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Overview of Different Material Used in The Pressure Vessel for The Storage of Liquid Hydrogen

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Abstract - The declining supplies of fossil fuels, accompanied by their major environmental issues, have led the energy world to search for some alternate sources of energy. The high energy content of hydrogen along with the possibility of having zero-emission applications make it a potential candidate in the list. Most production techniques of hydrogen include methods such as electrolysis, steam methane reforming, and biomass gasification. Storing hydrogen has several drawbacks despite its potential. These drawbacks include low volumetric density and high diffusivity. Pressure vessels, then, are crucial in hydrogen storage: they need materials capable of working with pressure and avoiding hydrogen embrittlement. Most common materials used here include high-strength steel, aluminum alloys, Titanium alloy and composites. High-strength steel, for instance, can present quite robust mechanical properties. Aluminum alloys offer better resistance to hydrogen. Composites, including carbon fiber-reinforced polymers, offer a lightweight and corrosion-resistant alternative. Operating pressure, temperature, and hydrogen purity affect the storage of hydrogen in these materials. The objective is to review different materials to ensure that the materials can adequately balance mechanical strength, hydrogen-induced degradation resistance, and affordability.

***Key Words*:** Hydrogen storage, different metals, challenges face during hydrogen storage**.**

1.INTRODUCTION

In the pursuit of sustainable energy solutions, the global energy sector is increasingly turning its focus away from fossil fuels due to their diminishing reserves and significant environmental impacts. Hydrogen, with its high energy content and potential for zero-emission applications, has emerged as a promising alternative. Among the various forms of hydrogen, liquid hydrogen stands out for its high energy density and suitability for a wide range of applications, from automotive to aerospace sectors.

Liquid hydrogen storage, because of its low volumetric density and high diffusivity, poses some problems. Many techniques have been developed to overcome the associated difficulties, such as storing in cryogenic tanks, in high-pressure gas cylinders, or as metal hydrides. In cryogenic tanks, because they can store large volumes of hydrogen at low temperatures, the boiling off rate has to be minimized through advanced insulation techniques.

Critical factors for the performance and safety of these storage systems involve the materials used for constructing them. High-strength steel, aluminum alloys, and composite materials are very common. High-strength steel offers good mechanical properties, and they are valued for such attributes but highly susceptible to hydrogen-induced cracking. Aluminum alloys, conversely, have higher resistance against hydrogen embrittlement but cost a premium price for those aspects with lower pressure tolerance. Composites, such as carbon Fiber-reinforced polymers, are lightweight and corrosion resistant but have challenges related to cost and long-term durability.

Despite these advances, several challenges exist in the storage of liquid hydrogen. These include managing operating pressure and temperature, hydrogen purity, and materials that do not degrade due to hydrogen-induced degradation but are still economically viable. This review aims to provide a comprehensive overview of current methods and materials used in liquid hydrogen storage in relation to ongoing challenges and potential future directions in this critical area of research.

2. THE CHALLENGES OF LIQUID HYDROGEN STORAGE

This paper reviews different materials used in the storage of liquid hydrogen (LH2), focusing on the exclusive challenges presented by LH2's cryogenic temperature (20 K) and its inbuilt properties. Material choice is important for the safety and efficient storage and transport of LH2, as it is a vital fuel for many applications, notably aerospace [1] and potentially, the emerging hydrogen economy [2, 3]. Very low LH2 temperature requires materials that could retain exceptional cryogenic properties-high strength, ductility, and toughness at 20 K [4]. Moreover, with its low density, an efficient storage solution is of great importance to maximize the volumetric energy density in LH2 [5]. Hydrogen being flammable in itself calls for materials and design with leak-proof containment along with preventing the possibility of explosion. This review will examine several material classes, properties, and suitability for various applications in LH2 storage considering issues of cost, weight, durability, and safety. In addition, the ongoing efforts on research and development activities that aim to advance LH2 storage materials and technologies are also reviewed.

3. STAINLESS STEEL: THE WORKHORSE OF LIQUID HYDROGEN STORAGE

Stainless steel, 304L grade, has currently become the most used material for LH2 storage tanks. It has widely gained acceptance because of good mechanical strength as shown in Table1. at cryogenic temperatures satisfactory resistance to corrosion, and rather satisfactory weldability. Nevertheless, stainless steel performance at cryogenic temperature does not follow the same profile across all grades. Different grades of stainless steel have different properties at low temperatures, corrosion resistance, and weldability. This calls for careful selection of material according to the application requirements. The choice of stainless-steel grade is a compromise between several properties. For example, higher strength grades may provide better mechanical performance at 20 K but may sacrifice weldability or ductility. Fig.1. shows that how fracture toughness of stainless-steel changes as temperature changes. Therefore, the material's low-temperature performance, corrosion resistance, weldability, and other relevant properties should be assessed in detail for successful design and implementation [6].

