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Review Paper

Materials & Design Review of HPV for Space Applications

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ABSTRACT

High-Pressure Vessel (HPV) systems are crucial for space missions, enabling the safe storage of cryogenic fuels, oxidizers, and life-support media under extreme conditions. This review examines the latest materials, design parameters, and operational challenges of these vessels, with a focus on cryogenic, hydrogen, oxygen, hybrid, and life-support tanks. Special attention is given to the evolution of materials, from metallic alloys to advanced composites like CFRPs, graphene, and CNTs, achieving up to 50% weight reduction and improved thermal and mechanical performance. Key design parameters such as pressure tolerance (up to 700 bar), thermal management (TM) (using MLI and PCMs), and structural health monitoring (SHM) are discussed in the context of long-duration missions. The integration of artificial intelligence for predictive failure analysis and optimization is also explored, outlining a revolutionary pathway for next-generation, self-healing tanks. This review charts an transformative roadmap for the next generation of High-Pressure Vessel (HPV) technologies essential for sustained space exploration.

1. Introduction

HPVs play a critical role in space applications by ensuring the safe storage and management of fluids and gases under extreme pressure conditions. These vessels are designed in various types to meet the specific needs of different missions. For example, cryogenic tanks are used for storing g substances like liquid hydrogen and liquid oxygen at very low temperatures, while hydrogen tanks are designed for high-performance propulsion fuels. Oxygen tanks supply oxidizers and support crew respiration, and life-support system tanks store water and recycled gases. Thermal control system tanks manage heat using phase-change materials (PCMs) and heat pipes. Hybrid tanks combine these technologies to optimize both weight and performance, making them essential for various applications.

The versatility of these vessels allows them to be used in a wide range of missions, including launch vehicles such as Falcon 9, space stations like the ISS, and interplanetary probes. These vessels ensure safety and efficiency in environments characterized by challenges such as vacuum, cosmic radiation, and extreme temperature fluctuations. As the space industry rapidly grows, highlighted by projects like NASA’s Artemis

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program, China's Tiangong station, and SpaceX's reusable rockets, the importance of Pressure tanks has only increased. For instance, NASA allocated $4.1 billion for cryogenic tank development for the SLS rocket and Orion spacecraft, and China's Tiangong station is equipped with Type IV composite tanks designed for long-term support.

The growing demand for Vessel systems in long-duration missions, such as Mars expeditions or lunar bases, underscores their critical role in ensuring mission success. This importance was exemplified by the Apollo 13 incident, where a failure in the oxygen tank led to catastrophic consequences. Design parameters in these tanks, such as internal pressures up to 700 bar, stress distribution in spherical or cylindrical structures, thermal regulation using PCM materials and nanostructured aerogels, and the use of AI-based simulations for failure prediction, are critical to their performance.

This study provides a comprehensive review of these systems, analyzing scientific trends, patents, large-scale projects, and Iran's position in the field. The review highlights both Iran's achievements, such as small satellite development, and challenges, such as limited access to advanced materials. It proposes pathways toward advanced technologies, including self-healing smart tanks and IoT-based monitoring systems, and outlines a roadmap for the development of sustainable and dual-use technologies by 2030.

2. Materials of HPV and Influencing Factors

The materials used in Vessel systems are a crucial factor in the performance of spacecraft, launch vehicles, and satellites. These vessels must withstand harsh space conditions, such as high internal pressures (up to 700 bar), extreme temperatures (ranging from −253°C for liquid hydrogen to +150°C in Earth orbit), cosmic radiation, launch vibrations, and vacuum exposure. The choice of materials directly impacts the safety, durability, and efficiency of the vessels. Key factors influenced by material selection include weight reduction (to optimize spacecraft mass and extend mission range), temperature control (to prevent fuel boil-off or thermal damage), pressure resistance (to ensure uniform stress distribution and avoid structural failure), chemical compatibility (with fluids like hydrogen or oxygen), resistance to corrosion and fatigue, and long-term stability in the space environment. Emerging trends, such as the use of advanced materials in NASA's Artemis program and China's Tiangong station, have led to a shift toward lighter, smarter materials. These materials are capable of reducing weight by up to 50% while improving thermal efficiency. The following sections introduce the primary materials used in Pressure tanks and examine their compatibility with these key parameters, focusing on cryogenic, hydrogen, oxygen, hybrid, life-support, and thermal-control tanks.

