NASA/TM–20250007133

Choosing the Right Stuff: Material Selection for Liquid Hydrogen Aircraft Cryotanks

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July 2025

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Available from:

NASA STI Program / Mail Stop 050
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Abstract

A primary focus of liquid hydrogen-powered aircraft design surrounds the configuration and manufacture of the fuel storage tanks. Cryotank technology developed for space launch vehicles is applicable, but the prolonged lifecycle and passenger safety raise critical issues. The purpose of this white paper is to identify the decisions required in selecting composite or metallic material construction for cryotanks on commercial transports and provide recommendations based on the state of the art. Traditionally, metallic materials exhibit high damage tolerance and are a good choice for long-term durability. In contrast, composite materials exhibit high specific properties and are a good choice for lightweight structures. Emerging hybrid construction could potentially exploit the benefits of both material classes, but unaddressed issues of coefficient of thermal expansion (CTE) mismatch due to thermomechanical cycling obviate its near-term candidacy. The contributing factors considered here include cryotank weight/shape, boil-off/leakage, cost/manufacturability, crashworthiness, durability, inspectability, and tank locations. Although the ultimate design will depend on a complicated set of trade-offs, some preliminary conclusions can be drawn. Based on the key factors presented, metallic materials are favored due to the mature manufacturability (large-scales and high rate), good durability, and low cost, especially should the tanks be externally-mounted (on the wings) due to high impact resistance. However, composite materials show great promise if the durability concerns are overcome and probably favored should the tanks be internally-mounted (within the fuselage) due to the ability to create complex, conformal shapes.

Introduction

The National Climate Action Plan for Aviation calls for the U.S. aviation sector to reach net-zero carbon emissions by the year 2050. One approach to reducing carbon emissions is the maturation of hydrogen-powered aircraft to achieve zero-emission flight. Liquid hydrogen (LH_2) is a carbon-free fuel [1] that could satisfy this demand and enable greater range than incumbent kerosene-fueled aircraft (Jet A) [2]. However, the volume of LH_2 cryotanks will be four times larger than conventional Jet A fuel tanks because the volumetric energy density of LH_2 is only ≈ 8 MJ/L (vs. ≈ 32 MJ/L) [1]. Alternative hydrogen storage options, such as gaseous hydrogen and hydride fuels, are not viable candidates for large, commercial transports due to the excessive volume and weight penalties [2], [3]. The numerous technical challenges facing LH_2 cryotanks emphasize the need for a lightweight, durable, manufacturable, and low-cost cryotank material.

A major technological hurdle to hydrogen-powered aircraft concerns the effective design of the fuel storage tanks [3]. The challenges of LH_2 storage at cryogenic temperatures have been overcome in launch vehicles, i.e. maintaining -423ºF (-253ºC) and managing boil-off. However, commercial aviation faces many more challenges due to need to survive on the order of 10^4 thermomechanical cycles, while launch vehicles must survive three orders of magnitude less cycles (10^1). The long service life requires cryotanks with low susceptibility to hydrogen permeation and embrittlement as well as long fatigue life and low crack growth rates, the keys to exceptional durability [4]. Maintaining cryogenic temperatures also greatly increases the complexity of fuel stowage due to the required insulation and auxiliary components, such as heat exchangers, extraction lines and cryo-compatible subsystems [2].

Material selection strongly influences the design, service life, and performance of all aircraft components. Consequently, the two most likely candidates for cryotanks are aluminum alloys (type 1 pressure vessels (pv)) or polymeric composites (type 5 pv) [5]. The composite / metallic liner and composite overwrap pressure vessel (COPV) concepts show promise but are not considered viable candidates because the issue of CTE mismatch has yet to be resolved. Similarly, another promising choice of hybrid material are fiber metal laminates (FMLs), such as GLARE®, ARALL®, or CARALL®[1] [6]. In Europe, GLARE® is used extensively on the Airbus A380 [7] and has improved tensile properties at cryogenic temperatures [8]. However, FML materials have yet to be researched for cryotank applications in the USA and are not considered viable candidates due to the lack of maturity. The materials examined in this work are common candidate materials across literature for cryotanks for aviation - high-strength aluminum and carbon fiber-reinforced polymer (CFRP) composite.

