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COMPOSITE OVER-WRAPPED PRESSURE VESSEL TECHNOLOGY FOR SPACECRAFT PROPULSION SYSTEMS

Bin Yu[1,2*], TianJu Ma[2], Yun Zhang[2], Cheng Huang[1], SenDong Gu[2], HaiYan Li[2], LinFeng Chen[2]
[1]*Light Alloy Research Institute, Central South University, Changsha 410000, Hunan, China.*
[2]*Aerospace Pressure Vessel Division, Lanzhou Institute of Physics, Lanzhou 730000, Gansu, China.*
Corresponding Author: Bin Yu, Email: amtfyb@163.com

Abstract: This paper systematically reviews global progress in composite overwrapped pressure vessels (COPVs) for space applications and projects their trajectory, synthesizing key advances from the United States, Europe and leading Asian nations in structural and reliability design, stress-fracture and low-cycle-fatigue life prediction, material selection, forming, qualification and non-destructive testing, including high-strength fibers, ultra-thin metallic liners, inheritable design principles and validated failure models, and summarizing representative work by principal Chinese institutes and universities; on this basis it proposes future Chinese directions-high-strength fiber optimization, advanced liner alloys, burst-factor and performance-factor tuning, next-generation NDT, upstream pre-research and Standardization-to underpin independent R&D and technological upgrading of high-performance aerospace COPVs.
Keywords: Aerospace propulsion systems; Composite pressure vessels; Metal liners; Fiber-reinforced composites; Reliability; Stress fracture life

1 INTRODUCTION

Spacecraft and their subsystems necessitate a variety of pressure vessels for the storage of liquids and gases, encompassing gas cylinders and surface tension tanks for satellite and spacecraft propulsion systems, pressure vessels utilized in space station propulsion, fluid management, environmental control and life support systems, scientific and commercial experiment systems, as well as gas cylinders and cryogenic tanks for launch systems.
Composite pressure vessel (COPV) exhibit substantial advantages over all-metal containers, such as lightweight, high stiffness, high specific strength, high reliability, excellent fatigue resistance, long service life, compliance with the "leak before break" (LBB) safety mode, flexible design, low cost, and short production cycles, and are extensively applied in space systems. As a critical component, the development level of COPVs directly determines their performance, which in turn impacts the overall effectiveness of the aerospace system. Structural efficiency affects payload capacity, as COPVs typically account for a significant proportion. Reliability is crucial for launch and in-orbit safety. Safety is of utmost importance, as a rupture could lead to catastrophic consequences, so the LBB design must be strictly adhered to. Stress fracture life determines the in-orbit lifespan of the spacecraft, necessitating structural design to meet reliability requirements. Fatigue life limits the number of refills for reusable COPVs in space stations. Composite material structural technology is a key technique for enhancing the safety of cryogenic liquid krypton storage tank systems.

2 TECHNOLOGY ADVANCES IN US

2.1 Structural Composite Industries of US

In 1972, Landers from the Structural Composite Industries (SCI) of the United States compiled the "Design Specifications for Fiber-Reinforced Pressure Vessels," which provided comprehensive guidance on fiber-wound shells, metal-lined structures, and fatigue life prediction[1]. In the same year, the 2219-T62 aluminum alloy-lined K49 aramid-wound COPV developed by SCI achieved a 30% weight reduction compared to thin-walled TC4 titanium cylinders[2]. Morris reported that SCI's carbon fiber-wound COPVs have a volume range of 0.74 L to 327.74 L, a diameter range of Ø76.2 mm to Ø508 mm, and an operating pressure range of 12.77 MPa to 31.05 MPa, with linings manufactured by spinning[3]. In 1986, he developed a COPV with a 6061-T6 aluminum alloy liner and IM6 carbon fiber/REZ-100 resin, achieving a performance factor (pressure × volume/weight, PV/W) of 25.4 km. The strength was improved by 21% and 37% compared to K49 aramid and S2 glass fiber containers, respectively, with performance factors increased by 20% and 50% [4].
Rabel's 1989 study showed that high-fiber-stress COPVs fractured within 18–22 months, while medium- and low-stress ones remained intact for three years, indicating that fiber stress levels significantly influence stress fracture lifespan[5]. Haddock developed a T1000 carbon fiber-wrapped COPV in 1990, achieving a performance factor of 33.02 km[6]. In 1991, he further achieved compliance with the MIL-STD-1522A LBB safe fatigue failure mode through pre-fabricated defects in the metal liner[7]. Braun studied winding process factors in 1992, including liner performance, surface condition, corrosion resistance, thickness uniformity, pre-treatment, adhesive material aging sensitivity, curing, and thermal stress cycling, as well as composite material performance, winding parameters, and damage sensitivity[8]. The progress of COPV technology by SCI is shown in Figure 1.

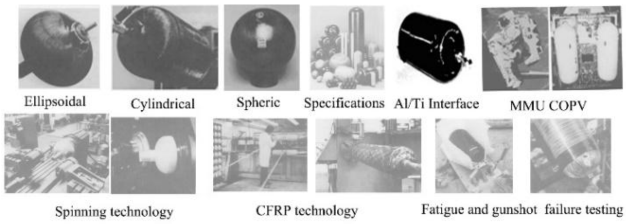

Figure 1 Advances in COPV Technology at SCI

The technical parameters of composite pressure vessels developed by SCI for aerospace applications, aviation applications, commercial aircraft, and civil applications are shown in Tables 1, 2, 3, and 4, respectively.

