Y-12

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Y-12
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**Final CRADA Report
for
CRADA Number Y-1295-0370**

**FABRICATION OF TOROIDAL COMPOSITE
PRESSURE VESSELS**

**W. G. Dodge
Lockheed Martin Energy Systems, Inc.
Aris Escalona
Arde Incorporated**

November 24, 1996

MASTER

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**Prepared by the
Oak Ridge Y-12 Plant
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400**

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UCN-13672 (28 8-95)

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ABSTRACT

A method for fabricating composite pressure vessels having toroidal geometry was evaluated. Eight units were fabricated using fibrous graphite material wrapped over a thin-walled aluminum liner. The material was wrapped using a machine designed for wrapping insulating tape on toroidal electrical coils. After wrapping, the graphite material was impregnated with an epoxy resin that was subsequently thermally cured. The units were fabricated using various winding patterns. They were hydrostatically tested to determine their performance. The method of fabrication was demonstrated. However, the improvement in performance to weight ratio over that obtainable by an all metal vessel probably does not justify the extra cost of fabrication.

INTRODUCTION

Several years previous to this study Lockheed Martin Energy Systems, Inc. (LMES) had participated in a project to develop toroidal composite pressure vessels. These vessels were to be used for hydraulic energy storage in the control system of a reentry vehicle. A method for fabrication was proposed and the required material and equipment were purchased; however, the project was terminated before any work was done.

Arde' Inc., of Norwood NJ, a supplier of pressure vessels for aerospace applications, became aware of this previous effort and expressed an interest in a joint project to evaluate the concept. This led to the establishment of a cooperative research agreement.

The agreement provided that Arde' produce thin walled aluminum liners which were subsequently over wrapped by LMES with composite material. The resulting composite vessels were tested by Arde' to determine their performance.

OBJECTIVE

The objective of this work was to evaluate a proposed technique for fabricating toroidal composite pressure vessels for military and spacecraft applications.

RESULTS

Eight vessels were fabricated using various combinations of materials and wrapping patterns. Seven of these units were tested to determine their performance. The performance obtained was not as high as desired and only slightly better than that which could be obtained from a high strength titanium vessel of the same geometry. However, information was obtained in this study which will make possible the achievement of higher performance in future designs.

DP BENEFITS

This work provided an opportunity for continued improvement in the Y-12 Development Division's core competency in composite technology. It also supported development of a capability to fabricate light weight, composite pressure vessels having toroidal geometry. This geometry offers unique packaging advantages for pressurized material and energy storage reservoirs in re-entry vehicle applications.

MATERIALS AND EQUIPMENT

The composite vessels were fabricated by wrapping tapes of graphite material over a thin-walled aluminum bladder. This material was impregnated with an epoxy resin that was subsequently thermally cured.

LINER

The liners were designed by Arde' Inc. and fabricated by O.W. Landergren, Inc. of Pittsfield, Mass. They were produced by welding the two toroidal half-shells along their girth. The half shells were formed from 6061-0 aluminum sheet material. Two 0.250 inch aluminum fill tubes are welded into one bladder half prior to joining. The major diameter of the finished bladders was ten inches and the minor diameter was 2.50 inches. Their minimum wall thickness was 0.075 inches. Except for the eighth unit, the finished bladders were heat treated and aged to a T6 condition. Figure 1 shows the dimensions of the major features of the bladder. The results from a burst test of a liner is given in Appendix 1.A. A photograph of the burst unit is shown in Figure 2.

FIBER REINFORCEMENT

Tapes, produced from two types of graphite material, were used in this study. All tapes were approximately one inch in width. One lot of material was purchased from Textile Technologies, Inc, of Greenville, SC. These tapes were produced using 12K filament count, Torey T-1000G graphite fiber in both woven and uni-directional form. The woven tape utilized a 0/90 plain weave with 10 tows per inch across the width and 8 tows per inch along the length. The uni-directional tape utilized 10 tows across its width and an E-glass weave in the transverse direction. The amount of E-glass was the minimum required to stabilize the tape.

A second lot of tapes were surplus material from a previous activity. These tapes were produced using 3K filament count, Hercules AS-4 graphite fiber by Eurocabon Tilburg B.V. of Tilburg, Holland in both woven and uni-directional form. The woven material utilized a 0/90 plain weave with 18 tows per inch across its width and 16 tows per inch along its length. The uni-direction material has 22 tows across the width and an E-glass weave in the transverse direction.

EPOXY RESIN SYSTEM

The resin system used to fabricate the units consist of a stoichiometric mixture of Shell EPON 828 epoxy resin and Ethyl Ethacure 100-A1 curing agent. The EPON 828 resin is an Epichlorohydrin/bisphenol A type diepoxide material with an equivalent weight of approximately 188. The Ethacure is a Diethyltoluene-diamine hardner with an epoxy equivalent weight of 45. The hardner contained a proprietary accelerator. This system was selected because it exhibited good physical properties and a viscosity that provided adequate resin coating while still allowing adequate impregnation of the woven material.

