure proper inspection.

(c) No fissure or other defect is acceptable that is likely to weaken the finish cylinder appreciably. Reasonably smooth and uniform surface finish is required. If not originally free from such defects, the surface may be machined or otherwise treated to eliminate these defects.

(d) The thickness of the cylinder liner bottom must not be less than the minimum wall thickness of the cylindrical shell, and must have an ellipsoidal contour configuration conforming to 178.__-10.

178.__-9 WELDING OR BRAZING

Welding or brazing for any purpose whatsoever is prohibited.

178.__-10 WALL THICKNESS

(a) The minimum wall of each cylinder shall be such that at operating pressure, the wall stress in the aluminum liner shall not exceed 60% of their minimum yield strength; stresses in the fibers shall not exceed 30% of their ultimate in that particular vessel configuration and at 0 psig pressure after first test pressure application, stress in the aluminum liner shall not exceed 90% of their compressive yield strength.

(b) The pressure vessel shall be designed by optimizing results received from Computer Code NASA CR-72124, "Computer Program for the Analysis of Filament-Wound Reinforced Metal Shell Pressure Vessels," May 1966.

178.__-11 ALUMINUM HEAT TREATMENT AND RESIN CURE

(a) The aluminum liner, prior to filament overwrap, must be uniformly and properly heat treated prior to test. Heat treatment of cylinders of the authorized analysis shall be as follows:

(1) Soak the metal liners at 940°F ± 5°F for 30 minutes.

(2) Directly after removal of the liners from the soak furnace, the liners are to be quenched by total immersion in cold water (75°F or less). During removal of parts from the furnace, the metal temperature should not get below 800°F before immersion in the quench water. Water volume should be sufficient to keep final temperature below 100°F during the quench cycle.

(3) The liners are then to be artifically aged for eight hours at 340°F + 5°F. An alternate aging is five hours at 365°F ± 5°F.

(b) The completed filament-wound cylinders shall be cured at temperatures and times varying from two hours at 350°F to twelve hours at 300°F ± 5°F, or until the epoxy matrix material is completly cured.

178.__-12 OPENINGS IN CYLINDERS AND CONNECTIONS FOR THESE OPENINGS

(a) Threads required to be clean cut, even, without checks, and to gage.

(b) Taper threads, when used, shall be of length not less than as specified for American Standard taper pipe threads.

(c) Straight threads having at least five engaged threads are authorized; to have tight fit and calculated shear strength at least four times the test pressure of the cylinder; gaskets required, adequate to prevent leakage.

178.__-13 SAFETY DEVICES AND PROTECTION FOR VALVES AND OTHER CONNECTIONS, IF APPLIED

Must be as required by the Department of Transportation Regulations that apply (see 173.34(d) and 173.301(g)).

178.__-14 HYDROSTATIC TEST

(a) By water jacket, or other suitable method, operated so as to obtain accurate data. Pressure gage must permit reading to accuracy of 1%. Expansion gage must permit reading of total expansion to accuracy either of 1% or 0.1 cubic centimeter.

(b) Pressure must be maintained for at least 30 seconds or longer to ensure complete expansion. Any internal pressure applied after heat treatment, previous to the official test, must not exceed 90% of the test pressure. If due to failure of the test apparatus the test pressure cannot be maintained, the test may be repeated at a pressure increased by 10% or 100 psi, whichever is the lower.

(c) Permanent volumetric expansion must not exceed 10% of total volumetric expansion at test pressure.

(d) Each cylinder shall be tested to at least 5/3 times service pressure.

178.__-15 MECHANICAL TEST

(a) Aluminum Liner Material

(1) To determine yield strength, tensile strength, elongation and reduction of area of the liner material, test two coupons cut from one cylinder representing each lot of 200 or less.

(2) Ultimate tensile strength, elongation and hardness of finished cylinders must conform to at least the minimum acceptable for aluminum alloys as specified in 178.__-5a.

(3) Coupons must conform and be tested in accordance with specification ASTM E8 (1972) covering Tension Testing of Metallic Materials. The specimen, exclusive of grip ends, must not be flattened. Grip ends may be flattened to within one inch of each end of the reduced section. When size of cylinder does not permit securing straight specimens, the specimens may be taken in any location or direction and may be straightened or flattened cold by pressure only, not by blows. When specimens are so taken and prepared, the inspector's report must show in connection with record of physical tests detailed information in regard to such specimens. Heating of specimens for any purpose is not authorized.

(4) The yield strength in tension must be the stress corresponding to a permanent strain of 0.2% of the gage length.

a. The yield strength shall be determined by either the "offset" method or the "extension-under-load" method, as prescribed in ASTM Standard E8-72T.

b. In using the "extension-under-load" method, the total strain (or "extension under load") corresponding to the stress at which the 0.2% permanent strain occurs may be determined with sufficient accuracy by calculating the elastic extension of the gage length under appropriate load and adding thereto 0.2% of the gage length. Elastic extension calculations shall be based on an elastic modulus of 10,000,000. In the event of controversy, the entire stress-strain diagram must be plotted and the yield strength determined from the 0.2% offset.

c. For the purpose of strain measurement, the initial strain shall be set while the specimen is under a stress of 6,000 pounds per square inch, the strain indicator reading being set at the calculated corresponding strain.

d. Cross-head speed of the testing machine must not exceed 1/8-inch per minute during yield strength determination.

