An overview of Ball Aerospace cryogen storage and delivery systems

J Marquardt, J Keller, G Mills and J Schmidt
Ball Aerospace & Technologies Corp., 1600 Commerce St., Boulder, CO 80301
USA

Abstract. Starting on the Gemini program in the 1960s, Beech Aircraft (now Ball Aerospace) has been designing and manufacturing dewars for a variety of cryogens including liquid hydrogen and oxygen. These dewars flew on the Apollo, Skylab and Space Shuttle spacecraft providing fuel cell reactants resulting in over 150 manned spaceflights. Since Space Shuttle, Ball has also built the liquid hydrogen fuel tanks for the Boeing Phantom Eye unmanned aerial vehicle. Returning back to its fuel cell days, Ball has designed, built and tested a volume-constrained liquid hydrogen and oxygen tank system for reactant delivery to fuel cells on unmanned undersea vehicles (UUVs). Herein past history of Ball technology is described. Testing has been completed on the UUV specific design, which will be described.

1. Introduction

For over 50 years, Beech Aircraft and Ball Aerospace & Technologies have been delivering tanks and dewars for cryogen storage and delivery in aerospace flight applications. The subject tanks and dewars were designed to deliver a fluid, which in most applications, provided an energy source for the mission. Ball has also delivered a large number of dewars that have cooled cryogenic instruments, but these applications are not discussed here.

This remarkable story begins in 1957 with the establishment of the Beech Aircraft Boulder division to build cryogenic systems for NASA and the Air Force. The first product was a 6,000 liter liquid hydrogen dewar [1] for the Air Force as ground support equipment. The site near Boulder was selected because of its proximity to the National Bureau of Standards in Boulder which at that time had the only source of liquid hydrogen in the United States. From 1964 to 1966 Beech built ground support dewars for the Gemini program. These units delivered cryogenic fluids liquid oxygen (LOX), liquid nitrogen (LN2) and liquid hydrogen (LH2) to the Gemini spacecraft on 12 missions.

In December 1986, Ball acquired the cryogenic assets of Beech Aircraft including the contracts for Space Shuttle Power Reactant Storage Assembly (PRSA) dewars, some cryogenic intellectual property and some of the cryogenic engineering staff. The fabrication and test of 16 PRSA dewars was performed at Ball. No relocation was needed since both Beech Aircraft and Ball are in Boulder.

Table 1 summarizes the 239 cryogen tanks and dewars that have been built at Beech Aircraft and Ball Aerospace for cryogen storage applications. They represent a wide range of cryogen type, volume, mass, and thermal performance. Highlights from within this design experience are highlighted herein to show progression to today’s work.
Table 1. Cryogen storage tanks built at Beech and Ball

| Program Name  | Program Dates | Quantity produced | Cryogen stored | Tank Volume, L | Dry Weight, kg | Test Environment, K | Heat Leak, Watts |
|---------------|---------------|-------------------|----------------|----------------|----------------|---------------------|-----------------|
| LH2 Trailer   | N/A-1957      | N/A               | LH2           | 6000           | 6800           | 295                 | 30              |
| Apollo H2     | 1962-1972     | 80                | Sc H2         | 193            | 32.7           | 289                 | 1.5             |
| Apollo O2     | 1962-1972     | 76                | Sc O2         | 132            | 36.2           | 289                 | 7.2             |
| OTTA          | 1964-1973     | 1                 | LO2           | 6464           | 2088.6         | 297                 | 1.3             |
| HTTA          | 1972-1973     | 1                 | LH2           | 22818          | 2136.4         | 297                 | 2.5             |
| ACFSA Ti      | 1973-1974     | 3                 | LN2 + misc    | 595            | 515.5          | 300                 | 59.3            |
| ACFSA Al      | 1974-1975     | 2                 | LN2 + misc    | 204            | 311.5          | 344                 | 59.7            |
| PRSA H2       | 1974-1991     | 34                | ScH2          | 614            | 103.2          | 317                 | 2.5             |
| PRSA O2       | 1974-1991     | 34                | ScO2          | 320            | 97.7           | 317                 | 3.7             |
| LNG Aircraft  | 1980-1981     | 2                 | LNG           | 68             | 43.2           | 297                 | 1.4             |
| LNG Helicopter| 1983-1985     | 1                 | LNG           | 87             | 25.5           | 297                 | 1.8             |
| HALE Aircraft | 2009-2010     | 2                 | LH2           | N/A            | 279.5          | 295                 | 620             |
| UUV H2        | 2013-2014     | 1                 | ScH2          | 29             | N/A            | 298                 | 1.8             |
| UUV O2        | 2013-2014     | 1                 | LO2           | 16             | N/A            | 298                 | 7.3             |