FM 73M film adhesive was used in fabricating one of the units. This is a filled epoxide adhesive film produced by CYTEC Industries Inc. of West Patterson New Jersey. It contains approximately 10% fiberglass and graphite fiber filler.

EQUIPMENT

A machine, designed for wrapping toroidal electrical coils, was used in fabrication of the toroidal vessels. This machine was manufactured by the Universal Manufacturing Company, Inc of Irvington, NJ and consists of a model UST machine base with a #16 roller table having 3-1/2 inch rollers. The winding head, used in this study, was the model 14TP, designed for winding tapes up to one inch in width. The machine, with the 14TP winding head installed, is shown in Figure 3.

The toroidal bladder is held in the machine by three rollers. Tape material is loaded onto a rotating ring located in the winding head. Roller type bearings, located on the inside of the ring, allow the material to traverse around the ring. These bearings can be seen in Figure 4. The tape material exits the ring from the inside and wraps around the mandrel as the ring rotates. Simultaneously, the mandrel is rotated in the horizontal plane to produce a helical wrap about the minor axis of the torus, see Figure 5.

A band, located on the outer periphery of the loaded material, provides drag to the material as it rotates within the head. This produces tension in the material as it is being wrapped. A problem with this system arises because the tension on the band is supplied by a spring. As the amount of material in the winding head varies, the load on the spring varies, and the tension on the tape varies. It was not possible to properly regulate the tension on the tape with this system.

To correct the problem, the spring was removed and a piece of string was attached to the plunger. The string passed over a pulley and a weight was affixed to the end. This system provided constant tension on the internal band and produced a more uniform tension during the winding operation. Elements of the system can be seen in the upper portion of Figures 3 and 5.

FABRICATION AND TEST

FABRICATION OF FIRST UNIT

Prior to winding, the bladder was cleaned using acetone and steel wool and a layer of FM 73 film adhesive was applied. The film adhesive was applied by hand, wrapping one inch wide strips in a helix. The pitch of the helix was such that successive strips lay adjacent to each other at the periphery of the torus. The weight of the bladder was 549.0 grams and 52.7 grams of FM 73 adhesive was applied.

Graphite tape was wound over the bladder using a lead rate such that each wrap overlapped the succeeding by approximately 50% at the outer diameter of the torus. This provided a uniform stacking of material layers and was a condition that could be visually observed and controlled. A 200-gram weight was applied to the tensioning device during all the winding operations.

The sequence used for winding the graphite material was to wind a layer of woven material, a layer of unidirectional, and a second layer of woven material. After each layer was wound, the part was removed from the machine and saturated with epoxy resin. The excess resin was wiped off and the part placed back in the machine. Wrapping of the woven material is shown in Figure 4 while winding of uni-directional material is shown in Figure 6. The amount of woven material applied was 286.8 grams while 108.9 grams of uni-directional material were applied. The direction of the helix advance was the same for all layers.

It was not possible to load enough material into the winding head to wind a complete layer; therefore, splices were required. The procedure used for splicing was to manually hold the end of the new material in place while the next several wraps were wound. The weight was removed from the tensioning device during this process. This technique seems to work reasonably well but did result in some irregularity of the wound structure.

Another irregularity in the winding was produced by the presence of the stem. The technique used to accommodate this perturbation was to cut the material, adjacent the stem, half way across its width. The stem could then protrude through the cut

material without perturbation of the winding.

Following completion of the winding, the part was wrapped with two inch wide shrink tape. The purpose of the tape was to produce consolidation on the composite material and force out the excess resin. The shrink tape was wrapped in a helix so that successive wraps overlapped by one third its width. It was heated by a hand-held heat gun to shrink the tape and seal the part. The part was then placed in an oven and cured. Figure 7 shows the part prior to being place into the oven for curing.

The part was cured for five hours at 70°C then heated to 90° C where it was cured for six hours. It was then heated to 120° C and cured for another six hours. In each case the heating rate was such that a thirty minute interval was utilized to ramp between subsequent temperature level. After completion of the cure, the part was removed from the oven and the shrink tape removed. The weight of the completed part was 1261.0 grams.

TEST OF THE FIRST UNIT

The exterior appearance of the unit was not good. There was nonuniformity in diameter and 'kinking' of the material due to compressive strains produced by the radial compaction of the shrink tape.

Several strain gages were attached to the outside of the vessel and the unit hydrostatical pressurized to failure. The unit suffered an axial type failure at 7,800 psi. pressure. Data from the test is given in Appendix A.2, the failed unit is shown in Figure 8.

It appeared that the failure occurred in the bond layer between adjacent layers of the woven material. The low strain at burst indicated that the liner and composite were not fully strained to their maximum strain capability of 0.015 in/in. Epoxy saturation in the area of failure was poor.

FABRICATION OF SECOND UNIT

In an attempt to increase the strength of the resulting unit, several changes were made in the fabrication process. One of the changes was to replace the layer of uni-directional material with an additional layer of woven material. It was thought that this should result in a slight reduction in the hoop strength but an increase in the axial strength.

