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COLLAPSIBLE CRYOGENIC STORAGE VESSEL PROJECT

David C. Fleming
Associate Professor
Mechanical & Aerospace Engineering Department
Florida Institute of Technology

KSC Colleague: Eric A. Thaxton
Spaceport Engineering & Technology Directorate

ABSTRACT

Collapsible cryogenic storage vessels may be useful for future space exploration missions by providing long-term storage capability using a lightweight system that can be compactly packaged for launch. Previous development efforts have identified an "inflatable" concept as most promising. In the inflatable tank concept, the cryogen is contained within a flexible pressure wall comprised of a flexible bladder to contain the cryogen and a fabric reinforcement layer for structural strength. A flexible, high-performance insulation jacket surrounds the vessel. The weight of the tank and the cryogen is supported by rigid support structures. This design concept is developed through physical testing of a scaled pressure wall, and through development of tests for a flexible Layered Composite Insulation (LCI) insulation jacket. A demonstration pressure wall is fabricated using Spectra fabric for reinforcement, and burst tested under noncryogenic conditions. An insulation test specimens is prepared to demonstrate the effectiveness of the insulation when subject to folding effects, and to examine the effect of compression of the insulation under compressive loading to simulate the pressure effect in a nonrigid insulation blanket under the action of atmospheric pressure, such as would be seen in application on the surface of Mars. Although pressure testing did not meet the design goals, the concept shows promise for the design. The testing program provides direction for future development of the collapsible cryogenic vessel concept.

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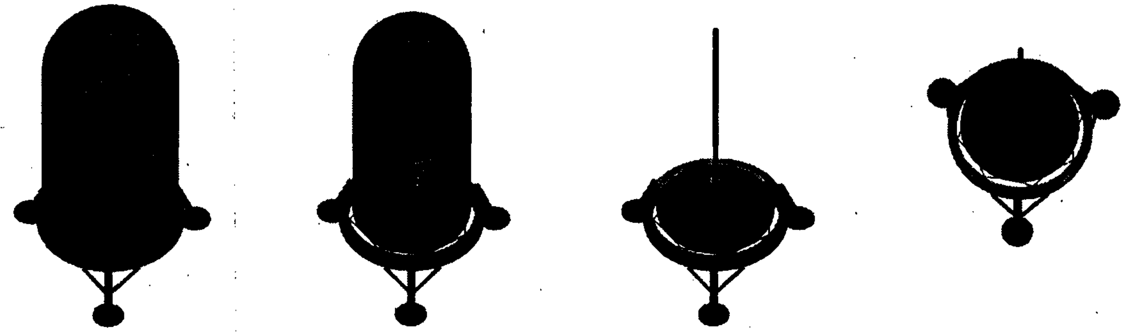
1. INTRODUCTION

Future exploration missions may take advantage of in situ resource production (ISRP) to increase mission effectiveness by allowing resources to be collected remotely rather than transporting them from Earth. For example, missions to Mars may use oxygen obtained from the predominantly carbon dioxide atmosphere for rocket fuel or for life support [1,2]. Such missions require the long-term storage of substantial quantities of oxygen. From volume considerations, the oxygen will be stored as a liquid. If the liquid oxygen is to be used primarily for rocket fuel, and if the flight vehicle arrives on site at the same time as the ISRP equipment, it may be reasonable to use the flight tanks as storage tanks. For other purposes or different mission scenarios, however, a dedicated cryogenic storage vessel would be required. Because of the inefficiency of launching a large, empty storage tank, a collapsible cryogenic storage vessel is desirable for this application.