Table 1 Aerospace Composite Pressure Vessel by SCI

Model	ODmm	OALmm	VL	WKg	Apply
ALT-366	353.1	360.7	20.16	8.16	SDI
ALT-388	711.2	436.9	65.66	25.13	LV
ALT-421	228.6	104.1	1.15	0.45	SDI
ALT-449	515.6	177.8	8.36	4.17	SDI
ALT-454	442.0	165.1	6.37	2.90	SDI
ALT-464	635.0	355.3	43.43	6.76	/
ALT-516	228.6	81.3	0.67	0.23	SDI
ALT-517	228.6	121.9	1.57	0.23	SDI
AC-5000	436.9	172.7	6.88	3.08	SDI
AC-5024	513.1	345.4	33.92	6.53	LV
AC-5040	228.6	106.7	1.16	0.45	SE
AC-5045	317.5	33.0	0.23	0.09	/
AC-5046	208.3	114.3	1.21	0.54	/
AC-5049	195.6	88.9	0.75	0.45	SDI
AC-5101	236.2	91.4	0.77	0.50	SDI

Table 2 Aviation Composite Pressure Vessel

Model	P_WMPa	VL	ODmm	OALmm	WKg	Fiber Type
183	20.7	6.06	178.31	420.37	4.38	KEVLAR
210A	20.7	3.28	136.14	375.92	2.22	KEVLAR
216A	20.7	16.39	222.25	643.38	7.62	KEVLAR
274	23.2	4.26	136.91	459.74	2.86	KEVLAR
351	20.7	3.69	136.14	411.48	2.40	KEVLAR
411	23.2	17.60	200.66	833.12	9.98	KEVLAR
554	20.7	10.65	198.12	542.54	6.84	KEVLAR
63	20.7	17.60	200.66	833.12	9.98	KEVLAR
715	22.7	24.74	257.81	703.58	10.52	CAR/GLS
716	22.7	26.61	257.81	746.76	11.43	CAR/GLS
726	22.7	19.66	220.98	734.06	8.48	CAR/GLS
727	22.7	21.29	220.98	784.86	9.03	CAR/GLS
736	12.8	24.58	237.49	762.00	7.26	CAR/GLS
738	23.2	18.27	210.82	734.06	7.94	CAR/GLS
745	26.2	26.61	257.81	741.68	12.56	CAR/GLS
749	22.7	5.90	156.97	454.66	3.31	CAR/GLS
750	22.7	4.92	156.97	393.70	2.86	CAR/GLS
751	22.7	10.65	182.88	601.98	4.90	CAR/GLS
789	22.7	2.05	115.57	322.58	1.54	CAR/GLS

Table 3 Commercial Aircraft Composite Pressure Vessel

Model	P_WMPa	VL	ODmm	OALmm	WKg	Fiber Type
279	12.8	10.65	172.72	635.00	3.59	KEVLAR
372	12.8	8.37	172.72	518.16	2.90	KEVLAR
280	12.8	4.83	132.08	502.92	1.81	KEVLAR
281	12.8	16.39	193.04	751.84	5.85	KEVLAR
282	12.8	24.58	231.14	800.10	8.21	KEVLAR
621	12.8	2.33	91.95	478.79	0.91	KEVLAR

Table 4 Civilian Field Aircraft Composite Pressure Vessel

Model	P_WMPa	ODmm	OALmm	VL	WKg
ALT747	19.98	343	1115	74	31.24
ALT881E	19.98	404	3048	308.1	113.95
ALT753	24.8	255	1870	71.4	39.04
ALT890S	24.8	333	1270	77.5	42
ALT890	24.8	333	1778	113.1	58.34
ALT807S	24.8	333	1905	120.2	70.1
ALT821	24.8	333	2180	135	67.65
ALT807	24.8	333	3048	195.6	95.79
ALT972	24.8	347	762	47.1	23.15
ALT867	24.8	347	889	57.2	28.38
ALT823F	24.8	388	1001	77.7	35.41
ALT823E	24.8	388	1850	162.8	67.65
ALT823A	24.8	388	1943	173	74.91
ALT918	24.8	388	1993	182.6	77.63
ALT823B	24.8	388	2548	233.2	94.16
ALT823D	24.8	388	3048	283.4	111.91
ALT881S	24.8	404	1803	172	67.65
ALT881L	24.8	404	1905	188.7	74.91
ALT881M	24.8	404	2159	211.4	80.36
ALT881	24.8	404	3048	308.1	114.86
ALT982L	24.8	415	914	81.7	39.95
ALT810P	24.8	415	1397	137	57.2
ALT982L	24.8	415	1524	150	57.2
ALT810A	24.8	415	1869	190.3	79
ALT810B	24.8	415	1905	191.9	81.72
ALT889S	24.8	415	2083	212.9	88.08
ALT810S	24.8	415	2083	204	86.26
ALT810M	24.8	415	2179	215.1	85.35
ALT889	24.8	415	2540	266.4	106.69
ALT810N	24.8	415	3048	312.9	123.94
ALT891	24.8	462	2667	342	123.49
ALT820SG	24.8	532	2032	318.1	163.89
ALT820G	24.8	532	2180	344.6	175.24
ALT604	31.01	183	533	9.2	5.49
ALT988	34.45	183	490	7	5.31
ALT848	34.45	432	1074	92	59.93
ALT836U	34.45	432	1003	90.2	59.47
ALT909s	34.45	419	2667	273.7	117.13
ALT909	34.45	419	3048	312.9	130.75
ALT962L	43.06	439	2976	304.1	190.68
ALT962L	43.06	439	3048	311.8	197.49
Alt861B	68.9	229	1093	27.4	30.74

2.2 ARDE Company of US

In 1982, Gleich from ARDE, a US space systems company, developed the CRES-301 stainless steel-lined AS4 carbon fiber-wrapped spherical COPV, which enhanced the performance factor to 27.94 km, representing a 30% increase over the K49 aramid container and a 60% weight reduction compared to the TC4 all-metal cylinder[9]. In 1988, Gleich further elucidated that COPVs exhibit two failure modes: stable crack propagation (LBB) and unstable brittle fracture[10]. In 1997, Sneddon developed a 0.71 mm ultra-thin I-718-lined T1000 carbon fiber cylindrical COPV (D4619) for the European Star 2000+ satellite, achieving a coupled design between the plastic liner and the composite shell[11]. In the same year, Escalona developed a CRES-301 stainless steel-lined T1000 carbon fiber spherical COPV (D4650) for the Atlas/Centaur rocket, proposing the spherical winding grid theory, which reduced weight by 11% and increased strength by 23% compared to the IM7-W container[12]. In 2006, Sneddon developed an I-718-lined T1000 carbon fiber cylindrical COPV (D4929) for the Delta II rocket, effectively suppressing axial stress concentration through a fully constrained bottom and axially constrained top structure[13]. In 2008, Ray developed an I-718 and 2219 -T62 aluminum-lined T1000 carbon fiber spherical cryogenic COPV (D4970/D4971) for the lunar landing program[14]. Using cryogenic composite technology, he revealed the coordinated deformation mechanism between the liner and composite under pressure-temperature coupling, resolving delamination issues under thermal shock. The progress of COPV technology by ARDE is shown in Figure 2.

