



Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications

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Abstract

Due to its high specific energy content, liquid hydrogen (LH₂) is emerging as an alternative fuel for future aircraft. As a result, there is a need for hydrogen tank storage systems, for these aircraft applications, that are expected to provide sufficient capacity for flight durations ranging from a few minutes to several days. It is understood that the development of a large, lightweight, reusable cryogenic liquid storage tank is crucial to meet the goals of and supply power to hydrogen-fueled aircraft, especially for long flight durations. This report provides an annotated review (including the results of an extensive literature review) of the current state of the art of cryogenic tank materials, structural designs, and insulation systems—along with the identification of key challenges—with the intent of developing a lightweight and long-term storage system for LH₂. The broad classes of insulation systems reviewed include foams (including advanced aerogels) and multilayer insulation (MLI) systems with vacuum. The MLI systems show promise for long-term applications. Structural configurations evaluated include single- and double-wall constructions, including sandwich construction. Potential wall material candidates are monolithic metals as well as polymer matrix composites and discontinuously reinforced metal matrix composites. For short-duration flight applications, simple tank designs may suffice. Alternatively, for longer duration flight applications, a double-wall construction with a vacuum-based insulation system appears to be the most optimum design. The current trends in liner material development are reviewed in the case that a liner is required to minimize or eliminate the loss of hydrogen fuel through permeation.

1.0 Introduction

The interest in developing aircraft utilizing alternative energy sources such as hydrogen is driven primarily by the fact that hydrogen provides low to zero emission of environmentally harmful products. Among the applications being considered, flight durations can range from several minutes to many days. A couple of current NASA unmanned long-flight-duration aircraft are illustrated in figure 1. Specifically, NASA's Helios HP03 vehicle was a solar-powered unmanned aerial vehicle (UAV) utilizing a regenerative fuel cell system for energy storage. It was capable of flight durations as long as a month but with a limited payload capacity of 230 kg (550 lb) that had to be distributed along the wings, and it could fly at a peak altitude of approximately 21 km (70 000 ft).

Commercial aircraft applications are likely to have a flight duration on the order of a few hours. The push for a larger payload capacity and longer flight durations requires the use of a higher specific power

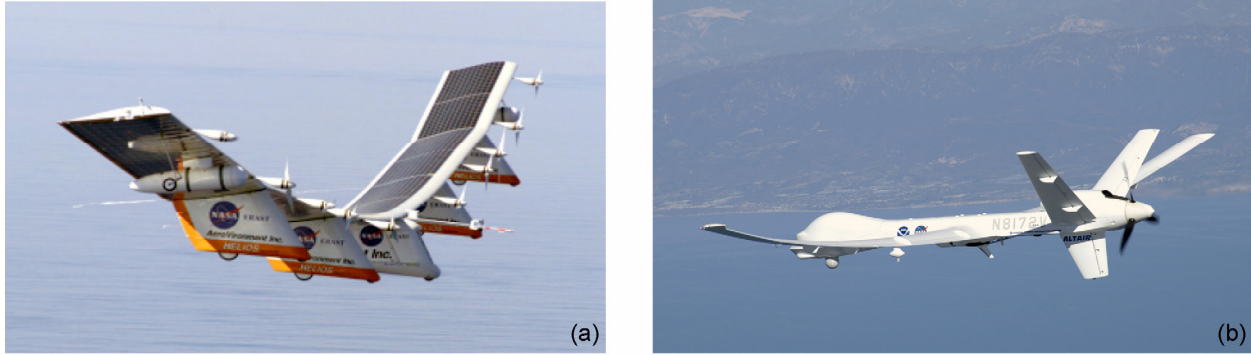


Figure 1.—Recent NASA research efforts utilizing long-flight-duration unmanned aircraft. (a) Helios, utilized hydrogen fuel. (b) Altair/Predator.

propulsion system with improved overall efficiency. The systems currently being investigated include the use of fuel cells with electric motors and internal combustion engines. Current preliminary mission requirements that are pushing the long-flight-duration hydrogen aircraft development include a 14-day (336-h) flight duration with a payload capacity that is sufficient to accommodate the instrumentation required for the various missions.

Hydrogen offers the most energy per unit mass of the various types of liquid and gaseous fuels as noted by Thomas (2000). Hydrogen stored as a liquid significantly enhances its energy per unit volume relative to gaseous hydrogen (GH_2). Gaseous hydrogen stored at 35 MPa (5 ksi) and 20 °C (68 °F) has only one-third of the energy content per unit volume of liquid hydrogen (LH_2) as illustrated by Thomas. Although there is a weight penalty with the needed insulation for storing LH_2 at a low pressure and cryogenic temperature, it is less than the combined weight and volume penalty that comes with storing GH_2 at a high pressure. Another method for storing hydrogen in a compact and safe form is with a metal hydride. Unfortunately, metal hydrides present a significant problem with excessive weight, precluding their use in weight-sensitive applications such as flight vehicles.

Currently, cryogenic storage tank applications in aerospace applications, where weight is of prime importance, are limited to short flight durations, such as with space launch vehicles. The cryogenic fluids are transferred to the vehicle storage tanks just prior to the launch with the majority of the fluids being depleted during the launch to orbit, on the order of a few minutes. The cryogenic fluids are depleted at a rate where boiloff does not pose a significant problem. In these applications, lightweight foam insulation is usually sufficient for the storage tanks. In deep space the heat transfer to the cryogenic fluid is significantly less than at the ambient condition on the Earth's surface, reducing the need for an ultra-low-conductivity and heavy insulation system. It is for the aircraft with relatively long flight durations on the order of days that provide the greatest engineering challenges to develop long-term and lightweight hydrogen storage systems.

The need for reduced weight in combination with good insulating properties for long-term storage provides a new challenge for cryogenic tank design as noted above. It provides an opportunity to apply more advanced materials and structural concepts in an effort to reduce the overall weight and keep the volume at an acceptable and practical magnitude.

This report addresses the structural and thermal components of the cryogenic storage tank system for an aircraft. The following sections will cover the individual components of the tank system. After detailing the key challenges next, the subcomponents of the tank system will be covered in the following sections. Materials and their thermal and chemical compatibility with the environments involved with an LH_2 storage system will also be discussed. Construction techniques for the tank will be covered. This includes evaluating metallic and polymer matrix composite (PMC) materials and the architecture used for creating the tank. The potential use of liners will also be discussed. Other important areas of the tank structure—including mounting methods for integrating the tank system with the airframe, stiffeners, fuel slosh baffles, and ports—are not discussed in detail as they are outside the scope of this report. Insulation

methods will be reviewed to determine an optimum system for the aircraft applications. More recent developments with silica-based aerogels as an insulating material, as noted by Fesmire et al. (2001), will also be evaluated. Lastly, a summary of the findings will be provided along with recommendations for design or further investigation of promising systems. Appendix A provides a list of the acronyms used throughout this report. Appendix B lists references for further reading on cryogenic storage tanks. These references are separated into groups according to the component of the fuel tank system they refer to.

2.0 Key Challenges

The successful realization of future lighter weight and environmentally friendly aircraft require the synergistic integration of a number of revolutionary and leading-edge technologies as well as the development of novel engineering tools and manufacturing techniques. As mentioned above, there is a particular interest in hydrogen-fueled aircraft with a flight duration of several days. Hydrogen can be stored either in gaseous or liquid form. Gaseous hydrogen would require 5.6 times the volume compared to that of LH₂ when GH₂ is stored at approximately 163 atm (2400 psi) and at a temperature of 15 °C (60 °F). The excessive volume required, the weight of the container, and the safety issues related to high-pressure storage preclude the use of GH₂ as fuel for this application. Alternatively, metal hydrides can store hydrogen compactly and safely, although these systems will be excessively heavy and thus impractical. In addition, most metal hydride systems would take days or even weeks to recharge. The MgNi hydrides can achieve approximately 5 percent hydrogen by weight but require higher temperatures to activate the bed. The metal hydride issues were summarized by Brewer (1991), who noted their current impracticality for aero applications. Liquid hydrogen in a saturated state is a viable option for long-flight-duration aircraft. However, the design of a cryogenic LH₂ storage tank, coupled with the use of LH₂ as aircraft fuel, involves many challenges. Some of the key challenges including geometry, temperature, permeation, hydrogen embrittlement, and safety factors are briefly discussed below.

2.1 Geometry and Size

Even though LH₂ has a high heat of combustion, its low density coupled with the potential long flight duration and the use of a nonregenerative storage system may result in a need for large tank volume. A nonintegral (i.e., not loaded as part of the aircraft's structure) large tank means higher frontal and surface area, which will result in higher drag. Successful configurations will require innovative designs with small frontal and surface areas. Large tanks with curved surfaces using advanced materials for wall construction and insulation similarly pose manufacturing difficulties due to the sheer size and volume. Integration of a large tank on an airplane is in itself a significant challenge. Integral tanks, alternatively, require a complex architecture and will pose many manufacturing challenges. Integral tanks serve as the aircraft structure and carry fuselage loads as well as providing for fuel containment. Nonintegral tanks serve only as fuel containers and are mounted within and supported by a conventional airframe (Brewer, 1991). As mentioned previously, nonintegral tanks do not have to conform to the shape of the aircraft; their architecture can be relatively simple like spherical or cylindrical. Spherical-shaped tanks provide minimum surface area for a given volume, so the passive heat into the tank can be minimized, which minimizes the boiloff of LH₂. However, the spherical shape poses some unique manufacturing difficulties and has a higher frontal surface area, resulting in higher drag forces compared with a cylindrical-shaped tank. Alternatively, cylindrical shapes are easier to manufacture but have a higher surface area to volume ratio thus resulting in a higher passive heat load into the tank.

2.2 Cryogenic Temperature

The normal boiling point of LH₂ is -252 °C (-423 °F). The LH₂ needs to be kept below this temperature to minimize boiloff, that is, the loss of fuel and buildup of pressure within the tank. During ground operations, the maximum temperature difference between the inside and outside of the tank

structure is expected to be as high as $\Delta T = 300\text{ }^{\circ}\text{C}$ ($540\text{ }^{\circ}\text{F}$). Lightweight, low-conductivity insulation is obviously necessary to maintain such a large temperature gradient. As mentioned before, most previous applications of cryogenic fuels such as LH_2 were limited to a short duration of a few minutes as in launch vehicles where the problem of fuel boiloff is not critical. However, for long-duration flights, excessive boiloff is very undesirable and limits the flight duration of the aircraft. Hence, the amount of passive heat that goes into the tank and causes the LH_2 to boil off needs to be limited. Storage of LH_2 on the ground has similar problems and requires specialized equipment and procedures to handle it. It has been established that if the LH_2 is maintained at a constant absolute pressure of approximately 170 kPa (25 psia), the boiloff will be kept at an acceptable level and without an excess weight penalty on the tank design (Brewer, 1991). In addition, the tank and any connecting lines or attachments will need to be completely isolated from the outside atmosphere because all gases, with the exception of helium, solidify at the temperatures of LH_2 and raise the potential for obstructing the flow lines and other components.

2.3 Permeation

As hydrogen molecules are very small, they are extremely prone to permeating through the tank wall. The permeation by hydrogen is perhaps the most critical issue in the tank design. Metallic tanks are an obvious solution to this problem, as hydrogen permeates metals at a slower rate than through the nonmetallic materials. For an aircraft, however, the metallic tank mass may limit its payload capacity and flight duration. A PMC tank using a thin metallic liner would also solve the permeability problem, but the weight may still be an issue. Furthermore, the coefficient of thermal expansion (CTE) mismatch between the composite tank wall and the metallic liner will cause them to contract differently, possibly inducing stresses in the material that may result in separation of the liner from the tank and/or fracture of the liner, thus making such a design undesirable.

Hydrogen permeation studies performed during the National Aerospace Plane program were encouraging, and it was shown that composite tanks without any liner were sufficiently impermeable. However, the failure of the PMC LH_2 tank of the X-33 demonstrator project during ground testing was thought to be initiated by the microcracking of the polymer matrix in the composite inner skin of the tank structure (Grimsley et al., 2001). The microcracking of the composite resulted from the CTE mismatch in the carbon fiber and the polymer matrix in combination with a large difference between use and composite fabrication temperatures. The microcracks provided a path for the pressurized hydrogen to leak or permeate through the wall and enter the honeycomb core. When heated, the matrix cracks closed, the liquid evaporated and the resulting gases having no place to escape caused a rise in pressure and eventual delamination of the core from the inner composite skin.

Lately, there have been some studies to evaluate polymeric films and coatings that could be applied to the composite inner skin and act as a barrier to contain the LH_2 in the tank. The task of fabricating lightweight and impermeable tanks using advanced materials for a cryogenic application is a challenging one.