Fleming and Hegab [3-5] evaluated preliminary design concepts for a collapsible liquid oxygen storage tank for use on Mars. The most promising design concept was an "inflatable" design, as illustrated in Figure 1, from Reference 3. In this design, the cryogen is contained within a flexible pressure wall comprised of a flexible bladder supported by external fabric reinforcement. A flexible, high performance insulation material is contained within a flexible vacuum barrier surrounding the pressure wall. High vacuum conditions are maintained in the insulation space by getter materials. Because the outer barrier of the insulation material is flexible, the small atmospheric pressure of Mars (approximately 7 torr) must be reacted by the insulation material. External to the insulation, additional flexible materials (not shown in Figure 1) for impact protection and abrasion resistance to the Mars dust must be added. The flexible pressure wall, insulation, and environmental protection systems are supported by rigid structure on the lower end of the tank. The tank collapses by folding along the vertical axis of the tank and is deployed by initial pressurization with gaseous oxygen prior to the introduction of the cryogen. This report describes ongoing development of this collapsible cryogenic tank concept and physical testing in support of the development of this concept.



(a) (b) (c) (d)

Figure 1 Schematic of the inflatable tank concept emphasizing (a) the flexible insulation jacket, (b) the pressure membrane, (c) the support structure including a rigid end cap, external support structure and legs, and (d) the suspension system (dark lines connecting the endcap to the external ring) (from Reference 3)

2. EXPERIMENTAL TESTING

Development and testing is done for two primary components of the collapsible cryogenic storage vessel: the pressure wall (comprising the cryogen containment bladder and the reinforcement material) and the flexible insulation material.

2.1. Pressure Wall

The flexible pressure wall is comprised of two main components: a bladder that serves to contain the cryogen, and which acts as the inner vacuum barrier for the insulation space; and a fabric reinforcement to resist the primary loading. A demonstration pressure wall is fabricated to verify the suitability of this approach. The full-scale design in References 3 and 4 is for a large manned mission, and the tank was sized to a capacity of 110,000 lb_m using a cylindrical tank with a 10 foot inside diameter. The concept is evaluated using an 18-inch diameter vessel. The basic design of the pressure wall is evaluated by burst testing the demonstration vessel. For scaling, the pressure wall is sized to resist the loading that would be experienced in the full-scale design article at a design burst pressure of 20 psi. Thus, the scaled demonstration pressure wall is designed to a burst pressure of 133 psi.

2.1.1. Bladder

The bladder contains the cryogen. As described in Reference 3, perhaps the only material that meets the combined requirements of oxygen compatibility, low-temperature performance and flexibility is Teflon. FEP Teflon offers somewhat better performance than other grades of Teflon. Teflon has poor oxygen permeability and thus the bladder must be metalized to prevent the rapid degradation of the vacuum in the sealed insulation space bounded on one side by the bladder. Metalized FEP film, a specialized material, was cost prohibitive for the current project. Because the function of the metal layer is not structural it was decided to use nonmetalized bladders. External fabrication of the Teflon bladder was pursued, however this option was also cost prohibitive, and difficult to implement in the limited time period of the project. Thus, it was decided to fabricate the necessary bladders in-house for the current project. FEP Teflon materials were secured for this purpose. However, difficulty in working with this material prevented its use. As a substitute for the current structural testing bladders were fabricated from a Mylar barrier material described below in Section 2.2.

Teflon and other polymer films can be fabricated in various ways including heat sealing, thermoplastic welding, and thermoforming [6]. Among these methods, the one judged most practical for the current project was heat sealing. In heat sealing, pieces of material to be joined are locally heated under the application of pressure. The material melts and fuses. Equipment for heat sealing materials is widely used for packaging and food handling. Heat sealers designed to reach sufficient temperature for Teflon are less common, but available. A variety of heat sealing equipment was purchased for use in this project including a foot-operated double impulse heat sealer that produces a linear seam up to 18 inches long. To fabricate a cylindrical bladder with hemispherical ends using this sealer, the bladder was assembled from gore segments extending along the entire axial length of the bladder, except for small openings left at each end. Simple geometrical relationships were used to determine the approximate shape of the gore segments. The curved shape of the gore segments was further approximated by straight lines because only linear seams can be produced by the heat sealer. Twelve gore segments were used to produce the bladder.

