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RECENT ADVANCES IN LIGHTWEIGHT, FILAMENT-WOUND COMPOSITE PRESSURE VESSEL TECHNOLOGY

by R. F. Lark
Lewis Research Center
Cleveland, Ohio 44135

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R. F. Lark

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A review of recent advances is presented for lightweight, high-performance composite pressure vessel technology that covers the areas of design concepts, fabrication procedures, applications, and performance of vessels subjected to single-cycle burst and cyclic fatigue loading. Filament-wound fiber/epoxy composite vessels were made from S-glass, graphite, and Kevlar 49 fibers and were equipped with both structural and nonstructural liners. Pressure vessel structural efficiencies were attained which represented weight savings, using different liners, of 40 to 60 percent over all-titanium pressure vessels. Significant findings in each area are summarized including data from current NASA-Lewis Research Center contractual and in-house programs.

INTRODUCTION

Filament-wound (FW) composite pressure vessels utilizing high strength-to-density and modulus-to-density ratio materials offer significant weight savings over conventional, all-metal pressure vessels for containment of high pressure gases and fluids. All-metal pressure vessels made from various stainless steel, aluminum, and titanium alloys are frequently used for containment of high pressure gases and fluids in aerospace applications where high structural efficiency is needed. The structural efficiencies of the all-metal pressure vessels range from 0.3 to 0.6×10^6 inches based on a pressure vessel performance factor (P_bV/W) where P_b is the burst pressure, V is the contained volume, and W is the vessel weight. FW composite pressure vessels are capable of yielding P_bV/W values ranging from 0.8 to 1.2×10^6 inches when made using advanced fiber/resin composites and equipped with metallic liners. FW composite pressure vessels can therefore provide greater structural efficiencies (hence lower weight) than all-metallic pressure vessels of similar volume and pressure rating.

The objective of this paper is to provide a summary of the advances in lightweight

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FW composite pressure vessel technology and to invite attention to the significant weight saving advantages that can be attained by using the composite overwrap/liner design approaches that are described. Programs for the development of materials and design technology for lightweight FW composite pressure vessels that have been sponsored primarily by the NASA-Lewis Research Center are summarized. Various designs utilizing combinations of the advanced fiber and epoxy resin matrices with elastomeric and metallic liners are compared with each other and with all-metal pressure vessels. Throughout, there is an added emphasis on recently-developed FW composite pressure vessels made from high modulus, high strength organic (Kevlar 49) and graphite fibers, improved epoxy resins, and thin, lightweight metallic liners. This paper is divided primarily into two major sections. The first section deals with a review of lightweight composite pressure vessel technology developed before mid-1973 (References [1] and [2]. The second section deals with recent (since mid-1973) advances in thin-lined composite pressure vessel technology.

GENERAL DESIGN CONSIDERATIONS

FW composite pressure vessels for high performance applications are designed to load the fibers in the composite overwrap to high stress levels (ranging from 60 to 70 percent of fiber ultimate strength). High fiber stress levels result in significant elongations of the composite (0.5 to 2.0 percent) and extensive crazing or cracking of the resin matrix between the fibers. Resin crazing generally becomes significant at a composite stress (between about 10 to 40 percent of ultimate fiber strength) which is considerably lower than the operating stress of high performance FW composite pressure vessels. The resin matrix craze paths can join to provide a leak path shown schematically in Figure 1, and an internal liner must then be provided to prevent leakage of the contained fluid or gas. The liner must be both chemically compatible with and impermeable to the contained fluid. Furthermore, the liner must be capable of straining or elongating with the composite during pressurization and of returning to a stable and nonbuckled position after pressure is reduced in the vessel. Conventional low-pressure FW composite piping and pressure vessels generally operate at fiber stress levels of 10 percent or less of fiber ultimate strengths. Such low pressure structures do not need to be equipped with special liners because of the resultant low elongation levels. A resin-rich gel coat applied to the internal surface of the composite pipe or vessel serves as an impermeable liner to contain fluid or gas.

Elastomers such as butyl rubber are currently being used as liners for FW composite pressure vessels subjected to moderate temperatures and pressures. Elastomers are inadequate, however, at cryogenic temperatures and/or high pressures. At cryogenic temperatures, elastomers exhibit brittle behavior and cannot strain with the composite overwrap without cracking. At high pressures, all of the commercially-available elastomers exhibit high degrees of permeability to gases. High pressure gases can also be absorbed by elastomeric materials and cause severe blistering of the liners as the absorbed gases are released during vessel depressurization.

As indicated above, an ideal liner material must be impermeable to the contained fluid or gas. In addition, to achieve the desired cycle life capabilities, it is necessary to match the strain capabilities of the liner to that of the composite overwrap. The strain capabilities of typical composite overwrap and liner materials are listed in Table 1. Elastomers have the highest strain capabilities at moderate temperatures and can strain as much as 700 percent at 75° F. However, elastomers have virtually no strain capability at cryogenic temperatures such as the temperature of liquid hydrogen (-423° F). Metals have an elastic strain capability that is a small fraction of the strain capability of S-glass/epoxy composites, but have a high plastic strain capability over a wide range of temperatures. This effect is shown schematically in Figure 2. Very significant differences in Young's moduli exist between metals and S-glass/epoxy composites. For example, steel alloys have a modulus of about 30×10^6 psi and titanium alloys about 16×10^6 psi. The corresponding modulus of S-glass/epoxy composites is about 8×10^6 psi. Furthermore, the design problems associated with differences in moduli (and strain capabilities) are compounded by the fact that the S-glass/epoxy composite strain is essentially elastic while only a small portion of the metal strain is elastic.

Due to the limited extensibility of elastomeric materials at low temperatures and their high permeability to gases at high pressures, the FW composite pressure vessel technology programs at the NASA-Lewis Research Center were directed primarily toward the development of vessels equipped with metallic liners. The use of metallic liners in composite pressure vessels requires that the mismatch in strain capabilities of the composite and liner materials be compensated for by allowing the metal liner and composite materials to operate at their respective best strain conditions, as dictated by design service life and safety factor requirements.

Two different liner design approaches have been developed from the composite overwrapped pressure vessel technology programs, namely, the thin-liner and the load-bearing (or load-sharing) liner concepts. The thin-liner concept utilizes the high strength composite overwrap as the primary load carrying element of the structure. A metal liner of minimum thickness and weight is used as a leakage barrier. In this concept, the liner contributes negligible weight and load carrying capability. In the load-bearing liner concept, both the liner and the composite overwrap share the internal pressure loads. The liner in this concept must be made from a structurally efficient material since its weight is a significant part of the total composite pressure vessel weight. Details of these composite pressure vessel combinations are discussed as follows.

Thin-Metal Lined Composite Pressure Vessels

In order to minimize the weight of a FW composite pressure vessel structurally efficient composite overwrap materials must be used. Commercially-available elastomeric-lined composite pressure vessels are currently in use for medium pressure service in aircraft and other weight-critical applications. The composite overwrap is the sole structural element and the elastomeric liner serves only as a leakage barrier. In applications where a lightweight vessel design is desired and elastomeric liners are unacceptable (cryogenic temperature and/or high pressure gas service) a lightweight metal liner must be selected. The choice of a suitable metallic liner material is difficult in cases where the vessel must be designed for a high cyclic life, particularly for FW glass fiber/epoxy composite vessels. The thin-metal liners are subjected to severe plastic straining during pressure cycling, as shown in Figure 3. The liner must be capable of withstanding both high plastic tensile and compressive strains while providing a reasonable cyclic life. Because the liner is forced into compression upon depressurization of the vessel, the liner must be well-bonded to the inside wall of the composite overwrap in order to prevent the formation of wrinkles and disbonded areas which can result in leakage during subsequent pressure cycles. In addition, the liner materials must have the capability of being readily processed and welded into impermeable liner assemblies.

The inherently fragile nature of thin-metal liners requires that the liners be supported during the filament-winding process to prevent liner distortion. This is typically accomplished by casting an expendable, wash-out type mandrel material, such as plaster or inorganic salts inside the liner, and by providing suitable winding shafts for attachment to the filament-winding machine. The mandrel is removed by flushing with hot water or weak acids after the composite overwrap is wound and cured. An alternate method for supporting the thin liner involves the use of hydraulic oil or gaseous pressure stabilization during the winding and curing processes.

The thin-metal lined composite pressure vessel concept has been extensively evaluated in NASA-Lewis Research Center programs. In general, the results and success of these programs have depended greatly upon the selection of suitable composite overwrap and liner materials. Ideally, the composite overwrap should be made from lightweight, high modulus fibers and the liners should be made from low to medium-modulus, high-yield strength (high elastic strain capability) metal foils. The strength-to-density versus the modulus-to-density ratios for a number of the advanced fibers are shown in Figure 4. Also shown are typical values for two metals used for construction of high-performance metallic pressure vessels. The advanced fibers have significantly higher modulus-to-density ratios than do S-glass fibers and have generally provided the best approach for fabrication of lightweight, high cyclic life, thin-metal lined composite pressure vessels.

Composite Pressure Vessels with Load-Bearing Liners

During the development of thin-lined composite pressure vessels, another concept was developed and indicated a high potential for achieving a near-term solution to construction of reliable, lightweight, high cyclic life composite pressure vessels. This concept, originally developed by Johns and Kaufman (Reference [3]) is referred to as the composite pressure vessel with load-bearing (or load sharing) liner concept. This concept utilizes a relatively thick metal liner to contain the pressurized fluid or gas and to support from one-third to one-half of the internal pressure load of the vessel. The remainder of the load is carried by the composite overwrap. During the initial (proof) pressure cycle of the vessel, the metal liner is plastically strained while the composite overwrap is strained elastically (Figure 5). Upon release of the internal pressure, the liner, which has now been subjected to a permanent set, is forced into compression by the composite overwrap trying to return to its original, unstrained, condition. Since this initial (proof) pressure cycle plastically deforms or "sizes" the liner, it is referred to as the "sizing" cycle. Subsequent cycles at operating pressure (lower than the sizing cycle pressure) result in loads that can be carried within the elastic capabilities of both the composite overwrap and the liner materials.

The overwrapped load-bearing liner concept has proven to be an efficient design for attainment of significant weight savings (40 percent) over the best all-titanium pressure vessel design used in aerospace applications. A Kevlar 49/epoxy composite pressure vessel equipped with a cryoformed 301 stainless steel load-bearing liner achieved a P_bV/W of 0.84×10^6 inches compared to 0.6×10^6 inches for a titanium pressure of similar shape, contained volume, and pressure rating (Reference [4]).

Load-bearing liner technology has matured more quickly than the thin metal lined composite pressure vessel technology and provides a near-term solution to a lightweight, reliable composite vessel design. However, the thin-metal lined composite pressure vessel concept provides a greater weight savings potential than does the load-bearing liner concept. The load-bearing lined composite vessel concept is currently utilized for high pressure gas containment vessels on the Shuttle Orbiter, escape chute inflation pressure vessels on some commercial aircraft, and for firefighters' and scuba divers' air breathing pressure vessels.

