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STRUCTURAL CONSIDERATIONS IN DESIGN OF LIGHTWEIGHT GLASS-FIBER COMPOSITE PRESSURE VESSELS

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ABSTRACT

Presented herein is an overview of NASA-Lewis Research Center (LeRC) contractural efforts directed toward the development of structurally efficient, metal-lined, glass-fiber composite pressure vessels. Both the current state-of-the-art and current problems are discussed along with fracture mechanics considerations for the metal liner. Several design concepts are compared with each other and with homogeneous metal pressure vessels.

INTRODUCTION

This paper describes the design concepts used for metal-lined, glass-fiber, composite pressure vessels and compares the structural characteristics of the composite designs with each other and with homogeneous metal pressure vessels. Specific design techniques and available design data are identified. Results of a current program to evaluate flaw growth and fracture characteristics of the metal liners are reviewed and the impact of these results on composite pressure vessel designs is discussed.

The purpose of this paper is to provide an up-to-date summary of the development status of glass-fiber composite pressure vessel technology programs and to direct attention to the substantial benefits that can be achieved through a composite design approach. The discussion centers around two distinctly different design concepts which are used to incorporate a

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metal liner into a glass-fiber composite pressure vessel. These two con-
cepts provide the basis for defining metal lined composite vessels as
either (1) thin-metal lined or (2) glass fiber reinforced (GFR). Both
concepts are described and associated development problems are identified
and discussed. Relevant fabrication and testing experience from a series
of NASA-LeRC development efforts is presented. Additional development re-
quirements and the limitations of current design methods are discussed.
The contents of a design handbook, reference 1, which was developed for
the GFR concept are described. Structural efficiency comparisons among
the thin-metal lined, GFR, and homogeneous metal pressure vessels are made
for a range of configurations to illustrate the advantages of the composite
concepts. Additional advantages of failure mode control through suppres-
sion of fragmentation are described. These advantages are then used to
suggest general applications which can benefit from glass fiber composite
pressure vessel technology.

DESIGN CONSIDERATIONS

Structurally efficient glass fiber filament wound composite pressure
vessels are inherently porous to the contained fluids. The spacing be-
tween fibers can result in a very thin resin matrix that is locally highly
strained. When the ultimate strain capability of the matrix is exceeded,
local cracking of the resin, generally referred to as crazing, will occur.
Resin crazing generally becomes extensive at a composite average stress
which is considerably lower than the composite design operating stress
and the craze lines then join to provide a leak path as shown in figure 1.
Thus, if the pressure vessel is to be used efficiently, a liner must be
provided to prevent loss of the contained fluid. The liner must be nonporous,

must be capable of straining with the composite, and must be able to return to a stable and nonbuckled position after the pressure in the tank is relieved.

Polymers such as Teflon and Mylar and elastomers such as butyl rubber have been used as liners for filament wound pressure vessels in many applications where the service temperature is between 0° F (255 K) and +500° F (533 K). However, at cryogenic temperatures where both polymers and elastomers become quite brittle and at high pressures where permeability of all polymers becomes significant, a different type of liner is required. Figure 2 illustrates the problem of providing liners for liquid hydrogen tanks which operate at -423° F (-20 K). As can be seen in figure 2a, elastomers that can strain as much as 700 percent elastically at room temperature have essentially no elastic capability at -423° F (20 K). Even Teflon can only strain elastically to 60 percent of the capability of the glass fibers. In addition, the elastomers and polymers have virtually no plastic strain capability at -423° F (20 K). Metals, while having an elastic strain capability that is only 25 percent of the glass capability, have a large plastic strain capability as shown in figure 2b. But, as figure 2b illustrates, there can be vast differences in Youngs moduli between metals and the glass filaments (or glass composites). For instance, steel and Inconel alloys have a modulus of about 30×10^6 psi (206.7×10^9 N/m^2), titanium has a modulus of 16×10^6 psi (110.2×10^9 N/m^2). The equivalent glass composite modulus is 12×10^6 psi (82.7×10^9 N/m^2). The modulus difference is compounded by the fact that the glass composite strain is totally elastic while only a small portion of the metal strain is elastic. Due to the limited extensibility of polymers and elastomers at cryogenic

temperature and their high permeability at high pressures, the major effort has been to develop technology for making metallic liners work efficiently with a glass-fiber filament-wound pressure vessel. The solution to the metal liner problem then requires providing for the mismatch in strain capabilities, the difference in Youngs moduli, and having both the metal liner and glass fiber composite operating at their respective best strain condition as dictated by design service life and factor of safety requirements.

Using two entirely different approaches, two design concepts for metal lined, glass composite pressure vessel systems have been developed in NASA programs. The first design concept that was investigated utilized the high strength composite as the load carrying structure and a metal liner of minimum weight to prevent leakage. This concept is referred to as the thin liner concept. The liner contributes both negligible weight and load carrying capability. The second concept of composite pressure vessel design utilizes a parallel-element load carrying technique whereby both the liner and the composite share the pressure load. In this concept, the liner must itself be a structurally efficient material since it contributes a significant amount to the total weight of the vessel. Specific details of the design techniques used, the advantages and disadvantages, and the types of applications of the two types of composite pressure vessels are discussed below.

THIN-LINER CONCEPT

Concept Definition

In order to minimize the weight of a pressure vessel, it is necessary to maximize the usage of high structural efficiency materials. This is

essentially the philosophy used in the fabrication of thin elastomer lined
pressure vessels where the composite is the major structural element and
a minimum weight elastomer liner is used to prevent leakage. For applica-
tions where an elastomeric liner is unacceptable (e.g., cryogenic liquid
containment) but minimum weight is required, the most desirable solution
is to substitute an acceptable lightweight liner material for the elastomer
while still using the glass-fibers to carry the pressure loads. Finding
an acceptable liner material for cryogenic applications is complicated,
however, due to the incompatibility of the glass-fiber composite stress-
strain curve with those of candidate cryogenic liner materials (see fig. 2).
Thin bonded metallic foils have been used successfully, but when they are
constrained to operate at the same strain level as the glass-fiber composite,
plastic deformation occurs as depicted in figure 3. Here it can be seen
that the filaments operate elastically (generally to 1.5 to 2.0 percent
strain) while the liner goes through a plastic hysteresis loop on every
pressure cycle. Selecting a liner material for this application then in-
volves the following considerations.