(b) Glass-Epoxy Materials

The strength of the approved roving/resin system shall be tested using:

(1) ASTM D-2343-65T strand test,

(2) Weight/yard/end weight test, and

(3) ASTM D-223-65T water boil shear test,

fabricated with the same winding tension and cure cycle. At least two tests shall be conducted on the materials to be utilized for 200 cylinders or less. The composite material shall demonstrate minimum properties as follows:

Strand Test, psi	450,000
Water Boil Shear Test, psi	6,000
Weight/Yard/End, gms	0.0269-0.0336

(c) In lieu of (a) and (b), above, the strength of the cylinder shall be determined by burst of one production unit taken at random out of each lot of 200 or less. (Individual strengths of samples cut from composite units are interpreted only with great difficulty and potential inaccuracy). The burst pressure of the production unit shall be greater than 20/9 times the maximum service pressure.

178.__-16 REJECTED CYLINDERS

Liner reheat treatment is authorized; subsequent thereto, acceptable liners must pass all prescribed tests. Repair by welding or spinning is not authorized.

178.__-17 MARKING

(a) Marking on each cylinder shall be permanent bonding of a label on shoulder, top head, or cylindrical body as follows:

(1) DOT TBD followed by service pressure.

(2) A serial number and an identifying symbol or letters; location of number to be just below or immediately following the DOT mark; location of symbol to be just below or immediately following the number. The symbol and numbers must be those of a purchaser, user, or maker. The symbol must be registered with the Bureau of Explosives; duplication unauthorized.

(3) Inspector's official mark near serial number; date of test (such as 6-74 for June 1974), so placed that dates of subsequent tests can easily be added.

(4) Marks to be at least 1/4" high if space permits.

(b) Other marks authorized provided they are made in nonstress areas and are not of a size and depth that will create any stress concentrations. No marks allowed which are of a depth which will cause a reduction in minimum wall thickness, or which conflict with DOT required markings.

178.__-18 DESIGN QUALIFICATIONS

(a) Cycling Tests

(1) Prior to the initial shipment of any specific cylinder design, cyclic pressurization tests must have been performed on at least one representative sample without failure as follows:

> Pressurization must be performed hydrostatically between approximately zero psig and the service pressure at a rate not in excess of 4 cycles per minute. Adequate record instrumentation must be provided if equipment is to be left unattended for periods of time.

(2) Tests prescribed in subparagraph (a) (1) of this paragraph must be repeated on one random sample out of each lot of cylinders. Cylinder may then be subjected to burst test.

(3) A lot is defined as a group of cylinders fabricated by the same process and heat treated in the same equipment under the same conditions of time, temperature, and atmosphere, and must not exceed a quantity of 200 cylinders.

(4) All cylinders used in cycling tests must be destroyed.

(b) Burst Test

(1) One cylinder taken at random out of each lot of cylinders shall be hydrostatically tested to destruction.

(c) Results of Cycle and Burst Test

(1) Cycling for at least 10,000 cycles without failure.

(2) Burst pressure must exceed 20/9 times service pressure.

178.__-19 RETEST

Each cylinder must be hydrostatically retested every three years in accordance with 49 CFR 173.34(e) as prescribed for DOT Specification 3HT cylinder, except that retest dates must be imbedded in the epoxy coating in a permanent manner other than stamping.

Inspector's Report

(a) Required to be clear, legible, and in the following form:

Place..

Date...

Gas Cylinders
Manufactured for..................................Company
Location at..
Manufactured by..................................Company
Location at..
Consigned to......................................Company
Location at..
Quantity...
Size..................inches outside diameter by.........inches long
Marks stamped into the label of the cylinder are:

Specification DOT.....................................
Serial numbers..................to...........inclusive
Inspector's mark......................................
Identifying symbol (registered)........................
Test date...
Tare weights (yes or no)...............................
Other marks (if any)...................................
These cylinders were made by process of...............
....

The material used was identified by the following:

Batch-heat-purchase order numbers:

Liner _______________
Resin _______________
Glass _______________

The heat numbers (were/were not) marked on the material. All material was inspected, and each cylinder was inspected; all that was accepted was found free from seams, cracks, laminations, and other defects which might prove injurious to the strength of the cylinder. The process of manufacture and heat treatment of liners was supervised and found to be efficient and satisfactory. The cylinder walls were measured and the minimum thickness noted was _______ inches.

Hydrostatic tests, tensile tests of material, and other tests, as prescribed in specification number ________ were made in the presence of the inspector and all material and cylinders accepted were found to be in compliance with the requirements of that specification. Records thereof are attached hereto.