2.4 Hydrogen Embrittlement

Many materials when exposed to hydrogen in large concentrations become embrittled. The effect of hydrogen on material behavior has been well documented (e.g., Moody and Thompson, 1990). This is a type of material deterioration. As a material becomes more brittle, its reliable load-carrying capacity and ductility are reduced. Thus, catastrophic failures can occur without significant deformation or obvious deterioration of the structural component. This limits the use of many advanced materials in the tank wall construction. Breakthrough material technologies are necessary to overcome these issues. Tensile stresses, a susceptible material, and the presence of hydrogen are necessary to cause hydrogen embrittlement. Hydrogen embrittlement can result in cracking at stress levels significantly below yield stresses. While hydrogen embrittlement is documented most for high-strength steels, all materials possess a certain degree of susceptibility. Resistance to hydrogen embrittlement should be a significant consideration for tank wall materials.

2.5 Safety Factors

The use of mandated safety factors in the range of 1.4 to 2.0, which are usually augmented by conservative material strength estimates (such as A-basis allowables), make it very difficult to achieve a lightweight design. This is particularly true when nontraditional advanced materials are used in the construction of such structures. Furthermore, new and/or advanced materials are not very well characterized, especially at cryogenic temperatures, and manufacturing and fabrication processes introduce additional variability in the material properties. All of this causes the material properties to show a significant scatter, necessitating significant difference between average measured and allowable values. Future tank structures will certainly require innovative designs calibrated with tests and include integrated health-monitoring techniques to reduce the explicit and implicit safety factors.

In summary, it poses a major challenge to find the right balance among (1) minimizing the weight of a durable tank structure that carries the required amount of fuel, (2) surviving the required number of mission cycles involving fuel fill and drain cycles and their corresponding thermomechanical loading, and (3) creating a design that can actually be manufactured, inspected, and used with confidence.

3.0 Previous Cryogenic Tank Applications

Research in the area of storage of LH₂ for aircraft and spacecraft has been conducted for many years. With aircraft and spacecraft having similar requirements, a brief summary follows for past aerospace cryogenic tank applications in chronological order. Other applications, including mobile and stationary ground-based storage applications, are also summarized.

3.1 Early Hydrogen-Fueled Aircraft

One of the earliest documented applications of cryogenic hydrogen storage tank and hydrogen fueling application for a flight vehicle was reported by Hall and Silverstein (1955) and Reynolds (1955). A U.S. Air Force twin engine B-57 bomber was modified to have one engine operate on hydrogen. This was part of a program at NASA Glenn Research Center, Cleveland, Ohio (formerly Lewis Research Center), to demonstrate the characteristics of hydrogen combustion in an aeronautical gas turbine application as noted by Brewer (1991): Brewer had provided an extensive overview of the needs and the status of technology for utilizing LH₂ for aircraft. It should be noted that the emphasis of the program was on the successful operation of a gas turbine engine on hydrogen; hence, there was no emphasis to develop a lightweight cryogenic storage tank system.

3.2 Saturn V

The Saturn V rocket was NASA's heavy launch vehicle used during the 1960s and 1970s. The Saturn V rocket used aluminum tanks with foam insulation. The single-wall metallic tank with foam insulation is fairly representative of typical Earth-to-orbit launch vehicles using LH₂ as propellant. Being an Earth-to-orbit launch vehicle made it a short-duration storage situation. The upper two stages of the Saturn V engine utilized LH₂ along with liquid oxygen (LO₂) as the propellants. Glaser (1967) showed the second stage consisting of an aluminum wall, surrounded by a foam infiltrated honeycomb core, then a nylon phenolic coating, and a final layer of Tedlar (DuPont) plastic film for protection from aerodynamic heating. The foam was purged with helium. Glaser described the third stage as using foam on the inside of the tank wall. The location of the foam reduced the need for special methods and adhesives for mounting the foam. As a result, the tank wall operated at a higher temperature and did not need protection from aerodynamic heating. A vapor and liquid barrier was incorporated at the inside surface of the insulation.

3.3 Space Shuttle External Tank

From the early 1980s to the present, NASA used the space shuttle as their heavy launch vehicle, where the space shuttle's external tank (ET) is a state-of-the-art lightweight cryogenic storage structure that is currently in service. The ET is a load-bearing structure within the space shuttle system. It is designed to carry the weight of the LH₂ and LO₂, the load from the shuttle orbiter, and the loads from the solid rocket boosters (SRB). In addition, the liquid cryogenic fluids are stored under pressure of approximately 2 atm. The ET is an expendable component that is filled just prior to the launch, and is used for the short duration in taking the shuttle from the launch pad to low Earth orbit in approximately 8.5 min. The weight of LH₂ stored is 1.0 MN (228 000 lb) with a boiloff rate of approximately 4.4 N/s (1 lb/s) upon stabilizing the tank (P. Rogers, 2006, NASA Marshall Space Flight Center, Huntsville, AL, personal communication) which corresponds to approximately 1.6 percent by weight of LH₂ per hour.

The pressurized portion of the ET is constructed with an aluminum-lithium alloy, 2195. The original aluminum alloy was 2219, which was later substituted with the aluminum-lithium alloy 2195 as described by Bickley and Schwinghamer (1999). The aluminum-lithium alloy provides an increase in strength and a slight reduction in density relative to the previously used 2219 alloy. Figure 2 illustrates an exploded view of the space shuttle ET. In addition, the materials of the key components are also noted in figure 2. The ET is an aluminum semimonocoque structure of fusion-welded barrel sections, five major ring frames, and forward and aft ellipsoidal domes according to Petty (2006). Thermal protection is provided by spray-on foam and premolded ablator materials. At NASA's Web site on the ET, Petty provides a good overview of the tank.

3.4 NASP Tank

The joint U.S. Department of Defense (DOD) and NASA effort to develop a National Aerospace Plane (NASP) during much of the 1980s included an attempt to develop lightweight cryogenic storage tanks for a single-stage Earth-to-orbit vehicle. Some of the NASP efforts were summarized by Cope and Thorndyke (1992) and Hellwig et al. (1992). NASP was originally a feasibility study for a single-stage-to-orbit vehicle that could take off and land horizontally, as summarized by Jenkins et al. (2003). The potential prototype was designated the X-30. The program's scope was modified later to develop a hypersonic intercontinental aircraft.

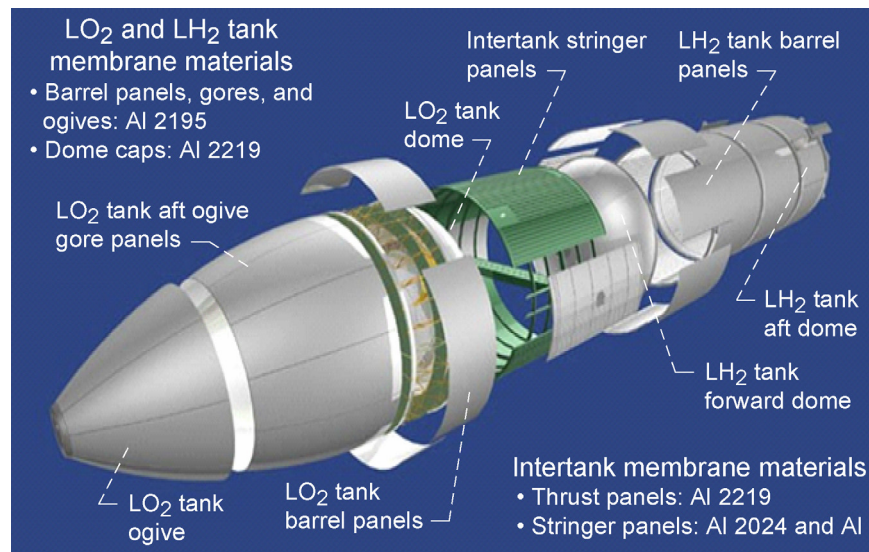


Figure 2.—NASA's space shuttle super-light-weight tank general configuration with Return to Flight mission ET-120.

The demanding requirements of a single-stage-to-orbit vehicle or hypersonic intercontinental aerospace vehicle enhanced the importance of weight savings. The NASP project used a multilobed composite tank for storing LH₂. It was an early attempt for using PMCs with cryogenic fluids for weight savings relative to the more common metallic structures. The tank was fabricated from a thin shell carbon-fiber-reinforced epoxy matrix composite with stiffening elements as reported by Hellwig et al. (1992). In addition, the tank utilized internal restraints to reduce tank wall deformations upon pressurization (Lohmueller, 1992) and did not have any liner (Robinson, 1994).

3.5 First Aircraft Application Fueled Solely by Hydrogen

Brewer (1991) described the first aircraft to be completely powered on hydrogen fuel. The flight took place on June 19, 1988. Previous aircraft utilized multiple engines having only one engine running on hydrogen. The aircraft, described by Brewer, used a cylindrical storage tank with ellipsoid end caps for the LH₂. The tank was fabricated from Type 304 stainless steel. The container was mounted within an aluminum outer jacket and supported at multiple points by low-conductivity spacers. The space between the tank and jacket was evacuated to minimize the thermal conductivity and used MLI within the evacuated space to minimize radiation heat transfer. However, the overall objective of the program was to demonstrate a flight powered solely by a hydrogen-fueled engine, and not necessarily to develop a lightweight LH₂ storage tank for long duration.

3.6 X-33 Liquid Hydrogen Tank

The X-33 technology flight demonstration program was a natural progression following the NASP project. NASA's X-33 program was a significant project that utilized advanced materials and concepts in an effort to enhance cryogenic storage tank technology. The suborbital X-33 was designed to demonstrate advanced technologies that would dramatically increase launch vehicle reliability and lower the cost of launching payloads to low Earth orbit. The X-33 vehicle was supposed to be the technology demonstration vehicle for the VentureStar. Much of the work with the X-33 was summarized in a NASA George C. Marshall Space Flight Center report (2000).

The X-33 vehicle had two LH₂ fuel tanks, each being 8.7 by 6.1 by 4.3 m (28.5 by 20 by 14 ft) in size. Figure 3 is a schematic view of X-33 and its tanks along with a photograph of an actual tank. Hydrogen permeability studies performed during the NASP program were encouraging and it was thought that composite tanks without any liner were sufficiently impermeable. The X-33 used a more complex sandwich structure than the one used in the NASP program. The sandwich structure consisted of graphite/epoxy inner and outer skins and a Hexcel Composites graphite/epoxy unvented core as described by Dornheim (1999). It consisted of a multilobed and linerless configuration with integrally bonded, woven composite joints. The tanks had three major subcomponents: the aft dome and bulkhead, the barrel

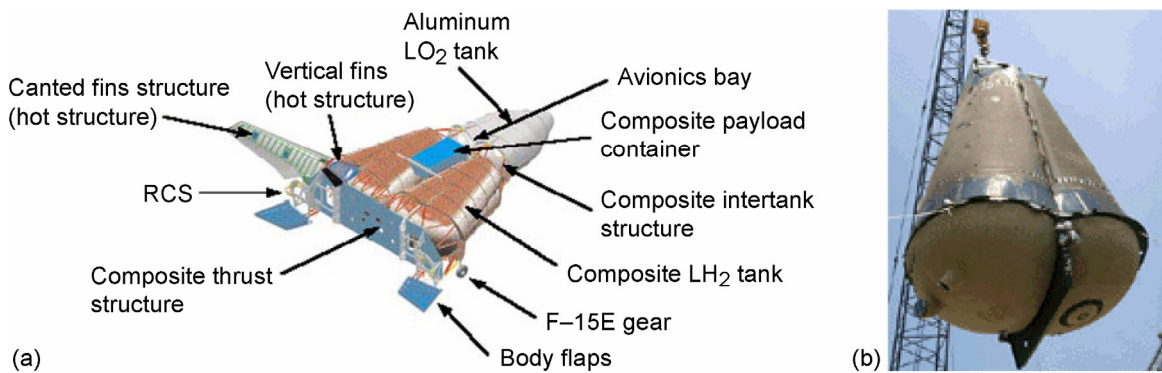


Figure 3.—X-33 vehicle. (a) Internal configuration. (b) Composite LH₂ tank.

section, and the forward dome and bulkhead. The tanks were also an integral structural part of the vehicle's primary body and would have had a very complex stress state. These tanks were tested at NASA Marshall Space Flight Center in Huntsville, Alabama, during November 1999 to verify structural integrity of the LH₂ tanks under cryogenic temperature and various pressure and mechanical loading conditions anticipated as typical for use in the X-33 vehicle.

After the successful completion of the first prototype pressure and load test, the test article was drained of its LH₂ and a purge of the tank began. Approximately 15 min after the tank was drained, failure occurred: the outer face sheet and the core of one of the lobes separated from the inner face sheet. It was determined that the test procedures and parameters were all within the design limits of the test article.