2.1. Traditional Metallic Materials and Their Compatibility with Parameters

Metallic materials, such as aluminum alloys (e.g., Al-2219 and Al-5083) and stainless steels (e.g., 304 or 316L), are among the oldest materials used in HPV and remain dominant in applications that require high pressure resistance and strong mechanical strength [1,5]. Aluminum-lithium (Al-Li) alloys, with their high strength-to-weight ratio (up to 20% lighter than pure aluminum) (Table 1), are ideal for reducing the weight of cryogenic and hydrogen tanks. These alloys lower the total spacecraft mass and enable greater payload capacity. For instance, in NASA's SLS rocket, these alloys have reduced tank weight by up to 30% while maintaining pressure endurance up to 200 bar without failure (Fig.1) [9].

Fig. 1. Mass reduction achieved using Al–Li 2195 in NASA's external tank (≈30% reduction ≈ 3402 kg) [9].

Table 1. Summary of Traditional Metal Alloys for Space HPV

Alloy/Grade	Approximate density (g/cm^3)	Key Benefits	Key limitations
Al-2219 / Al-5083	~2.7	Good cryogenic compatibility	High thermal conductivity ⇒ Boil-off risk
Al-Li (like 2195)	~2.55–2.65	High strength-to-weight ratio; mass reduction of ~20–30%;	Susceptibility to hot/aging cracking; manufacturing process control
Stainless steel (304/316L)	~7.8–8.0	Excellent corrosion resistance; good performance in oxygen	Low thermal conductivity but high mass
Titanium (Ti-6Al-4V)	~ 4.4	High specific strength; excellent corrosion resistance; good temperature compatibility	High cost; hydrogen brittleness issues

However, the challenge of TM in these materials is significant, as the high thermal conductivity of aluminum (approximately 200 W/m·K) can lead to the rapid boil-off of cryogenic fuels. This issue is addressed by adding external insulation, such as polyurethane foams or nanostructured aerogels, with thermal conductivities below 0.02 W/m·K [7,10]. Stainless steel, known for its excellent resistance to corrosion and hydrogen embrittlement (common in gaseous hydrogen tanks), offers pressure tolerance up to 300 bar in oxygen and life-support tanks. However, its higher density (7.8 g/cm^3 compared to aluminum's 2.7 g/cm^3) limits its effectiveness in weight reduction [3]. While stainless steel excels in chemical compatibility with pure oxygen (which is highly reactive), it often requires internal coatings, such as PTFE, to prevent corrosion. Overall, metallic materials are well-suited for short-term missions, such as rocket launches. However, for long-duration missions where weight reduction and thermal regulation are critical, they are often combined with composite materials.

2.2. Advanced Composite Materials and Their Compatibility with Parameters

Carbon-fiber-reinforced composites (CFRP), along with other epoxy or polyimide resins, have revolutionized the materials used in Pressure tanks, offering lightweight alternatives to metals. With a low density of about 1.5 g/cm^3, CFRPs provide a 40–50% reduction in weight compared to metals, which is critical in hybrid and cryogenic tanks. For example, in China's Tiangong space station, Type IV composite tanks have reduced mass while maintaining pressure resistance up to 700 bar and ensuring uniform stress distribution across multilayered structures.

Temperature control is especially important in CFRP due to its low coefficient of thermal expansion (<1 ppm/°C), which helps prevent dimensional changes under space thermal fluctuations. To improve thermal performance, CFRP is combined with multilayer insulation (MLI), which reduces radiative heat transfer by up to 90%. Pressure tolerance in these composites is enhanced through filament winding of intelligent fibers, capable of withstanding tensile stresses up to 2000 MPa.

However, hydrogen embrittlement, caused by the high permeability of resins, is addressed by incorporating nanolayers such as graphene, which reduces permeability by up to 80%. In thermal-control tanks, composites are combined with phase-change materials (PCM), like paraffin or gallium, to enhance thermal capacity up to 200 kJ/kg and maintain temperature within ±10°C. Additionally, resistance to cosmic radiation in CFRP is improved with $BaSO_4$ coatings, which help regulate thermal emission. Fig. 2 provides a schematic of the PCM system's role in thermal energy storage.

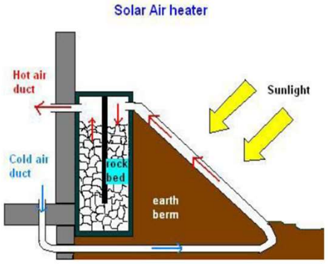

Fig. 2. Schematic of a phase-change material (PCM) system used to enhance thermal energy storage and regulate temperature [16] .