I hereby certify that all of these cylinders proved satisfactory in every way and comply with the requirement of Department of Transportation specification number _______, except as follows:

Exceptions ____
____
____

(Signed) __________________________
Inspector

(Place) ....
(Date) ....

Record of Chemical Analysis of Material for Liners.

Numbered............. to ....inclusive
Size................inches outside diameter by...............inches long
Made by .... Company
For...Company

NOTE: Any omission of analyses by heats, if authorized, must be accounted for by notation hereon reading "The prescribed certificate of the manufacture of material has been secured, found satisfactory, and placed on file." or by attaching a copy of the crtificate.

Test No.	Heat No.	Check analysis No.	Cylinders represented (serial Nos.)	Liner Chemical analysis							
				Si	Fe	Cu	Mn	Mg	Zn	Ti	Other

The analyses were made by ....

(Signed)..............................

(Place)............................
(Date).............................

Record of Physical Tests of Material for Liners

Numbered..................to...............inclusive
Size.......................inches outside diameter by ....inches long
Made by.. Company
For .... Company

Test No.	Cylinders represented by test (serial Nos.)	Yield strength at 0.2 per-cent offset (pounds per square inch)	Tensile strength (pounds per square inch)	Elongation (percent in 8 inches)	Reduction of area (percent)	Burst test

(Signed)..................................

RECORD OF HYDROSTATIC TESTS ON CYLINDERS

Numbered .... to .... inclusive.
Size .... inches outside diameter by .... inches long.
Made by .... Company.
For .... Company.

Serial Nos. of cylinders tested arranged numerically	Actual test pressure (lbs. per square inch)	Total expansion (cubic centimeters) 1/	Permanent expansion (cubic centimeters) 1/	Percent ratio of permanent expansion to total expansion 1/	Tare Weight (lbs)2/	Volumetric capacity
....	....	....	....	....	....	......
....	....	....	....	....	....	......
....	....	....	....	....	....	....

1/ If the tests are made by a method involving the measurement of the amount of liquid forced into the cylinder by the test pressure, then the basic data on which the calculations are made, such as the pump factors, temperature of liquid, coefficient of compressibility of liquid, etc., **must also be given.**

2/ Do not include **removable cap but state whether with or without valve. These weights must be accurate to a tolerance of 1%.**

(Signed) ....

APPENDIX G

FAILURE ANALYSIS QUALIFICATION VESSEL 6A

By

W. L. Castner
NASA-JSC

FAILURE ANALYSIS OF OVERWRAPPED FIREMAN'S BREATHING OXYGEN BOTTLE QUALIFICATION TANK #6A

INTRODUCTION

The subject qualification tank (6A) developed a leak during qualification testing. The qual test consisted of a high temperature (600°F) exposure for 5 minutes, 20 thermal cycles from -60°F to +200°F, salt fog exposure for 48 hours, and 10,000 cycles to the operating pressure (4000 psi) plus 100 cycles to the proof pressure (6750 psi). After completing the thermal exposure tests, salt fog test, and 6633 cycles to operating pressure the tank developed a leak on the eighteenth cycle to proof pressure. The leak site was identified as a crack which extended through the thickness of the metal liner, but not through the overwrap. The overwrap by itself is not a leak tight container.

ANALYSIS AND RESULTS

The leaking tank was submitted to the Structures and Mechanics Division for a failure analysis. The analysis consisted of a dye-penetrant and visual examination to verify the leak site and to locate other cracks; a metallurgical examination to determine the nature and extent of other cracks; and a fractographic analysis of the through crack fracture surface to determine the fracture mode, i.e., overload, stress corrosion, fatigue, etc. The latter analysis, fractography, is an analytical method for categorizing the various fracture modes. This is possible because the different fracture modes produce characteristic features on the fracture surface.

Dye-Penetrant and Visual Examination - Dye-penetrant examination of the as-received tank, shown in figure 1, revealed literally thousands of crack indications on the inside surface. All indications ran parallel to the longitudinal axis of the tank. The leak site was located using dye-penetrant. A magnified view of the leak site is shown in figure 2. Visual examination showed the many crack indications were produced by long, shallow cracks that were quite wide open. The leak site was also associated with one of the shallow, open cracks.

Metallurgical Examination - Several sections were removed from the tank near the leak site to determine the nature and extent of the other crack indications. These sections confirmed that the I.D. surface contained many shallow, open flaws. These flaws had a depth of about .002" and about the same width. Some of these flaws had much tighter cracks extending out of the bottom of the shallower ones. Both of these conditions are shown in figure 3. The shallow flaws were considered to be associated with the forming operation performed on the metal liner, while the tighter cracks were associated with fatigue during the pressure cycling phase of the qual test. For comparison purposes, a metal liner which had not been overwrapped and had no pressure cycle history was examined in the same manner. This liner had similar shallow, open flaws but there was no evidence of tight cracks extending out of the shallow ones. The flaws in the unwrapped liner are shown in figure 4. This comparison confirms that the shallow flaws occur during the forming operation, but the tight cracks do not. After the forming operation, the only reasonable source of the tight cracks is the fatigue cycling experienced during the qual test. The shallow flaws produced by the forming operation are most accurately described as forming tears rather than cracks, since cracks generally mean flaws whose depths are significantly greater than their widths.