Liner Material Considerations

In selecting a liner material, it was first necessary to consider the
required mechanical properties. Thus the liner must be capable of under-
going a series of strain cycles that include both high plastic tensile
strain and high plastic compressive strain. In addition, the liner must be
able to strain to the ultimate capability of the glass-fiber composite
structure. All of these requirements must be achieved at cryogenic tempera-
tures without pinholing or tearing the liner. This combination of required
properties dictates that a relatively low strength, strain-softening material

must be used for the liner. With these material characteristics defined, it is then necessary to consider the liner assembly and pressure vessel fabrication requirements that would impact material selection.

In addition to having the required mechanical properties, the liner material must also exhibit low permeability and fabrication properties such that pinholes and tears are not introduced during forming, assembly, and/or welding. Also, since the liner cannot be applied inside the composite, it is necessary to filament wind the glass fibers over the liner. Thus the liner must be supported for the winding operation by assembling the liner around a removable mandrel or by casting a plaster or salt type mandrel inside the liner. To accommodate these operations, the liner material must be relatively easily handled and damage tolerant. Using these requirements as a guide, a number of candidate liner materials were selected and tested for mechanical properties and fabricability (refs. 2 and 3). Included were various metallic foils, polymers, and electro-deposited silver, copper, nickel, and aluminum seamless liners. In general, the results of these tests on liner materials can be summarized as follws:

1. In the present state-of-the-art, electrodeposited metallics can be easily formed into a seamless liner shape but severe problems with limited elongation capability, pinholes, tears, process variances, and membrane-to-boss-attachments prohibits their usefullness in a composite pressure vessel structural system.

2. Stainless steel and aluminum foils have the necessary mechanical properties for application as liners in composite pressure vessels and are readily available and relatively inexpensive as raw materials.

3. Fabrication of a reliable liner can be more readily accomplished with

stainless steel foil than with aluminum foil of an equivalent weight per unit area.

4. Polymeric materials do not have the necessary mechanical properties for successful application at cryogenic temperatures.

5. Metallic foils other than stainless and aluminum do not appear to provide mechanical property, fabrication, or cost advantages.
Thus, the two primary liner materials to emerge from the technology efforts were stainless steel and aluminum foil.

Buckling Restraint

The second area to which major technology efforts were directed was that of providing stabilization for the liner during depressurization such that buckles and wrinkles, which eventually lead to pinholes and tears, could be prevented. Two different stabilization techniques were investigated; one provided stabilization by bonding the thin liner to the rigid composite wall (ref. 3) and the other ref. (4) utilized a pleated liner which was free to expand and contract with the composite shell (fig. 4). The pleated liner concept was intended to provide enough excess liner material so that the liner would expand by elastic bending rather than plastic deformation. This concept was unsuccessful, apparently due to the inability to prevent the pleats from collapsing into folds which resulted in sharp corner bending and subsequent tearing and pinholing of the liner.

The bonding technique required development of an adhesive which could maintain the bond integrity at the high cyclic strains and at temperatures as low as $-423°$ F (20 K). This approach was successfully developed on both contract and in-house NASA programs. Pressure vessels capable of more than 100 leak-free pressure cycles were obtained. The adhesive system developed

by the contract programs is described in reference 3 and is a modified polyurethane epoxy-Adiprene L-100/Epi-Rez 5101/MOCA(80/20/70, pbw). This system was applied in a scrim cloth (J. P. Stevens No. 4168-2). Concurrent in-house programs at NASA LeRC identified an effective polyester adhesive system. This system is currently identified as Goodyear adhesive, Plybond 4001 and curing agent, Plybond 4004. References 5 and 6 describe these in-house programs. In these references the adhesive is identified as G-207, When either adhesive is applied properly, the mode of failure is fatigue of the liner without buckling or peeling of the adhesive system. Thus, the ultimate cyclic life capability of these adhesive systems is still an unknown.

Other Design and Fabrication Considerations

The test specimens that were used to identify an effective cryogenic adhesive system were open ended cylindrical tubes which were subsequently closed with massive end closures. This provided effective simulation of only the cylindrical portion of an operational vessel. No double curvature or cylinder-to-head transition problems were addressed in these early programs. Subsequent contractural efforts have been directed to applying thin liner materials and adhesive systems to representative pressure vessel configurations. Initial attempts were plagued with many failures which were primarily due to high local liner strains in the area of the boss-to-liner-attachment. These high strains resulted in premature tearing of the liner and subsequent loss of pressure capability. In many cases, the pressure vessels would not be capable of sustaining one cycle to the operating pressure prior to leakage. After several redesigns of the composite shell and of the liner to boss attachment were unsuccessful in reducing the high local

strain, an entirely different boss-to-liner membrane joint concept was developed (refs. 7 and 8). Figure 5 depicts the resulting design which is referred to as the hinged boss concept. Rather than having a very stiff circular reinforcement in the dome, this design allows high local strains to be redistributed through bending in the "hinge area." Thus as the composite shell expands under the pressure load, the hinge bends to allow the liner to move out with the shell. Using this concept, 100 pressure cycles to 2 percent composite strain have been achieved without failure of the liner in the boss area.

There are, however, still several problems with the thin liner approach that must be overcome before its application to glass fiber composite pressure vessels becomes viable. First, significant difficulty is encountered in fabricating thin aluminum liners having thicknesses ranging from 0.003-inch to 0.010-inch (0.0076 cm to 0.0254 cm) and both the individual cost and scrap rate are high while the reliability is low. Fabrication of stainless steel liners, while somewhat more reliable, results in a significant weight penalty for smaller vessels due to its greater density. In addition, stainless steel is more difficult to bond reliably to the composite wall. Extreme care must be taken in handling of these thin liners after fabrication since they are very fragile. Small dents can be removed with internal pressure but scratches and sharp bends will ultimately result in liner failure. Also, even after assembling a leak-free liner and successfully overwrapping with glass fiber composite, the life of the pressure vessel may be limited to a very low number of cycles (less than 10) by local high strain areas such as in a cylinder to dome transition. Under a current NASA-LeRC sponsored program, Contract NAS3-13318 with Structural Composites

Industries, selective composite reinforcement to redistribute these high local strains is being incorporated in the vessel design. Results of that program are not yet complete but there is evidence that the cyclic capability of thin aluminum lined glass composite vessels can be improved with appropriate design techniques. However, the cyclic capability of these vessels will probably always be less than 1000 cycles to 2 percent strain.