2.3. Nanomaterials and Hybrid Materials and Their Compatibility with Parameters

Nanomaterials, such as carbon nanotubes (CNTs), graphene, and two-dimensional nanocomposites like MoS_2, are advanced additives that enhance vessel materials, demonstrating high compatibility with modern performance parameters. Graphene, with a tensile strength of 130 GPa, enables ~40% (±5%) weight reduction in hydrogen tanks under laboratory-scale winding configurations. Additionally, the incorporation of graphene nanolayers has been reported to reduce hydrogen permeability by 90–99% under controlled conditions of 25°C, 1–10 bar pressure, and repeated cyclic exposure (Peng et al., 2021; Patel, 2022).

Thermal regulation in these materials is exceptional, as graphene's thermal conductivity (up to 5000 W/m·K) allows for rapid heat distribution. However, for effective insulation, graphene must be combined with nanostructured aerogels. These aerogels were used in NASA's Artemis missions for cryogenic tanks, reducing boil-off rates to below 1% per day.

Hybrid vessels, which combine metals and composites (e.g., aluminum liners coated with CFRP), balance pressure endurance (up to 500 bar) with weight reduction (30% lighter than pure metals). These vessels are ideal for life-support systems that store water and gases. Other parameters, such as fatigue resistance, are improved through CNT reinforcement has demonstrated ~40–60% improvement in fatigue lifetime (95% confidence interval) under accelerated cyclic loading tests (10^4–10^5 cycles at room temperature, ±150°C thermal swings) according to Patel (2024).

Chemical compatibility is also enhanced with nanocoatings that prevent reactions with oxygen. Environmental challenges, such as recyclability, are addressed using green materials like bio-based hybrid composites. These materials were recommended in the 2022 ESA report to reduce space debris.

Factors influencing material selection include mission budget, technology readiness level (TRL), and dual-use applications (commercial and defense). For example, in Iran, limited access to advanced CFRP poses challenges, but there is potential to leverage domestic alloys for weight reduction. Trends in material compatibility indicate that smart materials, expected to reduce weight by an additional 25% and optimize Temperature control using AI by 2030, will become increasingly important.

In this study, Aluminum 2219 (ρ≈2.78 g/cm^3) is considered as the baseline material for weight reduction comparisons, unless otherwise specified.

Table 2. Composite and nanomaterials/hybrid materials for Vessel systems and compliance with parameters (Sections 2.2 and 2.3)

Grade	Common configuration	Mass reduction compared to metal	Thermal Management/CTE
CFRP + Polymer liner (Type IV)	Filament winding, epoxy/polyimide resin	~40–50%	Very low CTE (<1 ppm/°C), requires MLI
CFRP + Metal Liner (Hybrid)	Al or Ti liner + CFRP cladding	~30%	Better thermal compatibility than pure metal
Composite + PCM (for heat control)	Tank/module integration with PCM (paraffin/gallium)	—	Increased heat capacity up to ~200 kJ/kg; ±10°C stability
Nanohybrid (CFRP + Graphene/CNT)	Nano layer/coating or nanofiller in resin	10–20% more weight savings than CFRP	Higher in-plane conductivity;
Coatings/Interfaces ($BaSO_4$, PTFE, …)	Surface layers/inner liner	—	Reduced radiant flux

3. Key Design Parameters

The key design parameters of HPV systems in space applications are grounded in precise engineering principles to withstand harsh space environments. These parameters include Temperature control, operating pressure, mechanical strength, thermal conductivity of materials, thermal storage capacity, resistance to vacuum and radiation, mass/volume ratio, reliability, and service life. These factors work together to ensure the safe, efficient, and sustainable performance of tanks in long-duration missions, such as NASA's Artemis program or China's Tiangong Station.