2. Apollo dewars

In 1962, NASA awarded Beech a contract to build cryogenic oxygen and hydrogen dewars for the Apollo spacecraft program. The oxygen was used for life support, and the oxygen and hydrogen were used for fuel cell reactants. Eventually, 80 hydrogen and 76 oxygen dewars were produced [2]. Figure 1 shows a photo of these dewars.

Both dewars operated at supercritical conditions with the oxygen dewar operating at 1020 to 1357 psia and the hydrogen dewar operating at 300 to 400 psia. The oxygen pressure vessel material was Inconel 718, and the hydrogen pressure vessel was 5Al-2.5Sn ELI Titanium. The pressure vessel hemispheres were forged, machined and joined by electron beam welding. Several titanium design difficulties were overcome in the development program. The problem of titanium creep above 75 percent of yield stress resulted in a reduction in the allowable stress for titanium. The incompatibility of hydrogen gas and titanium vent lines was solved by the use of stainless steel lines and bimetal joints. The use of vacuum ionization pumps to maintain the annular vacuum was pioneered on this program for spacecraft applications.

Figure 1. Apollo Oxygen and Hydrogen Dewars
3. OTTA and HTTA dewars
Following Apollo, in 1969 and 1971, under NASA contract, Beech built two ground test dewars to
demonstrate techniques for very efficient storage of cryogens. They remain among the most
thermally efficient dewars ever built. The oxygen thermal test article (OTTA) was 7.0 ft. diameter
near-sphere with a 6,456 liter tank volume. It had fiberglass tank supports, a total of 46 silverized
Mylar and silk layers in the MLI blankets and two vapor cooled shields. It was tested with liquid
nitrogen and liquid hydrogen and demonstrated boil-off rate of 0.022%/day and 0.056% per day
respectively [3]. A photo of the tank is shown in figure 2.

![Figure 2. OTTA dewar tank and strap supports](image)

The hydrogen thermal test article (HTTA) was 21.8 ft. long x 9.2 ft. diameter. It used all known
technologies for maximizing thermal performance in a flight like dewar including fiberglass strap
supports, 68 layer, aluminized Mylar MLI blankets and two vapor cooled shields. It was made
from spun and welded 2219 aluminum. It was tested with liquid hydrogen and demonstrated a
boil-off rate of 0.022%/day or 8%/year [4]. A photo is shown in figure 3.

![Figure 3. Completed HTTA dewar](image)

4. Power Reactant Storage Assemblies
While the specific OTTA and HTTA designs were never built for flight, design approaches from
them were incorporated in the PRSA designs. The PRSA tanks are sets of oxygen and hydrogen
tanks that provided reactants for the Space Shuttle orbiter and electrical power generation and life
support to the shuttle crew (figure 4). PRSA tanks stored cryogenic oxygen and hydrogen in a
supercritical state. The operating pressure the hydrogen tanks was 220 to 226 psia, and the
operating pressure of the oxygen tanks is 840 to 852 psia. When the oxygen and hydrogen combine and react chemically in the power generation system (fuel cells), they produce electricity for the orbiter and drinking water for the crew. Oxygen is also mixed with nitrogen for crew cabin pressurization and atmosphere.