An investigation team was assembled and listed the most probable cause of the failure as a combination of following phenomena (NASA Marshall report, 2000):

- (1) Microcracking of inner facesheet with subsequent GH₂ infiltration
- (2) Influx of exterior nitrogen purge gas into the vacuum and subsequent liquifaction upon contact with cryogenic boundary
- (3) Reduced bondline strength and toughness
- (4) Manufacturing flaws and defects
- (5) Infiltration of GH₂ into the core, which produced higher than expected core pressure

The last phenomenon was an unexpected contributor to the failure mechanism. The tank design pushed the limits of technology and combined many unproven technology elements, creating a very complex system. The use of a conformal composite tank not only to carry propellant but to transfer structural loads was a rather bold decision at the time. The manufacturing process revealed some of the complexities associated with the scaleup of large composite structures that were not understood previously. The main lesson learned from this experience was the phenomenon and significance of microcracking of composite facesheets of cryogenic tanks under thermal and mechanical loads. The failure of the X-33 demonstrator during ground testing was summarized by Grimsley et al. (2001), and it revealed that hydrogen permeation into the core of the composite sandwich structure through matrix microcracks caused the failure.

However, it was mentioned by the failure investigation team (NASA Marshall report, 2000) that the results of the investigation do not invalidate the use of composite materials for cryogenic tanks. The lessons learned from this test, if applied to composite cryogenic tank technology in terms of design and manufacturing, should advance the technology and aid in the successful use of composites for future cryogenic tanks. Near the end of the program, it was decided to continue with an aluminum alloy hydrogen tank for the X-33 demonstrator upon encountering difficulties with the PMC tank.

The X-33 program highlighted the areas that need further investigation and development including addressing composite microcracking, use of liners, and other tank wall construction details.

3.7 NGLT Liquid Hydrogen Tank

The Next Generation Launch Technology (NGLT) program was a followup to the X-33 program to continue development of the next generation of reusable aerospace vehicles. The NGLT effort built on the experiences with the X-33. A preliminary analysis of a tank design concept was performed by Abumeri et al. (2004) under NASA's NGLT program. The design concept consisted of a PMC tank with thin walls and additional stacks of laminates internally forming longitudinal stiffeners. Another investigation by Robinson et al. (2004) illustrated studies to determine the tank architecture for the next reusable launch vehicle. Results from these types of research activities led to the carbon fiber composite tank with a honeycomb core sandwich structure used with the X-33 and the NGLT effort. With more research a barrier film on the interior wall was introduced with the NGLT work.

As a followup to the X-33 cryogenic tank designs, NASA and Northrop Grumman designed and completed tests of a scaled-down composite cryogenic tank at Marshall. These tanks were an integral part

of the key reusable elements of NASA's NGLT program. These tank designs were also integral to the airframe; that is, they carried launch loads and wing loads in addition to the propellant. The quarter-scale cylindrical tank 4.6 m (15 ft) long and 1.8 m (6 ft) in diameter was pressurized to about 779 kPa (113 psi). This test pressure is about four times the operating pressure in the actual full size tank to induce similar wall stresses encountered during launch due to fluid loads, acceleration loads, and so forth. Test plans had called for the tank to be chilled, refilled, and stressed about 40 times in a period of a few months (Glass, 2004, and Sharke, 2004). These tests were successfully completed according to a news release by the NASA contractor Northrop Grumman (McKinney and Neiwert, 2004).

Based on the X-33 experience, the NGLT tanks utilized an impermeable barrier film between the inner tank wall and the honeycomb. Once again, based on the findings of the X-33 tank investigation report, many tiny holes were laser drilled in the honeycomb core, which permitted evacuation of the interior wall volume and provided a means of preventing localized pressure buildup due to any hydrogen that did manage to permeate past this barrier.

In an effort to process and manufacture large-scale composite structures, a process without the use of an autoclave curing was investigated. In this effort, a single-piece half tank was fabricated without an autoclave and tested. This project was also an example of a short-duration application of the cryogenic tank technology.

The NGLT program was instrumental in developing large conformal composite cryogenic tanks that can be fabricated without an autoclave and are suitable for use on a single-stage-to-orbit vehicle. Such technological developments will play a crucial part in the development of civilian hydrogen-fueled aircraft as well as space launch vehicles.

3.8 Other Cryogenic Storage Applications

There is ongoing research for low-cost lightweight cryogenic storage for ground transportation. Ground transportation vehicles have requirements for long-term storage similar to those for the needed durations of civilian aircraft. The U.S. Department of Energy (DOE) has had a long history of working with hydrogen as a fuel for transportation systems. One effort included a LH₂-fueled automobile as presented by Stewart (1982). That effort utilized a more conventional design storage tank, that is, a metallic tank with MLI insulation. System weight is an important issue with ground transportation, such as automobiles, but not to the degree as it is with air- and space-based vehicles. Overall cost tends to be a significant driving force along with the low-weight requirements.

Other automotive projects are briefly summarized by DaimlerChrysler (2004). An example of an automotive cryogenic tank is presented by Magna Steyr (2005), which is part of a collaborative effort between BMW AG, Linde AG, and Magna Steyr, consisting of a double-walled tank made of austenitic steel. The volume between the walls uses MLI and is held at a high vacuum of 10⁻⁹ bar. This is similar to the early DOE project design presented by Stewart (1982).

Stationary ground-based storage facilities do not have the strict weight and size restrictions imposed by mobile systems. Thus, such tanks can also be made from austenitic steel surrounded by a vacuum jacket with MLI. Also, a refrigeration unit can be utilized for long-term storage. However, hydrogen storage tank systems used in aircraft require the use of extremely lightweight construction. The need for lightweight, well-insulated flight-worthy storage systems poses a true engineering challenge.

It should be noted that many of the research and development efforts, including the NASP, X-33, and NGLT, were for applications that require relatively short durations for operation. The short duration allows for greater losses due to leaks and boiloff relative to the long-term flight duration hydrogen aircraft application. Many of the applications mentioned above focused on propulsion systems operating on hydrogen. As a result, minimal details of the structural designs of the storage systems used in those applications were provided in the published reports. Although the above-mentioned launch vehicle programs did advance the technology for lightweight cryogenic storage tanks, there is still a need to develop a tank-insulation system that is lightweight and able to keep leakage and boiloff to an acceptable level.

4.0 Potential Design Solutions

Previous developments dealing with the design of cryogenic LH₂ tanks had a requirement that the propellant had to be maintained and stored for a relatively short duration of time, as it is consumed rather quickly—generally on the order of minutes. Because of the short cycle time, a higher boiloff rate is acceptable. For example, space shuttle operation accepts a loss rate of approximately 1.6 percent of LH₂ by weight per hour as noted previously. Alternatively, for an aircraft application, especially long flight durations, an acceptable rate of boiloff of LH₂ is on the order of 0.1 percent by weight per hour (M. Millis, 2005, NASA Glenn Research Center, Cleveland, OH, personal communication). The current task seeks the development of cryogenic tanks that can hold the LH₂ for significant periods of time ranging from a few hours to several days. As noted earlier, durable, lightweight cryogenic propellant storage and feed systems are critical to enable the development of hydrogen-fueled aircraft. Other areas not considered in this report that are also critical include tank penetration schemes, feed lines, transfer lines, and instrumentation.

Here we will discuss in greater detail the key components of a lightweight LH₂ storage system. System requirements will be discussed that are dependent upon flight duration. Short flight durations are defined as those that are on the order of minutes to hours. Alternatively, long flight durations are those lasting from a few hours to days. The components that are covered individually include the insulation, structural tank wall, and tank wall liner. Also, a section on fabrication and other relevant issues is included. The available materials relevant to the components are discussed within each section.

Multiple design configurations can be envisioned from a single tank with insulation to hybrid tanks with either insulating materials or pure vacuum in between walls or various combinations thereof. The overall objective of the design is to have a safe, lightweight, thermally efficient cryogenic storage system. Some important tank system parameters relative to flight durations are presented in table I. The materials, tank structural configurations, and insulation system options are numerous and interdependent. One approach to reduce the number of design choices is to turn to the concept of performance indices (e.g., material and structural), as put forth by Ashby (2005). Consequently, the objective of this section is to help guide the reader in downselecting a class of materials and structural configurations that result in optimum performance. The order of importance of the key tank parameters listed in table I is dependent on a specific application in general and flight duration in particular.

TABLE I.—IMPORTANT TANK SYSTEM PARAMETERS
RELATIVE TO FLIGHT DURATION
[Listed in order of importance.]

Short flight duration	Mass density Strength and toughness Coefficient of thermal expansion Stiffness Thermal diffusivity Thermal conductivity
Long flight duration	Mass density Thermal conductivity Strength and toughness Coefficient of thermal expansion Stiffness Thermal diffusivity

The performance, P , of a structural element is a function of three, typically independent, aspects: the functional requirements F , the geometry G , and the properties of the material M of which it is made.

$$P = f(F, G, M) \quad (1)$$

When this group of parameters is said to be separable,

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M) \quad (2)$$

These parameters are assumed to be independent of each other; that is, the optimal choice of materials is independent of geometry of the structural component. One may be able to identify the optimal subset of materials without solving the complete design problem. Subsequently, we utilize the particular material index and possibly other indices to assist us in downselecting the various options available. The key material indices applicable for both thermal and mechanical issues of interest here are shown in table II.

TABLE II.—PERFORMANCE INDICES FOR THERMAL AND MECHANICAL COMPONENTS OF CRYOGENIC STORAGE TANK

Function and constraints	Performance index, maximize ^a
Thermal ^b	
Minimum heat flux at steady state, fixed thickness	$1/k$
Minimum temperature rise in specified time, fixed thickness	$1/a$
Maximum energy stored for given temperature rise and time	$k/a^{1/2}$
Minimum thermal distortion	k/α
Mechanical	
Strength-limiting design with minimum mass	σ_f/ρ
Damage-tolerant design with minimum mass	K_{Ic}/ρ
Deformation-limiting design with minimum mass	E/ρ

^a k = thermal conductivity

$$a = \text{thermal diffusivity} \left(\frac{k}{\rho C_p} \right)$$

ρ = mass density

C_p = specific heat

α = coefficient of thermal expansion

σ_f = strength

K_{Ic} = mode I fracture toughness

E = Young's modulus

^bTime, $t = w^2/2a$ with w = thickness.

As mentioned earlier in this report, the functional requirements are that LH₂ be maintained between its freezing and boiling points, $-259 \text{ }^\circ\text{C}$ ($-435 \text{ }^\circ\text{F}$) and $-253 \text{ }^\circ\text{C}$ ($-423 \text{ }^\circ\text{F}$), respectively. The temperature difference between ambient conditions and LH₂ can be as high as $\Delta T = 300 \text{ }^\circ\text{C}$ ($540 \text{ }^\circ\text{F}$). Another vital concern is tank wall and/or liner permeation by hydrogen or just leakage of the hydrogen through microcracks. Material selection for the tank wall and the need for a liner will be based partially on the material's ability to contain the LH₂ for the required duration under the conditions discussed above. These issues will be covered under the sections for the tank wall structure and the liner. There are other important issues associated with the cryogenic tank design such as vapor management (a proper vent system), fuel transfer, pumping a saturated cryogenic fluid such as LH₂, and the possibility of the cold energy utilization. However, these issues are beyond the scope of this report and thus will not be discussed here.

4.1 Thermal Load Design: Insulation

As previously discussed, an appropriate thermal insulation system is critical for LH₂ storage tanks, particularly for long-duration applications. An efficient and lightweight insulation system will minimize the boiloff of LH₂ while adding minimum mass to the overall tank structure. Another function of

insulation is to prevent condensation and subsequent solidification of atmospheric gases onto the tank. This can be overcome by using either a vacuum-jacketed system or by using a purged system (such as helium purged), where a noncondensable gas has replaced the air. Maintaining an adequate vacuum level is one of the major difficulties with a vacuum jacket system and of course becomes more difficult as higher vacuum levels are required to maintain the thermal properties. An additional issue is the ability of the insulation system to handle dimensional variations due to the imposed thermal cycles as a result of filling it with cryogenic hydrogen. Consequently, the CTE mismatches between the components of the tank system are key factors. When designing a tank system, the issues related to the CTE mismatches between the tank wall components should be evaluated and accounted for in the design. Additionally, mechanical compression of the insulation system may occur due to weight, the pressure differential across the insulation, shock and vibration, dimensional changes, or any combination of these loads and reduce its effectiveness. An insulation system is said to have low contact resistance if its thermal conductivity is sensitive to the compression load placed on it. Finally, it is desirable that an insulating system and its key constituents possess a low thermal conductivity along with low thermal diffusivity and low mass density. It is also desirable to have a low radiation heat transfer coefficient.