LOAD BEARING LINER APPROACH

Concept Definition

During the development of the thin liner concept, another concept was conceived which alleviated the problems of fabricating and handling metal foil liners. This concept (ref. 9), which is referred to as the load bearing liner, or as the glass fiber reinforced (GFR) metal pressure vessel, utilizes a metal liner to contain the pressurized fluid and to carry 1/3 to 1/2 of the pressure load at the operating condition. The remainder of the pressure load is, of course, carried by the glass fiber composite reinforcement. Figure 6 presents the stress (or pressure)-strain curve for the bi-element GFR concept. As can be seen from figure 6, during the proof pressure cycle of the pressure vessel, the metal liner is strained plastically while the glass filaments are straining elastically. Upon subsequent release of pressure, the liner material, which has now taken a permanent set, is forced into compression by the filaments trying to return to their original position. Since the proof pressure cycle plastically deforms or "resizes" the liner it is referred to as the "sizing" cycle. Subsequent cycles to the operating pressure produce loads that can be carried completely within the elastic capabilities of both the glass filaments and liner material. The guide-lines to be used in designing the GFR metal pressure vessels are to

(1) achieve the maximum stress capability of the liner ($\sigma_{tension}$ –
$\sigma_{compression}$ = maximum) compatible with the cyclic life requirements,
(2) operate the filaments at a stress compatible with their cyclic life
capabilities, and (3) not exceed compressive yield or the buckling strength
of the liner at zero pressure. If these three criteria are met, the burst
pressure of the vessel will be controlled by the maximum strain capability
of the glass filaments or of the sized liner material. Thus if the liner
can strain more than the filaments, the vessel will fail by rupture of the
composite and conversely, if the 2.7 to 3.0 percent elastic (or total) strain
capability of the fibers is greater than the total strain capability of
the liner, the vessel will fail due to cracking of the liner.

Liner Material Considerations

Since the GFR metal shell is a structural member it must be structur-
ally efficient (high strength to weight ratio) and since it must withstand
an initial plastic flow during the sizing cycle it must also be relatively
ductile and tolerant of flaws. Four such materials have been or are being
investigated for GFR pressure vessel application. Inconel X750 was the
first material to be investigated and was selected because of its excellent
ductility (25 to 30 percent elongation at both room and cryogenic tempera-
ture); reasonable structural operating efficiency (PV/W = 0.395x10^6 (1.0x10^6
cm)), good cryogenic strength, and overall potential as an aerospace pressure
vessel material (ref. 10). A specialized computer program for the design of
the GFR vessels was also developed as a part of the program (ref. 10). Sub-
sequent fabrication and testing of the pressure vessels provided a successful
demonstration of the computer design capability and the overall suitability
of the GFR metal pressure vessel concept.

Following the Inconel X750 demonstration program, two other demon-
stration programs were undertaken simultaneously. Both programs were
aimed at producing high-efficiency pressure vessels by applying the GFR
technique to high-strength liners (titanium 5Al-2.5Sn (ELI) in one program
and cryogenically stretchformed 301 stainless steel in the other program).
The titanium program (ref. 11) met with extreme difficulties in the fabri-
cation of the titanium shell. Cracks during explosive forming and lack of
fusion during welding (electron beam) caused loss of 75 percent (6 to 8)
of the liners before the "sizing" pressure was reached. Two vessels were
sized successfully, however, and provided both a single cycle burst and a
cyclic loading failure data point; both failures were lower than antici-
pated--apparently due to insufficient liner ductility caused by aging
problems of the titanium. The conclusions of the program thus indicated
that titanium could be used successfully in a GFR metal pressure vessel
but that extreme care would be required in both the procurement of the
starting material and in subsequent processing in order to insure high
quality welds and adequate ductility.

Processing of the cryoformed 301 (ref. 12) vessels required fabricating
the 301 stainless shell, an initial cryostretch (plastic deformation at
liquid nitrogen temperature), overwrapping with the glass fiber composite,
cure of the resin system, and a final cryogenic "sizing" or proof cycle.
The early phases of the program were fraught with problems because signifi-
cant age hardening of the partially cryoformed 301 occurred during the resin
cure cycle (maximum temperature of 350° F (175° C)). Also, the 301 thickness,
0.02-inch (0.0508 cm), contributed to critical weld mismatch and distortion
problems because very small deviations were still a large percentage of the

parent metal thickness. However, thirteen vessels were fabricated and satisfactorily "sized". These vessels were subsequently tested at room, liquid nitrogen, and liquid hydrogen temperature. The results from testing at liquid nitrogen temperature were very encouraging while both the room temperature and liquid hydrogen test results showed low strain capability in the cryoformed 301. The room temperature results were somewhat expected since the 301 material (a low silicon heat) was selected for its capabilities at liquid hydrogen temperature. The more standard (conventional silicon) 301 material would be expected to provide considerable improvement in a GFR vessel designed for room temperature operation.

Currently, the design, fabrication, and testing of a GFR 2219-T62 aluminum pressure vessel is being undertaken on another NASA LeRC sponsored program, Contract NAS3-16770 with Structural Composites Industries. Both cylindrical 30-inch diameter x 60-inches long (76.2 cm diameter x 152.4 cm long) and spherical 42-inch diameter (106.7 cm diameter) pressure vessels will be fabricated and subjected to hydraulic and pneumatic burst tests, cyclic, and time under load tests. A 36 percent weight savings is expected for these GFR vessels as compared to equivalent homogeneous aluminum construction.