Fractographic Examination - A section containing the through crack was removed from the liner and fractured to expose the fracture surface. A macrophotograph of the fracture surface is shown in figure 5. The fracture surface had a semi-elliptical, flat zone, which extended halfway through the thickness. The remaining ligament shows a shear failure at a 45 degree slant. In a reasonably ductile material such as the liner alloy (6351-T6 Al) and in this thickness range, overload fracture is characterized by a 45 degree slant or shear failure. The occurrence of a flat or 90 degree fracture is typical of fatigue where at least the flat part of the fracture grows by fatigue cracking.

Conclusive proof that the through crack resulted from fatigue was obtained by examining the fracture surface at high magnification with the aid of the scanning electron microscope. In the flat or semi-elliptical zone, the fracture surface was characterized by curvilinear markings or striations. These markings or striations are produced by fatigue crack propagation where each striation represents one load cycle. The classic fatigue striations found on this fracture are shown in figure 6.

An estimate of the number of striations or load cycles evident on the fracture was performed. By counting the number of striations occurring over a known distance, an estimate of the crack growth rate (dA/dN) is obtained. Averaging dA/dN values from several locations provides an average dA/dN value (1.5×10^{-5}) which divided into the flaw depth gives the number of cycles. In this case, the estimated number of cycles observable was 5300. The actual number of pressure cycles was 6650. When considering that some of the initial cycles do not cause measurable crack growth, the correlation between observed and actual cycles is quite good.

A graph of the liner stress versus pressure is shown in figure 7. Cycling from zero to the operating pressure produces a liner hoop stress ranging from -36 Ksi to +9 Ksi. Since the maximum stress is only 9 Ksi, it is difficult to understand how a fatigue crack could grow significantly in 6000 cycles. A fracture mechanics fatigue analysis using 6061-T6 data shows that the calculated crack growth rate (1.5×10^{-6}) is an order of magnitude less than the observed rate. Data from MIL-HDBK-5 on 6061-T6 smooth specimens predict a life of millions of cycles at these stresses. These observations lead to the conclusion that the liner was operating at stresses significantly higher than the graph predicts.

CONCLUSIONS

All liners have shallow forming tears that act as stress concentrators for initiation of fatigue cracks. The leaking tank resulted from a fatigue crack that initiated at a forming tear. The observed fatigue crack growth rate is significantly higher than expected. In the case of the leaking tank the liner stress must have been higher than predicted.

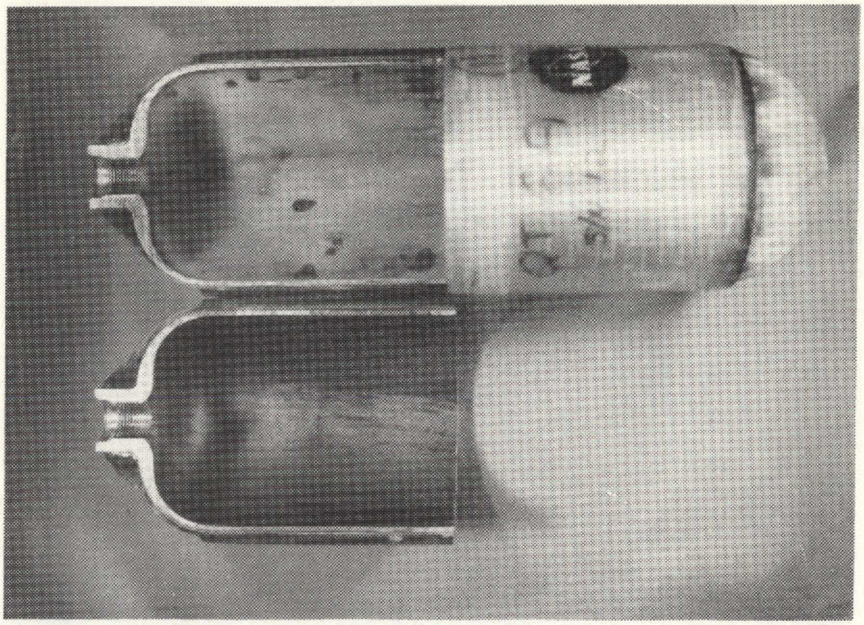

Figure 1.- This photograph shows the leaking qual tank in the as-received condition. The leak site is approximately in the center of the lower quarter segment.