To produce the bladder, pieces of material were cut to a rectangular shape, and markings for the various seams were transferred to the material using paper patterns produced for each of the seams. Adjoining rectangles were then tacked together in the scrap portion of the material using the handheld sealing iron to keep the segments in position during the sealing operation. One side of each pair of adjoining gore segments was then sealed using the foot-operated heat sealer. As each gore was assembled, the already-assembled gores were folded out of the way, taking care to avoid creasing of the material (though in practice this was impossible to avoid entirely). On the last seam initially only one or both of the seams of the dome ends of the gore were sealed, and the cylindrical seam left open. This permitted access to the interior of the bladder. At this point, circular openings remained on the domes of the bladder. These were closed using discs of material that were hand-sealed using the hand-held iron. This was a difficult operation, as the dome ends needed to be stretched open to prevent wrinkling while simultaneously applying pressure and heat using the sealing iron. It is unlikely that a near perfect air tight seal could be made by this process, and leakage of the bladder is most likely due to imperfect closure of the dome end pieces. An opening was left on one of the dome ends, and a fitting passed through it. Then, the remaining gore segments seams were closed, completing the bladder assembly. Bladders were checked for gross leaks by inflation and slight pressurization with gaseous nitrogen. Figure 2 illustrates the bladder fabrication procedure.

Two bladders made of the Mylar barrier film material were produced. Because the intent is to keep the bladders from being fully strained, they were designed to be approximately 10% oversize, as compared with the fabric reinforcement. The elongation of the Spectra reinforcement is approximately 4%, and deformation of the seams is likely to increase the average value of deformation to failure beyond this amount. The first Mylar bladder was found to have imprecisely shaped ends (much shallower than intended) which was attributed to the nature of the approximation of the gore segments used in this bladder. The total length of the first bladder was only about 4% greater than the nominal reinforcement bag length. The pattern was modified for the second bladder producing a closer approximation of the intended gore shape and an increase in the cylinder length of two inches. This resulted in an improved shape of the end domes. Because of the nature of the construction technique, the bladder collapses very efficiently in the circumferential direction.

2.1.2. Reinforcement

The bladder material alone is not sufficiently strong to resist the pressure and weight loading of the vessel. Therefore, it must be reinforced. For a high strength, flexible reinforcement, fabric

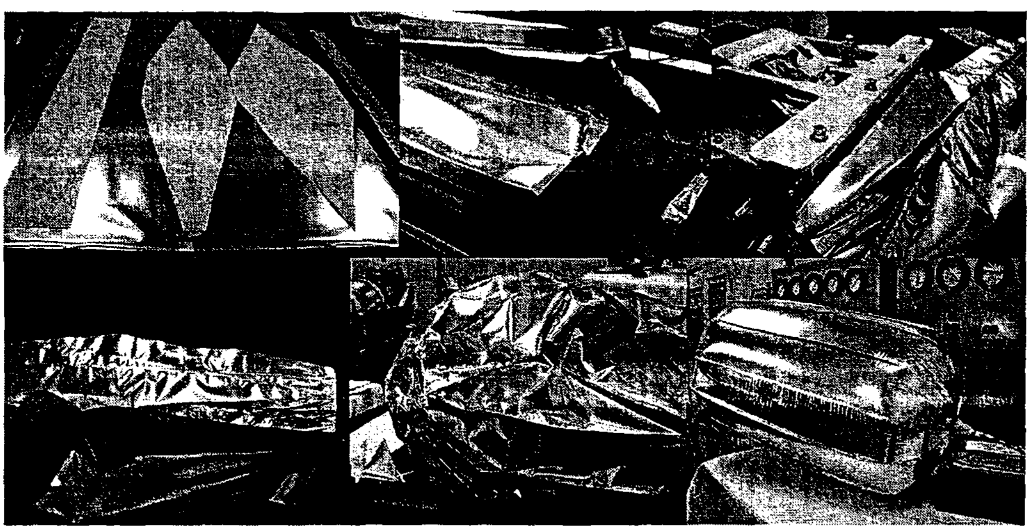


Figure 2 Fabrication of Mylar bladder illustrating (left to right starting from top): a) layout of pattern on Mylar, b) taking of adjoining gore segments, c) heat sealing of gore segments, d) partially assembled bladder showing seam pattern, e) end closure added by hand sealing, f) complete bladder