Constructing material property diagrams that enable one to assess the thermal and mechanical performance indices in table II will provide insight in designing an efficient insulation scheme for long-duration flights. As noted earlier, performance indices can aid in narrowing the viable choices of engineering materials and systems for an insulation system for a long-term lightweight cryogenic fluid storage structure. Figure 4 shows a plot of thermal conductivity versus mass density, as the low weight requirement for an aircraft application is crucial. For a long-term application, a low thermal conductivity is extremely important. Insulating schemes that utilize materials like low-density polymer foams, including newer aerogel materials, are desirable as can be noted in figure 4. Also from figure 4, the current silica aerogels have a range of thermal conductivities and densities that place them near the family of foams. Combination of a vacuum jacket and MLI has a range of densities that is comparable to low density foams and an apparent thermal conductivity that is approximately two orders of magnitude lower than the best low-conductivity foams (beyond the range available in fig. 4).

Figure 5 shows a plot of thermal conductivity versus thermal diffusivity for a variety of materials. MLI offers a thermal diffusivity that is comparable to the family of metals but an apparent thermal conductivity that is approximately two orders of magnitude lower than the polymer foams. For a given insulation thickness, one should select a system with the lowest thermal conductivity to minimize steady-state heat flux and a low thermal diffusivity, that is, high specific heat, to maximize the time required for thermal energy to reach the cryogenic fluid. The following equation relates the time to reach steady state, t , with wall thickness, w , and thermal diffusivity, a .

For a given wall thickness, it is desirable to minimize the thermal diffusivity in order to maximize the time it takes to reach a steady-state condition especially for short-duration applications. As per table II, minimizing the ratio $k/a^{1/2}$, where k is the thermal conductivity, results in maximizing the energy stored in a material for a given temperature rise and time. It maximizes the time required for heat to reach the stored cryogenic fluid.

$$t = \frac{w^2}{2a} \quad (3)$$

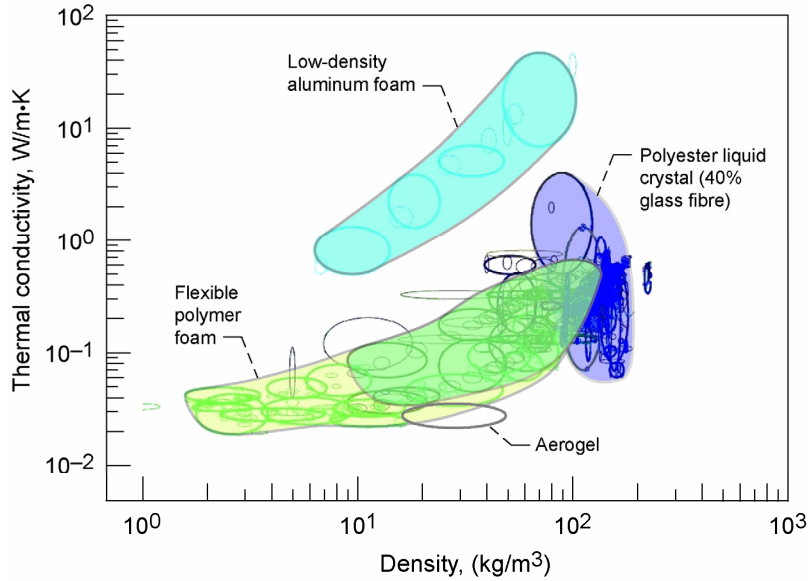


Figure 4.—Thermal conductivity versus mass density for various engineering materials (from Ashby, 2005). Approximate aerogel regime is based on data from M.A. Meador (2005, NASA Glenn Research Center, Cleveland, OH, personal communication).

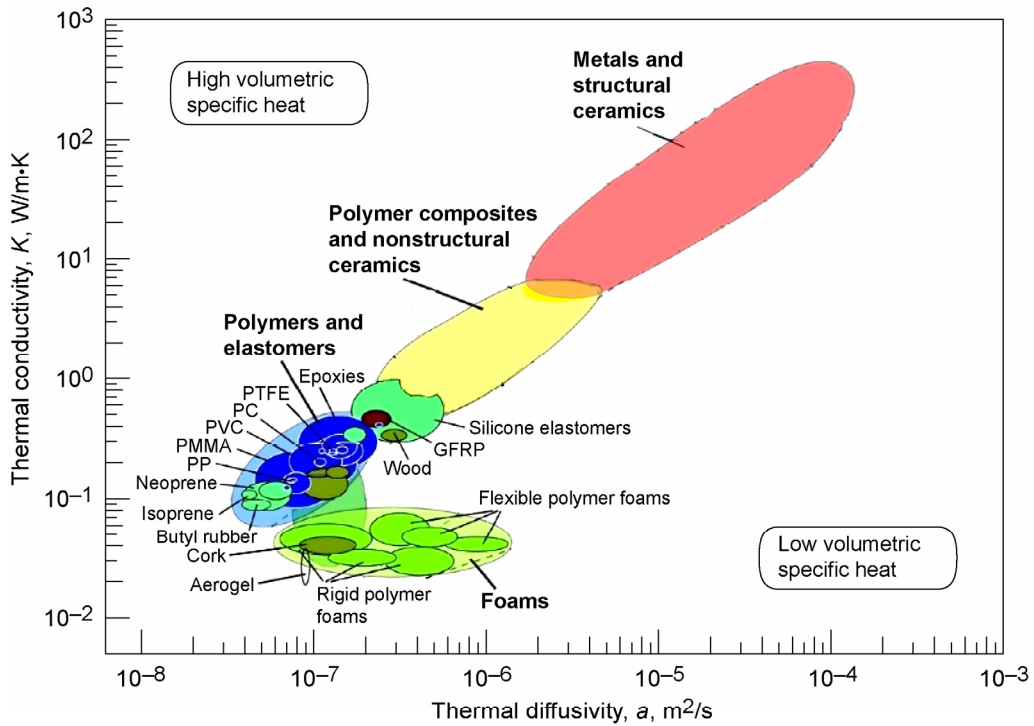


Figure 5.—Thermal conductivity versus thermal diffusivity for various engineering materials (from Ashby, 2005). Approximate range for aerogel is based on data from M.A. Meador (2005, NASA Glenn Research Center, Cleveland, OH, personal communication). GFRP is glass-fiber-reinforced plastic; PC, polycarbonate; PMMA, polymethylmethacrylate; PP, polypropylene; PTFE, polytetrafluoroethylene, and PVC, polyvinylchloride.

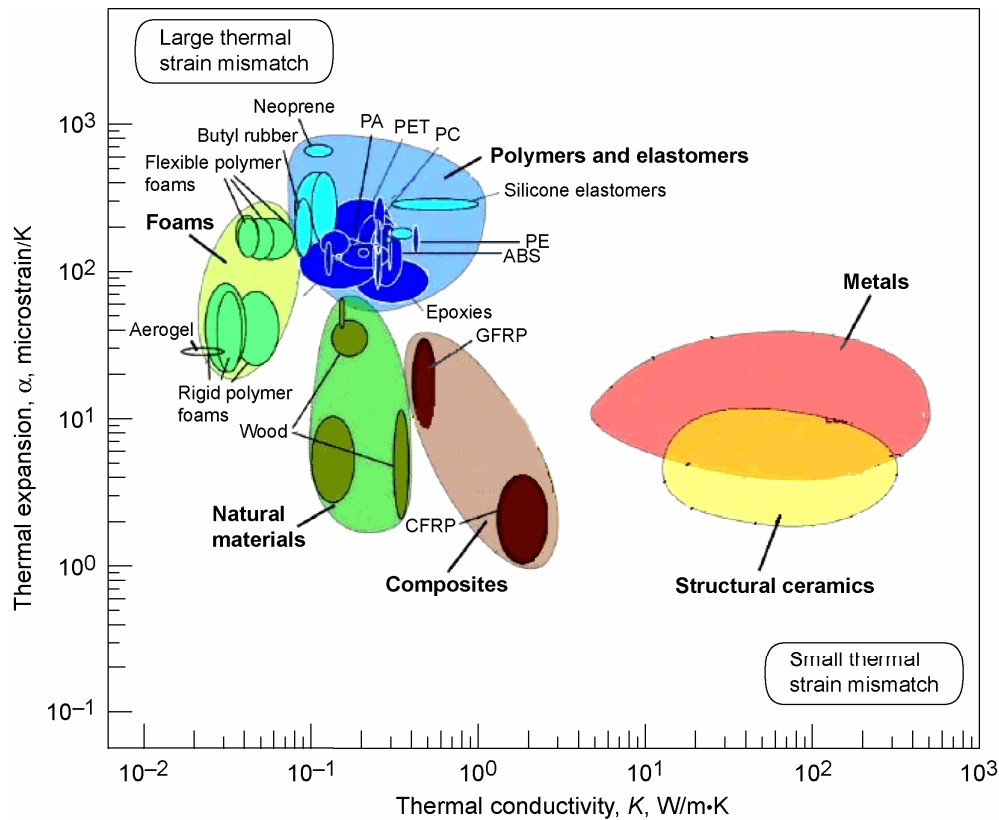


Figure 6.—Thermal expansion coefficient versus thermal conductivity of various engineering materials (from Ashby, 2005). ABS is acrylonitrile butadiene styrene; CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer; PA, polyacrylonitrile; PC, polycarbonate; PE, polyethylene; PET, polyethyleneterephthalate; and PMMA, polymethylmethacrylate.

Figure 6 shows thermal conductivity versus thermal expansion coefficient for different material systems. The authors of this report have added an approximate aerogel regime to the figure based on the data from M.A. Meador (2005, Glenn Research Center, Cleveland, OH, personal communication). This chart is useful for assessing thermal distortion. The value of k/α , where α is the CTE, can be used as a measure of thermal distortion. Materials with a large value of this index show small thermal distortion. Insulating materials by their functionality, having low thermal conductivity values, show large thermal gradients and consequently high thermal distortion. Thus, materials exhibiting low thermal conductivity and secondarily having a low CTE are desirable. The high thermal distortion may lead to a comparatively large relative displacement, which can induce stress within the insulating material that can exceed the material strength. Mechanical failure can lead to degradation in thermal properties of the insulating system. Once a class of materials has been chosen based on their thermal performance, materials with the lowest value of α should be used to minimize thermal distortion and the resulting induced stresses. Low thermal conductivity is an important property for any insulation system, especially for a long-term application. As a result, it can be noted from figure 6 that rigid polymer foams including aerogels are viable insulation system as they provide low thermal conductivity. Aerogels within this group seem to offer a lower CTE. As shown in figure 6, metallic materials offer lower CTEs, which will result in lower distortions; however, their higher thermal conductivities (and densities) disqualifies them from consideration as insulating materials.

It can be noted in figures 4 to 6 and the associated discussion, various foams and MLI systems provide desirable material properties for aerospace applications. Given this information, it is not surprising why previous investigators have chosen to use foams, perlites, aerogels, vacuum jackets, and

MLI systems for cryogenic insulation systems. Table III shows a list of advantages and disadvantages of various viable insulation systems in the order of increasing thermal performance.

TABLE III.—ADVANTAGES AND DISADVANTAGES OF VARIOUS INSULATION METHODS
[Listed in order of increasing thermal insulation performance.]

Location		Discriminators
Foam		
Outside	Advantages	Currently in use, well established Low cost, easy to implement Light weight and low density
	Disadvantages	Limited to short duration missions because of excessive thermal conductivity Low resistance to thermal radiation Potential damage from environmental hazards
Inside	Advantages	Low cost Structural wall not exposed to cryogenic conditions Reduced CTE mismatch issues of composite constituents, resulting in reduced microcracking
	Disadvantages	Necessitates larger structural tank wall, resulting in increased mass Difficult to seal from cryogenic fluid <ul style="list-style-type: none"> • Fluid infiltration leads to increased thermal conductivity • Potential loss of structural wall integrity May interfere with fluid management upon failure
Perlite		
Between walls	Advantages	Low cost, well established Some compressive load-bearing capability Resistance against thermal conductivity and radiation
	Disadvantages	Limited to short duration due to excessive thermal conductivity Excessive mass for aerospace applications
Aerogel		
Between walls	Advantages	Extremely low thermal conductivity ^a
	Disadvantages	New material, not well characterized Limited mechanical properties
Vacuum		
Between walls	Advantages	Near zero thermal conductivity Well established
	Disadvantages	Heavier tank walls required Costly to implement and maintain No resistance to radiation heat transfer Near catastrophic failure upon loss of vacuum
MLI		
Between walls	Advantages	Very low thermal conductivity and radiation heat transfer ^b Extremely low density Well established
	Disadvantages	High vacuum required Heavier tank walls required Costly to implement and maintain Near catastrophic failure upon loss of vacuum

^aThe balance between the structural and thermal properties can be altered to optimize for the application.

^bMLI is available in graded form to improve thermal properties and to reduce the density, but at a higher cost.