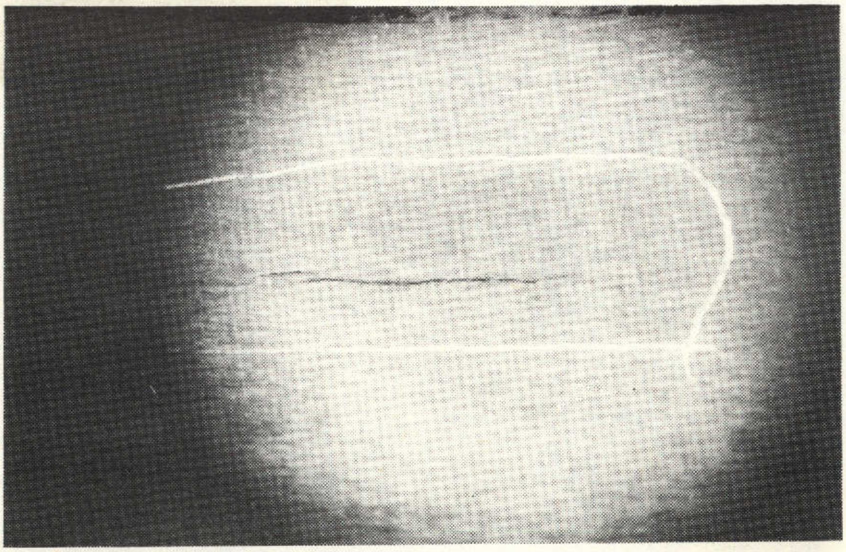

Figure 2 - This macrophotograph shows the crack which extended through the thickness and permitted leakage. This photo was taken on the I.D. Magnification: 5X

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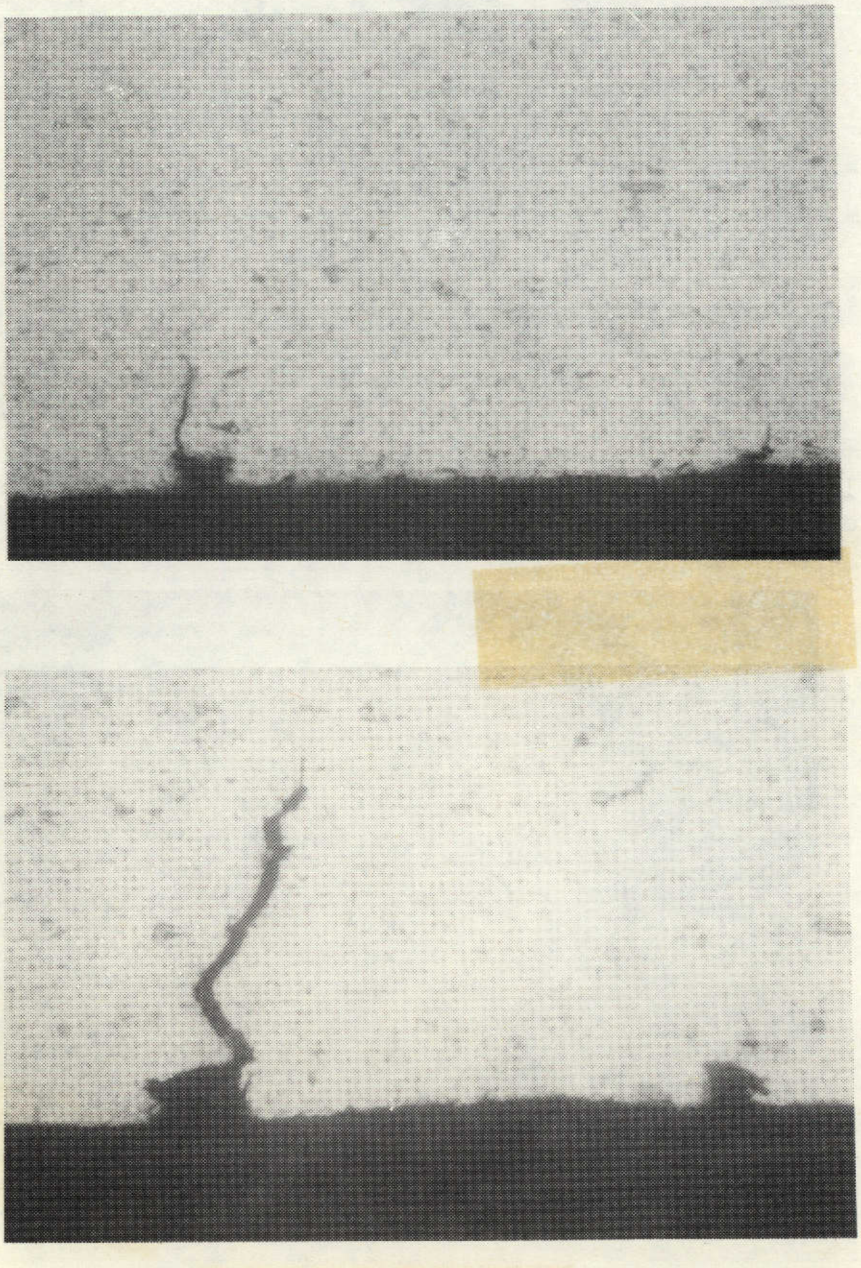

Figure 3.- These photomicrographs show polished and etched cross sections of the I.D. away from the leak site. The shallow, open flaws result from the forming operation while the deeper tighter flaws are fatigue cracks. It is obvious that the forming tears provide enough stress concentration to initiate fatigue cracks. Magnification: 500X