A review of the key aspects of the rapid technology maturation needed to enable LH_2-fueled aircraft and meet national emission reduction targets is divided into three parts. First, the material properties of high-strength aluminum and carbon fiber-reinforced polymer composites are compared. FML mechanical property data is also presented to demonstrate potential as a candidate cryotank material. Second, key issues facing cryotanks for aviation are examined and each material system is evaluated. The cryotank design is assumed to be a double-walled, vacuum pressure vessel that maximizes thermal management and minimizes insulation requirements [9] to focus the review on the material selection rather than the structural design. Similarly, the compatibility and integration into the other systems of the aircraft, although important, are excluded from the review. The reader is referred to Brewer [5] or Bagarello [2] for an holistic assessment of hydrogen-powered aircraft. The review is concluded with summary of the viability of metallic and composite cryotanks with recommendations for future research.

Material Properties

The intrinsic material properties that typically govern selection for cryotanks are density, tensile and compressive strength, stiffness, and toughness [4]. In the case of a metallic tank, a likely candidate material is a modern aluminum-lithium alloy, such as Al 2050. In the case of a composite tank, Celion 12k-938 unidirectional tape is chosen as a representative epoxy-based CFRP composite material. In the case of a hybrid tank, and GLARE grade 4 is selected as a representative FML material. The key properties for candidate LH_2 cryotank materials are listed in Table 1.

[1] Specific vendor and manufacturer names are explicitly mentioned only for accurate reporting. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government nor does it imply that the specific material is the best available.

Table 1. Summary of room and cryogenic temperature properties of candidate LH_2 cryotank materials.

Material Property	**Temperature (°F)**	**Al 2050-T84[a] [10]**	**Temperature (°F)**	**CFRP Composite[b] [11]**	**FML[c] [12]**
Density (lbs/in^3)	75	0.098	75	0.057	0.09
Ultimate Tensile Strength (ksi)	75	73.9 – 79.2	75	273	149
	-320	88.8 – 95.7	-67	278	N/A
Compressive Yield Strength (ksi)	75	69.6 – 74.9	75	201	52.9
	-320	76.5 – 86.4	-67	240	N/A
Young's Modulus (Msi)	75	10.9	75	19.7	8.3
	-320	11.9 – 12.2	-67	19	N/A
Fracture toughness (ksi √in)	75	38.4	75	1.8-5.5[d] [13]	222.9
	-320	32.4	-67	N/A	N/A

a) Data are collected in the rolling direction and at two different locations through the thickness of a 4" plate.
b) Data are collected in the fiber direction.
c) Data are for a 3 aluminum - 2 composite layer sandwich GLARE® specimen tested in the fiber direction.
d) Fracture toughness data is for T300/#2500 Toray Industry Inc.

The CRFP composite has the highest ultimate tensile, compressive strength, specific strength, and Young's modulus (stiffness), which heightens interest in the material for aerospace applications such as cryotanks. FMLs have high tensile strength, but have lower compressive strength and stiffness than Al 2050. The fracture toughness is where FMLs show an advantage with an excellent crack tolerance, but cryogenic mechanical property data for FMLs are scarce. Work by van de Camp [8] is an example, but the material tested appeared to have contain defects in the epoxy matrix. The reported value for ultimate tensile strength at room temperature is only 8.7 ksi. However, the cryogenic Young's modulus and ultimate tensile strength roughly double at cryogenic temperatures and the fatigue life increases by a factor of 20, which does highlight the potential for FMLs as a cryotank material. Comparing all three materials, the CRFP composite has eye-catching properties in uniaxial tension and compression, but to evaluate the real-world performance, additional factors must be considered.