construction is a logical choice. Fabric materials have relatively high strength, and by their construction can flex and fold without damaging the material. Initial evaluation of materials for the reinforcement layer [3] called for fiberglass fabric to be used. This was selected based on oxygen compatibility requirements. However, because the fabric will be exterior to the containment bladder, and therefore in the insulation space, the reinforcement will not be exposed to significant concentrations of oxygen except in the event of bladder failure. Because bladder failure can be considered a system failure, the requirement for an oxygen compatible reinforcement material was relaxed. For a full-scale tank, the design burst pressure was estimated to be 20 psi. Hoop stress in the cylindrical portion is the critical load. For a 10-foot diameter, this results in a peak line loading of 1200 lb_f/in. This is within the range of commonly produced commercial glass fabrics. However, superior strength-to-weight properties can be obtained for other fabric types, such as Kevlar or Spectra. Based on availability of material, and working experience with the material by the KSC Parachute Refurbishment Facility, which was to fabricate the reinforcement bag, Spectra fiber fabric was selected for the demonstration article. The fabric used has breaking strength of greater than 400 lb_f/in, for a specimen containing a seam. Thus, three layers of material are necessary to fabricate the reinforcement bag.

The reinforcement bag was comprised of three main pieces: a central cylindrical portion, and two hemispherical end domes. The cylinder was fabricated from a single triple layer of Spectra with a single longitudinal seam. Domes were fabricated from eighteen identical gore segments. Longitudinal seams between gore segments were reinforced with Kevlar webbing. This Kevlar webbing passed from equator-to-equator in a single piece. Kevlar reinforcement was also placed at intervals in the latitudinal direction. The domes were connected to the cylindrical portion of the reinforcement bag through doubler material in the cylinder. There were six rows of stitching attaching the gore pieces to the cylinder. Kevlar stitching was used for all seams.

An inlet for the vessel was provided by a ½" Polypropylene bulkhead fitting which was included in the center of one dome on the bladder. Because the bladder material cannot resist the full pressure loading of the vessel, hard reinforcement is necessary around the fitting. In the full-scale design, a rigid lower endcap structure will serve this function. For the test article, a simple flat circular plate was used for this purpose. A circular bulkhead of 8 inches in diameter was fabricated in the KSC Prototype Shop, and a hole cut out to accept the fitting. Because the bulkhead is not representative of the actual full scale design, it was designed to a higher design pressure to ensure that it would not be the critical part during the burst test. The minimum required thickness for an Aluminum 6061-T6 bulkhead was calculated to be 5/16 inch. Based on material availability, a thickness of ½ inch was used. A radius was machined around the edge of the bulkhead to eliminate sharp edges that might damage either the reinforcement bag or the bladder material. Assembly of the dome with the fitting was completed with the bladder and bulkhead inside the reinforcement bag. An opening of 6-inch diameter was left in the end of the reinforcement dome where the fitting was placed. Seams near this opening were made such that the width of the gores was reduced near the end to account for the flat end. The Kevlar webbing was fabricated with loops extending into the space of the opening. Kevlar cord was placed through the loops, cinched tight and tied. Figure 3 shows the complete pressure wall.

The complete pressure barrier was checked out by lightly pressurization (½ psi gage pressure) with gaseous nitrogen. At this pressure, it was found that complete engagement of the Mylar to the reinforcement was obtained, and no obvious gas leak was observed. The vessel was then burst tested, as described in Section 3. A second vessel was fabricated for demonstration purposes.