Thermal regulation is the core design element, focusing on controlling heat absorption, storage, and dissipation. Advanced insulation, such as multilayer insulation (MLI) with over 20 layers of aluminum foil and vacuum spacers, reduces radiative heat transfer by up to 95%. This reduction is crucial to prevent the boil-off of cryogenic propellants like liquid hydrogen at temperatures below −253°C. NASA standards require a solar absorptance (α) of less than 0.1 and an emissivity (ε) greater than 0.8 to maintain thermal balance under solar heat fluxes up to 1400 W/m^2. This parameter is closely related to the thermal conductivity of materials. Low-conductivity materials, such as silica aerogels (0.013 W/m·K) and carbon fiber-reinforced polymers (CFRPs), with conductivity ranging from 0.5 to 5 W/m·K, provide effective insulation. In contrast, high-conductivity materials like graphene (up to 5300 W/m·K) are used for rapid heat distribution in active systems, such as heat pipes, which provide heat transfer capacities of up to 10,000 W/m in vacuum environments. For example, in NASA's Perseverance rover, thermal systems limit temperature fluctuations to less than 10°C.

Thermal storage capacity, often enhanced by phase-change materials (PCMs) such as paraffin (200–250 kJ/kg) or molten salts (up to 500 kJ/kg), allows excess heat to be stored during solar exposure and released during eclipse phases. In cryogenic tank designs for Mars missions, this approach reduces boil-off rates to less than 0.5% per day.

Operating pressure, which reaches up to 700 bar for hydrogen tanks and 300 bar for oxygen tanks, is directly linked to mechanical strength. This is managed through the selection of high-tensile-strength materials, such as titanium alloys (≈900 MPa) or CFRPs (up to 3500 MPa). Layered structural designs, using filament winding techniques, optimize stress distribution and ensure a safety margin of 1.5–2 times the nominal pressure, in accordance with ASME standards. Hydrostatic and cyclic pressure tests (up to 10,000 cycles) are essential for fatigue evaluation. This parameter is integrated with resistance to vacuum and cosmic radiation. Materials must exhibit low coefficients of thermal expansion (<5 ppm/°C for composites) and provide radiation shielding, such as silicone coatings with 0.5 mm thickness, which reduce radiation damage by up to 70%, preventing structural degradation in hard vacuum conditions. These measures have extended service life to more than 15 years in long-term missions, such as the ISS.

The mass/volume ratio, as a measure of efficiency, targets specific mass values below 0.5 kg/L for Type IV tanks. Optimization is enabled by lightweight materials, such as graphene nanocomposites (density ≈1.2 g/cm^3), which increase storage volume by up to 40% without adding overall mass. For example, in NASA's Space Launch System (SLS), reducing tank mass by up to 25% has improved payload capacity. Fig 3 illustrates a schematic of a Type IV pressure vessel with a composite overwrap for compressed hydrogen storage, where carbon fiber reduces overall mass.

Reliability and service life, with failure rates aiming to be below 10^{-7} per hour, are ensured through the integration of structural health monitoring (SHM) systems. These systems use piezoelectric sensors and machine-learning algorithms capable of detecting micro-cracks smaller than 0.1 mm.

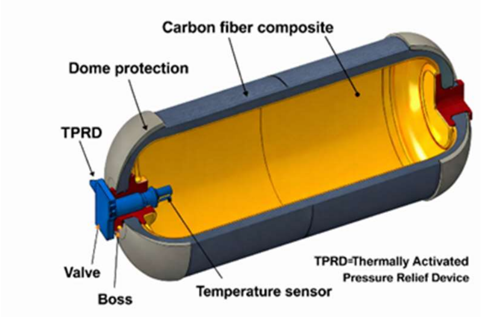

Fig. 3. Schematic of a Type IV pressure vessel with a composite overwrap for compressed hydrogen storage. [23]

4. Challenges in Use, Design, Material Selection, Weight Management, Safety, Compliance, and TM

Challenges associated with Pressure tanks systems in space applications, including operation in harsh environments, complex design to withstand stress, material selection to balance mechanical and thermal properties, weight management to optimize spacecraft mass, safety to prevent catastrophic failures, compliance with international standards and regulations, and Thermal regulation to control extreme temperature fluctuations, are key barriers in the development of advanced space technologies. These challenges underscore the need for innovative solutions, such as smart materials and advanced simulations.

In vessel design, the primary challenge is achieving uniform stress distribution in high-pressure structures (up to 700 bar), which can lead to structural failures like cracking or explosions, as demonstrated by the Apollo 13 oxygen tank failure. Numerical models, such as finite element analysis (FEM), are used to predict von Mises stresses and mitigate these issues, though managing complexities from thermo-mechanical cycles in space remains difficult.