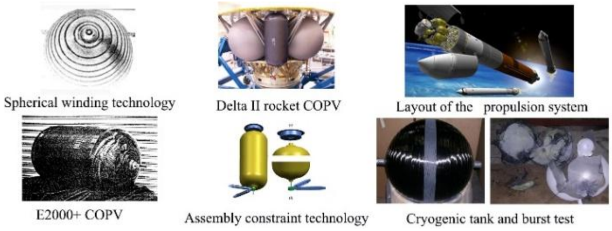

Figure 2 Advances in COPV technology at ARDE

The technical parameters of composite pressure vessels developed by ARDE for aerospace applications are shown in Table 5.

Table 5 Aerospace Composite Pressure Vessel by ARDE

Model	D4619 COPV	D4650 COPV	D4929 COPV	D4970 COPV	D4971 COPV
Apply	E2000+	C LV	DII LV	Altair	Altair
Time	1997	1997	2006	2008	2008
Medium	He	He	He	He	He
Shape	Cylinder	Spherical	Cylinder	Spherical	Spherical
V (L)	97	132	50.8	51.5	51.5
M (kg)	18.33	26.3	10.89	11.54	10.5
OD (mm)	423	660.4	330	460.25	460.25
Fiber	T1000	T1000	T1000	T1000	T1000
Resin	H 53	H 53	H 53	31-43B	31-43B
Liner	I-718	301	I-718	I-718	2219
L_T (mm)	0.71	—	0.71	-	-
P_W (MPa)	31.05	27.6	29	31	31
P_b (MPa)	46.58	41.4	43.5	46.5	46.5
SF	/1.5	/1.5	/1.5	/1.5	/1.5
QS	34%	48%	35%	58%	71%
ABF	2	2.2	2	2.37	2.55

2.3 Space Pressure Systems Inc. of US

Space Pressure Systems Inc. (ATK-PSI) has achieved several milestones in the development of composite overwrapped pressure vessels (COPVs). In 1996, ATK-PSI developed the CP-3 pure titanium-lined T1000 carbon fiber-wrapped xenon COPV, which significantly advanced the design and manufacturing technology of conical gas cylinder winding patterns[15]. In 2000, the company further expanded its technological capabilities by developing a 0.8 mm ultra-thin-walled TC4 titanium alloy-lined T1000 carbon fiber cylindrical COPV for the ETSⅧ spacecraft's electric propulsion system, thereby establishing the foundation for algorithms that govern the elastic state of high-strength metal-lined structures[16]. In 2004, ATK-PSI conducted research on composite material interface technology, which included fiber-wrapped reserved structures, composite material support skirts, and metal ear plates[17]. In 2006, the company developed a 0.5 mm ultra-thin-walled CP-3 pure titanium-lined T1000 carbon fiber cylindrical COPV for the ESA Vega rocket propulsion and orbit control system, achieving a performance factor of 39.8 km (burst pressure 57.2 MPa, volume 81.4 L, weight 11.7 kg), which represented the highest reported performance factor for metal-lined COPVs at that time[18]. The progress of COPV technology by PSI is shown in Figure 3.

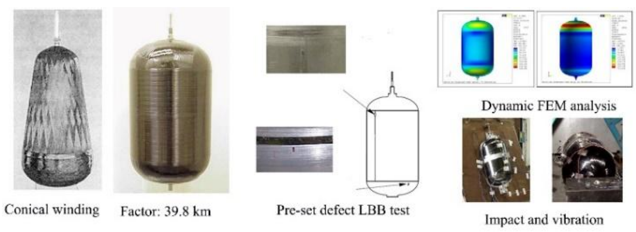

Figure 3 Advances in COPV technology at PSI

Table 6 summarizes PSI applications in communications, science, and military satellites, and Table 7 lists those for spacecraft, launch vehicles, and platforms.

Table 6 PSI Applications in Communications, Science, and Military Satellites

No.	Communication satellites	Scientific satellites	Military satellites
1	A2100	CHANDRA	DMSP
2	ACTS	EOS	DSCS III
3	ARABSAT	ETSVII	DSP
4	ASTROLINK	GOES	FLTSATCOM
5	B.SAT	GRO	GEOSAT
6	BRASILSAT	HEAO	GEOSAT F/O
7	ETS8	KOMPSAT	GPS II
8	FS 1300	LANDSAT	MILSTAR
9	HS 376	ROCSAT	NATOIV
10	HS 601	SOHO	SKYNET
11	INDOSTAR	STEP	TORSS
12	INMARSAT	TIROS	UHF &UHF
13	INTELSAT	TOMS	F/0
14	IRIDIUM	TOPEX	P81
15	MTSAT.2	TRMM	SBIRS LOW
16	N-STAR	UARS	NUMEROUS
17	ORBCOM	WORLOVIEW	CLASSIFIED
18	S3000	ORBVIEW	PROGRAMS
19	S4000	QUICKBIRD	
20	S5000	RADARSAT	
21	S7000	HIPPARCOS	

Table 7 PSI Applications in Spacecraft and Launch Vehicles & Platforms

No.	SPACECRAFT	LAUNCH VEHICLES & PLATFORMS
1	MARINER	ATLAS I
2	PIONEER	ATLAS II
3	VOYAGER	ATLAS IIA
4	VIKING	ATLAS IIAS
5	MAGELLAN	ATLASIIIA
6	ULYSSES	ATLASV
7	CLEMENTINE	CENTAUR
8	NEAR	DELTA III
9	MARS	DELTAIV
10	PATHFINDER	EURECA
11	CASSINI	IUS
12	MARS	KISTLER
13	SURVEYOR	SPACE
14	MARS '98	SHUTTLE
15	LANDER	SPACE
16	DEEP SPACE	STATION
17	ONE	STAR 48
18	LUNAR	TITAN II
19	PROSPECTOR	TITANIII
20	MESSENGER	X38
21	MARS ROVER	
22	STEREO	
23	DEEP IMPACT	
24	MARS ORBITER	

The technical parameters of composite pressure vessels developed by ARDE for aerospace applications are shown in Table 8.