MAJOR RESULTS AND CONCLUSIONS OF COMPOSITE PRESSURE VESSEL RESEARCH TO MID-1973

In summary, the key results of the thin-lined composite pressure vessel technology are as follows:

1. A successful, high-cyclic-life, highly loaded, thin-metal lined glass/epoxy composite pressure vessel design had not been achieved due to the significant strain mismatch between the composite overwrap and the liner.
2. Stainless steel liners were not suitable due to difficulties in attaining reliable adhesive bonds to the composite overwrap.
3. Aluminum appeared to have a good potential for providing low-cost, medium-cycle-life liners when used with high strength, high-modulus fiber/resin composites.
4. Feasibility had been established for constructing pressure vessels from Kevlar 49 and graphite/epoxy composites. These were significantly lighter than all-titanium pressure vessels of comparable design.
5. Kevlar 49/epoxy composite pressure vessels were 40 percent lighter and stiffer by a factor of 2 than S-glass/epoxy composite pressure vessels of similar design. Kevlar 49/epoxy composites could provide a lightweight, medium cycle life vessel design due to a good strain match with thin aluminum or high yield strength metal liners.
6. Average composite hoop strains of Thornel 400 graphite/epoxy composite pressure vessel ranged from 0.9 to 1.1 percent and were less by a factor of 3 than hoop strains in S-glass/epoxy composite vessels (at similar stress levels). Reduced strain in the composite overwrap could provide more favorable strain matching conditions with thin-metallic liners and would be expected to result in a higher cycle life design.

RECENT ADVANCES IN THIN-LINED FW COMPOSITE PRESSURE VESSEL TECHNOLOGY

The thin-lined composite pressure vessel technology that is summarized below covers the work done in the past 4 years and is taken from both available literature and some unpublished in-house work. Composite overwrap and liner combinations that were evaluated are shown in Table 2.

Properties of Kevlar 49/Epoxy Composite Strands

A recently developed high-strength, high-modulus organic fiber, Kevlar 49, has the highest strength-to-density ratio of any known material (Figure 4). The combination of high strength and stiffness, and low density of this fiber indicated its use has a high potential for lightweight FW composite pressure vessels. Kevlar 49 was originally evaluated in two exploratory composite pressure vessel programs for NASA by The Boeing Company. The results of these programs are described in References [2] and [3], as indicated in a previous section of this paper, and feasibility was established for making high performance FW composite pressure vessels from Kevlar 49 fibers.

A more extensive evaluation of this fiber for FW composite pressure vessels was conducted by the Lawrence Livermore Laboratory (LLL) under NASA/ERDA Interagency Agreement C-13980-C. This program commenced with a detailed study of the mechanical properties of Kevlar 49 using fiber/epoxy composite strand specimens. The Kevlar 49 fiber mechanical strength properties are shown in Table 3. The Kevlar 49/epoxy composite mechanical strength properties were determined by testing epoxy resin-impregnated strands having a gage length of 10 inches. Individual strands were bonded to metallic clamps using a room-temperature cure epoxy. Tensile strength tests were conducted using a conventional test machine. The apparatus for the sustained load tests is shown schematically in Figure 6.

Because of the large number of tests involved, the data for the strand tests were presented on probability plots. The abscissa was arbitrarily normalized to the median value in each case. The fiber strength distribution is shown in Figure 7. Strand tensile strength properties are summarized in Table 4. Typical stress-strain curves of strand and bare epoxy resin specimens are shown in Figure 8. The strand specimens were also subjected to sustained loading (creep rupture) tests at: 90, 87, 84, 80, 70, 60, and 50 percent of the average ultimate strength. The test results at the four higher levels are given in Figures 9 and 10. There is no agreement on whether simple sustained-load strand data can be applied directly to the design of FW composite structures. It is believed, however, that strand data can serve as a basis for material selection. A comparison of the sustained-loading properties of Kevlar 49/epoxy versus S-glass/epoxy strands is shown in Figure 11. The sustained-loading data on the S-glass/epoxy strands was conducted by LLL under an ERDA-supported program.

The sustained-loading behavior of the Kevlar 49/epoxy system is superior to the S-glass/epoxy system. A Kevlar 49/epoxy strand can be loaded at a higher percentage of its ultimate strength than an S-glass/epoxy strand for the same time to failure. The rate of degradation under load of a Kevlar 49/epoxy strand is about one-half that of an S-glass/epoxy strand. The data suggest that Kevlar 49 is currently the best material for fabrication of many composite structures as well as pressure vessels in tensile and weight-critical applications because of the high strength and modulus and low-density properties of this fiber.

4-Inch Diameter FW Kevlar 49/Epoxy Composite Pressure Vessels

This program was conducted by LLL under a NASA/ERDA Interagency Agreement to develop design data for Kevlar 49/epoxy composite pressure vessels. The effect of the following variables on vessel performance was studied: length-to-diameter ratio (L/D), boss-to-diameter ratio (d/D), and shape of the closed ends of the vessels or "dome contours." The dome contours can be either hemispherical or other shapes which are dependent primarily upon the filament winding process employed. For the process dependent contours, the dome geometry is dictated by minimizing arc length and buildup of filaments during winding. Four-inch diameter, cylindrical composite pressure vessels were fabricated as follows using an in-plane filament-winding wrap process:

1. In-plane wrapped (filament winding process) dome contour with L/D ratios of 1.37, 2.0, and 3.0.
2. In-plane wrapped dome contour, a constant L/D, and d/D ratios of 0.104, 0.166, and 0.234.

3. A constant d/D of 0.104, L of 4 inches, and in-plane wrapped, helical wrapped (filament winding process), and hemispherically shaped dome contours.

These vessels are shown in Figure 12. The dimensions for the vessel with an L/D of 1.37 are shown in Figure 13. All vessels were filament-wound using a numerically controlled filament-winding machine. The fibers were epoxy resin-impregnated while passing through a vacuum chamber controlled to about 5 mm Hg. The fibers were wound directly over a 0.1-inch thick elastomeric liner supported on a wash-out type plaster mandrel.

Single-cycle burst tests were conducted using hydraulic fluid pressurization. The vessels were instrumented with strain gages to determine hoop and longitudinal strains. All of the test results are shown in Table 5. The effects of varying the L/D ratio are shown in Table 5 in columns 1, 2, and 3. No statistically significant effects at the 0.05 probability level were observed for L/D ratios up to 3.0. A larger L should result in an increased P_b due to the reduced polar angle (hence an improved structural efficiency) for a given vessel diameter D with a fixed boss diameter d. The investigators believed that this gain may be offset, in practice, by the large variation of longitudinal fiber tension on the cylindrical section of the mandrel when using an in-plane filament-winding technique. The effects of the d/D ratio on vessel performance are shown in columns 1, 4, and 5 of Table 5. No significant differences were noted in vessel performance over a 10- to 23-percent difference in d/D ratio range. The effect of varying the dome contours on structural efficiency (P_bV/W) is shown in columns 4, 6, and 7 of Table 5. The in-plane dome contour was the most efficient followed closely by the helical dome contour. The hemispherical dome contour was previously predicted to be inefficient for glass/epoxy vessels. This has been verified by limited testing in this program.

The investigators optimized the vessel design by identifying and reinforcing areas where the fibers were highly stressed in exploratory work prior to initiating the 4-inch diameter vessel program. Internal pressurization and thermal expansion techniques were used to effect minute deformations in the vessel. These deformations were located and quantified by means of holographic interferometry techniques and analytical methods (Reference [5]). This NDE technique identified the locations of highly stressed fibers near the knuckle area (transition between the cylindrical and dome sections of a vessel). This area was subsequently reinforced locally with Kevlar 49/epoxy composite material. A retest of the modified vessel design showed that structural efficiency was improved about 10 percent.

In this program, it was demonstrated that a well-designed FW Kevlar 49/epoxy composite pressure vessel can exhibit hoop fiber stress values of about 450 ksi. This stress value is significantly higher than can be obtained for most of the other advanced high modulus fibers used for filament-winding of composite pressure vessels. High fiber stress values in combination with the low fiber density of Kevlar 49/epoxy results in high composite pressure vessel structural efficiencies. The winding pattern and fabrication process (e.g., winding tension, cure cycle, and resin selection), in general, are considered key factors affecting quality and consistency of highly structural efficient FW vessels. Cylindrical composite pressure vessel performance is optimized by the use of: in-plane band winding (reduces composite buildup at the bosses), in-plane dome contour, d/D less than 0.1, L/D less than 3, hoop/longitudinal fiber ratio about 1.81, and addition of local composite reinforcement at the knuckles of the vessels.

8-Inch Diameter KW Kevlar 49/Epoxy Composite Pressure Vessels

Further work was conducted by LLL in the same program to determine the effect of size scale-up on composite pressure vessel performance, to compare the structural efficiencies of cylindrical and spherical shaped vessels, and to conduct exploratory vessel tests at -423° F. The same batch of Kevlar 49 fiber used for the strand and 4-inch diameter vessel studies was also used to fabricate the 8-inch diameter composite vessels. Both room temperature cure and elevated temperature epoxy matrix resins were used to fabricate the vessels. The cylindrical vessel was designed as follows: L/D of 1.65, d/D of 0.11, in-plane dome contour, reinforced knuckles, and a hoop/longitudinal fiber ratio of 1.7. The cylindrical vessels were equipped with either thin aluminum or elastomeric liners. The cylindrical and spherical vessels were designed to have burst pressures of 2000 and 5000 psi, respectively. All of the spherical vessels were equipped with thin aluminum liners. The liner and mandrel designs for the cylindrical and spherical vessels are shown in Figures 14 and 15. The cylindrical vessels were filament-wound using a numerically controlled filament-winding machine. The spheres were wound on a custom-made horizontal filament-winding machine. Details of the special wide-band, multiangle spherical winding pattern and winding procedure may be obtained from Reference [6].

Single-cycle burst and cyclic testing of the cylindrical and spherical vessels was conducted at room temperature and at -423° F. The cylindrical and spherical vessels were cycled to failure at 70 and 67 percent of their measured burst pressures or 1400 and 4200 psi, respectively. Cylindrical vessel test results are shown in Tables 6, 7, and 9, and spherical vessel test results are shown in Tables 8 and 9. The cyclic fatigue tests of the cylindrical vessels equipped with 1100-type aluminum liners resulted in about 550 cycles prior to leakage. The data indicated that the vessels failed by liner leakage. Epoxy resin type showed no appreciable effect on vessel performance as indicated by the test results of vessel P-148 in Table 6. This vessel was made using an elevated cure epoxy while the remainder of the vessels were made using a room temperature cure epoxy resin. The investigators have recommended, however, that room temperature cure epoxies be used since they have observed delamination problems when Kevlar 49/epoxy vessels were cured at 250° F (without allowing resin gelation before tank curing). It was believed that the delaminations were caused by high residual stresses in the overwrap as a result of the elevated temperature cure. This problem was also observed in an exploratory Kevlar 49/epoxy composite pressure vessel (Reference [2]) in which a thin steel liner microbuckled during the curing of the epoxy matrix resin at elevated temperatures (e.g., 300° F).

The following major findings resulted from the 8-inch diameter Kevlar 49/epoxy composite pressure vessel study:

1. In testing to optimize the performance of the composite overwrap, the best P_bV/W obtained was 1.81×10^6 inches (overwrap alone) for a spherical vessel equipped with a 0.030-inch thick aluminum liner. This should result in a total P_bV/W on the order of 1.2×10^6 inches for thin aluminum-lined vessels.
2. The effect of a -423° F test temperature was negligible when compared to vessel performance at room temperature.
3. Vessels equipped with 1100-type aluminum liners yielded a cyclic life of about 550 cycles prior to failure by liner leakage.