Another change was to reverse the helix direction with each layer. The resulting crossing pattern was thought to provide additional reinforcing of the inner-layer bond. As with the first unit, the pitch of the helix produced a 50% overlap of

adjacent wraps.

To improve the impregnation of the fiber the resin was heated to approximately 40°C prior to application. This reduced the viscosity of the resin and allowed it to better penetrate the wound material. After application, the resin was 'spot heated' locally using a hand-held heat gun to further enhance penetration.

Prior to winding, the bladder was cleaned with acetone and steel wool but no FM 73 film adhesive was applied. After wrapping, the part was placed in an oven and cured. It was not wrapped with shrink tape, as was done with the first part.

While curing, the part was supported in a fixture and rotated about the axis of the torus. Figure 9 shows the part mounted in the supporting fixture. The unit was cured for five hours at 70°C then heated to 90° C where it was cured for six hours. It was then heated to 120° C and cured for another six hours and finally to 150°C where it was cured for another six hours. In each case, the heating rate was such that a thirty minute interval was utilized to ramp between each temperature level.

The second unit contained 448.4 grams of woven material and 353.8 grams of epoxy. This combined with the 549.0 gram bladder resulted in a final part weight of 1360.2 grams.

TEST OF THE SECOND UNIT

Several strain gages were attached to the outside of the vessel and the unit was hydrostatical pressurized to failure. The unit failed at 9550 psi. pressure. This represented a significant improvement over the performance of the first unit. The results of the test are given in Appendix A.3. Again, it appeared that the failure was due to inadequate bond between adjacent layers of the woven material. Epoxy saturation in the area of failure was much better than that obtained in the first unit.

FABRICATION OF THIRD UNIT

In an attempt to increase the axial strength of the third unit three belts of uni-directional material graphite material were wrapped around the periphery of the liner prior to wrapping the woven material. The belts of uni-directional material can be seen in Figure 5. Two of the belts were placed side-by-side and the third belt was centered on top of the first two. The belts were 'tacked' in place using 5-minute epoxy.

Two layers of woven material were wrapped over the uni-directional belts. The material was wrapped with a 50% overlay and the helix direction was reversed with each layer. A single layer of uni-directional material was wrapped on the outside. Between winding of each layer the part was removed from the machine and coated with heated resin. The same cure cycle that used to cure the second part was used to cure this part.

The finished unit contained 292.5 grams of woven material and 122.1 grams of uni-directional material. The later includes 14.0 grams in the belt. There was also 307.8 grams of epoxy. This combined with the 566.4 gram bladder resulted in a final part weight of 1288.8 grams.

TEST OF THE THIRD UNIT

Several strain gages were attached to the outside of the vessel and the unit was hydrostatical pressurized to failure. The unit failed at 9100 psi. pressure. A photograph of the failed unit is shown in Figure 10, test results are given in Appendix A.4. Failure was of an axial nature due to inadequate bond between adjacent layers of the woven material. The use of unidirectional belts did not significantly improve the performance of the unit.

FABRICATION OF FOURTH UNIT

In the previous units, the low axial strength seemed to be due to inadequate inner-laminar strength between adjacent layers of wrapping. In the fourth unit the winding pattern was modified so as to increase the number of layers. By increasing the number of layers the average stress in the individual layers is reduced. This was accomplished by wrapping the material with a pitch that produced side-by-side layering, rather than the 50% overlap used on the previous units, and doubling the amount of layers wound. The side-by-side layering increased the pitch of the wrap, relative to the 50% overlay wrap. With this approach, it was also possible to load enough material to wind a complete layer; therefore, splices within the layers were eliminated.

An additional change that was introduced in the fabrication of this unit was to use tapes produced from Hercules AS-4 graphite fiber rather than the Toray T-1000G material. Using the 3K tow Hercules material rather than the 12K tow of the Torey material resulted in thinner tapes that produced thinner layers.

Another significant factor is that the quality of the weaving in the AS-4 material was much superior to that of the Toray material. Because of its larger tow size, the Toray material produces a much coarser weave. There are also more

imperfections present in the woven Toray tapes. The handling characteristics of the woven AS-4 material were also much better which resulted in a higher quality fabrication operation.

Eight layers of woven material were wrapped over the bladder with the direction of wrapping reversed with each layer. As before, the part was removed from the machine and coated with heated resin between the winding of each layer. The unit was cured using the cure cycle used for the previous unit.

The fourth unit contained 448 grams of woven material and 322 grams of epoxy. This combined with the 558.9 gram bladder resulted in a final part weight of 1328.9 grams.

TEST OF THE FOURTH UNIT

Several strain gages were attached to the outside of the vessel and the unit was hydrostatically pressurized to failure. The unit failed at 8190 psi. pressure. The failure was not the axial type failure as seen in the previous units but a 'clamshell' type rupture as seen in test of the unwrapped liner, see Figure 11. Test results are given in Appendix 5.A.

It appeared that the modifications incorporated into the fabrication of this unit resulted in an adequate bond between adjacent layers to prevent the axial type mode of failure exhibited by the previous units.