2.2. Flexible Insulation

One of the most critical components of the proposed collapsible cryogenic storage vessel concept is the insulation. The insulation must be sufficiently flexible to permit folding for deployment, yet retain its performance after being folded then deployed. Salerno and Kittel [7] describe considerations for

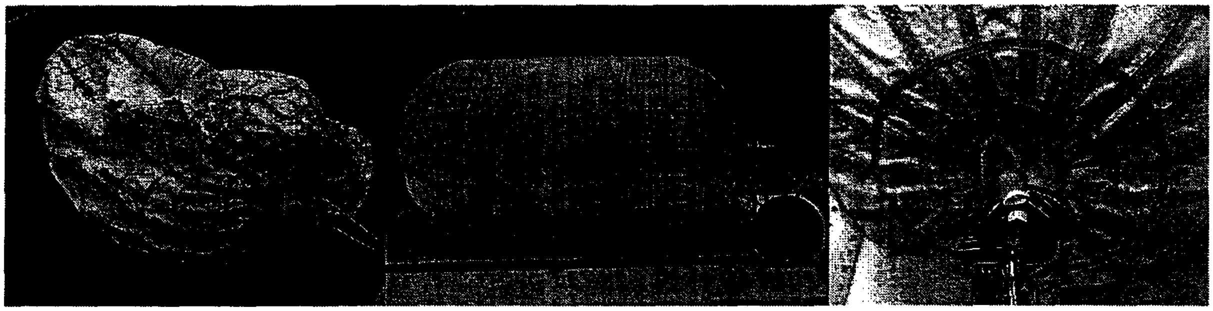


Figure 3 Complete reinforcement wall showing (from left to right): a) reinforcement with no inflation, b) under light inflation, c) detail of reinforcement around inlet fitting

cryogenic storage systems on Mars. Minimum mass systems are obtained when cryocoolers are used with effective passive insulation systems. Hegab [4] examined candidate insulation systems for a proposed collapsible liquid oxygen tank and found that optimum system mass required a high-performance insulation system, such as the NASA KSC-developed Layered Composite Insulation (LCI) systems [8] operating under high vacuum conditions. LCI insulation is similar to conventional multi-layer insulation (MLI), in that it combines reflective materials with nonconductive spacers, but the spacer materials are unconventional and the overall system is more effective under soft vacuum conditions than other insulations and is expected to be more robust under mechanical loading effects [8].

The proposed tank design calls for the layered composite insulation to be contained within a vacuum jacket surrounding the pressure wall of the collapsible tank. Although LCI was developed in part to give good insulation performance at soft vacuum conditions, such as would be experienced if the vacuum space were vented to the Mars atmosphere, high vacuum conditions are required in the insulation of the collapsible cryogenic tank to avoid prohibitive insulation mass [4]. Vacuum will be maintained in the insulation space by sealing the insulation space and using getters, or LCI materials that act as getters to absorb particles in the insulation volume that either permeate through the barriers, or that outgas from the insulation materials. This approach is the same as that used in vacuum insulation panels.

Although the ideal performance of various LCI systems is known (see, for example, Reference 8), the use of the material in the proposed fashion raises some concerns. In particular: 1) It is not known to what degree folding and unfolding the material will degrade the performance; and 2) because the insulation is in a flexible vacuum jacket, the local atmospheric pressure will be reacted by the insulation medium. For a MLI system, Black et al [9] showed that even small compressive loads of 10 torr were sufficient to seriously degrade the thermal performance. Although it is expected to be more robust, the LCI insulation may observe a similar response. Sufficient funding and time was not available to do an in-depth study of the problems of the insulation system for the proposed Mars liquid oxygen storage tank. However, because the feasibility of the proposed insulation system is a major driver of the proposed tank design, it is important to address these issues, at least in a preliminary fashion. Thus, a brief series of tests on the most promising LCI candidate material is proposed to obtain an initial impression of the seriousness of the issues identified above with respect to the use of a flexible LCI insulation jacket for the tank. A series of four tests using a single insulation specimen will be conducted as described below. The test specimen for the insulation tests has been fabricated, and a testing program established. Due to scheduling issues, the insulation testing will not be completed until after the term of the NASA Faculty Fellowship Program.