4. It is believed that a room temperature cure epoxy system is preferable to an elevated temperature cure epoxy since low cure temperatures result in lower composite residual stresses.

5. Cylindrical and spherical shaped Kevlar 49/epoxy composite pressure vessels have essentially the same structural efficiencies. Any experimental differences that may be noted between vessel shapes are a result of design and/or fabrication factors such as an inefficient winding pattern, low fiber volume content, and nonuniform control of fiber tension during filament-winding.

4-Inch Diameter Thornel-Special Graphite/Epoxy Composite Pressure Vessels

The structural efficiencies and cyclic life of 4-inch diameter, cylindrical composite pressure vessels made by using a high-strength, high-modulus graphite fiber/epoxy composite overwrap in combination with a thin, high yield strength titanium (6Al-4V) liner were also studied in the NASA/ERDA program at LLL and reported in Reference [7].

The vessel liners were machined from solid round stock to form liner half-shells. The bosses were machined integrally with the liners. The thickness of the liners in the cylindrical section was 0.020 inch. The liner half-shells were joined by one electron beam (EB) girth weld.

These vessels were subjected to single-cycle burst and cyclic fatigue tests. The P_bV/W values for the vessels averaged about 0.6×10^6 inches and the cyclic life averaged about 2500 cycles when pressurized to 50 percent of the average burst pressure. The vessels failed by liner leakage due to cracking in the weld areas during cyclic tests.

Because of the relatively low structural efficiencies attained for the vessels equipped with 0.020-inch thick titanium liners, additional work was done by LLL to design, fabricate, and test composite pressure vessels equipped with 0.010-inch thick titanium liners (Reference [8]). The specific objectives of this additional work were to improve the P_bV/W values to a minimum of 0.9×10^6 inches and to determine the cyclic fatigue life of composite pressure vessels equipped with ultra-thin titanium liners.

The 0.010-inch thick titanium liners were made by hot-forming circular blanks, cut from 0.6-inch thick titanium (6Al-4V) plate, into half-shells. The half-shells were machined, vacuum annealed and then joined by an EB girth weld. The dimensions of the liner are shown in Figure 16.

The same type of graphite fiber (Thornel-Special) used for the 0.020-inch thick titanium lined composite pressure vessel study was also used for the 0.010-inch thick lined vessels. The average fiber properties of Thornel-Special graphite fiber are: a mean fiber stress at fracture of 517 ksi, a failure strain of 1.7 percent, and a tensile modulus of 30×10^6 psi. Vessel design and fabrication details are given in Reference [8].

The vessels were subjected to single-cycle burst or cyclic fatigue testing at 50 percent of their average burst pressure. The vessel liners were examined after three of the first four burst test attempts resulted in liner leakage before rupture occurred. It was determined that leaks were caused by stress concentrations at the boss-to-liner transition. The interiors of the vessel liners at the boss-to-liner transition areas were then coated with a sealing compound and the vessels were retested for burst strength and cyclic life. The test results for this initial design set (set one) of vessels are shown in Table 10. The initial fatigue tests showed that the weld areas of the vessel liners were capable of at least 2000 cycles prior to weld cracking.

The remaining vessel liners of the initial design (boss-to-liner transition problem) were internally coated at the transition area and were then used to sequentially fabricate and test vessels to develop an optimum winding pattern and the lower bounds on weldment fatigue life. Test results for this set of vessels (set two) are shown in Tables 11 and 12. Finally, tanks with optimized winding patterns and a modified design liner were fabricated (as described in Reference [8]). The basic difference in the redesigned liner and the initial design was a more gradual transition from the boss to liner thickness as shown on the dome coordinates listed in Figure 16. These vessels were then subjected to single-cycle burst and fatigue tests. The results for this set of vessels (set three) are shown in Table 13.

In vessel sets one and two (liners with the stress concentration problem), all of the vessels subjected to cyclic fatigue tests, except one, exhibited low cyclic lives because the weld cracks in the transition zones propagated beyond the coated areas. The exception was a vessel that exhibited a crack in the weld area. All of the vessels in the third set (redesigned liners with optimized winding patterns) failed by leakage in the weld and no problems were experienced in the transition areas.

The mean P_bV/W (based on total vessel weight) of 0.97×10^6 inches, from Table 11, is a significant achievement for small diameter composite vessels. Particularly for vessels having bosses whose combined weight totals about 7 percent of total vessel weight. This pressure vessel performance factor is significantly higher than the best value attained for an optimized composite vessel equipped with a load-bearing liner (cryoformed stainless 301/Kevlar 49 tank from Reference [4], having a P_bV/W of 0.84×10^6 inches). The mean P_bV/W value of the vessels listed in Table 11 are about 15 percent higher than the above vessels equipped with load-bearing liners. The redesigned titanium vessel liner for the 4-inch diameter graphite/epoxy composite vessels solved the problem of stress concentration failures in the transition areas. Metallographic examinations of the liner cross sections showed that the liners that were precision fitted and welded exhibited the best fatigue lives.

The following major results and conclusions may be drawn from the results of the 4-inch diameter, Thornel-Special graphite/epoxy composite vessel study:

1. 0.010-inch thick titanium liners can be successfully made by machining hot-formed plate stock.
2. Thornel-Special graphite composite vessels equipped with precision fitted and welded 0.010-inch thick titanium liners can attain high structural efficiencies and high cyclic lives. The data indicate that fatigue lives in excess of 3000 cycles are obtainable for 4-inch diameter composite pressure vessels cycled at 50 percent of their average burst strength.
3. The optimum composite overwrap/liner combination studied in this program can meet a 2000 cycle life design originally provided as a NASA guideline for potential Space Shuttle pressure vessel applications.

Matrix Resin Study to Determine Effects on Vessel Performance

The structural efficiencies of FW Kevlar 49/epoxy composite pressure vessels were significantly affected by the types of epoxy resins used during the early development of lightweight, Kevlar 49/epoxy rocket motor cases. In the above program, FW composite vessels made of the highly extensible and low modulus epoxy resins exhibited higher P_bV/W values than vessels made of conventional, high modulus epoxy resins. However, developmental work was terminated since rocket motor cases must have higher transverse and shear strength properties than exhibited by composites made from the highly extensible resins. Because of the potential of the highly extensible epoxy resins for construction of lightweight composite vessels (an application where the composite structure is not subjected to high transverse and shear loading) an exploratory NASA-Lewis Research Center in-house program was conducted to evaluate the effects of epoxy resins on the performance of lightweight FW composite pressure vessels.

Elastomer-lined FW composite pressure vessels were fabricated by Hercules, Inc. in accordance with NASA specifications given under NASA Contract NAS 3-20244. Six-inch diameter by 14-inch long cylindrical composite vessels were made of AS-type graphite and Kevlar 49 fibers, each with three different epoxy resins. All of the vessels were designed to have a longitudinal-to-hoop wrap stress ratio of 1.0 and a nominal burst pressure of 4500 psi. Other design features included an L/D ratio of 2.5, and a d/D ratio of 0.38. The properties of the epoxy resins used are listed in Table 14. The vessels were constructed by filament-winding a longitudinal helical and a hoop wrap pattern over a three-piece reuseable aluminum mandrel. Details of the aluminum mandrel are shown in Figure 17. One-half of the vessels in the program were reinforced in the dome area with epoxy-impregnated glass cloth plies. The remaining vessels were constructed without the use of dome reinforcement cloth plies. This was done to evaluate the combined effect of resin type and local dome reinforcement on vessel performance. Details of the dome reinforcement cloth plies are shown in Figure 18. The vessel mandrels were covered with an elastomeric liner before winding. The liner seams were bonded together and to two aluminum vessel bosses to provide a leak-free liner/boss assembly. An adhesive was also applied to the liner exterior surfaces to promote adhesion of the liner to the composite overwrap. After completion of filament-winding, the composite overwrap was cured in accordance with the cure cycle listed in Table 15. A passageway for hydraulic fluid was provided between the joints of the three-piece aluminum mandrel to effect pressurization of the vessel/liner assembly during tests.

The vessels were subjected to single-cycle burst strength tests using hydraulic pressurization at an 8000 psi per minute rate. Typical views of the tested graphite/epoxy and Kevlar 49/epoxy composite vessels are shown in Figures 19 and 20, respectively. The average P_bV/W values along with other vessel properties are listed in Table 16. Comparisons of the average P_bV/W values attained for the three resins are shown in Figure 21.

Kevlar 49/epoxy composite vessels made of the HBRF-89 epoxy resin showed the highest P_bV/W and burst pressure values, followed by the HBRF-55A and HBRF-30 epoxy resins. However, the effect of epoxy matrix resin type on the performance of graphite/epoxy composite vessels was not as evident. The effect of dome reinforcement was significant for one of three resins used in the graphite vessels and was not significant for the resins used in the Kevlar 49 vessels.

The following major results and conclusions resulted from this program:

1. Kevlar 49 vessels made with the HBRF-89 resin can show as much as a 35-percent increase in structural efficiency over Kevlar 49 vessels made from the conventional high modulus epoxy resin studied (HBRF-30).

2. None of the three resins studied has a significant effect on the performance of graphite composite pressure vessels.

3. Dome reinforcement results in some improvement of vessel efficiencies for graphite/epoxy composite vessels made with the HBRF-55A and HBRF-30 resins.

Further work with Kevlar 49 composite pressure vessels made with highly extensible resins is warranted and, in particular, the effect of epoxy resin matrix type on fatigue properties should be evaluated.

OVERALL SUMMARY OF KEY RESULTS AND CONCLUSIONS OF WORK IN THE AREA OF LIGHTWEIGHT FILAMENT-WOUND COMPOSITE PRESSURE VESSEL TECHNOLOGY

1. Based on strand data sustained loading behavior of Kevlar 49/epoxy composites is superior to S-glass/epoxy composites. The rate of strength degradation of the Kevlar 49/epoxy composites is about one-half that of the S-glass/epoxy composites under sustained loading.

2. Kevlar 49/epoxy composite pressure vessels fabricated with in-plane winding pattern dome contours are more efficient than helical winding pattern dome contours. A hemispherical shaped dome contour is structurally inefficient.

3. The shape of a Kevlar 49/epoxy composite vessel (cylindrical or spherical) has very little effect on vessel structural efficiency.

4. A P_bV/W (composite overwrap alone) value of 1.81×10^6 inches was attained for a spherical Kevlar 49/epoxy vessel equipped with a 0.030-inch thick aluminum liner. This should result in a total vessel performance on the order of 1.2×10^6 inches for a thin aluminum lined composite pressure vessel.

5. 0.010-inch thick titanium liners can be successfully made by machining hot-formed plate stock.

6. 4-inch diameter, cylindrical, Thornel-Special graphite/epoxy composite pressure vessels equipped with 0.010-inch thick titanium liners can attain fatigue lives in excess of 3000 cycles when pressurized to 50 percent of the average burst strength (6900 psi). The mean P_bV/W attained for these vessels was 0.97×10^6 inches.