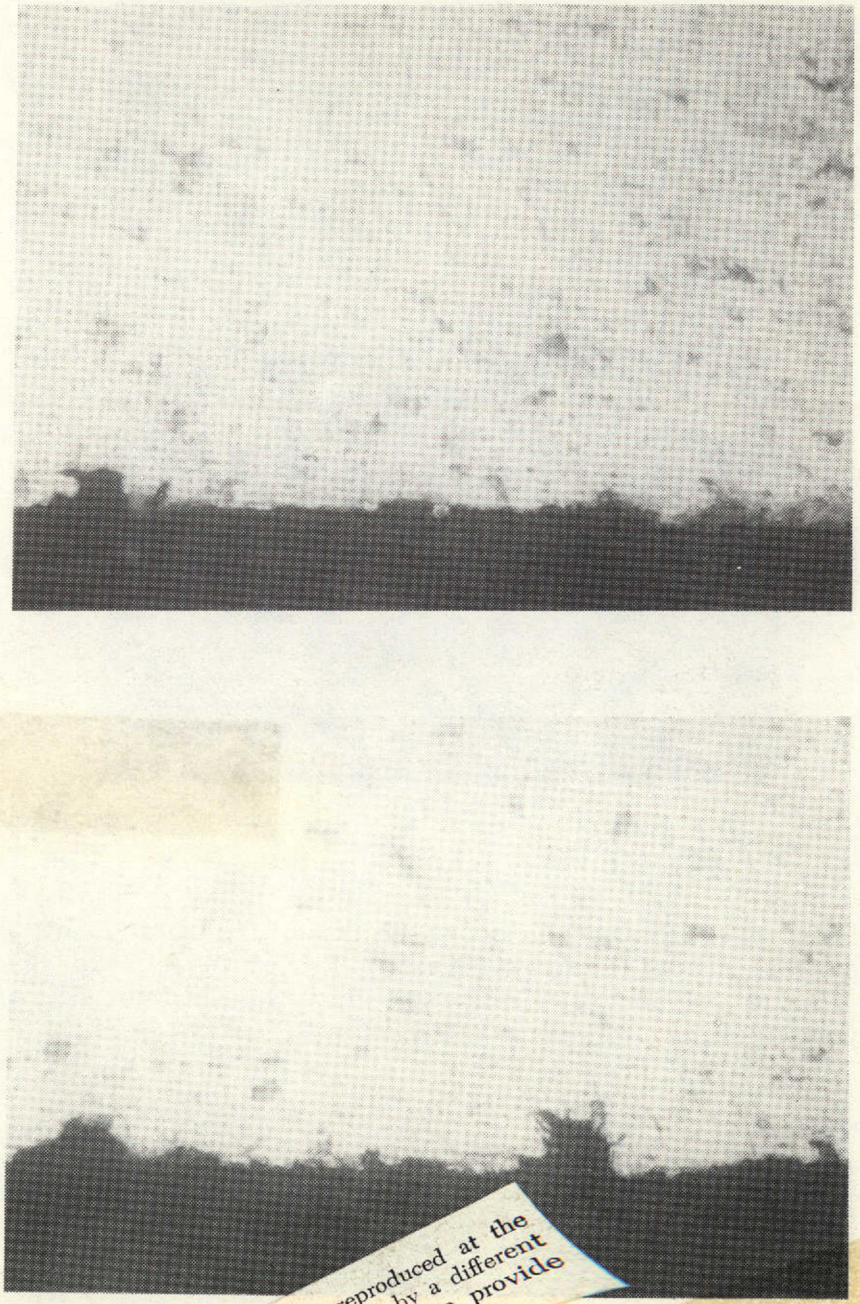

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Figure 4.- These photomicrographs show polished and etched cross sections of the I.D. from a liner that was not overwrapped and had no cyclic history. The shallow flaws are evident and can only result from the forming operation. Note the absence of the tight fatigue cracks. Magnification: 500X