The tensile behavior and fracture toughness of 304L stainless steel at cryogenic temperatures are important properties to understand. At cryogenic temperatures, the material has a phenomenon known as discontinuous yield, which is described by sudden drops in stress and stepwise deformation. This behavior complicates the stress-strain curves and requires more advanced techniques for analysis. Determining fracture toughness at 20 K is difficult because calculating the crack length cannot be determined directly by conventional methods such as the J-integral compliance method. This made researchers seek other methods and comparative analyses that would guarantee the reliability of LH2 storage vessel designs [4].

International and national standards also have a great role to play in ensuring the safety and reliability of LH2 storage vessels. Standards like ISO 13985-2006 and CGA H-3 detail material requirements, testing procedures, and design criteria for cryogenic applications. This standards cover various aspects of LH2 storage vessel design such as material selection, fabrication techniques, and testing protocols. Ensuring that LH2 storage systems work safely and reliably requires the following standards to be adhered to [6]. Some Chinese standards include GB/T 40060-2021, T/CATSI 05006-2021, and T/CATSI 05007-2023 that offer specific technical requirements in aspects such as vessel type, pressure, volume, material, design, and testing in relation to liquid hydrogen storage and transportation vessels [6].

Table -1: Stainless steel properties

Stainless Steel Grade	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
304	215	505	70
316	240	590	60
410	415	700	20
430	310	483	30
2205	450	620	25
17-4PH	1170	1310	10

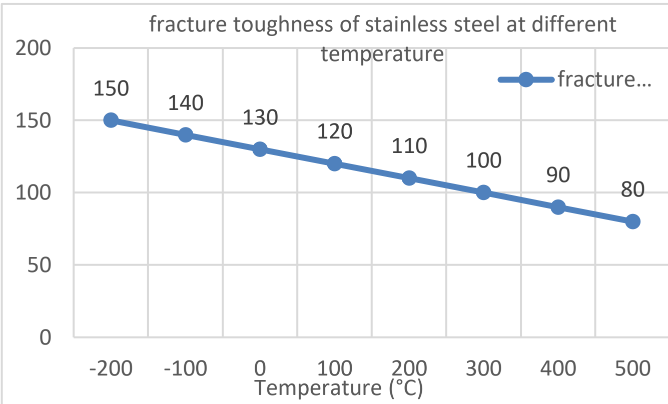

Fig -1:. Cryogenic fracture toughness of stainless steel at different temperatures.

4. ALUMINUM ALLOYS: LIGHTWEIGHT CHAMPIONS FOR SPACE APPLICATIONS

Aluminum alloys are finding increasing use in LH2 storage, especially in aerospace where the premium on saving weight is at a high value [1]. With cryogenic strength-to-weight ratio, they offer important benefits [7] and are widely used in liquid hydrogen storage tanks for aircraft [8] and other space vehicles [9]. Because of its lower density than stainless steel, aluminum storage vessels are lighter, which translates to lower payload weight and, consequently, better fuel efficiency. Among the most common aluminum alloys are 6061 and 7075, because they exhibit better mechanical properties as shown in Table2. at cryogenic temperatures [10]. In choosing an aluminum alloy, several factors must be considered: strength, ductility, weldability, and corrosion resistance at cryogenic temperatures, the relationship between fracture toughness and temperature is shown in Fig. 2.

However, mechanical properties of aluminum alloys need to be considered at cryogenic temperatures. Al though aluminum alloys exhibit increased strength at low temperatures, it is detrimental to ductility and toughness. The tensile behavior along with fracture toughness at 20 K needs to be examined in detail to ensure that the material can withstand the stress and strain values for LH2 storage [7]. Additionally, the fabrication of aluminum alloy LH2 storage tank requires special techniques. Assembling and welding operations need to be well controlled to avoid developing defects that would undermine the structural integrity of the tank. The reliability and safety of aluminum alloy LH2 storage tanks thus require advanced welding techniques, and strict quality control measures [10]. The development of additively manufactured cryogenic heat exchangers for hydrogen-electric aircraft propulsion highlights the potential of advanced manufacturing techniques in enhancing the performance and reducing the weight of LH2 storage systems [8].