Metal Liner Flaw Considerations

One of the problems remaining for the GFR concept is to define the performance degradation that may be expected due to a flaw in the liner. Past programs have taken extreme care to eliminate such problems, but in practice, weld flaws and material defects will occur and must be considered in the pressure vessel reliability analysis. There are several reasons to believe that the behavior of a flaw in the liner of a GFR metal pressure vessel will not be the same as in a homogeneous metal tank. In the GFR concept the

operating stress levels may be higher than those used for design of an all-metal tank and the operational stress range (compression to tension) is approximately twice that that will occur in an all-metal tank. In addition, the glass filaments provide some restraint to the flaw opening. A current program (ref. 13) is thus trying to develop an empirical relationship (1) between flawed uniaxial tensile specimens with and without an initial plastic deformation and (2) between those tensile specimens and both biaxial (cylinders) glass composite overwrapped metal specimens and biaxial metal specimens that were not overwrapped. Three materials are being studied: Inconel X750, 2219-T62 aluminum, and cryoformed 301. The most significant data to date is that for a given maximum operating stress, the cyclic life of a preflawed and overwrapped tank would be approximately 25 percent of that predicted from preflawed uniaxial data. This is attributed to the much higher stress range in the cylinder (compression to tension as compared to the zero to tension for uniaxial data). This decreased life can be compensated for by an approximate 10 percent reduction in the maximum operating stress ($\approx$5 percent reduction in total stress range and $\approx$4 percent reduction in pressure vessel efficiency). Ultimately, the information currently being obtained, along with planned future studies on titanium, will be provided in handbook form such that with a set of volume, shape, and operating conditions, the designer may, through a series of parametric design curves, rapidly determine the optimum weight GFR pressure vessel thicknesses and performance characteristics. Reference 1 contains this information for 2219 aluminum and Inconel X750, and a limited amount of cryoformed 301 data. Figure 7 shows the more important parameters for a typical GFR tank (circumferential wrap only) and a homogeneous 6.5-inch (16.5 cm) diameter 2219-T62 aluminum cylinder designed

using the results of the reference 13 program. Design points of 2000 cycles and 1840 psi (12.7 MN/m^2) are used. The first two items shown in figure 7, Pp/Po and $\sigma p/\sigma o$, are the proof to operating pressure (P) and liner stress (σ) ratios. Note that for the homogeneous aluminum they are the same. However, for the GFR case, a lower proof (or "sizing") pressure actually results in a higher margin of safety for the liner stress (0.43 compared to 0.35 for the homogeneous case). In addition, due to the high proof stress (plastic strain required) of the GFR concept, the 2219 liner can be operated at a stress (σo) about 5 ksi (33 MN/m^2) higher than the all aluminum vessel. The flaw size screened by proof, a_{cr}, is three times as large for the all-metal vessel as for the GFR concept. While the larger flaw of the homogeneous aluminum tank is easier to find through nondestructive inspection, the critical flaw size to wall thickness ratio (a_{cr}/t) suggests that if the operating pressure or diameter requirements were allowed to decrease, with other factors remaining constant, the all-metal design would reach a point where cyclic life could not be guaranteed by proof testing ($a_{cr}/t = 1.00$) more rapidly than the GFR concept. In addition, the thinner metal used for the GFR concept tends to provide a leakage type of failure where the heavier gage walls of the homogeneous metal tanks are more often catastrophic rupture type failure. The final entry in figure 7 is ε_r, the relative efficiencies of the two pressure vessels. As can be seen, the GFR concept is potentially 70 percent more efficient than the all-aluminum vessel.

Another important liner flaw growth consideration is suggested by the fact that at zero internal pressure, the liner of a GFR pressure vessel is experiencing a relatively high compressive load (70 to 80 percent of compressive yield). At the normal operating pressure, the liner would be in tension.

However, by selecting an operating pressure lower than normal, it would be possible to restrict the stress range of the liner to always be in compression. Thus, any flaws that may have been introduced in the liner during fabrication would be held in compression and subsequent flaw growth would not occur. In addition, new flaws could not originate in the compressive stress field. It would thus be possible to design a completely fail safe pressure vessel since any liner flaws that escaped detection during the sizing cycle would be restricted from further growth and causing failure. Should failure of the glass fiber composite occur, the liner itself would be able to carry the pressure load for a limited number of pressure cycles until the filament failure was detected and the pressure vessel could be replaced.

Remaining Problems

The fact that the fracture data for the GFR pressure vessel concept is not yet complete is considered to be one of three remaining problems facing the acceptance of composite pressure vessels. As such it can be dealt with directly. The other two problems--both of which really deal with confidence--are both more difficult to resolve. The first problem is one of setting a rational factor of safety for composites. In the case of a homogeneous pressure vessel, the margin or factor of safety on stress is identical to that calculated on a pressure basis. In the case of the GFR vessel, the same is not true. For example, the GFR cryoformed 301 stainless steel vessels of reference 9 had a factor of safety of only 1.17 based on pressure while the factors of safety on stress were 1.50 for the filaments (or composite) and 1.41 for the cryoformed 301. Thus, if the reason for requiring the factor of safety is due to the uncertainties in the

operating condition, then, and only then, should the pressure factor be used for design. In any case, the simple substitution of homogeneous metal vessel design requirements into a GFR metal design should be avoided.

The other problem, designer confidence, is one that current programs are dealing with directly. Until the GFR concept has been fully documented and test results published, there will be real (and well founded) concern for the validity of the advantages claimed. In addition, since the design of these vessels requires more than simple PR/t calculations there is reluctance to spend either the time or the money required to incorporate and use the necessary computer design programs. The current NASA-LeRC contractural efforts are attempting therefore to fabricate real type hardware and demonstrate the capability of the concept by rigorous mechanical testing. In addition, as discussed above, a design handbook (ref. 1) has been prepared such that designers can rapidly determine the appropriate design thicknesses and weight of GFR pressure vessels and make comparisons with equivalent homogeneous metal tanks. And, while this handbook will not be satisfactory for developing shop drawings, it will provide reliable information as to whether the added effort for the finalized composite design is justified.

In the aerospace industry, justification has generally been centered on decreased weight. And while low weight is one attractive feature of composite pressure vessels (both the thin liner and GFR technique) there are other advantages which may be as significant (if not more so) and which relate more directly to other industries. These are detailed in the following section.