7. The use of highly extensible epoxy resins in Kevlar 49/epoxy composite pressure vessels can show as much as a 35-percent increase in P_bV/W over vessels made with conventional high modulus epoxy resins.

8. Based on the findings of the programs reviewed in this paper, FW composite pressure vessels made from a Thornel-Special graphite/epoxy composite overwrap and a thin titanium liner should provide the lowest weight and highest cyclic life. Kevlar 49/epoxy (extensible) composite pressure vessels equipped with thin aluminum liners should provide almost a comparable weight, a medium cycle life, but at a lower cost.

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[7]. M. A. Hamstad, T. T. Chiao, and R. G. Patterson, "Fatigue Performance of Metal Lined Graphite/Epoxy Pressure Vessels," Composites, Vol. 6, pp. 249-253, 1975.

[8]. M. A. Hamstad and T. T. Chiao, "Graphite/Epoxy Pressure Vessels Lined With Ultra-Thin Titanium," presented at the Proceedings of the 22nd National SAMPE Symposium/Exhibition, San Diego, Calif., Apr. 26-28, 1977.

Table 1. Extensibility of Vessel and Liner Materials

Materials	Maximum elastic strain, per cent[a]	
	Test temperature	
	75° F	-423° F
S-glass epoxy	3.5	3.8
Kevlar 49/epoxy	2.5	N/A
Thornel-Special graphite/epoxy	1.7	N/A
Thornel 400 graphite/epoxy	1.6	N/A
Elastomers	700	0
Aluminum (maximum elastic strain)	.07	.1
Titanium (6Al-4V), annealed (maximum elastic strain)	.6	N/A

[a] Based on fracture strain.

Table 2. Matrix of Composite Overwrap and Liner Material Combinations Reported

Composite overwrap	Liner materials		
	Elastomeric	Aluminum	Titanium
Kevlar 49/epoxy	X	X	--
Thornel-Special graphite/epoxy	--	--	X
AS-type graphite/epoxy	X	--	--

Table 3. Kevlar 49 Fiber Properties[a]

Property	Value
Tensile strength	400 ksi, (min)
Elongation	2.0 percent
Tensile modulus	19×10^6 psi
Density	0.052 lb/in^3
Moisture regain	1.5 percent
Filament diameter	4.6×10^{-4} in.
Number of filaments/yarn	285

[a] Yarn twist of about 0.01 turn/inch.

Table 4. Kevlar 49/Epoxy Composite Strand Tensile Strength[a]

	Stress	Strain	Modulus
Average	506 ksi	2.40 percent	20.7×10^6 psi
Median	510 ksi	2.42 percent	20.7×10^6 psi
Standard deviation	33 ksi	0.16 percent	0.75×10^6 psi
Coefficient of variation, percent	6.5	6.7	3.3
Number of tests	363	363	363

[a] Based on samples from 37 spools.

Table 5. Test Results of Rubber-Lined 4-Inch Diameter Kevlar 49/Epoxy Composite Pressure Vessels

	Control[a]	L/D ratios		d/D ratios		Dome contours	
	1	2	3	4	5	6	[b]7
Vessel design							
Dome contour	In-plane	In-plane	In-plane	In-plane	In-plane	Helical	Hemispherical
Boss/diameter, d/D	0.23	0.23	0.23	0.10	0.17	0.10	0.10
Length/diameter, L/D	1.38	2.00	3.00	1.38	1.38	1.38	1.38
Single-cycle burst pressure,[c] P_b							
Mean, psi	2700	2570	2490	2690	2770	2490	880
Failure location[d]	17H+4F	8H+1K	3H+2K	9H	7H+1K	5H+4K	1H (equator)
Composite modulus at failure $\times 10^6$ psi							
Longitudinal	4.8	4.9	5.2	5.0	5.0	5.0	5.0
Hoop	8.2	7.8	8.6	8.4	8.4	8.2	7.5
Rupture strain, %							
Axial	1.7	1.6	1.5	1.7	1.7	1.5	0.5
Hoop	2.0	2.0	1.8	2.0	2.0	1.9	0.7
Weight of composite, lb	0.10	0.15	0.22	0.10	0.10	0.10	0.11
Volume of vessels, in^3	57.91	86.65	134.25	56.61	56.63	57.30	68.35
P_bV/W, 10^6 inches, composite, mean	1.56	1.49	1.52	1.52	1.57	1.43	0.55
Fiber content, by volume, %	67.8	66.7	69.1	68.0	66.7	65.9	66.3
Density, lb/in^3	0.0497	0.0498	0.0499	0.0499	0.0500	0.0496	0.0499
Vessel thickness, inch	0.033	0.033	0.032	0.032	0.032	0.032	0.032
Longitudinal winding	0.013	0.014	0.012	0.012	0.012	0.012	0.014
Hoop winding	0.020	0.019	0.020	0.020	0.020	0.020	0.018
Calculated fiber hoop failure stress, ksi, mean	427	419	416	433	443	400	131

[a] Standard 4-inch diameter model vessels.

[b] One vessel only.

[c] Tested at ambient temperature.

[d] Nominal failure locations are: (1) H for hoop, K for knuckle, and F for fitting; thus 2H and 1K indicate two vessels failed in hoop and one in knuckle. Note - the number preceding the letter indicates the number of vessels tested.

Table 6. Test Results of Cylindrical Rubber-Lined[a] 8-Inch Diameter Kevlar 49/Epoxy Composite Pressure Vessels

[Test temperature, 70° F.]

Vessel test results											
Vessel number	P-142	P-144	P-148	P-151	P-152	P-153	P-156	P-157	P-158	P-159	P-160
Volume, in^3	← 566 →										
Single-cycle burst pressure, ksi	2.06	2.05	2.24	2.06	1.89	1.88	2.27	2.17	2.04	1.90	2.13
Failure location[b]	H	F	F	F	K + F	F	F	F	F	F	F
P_bV/W, 10^6 inches, composite	1.44	1.49	1.46	1.51	1.29	1.27	1.61	1.54	1.37	1.28	1.51
Composite data											
Wall thickness, in.	0.055	0.057	0.055	0.053	0.053	0.054	0.053	0.053	0.053	0.053	0.053
Longitudinal wrap	0.022	0.022	0.021	0.020	0.020	0.021	0.020	0.020	0.019	0.020	0.020
Hoop wrap	0.033	0.035	0.034	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
Weight, lb	0.81	0.78	0.87	0.77	0.83	0.84	0.80	0.80	0.84	0.84	0.80
Fiber content, vol.%	69.4	72.4	65.8	75.0	67.3	70.1	71.6	72.4	67.8	69.2	73.8
Calculated fiber stress, ksi											
Hoop	358	353	387	366	327	324	392	366	353	328	367
Axial	321	319	349	321	294	292	354	337	318	296	331

[a] 0.020-inch thick liner.

[b] H for hoop, K for knuckle, and F for fitting.

Table 7. Test Results of Cylindrical Aluminum-Lined[a] 8-Inch Diameter Kevlar 49/Epoxy Composite Pressure Vessels

[Test temperature, 70° F.]

Vessel test results						
Vessel number	P-143	P-145	P-147	P-149	P-177	P-180
Volume, in^3	← 566 →					
Single cycle burst pressure, psi	2.08	2.13	2.04	2.48	2.20	2.06
Failure location[b]	H	H	F	H	F	H
P_bV/W, 10^6 inches, composite	1.42	1.51	1.43	1.78	1.62	1.58
Composite data						
Total wall thickness, inch	0.058	0.056	0.057	0.054	0.055	0.054
Longitudinal wrap, inch	0.024	0.021	0.020	0.020	0.020	0.020
Hoop wrap, inch	0.034	0.035	0.037	0.034	0.035	0.034
Weight, lb	0.83	0.80	0.81	0.79	0.77	0.74
Fiber content, vol.%	76.5	69.9	68.6	70.3	71.3	69.7
Calculated fiber stress, ksi						
Hoop wrap	362	367	352	428	410	375
Axial	432	331	386	343	336	321

[a] 0.030-Inch thick liner.

[b] H for hoop, F for fitting.

Table 8. Test Results of Spherical 8-Inch Diameter Kevlar 49/Epoxy Composite Pressure Vessels

Vessel properties			
Liner	Aluminum (0.03 in.)	Aluminum (0.08 in.)	Rubber[a]
Boss type	Large double	Small single	Small single
Number of vessels	10	6	4
Volume, in^3	--	250	--
Composite wall thickness, in., at equator	0.087	0.081	0.085
Composite weight, lb	0.78	0.75	0.79
Fiber content, vol.%	69.9	67.9	68.1
Test data			
Single cycle burst pressure, mean, ksi	4.17	[b]5.65	5.14
P_bV/W, 10^6 inches, composite, mean	1.34	[c]1.66	1.63

[a] Rubber liner over perforated aluminum.

[b] Strength contribution of liner not considered in calculations.

[c] Data corrected for liner strength contribution.

Table 9. Test Results of Spherical and Cylindrical 8-Inch Diameter Kevlar 49/Epoxy Composite Pressure Vessels

[Tested at -423° F.]

Vessel number	P-154	P-155	0423	0434	0686
Vessel shape	Cylindrical	Cylindrical	Spherical	Spherical	Spherical
Aluminum liner thickness, in.	0.030	0.030	0.030	0.030	0.080
Volume, in^3	566	566	250	250	250
Composite wall thickness, in.	0.055	0.055	0.088	0.087	0.081
Composite weight, lb	0.80	0.80	0.74	0.81	0.76
Fiber content, vol.%	70.8	69.7	75.6	72.8	70.2
Single-cycle burst pressure, ksi	2.25	2.40	4.63	4.35	6.28
P_bV/W, 10^6 inches, composite	1.60	1.70	1.57	1.35	[a]2.06
Failure location[b]	H	H	I	I	I

[a] Not corrected for liner strength contribution.

[b] H for hoop, I for intermediate.

Table 10. Test Results (Set One) of Titanium-Lined 4-Inch Diameter Thornel-Special Graphite/Epoxy Composite Pressure Vessels

Vessel properties										
Number	2	5	6	7	8	9	10	11	12	A
Volume, in^3	← 58.74 →									
Weight of composite, lb	0.26	0.27	0.16	0.16	0.15	0.25	0.15	0.27	0.27	0.27
Total weight of vessel, lb	0.43	0.44	0.33	0.33	0.33	0.42	0.33	0.43	0.44	0.44
Fiber content, vol.%	67.3	63.4	68.6	65.2	67.3	66.6	68.4	63.8	63.5	63.2
Single-cycle burst pressure, ksi	6.71	6.96	4.44	4.98	4.43	(a)	----	5.95	6.54	(a)
P_bV/W, 10^6 inches, composite (overwrap only)	1.54	1.50	1.61	1.82	1.76	----	----	1.30	1.41	----
P_bV/W, 10^6 inches, total vessel	0.91	0.92	0.78	0.89	0.80	----	0	0.80	0.87	----
Failure location[b]	H	F	F	F	H	F	L	F	F	Weld

[a] Vessel 9 was cycled to 3400 psi for 3400 psi for 3400 cycles; vessel A was cycled at same pressure level for 4000 cycles.

[b] H for hoop, F for fitting, L for liner failure (leakage). All vessels were equipped with 0.010-inch thick titanium liners.