Based on consultation with Dr. James Fesmire, Lead Engineer, Cryogenic Systems, NASA Kennedy Space Center, and considering available materials, the LCI system chosen for the insulation tests was a modified version of LCI type C115 [8]. The system used for the insulation test specimen uses Hollingsworth & Vose Grade TR2402B polyester non-woven blanket material with wrinkled double aluminized Mylar as the radiation barrier. Cab-O-Sil 530 silica powder is placed between the Mylar and the polyester. Because the vacuum in the insulation must be independent from the surrounding volume, the insulation is sealed within a barrier film. The test specimen uses Mylar 350SBL300 vacuum barrier film to contain the insulation. This is a nonmetallic film with excellent vacuum barrier properties. One problem with metalized barrier films is that folding of the material can cause pinholing of the metal that adversely affects the overall permeability of the system. It is expected that the nonmetallic nature of the film might avoid this problem, and thus permit better barrier performance after folding and unfolding. On this topic, it should be noted that this is the same material that was used for fabrication of the bladder described in Section 2.1.1. As an unavoidable part of the bladder fabrication process used, the material was subject to considerable amounts of handling. The complete bladder showed numerous visual defects resembling scratches or creases on the surface. It is not known to what extent, if any, this affects the barrier properties of the film. The specimen is fabricated to fit over a cylindrical cold mass 6.57 inches in diameter. The insulation has a total length of approximately 36 inches, with additional length in the barrier layers for sealing.

The insulation specimen was produced by wrapping the materials around a mandrel shaped to the size to fit in the cylindrical cryostat cold mass. A cylinder of barrier material is first fabricated to slide over the mandrel. Next, the insulation materials are wrapped around the inner barrier layer in a process as described in Reference 10. Silica powder is sprinkled over the Mylar film from a mechanical shaker container during the wrapping process. Ten layers of insulation, forming a total insulation thickness of approximately ½ inch were used for the test specimen. After the insulation is applied, an outer cylinder of barrier material is placed over the assembly, and the ends of the two barrier layers are sealed together using a linear heat-sealing machine and a handheld sealing iron. Before sealing, a small vacuum fitting is placed in the outer barrier layer to allow vacuum to be drawn in the insulation specimen. Figure 4 illustrates the insulation specimen fabrication process.