The structural design of cryotanks, which are subjected to multi-directional stresses, must account for the mechanical anisotropy of candidate materials. Table 1 presents the properties from the optimal orientation, which are typically in the rolling direction for metals and in the fiber direction for composites. Strength values selected for structural design will represent the peak strength, but in the weakest direction. Figure 1 shows the cumulative influence of anisotropy and environmental factors on the mechanical performance of CFRP and Al 2050. The knockdown factors for CFRP were taken from Wanhill [14] and applied to the tensile and compressive strengths of CFRP presented in Table 1. The anisotropy in mechanical properties for the Al 2050 alloy is from Hafley [10].

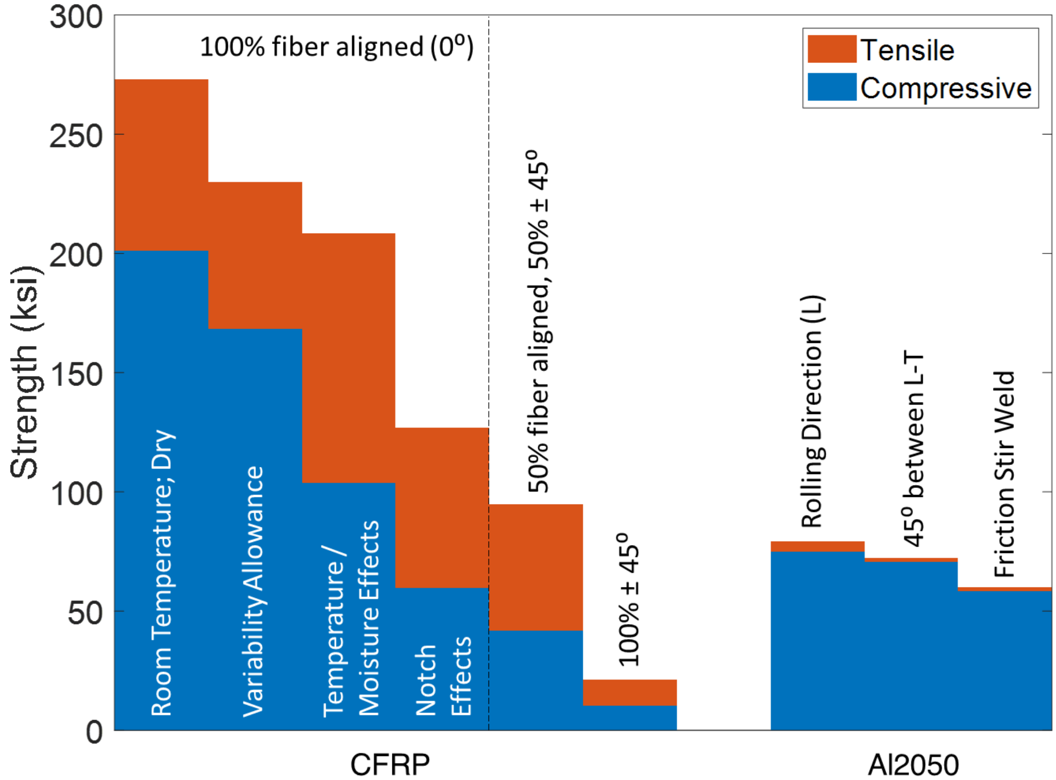

Figure 1. Comparison of CFRP and metallic environmental and anisotropy mechanical property knockdowns.

Figure 1 shows knockdown factor extremes for CFRPs, however the cases are realistic for cryotank materials in aircraft. The first knockdown for composites is variability allowances that account for the typical variations in strength caused by manufacturing defects. The second knockdown is the effect of temperature and moisture, where the latter can degrade the matrix material [15]. Cryogenic property data for CFRP is sparse in the open literature. Data presented in Table 1 indicate no change in properties down to -67ºF, but data in Figure 1 suggest otherwise. Trends in proprietary data show that there is a notable knockdown at -423ºF. The third knockdown is the notch effect, which accounts for feedthrough holes introduced that lead to stress concentrations and can disrupt fibers [16], [17]. The fourth knockdown concerns anisotropy, the degradation in strength of CFRP as the loading axis deviates from the primary fiber direction. The anisotropy of the CFRP can be reduced by using different fiber layup patterns, but that reduces the achievable peak strength. Additionally, the large decrease in strength from tensile (orange) and compressive (blue) loading for CFRP is important to understand when considering the loading of the structure. Al 2050 also exhibits mechanical anisotropy, with reduced strength at the 45º orientation between the L and T directions, plus in the ST orientation. The welding process, specifically friction stir welding, also degrades the tensile strength of Al 2050 by an estimated ~83%, which is an average of the tensile strength taken from two studies in the open literature [18], [19]. However, the knockdown factor for metallic materials is generally much less severe than for CFRP composites. Consequently, the strength (and specific strength) of CFRP composites could be less than or equal to Al 2050, if all factors are considered. This eventuality dictates careful analysis of the specific application within the overall structural design.