Table 11. Test Results for Optimized Winding Pattern (Set Two) for Cylindrical 4-Inch Diameter Titanium-Lined T-Special Graphite/Epoxy Composite Pressure Vessels

Vessel properties							
Number	13	14	15	16	17	18	Mean
Volume, in^3	← 58.74 →						----
Weight of composite, lb	0.24	0.23	0.23	0.23	0.23	0.23	0.23
Total weight of vessel, lb	0.40	0.39	0.38	0.39	0.38	0.38	0.39
Fiber content, vol.%	67.3	71.5	73.5	73.0	74.4	69.0	71.5
Test data							
Single-cycle burst pressure, ksi	6.84	7.30	7.30	6.73	7.10	6.06	6.89
P_bV/W, 10^6 inches, composite	1.54	1.75	1.76	1.60	1.72	1.44	1.63
P_bV/W, 10^6 inches, total vessel	0.94	1.03	1.04	0.94	1.01	0.86	0.97
Failure location[a]	F	F	F	F	F	H	----

[a] F for fitting, H for hoop.

Table 12. Cyclic Tests of Cylindrical 4-Inch Diameter Titanium-Lined, T-Special Graphite/Epoxy Composite Pressure Vessels - Optimized Winding Pattern[a] (Set Two)

Vessel number	Cyclic life,[b] cycles
T-19	3140
T-20	2020
T-21	3050
T-22	[c]1935
T-23	1935
T-24	3485
T-25	2720

[a] Vessels made identical to vessels T-13 to T-18.

[b] Vessels leaked due to propagation of end cracks beyond the coated region. Vessels were cycled from 1 to 50 percent of their average burst pressure.

[c] Minimum value, chart recorder malfunction.

Table 13. Tests of Cylindrical 4-Inch Diameter Titanium-Lined, T-Special Graphite/Epoxy Composite Pressure Vessels-Optimized Winding Pattern[a] and Modified Liner[b] (Set Three)

Vessel number	P_bV/W, 10^6 inches, total vessel	Cyclic life,[c] cycles
T-26	-----	8400
T-27	-----	1600
T-28	-----	1186
T-29	-----	1650
T-29	-----	1650
T-30	[d]0.95	----
T-31	-----	600
T-32	-----	402

[a] Composite overwrap same as vessels T-13 to T-18.

[b] The redesigned liner resulted in about a 5-percent increase in total vessel weight. All vessels except T-26 exhibited incomplete penetration of welds.

Table 14. Epoxy Resin Property Data

Property	Resin type		
	HBRF-89[a]	HBRF-55A[b]	HBRF-30[c]
Density, lb/in^3	0.0394	0.0437	0.0477
Ultimate strength, ksi	1.22	13.5	16.4
Ultimate elongation, percent	61.0	7.0	4.3
Initial modulus, proportional limit, 10^6 psi	0.02-0.05	0.45	0.61
Stress, ksi	N/A	8.0	7.0
Toughness, 10^3 in-lb/in^3	1.03	0.63	0.33
Water absorption, 28 days, percent	2.16	3.39	3.52
Heat distortion temperature, °F	77	246	N/A

[a] EA 953A (100 pbw)/EA 953B (15 pbw).
[b] 826 (100 pbw)/RD-2 (25 pbw)/Tonox 6040 (30 pbw).
[c] Gly-col-A-100 (100 pbw)/MDA (31.5 pbw).

Table 15. Epoxy Resin Cure Cycles

Epoxy resin type	Cure cycle
HBRF-89	4.5±0.25 hours at 200° F ± 15° F
HBRF-55A	2.5±0.25 hours at 200° F ± 15° F 4.0±0.25 hours at 300° F ± 15° F
HBRF-30	2.0±0.25 hours at 200° F ± 15° F 4.0±0.25 hours at 300° F ± 15° F

Table 16. Elastomeric Lined AS-Type Graphite and Kevlar 49/Epoxy Composite Pressure Vessel Properties and Test Results

Vessel numbers	Resin	Fiber	Dome reinforce-	Average[a] composite weight, lb	Average[a] resin percent, by weight	Average[a] fiber, percent, by volume	Average[a] burst pressure,	Average[a] P_bV/W, 10^6 in.
001, 002 025, 026	HBRF-89	AS	None	1.42	30.4	57.6	3905	0.94
003, 004 027, 028		AS	Glass	1.49	30.0	56.7	4125	.92
005, 006 029, 030		Kevlar 49	None	1.30	33.9	59.4	5546	1.42
007, 008 031, 032		Kevlar 49	Glass	1.36	32.6	61.0	5482	1.34
009, 010 033, 034	HBRF-55A	AS	None	1.40	30.1	58.8	3130	.75
011, 012 035, 036		AS	Glass	1.42	28.9	61.4	3687	.86
013, 014 037, 038		Kevlar 49	None	1.31	35.0	60.8	4776	1.22
015, 016 039, 040		Kevlar 49	Glass	1.39	34.9	58.5	5015	1.28
017, 018 041, 042	HBRF-30	AS	None	1.43	31.0	61.5	3726	.87
019, 020 043, 044		AS	Glass	1.42	29.5	60.8	3905	.92
021, 022 045, 046		Kevlar 49	None	1.41	38.7	58.9	4433	1.05
023, 024 047, 048		Kevlar 49	Glass	1.44	37.9	58.3	4539	1.05

[a] Average values based on four replicates.

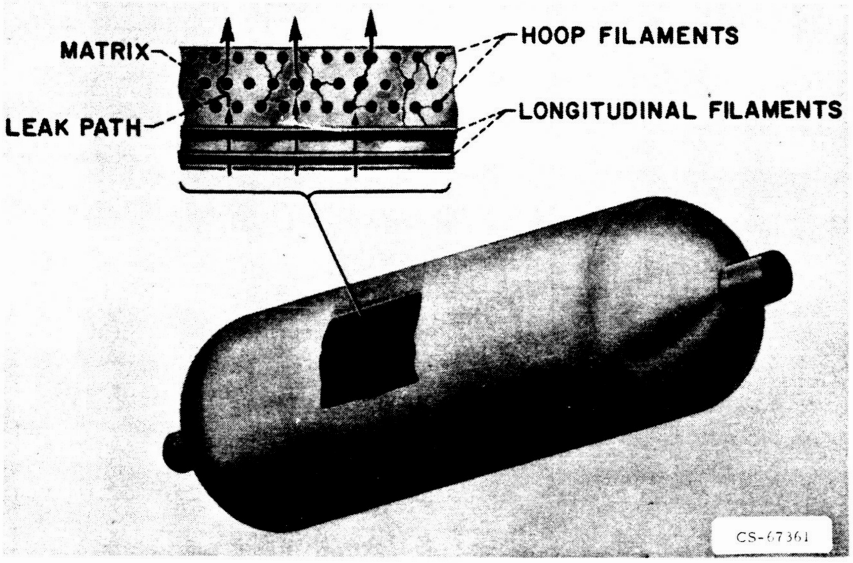


Figure 1. - Fiber/resin filament-wound composite pressure vessel.

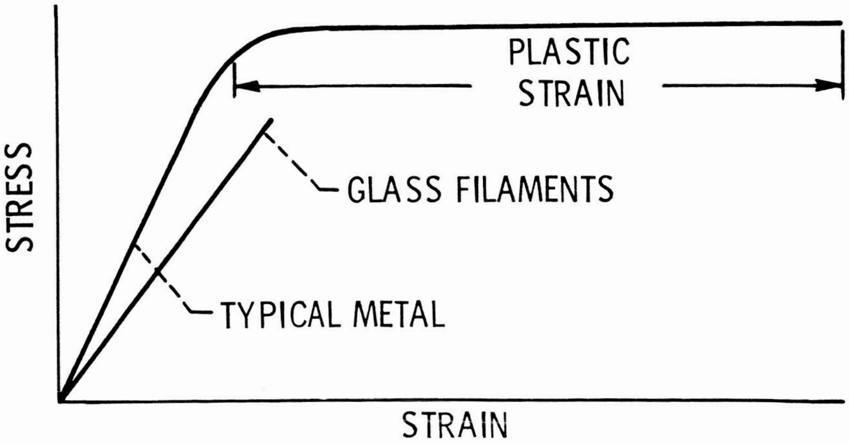


Figure 2. - Extensibility of S-glass/epoxy composite pressure vessel overwrap and liner materials.

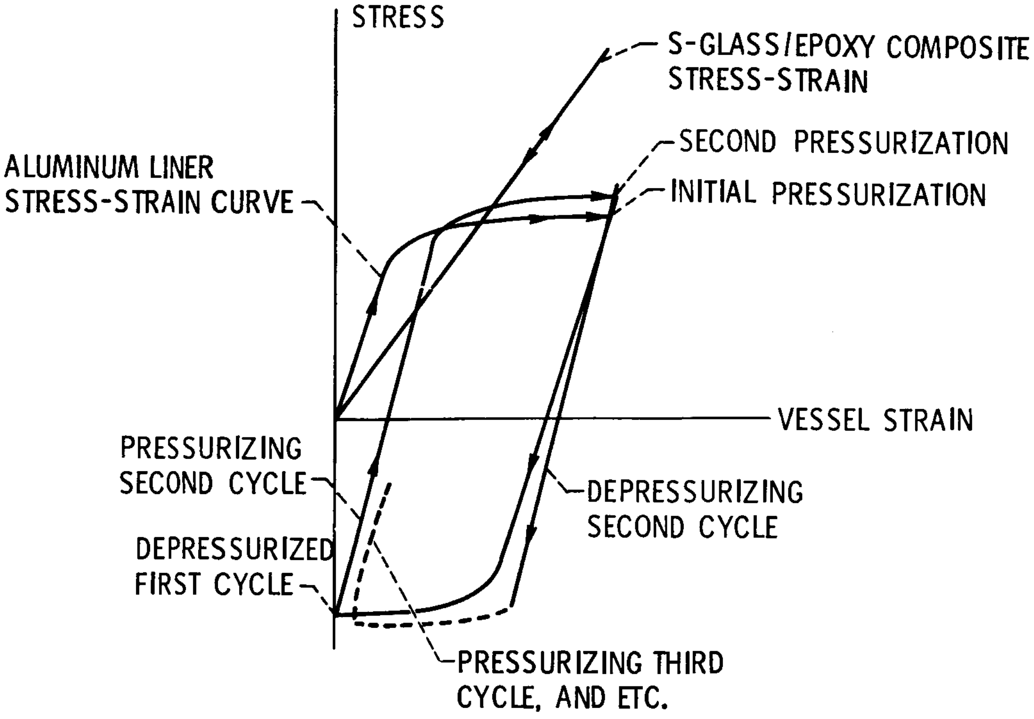


Figure 3. - Typical stress-strain plot for a filament-wound glass fiber/epoxy composite pressure vessel equipped with an adhesively-bonded thin aluminum liner.