Each tank set consists of vacuum-jacketed storage vessels; supply, vent, and fill lines; electrical subsystems for instrumentation, internal heaters and fluid quantity gauging; and mounting provisions for installation into the orbiters mid-body section. The PRSA tanks were designed for a 100-mission service life. They function under a range of severe environments: from zero to ±5 g acceleration, vibrations up to 4.5 grms for the hydrogen tank and 1.5 grms for the oxygen tank, and shocks up to 1.5 g for 0.260 second.

Ball built additional PRSA tanks for NASA’s Extended Duration Orbiter (EDO). Increasing the numbers of PRSA tanks on an orbiter allows shuttle missions to be extended. The tank sets for the EDO fit into a pallet structure and in the main payload bay. The tanks hold a minimum of 335 kg of oxygen at 91 K and 42 kg of hydrogen at 22 K, respectively.

![PRSA Oxygen and hydrogen tanks in tooling fixtures](image)

**Figure 4. PRSA Oxygen and hydrogen tanks in tooling fixtures**

Flight operations, from just before launch to landing, require that the oxygen and hydrogen be supplied at design flow rates. Both the hydrogen and oxygen fluid must be maintained at maximum continuous flow rate with constant pressure. To maintain the operating pressure, heat must be added to the stored cryogens by electrical heaters immersed in the cryogens. The heat keeps the fluids above critical pressure so they are single phase. Two heaters are used in the oxygen tank and one is used in the hydrogen tank. Each heater consists of two elements, a temperature sensor and a support tube with a mounting bracket welded to each end.

5. **Light Aircraft LNG Dewar and Fuel System**

The final tank program Beech completed was performance evaluation of a single engine, propeller driven four place light aircraft fueled with liquid natural gas (LNG), also called liquid methane using a Beech Aircraft Sundowner. The back seat was removed and two 68 liter LNG dewars installed. The dewars had a stainless steel pressure vessel and a steel vacuum shell with multilayer insulation. The LNG was vaporized by heat exchanging with the engine exhaust. An automotive-type air-natural gas mixer was installed on stock 180 HP Lycoming internal combustion engine. There was 10 percent loss in maximum power due to lower density fuel-air mix. The Sundowner shown in figure 5 performed the first recorded flight of an aircraft fueled with LNG on September 15, 1981.

The Sundowner work led to an Army demonstration program to convert a TH-55A training helicopter in at Ft. Rucker, AL to LNG fuel. This helicopter first flew on LNG in October 1984. The use of LNG as a light aircraft fuel was not developed further by Beech due the cost of developing new aircraft and associated cost to develop a LNG refueling infrastructure. Recently, there has been interest from the Air Force in developing LNG as fuel for large transport aircraft. LNG currently is significantly cheaper than jet fuel.
6. Phantom Eye HALE aircraft

More recently, the Phantom Eye High Altitude Long Endurance aircraft (HALE) is an unmanned vehicle system being built by The Boeing Company Phantom Works used for long term persistence. The first phase is a propeller-driven demonstrator capable of a 4-day flight. The aircraft has a 150-foot wingspan and two engines and flies at an altitude of about 65,000 feet while carrying a payload of 450 pounds. Eventually a larger HALE system will be built which will fly for 10 days. Liquid hydrogen was selected by Boeing as a fuel for the HALE aircraft. Ball was selected to build the liquid hydrogen tanks.

Some of the driving requirements for the HALE tank included:

- Maximum operating pressure: 95 PSIG
- Maximum empty weight: 705 pounds
- A vertical slosh baffle with 4 panels, 90 degrees apart
- Envelope: fit inside the Phantom Eye airframe with a specified clearance.

