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LIGHTWEIGHT COMPOSITE PRESSURE VESSELS

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FOREWORD

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LIGHTWEIGHT COMPOSITE PRESSURE VESSELS

ABSTRACT

We have fabricated organic and graphite fiber/epoxy pressure vessels (10.2 cm diam) and have lined some of them with alternating layers of rubber and polymer and some of them with aluminum. We subjected the vessels to permeation tests, fatigue cycling, and burst tests and measured the performance (pressure $\times$ volume/mass), fatigue life, and leak rates of the vessels. Both liners performed well. Next we fabricated proportionately larger pressure vessels and subjected them to the same tests and measurements mentioned above. We encountered liner leakage problems in both the polymer- and aluminium-lined vessels. We have identified some of the causes of the leaks and have recommended some solutions.

INTRODUCTION

We have been evaluating the performance of Kevlar 49^{*} epoxy composite material systems in lightweight filament-wound pressure vessels. That evaluation included:

- Characterizing the tensile properties of the fiber in an epoxy matrix^{1,2}
- Developing the optimum design for filament winding³
- Studying the stress-rupture behavior of fiber/epoxy strands⁴
- Comparing the performance of cylindrical and spherical vessels at room and liquid hydrogen temperatures⁵
- Studying how effectively polymer liners contain nitrogen⁶
- Measuring the cyclic fatigue life of 10.2-cm-diam vessels⁷

VESSEL DESIGN

In previous experiments,⁶ we have designed and tested four 10.2-cm-diam pressure vessels lined with alternating layers of rubber and polymer (Figs. 1 and 2). Based on that design, we have fabricated two proportionately larger vessels, one 20.3 cm in diameter (approximately twice the size of the 10.2-cm vessel) and one 38 cm in diameter (a full-size replica of the one used by NASA in its tests).

Twenty-one 20.3-cm vessels were wound — the first three with 380 denier fiber, the rest with 1420 denier. Both denier fibers had comparable tensile strength, so switching them did not degrade vessel performance. [Ten tensile tests on the 1420 denier fiber/epoxy strands produced 3,360 MPa (488 ksi) average failure stress vs 3,510 MPa (509 ksi) for the 380 denier.] Furthermore, by switching fibers, we reduced fabrication time to less than one 8-h shift. After winding and testing eight vessels, the winding pattern was fixed (Table 1). Vessels intended for permeation studies were wound on Saran-coated mandrels.

Five 38-cm-diam vessels were wound — four with a special 4-end, 4560 denier roving (Fig. 3). The winding time was approximately 10 h. The fifth vessel was wound with 1420 denier fiber in 22 h. Once again fiber choice was based on length of winding time (10 h vs 22 h) and tensile strength. [Eight elongated NOL rings were wound with 1420 and eight with 4560 fiber. The 1420 fiber had an average failure stress of 2740 MPa (398 ksi); the 4560 had an average failure stress of 2590 MPa (376 ksi).] Table 2 shows the final winding pattern.

Table 3 summarizes the pattern design for the three vessel sizes (see Fig. 1) and Fig. 4 compares the three vessels.

VESSEL TESTS (POLYMER LINER)

Introduction

We subjected the vessels described in the previous section to permeation, fatigue cycling, and burst tests. We were particularly interested in the performance, fatigue life, and leakage problems of the scaled-up vessels. In the following sections, we discuss the three vessel sizes in turn, the tests we made on them, and the results of those tests.

Fig. 1. Typical dimensions of a 10-cm filament-wound vessel. Coatings are not shown.⁶

Fig. 2. Wall cross sections of the four vessels tested.⁶

Table 1. Pattern development of rubber-lined 20.3-cm Kevlar 49/epoxy vessels (0.5-mm liner, test temperature 23°C).