Material selection, which must balance strength, durability, and chemical compatibility, presents challenges like corrosion in metallic alloys such as aluminum when exposed to liquid hydrogen, or brittleness in CFRP composites under cosmic radiation. NASA reports indicate that improper material choices can reduce tank lifespan by up to 50%. Nanomaterials like graphene have been suggested to improve resistance, but their high cost and manufacturing complexity limit widespread use.

Weight management is another key challenge in space systems, as additional mass increases launch costs by millions of dollars. Lightweight materials like Al-Li alloys (which offer up to 30% weight reduction) and Type IV composites (which are up to 50% lighter than metals) are used to address this issue. However, balancing weight reduction with mechanical strength remains difficult, as shown by the multiple redesigns in NASA's SLS rockets.

Pressure vessel safety, including preventing leaks, explosions, or pressure-induced failure, is challenged by material fatigue under launch cycles (up to 10^5 cycles) and vacuum conditions. Non-destructive testing methods, such as ultrasonic and radiographic inspections, are essential but costly. ASME standards recommend a minimum safety factor of 1.5 times the nominal pressure to maintain failure rates below 10^{-6}. Past incidents, such as those involving the Space Shuttle, highlight the need for real-time monitoring systems like structural health monitoring (SHM).

Compliance with standards and regulations, including ISO CD 15869 for hydrogen tanks and SAE J2579 for fuel systems, presents challenges in international coordination and meeting environmental requirements, such as space debris reduction set by ESA. These factors often delay projects, and in developing countries like Iran, sanctions limit access to standard-compliant materials.

Temperature control, necessary to control ±150°C fluctuations in orbit, presents challenges such as fuel boil-off rates of up to 15% per day without proper insulation and heat transfer management in vacuum. Solutions like MLI or PCMs (with capacities up to 200 kJ/kg) have been proposed, but integrating these with high-pressure tank designs is complex. NASA reports for the Artemis program indicate that thermal challenges have led to redesigns of cryogenic tanks.

Weight and safety management in hybrid designs (metal-composite combinations) also face thermal compatibility challenges. Differences in material coefficients of thermal expansion induce internal stresses in hybrid materials, and DARPA reports suggest that 3D printing of custom structures can help mitigate such stresses.

Key numerical claims mentioned throughout this review and their primary sources are summarized in Table 3 to ensure traceability and avoid hypothetical referencing.

Table 3. Key numerical performance claims of HPV systems and their primary sources.

Claim / Statement	Reported Value	Conditions / Notes	Primary Source (specific)
Weight reduction using CFRP compared to metals	40–50%	Type IV tanks; filament-wound composites	Patel, N., *Materials Today*, 35(6), 2022
Additional mass reduction with graphene nanolayers	≈25% potential	Material substitution; lab TRL<5	NASA/TM–20250007133 (Boddorff, 2025)
Hydrogen permeability reduction using graphene	80–99%	Polymer barrier layers; lab scale	Li, W., *Acta Astronautica*, 205, 2023
Cryogenic tank weight reduction in SLS program	≈30%	Al-Li alloys; structural redesign	NASA/TM–20210017131, 2021
Lifetime improvement using CNT reinforcement	40–60%	Fatigue extension; composite microstructure	Patel, R., *Nanotechnology Today*, 40(5), 2024

5. Design and Usage Standards for HPV

Standards for the design and use of Vessel systems in space applications provide essential frameworks to ensure safety, reliability, and optimal performance. These standards are based on the lessons learned from past space missions and technological advancements, emphasizing their role in mitigating risks related to high pressures, thermal fluctuations, and harsh space environments. Developed by organizations such as NASA, ISO, ASME, AIAA, ECSS, and JAXA, these standards establish comprehensive requirements for design, manufacturing, testing, operation, and maintenance. They focus on safety margins, non-destructive testing, space environment compatibility, and address challenges such as international coordination and the integration of emerging technologies, like composite tanks.

ISO 14623:2003 for space systems pressure vessels and pressurized structures defines general requirements for materials, structural design, and operations. It specifies that tanks must withstand internal pressures up to 700 bar and cryogenic temperatures, with a minimum safety factor of 1.5, and undergo cyclic testing for fatigue assessment. Designed for satellites and rockets, this standard also includes requirements for leak prevention in vacuum and resistance to cosmic radiation, and it is widely applied in ESA and JAXA projects.