Another critical property is velocity-dependent impact resistance, which is an indicator of crashworthiness, bird strikes, hail damage, hits from runway debris, and maintenance tool drops. Table 2 presents a comparison of impact strengths in static, low velocity, and high velocity scenarios for Al 2024-T3, CFRP (thermoplastic), and FML (Glare) [7]. Similar to damage tolerance, FML has the highest impact strength across all velocities. Al 2024-T3 has 2.7x, 1.4x and 5.8x greater impact resistance than CFRP in the static, low velocity, and high velocity regimes.

Table 2. Impact strength of Al 2024-T3, CFRP, and FML at various velocities.

Material	Static (J)	Low Velocity (J)	High Velocity (J)
Al 2024-T3	13.0	8.8	37.3
CFRP	4.9	6.5	6.4
FML	18.1	38.4	95.6

Key Factors

Weight and Shape

The mass efficiency of cryotanks is often called the gravimetric efficiency, which is defined as the ratio between the fuel weight and the sum of the dry cryotank plus fuel weight [20]. The gravimetric efficiency also covers many other factors that include the location of the cryotank, type/amount of insulation, and primary material [20]. Single-piece construction tends to be easier for composite lay-ups with compound curvature, rather than cylindrical, designs. For example, conformal shapes could be necessary when attempting to stow the cryotanks in a double-lobed fuselage. Complex-shaped metallic tanks may require multi-piece construction to create conformal shapes. The associated increase in part count and joints, that might require welding or fasteners, could lead to greater weight or lower service property margins.

The choice of fuel controls the gravimetric efficiency of cryotanks. High-pressure, gaseous hydrogen tanks are feasible for short range aircraft, even though the approach represents a low gravimetric efficiency (~15%) [2]. As the tank pressure increases, the volumetric efficiency (fuel per unit volume) increases, but a larger wall thickness is required and the mass efficiency decreases [2]. In the case of long-range aircraft, LH_2 is the fuel of choice from the gravimetric efficiency perspective because of the lower pressures required for fuel containment. However, this comes at the cost of design complexity and the additional weight associated with maintaining cryogenic temperatures. The best candidate cryotank designs achieve gravimetric efficiencies between 65-70% [21]. It should be noted that there are other hydrogen storage technologies being developed [22], but maturity is at a lower technology readiness level (TRL) than LH_2 and the methodology will not be discussed.

Composite cryotanks have the potential to be 25% lighter than metallic (aluminum) cryotanks [3]. However, this is unlikely to be realized at cryogenic temperatures because of structural fortification to account for the possibility of microcracks, which will add weight [23]. Composite structures may also need to be ‘beefed-up’ for long-life thermo-mechanical cycling due to susceptibility of the matrix material to low-temperature embrittlement. In addition, composite materials can suffer from delamination during hole drilling (see Figure 1) to accommodate piping and feedthroughs [16], [17]. The durability concerns and reduced strength when considering knockdown factors (see Figure 1) will reduce the “25%” weight advantage often cited. In reality, Federal Aviation Administration (FAA) airworthiness requirements for LH_2 cryotanks for aircraft is needed for calculating true weight savings.