Table 8 Aerospace Composite Pressure Vessel By PSI

Model	CXT	XT	Tank	Vega GT
Apply	XIPS	ETS VIII	Space	ESA Vega LV
Times	1996	1999	2001	2006
Medium	Xe	Xe	N2H4	He
Shape	conical	Cylinder	Cylinder	Cylinder
V (L)	32.12	50	171	87
W (kg)	6.12	7	19.1	23
OD (mm)	337	337	580	337
OAL (mm)	752	683	860	683
Fiber	T1000 CF	T1000 CF	T1000 CF	T1000 CF
Resin	Epon 826	Epon 826	/	Epon 826
Liner	CP-30	TC4	TC4	CP-30
L_T (mm)	0.81	0.8	1.01	0.8

Model	CXT	XT	Tank	Vega GT
P_W (MPa)	17.25	15	3.8	31
P_b (MPa)	25.86	22.5	5.7	62
QS	41%	10%	87%	46%
ABF	2.12	1.7	2.4	2.92

2.4 Boeing Company of US

In 1999, Boeing's Babel evaluated the stress cracking, impact damage, and leakage risks of the Delta IV rocket's composite overwrapped pressure vessel (COPV) in orbit, focusing on four aspects: sustained load stress cracking, composite material impact damage, liner crack propagation leakage, and stress overload[19]. The study concluded that leveraging inherited technology could significantly enhance reliability. In 2000, Ledesma compared three predictive models for COPV stress fracture life: ASTM-D2992, the Thomas method, and the Robinson method[20]. ASTM-D2992 is specifically designed for glass fiber COPVs, while the Thomas method's parameters α and β are derived from burst tests. The Robinson method, based on fiber bundle tests and the Weibull distribution, is particularly suitable for long-term life prediction. In 2003, Abdi developed the GENOA model to simulate crack initiation, propagation, and failure behavior in composite low-temperature storage tanks, validating its algorithmic accuracy through finite element comparisons[21]. In 2004, Robinson investigated liquid hydrogen/liquid oxygen cryogenic tanks and discovered that using an aluminum alloy lining in conjunction with IM7 carbon fiber effectively mitigates thermal expansion coefficient disparities and electrochemical corrosion issues between the materials[22]. The progress of COPV technology by Boeing is shown in Figure 4.

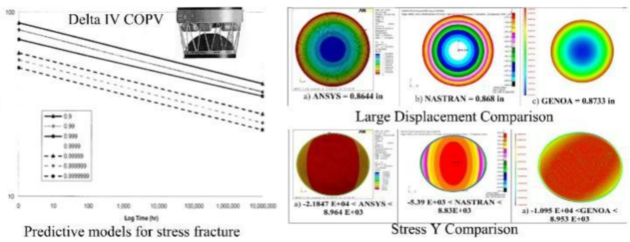

Figure 4 Advances in COPV technology at Boeing

2.5 Air Force Research Laboratory of US

In 2001, the U.S. Air Force Research Laboratory (AFRL) investigated liquid oxygen/liquid hydrogen composite cryogenic tanks for single-stage-to-orbit (SSTO) spacecraft. Arritt developed a low-temperature-resistant resin system and optimized the winding structure to inhibit the propagation of low-temperature microcracks, thereby addressing delamination issues under temperature cycling and achieving a 50% weight reduction compared to aluminum alloy tanks[23]. In the same year, Arritt also developed self-healing composite materials that can autonomously repair cracks within 48 hours without external loading, restoring 75% of their original strength. In 2005, Mallick proposed a multi-scale system design concept for lightweight composite material tanks, establishing cross-scale correlations between materials, design, and manufacturing, and elucidating the material-structure coupling mechanisms from the microscopic to the macroscopic scale[24]. In 2006, Bechel demonstrated through temperature shock tests at -196°C to -177°C using different linear IM7 specimens that the crack propagation behavior of composite materials varies with structure, and the introduction of flexible ES fiber layers can significantly reduce cracks[25]. In 2007, Falugi compared various low-temperature tank configurations and found that the shared partition structure was the lightest, while the stacked structure was easier to manufacture but heavier[26]. The progress of COPV technology by AFRL is shown in Figure 5.

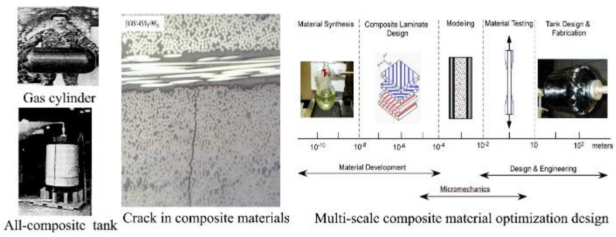

Figure 5 Advances in COPV technology at AFRL

2.6 Glenn Research Center

Revilock at the Glenn Research Center (GRC) in the United States utilized a dual high-speed camera 3D system to precisely measure the strain of composite spherical gas cylinders under repeated pressurization, revealing system behavior more accurately than traditional strain gauges[27]. Increased local strain indicates that the liner may fracture. In 2007, Murthy established a stress rupture model based on Weibull statistics, accounting for parameter uncertainty[28, 29]. Combining 35 years of experimental data from the Lawrence Livermore National Laboratory, he used the Phoenix model to achieve precise predictions of COPV stress rupture life. In the same year, Murthy also established a spacecraft full-life stress rupture model, clearly defining the quantitative relationship between fiber stress ratio and lifespan, and provided data support through accelerated aging tests simulating in-orbit COPV[30]. In 2010, Murthy proposed a stress rupture lifespan assessment model considering structural damage, developing a microscopic mechanical fiber rupture model based on progressive damage theory, effectively reducing uncertainty and improving prediction accuracy[31]. In 2012, Murthy further pointed out that the fiber stress ratio (the ratio of stress to strength under working pressure) has a much greater impact on reliability than other parameters, a finding verified through experiments and calculations[32]. The progress of COPV technology by GRC is shown in Figure 6.