Table -2: Aluminum alloy properties

Aluminum Alloy Grade	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
2024	290	430	10
6061	276	310	12
7075	503	572	11
5083	215	290	12
356	165	228	3
6063	241	270	16
1050	34	90	50
3003	41	110	25

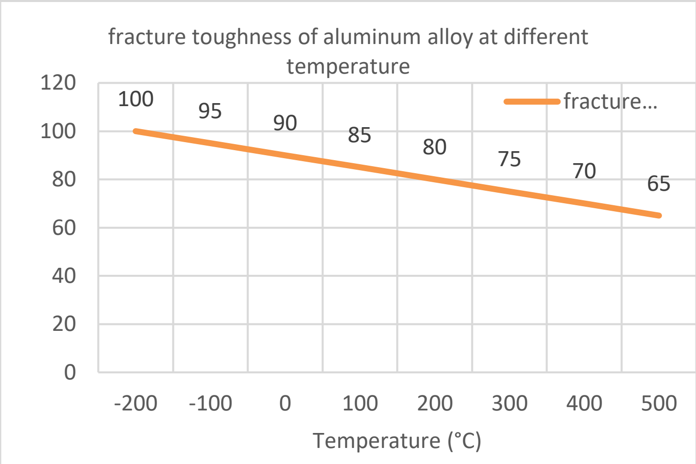

Fig -2: Cryogenic fracture toughness of aluminum alloy at different temperatures.

5. TITANIUM ALLOYS: HIGH-STRENGTH, HIGH-PERFORMANCE OPTION

The third material for LH2 storage is titanium alloys, which besides corrosion resistance, have an excellent strength-to-weight ratio. These materials have great strength and low density; titanium alloy have high tensile strength and yield strength as shown in Table3. Thus they are being explored in weight-critical applications, such as aerospace and high-performance vehicles. Titanium alloys also display excellent cryogenic properties, holding good strength and ductility at 20 K as shown in Fig.3. Their corrosion resistance is better than aluminum alloys and stainless steel in some environments, thus, they can be used in applications that have a potential of exposure to aggressive chemicals or moisture [1].

Although titanium alloys possess great advantages, they are rarely found in LH2 storage, despite their higher price compared with the stainless steel and aluminum alloys. Processed titanium is expensive, thus any LH2 storage system built using this material will prove too costly. Therefore, research is critical for the study of cost-effective fabrication methods and design optimizations of titanium alloy LH2 storage tanks to minimize material utilization while maintaining performance. More research is required in the complete characterization of the cryogenic properties of titanium alloys under different loadings and the long-term durability for LH2 storage application conditions [1]. New alloys with better properties and lower costs may further expand the application of such materials in LH2 storage.

Table -3: Titanium alloy properties

Titanium Alloy Grade	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Ti-6Al-4V	880	950	14
Ti-6Al-2Sn-4Zr-6Mo	1100	1170	10
Ti-5Al-2.5Sn	825	895	18
Ti-10V-2Fe-3Al	1200	1250	10
Ti-3Al-2.5V	620	700	15
Ti-6242	1030	1075	11

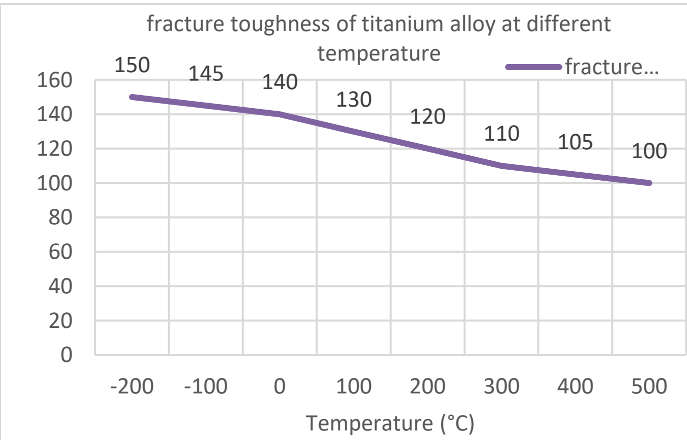

Fig -3: Cryogenic fracture toughness of Titanium alloy at different temperatures.