An oft-forgotten cryogenic tank concept, pressure-stabilized, may well be worth revisiting for large, LH2-propelled aircraft. A sub-category of metallic tanks is the pressure-stabilized approach, which is a thin-walled, minimal dry mass design with pedigree. The fabrication technology for stainless steel was developed on a commercial scale for lightweight LH_2 tanks on Centaur (Atlas) rockets in the 1960's [24]. A structurally efficient, double-walled tank design could comprise a containment vessel (as the outer wall) and a fuel bladder (as the inner wall), separated by a vacuum jacket with minimal heat shorts between the two. In this case, 'vacuum-stabilized from the outside' creates the same positive differential across the bladder wall as 'pressure-stabilized from the inside' for shape retention. It is envisioned that the structural mass savings might outweigh the fact that the concept is likely restricted to cylindrical configurations.

Boil-off and Leakage

One of the most significant technical challenges facing LH_2 storage is that the fuel must be kept at very low temperatures (-423ºF) in order to minimize evaporation. Avoiding boil-off is a major obstacle to rendering LH_2-powered flight feasible [2]. Vaporization can lead to over-pressurization of the cryotank that constitutes a dangerous situation and fuel must be vented to atmosphere until pressure drops below specified limits [25]. In addition, boil-off creates gaseous hydrogen within the tank, which is hard to contain as susceptibility to leakage is greater than for LH_2 [26]. In such a scenario, aircraft may need to land prematurely due to the decreased fuel load, an undesirable impact on operational costs.

Boil-off can be mitigated by minimizing the surface area of the cryotanks relative to the fuel load, which favors spherical or cylindrical configurations [3], and via insulation. There is a trade-off between the cryotank shape and the optimal shape of the aircraft with respect to where the cryotank is positioned. Insulation plays a key role in minimizing boil-off, so the mass and cost of each insulation type needs to be assessed [3], [20]. Multilayer insulation (MLI) in a vacuum has the lowest density and thermal conductivity compared to common insulation materials like perlite and aerogels [3], [27]. New insulation materials are being researched for cryogenic fuel storage in launch vehicles such as hollow glass microspheres – see Claussner [27] for a review of insulating materials.

The choice of cryotank material also depends on the thermal conductivity and susceptibility to leakage. Composite structures have lower thermal conductivity, but are more prone to leaks, particularly when subjected to thousands of pressurization cycles due to microcracking [26]. Metallic structures have higher thermal conductivity, but tend to be leak-resistant, especially at low temperatures due to lower diffusion rates [4]. If a double-walled, vacuum insulated structure is chosen, a metallic cryotank could likely use composite support structure to reduce heat transfer and provide lightweight structural support [5].

Cost and Manufacturability

The cost per unit and manufacturing rate for full-scale production of cryotanks is pivotal given the near-term target of replacing domestic fleets with zero carbon emission aircraft by 2050. Examining cost first, composite cryotanks are widely considered to be more expensive than metallic tanks [3], [28]. The quantitative metrics for existing aircraft will be used as a proxy to compare manufacturing costs of composite and metallic aerospace structures. Specifically, the composite-centric Boeing 787 and metalliccentric Boeing 777 represent state-of-the-art construction for each candidate cryotank material. It is assumed that the difference in sales price between the two aircraft reflects the relative manufacturing costs. Further, any difference in size, and therefore quantity of material used, can be normalized by calculating the cost per seat. The composite Boeing 787-8 is estimated to cost $248M per aircraft [29] with a typical capacity of 248 seats [30]. The metallic Boeing 777-200ER is estimated to cost $306.6M [29] with a typical capacity of 383 seats [31]. The relative cost per seat for the composite Boeing 787 is $1M, while the cost per seat metallic Boeing 777 is $0.80M. The metallic manufacturing costs is approximately 20% lower, suggesting metallic cryotanks will be the more cost-efficient option.

Composite aircraft are also more expensive to operate from the recurring costs perspective, likely due to complexity of the inspections and repairs. Again, using the composite Boeing 787 to the metallic Boeing 777 as representative aerospace structures, the annual recurring cost per aircraft per seat for the Boeing 787 is $0.12M , while for the Boeing 777 is $0.10M [32]. The operating cost for the composite aircraft is higher than the metallic aircraft even though the composite aircraft having 33% better fuel efficiency [33]. Assuming other operating costs are equal, higher fuel efficiency may be negated by increased maintenance requirements.