Typical apparent thermal conductivity along with mass density and thermal diffusivity values for various materials are summarized in table IV. The ranges in values for thermal conductivity of the various materials are due to vacuum level and temperature differences. For example, MLI systems provide very low values of apparent thermal conductivity on the order of 10^{-6} W/m·K ($\sim 6 \times 10^{-7}$ Btu/ft·hr·°F). MLI systems use a number of thermal radiation shields perpendicular to the direction of heat flow. The radiation shields are alternating layers of a low-emissivity metal foil (usually aluminized Mylar (DuPont))

and a thin insulating spacer (usually polyester or glass fiber paper) combined such that metal-to-metal contact is avoided. However, there are stringent requirements that must be addressed when choosing an MLI system. The foremost requirement for an MLI system is that a vacuum level below 13 mPa (10^{-4} torr) must be maintained for the MLI to maintain its effectiveness. Heat transfer by residual gas conduction occurs under degraded vacuum conditions. Perforation holes in the Mylar layers are critical to allow evacuation of residual gases upon setting up the vacuum insulation and/or MLI system. Also, its thermal properties are highly anisotropic and sensitive to mechanical compression (low contact resistance). An MLI system was first patented by Matsch (1961).

TABLE IV.—THERMAL CONDUCTIVITY, MASS DENSITY, AND THERMAL DIFFUSIVITY VALUES FOR VARIOUS MATERIALS AND INSULATING SYSTEMS
[Listed in order of increasing thermal conductivity.]

Material and/or system	Thermal conductivity, k , W/m-K	Mass density, ρ , kg/m ³	Thermal diffusivity, I_2 , m ² /s
^a Multilayer insulation (MLI) in high vacuum	10^{-5} to 10^{-8}	(b)	(b)
^a Vacuum (polished surfaces, minimum k value, $<10^{-5}$ torr)	10^{-6} to 10^{-7}	(b)	(b)
^{a,c} Aerogel	10^{-2} to 10^{-7}	100 to 500	(b)
^a Perlite powder	10^{-5} to 10^{-6}	128	(b)
^a Fiberglass	10^{-5} to 10^{-6}	16	(b)
^a Cellular glass foam (−83 °C (−118 °F), 760 torr)	3.3×10^{-5}	128	(b)
^a Polyurethane foam	10^{-2} to 10^{-4}	32 to 64	(b)
^d Air	10^{-3} to 10^{-2}	1.17 to 3.6	2.51×10^{-6}
^e Polyvinylchloride (rigid, closed cell, −79 °C (−110 °F))	1.5×10^{-2}	49.7	(b)
^e Polymethacrylimide (rigid, closed cell, 6 °C (43 °F))	3.1×10^{-2}	35.2	(b)
^d Hydrogen gas	10^{-3} to 10^{-1}	0.08 to 0.25	10^{-4} to 10^{-5}
^d Polyimide	3.5×10^{-1}	1430	2.20×10^{-7}
^d Water (0 °C (32 °F))	5.6×10^{-1}	999.8	1.33×10^{-7}
^f Polymer matrix composites	2 to 70	(b)	(b)
^d Ice (0 °C (32 °F))	2.2	917	1.15×10^{-6}
^d Aluminum (20 °C (68 °F))	237 to 302	2707	9.61×10^{-5}

^aAugustynowicz et al., 1999.

^bNot available.

^cFrom M.A. Meador, 2005, NASA Glenn Research Center, Cleveland, OH, personal communication.

^dLienhard IV and Lienhard V.

^eBrewer, 1991.

^fSmith, 2000.

Recent advances in MLI for cryogenic storage tanks have included the development of variable density MLI (VD-MLI), where the layer spacing varies across the MLI cross section. Radiation heat transfer generally dominates in the warmer outer layers of a standard MLI system, whereas conduction plays a larger role within the colder inner layers. By spacing the inner layers further apart, both the VD-MLI mass and thermal leaks are decreased. A hybrid spray-on foam insulation (SOFI) and VD-MLI system for orbital applications has recently been tested by Hastings et al. (2004). This arrangement is designed to rely on the SOFI at high pressures during ground hold and launch and on the MLI during orbit. The 45-layer VD-MLI blanket ranged from 8 layers/cm (20 layers/in.) in the cold region to 16 layers/cm (41 layers/in.) in the warm region. Tests showed a reduction in boiloff of 41 percent, compared with the standard MLI with 70 evenly spaced layers.

Another proposed insulation system was microsphere insulation, which consists of hollow glass spheres of varying diameters and wall thicknesses. It is not as sensitive to vacuum conditions as MLI and also provides some structural support with a minimal increase in its low thermal conductivity under compressive loads. The effects of two interstitial gases, nitrogen and helium, at various pressures on the apparent thermal conductivity of microsphere insulation have been experimentally evaluated and correlated with analytical models by Cunnington and Tien (1978). Further efforts by Parmley and Cunnington (1979) yielded design data for a flexible, stainless steel, vacuum-jacketed microsphere insulation system. Current developments involve manufacturing autonomous evacuated microsphere insulation panels, encased in a flexible vacuum-barrier film (Allen et al., 2004). These panels exhibit thermal conductivity that is about one-half of the thermal conductivity of polyurethane foam.

Another class of materials that is being considered for cryo-insulation is silica aerogel. Silica aerogels are high-porosity, very low density solids that consist of interconnected particles that form an “open” microstructure. The thermal conductivity of silica aerogels tends to be very low, typically less than $40 \times 10^{-3} \text{ W/m}\cdot\text{K}$ ($23 \times 10^{-3} \text{ Btu/ft}\cdot\text{hr}\cdot^\circ\text{F}$), due to the very low thermal conductivity of silica as well as the pore sizes that are on the order of nanometers. The extremely low thermal conductivity makes silica aerogels very desirable for a wide variety of insulating applications. However, the same properties of aerogels that make them extremely good insulators—high porosity and low density—also make them inherently fragile and brittle. Thus, their use in load-bearing applications (such as cryogenic LH₂ storage tanks for flight applications) is challenging. Currently, research is underway on improving the mechanical properties of aerogels without excessively sacrificing their other unique properties. However, it is recognized that any improvement in mechanical properties comes at the expense of increased mass density and thus, increased weight and thermal conductivity. One approach that has been taken by Cunnington, Lee, and White (1997) is to create fiber/aerogel composites by adding a small volume fraction (less than 5 percent) of short silica or silicon carbide fibers. The fibers reduce the transparency to thermal radiation at temperatures higher than ambient, thus increasing the thermal performance. The fibers also strengthen the aerogel. However, this approach is only significant when radiation is the primary heat transfer mode, relative to the solid- and gas-phase conduction modes, which occurs at temperatures greater than 27 °C (80 °F) and 127 °C (260 °F), respectively. Work is also going on at NASA Glenn Research Center to develop cross-linked silica aerogels that are modified with epoxies to develop a mechanically strong yet lightweight porous material (Meador et al., 2005, and Leventis et al., 2003).

As an illustrative example, an approximate value for an apparent thermal diffusivity for an MLI system is $9 \times 10^{-6} \text{ m}^2/\text{s}$ ($1.4 \times 10^{-2} \text{ in.}^2/\text{s}$) as presented by Geng and Macosko (1999). For a practical thickness of 0.05 m (2 in.) of an MLI system, the time to reach steady state would be slightly greater than 2 min as per equation (3). This indicates that for most flight applications, the primary design issues of heat transfer for practical thicknesses of MLI are conduction and radiation. Thermal diffusivity will not be a controlling parameter.

Similarly, for a relatively dense aerogel system of a mass density of 0.48 g/cm^3 ($1.7 \times 10^{-2} \text{ lb/in}^3$), the specific heat is $1.0 \text{ J/g}\cdot\text{K}$ ($4.2 \text{ Btu/lb}\cdot^\circ\text{F}$) as per M.A. Meador (2005, NASA Glenn Research Center, OH, personal communication). For a thermal conductivity value of $41 \times 10^{-3} \text{ W/m}\cdot\text{K}$ ($24 \times 10^{-3} \text{ Btu/ft}\cdot\text{hr}\cdot^\circ\text{F}$) from table III, this results in an apparent thermal diffusivity value of $9 \times 10^{-8} \text{ m}^2/\text{s}$ ($1.4 \times 10^{-4} \text{ in.}^2/\text{s}$). For a practical thickness of 0.05 m (2 in.), the time to reach steady-state conditions is approximately 4 h. This indicates that the system does not reach a steady-state condition for a typical short-duration flight. This makes the thermal diffusivity of the insulation system a significant parameter. For long-duration applications, the time to reach steady state may only be a small fraction of the total flight duration. Therefore, the majority of the mission is in a near-steady-state condition. As a result, the governing conditions for the insulation system are based on minimizing the heat flux under near-steady-state conditions and hence are driven by the need to minimize the thermal conductivity, as well as mass density, of the insulation system. This demonstrates that silica aerogels may find use in short-flight-duration applications.

Because of a large temperature difference between the ambient conditions and the cryogenic fluid, managing the radiation heat transfer becomes an important issue. The radiation heat flux, Q , can be computed by using the following equation

$$Q = \varepsilon\sigma(T_1^4 - T_0^4) \quad (4)$$

where ε is the emissivity (1 for black body), σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$) and T_1 and T_0 are absolute temperatures across the insulation system. To get an approximate value of radiation heat flux for this application, a typical emissivity value of 0.045 is assumed, which corresponds to a highly polished aluminum surface; this, along with a ground-level condition T_1 value of approximately 323 K and a LH_2 temperature for T_0 of approximately 21 K, the radiation heat flux (from eq. (2)) is computed to be 28 W/m^2 . It is desirable to limit the total heat flux for this application to a maximum of 70 W. Based on the required tank geometry, this results in a maximum heat flux allowed into the tank of approximately 4 W/m^2 . This shows that the radiation heat transfer plays an extremely important role in total heat transfer in this application and needs to be controlled by using an appropriate insulation system scheme.

As shown above, it has been illustrated that low thermal conductivity, low emissivity, and low mass density are the most important parameters for an insulation system utilized in a long-term aerospace application. These are the key properties that need to be measured for any insulation system. In addition, low thermal diffusivity, low CTE, and an ability to accommodate the thermal distortions induced by large thermal gradients are important considerations.

The current state of the art suggests that the use of a high vacuum with highly polished wall surfaces with or without an MLI system could provide the required insulation needs for lightweight long-term cryogenic applications. The MLI provides additional insulation against radiation heat transfer relative to a simple vacuum jacket. However, either system is very sensitive and dependent on maintaining a very high level of vacuum. Any degradation in the vacuum level significantly degrades the insulating properties, leading to mission failure. Any currently available foam-based system, possibly including current aerogels, may require continued enhancement in their thermomechanical properties for aircraft application. Foam-based insulation may be appropriate for short-duration applications and possibly as a supplementary system for longer duration applications.

4.2 Potential Structural Tank Materials and Architectures

The storage of LH_2 in a lightweight tank provides significant challenges in itself. The lower density of the hydrogen fuel results in the need for a higher volume storage vessel relative to other fuels. Mechanical tank loads are derived from (1) the difference between the pressure within the tank and the ambient conditions, (2) fuel weight, (3) vehicle acceleration loads, (4) fuel slosh due to aircraft maneuvers, and (5) tank system weight and its supports. Fuel slosh is bound to be encountered as the aircraft maneuvers or as it encounters air turbulence during the flight.

The internal tank pressure will have to be maintained at a constant absolute pressure in order to maintain the hydrogen in a liquid state. The pressure will aid in pumping hydrogen from the tank to the power source also. Hall and Silverstein (1955) have suggested that 2 atm (200 kPa, 29 psia) would be adequate for pumping fuel at a cruise condition for an aircraft. It has also been documented by Petty (2002) that the space shuttle ET operates in the pressure range of 220 to 230 kPa (32 to 34 psia), which is close to the suggested range by Hall and Silverstein. Furthermore, the designed tank weight increases with increasing operating pressure. Thus, it is highly desirable to keep the tank pressure as low as possible, as noted by Reynolds (1955). Typically, GH_2 is used as the pressurant for LH_2 .

Two important criteria for the tank wall include material selection and wall architecture. Many options are available, and these are discussed in the following sections. Advantages and disadvantages of various options are discussed, and guidelines are provided for choosing an optimum system.