PRESSURE VESSEL PERFORMANCE COMPARISONS

Weight Efficiency

Since decreased weight was the initial reason for developing composite

pressure vessel technology it is the obvious first item for comparing both the thin liner and GFR concepts to each other and to homogeneous metal vessels. To make generalized weight comparisons of pressure vessels, an efficiency term, PoV/W, has been identified where Po is the design operating pressure, V the volume, and W the weight. For a homogeneous metal pressure vessel, the efficiency is directly proportional to the strength (σ) to density (ρ) ratio with the proportionality constant being a function of shape. As indicated in figure 8, the most efficient metal shape is a sphere where PoV/W = 2/3 (σ/ρ), while the least efficient all metal shape is a long cylinder where PoV/W approaches 1/2 (σ/ρ). The reverse is generally true for composite pressure vessels since the composite is most efficient as a unidirectional circumferential reinforcement. Thus to draw accurate comparisons from figure 8 it is necessary to compare the opposite ends of the bars. For example, comparing homogeneous Inconel spheres to GFR Inconel, the all-metal point is taken from the top of the all-metal bar, 0.18×10^6 inch (4.5×10^6 mm) and the GFR point is from the bottom of the GFR bar, 0.256×10^6 inch (6.5×10^6 mm). And, for a cylinder of L/D = 4, the top of the GFR bar would be compared to the bottom of the homogeneous metal bar. Note that for 2219 aluminum in figure 8, only a cylindrical wrap is indicated for the GFR concept since due to both the strain mismatch and the aluminum buckling allowable, it is not generally advantageous to use a complete over-wrap. Because processing of a GFR cryoformed 301 cylinder will present problems which have not yet been addressed, only a spherical GFR configuration is shown. Figure 8 reveals, however, that in all cases, the addition of a glass fiber reinforcement can increase the efficiency of a metal when used as a pressure vessel. In addition, in the case of the open bars which indicate

the thin liner concept, the 2 to 1 (glass) increase in efficiency when compared to even the GFR concept is apparent. Also, boron and graphite composite vessels while having a higher modulus and less severe liner problems do not have the potential of both the low material cost and high efficiency of glass. The small open circles represent actual test data points for the materials shown. The last item shown in figure 8 is the extremely high efficiency of a new material (PRD 49 Type III) which is an organic fiber. It appears to be as easily handled as glass, has twice the modulus of glass and equal strength at lower density and is thus very attractive. The applicability of the PRD-49 material is currently a part of several NASA programs and has already been used in fabrication of a number of 4-inch and 8-inch diameter (10 cm and 20 cm diameter) pressure vessels with both elastomeric and aluminum liners.

Pressure Vessel Shape Considerations

Figure 9 depicts what is referred to as the "packaging advantage" of composite pressure vessels. For the specific configuration shown, a 314 feet^3 (8.9 m^3) vessel for storage of supercritical hydrogen at 400 psi (2.758x10^6 N/m^2), the effect of the final tank shape is apparent. In the case of the all aluminum vessel, going from the sphere at 650 lb to a long cylinder (L/D = 6) there is a 27 percent (200lb) weight penalty. If a composite tank were used (one with just a circumferential overwrap) a 40 percent (300 lb) weight savings could be obtained compared with the homogeneous aluminum L/D = 6 cylinder. And, if the thin-lined all-glass composite concept could be used, a minimum 50 percent weight savings could be expected. As can be seen in figure 9, the weight of vessels using the thin liner concept is independent of shape since the liner contributes a

negligible weight and the filaments are positioned to carry the loads in a uniform and effective manner. Thus, the application of composites to pressure vessels could provide the advantage of packaging pressurants in long cylinders without the disadvantage of greatly increased weight.

Failure Mode and Safety

Perhaps the greatest advantage of composite pressure vessels, their controlled failure mode, has just recently been emphasized. Figure 10 shows a failed, thin liner style, vessel and figure 11 shows the failure of a GFR cryoformed 301 stainless steel vessel. In neither case was there fragmentation which could have resulted in destruction of surrounding equipment. Referring to figure 11, the picture on the left was taken after the tank was removed from the liquid hydrogen burst test facility. The tank was then sectioned to expose the shattered metal liner shown in the right hand photo. The composite overwrap had contained all the fragments and the only evidence of failure had been the rapid pressure loss. And, since in many cases of homogeneous metal pressure vessel failures, the loss of the vessel was of secondary importance to the damage to surrounding structures and equipment, controlled failure mode with no fragmentation can be an important feature for composite pressure vessels.

Cost

One other potential advantage of glass composite pressure vessels is cost. If thick section multi-pass welding or heavy forgings are required for a homogeneous metal pressure vessel, there is an attendant high cost. Since composite reinforcement can reduce the metal thickness by as much as 70 percent, the decreased metal fabrication cost can more than offset the added design and glass composite fabrication effort and result in a lower cost

vessel. However, in most cases the thick section welding and/or expensive forgings are not required and the added design effort and extra fabrication work required for a composite pressure vessel will result in higher costs. (The actual raw material costs on a dollar-per-unit-load-carried basis are approximately the same for glass composite and for metals.)

Cyclic Life

The main disadvantage for glass composite pressure vessels is their limited cyclic capability. To achieve the 10,000 cycle capability that is routine with metals, the operational stress in the glass filaments must be reduced to as little as 40 percent of ultimate (ref. 1). Thus, while other filaments, such as PRD-49 and graphite, seem to be less affected by cyclic loading, the efficiency of a glass composite vessel is degraded for high cyclic life application.

RECOMMENDATIONS

Two recommendations that can provide improvement in composite pressure vessels can be made. The organic filament PRD-49 is currently being investigated in several NASA programs and offers promise of providing increased efficiency, better cyclic life and less complex liner manufacturing problems. As such, PRD-49 filaments are the likely "next generation" replacement for glass filaments. The thin liner concept offers the greatest efficiency advantage but requires development of fabrication techniques for low cost thin aluminum (or stainless steel) liners. In addition, the development of techniques for damping high local strains in the thin liner concept is required if reliable life of 100 to 400 cycles is to be achieved.

CONCLUSIONS

There are a number of conclusions that can be drawn from the composite

pressure vessel work. First, the glass-fiber reinforced (GFR) pressure vessels are well developed, both in design aspects and manufacturing technology. Stress-strain data obtained from test programs have generally agreed with theory. High order cyclic life (>10,000 cycles) can be achieved with the GFR concept. In the case of the thin liner configuration, continuing problems with the fabrication of the thin metal liners have hampered fabrication of test specimens. At this time, there is appreciable risk involved with the manufacture of such a vessel for even a limited cyclic life. Use of higher modulus PRD-49, graphite, and boron filaments have the potential for easing the problems of the thin-liner approach; but this potential is, as of now, unproven.