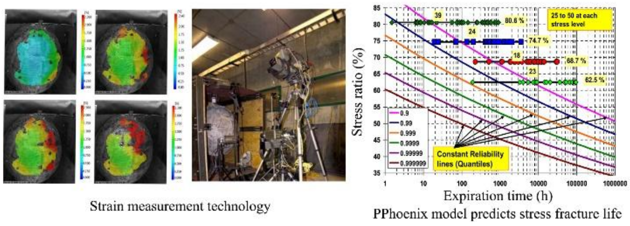

Figure 6 Advances in COPV technology at GRC

2.7 Lockheed Martin Space Systems Company

In 1995, Emery from Lockheed Martin Space Systems Company (LMT) integrated fiber optic sensors into wound fiber layers, enabling automatic diagnosis and health monitoring of various parameters such as fiber strain, delamination, fracture, operating temperature, and medium leakage[33]. In 2005, Achary conducted systematic research on critical components such as low-temperature liquid hydrogen/liquid oxygen tanks, pressurized gas cylinders, and fuel supply lines for the X-33 and X-34 spacecraft, and completed the design and manufacturing of low-temperature tanks using an all-composite material structure[34]. The progress of COPV technology by LMT is shown in Figure 7.

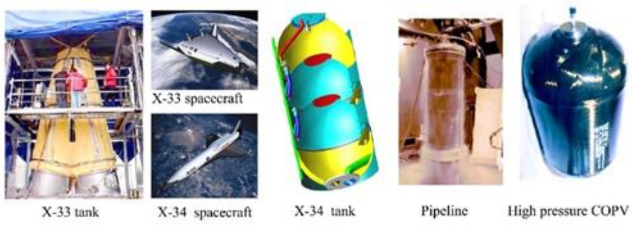

Figure 7 Advances in COPV technology at LMT

2.8 Brunswick Composite Company

Brunswick Composite Materials initiated fiber-overwrapped COPV research in the 1950s, delivered a composite solid rocket motor in 1959, founded a mass-production facility for such motors in 1963, and transferred filament-winding expertise to COPV development the same year; early rubber-lined, glass-fiber-overwrapped COPVs served jet-engine restart systems, whereas the aerospace sector's escalating demand for lightweight, high-strength, minimal-leakage storage has since elevated metal-lined COPVs to the dominant configuration.

Brunswick's Veys introduced a 2219-Al plastically-worked COPV validated by ground tests in 1989[35]; in 1990, he examined carbon-wrapped COPVs with 6061/5086-Al liners, demonstrating that weld reinforcement, weld-adjacent strength design, uniform-thickness regions and smooth transitions dominate strength and fatigue, which can be improved by pre-stressing the liner during filament winding to equalize strain[36]. In 1991, Veys performed fatigue tests on 6061-T6-Al-lined COPVs and created Coffin-Manson-based software that predicts life by computing fiber/metal stress–strain loops during load/unload[37]; the model treats the composite as purely elastic and the liner as elastic-plastic via J2 plasticity plus Ramberg-Osgood, calibrated with four empirical constants, thus establishing the basis for aerospace low-cycle-fatigue design of plastic liners. Murray in 1993 developed an all-composite space COPV with an HDPE liner[38]; ANSI/AIAA S-080-2000 only guides metal-liner selection, whereas ANSI/AIAA S-081 is the definitive reference for COPV liner materials[39, 40].

The technical parameters of composite pressure vessels developed by Brunswick for aerospace applications are shown in Table 9.

Table 9 Aerospace Composite Pressure Vessel by Brunswick

P_WMPa	VL	Shape	ODmm	Fiber	FatigueCycles
34.5	5	Cylinder	178	GFRP	5000
20.7	7.13	Cylinder	127	AFRP	1800
22.08	8	Spherical	266.7	AFRP	400
10.65	9.83	Cylinder	203	GFRP	10000
24.15	11.8	Cylinder	221	AFRP	400
22.43	12.7	Cylinder	221	GFRP	400
20.7	49.16	Cylinder	558	AFRP	1000
41.4	0.25	Cylinder	53	AFRP	10000
21.25	12.7	Cylinder	241	AFRP	2200
30	20.5	Ellipsoid	355.6	AFRP	1000
69	0.57	Spherical	114.3	CFRP	50
34.5	8	Spherical	266.7	CFRP	200
27.6	49.33	Spherical	457.2	CFRP	60
27.6	134.1	Spherical	660.4	CFRP	60
20.7	308	Spherical	914.4	AFRP	100
34.5	41.8	Spherical	469.9	AFRP	120
103.5	4.5	Cylinder	127	AFRP	100

2.9 Marshall Space Flight Center

Marshall Space Flight Center (MSFC)'s Grant experimentally confirmed that FBG sensors survive pressurization and that internal pressure and FBG-reported strain are linearly related[41]; Grant subsequently embedded these sensors in a COPV to reveal its damage mechanism, finding after hydraulic fatigue that circumferential fibres and mid-cylinder longitudinal fibres developed positive residual strain whereas longitudinal fibres near the dome turned negative, with the longitudinal component consistently smaller than the circumferential, a pattern that successfully predicted the eventual burst site[42]. The progress of COPV technology by MSFC is shown in Figure 8.