4.2.1 Tank wall material selection.—Clearly it is desirable to use materials that possess high strength, high fracture toughness, and high stiffness, as well as low density and low permeation to liquid and gaseous hydrogen; however, no single material provides all these attributes simultaneously. Consequently, material performance indices associated with these properties, such as those given in table II, must be used to identify the best material candidates for tank wall construction. Among these parameters, strength and density tend to dominate the design criteria. Figure 7 shows strength versus mass density for various engineering materials. In this case, materials in the upper left corner are preferable. Composite materials exhibit high specific strength relative to metals and are quite suitable for aerospace applications. In particular, it is apparent from figure 7 that continuous-fiber-reinforced polymer (CFRP) composites provide the highest strength yet lightest choice. However, the use of continuous-fiber-reinforced composite materials most likely will involve higher initial manufacturing costs. As per figure 7, the materials that have the sufficient strength and acceptable low density are PMCs and metallic materials. Ceramic materials also offer high specific strength, but because of their low fracture toughness, they are not viable for a tank wall material.

A potential lower cost alternative to continuous-fiber-reinforced composites may be discontinuous reinforced metallic composites (DRX), specifically discontinuous reinforced aluminum (DRA) as described by Miracle (2001). DRAs are essentially isotropic and can be manufactured using less expensive techniques such as casting. Figure 8 illustrates the specific modulus relative to specific strength. In this figure, materials closer to upper right corner are desirable. DRX materials compare well with polymer-based composite systems. The DRX materials have the added benefit of extremely low (if not negligible) hydrogen gas permeability issues typically associated with polymer matrix composite systems.

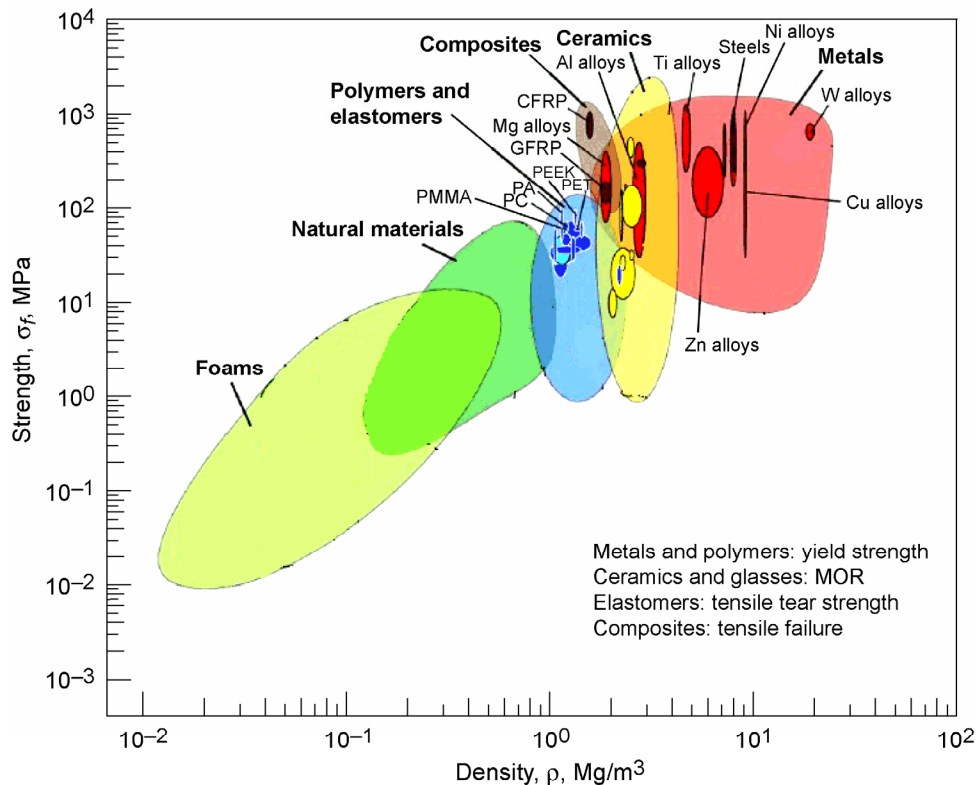


Figure 7.—Strength versus mass density for various engineering materials (from Ashby, 2005). CFRP is carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer; PA, polyaniline; PC, polycarbonate; PEEK, polyetheretherketone; PET, polyethylene terephthalate; and PMMA, polymethylmethacrylate.

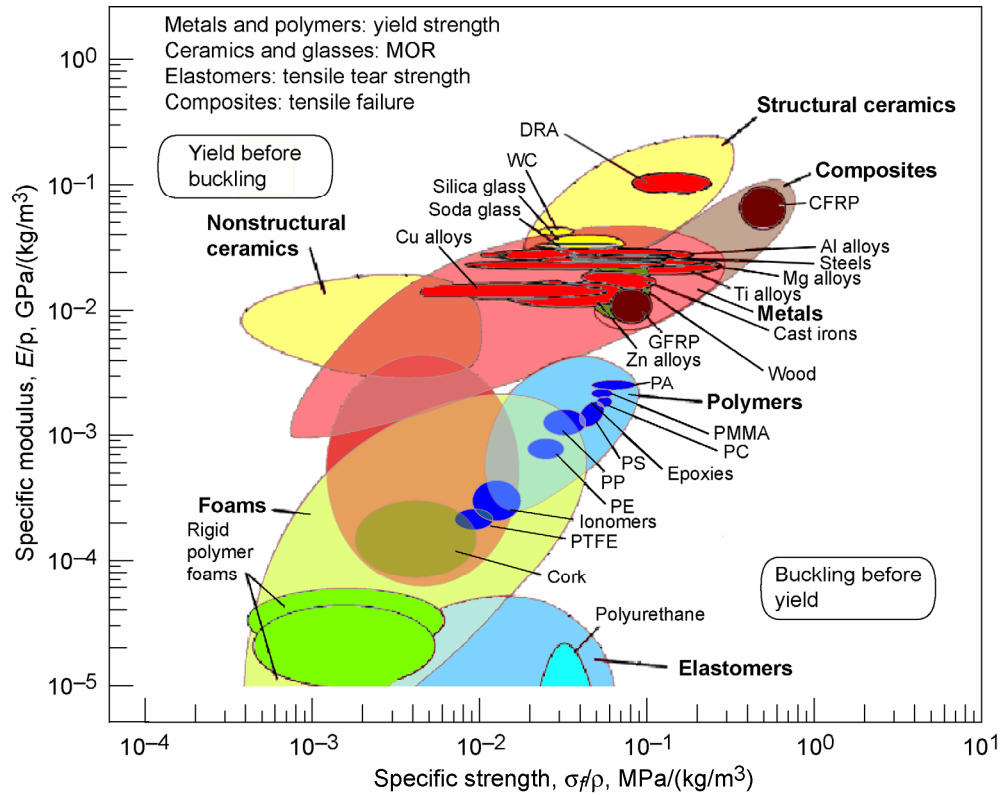


Figure 8.—Specific stiffness versus specific strength for various engineering materials (from Ashby, 2005). CFRP is carbon-fiber-reinforced polymer; DRA, discontinuous reinforced aluminum; GFRP, glass-fiber-reinforced polymer; PA, polyaniline; PC, polycarbonate; PE, polyethylene; PMMA, polymethylmethacrylate; PP, polypropylene; PS, polystyrene; and PTFE, polytetrafluoroethylene.

Key material properties that are important considerations for the design of high-pressure vessels but may also be applicable to low-pressure cryogenic storage tanks are yield-before-break, K_{Ic}/σ_f , and the leak-before-break, K_{Ic}^2/σ_f . These can be derived from figure 9, where K_{Ic} is the fracture toughness and σ_f is the strength of the material. Utilizing the first index ensures that the stress required to propagate a critical flaw is greater than that to yield the material. In this way the vessel would deform stably in a way that could be detected. The second criterion, used primarily on larger vessels, ensures that maximum pressure carried would result in the stable growth of a crack just large enough to penetrate both the inner and outer surface so that the leak could be detected prior to catastrophic failure. Note both indices can be maximized by making the yield strength of the wall very small; however, this may not only limit the pressure capability of the vessel, but it could also result in an excessively large wall thickness and thus a very heavy tank. The tank thickness t is given by the following equation for thin-walled spherical tanks:

$$t \geq \frac{pR}{2\sigma_f} \quad (5)$$

where p is the tank pressure, R the tank radius, and σ_f the strength of the tank material as designated in figure 8. In order to minimize the tank mass, and realizing that the tank mass is directly proportional to the tank wall thickness, it is desirable to choose a tank wall material that maximizes the specific limit strength.

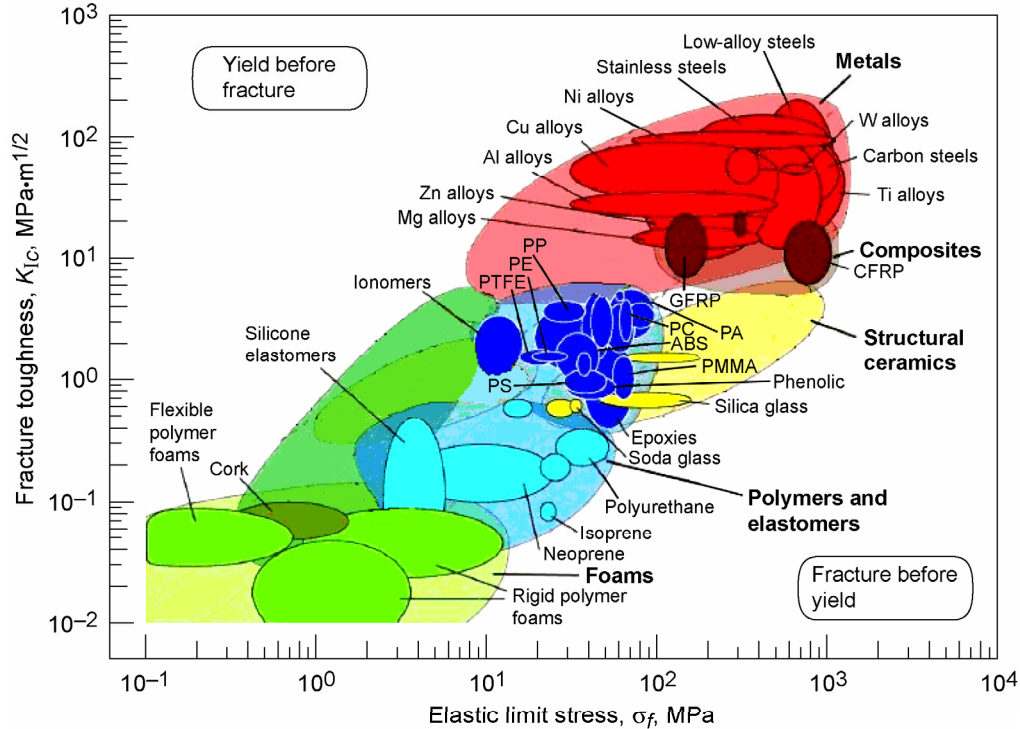


Figure 9.—Fracture toughness versus strength for various engineering materials (from Ashby, 2005). ABS is acrylonitrile butadiene styrene; CFRP, carbon-fiber-reinforced plastic; GFRP, glass-fiber-reinforced plastic; PA, polyaniline; PC, polycarbonate; PE, polyethylene; PMMA, polymethylmethacrylate; PP, polypropylene; PS, polystyrene; and PTFE, polytetrafluoroethylene.

Figure 10 shows a plot of two material performance indices

$$M_1 = \frac{\rho}{\sigma_f} \quad (6a)$$

$$M_2 = \frac{\rho}{K_{Ic}} \quad (6b)$$

The first index M_1 is based on the constraint that the wall material strength not be exceeded, while the second material index M_2 is based on the requirement that the fracture toughness of the material not be exceeded. The mass of a thin wall spherical tank with a radius R and a wall thickness t is given by

$$m = 4\pi R^2 t \rho \quad (7)$$

The tensile stresses in the tank wall σ_w , due to internal pressure p are given by rearranging equation (5):

$$\sigma = \frac{pR}{2t} \quad (8)$$

Minimizing the mass of the tank as shown in equation (7) subject to the above-mentioned constraints provided by equation (6) leads to a coupling of the two performance indices given by

$$M_1 = (\pi c)^{1/2} M_2 \quad (9)$$

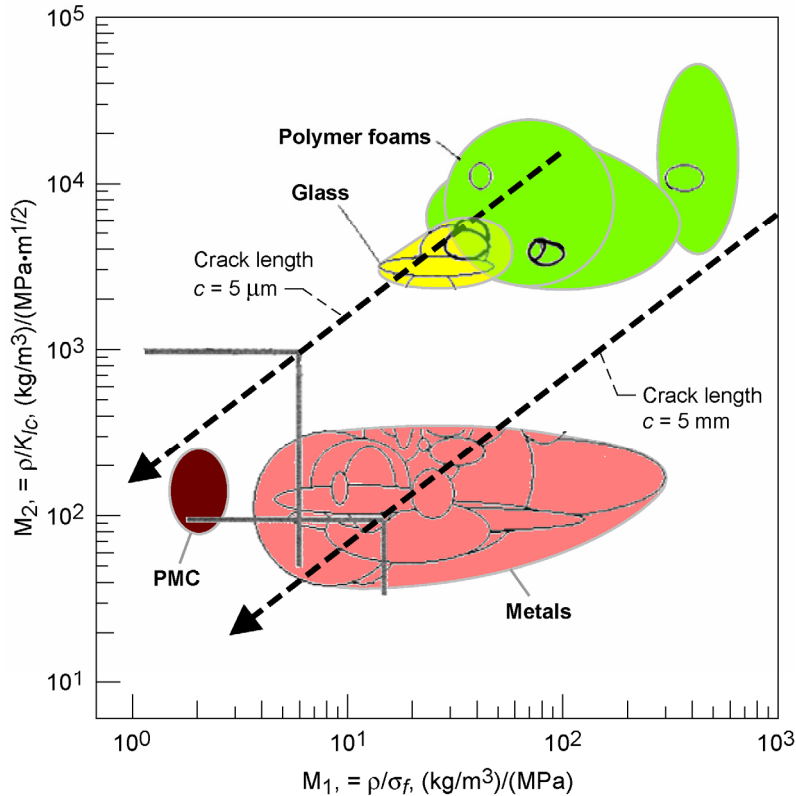


Figure 10.—Plot of two material performance indices for various engineering materials (from Ashby, 2005): M_1 , density/strength, versus M_2 , density/fracture toughness. PMC is polymer matrix composite.

where c is the critical crack size for a given material. Figure 10 shows the appropriate chart with two coupling lines corresponding to crack lengths of 5 mm and 5 μm . It shows that the choice of the material may be limited by the ability to detect cracks of a given size. For example, the material choices will be limited to monolithic metallic alloys if one can only detect cracks larger than 5 mm. However, as per figure 10, other materials including ceramics and elastomers could be viable materials if cracks of 5 μm or larger could be detected.