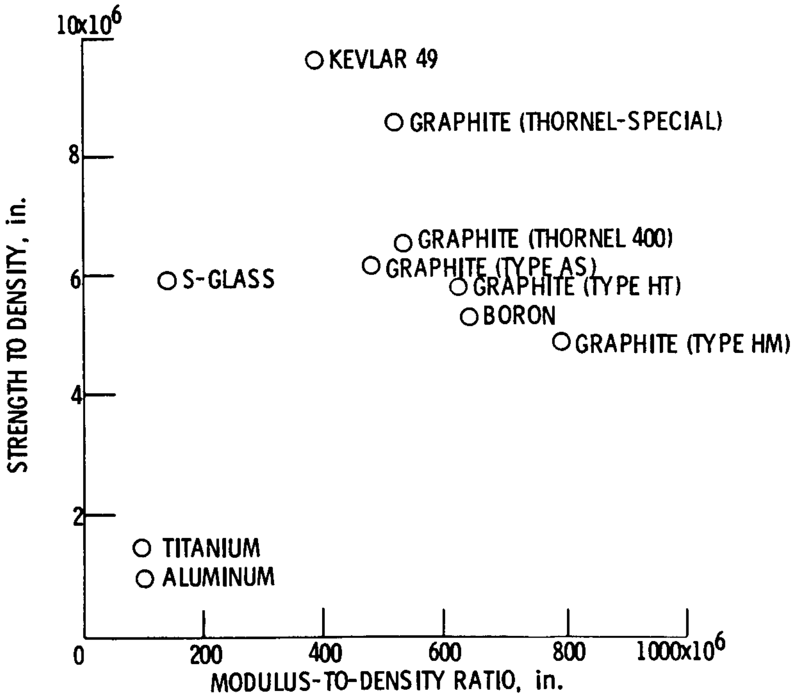


Figure 4. - Strength-to-density and modulus-to-density ratios of fiber/epoxy strand properties (based on tensile strength tests of epoxy resin-impregnated strain specimens).

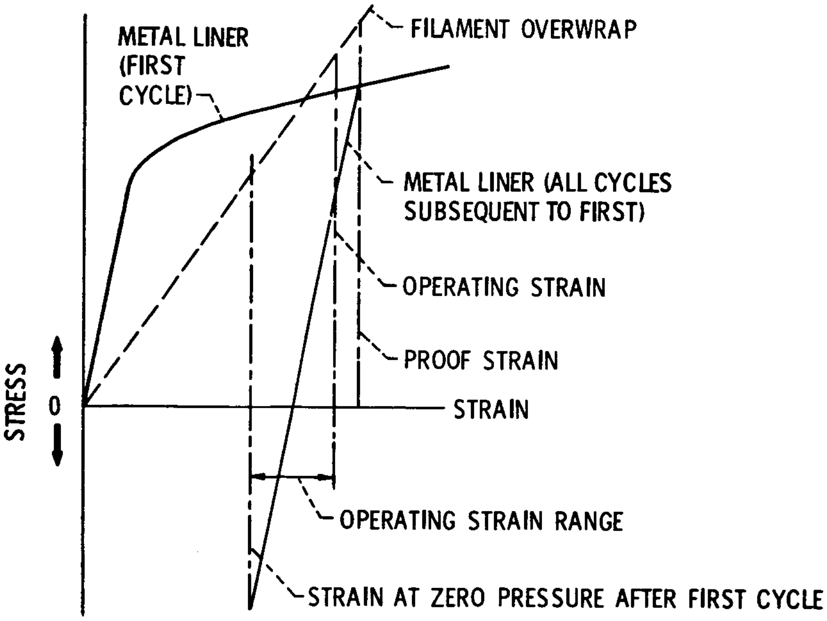


Figure 5. - Typical stress-strain plot for a filament-wound S-glass fiber/epoxy composite pressure vessel equipped with a metallic load-bearing liner.

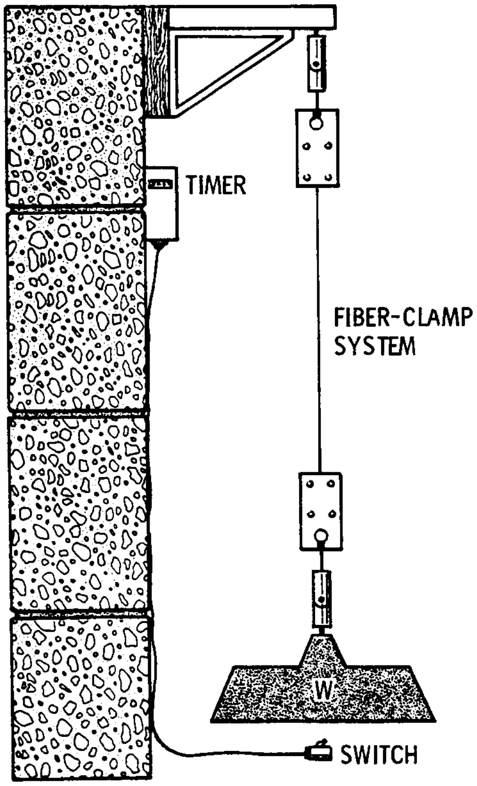


Figure 6. - Schematic of equipment for conducting sustained-loading tests on strand tensile specimens.

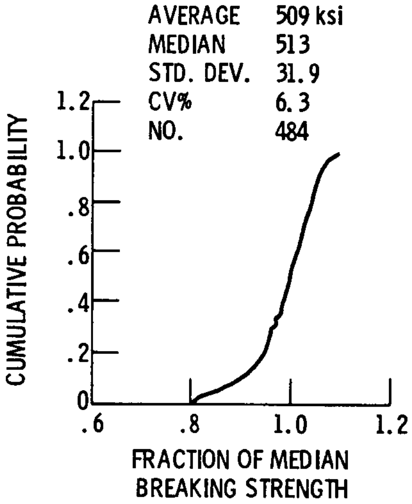


Figure 7. - Fiber strength distribution of Kevlar 49/epoxy composite strands.

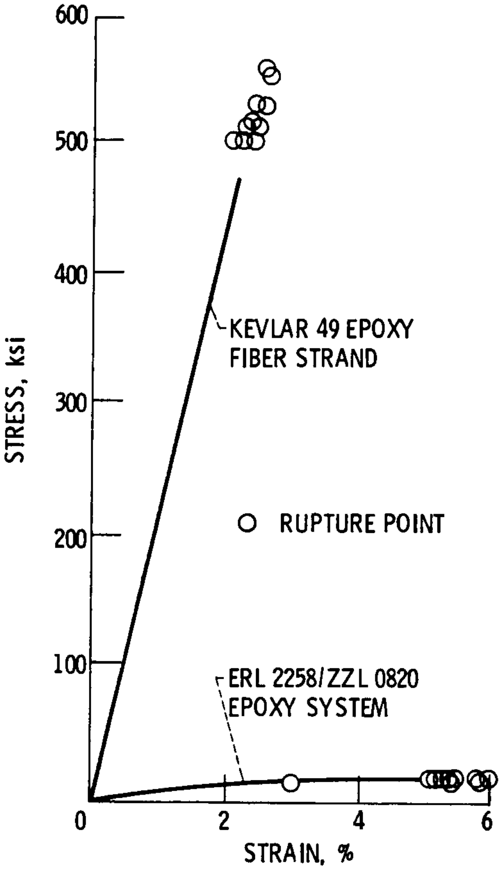


Figure 8. - Typical stress-strain curve of the fiber/epoxy composite strands and the epoxy matrix resin system.

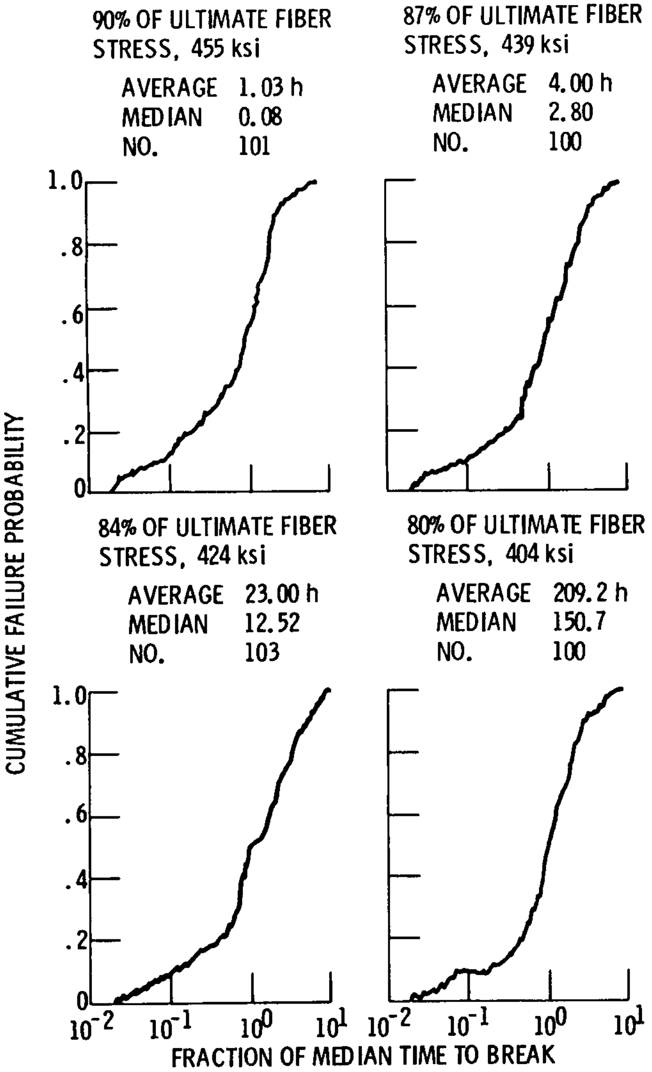


Figure 9. - Stress-rupture tests of Kevlar 49/epoxy composite strands.

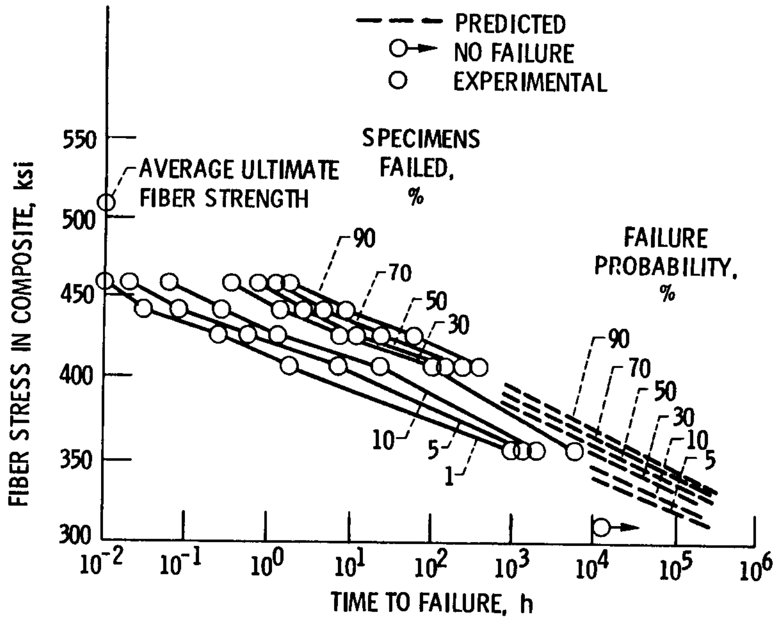


Figure 10. - Stress-rupture failure contour lines for Kevlar 49/epoxy composite strands.