Ball designed, fabricated and tested two tanks that met these and other requirements [5]. Several trade studies were performed in the process of designing the tanks. Different overall tank geometries were considered including spherical, near spherical (hemispherical heads with a short cylindrical section) and joined near spheres. A spherical geometry was the simplest to design and fabricate but had the least clearance on the existing airframe design. The near sphere and joined near sphere had improved clearance but would be more complicated to design and fabricate. A spherical geometry was selected.

Several different tank wall materials were considered. Given the low operating pressure, composite materials such as graphite-epoxy would provide only a marginal reduction in mass, at potentially greater cost in money and schedule. Among metals, the most experience in spinning large, thin domes for flight applications existed for aluminum, which was therefore selected.

The tank insulation had to meet several somewhat conflicting requirements. It had to have low enough heat leak to allow the tank system to meet the boil-off requirements but be light enough that to allow the tank system to meet the mass requirement of less than 705 pounds. Because program budget and schedule did not allow for significant technology development, a high Technology Readiness Level (TRL) for the insulation was also required.

Spray-On Foam Insulation (SOFI) was used to insulate the Phantom Eye tanks. It was the only mature technology that could meet the mass requirement. If a thickness of approximately 5 inches was used, the mass requirement could be met and the boil-off requirement could be met with no margin. By carefully screening and testing of candidate SOFI, it was felt that the heat leak performance of the SOFI used could be maximized, and the lack of margin could be managed. A photo of one of the completed tanks is shown below in figure 6. The sprayed and machined SOFI can be seen on the tank.
Figure 6. Completed, insulated tanks installed into Phantom Eye airframe.

The Phantom Eye demonstrator aircraft completed its first flight on June 1, 2012 at Edwards Air Force Base. It reached an altitude of 4,000 ft and a speed of 62 knots (115 km/h) for 28 minutes. A total of nine flights have now occurred. The demonstrator's ninth flight occurred in 2014 for 9 hours at 54,000 ft, after which it was placed in storage at NASA’s Armstrong Flight Research Center. Boeing is looking for opportunities in the military or commercial sectors to continue development. Initially conceived as high-flying satellite surrogate for ground surveillance or communications relay, Boeing is looking to see if a solid-state laser could be mounted to perform missile defense; a solid-state laser is desired over chemical lasers, like the one used in Boeing's previous YAL-1 Airborne Laser Testbed. A photo the demonstrator aircraft in flight is shown in figure 7.

Figure 7. Phantom Eye demonstrator aircraft in flight

7. UUV- IRAD Development Dewar
Ball’s latest tank development focuses on unmanned underwater vehicles (UUVs). For several decades, UUVs have been in need of long endurance, air independent energy storage solutions exhibiting 3x to 4x higher energy densities than what is currently available with state of the art primary or secondary batteries. In 2011, Office of Naval Research (ONR) released both the Long Endurance Undersea Vehicle Propulsion (LEUVP) Future Naval Capability (FNC) Broad Agency Announcement (BAA) [6] as well as the Large Displacement Unmanned Underwater Vehicle Innovative Naval Prototype (LDUUV INP) Energy Section Technology BAA [7]. These BAA calls for air independent energy storage and power technology development as well as other
emerging government and industrial prime contractor needs inspired Ball to initiate an Internal Research and Development (IRAD) program to meet these needs.

The IRAD investigated the packaging of both cryogenic liquid oxygen and liquid hydrogen into the most efficient possible form factor, achieving optimum passive thermal performance and minimum boil-off while also providing safe, reliable operation. Like the PRSA tanks for the Space Shuttle Orbiter, the oxygen and hydrogen reactants provided to a UUV would be continually consumed by a fuel cell, IC, Stirling Engine or other efficient energy conversion device to create electrical power, water and waste heat. Based on our experience with the HTTA and OTTA, we felt that by targeting our initial energy storage solution to a small diameter 21” UUV (as called for in the LEUVP BAA), the IRAD results would ultimately be scalable to a larger form factor as required by the LDUUV 48” diameter UUV. Hence our initial IRAD requirements were targeted around the ONR LEUVP BAA energy storage requirements given in table 2.