FABRICATION OF THE FIFTH AND SIXTH UNITS

The fifth and sixth units were fabricated using identical fabrication techniques. Six layers of woven Hercules AS-4 material and one layer of uni-directional material were wrapped over the bladder with the direction of wrapping reversed with each layer. As with unit four, the winding pitch was adjusted to produce side-by-side lay down. The parts were removed from the machine and coated with heated resin between the winding of each layer. They were cured using the cure cycle used for the previous units.

The fifth unit contained 333.8 grams of woven material and 76.3 grams of uni-directional material. This combined with 304.7 grams of epoxy and the 558.9 gram bladder resulted in a final part weight of 1270.6 grams.

The sixth unit contained 334.9 grams of woven material and 87.5 grams of uni-direction material. This combined with 269.2 grams of epoxy and the 557.6 gram bladder resulted in a final part weight of 1249.2 grams.

TEST OF THE FIFTH UNIT

Several strain gages were attached to the outside of the vessel and the unit was hydrostatical pressurized to failure. The unit failed at 9850 psi. pressure. The mode of failure was a 'clamshell' type rupture that appeared to initiate in the girth weld of the bladder. Data from the test is given in Appendix A.6.

TEST OF THE SIXTH UNIT

The sixth unit was not tested.

FABRICATION OF THE SEVENTH AND EIGHTH UNITS

The seventh and eighth units were fabricated using similar fabrication techniques. Six layers of woven Torey T-1000G material and one layer of uni-directional material were wrapped over the bladder with the direction of wrapping reversed with each layer. The winding pitch was adjusted to produce side-by-side lay down. The parts were removed from the machine and coated with heated resin between the winding of each layer. They were cured using the cure cycle used for the previous units.

The seventh unit contained 411.2 grams of woven material and 74.2 grams of uni-directional material. This combined with 362.4 grams of epoxy and the 559.8 gram bladder resulted in a final part weight of 1407.6 grams.

The eighth unit contained 447.5 grams of woven material and 89.6 grams of uni-direction material. This combined with 403.1 grams of epoxy and the 560.0 gram bladder resulted in a final part weight of 1500.2 grams. The bladder for this unit was in an annealed condition. The bladders for all other units were heat treated to a T6 condition.

TEST OF THE SEVENTH UNIT

Several strain gages were attached to the outside of the vessel. The unit was proof tested to 7500 psi., cycled fifty times between zero and 5000 psi, then hydrostatically pressurized to failure. The unit failed at 11800 psi. pressure. The mode of failure was an axial rupture across the two stems, see Figure 12. Data from the test is given in Appendix A.7.

TEST OF THE EIGHTH UNIT

Several strain gages were attached to the outside of the vessel and the unit was hydrostatical pressurized to failure. The unit failed at 12000 psi. pressure. The mode of failure was an axial splitting across the sections containing the stems. A photograph of the failed unit is shown in Figure 13, data from the test is given in Appendix A.8.

EVALUATION OF PERFORMANCE

One measure that is commonly used to rate the performance of pressure vessels is to divide the product of the burst pressure and internal volume by the weight of the vessel (PV/W). For a vessel containing an ideal gas this is a measure of the stored energy per unit weight of the vessel. It is also a measure of the amount of gaseous material that can be contained per unit weight of the vessel. Because this measure is not dimensionless, it is only appropriate for comparing vessels that have the same size and geometry. To obtain an evaluation of the toroidal composite vessels their performance was compared to values that could be expected from metal vessels having similar geometry.

The maximum stress in a thin-walled toroidal pressure vessel occurs at the inside diameter of the torus and is given by

$$\sigma = (pb/t)(r + a)/(2r)$$

where p is the internal pressure, b is the minor diameter of the torus, t is the wall thickness, a is the radius of the center-line of the torus, r is the radius to the inside of the torus. For the vessel under consideration

$$\begin{aligned}a &= 3.75 \text{ in.} \\b &= 2.5/2 = 1.25 \text{ in.} \\t &= .075 \text{ in.}\end{aligned}$$

and

$$r = 3.75 - 1.25 = 2.5 \text{ in.}$$

The 6061-T6 aluminum liner that was hydrostatically tested burst at a pressure 1790 psi. The calculated maximum stress at failure is 37,000 psi. This is in reasonable agreement with the quoted mechanical properties for the 6061-T6 aluminum of

$$\begin{aligned}\text{Yield strength: } & 35,000 \text{ psi.} \\ \text{Ultimate strength: } & 41,000 \text{ psi.}\end{aligned}$$

The demonstrated performance for the SN006A liner was $PV/W = .147 \times 10^6$, the estimated performance of other metal liners having the same toroid geometry is given in Table 1.

Best PV/W performance of the Al liner/T-1000 Composite Toroid is $.393 \times 10^6$ (Wrap # 7). Neglecting the liner, the composite $PV/W = .550 \times 10^6$ maximum (Wrap # 8). Note that Arde's spherical and cylindrical composite vessels have PV/W at $.900 \times 10^6$ to 1.4×10^6 range.