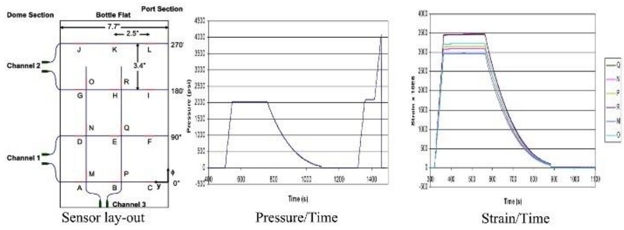

Figure 8 Advances in COPV technology at MSFC

2.10 Johnson Space Center

Beeson at Johnson Space Center (JSC) quantified low-energy impact damage in carbon-fiber COPVs in 1996, revealing an energy-dependent damage progression and a threshold above which visible surface damage appears, the magnitude of which scales with vessel geometry, laminate architecture, and impactor geometry and size[43]; in 2007, Greene used the NASA Engineering Safety Center framework to demonstrate that operational fiber stresses in T1000 carbon/aluminum COPVs exceed Luxfer-based predictions by 11 %[44], and later that year Greene validated remaining life and reliability of ISS K49-COPVs through fatigue and hydroburst tests on identical[45], co-aged specimens, confirming compliance with all performance specifications despite composite aging and prolonged storage; finally, Abraham in 2012 recorded broadband modal acoustic emission during intermittent tensile tests on T1000G/epoxy single -fiber specimens and introduced a statistically rigorous trend analysis that produced a more linear Felicity-ratio decay with load[46], enabling earlier and more precise failure prediction. The progress of COPV technology by JSC is shown in Figure 9.

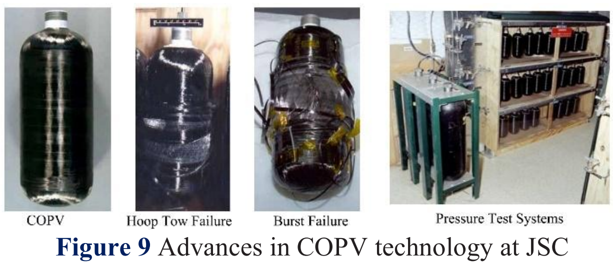

Figure 9 Advances in COPV technology at JSC

3 TECHNOLOGY ADVANCES IN OTHER COUNTRIES ABROAD

3.1 MT Aerospace of German

Since 1988, Radtke at Germany's MT Aerospace has advanced lightweight storage technology by producing ring-shaped and cylindrical propellant tanks, composite solid motors and COPVs for Ariane 3 and 4[47]; in 2006 Radtke introduced a net-shape spinning process for titanium-lined COPV domes[48], yielding a 0.7 mm-thick, 660 mm-diameter titanium liner and a 0.5 mm-thick, 1140 mm-diameter composite propellant-tank liner. The progress of COPV technology by MT is shown in Figure 9.

Figure 10 Advances in COPV technology at MT

3.2 AeroSpatiale Space Center of Frence

Since 1959 the Charpentier at the French AeroSpatiale Space Center has produced COPVs for TVSAT, TDF1, EUROSTAR, DFS, Tele-X and Ariane 4, and demonstrated that 1° forward or reverse fibre slippage during spherical-tank winding reduces strength by 2.9 % or 5.5 %, respectively[49, 50]; in 1995 Teissier delivered the Ariane 5 2219-Al liquid-oxygen tank, Ø1 303 mm, operating at 2.2 MPa[51].

3.3 National Space Development Agency of Japan

In 1999 Morino from National space development agency of JAPAN (NASDA) validated a cryogenic composite tank concept for reusable launch vehicles, reporting a 20 % loss in filament-wound toughened-resin properties and leakage driven by low-stress matrix cracking[52]; Torano fielded a 2.16 MPa Al-lined CFRP tank for the J-I second stage in 2001[53], achieving 3.24 MPa burst, 2.7 MPa proof, 12-cycle fatigue at working pressure and 5-cycle at proof pressure, with head failure eliminated via optimized liner geometry, enhanced interface bonding and controlled cure pressure; Ishikawa in 2003 derived the stress-free matrix-crack coefficient from crack-initiation-strain differences between ambient and liquid-nitrogen temperatures[54]; Masuda delivered in 2014 an Al-lined CFRP propellant tank incorporating an integrated management device[55]. The progress of COPV technology by NASDA is shown in Figure 11.

3.4 Korea Advanced Institute of Science and Technology

Hwang from Korea Advanced Institute of Science and Technology (AIST) quantified the size-induced strength decay of carbon fibres by testing fibre bundles[56, 57], UD laminates and COPVs, and then embedded three stochastic variables—elastic moduli of the composite, laminate strength and spiral-to-hoop layer thickness—into a probabilistic model that accurately predicted the circumferential strain and burst pressure of 10 COPVs spanning multiple diameters, with hydraulic-burst experiments validating the predictions.

4 TECHNOLOGY ADVANCES IN CHINA

4.1 Lanzhou Institute of Physics

The Lanzhou Institute of Physics has long been dedicated to the technical research and product development of space-grade ambient temperature and cryogenic pressure vessels. The institute has accumulated extensive experience in structural design[58], finite element analysis[59, 60], reliability and failure risk analysis[61], life prediction[62], impact damage assessment, welded structure design, surface modification, inspection and testing, standard application, cryogenic pressure tanks and supply systems[63-65], and space refrigeration unit development[66-70]. Its products include surface tension tanks, composite material pressure vessels, cryogenic tanks, and supply systems.

4.2 Xi'an Aerospace Propulsion Technology Research Institute

Chen of the Xi'an Aerospace Propulsion Technology Research Institute derived preliminary design formulas for COPV structures that encompass fiber-wrapped burst-strength calculation, composite shell critical axial-pressure prediction, deformation analysis of lined composite shells, and structural-design algorithms for fiber-wrapped conical shells.