It should be noted that composite materials, in general, provide high fracture toughness along with low mass density, which makes them desirable for this application. Fracture toughness becomes an issue especially at cryogenic temperatures, where many materials become excessively brittle. Higher fracture toughness materials are desirable as they provide more damage-tolerant systems. Any crack that propagates into the insulation system can compromise the thermal properties of the insulation system—resulting in the loss of the mission—as there will be rapid boiloff of the cryogenic fuel. Figure 11 presents Young’s modulus E versus mass density ρ for various engineering materials. Although not a primary design variable, it is desirable to choose a stiff material that will minimize the deformation under loads while maintaining low mass. As before, PMCs and metallic materials provide desirable specific stiffness for this application.

Analyzing figures 7 to 11, material options for the tank wall include metals, PMCs, and metal matrix composites (MMCs). Composite materials may also include sandwich construction as well as nanosize particulate reinforced materials. As noted by Esgar (1962), the strength to density ratio of the material has to be as high as possible with the material having minimal fabrication issues and not susceptible to catastrophic brittle fracture. Also, as noted in other parts of this report, hydrogen permeation of the tank structure has to be kept to a minimum. Metals that have acceptable properties from ambient to cryogenic temperatures include austenitic stainless steels, monels, and aluminum alloys as noted by Reynolds

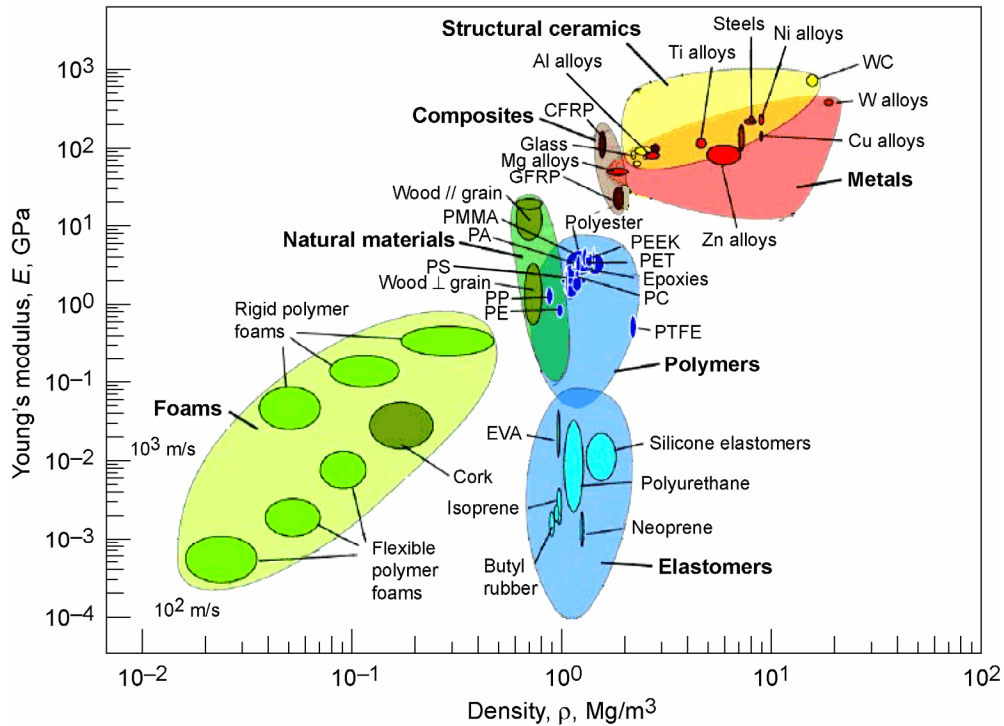


Figure 11.—Young's modulus versus mass density of various engineering materials (from Ashby, 2005). CFRP is carbon-fiber-reinforced polymer; EVA, ethylene vinyl acetate; GFRP, glass-fiber-reinforced polymer; PA, polyaniline; PC, polycarbonate; PE, polyethylene; PEEK, polyetheretherketone; PET, polyethylene terephthalate; PMMA, polymethylmethacrylate; PP, polypropylene; PS, polystyrene; and PTFE, polytetrafluoroethylene.

(1955). Also, titanium and copper offer acceptable properties for cryogenic service according to Vance (1964).

There is an advantage to using a monolithic material for tank construction like in the cases mentioned above. Using one material for the tank wall eliminates thermally induced internal stresses due to different CTE factors of various materials such as the typical constituents of a PMC or MMC material. However, most likely monolithic metallic tanks will not be as light as their PMC or DRX counterparts. A metallic structure is fine for ground-based systems where weight is not as significant a constraint as for aeronautics or space-based systems.

Composites, in particular PMCs, offer lower density and higher strength and stiffness than metals used for cryogenic applications. It is estimated that composites can offer a 25 percent weight savings relative to the latest monolithic aluminum tanks in this application, as reported by Sharke (2004). Although, the resins used with polymer matrix composites do tend to enable higher hydrogen permeation than metals. Brewer (1991) noted that conventional filament wound composite structures had not traditionally been used for hydrogen tanks due to hydrogen diffusion through the interstices of the bonding material over long durations. However, composite tank development began with the NASP program. Robinson et al. (2002) reported that based on results from initial studies, hydrogen permeability was not believed to be a technical barrier to the development of an unlined composite tank.

As mentioned in this section, tank design and analysis pose many challenges. In addition, aerospace structural design is performed with a multitude of explicit and implicit safety factors. Sometimes, these combined safety factors can more than double the weight of the structure. The metallic materials are generally well-characterized unlike the newer advanced composite materials. With composite materials being used in large temperature and moisture ranges, implicit safety factors are even higher because one

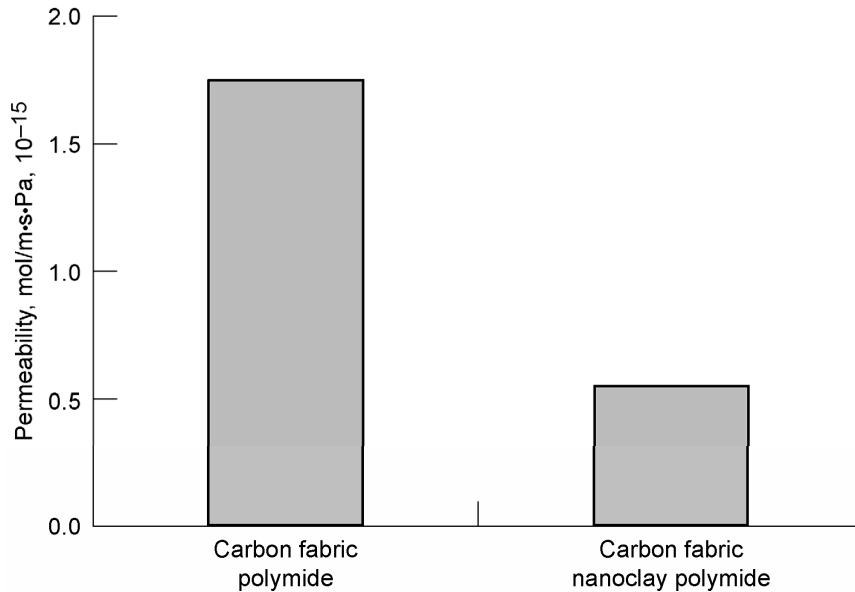


Figure 12.—Comparison of permeation by gaseous helium for two carbon-fiber-reinforced polymer composites as presented by Campbell et al. (2003).

must account for the wide range in measured properties. Safety factors pose a challenge for composite structures when such designs are compared with all metallic structural designs.

Permeation of the PMCs by the hydrogen was noted throughout this report. Currently available PMCs may not offer sufficient resistance to permeation by hydrogen. Another approach to address the permeability issue is to use polymer-silicate nanocomposites, which are being developed at NASA Glenn Research Center (Campbell et al., 2003). In addition, other research with carbon fiber nanoclay particle-reinforced polymer matrix composites for cryogenic applications has been reported by Timmerman et al. (2002, 2003). A T650–35 fiber, eight-harness satin-weave, eight-ply carbon fabric was used to reinforce a thermoplastic (BPADE–BAPP) polyimide/silicate nanocomposite matrix, with a fiber content of 60 wt%. The matrix had 2 wt% bentonite clay nanoparticles. The silicate layers were believed to be dispersed on the nanometer level. Helium permeability measurements show that the gas permeability was reduced by 70 percent, compared with that of the neat resin matrix composite, as shown in figure 12. Hydrogen permeability results were not reported. The reduction in permeability is believed to be due to an alignment of the silicate layers by the carbon fibers, thus lengthening the gas diffusion path. This composite shows an increase in stiffness but no increase in flexural or interlaminar shear strength with respect to the neat resin.

The materials that are suitable for this tank wall application include monolithic metals, continuous-fiber-reinforced PMCs, and DRXs. These are the classes of materials that should be evaluated further based on the performance indices discussed above. Mechanical properties, hydrogen permeation, manufacturability, and cost are some of the other significant issues that should be considered for determining the most optimum material system for tank wall construction. Table V briefly summarizes the advantages and disadvantages of various options for tank wall materials.

TABLE V.—ADVANTAGES AND DISADVANTAGES OF VARIOUS LIQUID HYDROGEN STORAGE TANK WALL MATERIALS

Discriminators	
Metallic	
Advantages	Well established, currently in use Relatively low cost, easy to fabricate Insignificant permeation, alleviating need for permeation barrier
Disadvantages	Higher mass High thermal conductivity
Composite^a	
Advantages	Low mass High specific strength and stiffness Tailorable properties
Disadvantages	Higher cost Prone to permeation by hydrogen Prone to microcracking due to constituent CTE mismatch Potential need for barrier or liner, resulting in component CTE mismatch issues Fabrication, processing, and joining issues
Hybrid construction^a	
Advantages	Potential optimum design for lowest mass
Disadvantages	Fabrication complexity Higher cost CTE mismatch issues

^aCTE is coefficient of thermal expansion.

4.2.2 Tank wall architecture.—Material selection for the tank wall is just one of the critical issues in the design process. The tank wall geometry is another significant issue. Various tank wall geometries have been utilized in the past. A brief description was provided in the Introduction of this report. Many of the previous aerospace applications were for relatively short-term durations. As a result, single-wall construction with stiffening ribs is common. Later, experimental projects utilized double-wall construction, including composite sandwich structures, but with a gas purge as opposed to a vacuum jacket.

Wall construction schemes will need a more indepth investigation to determine an optimum light-weight design with the appropriate insulation method to meet the needs of an aircraft application. Table VI briefly summarizes the advantages and disadvantages of various tank wall construction methods.

Bending stresses within a tank will arise from fuel slosh and loads induced at the supports, and the shape of the tank will affect its ability to accommodate these stresses. Certain geometrical shapes, such as a sphere, can minimize bending stresses within the wall of the tank. Thus, if the tank is to be made into a cylindrical configuration or a more complex conformal geometry, then it may be beneficial necessary to select a wall construction that can accommodate bending.