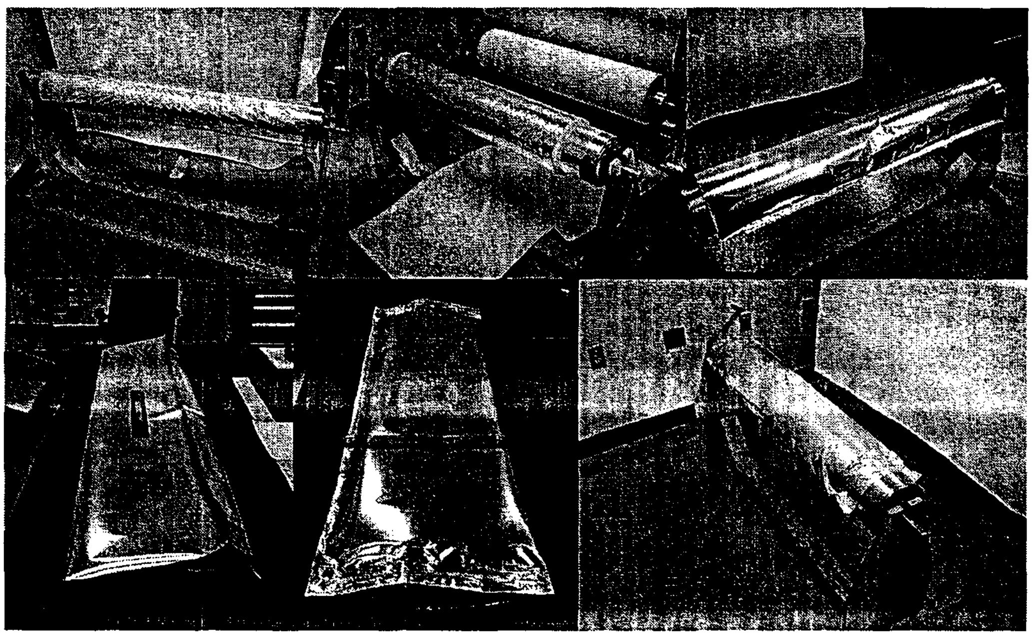


Figure 4 Fabrication of insulation specimen showing (left to right from top) a) Placement of inner barrier cylinder on mandrel b) Wrapping of insulation materials around mandrel (powder not shown in this photograph) c) placement of outer barrier cylinder containing vacuum fitting over the assembly d) assembly removed from mandrel prior to sealing the ends e) specimen with sealed ends f) complete specimen returned to mandrel

A series of four tests is proposed using the given insulation system. The first test will use the insulation specimen in it original manufactured condition. Apparent thermal conductivity, k_{app}, will first be determined for the specimen when equal high vacuum conditions are drawn in the specimen and in the vacuum vessel. This will provide a baseline value for the conductivity of the specimen. For the second test, high vacuum will be maintained in the specimen, while a pressure of 7 torr will be maintained in the outer vessel. Thus, the insulation will be subject to a compression effect due to the external pressure. Following this test, the insulation specimen will be removed from the cryostat, folded, and held in the folded state under light compression for a period of time. The specimen will then be unfolded and reinstalled in the cryostat. The specimen will then be tested under equal vacuum conditions, and under 7 torr of external compression, as before.

3. RESULTS AND DISCUSSION

3.1. Pressure Wall

The pressure wall described in Section 2.1 was tested to failure in a burst test cell. The initial intent was to test the vessel under hydrostatic pressure, though gaseous nitrogen was used for the final portion of pressurization. The available gages were not of a recording variety, so a video camera was used to film the gage throughout the test. An ordinary speed video camera filmed the test article during pressurization.

Because no rigid endcap or cradle structure was prepared for the test article, the specimen was tested in a horizontal orientation. Filling the vessel with water in preparation for the test was extremely time consuming due to the relatively large volume of the vessel and the lack of a vent. The tank was filled by placing a small water tube inside the bulkhead fitting with a loose seal to allow air to vent. The vessel started flat, and filled in a pillow fashion. This is not ideal because the weight of the water must tend to trap folds in the bladder material that may be difficult to remove in subsequent pressurization, perhaps overstressing the seams. During filling, it was attempted to manually extend the Mylar to prevent such folds, though it cannot be known to what degree this was successful. When the vessel was filled to the maximum extent possible, the vessel was connected to the pressurization system, and testing began. At the beginning of the test, the specimen still had a pronounced ovoid shape, and thus a substantial amount of time was required for the low-volume, high pressure pumping system to pump a sufficient volume of water into the tank such that the folds were removed and it began to take its intended shape. After a considerable time it was observed that the pressure was stable at a pressure of about 32 psi. Water was observed to be coming from under the vessel. The test was halted and the pressure observed. In a minute or two of observation no reduction in pressure was measured. The test was resumed, but no pressure increase could be maintained, and it became more apparent that water was leaking from the bladder. The rate of loss of water due to the leak had apparently equalized the rate of pumping from the low-volume system.