	K1	K2	K3	K4	K5	K6	K7
<u>Vessel</u>							
Volume, m ³ (in. ³)	0.009453 (576.7)						
Burst pressure, kPa (psi)	28100 (4075)	29650 (4300)	Leaked	28130 (4080)	29720 (4020)	26340 (3820)	24820 (3600)
Failure location ^a	K + H	K + H	—	H	H	K	H
Fiber performance (PV/W _f), kPa·m ³ /kg	443	436	—	421	414	359	384
Composite performance (PV/W _c), kPa·m ³ /kg	330	333	—	333	313	375	271
<u>Composite</u>							
Composite mass (W _c), kg	0.8043	0.8408	0.8533	0.7990	0.8376	0.9309	0.8653
Fiber mass (W _f), kg	0.5993	0.6425	0.6390	0.6324	0.6336	0.6944	0.6110
Fiber content, vol%	70.5	72.2	71	75.9	71.3	70.5	66.5
<u>Winding</u>							
Longo angle/winding tension	7°/17.8 N						
Hoop/Longo fiber ratio	1.7:1	1.6:1	1.6:1	1.5:1	1.5:1	1.57:1	1.55:1
Pattern	Closed 36 band						
Hoop	20 Layers	26 Layers	28 Layers	28 Layers	16 Layers	16 layers	16 layers
Interspersing	8 + 12	8 + 18	8 + 18	8 + 20	4 + 12	4 + 12	4 + 12
Total winding circuits	8952	9341	6354	—	2464	2624	2600
Longo	14 Layers	16 Layers	16 Layers	—	8 Layers	8 Layers	8 Layers
Interspersing	None						
Total winding circuits	8316	9216	9216	—	2448	2592	2592
Extra reinforcement: equators (circuits)	Helical 95 + Hoop 80	Hoop 130	Hoop 126	Hoop 30	Hoop 30	Hoop 35	Hoop 40
<u>Resin system (ratio)</u>							
Gelling, h/°C	16/21	58/21	18/21	18/21	18/21	18/21	18/100
Curing, h/°C	3/80						
					2/21	2/121	3/176

^aH — hoop failure; F — fitting failure; K — knuckle failure.

Fig. 3. Mandrel design for 38-cm cylindrical vessels.

Table 2. Winding pattern for 38-cm-diam vessels.

<u>Winding</u>	
Longo angle/winding tension	9° 39'/26.7 N
Pattern	Closed 36 bands
Hoop	26 layers
Interspersing	(8 + 18)
Total winding circuits	2340
Longo	10 layers
Interspersing	(8H + 10L + 18H)
Total winding circuits	4320
Extra reinforcement: equators (circuits)	56 revs per end
<u>Resin system (ratio)</u>	XD 7575.02/XD 7818/ERL 4206/Tonox 60-40 (50/50/30/38)
Gelling (hr/°C)	88/22
Curing (hr/°C)	5/120

Table 3. Summary of pattern design for 10.2- 20.3- and 38-cm diam vessels.

Wall cross section	Vessel size, cm		
	10.2	20.3	38
Butyl rubber liner, cm	0.05	0.05	0.096
Inner hoop wraps	0.018 cm wound at 90°	0.06 cm wound at 90°	0.19 cm wound at 90°
Longitudinal wraps	0.036 cm wound at 12.5°	0.13 cm wound at 7°	0.43 cm wound at 9.67°
Outer hoop wraps	0.035 cm wound at 90°	0.18 cm wound at 90°	0.48 cm wound at 90°

Fig. 4. The three cylindrical pressure vessels of this study.

Tests on the 10.2-cm-diam Vessels

The four 10.2-cm-diam pressure vessels described previously were subjected to permeation⁶ and fatigue cycling tests.⁷ In the permeation tests, the vessels were pressurized with nitrogen in a temperature-controlled ($21 \pm 3^\circ\text{C}$) test cell. Before the tests, the piping and valves in the pressurization system were all leak-checked with helium gas. The four vessels were pressurized to about 11.7 MPa (1700 psig; about 65% of the expected burst pressure based on previous vessels of the same design without coatings). The vessels were then valved off for about 4 h. Then each vessel was topped off to about 11.7 MPa and valved off for the remainder of the test. Four calibrated bourdon-type pressure gages on the vessel side of the isolation valves were used to obtain periodic pressure readings. Three months of data were accumulated and reported.⁶