At the outset of the IRAD, an initial dewar tank design was chosen that would be capable of storing 2.3-kg of hydrogen and 20-kg of oxygen within a common vacuum vessel having internal tank dimensions smaller than 18.5” diameter and an overall length much less than 30”. These reactant masses are suitable to achieve between 48- and 52-kWh of usable electrical energy when converted by a PEM fuel cell at various power levels and thereby exceeding the LEUVP threshold requirement of 42-kWh stored energy.

In mid-2011, Ball Aerospace partnered with UTC Aerospace Systems (UTAS) in response to the ONR BAAs. UTAS (prime) and Ball (sub) were selected by ONR for the LEUVP Phase I Base effort that contractually began in late 2012. The Phase I Base effort involved a TRL-4 demonstration of our cryogenic hydrogen and oxygen development dewar in brass-board combination with a UTAS PEM Fuel Cell as called for in the statement of work. The Ball development dewar used for this TRL-4 brass-board demonstration is shown in Figure 8 and was publically displayed recently at the 2015 ONR Naval Future Force Science & Technology EXPO held in in Washington DC February 4-5, 2015.

| Nominal Power Density (Watts/liter) | Threshold | Objective |
|------------------------------------|-----------|-----------|
| Energy Section Length | 76.2 cm (30’’) | 76.2 cm (30’’) |
| Energy Volume (liter) | 132 | 132 |
| Energy Mass (kg) w/o hull & bulkhead | 132 (neutrally buoyant) | 132 (neutrally buoyant) |
| Energy (kWh) | 42 | 68 |
| Duration (hrs) | >30 | >30 |

Figure 8. UUV Supercritical Hydrogen and Liquid Oxygen Development Dewar
With an outside diameter of 20” and a length of over 30”, the development dewar’s ASME-rated aluminum vacuum shell is larger and heavier than that called for in the LEUVP BAA. This was done to facilitate easy access to and serviceability of the inner tanks during development while simultaneously having an inner tank geometry that could be integrated into a flight dimension vacuum shell at a later time. While the exact internal hydrogen and oxygen tank configuration within the common vacuum space is proprietary, the design includes a 30-liter hydrogen tank capable of supercritical operation in optimum thermal communication with a 19-liter liquid oxygen tank. Extension of this design approach to a lightweight 18.5” outside diameter vacuum shell results in dewar energy densities of ~660-Wh/liter-dewar. This in combination with the required fuel cell and balance of plant volume is able to meet or exceed the LEUVP energy density goal of 515-Wh/liter.

To achieve optimum passive thermal performance, spaceflight heritage cryogenic design approaches as well as materials, thermal support struts, flexures, shields and MLI have been selected to achieve heat leaks into the hydrogen and oxygen tank of 1.8- and 7.3-Watts respectively. This heat leak is sufficiently low to keep the development dewar’s reactant boil-off well under the minimum power levels required by the UUV. Since cryogenic liquids are not passively storable, normal boil-off reactant flow must be managed outside the dewar in order to keep internal tank pressures from rising above relief valve settings throughout its fueled lifecycle. With this in mind the concept of operation of any cryogenically fueled UUV necessarily involves, as an example, inert unfueled/empty transport of the UUV to the point of in-water deployment where it is fueled and released to perform its mission. Similar considerations are made for UUV recovery to either directly refuel the UUV or detank and inert the dewar for storage/transportation.

8. Conclusions
Over 50 years of spaceflight cryogenic tank and dewar design has been leveraged to meet several new and emerging stored energy requirements ranging from high altitude long endurance UAVs to long endurance air-independent UUVs. Ball Aerospace has a unique cryogenic heritage it can apply to future cryogenic storage and delivery needs.

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