6. COMPOSITE MATERIALS: THE QUEST FOR ULTRALIGHT STORAGE

Composite materials, including carbon fiber reinforced polymers (CFRP), present the possibility for ultralight LH2 storage vessels. One of the principal advantages of composite materials is their strength-to-weight ratio, which enables the tanks to be designed significantly lighter compared to metallic alternatives. Composite materials have very hive tensile strength and yield strength as compared to steel and aluminum alloy as shown in Table4. In most applications, such as in aerospace, reduced payload weight is critical to being fuel-efficient and having payload capacity. Properly optimized geometries and shapes with such designs and facilities will also allow using CFRP, and this will lead to high storage capacity and geometries of tanks. In this way, structural integrity improves in comparison to usual metal tank structures [1]. The fracture toughness of composite materials decreases at the cryogenic temperature as shown in Fig.4.

Hydrogen leakage through composite material and partial and continuous loss of LH2 could eventually affect its general efficiency, though a couple of significant drawbacks of composite usage in LH2 storage have been discovered. Researchers are working to identify means of reducing hydrogen permeation by developing advanced composite materials with improved barrier properties. The long-term durability of composites at cryogenic temperature is also important as well. Repeated cycles of pressurization, temperature fluctuations, and exposure to LH2 may cause degradation in mechanical properties of composite. Therefore, large-scale testing and characterization are necessary to analyze the long-term material integrity of composite materials under cryogenic environments [11].

Composite materials have been utilized in pressurized vessels with combined pressure and deep temperature cyclic loads. The key problem in this context is the service response in relation to the fatigue strength of composite materials at cryogenic temperatures to ensure the safe LH2 storage system. The validation of the safe operation of CcH2 systems, using composite pressure vessels, is usually performed by means of a probabilistic approach. The uncertainties of material properties, manufacturing processes, and operating conditions are considered for assessing the likelihood of failure and to ensure that the system complies with severe safety requirements. As the development of appropriate composite materials for LH2 storage is a forward-moving research area [12], with the stress on improving hydrogen storage capacity, kinetics, and safety, as mentioned in [3].

Table -4: Composite material properties

Composite Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
CFRP (Carbon Fiber)	1000	1500	1
GFRP (Glass Fiber)	400	600	2.5
Kevlar	300	500	3
Hybrid (Carbon-Glass)	800	1100	2
Boron Fiber Composite	1400	1800	1.5

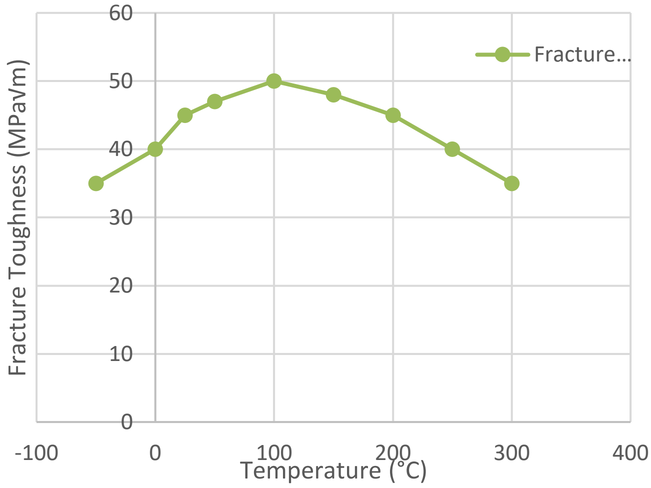

Fig -4: Cryogenic fracture toughness of Composite material at different temperatures.

7. OTHER MATERIALS AND APPROACHES FOR HYDROGEN STORAGE

Beyond these materials discussed above, many other strategies are also under investigation for hydrogen storage. Metal hydrides constitute a class of materials which absorb and desorb hydrogen through chemical reactions and hold an advantage in high gravimetric hydrogen density [13,14]. These usually suffer from slow kinetics as it may take considerable time for absorption and desorption of hydrogen and high operating temperatures. Research emphasizes improving kinetics and lowering operating temperatures of metal hydrides by alloying, doping, and nanostructuring [15,16]. One of the most promising synthesis techniques for preparing optimized intermetallic compounds to be used in hydrogen storage applications is through mechanical alloying.

Complex hydrides, such as sodium borohydride (NaBH4), have very high hydrogen storage capacities. However, their slow kinetics and regeneration difficulties are the main challenges. The research focuses on the enhancement of the kinetics of hydrogen release and absorption and developing efficient regeneration methods for complex hydrides. The use of catalysts and modification of the material structure are the main strategies to enhance the performance of complex hydrides [17]. Ammonia borane (AB) is another liquid hydrogen storage material with high hydrogen content. However, the slow kinetics of AB hydrolysis and unclear catalytic mechanism make it a challenge for its large-scale applications. Studies are currently focusing on efficient catalyst development and catalytic mechanisms to increase the hydrogen generation rate from AB. Supported catalysts on various materials, including metal oxides, carbon nitride, and metal-organic frameworks (MOFs), are being researched [18].