Because there was not enough time remaining in the program to disassemble the system and repair or remake the bladder, and because the leak was apparently small, it was decided to complete the testing using gaseous nitrogen as the pressurant (keeping as much of the existing water in the vessel as possible). For safety, all personnel were cleared from the test cell for the remainder of the test. The remainder of the test progressed rapidly. The test specimen quickly took the design shape, and almost immediately crackling noises (attributed to the breaking of threads) were heard, their frequency increasing toward the end of the test. At a pressure of about 60±10 psi, the vessel abruptly burst. Postmortem investigation showed that failure was concentrated in the upper dome, with separation of several of the longitudinal

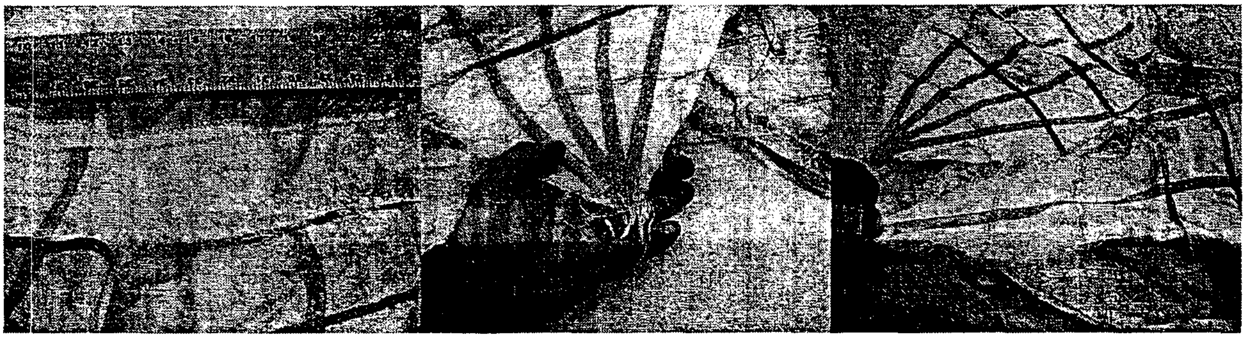


Figure 5 Failure of upper dome in reinforcement bag showing (from left to right) a) failure in hoop-cylinder seam, b) failure of Kevlar webbing at the apex, c) separation of seams between gore segments

gore seams and about ¼ of the dome-cylinder seam evident. Figure 5 shows the failed pressure wall. The inner bladder burst all of the seams in this dome, resulting in a "banana peel" appearance. Portions of several other bladder seams throughout the bladder were also separated, though it is not known whether they failed during pressurization or at burst.

The pressure wall failed at a pressure well below the design burst pressure of 133 psi. This is attributed to a premature failure of seams in the fabric dome. Because of the compressed time frame of this project, verification testing of the seams used in the domes was not done. Furthermore, analysis of the fabric structure accounting for details of the construction such as the Kevlar webbing needs to be done to improve and verify the design. The bladder also requires improvements. It was observed that leakage occurred at relatively low pressure during testing. The fabrication technique used for the bladder, particularly the manual sealing of the end closures, is not ideal, and results in a large number of seams. Alternate fabrication techniques such as heat forming should be pursued.[1] Some other improvements to the bladder should be made: the bladder should be indexed to the reinforcement bag so that it maintains its position relative to the reinforcement after packing and unpacking. For ease of testing, a vent should be placed in the bladder.

3.2. Flexible Insulation

Because of delays in producing the insulation test specimen and because of scheduling of the cryostat, testing of the flexible insulation system is not yet complete. Interested parties may contact the author for results from the thermal insulation testing.

4. CONCLUSIONS

A demonstration article was produced to illustrate key portions of the collapsible cryogenic tank concept. A burst test of a scaled pressure wall was conducted and preparation of a test specimen to validate the performance of the insulation system was made. Burst testing showed that the pressure wall did not meet design goals. However, it is anticipated that redesign of the reinforcement seams will produce an adequate design.

Although redesign of some components is necessary to meet design goals, the testing supports additional development of the design concept. Further development of the collapsible cryogenic tank concept should include: redesign of the reinforcement, development of the bladder for oxygen compatible

[1] Heat forming of bladders for positive expulsion bladders was pursued by Pope and Penner [11], though difficulties in permeation were found and the process was abandoned.

materials and to improve its manufacturing method, verification of system performance and durability under cryogenic conditions, design of support structures, and design of plumbing and diffuser structures appropriate for the collapsible design concept.

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