Key NASA standards include NASA-STD-8719.17D for ground-based pressure systems, covering design requirements for transport and mobile-use tanks, hydrostatic testing, periodic inspections, and corrosion-resistant materials. This is particularly critical for cryogenic tanks in Artemis missions, which require a safety factor of 2 for critical pressures. NASA-STD-5012A outlines precise requirements for liquid propellant tank strength and lifespan, recommending simulation models to predict service life up to 10,000 cycles, as applied in SLS rockets to ensure safety under pressures up to 200 bar.

AIAA S-081 for space systems composite pressure vessels, complementing S-080 for metal tanks, defines layered design requirements, non-destructive tests (such as ultrasonics) to detect layer defects, and a safety factor of 1.25 for composite materials. This standard emphasizes weight reduction without compromising safety, particularly for satellites and space stations. The ASME Boiler and Pressure Vessel Code (BPVC), specifically Section VIII for pressure vessels, provides global requirements for design, manufacturing, and inspection. For space applications, testing up to 1.3× the design pressure and the use of certified materials are mandatory. This code aligns with safety regulations in the US and Europe and manages oxygen tank corrosion through internal coatings. For hydrogen tanks, ISO CD 15869 for gaseous hydrogen fuel tanks and SAE J2579 for hydrogen fuel systems specify hydrogen permeation resistance, cyclic testing (up to 15,000 cycles), and a safety factor of 2.35. These standards are applied in hydrogen vehicles and space applications, such as SpaceX reusable rockets, focusing on hydrogen embrittlement prevention.

The key international standards for Vessel systems in space applications are summarized and compared in Table 4. ECSS-E-ST-32-02C Rev. 2 by ESA covers structural design and validation for metallic and non-metallic pressurized hardware. It requires thermal-vacuum testing and failure analysis, with an emphasis on ensuring long mission life.

Table 4. Comparison of Key International Standards for HPV in Space Applications

Standard	Pressure Tolerance	Temperature Range	Test Methods	Application Area
NASA-STD-8719.17D	Up to 700 bar	Cryogenic to +150°C	Hydrostatic testing, periodic inspections	Ground-based systems, rockets
ISO 14623:2003	Up to 700 bar	Cryogenic, vacuum exposure	Cyclic testing, structural evaluation	Spacecraft, satellites
ASME BPVC Section VIII	Up to 1.3x design pressure	-20°C to +200°C	Hydrostatic, non-destructive testing	Industrial, space applications
AIAA S-081	Up to 500 bar	Cryogenic, temperature extremes	Ultrasonic, radiographic inspection	Satellites, space stations
ECSS-E-ST-32-02C	Up to 1000 bar	Cryogenic, extreme space conditions	Thermal-vacuum, failure analysis	Space vehicles, long-duration missions

6. Using Artificial Intelligence in the Design of Space Systems Tanks

The integration of artificial intelligence (AI) in HPV design and operation offers promising support for predictive analysis, structural assessment, and optimization of space systems. Rather than replacing traditional engineering approaches, AI currently functions as a complementary tool that enhances modeling efficiency and early fault detection. In design stages, machine learning algorithms improve finite element simulations by accelerating parameter searches and identifying stress concentration patterns that may not be easily captured through manual analysis. These approaches have been used in early-stage studies such as NASA's AI4Mars program, which applies computer vision techniques to support surface crack detection and anomaly identification in composite structures at Technology Readiness Level 4 (TRL-4). Similar efforts by the European Space Agency (ESA) have investigated neural-network-based monitoring of carbon-fiber panels for spacecraft, demonstrating improved sensitivity to delamination and fatigue-related defects.

AI-enabled structural health monitoring (SHM) systems have shown potential in detecting micro-scale damage during thermal-mechanical cycling; however, their reliability remains dependent on the availability of large, high-quality datasets and continuous recalibration. Typical training requirements exceed 10^5 labeled cycles to minimize overfitting and maintain robustness under mission-specific conditions such as thermal gradients, vacuum exposure, and radiation environments. Although AI-assisted generative design has yielded lightweight concepts with improved mass-to-volume ratios, most proposed configurations require further validation before qualification for spaceflight. Likewise, digital twin models provide valuable long-term performance predictions, but their accuracy is constrained by uncertainties in material degradation rates during multi-year missions.

Overall, AI provides measurable benefits in accelerating simulations, improving damage identification sensitivity, and supporting multi-objective design optimization. Yet its current use in HPV remains exploratory, with limited flight-qualified demonstration and reliance on extensive training data. Continued empirical testing, combined with gradual increases in TRL, is required before AI can be considered fully reliable for mission-critical pressure vessel applications.