Performance values for the composite vessels fabricated in this study are given in Table 2. The test data showed that the final fiber wrapping technique employed in the toroidal composite test

program had a PV/W of $.377 \times 10^6$ to $.393 \times 10^6$ which is just slightly higher than an all-metal toroid made of Titanium. Therefore, the current wrapping technique does not produce vessels with significantly better performance than can be obtained from metal vessels having the same geometry.

The improvement needed in the toroidal composite vessel is to increase the structural support in the axial direction. This mode of failure is evident in the photographs of the failed units and from the low strain reading measured in the axial direction at burst. The liner material is capable up to .1800 in./in. (uniaxial) as tested separately and the T1000 composite is capable up to .0150 in./in. as demonstrated in other cylindrical and spherical composite pressure vessels manufactured by Arde'.

CONCLUSIONS

This study demonstrated that toroidal pressure vessels having reasonable performance can be fabricated by the process described in this report. It appears that higher performance can be obtained when smaller tow size material is used to fabricate the woven material.

INVENTIONS

No patentable inventions were developed.

COMMERCIAL VALUE

If improvement in the process leads to realization of the strength potential of the composite material and subsequent improvement in vessel performance then there is a potential market in excess of one million dollars over a five year period.

FUTURE COLLABORATION

There are currently no plans for future collaboration on this project.

Table 1: Estimated performance of metal pressure vessels

<u>Liner material</u>	<u>F_{tu}</u>	<u>Density</u>	<u>Weight</u>	<u>Burst Pressure</u>	<u>PV/W</u>
Al 6061-T6	41	.10	1.256	1790	.147x10 ⁶
Inconel 718, STA	180	.297	3.73	7858	.218x10 ⁶
Ti 6Al-4V, STA	165	.16	2.01	7204	.370x10 ⁶
Custom 455, H950	225	.28	3.517	9823	.289x10 ⁶

Table 2. Performance of composite pressure vessels

<u>Wrap</u>	<u>Weights (lbs.)</u>			<u>Volume (cu. in.)</u>	<u>Burst (psi.)</u>	<u>PV/W (in.)</u>
	<u>Liner</u>	<u>Composite</u>	<u>Total</u>			
-	1.256	-	-	103.4	1790	.147x10 ⁶
1	1.210	1.569	2.779	104.0	7800	.292x10 ⁶
2	1.230	1.768	2.998	103.6	9650	.334x10 ⁶
3	1.248	1.593	2.841	103.2	9100	.331x10 ⁶
4	1.232	1.698	2.930	103.26	8190	.290x10 ⁶
5	1.225	1.577	2.802	103.82	9850	.365x10 ⁶
6	1.229	1.524	2.753	Not tested		
7	1.234	1.868	3.102	103.23	11800	.393x10 ⁶
8	1.234	2.071	3.305	103.87	12000	.377x10 ⁶

SECTION A-A

SECTION C-C
TYP. 2 PLACES
SCALE: 2:1

SECTION B-B
TYP. 2 PLACES
SCALE: 2:1

8. COMPONENTS TO BE CLEANED PRIOR TO CLOSURE WELD.
7. STARTING SHEET THICKNESS .062. THICKNESS AFTER FORMING .052 MINIMUM.
6. SOLUTION HEAT TREAT AND AGE TO T6 CONDITION AFTER WELDING.
5. CLEAN PER AES 384 OR EQUIVALENT.
4. RADIOGRAPH PER AES 450 AND INSPECT PER NAS 1514 CLASS I.
3. PENETRANT INSPECT PER AES 455 AND 551.
2. WELD PER ASME SECTION IX OR MIL-W-8611 USING WELD WIRE AL 4043 PER AWS A5.10.
1. IDENTIFY PER AES 601, METHOD D.

NOTES:

2	2	SKB12861	PRESSURE STEM	AL6061-0100-A-225			
2	1	SKD12857	TOROIDAL HEAD	AL6061-0100-A-250			
			LINER, TOROIDAL				
QTY REQD PER DASH NO.	ITEM NO.	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	
PARTS LIST							
UNLESS OTHERWISE SPECIFIED			DRAWN BY	J BRUNO	10/31/95	ARDE, INC. NORWOOD, N.J.	
DIMENSIONS ARE IN INCHES			CHECKER				
TOLERANCES			MEL ENGR			TITLE LINER, TOROIDAL	
.125 - .1250 .0005			STRESS ENGR				
.125 - .1250 .0005			PROD ENGR			SIZE CAGE CODE D 05980	
.125 - .1250 .0005			MATL ENGR				
.125 - .1250 .0005			WEL			SKD12857	
.125 - .1250 .0005			QUAL CONTROL				
.125 - .1250 .0005			PROD MGR				
NEXT ASSEMBLY							
SKD12860							

Figure 1. Pressure vessel liner.

Figure 2. Aluminum liner after burst test.

Figure 3. Toroidal winding machine with tape winding head.