After ninety days, the vessels were depressurized. Two were then fatigue cycled for 2000 cycles at 20 cycles per minute with a sinusoidal pressure pulse.⁷ (Two control vessels were not fatigued.) The cycling pressure limits were 690 kPa to 11.7 MPa (100 psi and 1700 psig, respectively) or approximately 65% of the expected burst pressure. The two fatigued vessels and the control vessels were then repressurized with nitrogen to 65% of burst pressure. Figures 5 and 6 show the pressure vs time curves for the two fatigue-cycled vessels. In Fig. 5, note that the vessel failed in stress rupture between the 23rd and 26th day, but that it had lost less than 0.5% of its pressure before failure. In Fig. 6, the vessel had a substantially greater leak rate — about 7% pressure loss per month — than it had before cycling. This vessel had only Parylene C coatings. It could not be determined if this increased leak rate was caused by a poor fitting. The two control vessels showed the same small leak rates they had shown in the earlier permeation tests.

Tests on the 20.3-cm-diam Vessels

To determine the effects of scale-up, we fabricated 20.3-cm-diam polymer-lined pressure vessels and subjected them to burst, permeation and fatigue tests. We subjected ten of the vessels (K4-K8 and K19-K23) to burst tests (Tables 1, 4, and 5). Several problems were encountered. First, there was significant liner leakage with four of the vessels. Second, the average composite performance (pressure $\times$ volume/mass) was low, partly because end failures were the primary failure mode. Figure 7 shows the axial and hoop

Fig. 5. Percentage of original nitrogen pressure vs time, vessel 4.

Fig. 6. Percentage of original nitrogen pressure vs time, vessel 2.

Table 4. Rubber-lined 20.3-cm Kevlar 49/epoxy vessels (0.5-mm liner, test temperature 23°C).

Number	K8	K19	K20	K21	K22	K23
<u>Vessel</u>						
Volume (V), m ³ (in. ³)	0.009453 (576.7)					
Burst Pressure, kPa (psi)	31850 4620	28340 4110	28960 4200	31510 4570	29410 4265	29170 4230
Failure location ^a	H+F+K	F	F	F	K	F
Fiber performance (PV/W _f) kPa·m ³ /kg	445	432	442	445	392	399
Composite performance (PV/W _e) kPa·m ³ /kg	313	313	321	348	290	289
<u>Composite</u>						
Composite mass (W _c), kg	0.9620	0.8566	0.8526	0.8556	0.9594	0.9553
Fiber mass (W _f), kg	0.6768	0.6196	0.6189	0.6694	0.7101	0.6907
Fiber content vol%	66.4	68.4	68.5	68.4	70	68.4
<u>Winding^b</u>						
Longo angle/winding tension	7°/17.8 N					
Hoop/longo fiber ratio	1.55:1					
Pattern	Closed 36 bands					
Hoop	16 layers					
Interspersing	4 + 12					
Total winding circuits	2592					
Longo	8 layers					
Interspersing	None					
Total winding circuits	2592					
Extra reinforcement						
Equators (circuits)	40 each end					
Knuckles (circuits)	None					
Resin system (ratio)	7818/T-403 (100/49)					
Gelling (hr/°C)	18/85					
Curing (hr/°C)	3/190					

^aH — hoop failure; F — fitting failure K — knuckle failure.

^bWinding data is the same for all six vessels.

Table 5. Averages of K8, K19, K20, K21, K22, K23 (see Table 4).