4.3 Xi’an Aerospace Composite Materials Research Institute

Zeng of the Xi’an Aerospace Composite Materials Research Institute introduced the variable-pitch spherical COPV winding strategy in 2000, cutting composite mass by 24.6 % and raising the performance coefficient by 10.4 % at identical fiber stress; Wang examined F12/T800 hybrid COPVs, finding that longitudinal carbon-fiber plies combined with F12 hoop plies maximize efficiency; Wang dissected fiber-winding CAD/CAM platforms, pinpointing structural design, mathematical modelling, and numerical control as the core subsystems; Li derived geodesic equations and linear -control algorithms for accurate fiber trajectories on toroidal cylinders; Fang fabricated an aluminum-lined T700/EC8 glass-fiber COPV whose burst pressure surpassed 100 MPa, and after 58 MPa pre-tensioning achieved optimized liner stress distribution and a fatigue life exceeding 5 000 cycles.

4.4 Harbin Fiberglass Research Institute

Li introduced a network-theory design for metal-lined composite cylinders; Wang quantified the governing structural parameters. Jiang devised an algorithm for non-load-bearing isodiametric bipolar porous spherical COPVs using the fiber-strength-utilization position function F(X), a maximum-stress failure criterion, and tension-zone spherical-shell geometry. Lou presented a spherical-headed cylindrical COPV algorithm that applies multi-ring enveloping heads and network-theory cylinders. Jiang investigated unequal-polarity porous spherical vessels through weighted-average equal-polarity porous-sphere winding. Lin fabricated a welded, pure-aluminum-lined aramid-wound cylinder achieving 18.2 km performance factor. Wang identified the head-to-cylinder junction as the critical high-stress zone requiring local reinforcement. Lou derived the conical-shell winding profile and determined stable five-axis winding-machine motion patterns. Jiang developed aluminum-alloy-lined aramid-wound toroidal COPVs via dry winding, adhesive metering, and shrink-film curing.

4.5 Harbin Institute of Technology

Shen identified fiber-strength variability as the dominant factor in COPV reliability design; Hu quantified resin-cure kinetics in ultra-thin metal-lined COPVs, attributing liner wrinkling and reduced fatigue life to residual stresses induced by resin shrinkage, temperature gradients and thermal mismatch; Li delivered winding-process simulation software that captures the complete process and enables geodesic trajectory design; Wang advanced lightweight COPVs by introducing segmented heat-treatment spinning of thin-walled aluminum liners and a principal-stress-oriented fiber-winding strategy for vessels with unequal polar openings.

4.6 Dalian University of Technology

Ren formulated a multi-field coupled FE method for cure analysis that integrates cure kinetics, heat transfer and composite mechanics, revealing synchronous peak stresses throughout the vessel during initial cool-down; Chen surveyed multi-field studies on filament-wound shells and recommended setting overpressure via structural simulation; Sun noted that thermoplastic winding offers streamlined equipment, simplified processing and lower cost.

5 DEVELOPMENT OF STANDARDS FOR SPACE COPV

5.1 Development of Standards

Spacecraft and launch vehicles universally demand cylindrical pressure vessels for propulsion, fluid management, environmental control and experimental systems. The 1970s baseline, MIL-STD-1522, prescribed safe design and operation of pressurized missile and space systems; its 1984 revision, MIL-STD-1522A, tightened fracture control for metals and became the global aerospace reference. Composite cylinders, however, soon revealed the standard’s insufficiency-no provisions for carbon-fiber impact tolerance, glass/aramid stress-rupture life, leak-before-break (LBB) validation or composite NDI-prompting the Air Force and SMC to task a revision in 1993; USAF restructuring cancelled this effort, and in 1996 AIAA assumed responsibility, forming the Aerospace Pressure Vessel Standards Working Group (APVSWG).

The group issued ANSI/AIAA S-080 (approved December 1998, published January 1999) covering system analysis, structural design, materials, safety, production control, inspection, test and maintenance of space metal cylinders with a minimum safety factor $\geqslant 1.5$. Parallel development of ANSI/AIAA S-081 (published 2000) addressed composite vessels, permitting LBB or safe-life design for non-hazardous media, yet leakage events during acceptance and flight highlighted the need for dual-mode safety; S-081 was therefore revised into S-081A (2006), adding mechanical-damage control, stress-rupture life requirements and pre-launch inspection, pressure test and data-retention protocols.

S-081A mandates safety factors of 1.5, 1.65 and 2.25 for carbon, aramid and glass fiber, respectively, and defines proof test pressure PT as $PT = (1 + N)PMEOP/2$ for $N > 2$ and $PT = 1.5PMEOP$ ($\leqslant 0.8Pb$) for $N \leqslant 2$, with liner design in the elastic range referred to S-080 and otherwise to S-081A; it further requires Grade-A materials for full-scale composite cylinder fracture-strength testing and details mechanical-damage control, impact tolerance, composite strength design, NDI, LBB and functional verification. ISO 14623 (2003) complements these standards for space metal and metal-lined composite cylinders, imposing a safety factor ⩾1.5 and ⩾0.999 survival probability against stress-rupture; vessels with safety factor <4 and wall thickness <6.35 mm must incorporate systematic damage control. AIAA-S-110 specifies 1.25 for mechanically and thermally loaded components, while ASTM D2992 supplies life-analysis methods—fatigue and stress-rupture—for glass-fiber tubes and pressure vessels, routinely referenced for foreign glass-fiber COPVs.

5.2 Issues and Analysis in the Development of National Standards for COPV in China

China currently lacks national or military standards for aerospace-grade carbon-fiber-overwrapped composite pressure vessels, and as reinforcement has evolved from E-/S-glass through Kevlar-49, IM-6, T-40 and T-700 to the present baseline T-1000, design and acceptance remain unguided in performance indices, material selection, structural and safety design, life analysis, manufacturing processes, process control, testing and acceptance, even though aerospace vessels impose stringent reliability, safety, mass and performance demands; therefore an urgent standard is required for metal-lined, T-1000 carbon-fiber fully-wound cylindrical COPVs that consolidates domestic R&D achievements, matches actual manufacturer capability and selectively incorporates superior elements of international norms. Compared with domestic documents, ANSI/AIAA S-081A and ISO 14623 lead in life prediction, damage control, NDI and safety design, so the envisaged standard should adopt: (1) allowable-fiber-stress test protocols using both full-scale and sub-scale specimens; (2) stress-rupture and fatigue-cycle life prediction technologies; (3) mechanical-damage control processes encompassing detection, severity assessment and tolerance definition; (4) NDI techniques for liners and composites; (5) leak-before-break design criteria and verification methods for pre-existing liner flaws; and (6) qualification routes for liners, fibers and resins covering allowable conditions, structural design, fabrication, NDI and performance testing. With proliferating aerospace and commercial applications, COPVs are becoming safety-critical in multiple host systems, so unified national and military standards are indispensable to regulate design, manufacture, process control, inspection, testing and acceptance, guarantee in-service reliability and safety, and accelerate technology maturation while avoiding uncritical transplantation of foreign standards.