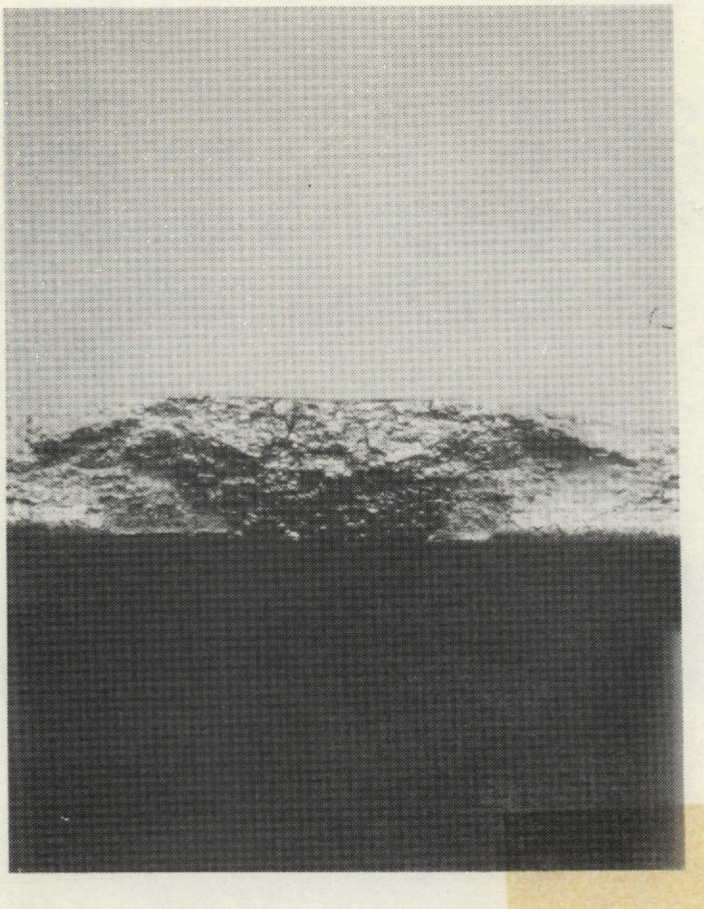

Figure 5.- This microphotograph shows the fracture surface of the through crack. The flat, semielliptical flaw typical of fatigue is readily apparent. At the inside surface the forming tear is just discernible and measures approximately .003 inch deep. Magnification: 5X

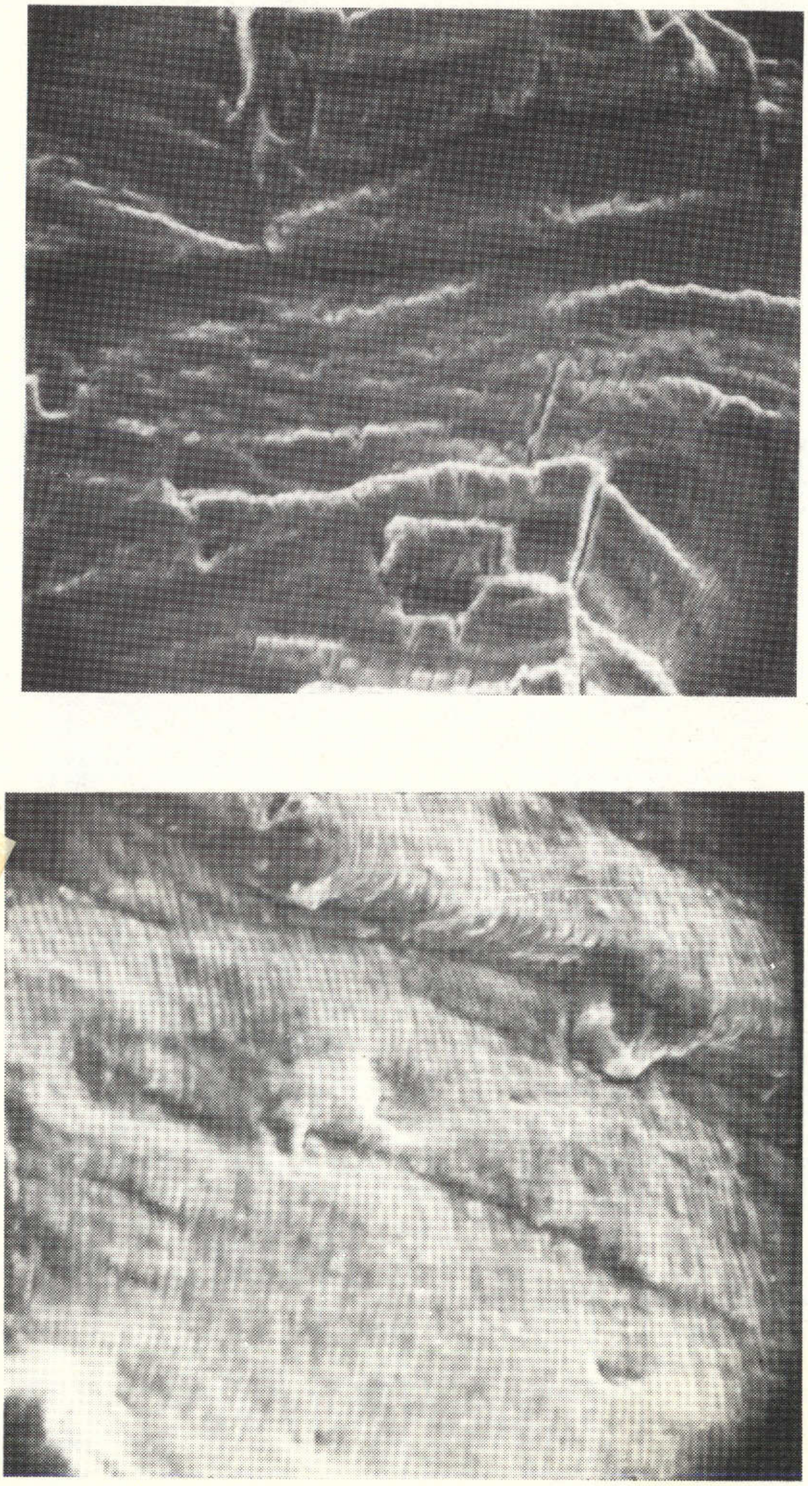

Figure 6.- These fractographs were taken near the center and end of the flat region and both show classic fatigue striations. The observed da/dN values at the center and end locations were 1.5×10^{-5} and 2.0×10^{-5} inches/cycle respectively. Note that the striations are so numerous that only cycling to the operating pressure could have produced them. Magnification: 1000X