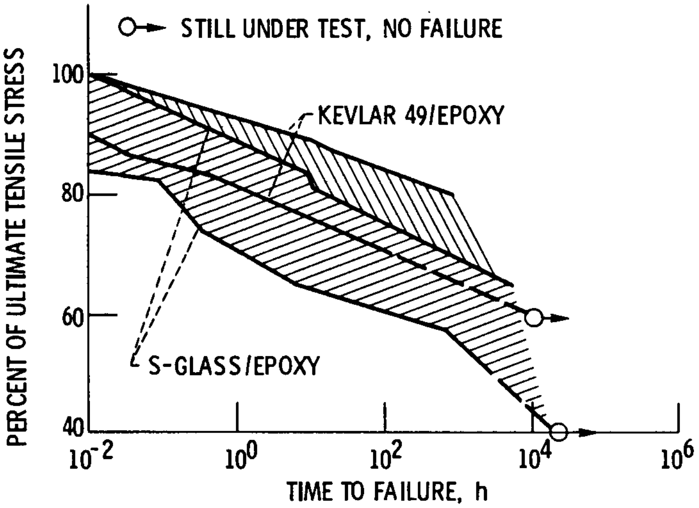
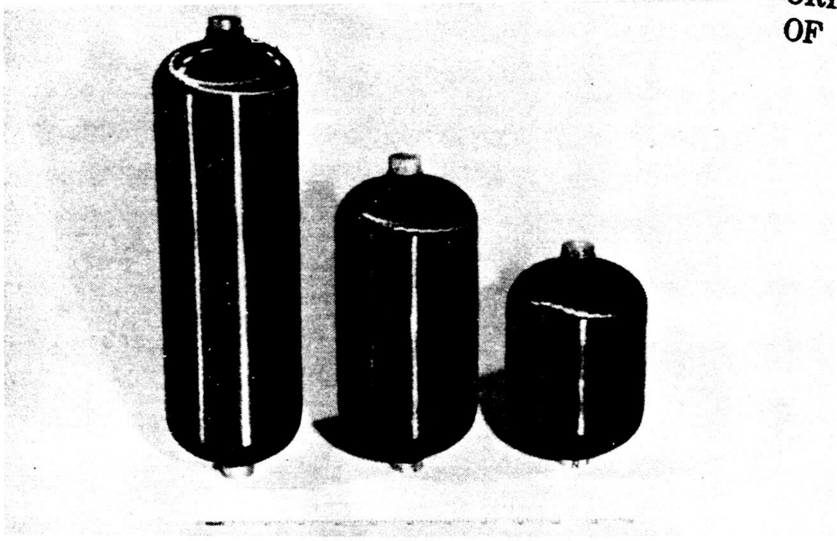
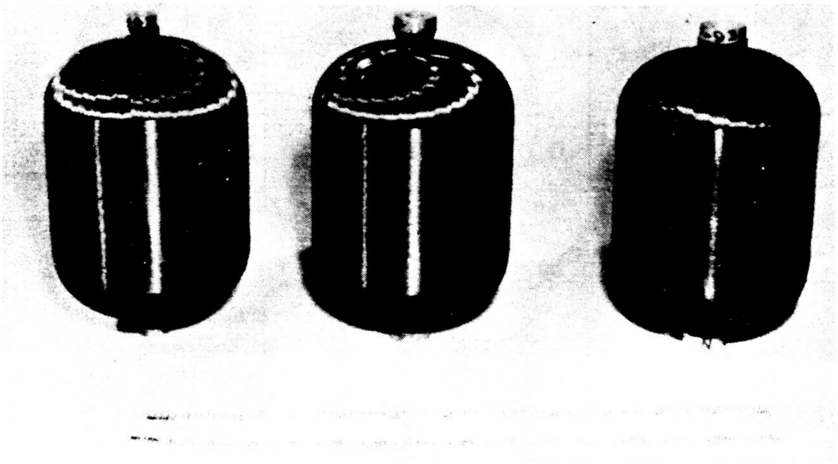


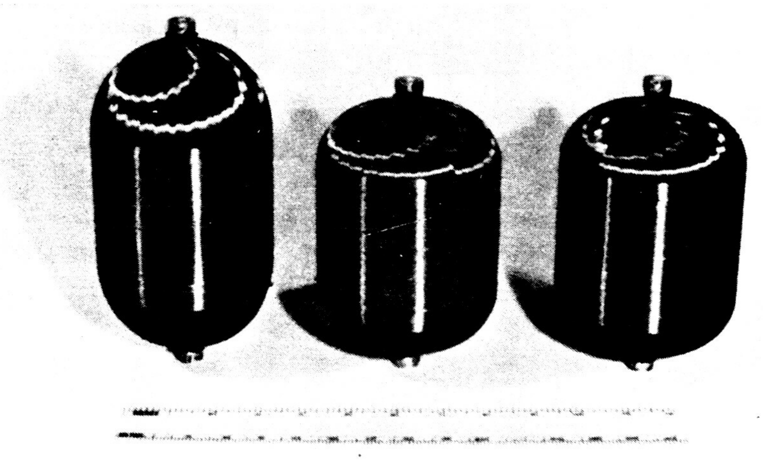
Figure 11. - Stress-rupture failure of the Kevlar 49/epoxy and S-glass/epoxy strands.



(a) L/D OF 1.375, 2 AND 3.



(b) d/D OF 0.104, 0.166, AND 0.234 AT CONSTANT LENGTH OF 5.5 IN.



(c) HEMISPHERICAL, HELICAL, AND IN-PLANE DOME CONTOURS WITH CYLINDRICAL SECTION ABOUT 3-IN. LENGTH.

Figure 12. - 4-Inch diameter cylindrical, composite pressure vessels.

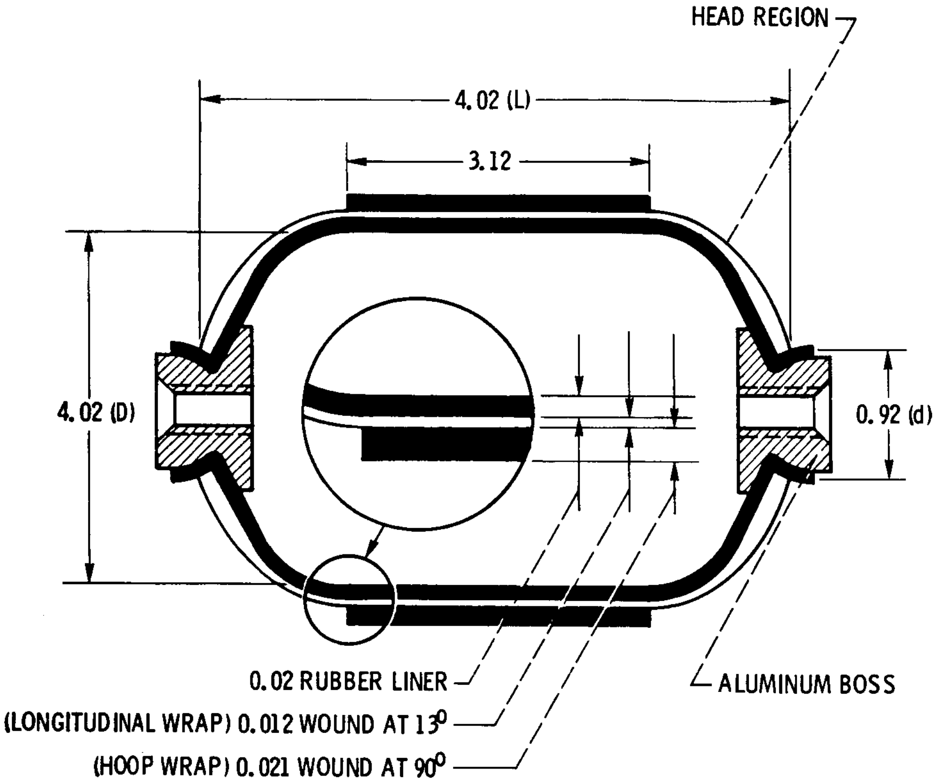
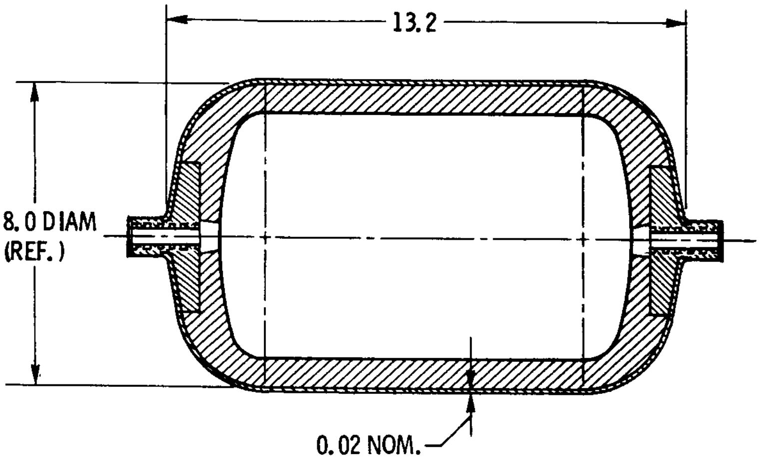
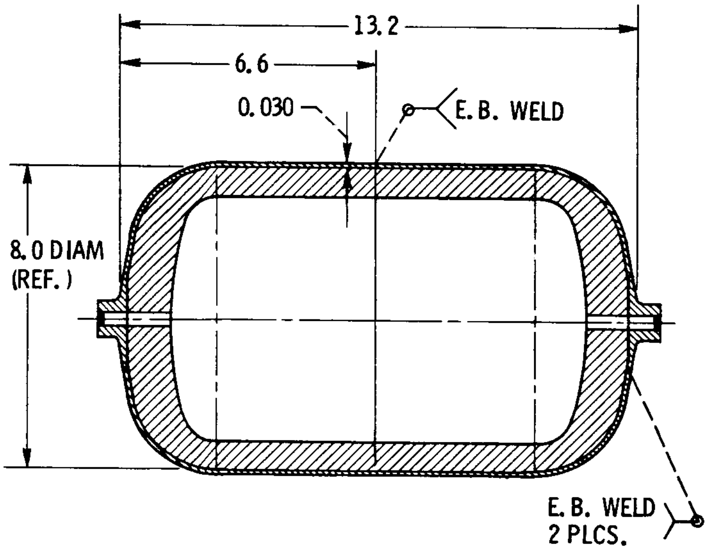


Figure 13. - Design of the 4-inch diameter composite pressure vessel.

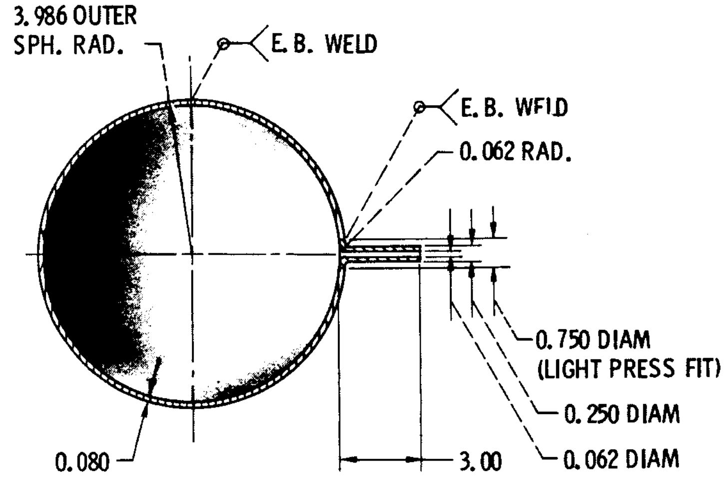


(a) 0.02-INCH RUBBER-LINED, AND PLASTER MANDREL.