	Average	CV ^b
<u>Vessel</u>		
Volume (V), m ³ (in. ³)	←0.009453 (576.8)→	
Burst pressure, kPa	29870	5
(psi)	(4332)	5
Failure location ^a	F	
Fiber performance (PV/W _f), kPa·m ³ /kg	426	6
Composite performance (PV/W _c), kPa·m ³ /kg	312	7
<u>Composite</u>		
Composite mass, (W _c), kg	0.9069	6
Fiber (W _f), kg	0.6642	6
Fiber content, vol%	68.4	2
<u>Winding</u>		
Longo angle/winding tension	7°/17.8 N	
Hoop/longo fiber ratio	1.55:1	
Pattern	Closed 36 band	
Hoop	16 layers	
Interspersing	4 + 12	
Total winding circuits	2592	
Longo	8 layers	
Interspersing	None	
Total winding circuits	2592	
Extra reinforcement:		
Equators (circuits)	40 each end	
Knuckles (circuits)	None	
<u>Resin system</u> (ratio)	7818/T-403 (100/49)	
Gelling (h/°C)	18/85	
Curing (h/°C)	3/190	

^aH - hoop failure; F - fitting failure; K - knuckle failure.

^bCoefficient of variation.

Fig. 7. Recorded axial and hoop strains for the K-23, 20.3-cm vessel.

strain measurements recorded for the K23 vessel. Figure 8 is a photograph of the failed K5 vessel where hoop failure was the primary failure mode.

The failure of the Parylene C and Saran coatings led to changes in manufacture and repair procedures. This problem and various attempted solutions and results are discussed on p.17.

We subjected four of the 20.3-cm vessels to the permeation test. All leaked to zero pressure in just a few days. We then fatigue-cycled four vessels and found significant liner leakage after less than 40 cycles. Suspecting a lack of total cure of the butyl rubber liner, we post-cured the three remaining vessels (originally scheduled for testing by NASA) at 121°C for 3 h. One vessel was burst tested and the other two were cycled to 70% of their expected burst pressure. The burst pressure was 27.6 MPa with no sign of leakage. The cycled vessels lasted 100 cycles and 23 cycles. The failures were caused by leakage through the liner. The liner leakage problem was not fully understood at this point in the experiment.

Tests on the 38-cm-diam Vessels

Four 38-cm-diam vessels were burst tested. The first vessel could not be burst because the rubber liner leaked, (the liner was of poor quality). Subsequent 38-cm vessels were coated before and after winding to prevent leakage (see p.17 for details). The second vessel failed in the hoop wraps at 34.8 MPa (41.4 MPa design pressure) and the third vessel leaked excessively at 34.5 MPa. The leakage was found to be due to failure of the inside coating at the edges of the flanges on the aluminum bosses.

The fourth vessel burst at 35.1 MPa with failure occurring in the hoop wraps. Since the composite performance was low ($212 \text{ kPa} \cdot \text{m}^3/\text{kg}$) the fifth vessel was wound using 1420 denier instead of the 4560 denier fiber. The vessel burst at 32.4 MPa. Because of leakage, a high flow rate was used, which may have contributed to the poor performance. All subsequent vessels were wound using 4560 denier fiber. The sixth vessel failed at 37.2 MPa. The winding pattern for the 38-cm vessel design was now fixed and four additional vessels were wound using this pattern. Table 6 gives the winding pattern and burst test results. The average composite performance was $236 \text{ kPa} \cdot \text{m}^3/\text{kg}$ ($0.95 \times 10^6 \text{ in.}$), with a volume of $43.5 \times 10^3 \text{ cm}^3$. The average burst pressure was 36.0 MPa (5215 psig). The relatively low performance of these vessels can probably be attributed to:

Fig. 8. Hoop failure in the K-5, 20.3-cm vessel.

Table 6. Rubber-lined 38.1-cm Kevlar/epoxy vessel (0.102-cm liner, test temperature 23°C).

Number	15-7	15-8	15-9	15-10
<u>Vessel</u>				
Volume (V), m ³ (in. ³)	← 43,525 (2656) →			
Burst pressure, MPa (psi)	37.5 (5,440)	35.2 (5,110)	36.6 (5,310)	34.5 (5,000)
Failure location ^b	K	K	H	H
Fiber performance (PV/W _f), kPa·m ³ /kg	342	323	335	326
Composite performance (PV/W _c), kPa·m ³ /kg	247	230	245	223
<u>Composite</u>				
Composite mass (W _c), kg	6.600	6.675	6.500	6.725
Fiber (W _f), kg	4.770	4.7492	4.7516	4.609
Fiber content, vol%	68.2	67.2	69.2	64.3

^aSee Table 2 for winding pattern.