6 CONCLUSION

6.1 Selection of High-strength Fibers

High-strength fiber selection directly governs COPV structural efficiency: T1000 carbon fiber is the present baseline for space-qualified vessels because its exceptional tensile strength delivers a high utilization factor and because extensive domestic and international stress-rupture life tests have validated T1000-COPV composites, with numerous flight units now demonstrating sustained on-orbit reliability; any prospective higher-strength fiber must undergo equivalent property, environmental and stress-rupture evaluations before adoption.

6.2 Development of Ultra-thin Metal Liners

Ultra-thin metallic liners enhance COPV structural efficiency provided that liner stress–strain remains within allowable limits and strength–fatigue specifications are preserved; their implementation hinges on ultra-thin forming and filament-wound composite shell technologies. Internationally, the principal liner alloys are Ti, stainless steel, Inconel 718 and Al, and foreign practice shows that both machined-and-welded and seamless spun ultra-thin liners are flight-ready. Advancing precision machining, thin-wall welding and continued refinement of flow-forming processes for ultra-thin liners is therefore imperative; metal-lined composite pressure vessels currently constitute the dominant trajectory for space COPVs worldwide.

6.3 Development of Diversified Lining Materials

Non-metallic liners—rubber, high-density polyethylene and related polymers—enable all-composite pressure vessels that combine low-cost forming, superior design flexibility and high structural efficiency while fully satisfying typical space and missile requirements; although ANSI/AIAA S-081 and S-081A address only metallic liners, this limitation does not constrain domestic standards. No national military standard yet governs Chinese space COPVs, yet the demonstrated domestic capability to fabricate and qualify non-metallic liners and their proven in-orbit reliability render these materials a credible option; therefore, incorporating non-metallic liners into the material palette of forthcoming national military standards for space COPV composite cylinders is both rational and feasible.

6.4 Structural Design Optimization

Leveraging heritage design and multi-physics tools such as GENOA and ANSYS, future COPV optimization will target fiber-path refinement, head/interface strain coordination and response prediction under cryogenic and cyclic extremes, while AI-driven algorithms will simultaneously enhance composite lay-up design and failure prognosis, thereby raising structural efficiency and reliability.

6.5 Discussion on the Actual Blast Factor (ABF)

Analysis of domestic and international COPV datasets shows that China's performance factor (PV/W) already rivals global benchmarks, reflecting advanced structural design, liner technology and composite processing, yet it does not quantify flight safety or reliability. AIAA S-081A mandates a carbon-fiber stress-rupture factor $\geqslant 1.5$ and a burst factor $\geqslant 1.5$, whereas operational foreign COPVs exhibit an actual burst factor (ABF) almost universally exceeding 2; the higher reserve capacity lowers operational fiber stress, the decisive variable for on-orbit life and reliability. Therefore, high-performance COPV development must couple PV/W optimization with a mission-specific ABF that exceeds the minimum standard, and key technical indices should be anchored in AIAA S-081A yet tailored to in-service realities to simultaneously enhance performance and assurance.

6.6 Characteristics of Space COPV Heritage Design

Space systems cannot tolerate the several-kilogram TNT-equivalent blast from a high-pressure COPV rupture, making reliability imperative for China's crewed flight and Tiangong-1/Shenzhou-8 heritage. The most effective safeguard is design inheritance: analyses of NASA's main composite cylinder supplier, SCI Composite Materials, and its surface-tension tank supplier, ATK Composite Materials, reveal that users and manufacturers converge on inheritable design, and the extensive on-orbit flight experience of both companies constitutes the primary reference dataset for this approach.

6.7 Development of Non-Destructive Testing Technology

Composite COPV strength is governed by winding and curing variability, and carbon-fiber layers are acutely vulnerable to impact; non-destructive inspection (NDI) is therefore mandatory to reveal any flaw or damage that could degrade performance. Although ANSI/AIAA S-081A prescribes rigorous fiber-winding and impact-damage control plans, NASA's White Sands Test Facility has advanced NDI by correlating sixteen distinct inspection techniques with structural anomalies and embedding these data in impact-damage assessment protocols, making NDI a gate criterion for flight-article acceptance. China must correspondingly mature NDI capability and promulgate dedicated technical guidelines or national military standards for space COPVs to secure in-orbit reliability.

6.8 The Importance of Pre-research on Space COPV

Surveying foreign COPV roadmaps and aligning with China's future space needs underscores that sustained pre-research is indispensable to compress spacecraft development cycles and secure in-orbit reliability; open literature is chronically outdated, so once critical technologies mature abroad, the domestic lag can span several years, and classified data further widen the gap. NASA's sustained investment in pre-competitive program awarded to SCI Structural Composites and Lincoln Composites demonstrates high transition rates from laboratory to flight, hence China must aggressively expand pre-research on space COPVs, accumulate validated data and technological reserves, and codify these findings for future inheritable designs.

6.9 Development of Standards for Space COPV Research

Domestic COPV capability has advanced rapidly, yet standards lag behind those of mature spacefaring nations whose iterative, flight-validated composite-cylinder specifications deliver proven reliability, safety and process control; China currently relies on institute or foreign standards that inadequately constrain design or quality, so urgent codification of national military standards—grounded in domestic R&D data, benchmarked against international best practice and formulated through broad industry consultation—is essential to underpin future development and quality assurance of space-qualified COPVs.

COMPETING INTERESTS

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