Figure 4. Inside view of tape winding ring.

Figure 5. Winding head dispensing woven graphite tape.

Figure 6. Winding of uni-directional graphite tape.

Figure 7. Wound unit wrapped with shrink tape.

Figure 8. First unit after completion of burst test.

Figure 9. Fixture for rotating part during cure.

Figure 10. Third unit after completion of burst test.

Figure 11. Fourth unit after completion of burst test.

Figure 12. Seventh unit after completion of burst test.

Figure 13. Eighth unit after completion of burst test.

Appendix A.1. Liner Test Results

P/N SKD 12860, SN 006A - liner
Only

Description: Liner made of
Aluminum 6061-T6 condition.

Weight = 1.256 Lb.

Before Test	Post test
D1 = 10.011/10.010 in.	10.010/9.990 in.
D2 = 4.963/4.955 in.	4.903/4.889 in.
D3 = 2.490/2.496/2.483/2.488 in.	2.584/2.592/2.595/2.613 in.
D4 = 2.523/2.525/2.527/2.528 in.	2.557/2.540/2.550/2.551 in.
$t_{\text{liner}} = .075$ in. min	.048/.051/.046 in.

Tare weight with fittings = 1.372 lb.

Filled weight = 5.102 lb.

Water weight = 3.730 lb.

Temperature = 70.2 F

Specific gravity = .99800

Volume = 103.453 cu. in.

Burst pressure: Transducer = 1790 psi.
Gauge = 1750 psi.

Strain by dimensional change:

D1 = $-.00105$ in/in. (Axial)
D2 = $-.01270$ in/in. (Axial)
D3 = $.04288$ in/in. (Meridional)
D4 = $.00940$ in/in. (Meridional)

Liner Burst Performance, $PV/W = 1790(103.45)/1.256$
 $= .147 \times 10^6$ in.

Mode of Failure: Clamshell rupture on the ID of the toroid at approximately one inch above the ID weld split line. This is the typical failure mode for a constant thickness toroid, where the meridional stress at the ID is the greatest and the axial stress is about half the value. The liner has a robust weld underbead (.125 thick x .25 wide), hence rupture is away from this ID split line but bias to the ID side.

Appendix A.2. Results from test of first unit

P/N SKD 12860, Wrap # 1

Liner # A - Al 6061-T6

Description: Fiber is Toray 1000. Two layers of woven tapes with one layer of unidirectional tape in between. All tapes wound with 50% overlay.

Liner Weight = 1.210 lb.
FM 73 = .116 lb.
Woven Fiber = .632 lb.
Unidirectional = .240 lb.
Epoxy Resin = .581 lb.

Total Weight = 2.780 lb

Before Test

$D1 = 10.228/10.259$ in.

$D3 = 2.872/2.890$ in.

$t_{\text{liner}} = .075$ in. min.

Tare weight with fittings = 3.566 lb.

Filled weight = 7.330 lb.

Water weight = 3.764 lb.

Temperature = 80F

Specific gravity = .99663

Volume = 104 cu. in.

Burst pressure: Transducer = 7800 psi.

Strain at burst: $S_{\text{axial}} = .0040$ in./in, $S_{\text{merid.}} = .0045$ in./in.

Assembly Burst Performance, $PV/W = 7800(104)/2.78$
 $= .292 \times 10^6$ in.

Composite Burst Performance, $PV/W = (7800 - 1790)(104)/1.570$
 $= .398 \times 10^6$ in.

Mode of Failure: Rupture is an inner-laminar shear between turns/wrap in the axial direction with liner fracture across the 2.5 in. diameter cross-section. The failure mode indicates a lack of support in the axial direction. The low strain at burst indicates that the liner and composite were not fully strained to their maximum capability of approximately .015 in/in.

Appendix A.3. Test results from second unit

P/N SKD 12860, Wrap # 2

Liner # 7 - Al 6061-T6

Description: Fiber is Toray 1000. Three layers of woven tape wrapped with 50% overlap.

Liner Weight = 1.230 lb.
Woven Fiber = .988 lb.
Epoxy Resin = .780 lb.
Total Weight = 2.998 lb

Before Test

D1 = 10.334/10.280 in.
D2 = 4.460/4.465 in.
D3 = 2.914/2.960/2.860/2.795 in.
D4 = 2.937/2.908 in.
 $t_{\text{liner}} = .075$ in. min.

Tare weight with fittings = 3.144 lb.
Filled weight = 6.846 lb.
Water weight = 3.732 lb.
Temperature = 79.4 F
Specific gravity = .99678
Volume = 103.640 cu. in.

Burst pressure: Transducer = 9500 psi.
Gauge = 9650 psi.

Strain at burst: $S_{\text{axial}} = .004$ in./in. , $S_{\text{merid.}} = .00965$ in./in.

Assembly Burst Performance, $PV/W = 9650(103.64)/2.998$
 $= .334 \times 10^6$ in.

Composite Burst Performance, $PV/W = (9650 - 1790)(103.64)/1.768$
 $= .460 \times 10^6$ in.