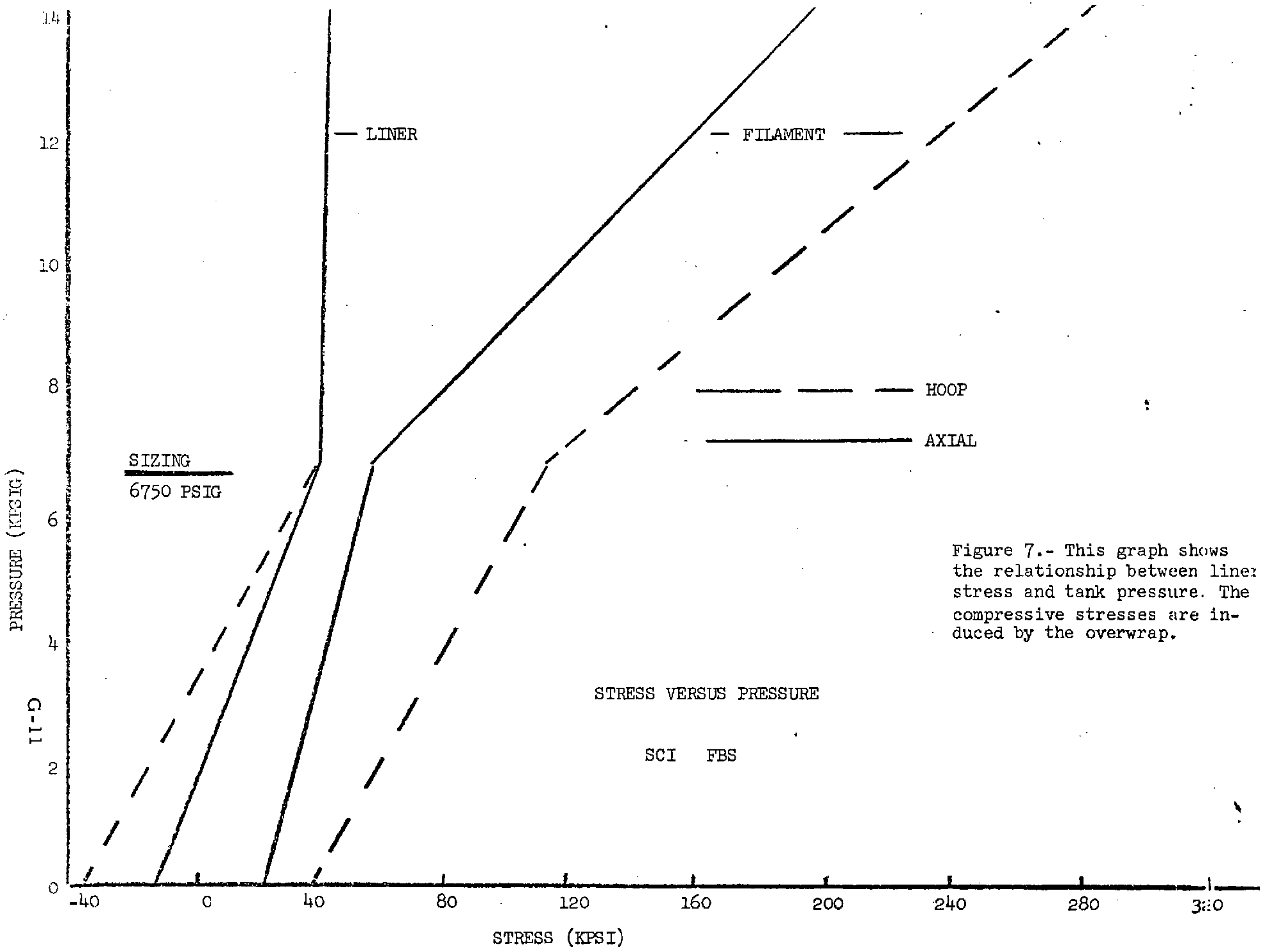

Figure 7.- This graph shows the relationship between liner stress and tank pressure. The compressive stresses are induced by the overwrap.

THE FOLLOWING PAGES ARE DUPLICATES OF ILLUSTRATIONS APPEARING ELSEWHERE IN THIS REPORT. THEY HAVE BEEN REPRODUCED HERE BY A DIFFERENT METHOD TO PROVIDE BETTER DETAIL