^bH — hoop failure; F — fitting failure; K — knuckle failure,

- A thick-wall effect
- The winding pattern
- Residual stresses.

Figure 9 shows a typical hoop failure. Figure 10 gives the recorded hoop strains of the 15-8 and 15-9 vessels (see Table 6). Axial strain measurements are not given in Fig. 10 because erratic gage behavior resulted in erroneous measurements.

LINER LEAKAGE PROBLEM

The rubber/polymer multilayered liner used successfully in the 10-cm vessel design failed consistently in the 20-cm and 38-cm vessels. In both of the larger vessel designs, the quality of the butyl rubber was poor. In the early 20-cm vessels, many liners were found pitted in the dome section (Fig. 11). Also, we found that the butyl rubber was not completely cured. Subsequent vapor deposition of the Parylene C resulted in a cell-like formation (Fig. 12) with no coating at the boundaries of the cells. Vaporization of dissolved solvents in the rubber was the cause. Another problem was that

Fig. 9. Hoop failure of a 38-cm diam Kevlar/epoxy pressure vessel.

Fig. 10. Recorded hoop strains for the 15-8 and 15-9 38-cm vessels.

Fig. 11. The interior of the 20.3-cm vessel, K-11, showing the pitted structure of the liner.

Fig. 12. The interior of the 20.3-cm vessel, K-9, showing the cell-like structure of the Parylene C liner.

we painted the Saran coating on the larger mandrels which did not seem to result in as good a coating as spraying.

Figure 13 shows four micrographs of wall sections taken from vessels with these liner problems. The dark centermost zone of both 13a and b is the rubber liner of a 20.3-cm vessel. These two figures dramatize the extent of the voids typically found. Figures 13c and d illustrate one effect of an inadequately cured liner. In this instance, the rubber has migrated into the composite wall of a 10.2-cm vessel during the composite curing.

Post-curing the butyl rubber for 3 h at 121°C still did not solve the problem. Static burst tests were successful but cyclic fatigue resulted in rapid failure in the liners.

Early 38-cm vessels could not be burst because the liner was leaking too much. Various coating schemes were tried to prevent this. The rubber liners of the second and third vessels were coated with two layers of Saran separated by a layer of flexible epoxy before winding, and also coated inside with urethane rubber after winding. Both vessels still leaked because of failure of the inside coating at the edge of the flanges of the aluminum bosses. Later, 38-cm vessels were similarly coated with the resulting performance noted on p.17.

We evaluated several coating systems for their ability to patch leaking rubber-lined vessels. All tests were made with 20.3-cm vessels. Table 7 summarizes the results. The best system based on successful burst tests and processing ease was the Mereco 4501 epoxy applied in thicknesses of 0.76 mm (0.030 in.) and 1.27 mm (0.050 in.).

Table 7. Coatings and test results.

Coating	No. of tests	Successful	Comments
Turco 5145 (solvent coating)	1	No	Thickness: 0.13 mm
50% Dow Corning 92-009 in UM and P (naphtha)	1	No	Thickness: 0.84 mm
Hexcel 7200 (urethane)	2	No	Thickness: 0.51 mm
Butany CTL II/ERL 0510/N,N-DMBA 100/10/0.5 (polybutadine rubber)	1	Yes	Thickness: 0.76 mm Material is more viscous than is desirable
Mereco 4501 (epoxy)	2	Yes	Thickness: 1.27 mm 1st test 0.76 mm 2nd test

(a) 20.3-cm vessel

(b) 20.3-cm vessel

(c) 10.2-cm vessel

(d) 10.2-cm vessel

Fig. 13. Photomicrographs of four wall sections illustrating the nature of the liner problem.