Glass composite pressure vessels offer a number of attractive advantages:

1. Composite pressure vessels can be lighter than metal pressure vessels by as much as 50 percent.

2. For certain applications, glass composite vessels are less expensive than homogeneous metal vessels.

3. Limiting the operating pressure of GFR vessels to that which will produce a net zero stress in the liner (liner always in compression) can result in a no-flaw-growth situation for the liner. Such a vessel would be completely fail safe since failure would occur by rupture of filaments and transfer of the load to the metal shell.

4. Composite pressure vessels provide failure mode control and prevent hazardous fragmentation and shrapnel damage.

5. The GFR concept can be applied to provide leak-before-break type pressure vessels.

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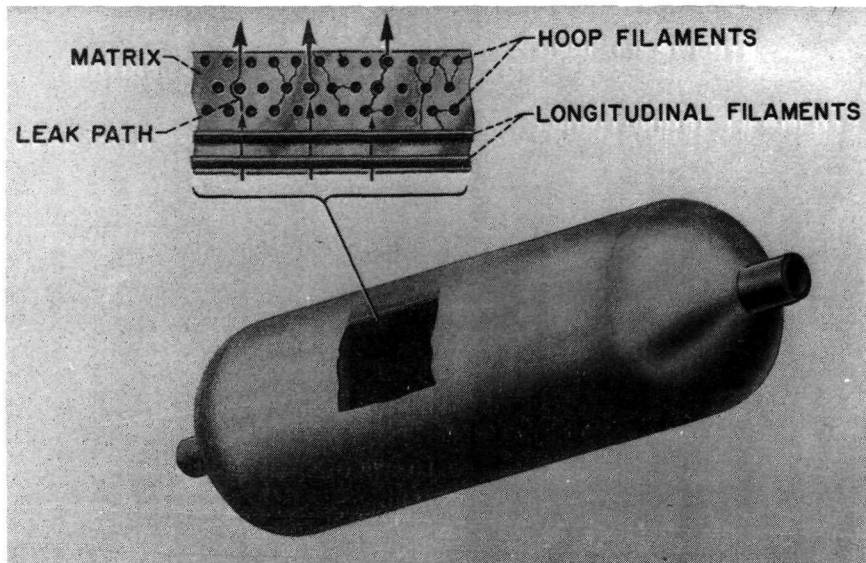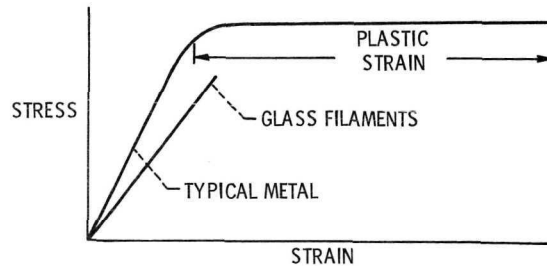
Figure 1. - Glass fiber filament wound pressure vessel.

MATERIAL	MAX ELASTIC STRAIN, %	
	75° F	-423° F
GLASS FIBERS	2.5	2.7
ELASTOMERS	700	~0
TEFLON	3.0	1.6
MYLAR	2.0	1.3
STAINLESS STEEL	.2	.3
ALUMINUM	.10	.10

(a) ELASTIC STRAIN CAPABILITY.

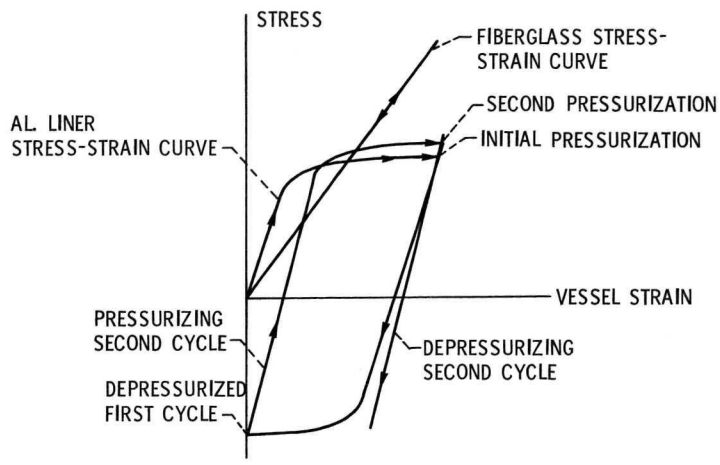(b) PLASTIC STRAIN CAPABILITY.

Figure 2. - Extensibility of liner materials.