Liquid organic hydrogen carriers (LOHCs) are promising alternatives to compressed or liquid hydrogen, which are safer and more easily transportable [19,20, 21,22]. LOHCs are organic molecules that can reversibly absorb and release hydrogen at elevated temperatures, typically using catalysts [23]. N-ethylcarbazole is a promising LOHC that has been extensively studied. In particular, the research is conducted for more efficient catalysts in dehydrogenation and hydrogenation to enhance overall efficiency and bring down the cost of LOHCs . The purification of hydrogen from LOHC is also proposed by coupled microstructured systems involving radial flow reactors along with membrane separation units [24].

Carbon-based materials, including carbon nanotubes (CNTs) and graphene, are being studied for their possible application in the storage of hydrogen by physisorption [2,25,26]. Physisorption refers to the weak physical adsorption of hydrogen molecules on the surface of the carbon material . But the storage capacity of hydrogen by these materials at room temperature is currently very limited. It investigates enhancing the hydrogen storage of carbon materials by modifying their structures and their surface areas and the distribution of pore sizes of materials. N2 incorporation into the structure of mesoporous carbons enhances the hydrogen uptake storage at room temperature. Another area of research is related to the use of two-dimensional (2-D) and three-dimensional (3-D) carbon structures, graphene and graphite flakes, in hydrogen storage applications. Graphene can uptake a higher amount of hydrogen as it has higher surface areas [27].

A very fascinating approach to hydrogen storage is in the form of clathrate hydrates, wherein hydrogen molecules are trapped in cages of water molecules. However, their high formation pressures and the difficulty of achieving reversibility in hydrogen storage make them not ideal. There is research in lowering the formation pressure and increasing the reversibility of hydrogen storage in clathrate hydrates. Key strategies in improving the performance of clathrate hydrates in hydrogen storage include the use of additives and optimizing the formation conditions [28].

8. CONCLUSION: FUTURE DIRECTIONS IN LIQUID HYDROGEN STORAGE MATERIALS

The development of advanced materials for LH2 storage will be a key enabler of large-scale deployment of hydrogen as a clean energy carrier. While stainless steel is currently market dominant, due to the relatively good balance of its properties and cost, considerable advantages exist in specific applications based on aluminum alloys and composite materials where weight reduction plays a primary role. Ongoing research into metal hydrides, complex hydrides, LOHCs, and carbon-based materials holds significant potential for further improving efficiency, safety, and cost effectiveness for LH2 storage. Issues such as hydrogen permeation in composite materials, enhancing the kinetics of metal hydrides, and the regeneration processes of LOHCs are areas that call for future research. Moreover, the development of industry standards and regulations for LH2 storage [6] will play a vital role in the safe and reliable implementation of LH2 technologies.

Advanced integration of materials with innovative insulation systems[29] is necessary in order to minimize boil-off losses and to enhance the general efficiency of LH2 storage. Minimization of BOG is an important step toward saving energy and making the economics of LH2 storage more attractive [30]. Selection of the appropriate insulation material, such as vacuum-jacketed design, multi-layer insulation (MLI), and bulk fill insulation materials, like perlite and hollow glass microspheres, must be made after considering the specific application and the cost-benefit analysis [31], [32]. In designing the insulation system, it is important to consider the impact of a fire incident, which may trigger a rapid release of flammable gases and even possible BLEVE events [33].

Continued interdisciplinary collaboration among materials scientists, engineers, and policymakers is necessary to realize the full potential of LH2 as a clean and sustainable energy source. Further improvements of more efficient and cost-effective hydrogen storage will have relevant implications in a wide variety of sectors such as transportation, energy, and industrial processes [34]. Techno-economic analysis will be needed for the comparison of feasibility and competitiveness among different LH2 storage technologies in certain applications [35]. Different criteria, including energy efficiency, cost, safety, and environmental impact should be included in such analysis [36]. Comparative studies of the various hydrogen storage methods such as liquid hydrogen, and ammonia should be conducted in order to determine the best choices for the most applications [37]. For full realization of the potential of hydrogen as a clean energy carrier, it is also important to develop a reliable hydrogen infrastructure through production, storage, transportation, and distribution [38].

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