Examining manufacturing rate next, composites face a steeper gradient for technology development (efforts are underway – see NASA's HiCAM project [34]) to achieve the efficiency and scale of current metal manufacturing. Single-piece, liner-less composite manufacturing requires a collapsible or dissolvable mandrel. The necessary inclusion of a permeation barrier to prevent leaks further complicates mandrel design [35], [36]. A Boeing and NASA partnership has demonstrated prototypes of out-of-autoclave, large-scale, and liner-less composite cryotank manufacturing for space applications [36]. However, the path to high-rate and high-volume manufacturing remains unexplored, whereas metallic manufacturing is mature. New fabrication techniques, such as metal spinning, are poised to widen the manufacturing gap towards even higher rates and lower costs [37], [38].

Existing manufacturing capabilities to support wide-scale production of cryotanks favor a metallic cryotank as the more manufacturable and lower cost option for aircraft. Even if it is assumed that composite cryotanks will be lighter weight and lead to lower fuel costs, the fuel savings must overcome the increase in maintenance costs. However, composite manufacturing may prove to be more economical than metallic manufacturing should complex-shaped or conformal designs be specified.

Crashworthiness

Crashworthiness is defined as the ability of an aircraft and/or its sub-systems to protect occupants from harm during a crash [39]. Tanks containing pressurized LH_2 will pose the greatest risk to passengers during a crash via cryogenic burns, asphyxiation, fire, and/or explosion [40]. It should be noted that airworthiness certification requirements for hydrogen-powered aircraft are currently under development, therefore the merits of different designs are harder to establish [41]. Intrinsic material properties that will influence crashworthiness, such as impact resistance and flammability, can still be compared without standard regulations being in place.

In a crash scenario, a key requirement will be that the cryotank does not fracture in a manner that breaks vacuum leading to boil-off and/or release of cryogenic fuels. Any fracture (through-crack) of the cryotank should be prevented, so a focus on material toughness and impact resistance (i.e. energy absorbance before fracture) is critical. Generally, CFRP is brittle and has poor impact resistance (see Table 2), while metals like aluminum have good ductility and toughness [42]. Hybrid composite-metal materials, such as FML, also show promise because the attractive properties of both types of material can be exploited. Finally, composite cryotanks face safety concerns in high-temperature scenarios, like a fire, due to the thermal softening of matrix and flammability [43]. It is evident that the crashworthiness of composite structures is inferior to metallic structures.

Durability

The durability of a cryotank in aviation is based on the ability to withstand thousands of thermomechanical refueling cycles (fatigue), flight loads, and environmental conditions (hydrogen embrittlement) without needing frequent repair. In contrast with a single-walled cryotank or fuselage, a double-walled, vacuum insulated pressure vessel cannot tolerate any cracks of any size, due to the loss of vacuum and resultant dangers. A material with a high fracture toughness is important, especially since at cryotemperatures many materials become more brittle [3]. Critical stress intensity factor (K_{IC}) values for metals are ≈ 38.4 ksi/√in [10], while the K_{IC} for CFRP range for mode I and II failure is 1.8-5.5 ksi/√in [13], rendering the metallic cryotank a wise choice for damage tolerance.

The fatigue performance of the cryotank is also of vital importance as the use case for aircraft (thousands of cycles) versus launch vehicles (tens of cycles) is much more demanding. Assuming an aircraft life (based on Boeing 737NG) of 60,000 flights and a life reduction factor of four (4) without cryotank replacement, the material must sustain at least 240,000 cycles at stress levels ranging from 25-34 ksi [5]. For example, Al2195-T6 tanks exhibit a fatigue life of ~500,000 cycles, taking the most severe loading of 34 ksi. In contrast, it has yet to be demonstrated that composite tanks can survive more than a few hundred thermomechanical cycles before microcracking occurs [2], [3], [36], [44]. On the other hand, hybrid tanks (type 3) can increase fatigue life from the metallic liner [45], but CTE mismatch can cause separation of the cryotank wall from the liner [3], [5].