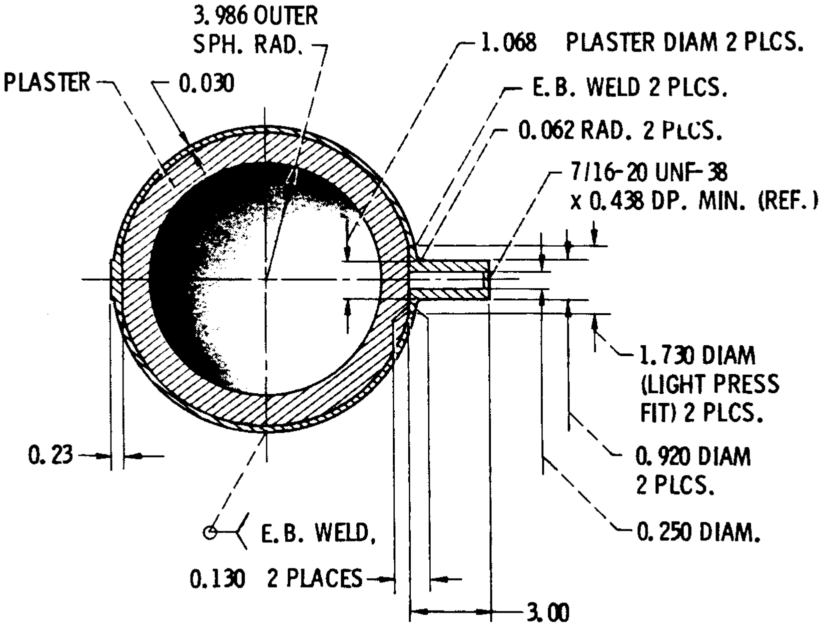


(b) 0.03-INCH ALUMINUM LINER AND PLASTER MANDREL.

Figure 14. - Liner designs for 8-inch diameter cylindrical composite pressure vessels.



(a) SINGLE-BOSS SPHERICAL ALUMINUM LINER.



(b) DOUBLE-BOSS SPHERICAL ALUMINUM LINER.

Figure 15. - Liner designs for 8-inch diameter spherical composite pressure vessels.

OUTER DOME CONTOUR COORDINATES

(a) INITIAL LINER DESIGN.

X	Y
0.00	2.00
.14	1.99
.31	1.95
.47	1.88
.74	1.71
.86	1.56
.96	1.42
1.04	1.27
1.10	1.11
1.15	.94

(b) MODIFIED LINER DESIGN.

X	Y
0.00	2.00
.29	2.00
.59	2.00
.89	2.00
1.39	2.00
1.62	1.99
1.95	1.88
2.35	1.56
2.53	1.27
2.64	.94
2.68	.75
2.72	.50
2.74	.40

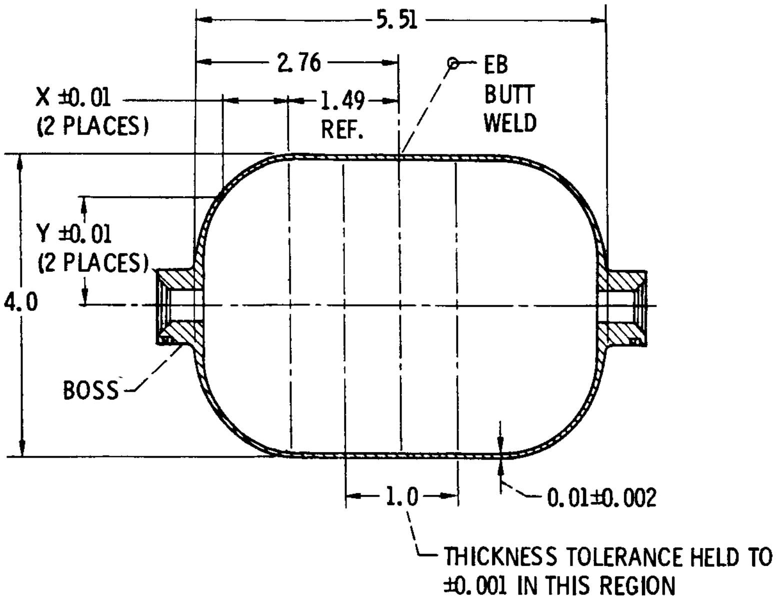


Figure 16. - Titanium (6Al-4V) liner designs.

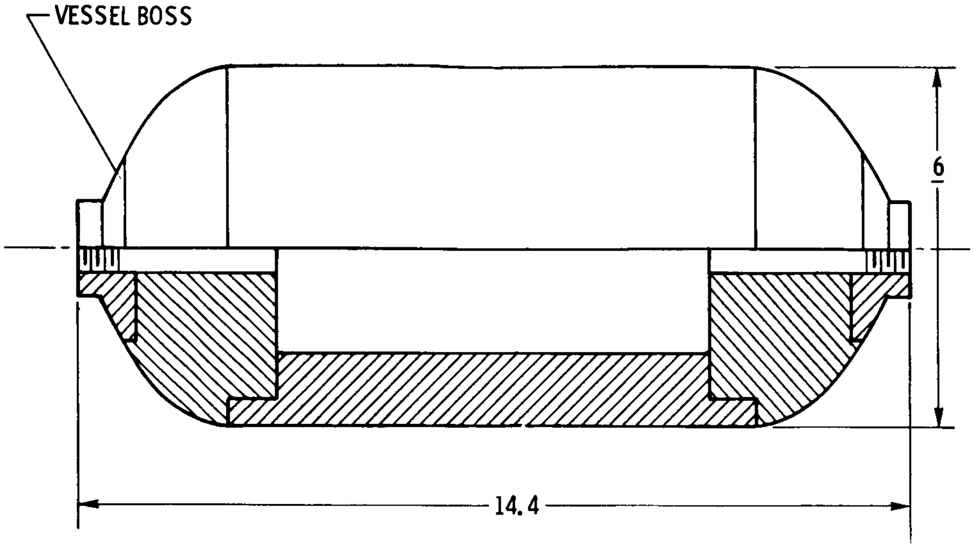
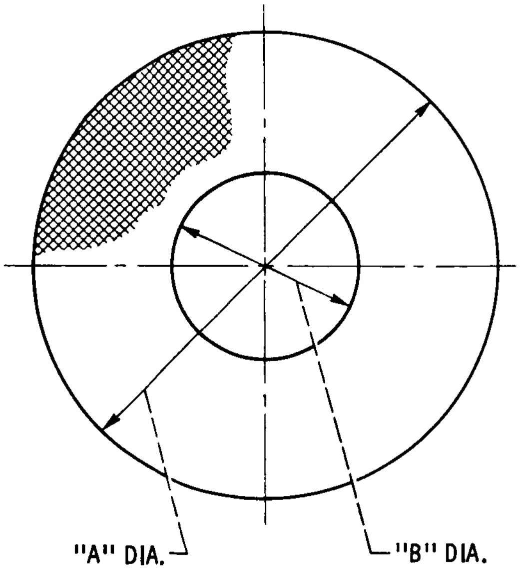


Figure 17. - 3-Piece aluminum tank mandrel for 6-inch diameter by 14-inch length graphite and Kevlar 49/epoxy composite pressure vessels.



DASH NO.	"A" DIA.	"B" DIA.
-1	3.11	8.5
-2	3.11	9.0

INSTALLATION INSTRUCTIONS

1. TWO PIECES OF EACH DASH NUMBER SHALL BE CUT FOR EACH VESSEL.
2. THE DOME REINFORCEMENT CLOTH SHALL BE IMPREGNATED WITH THE RESIN MATRICES USED AND SHALL BE INSTALLED IN THE ORDER SHOWN IN THE BOX. THE FIBER DIRECTION IN EACH DASH 2 CLOTH SHALL BE ORIENTED 45° FROM THE FIBERS IN THE DASH 1 CLOTH.

MATERIAL

STYLE 116-38 E-GLASS CLOTH WITH FINISH I-399.

Figure 18. - Dome reinforcement cloth details.

Figure 19. - Tested graphite/epoxy composite pressure vessels.

C-76-4105

Figure 20. - Tested Kevlar 49/epoxy composite pressure vessels.

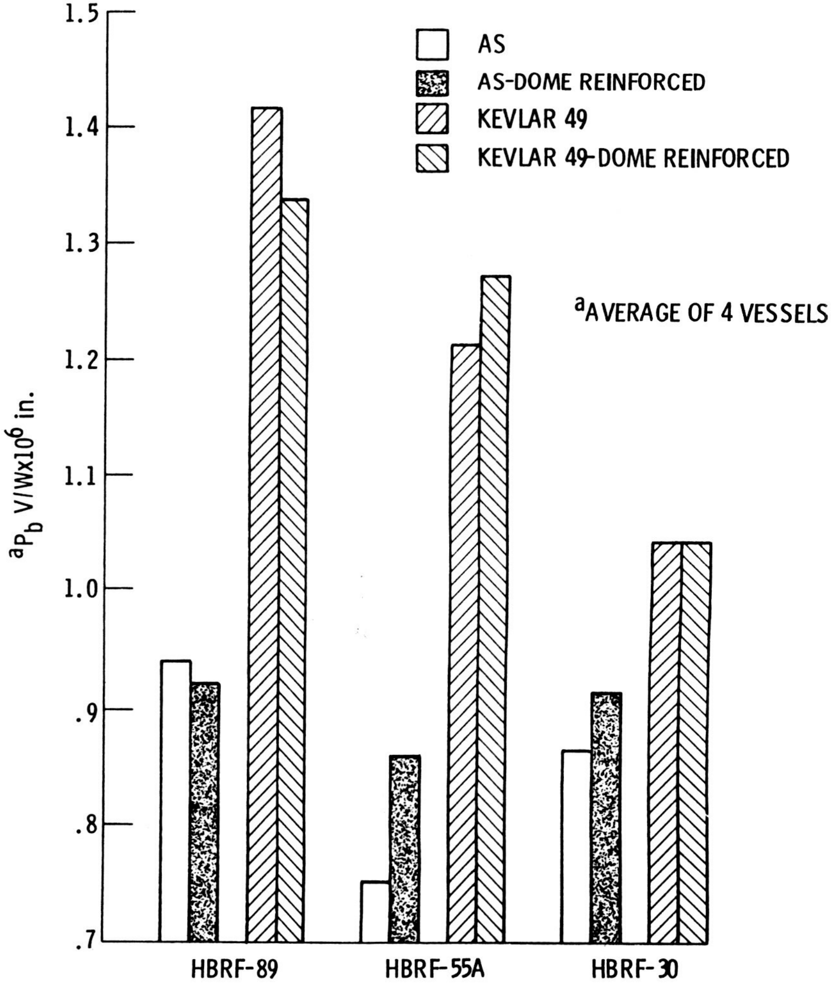


Figure 21. - Pressure vessel performance factor values for elastomer-lined composite pressure vessels.