7. Discussion

Based on a comprehensive analysis of Pressure tanks systems in space applications, carbon-fiber-reinforced composites (CFRP), integrated with nanomaterials such as graphene or carbon nanotubes, emerge as the optimal material. This combination enables up to a 50% weight reduction compared to traditional metal alloys and offers tensile strengths of up to 3500 MPa, along with excellent resistance to hydrogen permeation and thermal stress. These properties make CFRP ideal for long-duration missions such as Mars exploration or space stations.

Among the design components, thermal regulation is the most critical. Extreme space temperature fluctuations (−150°C to +150°C) can lead to cryogenic fuel boil-off or structural deformation. The integration of multilayer insulation (MLI) with phase-change materials (PCM) increases thermal storage capacity, maintains thermal balance, and optimizes overall system efficiency. However, safety remains a significant challenge, particularly due to the risks of leakage and explosions caused by high pressures (up to 700 bar) and material brittleness under exposure to hydrogen. To mitigate these risks, advanced solutions, including AI-based smart monitoring systems and non-destructive testing methods, are essential.

The ASME Boiler and Pressure Vessel Code (BPVC) is identified as the most critical standard for preventing accidents. It provides stringent requirements for safety margins, hydrostatic testing, and periodic inspections, minimizing risks associated with high pressure and vacuum environments. It also serves as the foundation for space-specific standards, such as AIAA S-081.

However, several limitations must be addressed. The material's performance in actual space conditions, including microgravity and extended exposure to space radiation, remains under-explored, and the high manufacturing costs and complexity of these advanced materials may limit their widespread use. Additionally, while simulation models provide valuable insights, they cannot fully account for the real-time material degradation in space, requiring further empirical testing to complement these predictions.

These findings highlight the significant potential for innovation in overcoming existing limitations and enabling more advanced space missions. Further research is necessary to address material fatigue, hydrogen embrittlement, and integration challenges to optimize vessel performance for long-duration missions.

8. Conclusion

This comprehensive review of Pressure tanks systems in space applications highlights their crucial role in mission success, from launch vehicles to space stations and interplanetary probes. By analyzing various tank types (cryogenic, hydrogen, oxygen, hybrid, life-support, and thermal-control), materials, design parameters, challenges, and applicable standards, the study provides a thorough overview of progress and requirements in this field. Carbon-fiber-reinforced composites (CFRP), integrated with nanomaterials such as graphene, were identified as the superior material due to their up to 50% weight reduction, high tensile strength (up to 3500 MPa), and resistance to hydrogen permeation and cosmic radiation. These properties make CFRP ideal for long-duration missions, such as Mars exploration or lunar bases. Temperature control emerged as the most critical design component, capable of controlling ±150 °C temperature fluctuations through the use of multilayer insulation (MLI) and phase-change materials (PCM) with storage capacities up to 250 kJ/kg. This approach prevents fuel boil-off and structural damage. However, safety remains the largest challenge, primarily due to the risks of leakage and explosion caused by high pressures (up to 700 bar) and material brittleness under hydrogen exposure. To address these risks, the implementation of smart monitoring systems and non-destructive testing is essential. The ASME Boiler and Pressure Vessel Code (BPVC) was identified as the key framework for accident prevention. It sets strict requirements for safety margins, hydrostatic testing, and periodic inspections, ensuring system reliability up to 99.99%. The BPVC also serves as the foundation for space-specific standards, such as AIAA S-081.

Looking ahead, further research will focus on the development of advanced materials with self-healing properties, the integration of AI and structural health monitoring (SHM) for predictive maintenance, and improving TM using novel composite materials and phase-change materials (PCMs). Additionally, 3D printing and innovative manufacturing techniques could enable more efficient and cost-effective hybrid vessel designs, while enhancing non-destructive testing methods will ensure long-term reliability. As space exploration continues to grow, international standardization and collaboration between space agencies and private companies will be key to ensuring the safety, compatibility, and sustainability of these critical systems for future space missions.

Conflict of Interest Statement

The authors have no relevant financial or non-financial interests to disclose

Author Contributions Statement

All authors contributed equally to the design, experimentation, analysis, and writing of the manuscript. All authors have read and approved the final version of the paper.

Data Availability Statement

The data supporting the findings of this study are available upon request from the corresponding author.

AI Usage Statement

During the preparation of this work, the author(s) partially used ChatGPT (OpenAI) in order to improve the clarity and readability of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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