Mode of Failure = Rupture is similar to a "bullet hole exit" at the OD of the toroid and the rupture line propagated around the 2.5 in. diameter cross-section. The fiber failed in an inner-laminar shear between turn/wrap.

Appendix A.4. Results from test of third unit

P/N SKD 12860, Wrap # 3

Liner # 1 - Al 6061-T6

Description: Fiber is Toray 1000. Wrapped with two layers of woven tape and one layer of unidirectional tape. All layers wound with 50% overlap. A belt of unidirectional material was wrapped adjacent the liner in the axial direction.

Liner Weight = 1.248 lb.
Woven Fiber = .645 lb.
Unidirectional = .238 lb.
Fiber Belt = .031 lb.
Epoxy Resin = .678 lb.

Total Weight = 2.841 lb.

Before Test
D1 = 10.332/10.312 in.
D2 = 4.532/4.502 in.
D3 = 2.790/2.830/2.800/2.830 in.
D4 = 2.937/2.908 in.
 $t_{\text{liner}} = .075$ in. min

Post test
10.386/10.370 in.
4.545/4.543 in.
2.830/2.823/2.876/2.844 in.
2.908/2.933/2.947/2.970 in.
.065 in.

Tare weight with fittings = 2.964 lb.
Filled weight = 6.682 lb.
Water weight = 3.718 lb.
Temperature = 79.4 F
Specific gravity = .99678
Volume = 103.247 cu. in.

Burst pressure: Transducer = 8950 psi.
Gauge = 9100 psi.

Strain at burst: $S_{\text{axial}} = .00245$ in./in., $S_{\text{merid.}} = .00695$ in./in.

Strain by dimensional change:

D1 = .0054 in./in. (Axial)
D2 = .0060 in./in. (Axial)
D3 = .0109 in./in. (Meridional)
D4 = .0058 in./in. (Meridional)

Appendix A.4. (Cont.) Results from test of third unit

Assembly Burst Performance, $PV/W = 9100(103.247)/2.841$
 $= .331 \times 10^6 \text{ in.}$

Composite Burst Performance, $PV/W = (9100 - 1790)(103.247)/1.593$
 $= .474 \times 10^6 \text{ in.}$

Mode of Failure: Rupture is similar to a "bullet hole exit" at the outside diameter of the toroid with a rupture line propagating around the 2.5 in. diameter cross-section. The fiber failed between turn/wrap.

Appendix A.5. Results from test of fourth unit

P/N SKD 12860, Wrap # 4

Liner # - Al 6061-T6

Description = Eight layers of woven AS4 wrapped with side-by-side laydown.

Liner Weight = 1.232 lb.

Woven Tape = .988 lb.

Epoxy Resin = .710 lb.

Total Weight = 2.930 lb.

Before Test

D1 = 10.331/10.280 in.

D2 = 4.405/4.325 in.

D3 = 2.846/2.840/2.823/2.879 in.

D4 = 2.996/2.930/2.994/2.961 in.

t_{liner} = .075 in. min.

Post test

10.330/10.292 in.

4.452/4.360 in.

2.850/2.866/2.857/2.862 in.

2.938/2.941/2.957/2.975 in.

.047/.055/.054 in.

Tare weight with fittings = 3.044 lb.

Filled weight = 6.780 lb.

Water weight = 3.736 lb.

Temperature = 70.2 F

Specific gravity = .99800

Volume = 103.620 cu. in.

Burst pressure: Transducer = 8190 psi.

Gauge = 8120 psi.

Strain at burst: S_{axial} = .00250 in./in., $S_{\text{merid.}}$ = .00710 in./in.

Strain by dimensional change:

D1 = .00053 in/in. (Axial)

D2 = .00939 in/in. (Axial)

D3 = .00413 in/in. (Meridional)

D4 = -.00589 in/in. (Meridional)

Appendix A.5. (Cont.) Results from test of fourth unit

Assembly Burst Performance, $PV/W = 8190(103.62)/2.93$
 $= .290 \times 10^6 \text{ in.}$

Composite Burst Performance, $PV/W = (8190 - 1790)(103.62)/1.70$
 $= .390 \times 10^6 \text{ in.}$

Mode of Failure: Clamshell rupture on the inside diameter of the toroid approximately 1.5 in. above the weld split line. Failure mode similar to that of liner only test.

Appendix A.6. Results from test of fifth unit

P/N SKD 12860, Wrap # 5

Liner # 3A - Al 6061-T6

Description = Fiber is AS4. There are six layers of woven and one layer of unidirectional material.

Liner Weight = 1.225 lb.
Woven Tape = .736 lb.
Unidirectional = .168 lb.
Epoxy Resin = .672 lb.

Total Weight = 2.802 lb.

Before Test		Post test	
D1 = 10.273/10.289 in.		10.328/10.303 in.	
D2 = 4.493/4.455 in.		4.550/4.541 in.	
D3 = 2.796/2.820/2.951/2.830 in.	2.810/2.814/2.933/2.873 in.		
D4 = 2.916/2.864/2.838/2.996 in.	2.907/2.871/2.927/2.835 in.		
t _{liner} = .075 in. min.		.053/.055/.054 in.	