Current FAA guidelines indicate that Jet-A tanks to be inspected at regular maintenance periods long before the 60,000-flight end-of-life mark. Thus, it is reasonable to assume that multi-use cryotanks will need to be examined at least as rigorously, if not more. Therefore, the 240,000-cycle life-expectancy is only a target for the fatigue performance required for safety margins. In reality, the cryotank would most likely reach a specified fraction of the full life-time cycles at which time maintenance and/or replacement would be mandated.

The phenomenon of hydrogen embrittlement is another concern associated with long-term use of cryotanks, specifically metals. Atomic hydrogen can diffuse into the material, often most susceptible in welds, lowering the ductility and toughness. All tanks will contain varying quantities of gaseous and liquid hydrogen, but atomic hydrogen only originates from the gaseous component. Typically, composites are resistant to hydrogen embrittlement, while certain metallic alloys exhibit susceptibility to degradation from repeated exposure to hydrogen [46]. Consequently, the current aluminum lithium alloy used in the LH_2 cryotanks on the Space Launch System (SLS), Al 2195, has demonstrated resistance to hydrogen embrittlement. However, further studies are required to evaluate the performance of welded Al 2195 structures during prolonged service, as the SLS tanks are expendable and have a shorter use life.

Lastly, for a given application, the threshold stress for crack initiation is likely higher in composites than metals, however the mode of crack growth is different. Metals tend to exhibit slow, ductile fracture, while composites exhibit tend to exhibit fast, brittle fracture. Crack growth rates for composites tend to be higher than metallics making prevention of catastrophic failure more of an issue. The crack growth rate should be sufficiently slow such the flaw is able to be caught and corrective action performed before catastrophic failure [47] The remedy is that all tanks will need to pass a leak before burst test [48].

Overall, the durability of metallic cryotanks surpasses that of composite tanks for the near-term, although research is targeting improvement of the cyclic performance of all-composite cryotanks.

Inspectability

Inspectability is defined here as the ability to access and detect critical defects reliably. A damage tolerance assessment is required to determine acceptable flaw size that, in turn, determines the viable NDE techniques [49]. NDE of composite aerospace cryotanks is complicated due to size of the structure, complexity of the possible damage, and the intricate geometries [50]. Frequently, multiple NDE techniques are required to guarantee that all damage/defect types and orientations are detected with high probability [49]. Composites require critical flaw size detection in the *micrometer* range, increasing the complexity of inspections [3]. Metallic materials have more established NDE techniques and more reliable damage predictions because critical flaw sizes are in the *millimeter* range [3].

Independent of material selection, deployment of structural health monitoring techniques, especially in light of the discussion of inspections in the Durability section, would be a critical asset in reducing the risk of catastrophic failure [50].

Location of Tanks

The impact of cryotank location on material selection hinges on environmental conditions, manufacturability, and frequency of inspection. Although those are the primary concerns, many other factors come into play, such as safety, aerodynamics, and architecture. The location of the cryotanks will definitely differ from the current configuration for kerosene fuels (Jet A) for two, main reasons. First, to stow the equivalent energy of Jet A, the storage volume of LH_2 is 4.15 greater, which calls for much more tankage in multiple locations. Second, the customary storage of the majority of the fuel within the wings, common in conventional aircraft designs, may not be feasible [2], [5]. LH_2 will need to be at -423ºF, which pushes the tank design towards spherical or cylindrical shapes. Figures 2 illustrates the current consensus on suitable locations for LH_2 storage that do not radically change the current aircraft design. Figure 2a shows tanks positioned in the fuselage and Figure 2b shows tanks suspended under the wing. Figure 2c shows an advanced concept involving a blended wing body design that has gained favor as a result of many other factors. Identifying satisfactory cryotank locations will probably be governed more by manufacturability, unit cost, safety margins, and inspectability.

Figure 2. The possible locations of LH_2 storage for commercial transport aircraft are a) inside the fuselage, b) suspended over the wing, or c) in a new blended wing body design.