By modifying the coating technique used for the outside of the rubber mandrel and choosing a successful filament winding technique, we were able to manufacture 20.3-cm Kevlar/epoxy polymer-lined vessels which held nitrogen gas at about 50% of the vessel burst pressure for 3 months with a steady-state leak rate of less than 0.4% per month. Four vessels were made in the same way as K23 except that the following coating procedure was used:

- Clean surface with Acetone and allow 2 h of air drying before proceeding.
- Apply 0.005 cm of XD 7151 Saran latex.
- Apply two separate coats of epoxy approximately 4 h apart (XD 7575.02/DER 732/Ethanol amine 80/20/11.9) (approximately 50 g of epoxy should have been applied).
- Apply 0.015 cm Saran XD 7151.
- Paint vessel with XD 7818/T403.

One other change in the procedure was that the winding tension for the first two hoop layers and the first longitudinal layers was reduced from a normal value of 17.8 N to 8.9 N. These two changes alleviated the problem of cracking of the coating sufficiently so that the vessels would hold gas at 50%. Unfortunately, these vessels all leaked fluids at about 70% of expected failure when we tried to burst them after the permeation test. Figure 14 shows the vessel gas containment performance as a percentage of the original pressure vs time for this improved liner system.

Based on our results and experience we speculate that the most likely causes of liner failure in the 20.3-cm vessel are:

- The increase in the pressure in the 20.3-cm vessel over that in the 10.2-cm vessel
- The poor quality of the rubber liner
- Cracks in the composite matrix propagating into the permeation barriers

At present we do not have solutions for all of these problems.

VESSEL TESTS (ALUMINUM LINER)

Introduction

The flexible polymer-lined composite vessels discussed above have successfully contained nitrogen gas, but have failed to contain such gases as helium. As a result, we have worked on a relatively thin, metal-lined

Fig. 14. Percentage of original pressure vs time, improved liner system, 20.3-cm vessels.

graphite/epoxy vessel that successfully contained helium-like gases. However, the metal liner had a poor fatigue life due to liner yielding and plastic deformation. Another problem was that the failure of the adhesive bond between liner and composite induced liner buckling when the vessel was depressurized. In response to the liner problems, we attempted to develop a 10.2-cm-diam aluminum-lined vessel that had a minimum fatigue life of 1000 cycles.⁸ The design consisted of an experimental high-strength graphite fiber, and a 0.51-mm-thick metal liner with high yield strength and a minimum of welds. This report presents performance data on a scaled-up version (20.3 cm diam) of that design (Fig. 15).

Mandrel Design

The mandrel halves were electron beam butt-welded with very close tolerances on weld parameters. On two vessels that were scheduled for fatigue testing, a multilayer adhesive-bonded aluminum foil band was built over the center weld region. Before winding, all mandrels were blasted with glass beads, degreased with trichloroethylene vapor and then coated with adhesive. The material properties and manufacturing procedures for winding are given in Ref. 8.

Burst and Fatigue Performance

Table 8 gives a summary of the winding pattern, vessel weights and burst performance. The high fiber performance of CS-50 was particularly encouraging. A resin content problem is evident in several vessels. Total vessel performance factors for the last two vessels, CS-52 and CS-54, were 239 kPa M³/kg (0.96×10^6 in) and 209 kPa m³/kg (0.84×10^6 in.) respectively.

Vessels CS-53, -55 and -56 were pressure cycled to approximately 50% of their expected burst pressure and sustained 230, 360, and 440 cycles, respectively before leaking. The latter two vessels were constructed with the three-layer adhesive foil band over the center weld section. In each case, fatigue cracks caused failure by leaking. In CS-53, the crack was in the weld while CS-55 and -56 sustained debonding of liner and composite in the region of the foil, initiating a weld failure and a bladder failure, respectively.

Figure 16 shows the CS-49 vessel with its hoop controlled failure. Figure 17 is the strain records of CS-51 and CS-52. The axial gages of both vessels failed without producing any data.