STRESS

FIBERGLASS STRESS-
STRAIN CURVE

SECOND PRESSURIZATION

AL. LINER
STRESS-STRAIN CURVE

INITIAL PRESSURIZATION

VESSEL STRAIN

PRESSURIZING
SECOND CYCLE

DEPRESSURIZING
SECOND CYCLE

DEPRESSURIZED
FIRST CYCLE

Figure 3. - Typical stress-strain curve for filament wound vessel
with a thin bonded liner.
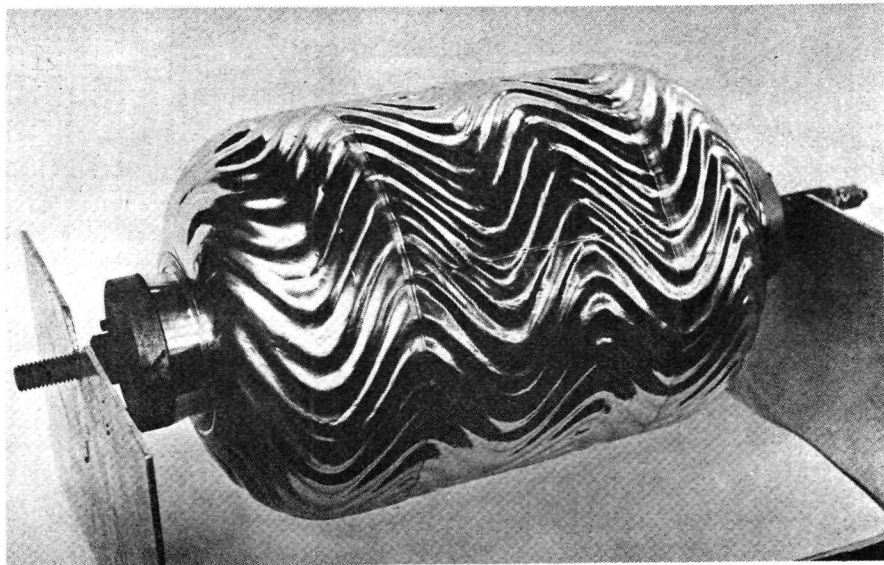
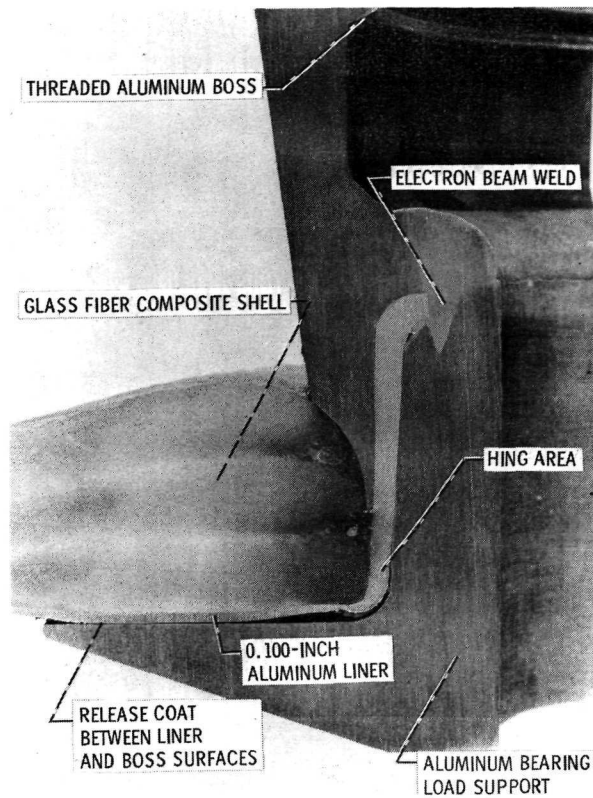Figure 4. - 3-mil stainless steel pleated liner after forming.

THREADED ALUMINUM BOSS

ELECTRON BEAM WELD

GLASS FIBER COMPOSITE SHELL

HING AREA

0.100-INCH
ALUMINUM LINER

RELEASE COAT
BETWEEN LINER
AND BOSS SURFACES

ALUMINUM BEARING
LOAD SUPPORT

Figure 5. - Cutaway view of hinged boss concept.

METAL
(FIRST
CYCLE)

FILAMENT OVERWRAP

METAL SHELL (ALL CYCLES SUBSEQUENT
TO FIRST)

OPERATING STRAIN

PROOF STRAIN

STRESS   0   STRAIN

OPERATING STRAIN RANGE

STRAIN AT ZERO PRESSURE AFTER FIRST CYCLE
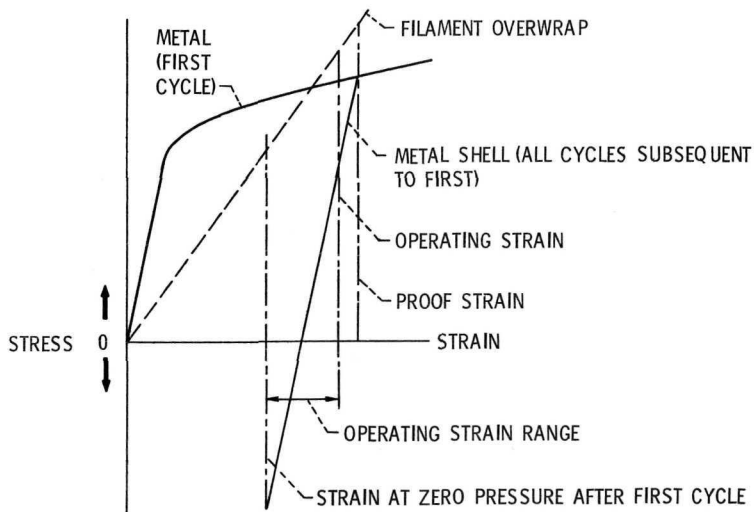
Figure 6. - Stress-strain curve for filament-overwrapped metallic pressure
vessel.

DIAMETER = 6.5 IN. (16.5 CM)
OPERATING PRESSURE = 1840 PSI (12.7 MN/M^2)
CYCLES REQUIRED = 2000

	HOOPWRAPPED ALUMINUM DESIGN	HOMOGENEOUS ALUMINUM
P_p/P_o	1.25	1.35
σ_p/σ_o	1.43	1.35
σ_o	33.6 KSI (231 MN/M^2)	28.7 KSI (198 MN/M^2)
a_{cr}	0.046 IN. (0.117 CM)	0.128 IN. (0.325 CM)
a_{cr}/t	51%	62%
r	1.7	1.0

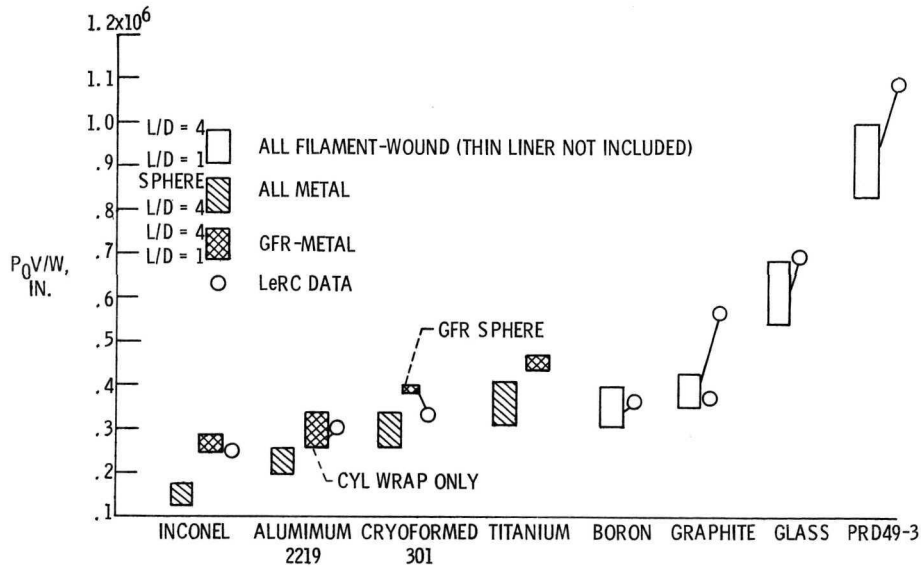Figure 7. - 2219-T62 Al cylinder design based on fracture program results.