Tare weight with fittings = 2.918 lb.
Filled weight = 6.662 lb.
Water weight = 3.744 lb.
Temperature = 68 F
Specific gravity = .99823
Volume = 103.82 cu. in.

Burst pressure: Transducer = 9850 psi.
Gauge = 9850 psi.

Strain at burst: $S_{axial} = .004$ in./in. $S_{merid.} = .0055$ in./in.

Plastic Strain by dimensional change:

D1 = .00335 in/in. (Axial)
D3 = .00289 in/in. (Meridional)
D4 = -.00637 in/in. (Meridional)

Appendix A.6. (Cont.) Results from test of fifth unit

Assembly Burst Performance, $PV/W = 9850(103.82)/2.802$
 $= .365 \times 10^6 \text{ in.}$

Composite Burst Performance, $PV/W = (9850 - 1790)(103.82)/1.577$
 $= .531 \times 10^6 \text{ in.}$

Mode of Failure = Clamshell rupture on the OD of the toroid at the girth weld line 4" wide x 2" deep on each hemi-toroid.

Appendix A.7. Results from test of seventh unit

P/N SKD 12860, Wrap # 7

Liner # 4A - Al 6061-T6

Description: Fiber is Toray 1000. There are six layers of woven material and one layer of unidirectional material.

Liner Weight	=	1.234 lb.
Woven Tape	=	.906 lb.
Unidirectional	=	.163 lb.
Epoxy Resin	=	<u>.799 lb.</u>
Total Weight	=	3.102 lb

Before Test	Post Proof	Post Burst
D1 = 10.327 in.	10.341 in.	10.395 in.
D2 = 4.361 in.	4.366 in.	4.405 in.
D3 = 2.943 in.	2.967 in.	2.925 in.
D4 = 2.938/3.028 in.	3.034/2.941 in.	3.060/2.980 in.
t _{liner} = .075 in. min.		.055 in

Tare weight w/fittings =	3.238 lb.	3.238 lb.
Filled weight =	6.960 lb.	6.994 lb.
Water weight =	3.722 lb.	3.756 lb.
Temperature =	70 F	70 F
Specific gravity =	.9980	.9980
Volume =	103.23 cu. in.	104.17 cu. in.

Prior to Burst: 7500 psi. proof, 50 cycles at 0 to 5000 psi.

Burst pressure: Transducer = 11800 psi.
Gauge = 11800 psi.

Strain at burst: $S_{axial} = .00675$ in./in., $S_{merid.} = .0052$ in./in.

Plastic Strain by dimensional change:

	Post Proof	Post Burst
D1 =	.00135 in/in.	.00658 in/in. (Axial)
D3 =	.00815 in/in.	-.00612 in/in. (Meridional)
D4 =	.00151 in/in.	.0124 in/in. (Meridional)

Appendix A.7. (Cont.) Results from test of seventh unit

Assembly Burst Performance: $PV/W = 11800(103.23)/3.102$
 $= .393 \times 10^6 \text{ in.}$

Composite Burst Performance:

$$PV/W = (11800 - 1790 \times 2)(103.23)/1.868 = .454 \times 10^6 \text{ in.}$$

Mode of Failure: The toroid split in half across the two pressure stems. Woven tape fiber failed in shear.

Appendix A.8. Results from test of eighth unit

P/N SKD 12860, Wrap # 8

Liner # 5A - Al 6061-T4 (Annealed)

Description = Fiber is Toray 1000. There are a six layers of woven material and one layer of unidirectional material.

Liner Weight	=	1.234 lb.
Woven Tape	=	.986 lb.
Unidirectional	=	.197 lb.
Epoxy Resin	=	<u>.888 lb.</u>
Total Weight	=	3.305 lb.

Before Test
D1 = 10.363 in.
D2 = 4.374 in.
D3 = 3.010 in.
D4 = 3.024/2.965 in.
 t_{liner} = .075 in. min.

Post Burst
10.467 in.
4.418 in.
2.841 in.
3.075/2.974 in.
.049 in.

Tare weight w/fittings = 3.435 lb.
Filled weight = 7.180 lb.
Water weight = 3.745 lb.
Temperature = 70 F
Specific gravity = .9980
Volume = 103.87 cu. in.

Burst pressure: Transducer = 12000 psi.
Gauge = 12000 psi.

Plastic Strain by dimensional change: (Post Burst)

D1 = .0100 in/in. (Axial)
D4 = .0100 in/in. (Meridional)

Assembly Burst Performance: $PV/W = 12000(103.87)/3.305$
 $= .377 \times 10^6 \text{ in.}$

Composite Burst Performance:

$PV/W = (12000 - (1790 \times 10/35) \times 2)(103.87)/2.071$
 $= .550 \times 10^6 \text{ in.}$

Mode of Failure: The toroid split in half across the two pressure stems. Woven tape fiber failed in shear.

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