Proponents of stowing the cryotanks in the fuselage (Figure 1a) cite two safety requirements. The first concerns having the fuel tanks located outside the rotor burst zone of the engines. The second concerns positioning within the fuselage to protect against foreign object damage and environmental exposure. The cryotanks would be positioned either above the main cabin, or fore and aft of the passengers [40]. Cryotanks inside the fuselage in the fore and aft sections may require more complicated designs to allow for crew access [51]. However, locating cryotanks within the fuselage increases the risk to passengers in terms of fire, explosions, cryogenic exposure, and asphyxiation. Finally, the access to perform inspection and maintenance is more difficult when fit inside the fuselage. Therefore, the frequency and complexity of maintenance must be considered.

The wing-mounted option (Figure 2b) is an attractive alternative, which could allow for a simple, two large tanks design. Cryotanks mounted below the wing(s) would also be in closer proximity to the engines, reducing the linear footage of insulated pipes and the distance that the cryogenic fuel has to travel [51]. The design of wing-mounted cryotanks would need to be more aerodynamic in shape in addition to minimize surface area to reduce boil-off. The access to and substitution of tanks would be easier than if housed inside the fuselage for inspection, maintenance, and emergency jettisoning of a fuel tank. Wing-mounted cryotanks represent increased safety from cryogenic fuel exposure. However, the exterior tank material needs to be impact resistant to foreign objects and tolerates exposure to the outside environment. Higher impact strength is required, but other environmental exposure factors also must be weighed such as moisture exposure (corrosion or degraded bonding strength) and greater temperature extremes.

Although selection of cryotank materials and locations will depend on a complicated set of trade-offs, conclusions can be drawn from the key factors presented here. If tanks are externally mounted, the two material systems are near equivalent from the perspective of manufacturability and inspection, but composites are not favored because of low impact resistance (Table 2). If tanks are internally mounted, metals and composites perform equally from the perspective of environmental conditions. Composites are favored due to ability to manufacture complex, conformal shapes, whereas metals are favored from the perspective of lower frequency of inspections. Ultimately, the decision of where to stow tanks, as well as material choice, is not binary – composite and metallic tanks could be used both inside and outside of the fuselage.

Summary

Metallic cryotanks offer a robust, viable solution to LH_2 storage that can currently be manufactured at scale. Composite cryotanks are showing promising properties but have technology gaps that need to be closed before the tanks are ready for commercial development. Table 3 lists the advantages and disadvantages associated with each material selection.

Table 3. Summary of advantages and disadvantages for metallic or composite cryotank material selection

	Metallic	Composite
Advantage	• Low leakage • Low cost • Readily manufacturable at high rates • Good ductility, impact resistance, and toughness (crashworthiness) • High fatigue resistance during thermomechanical cycling • Simple inspection techniques	• High specific strength and stiffness • High gravimetric efficiency • Readily manufactured in conformal shapes • Not susceptible to hydrogen embrittlement • High fatigue strength
Disadvantage	• Lower gravimetric efficiency due to greater density • Harder to fabricate complex geometries • Higher thermal conductivity • Lower specific strength (in optimal conditions) • Hydrogen embrittlement susceptibility	• Anisotropic properties • Susceptible to microcracking leading to leakage • Delamination fracture from drilling • Higher cost • Lower manufacturing rate • Lower impact resistance • Flammability and thermal softening • Unproven thermomechanical durability • More complex inspection techniques

Ultimately, metallic cryotanks are the wise choice for near-term use in LH_2-powered commercial aircraft, as evidenced by the use of metallic cryotanks in Airbus' ZeroE LH_2 demonstrator [52]. Composite cryotanks exhibit exceptional specific strength when in optimal conditions, but the anisotropy and knock down factors shown in Figure 1 erodes the advantage over metallics. Key viability questions remain for composites regarding large-scale manufacturability and the durability to withstand thousands of thermal cycles remain unanswered. Metallic-liner/COPV designs boast benefits from each material class but are likely to face issues with CTE mismatch. Alternatively, FML's are an intriguing, unexplored option as a cryotank material, although costs might be prohibitive. Finally, meaningful performance comparisons will only be possible by finding solutions to current research questions and cementing regulations so that truly representative designs can be manufactured and evaluated.

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