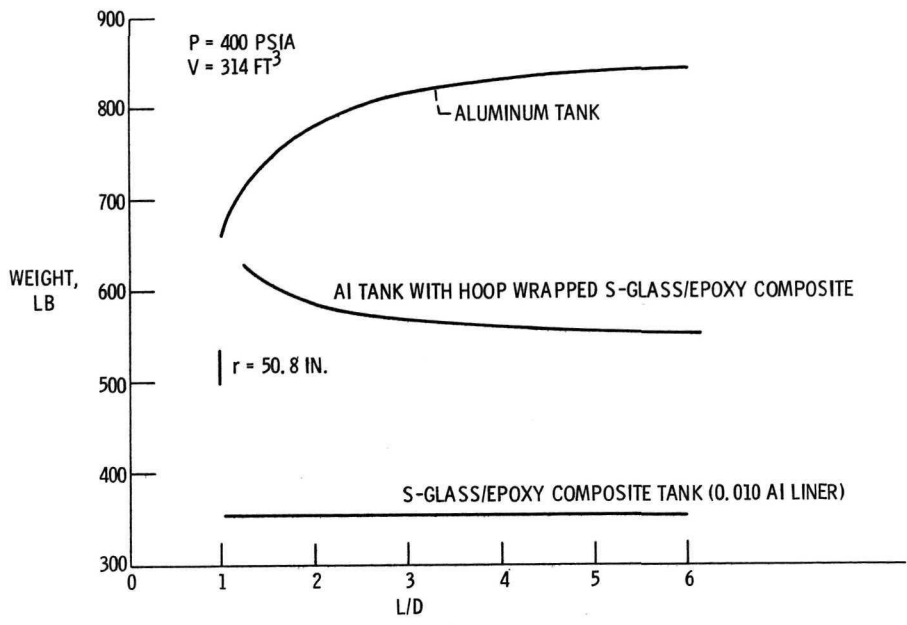Figure 8. - Pressure vessel performance factor based on operating pressure.

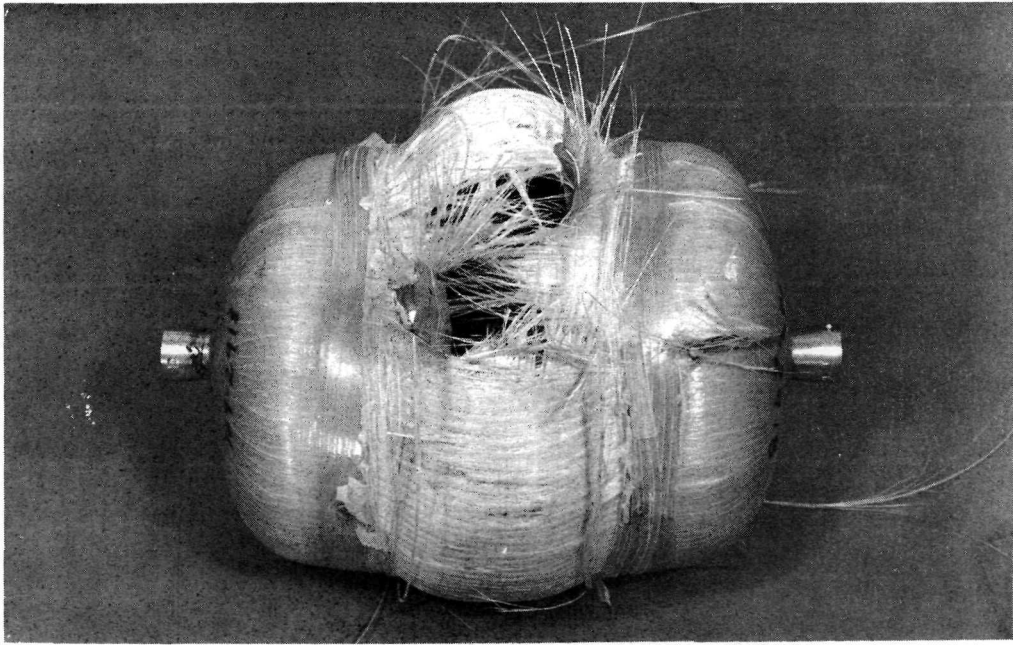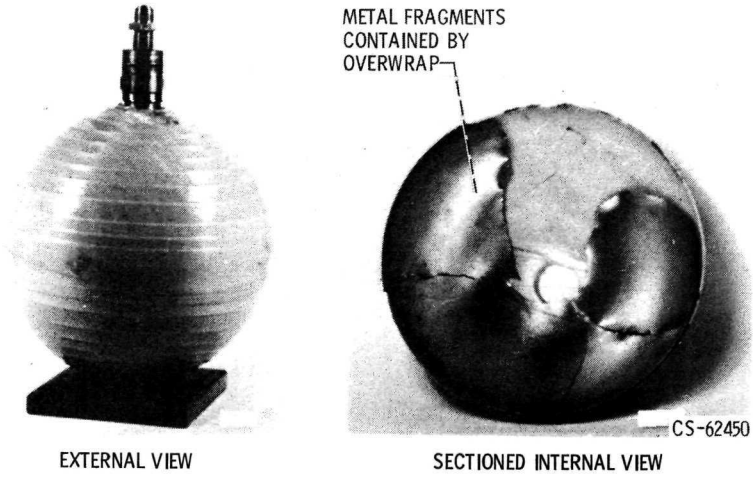Figure 9. – Supercritical hydrogen gas storage tank weights.

Figure 10. – Failure mode of thin aluminum lined glass composite pressure vessel.

METAL FRAGMENTS
CONTAINED BY
OVERWRAP

CS-62450

EXTERNAL VIEW   SECTIONED INTERNAL VIEW

Figure 11. - Composite pressure vessel failure mode control.

E-7359