Fig. 15. Metal liner design, 20.3 cm diam.

Table 8. Aluminum-lined 20.3-cm Thornel special/epoxy vessels (0.5-mm liner, test temperature 23°C).

Number	CS48	CS49	CS50	CS51	CS52	CS53	CS54	CS55	CS56
<u>Vessel</u>									
Volume (V), m ³ (in. ³)	0.009470 (577.9)								
Burst pressure, kPa (psi)	28100 (4075)	23800 (3445)	35090 (5090)	26410 (3830)	33510 (4860)	Cycled	29370 (4260)	Cycled	Cycled
Failure location ^a	H	H	H	F + K	F	Leaked	F + K	Leaked	Leaked
Total vessel performance (PV/W _f), kPa·m ³ /kg	217	203	265	191	339	—	289	—	—
Composite performance (PV/W _c), kPa·m ³ /kg	314	306	376	254	243	—	208	—	—
<u>Composite</u>									
Wall thickness, mm									
Longo typical	1.09								
Hoop typical	2.29								
Composite mass (W _c), kg	0.8484	0.7342	0.8843	0.9842	0.9395	1.0033	0.9611	0.9791	0.9017
Fiber (W _f), kg	0.6655	0.6125	0.7298	0.7246	0.7283	0.7108	0.7331	0.7046	0.7111
Fiber content, vol%	71.8	76.8	76	64.2	69.8	62.0	68.2	63.3	71.6
<u>Winding</u>									
Longo angle/winding tension	7°/4.4 N								
Hoop/longo fiber ratio	1.9:1	1.72:1	1.97.1	1.97:1	1.91:1				
Pattern	Closed 36 band								
Hoop	18 layers								
Interspersion	6 + 12								
Total winding circuits	6540	5832	7435	7380	7380				
Longo	10 layers								
Interspersion	None								
Total winding circuits	5220		5760						
Extra reinforcement:									
Equators (circuits)	None								
Knuckles (circuits)	None								
<u>Resin system</u> (ratio)	7818/T-403 (100/49)								
Gelling h/°C	18/room temp.								
Curing, h/°C	3/87.8								

^ah - hoop failure; f - fitting failure; k - knuckle failure.

Fig. 16. Hoop controlled failure of the CS49 vessel, 20.3 cm.

Fig. 17. Strain records of CS51 and CS52 vessels (20.3 cm, aluminum lined).

REFERENCES

1. T. T. Chiao and R. L. Moore, *J. Composite Materials* 6, 547 (1972).
2. T. T. Chiao and R. L. Moore, *Composites* 4, 31 (1973).
3. T. T. Chiao and M. A. Marcon, "Filament-Wound Vessel From an Organic Fiber/Epoxy System," in *Proc. SPI Reinforced Plastics/Composites Division, 1973* (Society of the Plastics Industry, Chicago, 1973), Sect. 9-B.
4. T. T. Chiao, J. E. Wells, R. L. Moore, and M. A. Hamstad, "Stress-Rupture Behavior of Strands of an Organic Fiber/Epoxy Matrix," *Third ASTM Symp. on Composite Materials: Testing and Design, 1973* (ASTM, Philadelphia, 1974).
5. T. T. Chiao, M. A. Hamstad, and M. A. Marcon, *SAMPE Quarterly* 5 (April 1974).
6. M. A. Hamstad, T. T. Chiao, and E. S. Jessop, "Polymer-Lined Filament-Wound Pressure Vessels for Nitrogen Containment," in *Proc. 1974 AIME Spring Meeting: Failure Modes in Composites II* (AIME, Pittsburg, 1974).
7. M. A. Hamstad, T. T. Chiao, and R. G. Patterson, "Fatigue Life of Organic Fiber/Epoxy Pressure Vessels," in *Proc. SAMPE 7th National Conf.* (SAMPE, Albuquerque, New Mexico, 1975).
8. M. A. Hamstad, T. T. Chiao, and R. G. Patterson, *Composites* 6 (1975).

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