Two general categories for tank wall construction are single-wall and double-wall architecture. Because of the need to maintain a low heat flux for an extended duration for this application, the insulation system as discussed in the previous section most likely would consist of a high-vacuum-based system, which would dictate the use of a double-wall tank construction.

TABLE VI.—ADVANTAGES AND DISADVANTAGES OF VARIOUS LIQUID HYDROGEN STORAGE TANK WALL CONFIGURATIONS

Discriminators	
Single wall	
Advantages	Simple construction Low cost
Disadvantages	Limited insulation schemes Not optimum for low weight Not practical for longer term application
Double wall	
Advantages	Optimum for low weight Allows for more insulation schemes
Disadvantages	Higher cost Complex fabrication
Constant thickness	
Advantages	Low cost Simple construction
Disadvantages	Limited insulation schemes (SOFI), not optimum for long duration Not optimum for low weight
Variable thickness (stiffeners)	
Advantages	Lightweight Tailorable properties Can be optimized for a specific application
Disadvantages	Fabrication Higher cost Limited insulation schemes (SOFI), not optimum for long duration
Structural core (sandwich construction)	
Advantages	Low weight Well suited for in-plane and bending loads Better mechanical properties Core may have insulating properties
Disadvantages	Fabrication issues for large structures Higher cost
Nonstructural core	
Advantages	Lightweight Well suited for extremely low thermal conductivity systems, including vacuum
Disadvantages	Thicker walls, higher weight Cost and complexity Critically relies on maintaining high level of vacuum, so loss of vacuum results in catastrophic failure

Single-wall constructions have the advantages of relatively simple construction and low cost. However, they can only be used with a foam-based or similar insulation system and thus are not likely to meet the low-heat-flux requirement for an aircraft application. A single-wall-foam system is quite suitable for a relatively short-term application, such as the space shuttle ET.

Double-wall construction, in contrast, may consist of a sandwich-type construction with a load-bearing core that supports various loads. In addition, the core material may exhibit insulating properties that limits the heat flux into the tank. Alternatively, the double-wall construction may utilize two structural walls with minimal physical contact with a high-vacuum-based insulation system.

4.2.3 Liner.—As mentioned above, a linerless tank (tank without the need for a liner) is preferred to minimize cost, weight, and compatibility issues. By eliminating the liner, a major portion of the tank mass, cost, and fabrication time can be saved. However, for advanced fiber-reinforced composites, even the state-of-the-art resin systems may be too permeable to contain liquid and gaseous hydrogen when subjected to high strains resulting from mechanical and thermal loads that are characteristic of efficient tanks. In addition, the thermal cycling associated with repeated filling and draining may cause material fatigue damage in the form of matrix microcracking, which may result in the leakage of hydrogen.

Composite materials, using continuous graphite fiber reinforcement and some sort of a polymeric resin matrix, will allow for optimization of a composite layup for material stiffness and strength, consequently leading to lower mass tank designs. Other composite materials that may meet the design criteria include MMCs, which also include DRXs. The characteristics that make composite materials attractive in tank applications are their tailorable stiffness and strength properties and a significant lower density than metals.

The composite tank material is subjected predominantly to biaxial stresses, which may result in transverse microcracking at levels of strain significantly below the strain to failure. In addition, all polymeric resins are gas permeable to a certain degree. The addition of fibers can cause microcracking due to the processing and the CTE mismatch of the two constituents. The obvious effect of these microcracks is to provide a leakage path for the contained gas or liquid from the interior of the tank. Therefore, it is necessary to prevent the gas from leaking through the tank walls. A further concern is to prevent moisture from entering the microcracks produced on the exterior of the vessel. If freezing of the moisture occurs, it can result in progressive damage to the composite laminate. A potential solution to these problems is to apply appropriately compliant coatings on the interior and exterior surface of the tank that are capable of isolating the microcracks.

Based on the X-33 tank experience (sec. 3.6), permeability issues may dictate the need for a thin foil-like metallic liner if the tank wall construction itself is nonmetallic. Robinson et al. (2004) mentioned that in a trade study conducted by Boeing, aluminum was considered the best performer as a liner material. However, there is such a large CTE mismatch between the metallic liner and the composite tank material that the two tend to separate when the cryogenic liquid is introduced. In addition, any liner material is very difficult to implement and maintain. Other potential liner materials may include DRXs, which have tailorable properties and may help reduce the CTE mismatch issues between the liner and the tank wall.

Various polymer and elastomer films have also been considered as a permeation barrier for gases such as helium, hydrogen, and oxygen through composite laminates (Jones and Li, 2003). Among them, ethylene vinyl alcohol and vinylidene chloride are superb barriers against the permeation of helium. Fluoropolymers offer even higher resistance to permeation by helium. Among the elastomers, polysulfide, polyurethane, nitrile, and butile have very low permeability. These include both cured-in-place (formed on the tool and cured with the composite) as well as sprayable materials that are secondarily applied to the cured composite. Data on hydrogen permeation of these materials is very limited.

5.0 Fabrication and Other Issues

The linerless composite tank construction would be the ideal configuration, offering minimum weight and cost. Composite materials offer the possibility of net shape manufacturing, which will lower the parts count, and those parts will require a lot less machining than comparable metallic parts. Metallic parts

require significant secondary processing such as heat treating, etching, chemical milling, anodizing, and so forth, some of which must be done several times—all in addition to major structural forming and joining that must be done. Any particular step is not necessarily expensive, but they add up to a costly total. However, the ply layup of composites may be labor intensive if the fabrication is not fully automated. Also, the joining of composites poses a significant challenge.

However, composite tanks present some issues that are unique to this type of construction. One of the issues has to do with tooling and fabrication. Among them, a primary issue is to decide whether the tank should be laid up and cured in two parts on conventional molds that are subsequently joined together. This obviously has some risks associated with it in designing a composite tank with a joint. A joint introduces the possibility of leaks. To fabricate a composite linerless tank in one piece, the reinforcing fibers must be wound onto a mandrel that is either mechanically attached, water soluble, collapsible, or otherwise removable. The applicability of each type of construction is dependent upon the size of the tank and the opening. The presence of any film or coating for permeation resistance will also limit the type of mandrel that is suitable. Other important considerations include the following:

- (1) The required tank service temperature
- (2) The thermal expansion mismatch between the tool and tank materials
- (3) The thermal mass of the tool and the potential difficulty of curing process control
- (4) The impact of tool's enormous size on fabrication site
- (5) Transportation, infrastructure, and logistics

Thermal expansion mismatches can be both beneficial and problematic. Aluminum tools on composite parts are often used because the higher CTE of the aluminum will cause it to separate from the part as both are cooled down after curing, resulting in a loose fit to make the removal of the tool easier. However, low-expansion tools made of other materials are preferred for better dimensional control, better part shape, and because of potential inconsistencies in the curing process. The large volume of the part will make it extremely challenging to achieve a uniform heating rate in an autoclave and follow the prescribed cure cycle. These issues are generally present in any situation but could be worse with metallic tools and if a two-piece tank approach is taken, as there exists a potential for thermal mismatch for the two pieces at the joint. In summary, the anticipated higher cost and the complexity in fabricating a large tank and potential difficulty in sealing such a tool has to be traded against the weight, costs, manufacturing difficulty, and the risks associated with designing a joint in the tank for the two-piece fabrication approach.

6.0 Summary and Recommendation

NASA is investing in technology development efforts and alternate fuel foundation technologies that will greatly reduce or even eliminate environmentally harmful emissions. Because of that, liquid hydrogen (LH₂) has emerged as a propellant to supply the fuel needs for future aircraft. Durable, lightweight cryogenic propellant storage and feed systems are required to enable the development of hydrogen-fueled aircraft. Systems should be able to maintain propellant storage volumes for significant periods of time for ground layover and for the full duration of a flight.

Any reusable aerospace structure is very sensitive to weight. One of the important criteria in these systems is the structural weight of the fuel tank as it constitutes a significant proportion of the total aircraft weight. As a result, attention should be paid to individual aspects of tank system design including material selection and architecture. This report provides an annotated review with an extensive literature search of the current state of the art for the cryogenic tank materials, structural designs, and insulation systems along with key challenges with the intent of helping guide the development of a lightweight storage system for LH₂.

An important design variable is the cryogenic insulation. The broad classes of insulation systems comprise foams, including advanced cross-linked silica aerogels, and/or variable-density multilayer

insulation (MLI). Mass density, thermal conductivity, thermal emissivity, thermal diffusivity, and CTE are important parameters for an insulation system, and a thorough understanding of the composite system's behavior is desirable when designing a lightweight system. However, the ranking of these parameters will be dictated by the specific application including flight duration, cost, and complexity. For example, a long-flight-duration application would put the highest emphasis on the low heat transfer including low thermal conduction and radiation heat transfer. Alternatively, a short-term application may compromise the low heat transfer requirement in favor of the complexity and cost of the insulation system. As noted in this report, the MLI systems, including variable-density MLI, with a vacuum jacket have low density and allow for a minimal heat transfer, making them especially suitable for long-flight-duration applications. New lightweight materials like advanced silica aerogels may provide viable insulation systems for short-flight-duration applications. In addition, foams and aerogels could potentially be used as supplemental insulation systems with MLI to alleviate catastrophic failure in the case of a loss of vacuum in the MLI system.

Another important consideration within the overall tank design is the selection of the structural tank wall material. As noted throughout this report, high specific strength, especially at cryogenic temperatures, is the most important parameter for a structural tank wall material. Other important tank wall material parameters are fracture toughness and stiffness. In addition, the tank wall material needs to provide the required permeation resistance to liquid and gaseous hydrogen. Potential wall material candidates that offer high specific strength are monolithic metals as well as polymer matrix composites and discontinuously reinforced metal matrix composites. The use of composite materials for the tank walls may offer weight advantage over conventional metallic designs. However, the primary impediment to the use of composite materials seems to be the permeation resistance as illustrated by the X-33 tank failure experience. Nanoclay-particulate-enhanced toughened epoxies using conventional continuous fiber reinforcement may potentially provide the necessary permeation resistance to hydrogen. Linerless construction is obviously desirable from weight considerations, but new materials and innovative designs would have to be employed to achieve the permeation resistance to hydrogen. Another class of materials is DRXs. These materials should also be further evaluated for tank wall construction as they offer the permeation resistance and isotropic properties like those of the monolithic metals with potential tailorable specific mechanical and thermal properties that are comparable to polymer matrix composites.

Potential structural configurations include single- and double-wall constructions including sandwich construction. For an aircraft application, a double-wall construction with a vacuum-based insulation system may turn out to be an optimum system as it minimizes total heat transfer into the tank. Tank wall architecture may utilize ribbed walls, sandwich construction, and/or isogrid geometry. The current trends in liner material development are also reviewed in the case that a liner is required to minimize or eliminate loss of hydrogen fuel through permeation.

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Appendix A Acronyms

CFRP	continuous-fiber-reinforced polymer
CTE	coefficient of thermal expansion
DOD	Department of Defense
DOE	Department of Energy
DRA	discontinuous reinforced aluminum
DRX	discontinuous reinforced metals
ET	external tank
GH ₂	gaseous hydrogen
LH ₂	liquid hydrogen
LO ₂	liquid oxygen
MLI	multilayer insulation
MMC	metal matrix composites
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NGLT	Next Generation Launch Technology
PMC	polymer matrix composites
SOFI	spray-on-foam insulation
SRB	solid rocket booster
UAV	uninhabited or unmanned aerial vehicle
VD-MLI	variable-density multilayer insulation

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13. ABSTRACT (Maximum 200 words) Due to its high specific energy content, liquid hydrogen (LH ₂) is emerging as an alternative fuel for future aircraft. As a result, there is a need for hydrogen tank storage systems, for these aircraft applications, that are expected to provide sufficient capacity for flight durations ranging from a few minutes to several days. It is understood that the development of a large, lightweight, reusable cryogenic liquid storage tank is crucial to meet the goals of and supply power to hydrogen-fueled aircraft, especially for long flight durations. This report provides an annotated review (including the results of an extensive literature review) of the current state of the art of cryogenic tank materials, structural designs, and insulation systems—along with the identification of key challenges—with the intent of developing a lightweight and long-term storage system for LH ₂ . The broad classes of insulation systems reviewed include foams (including advanced aerogels) and multilayer insulation (MLI) systems with vacuum. The MLI systems show promise for long-term applications. Structural configurations evaluated include single- and double-wall constructions, including sandwich construction. Potential wall material candidates are monolithic metals as well as polymer matrix composites and discontinuously reinforced metal matrix composites. For short-duration flight applications, simple tank designs may suffice. Alternatively, for longer duration flight applications, a double-wall construction with a vacuum-based insulation system appears to be the most optimum design. The current trends in liner material development are reviewed in the case that a liner is required to minimize or eliminate the loss of hydrogen fuel through permeation.				
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