An overview of Ball Aerospace cryogen storage and delivery systems

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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

Ball Aerospace & Technologies has over 50 years of delivering tanks and dewars for cryogen storage and delivery for aerospace flight applications. These tanks and dewars are designed to deliver a fluid. In most applications, the fluid 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 6000 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.

2. Apollo dewars

In 1962, Beech was awarded a NASA contract to build cryogenic supercritical 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.

Figure 1. Apollo Oxygen and Hydrogen Dewars

3. OTTA and HTTA dewars

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 boiloffs of 0.022%/day and 0.056% per day respectively [3]. A photo of the tank is shown in figure 2.

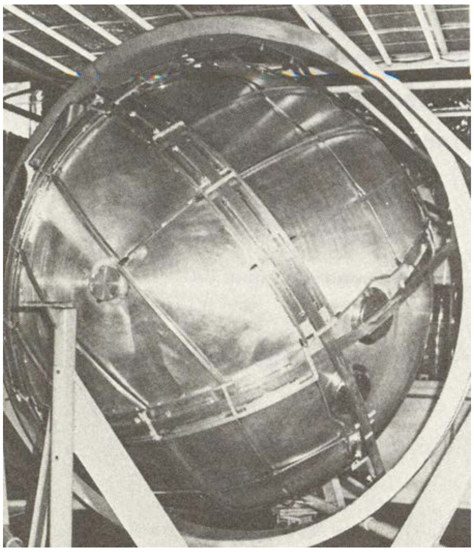

Figure 2. OTTA dewar tank and strap supports

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 boiloff of 0.022%/day or 8%/year [4]. A photo is shown in figure 3.

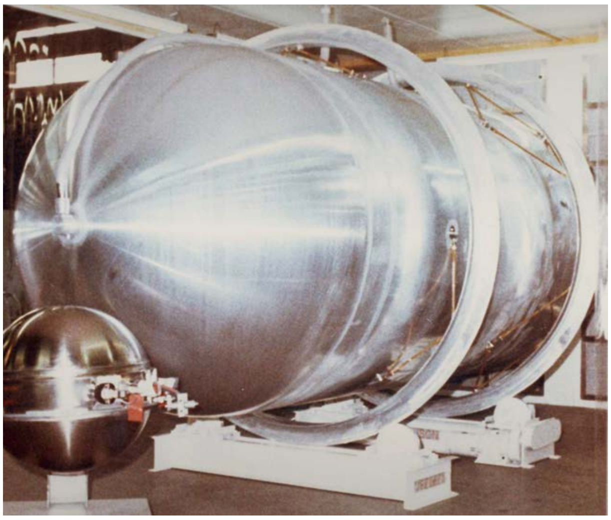

Figure 3. Completed HTTA dewar

4. Airborne cryogenic fuel storage assembly

Airborne cryogenic fuel storage assembly (ACFSA) tanks were provided to Pratt and Whitney Aircraft for the Airborne Laser Laboratory at Kirtland AFB. The requirements included the storage and transfer of helium, carbon monoxide and nitrogen at liquid nitrogen temperature and nitrous oxide at a higher temperatures.

Three tanks were built. One of the tanks had a pressure vessel machined from 6Al-4V Titanium and had an aluminum vacuum shell with MLI. Two of the tanks had pressure vessels spin formed form 2219 aluminum. One of the aluminum tanks was insulated with vacuum and MLI and the other was insulated with foam.

5. Power Reactant Storage Assemblies

Power Reactant Storage Assemblies (PRSA) 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. PRSA tanks stored cryogenic oxygen and hydrogen in a super critical 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. A photo of an oxygen tank and hydrogen tank is shown in figure 4.

Each set of tanks 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 midbody 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.

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.

6. Light Aircraft LNG Dewar and Fuel System

Beech Aircraft evaluated the performance of a single engine, propeller driven four place light aircraft fueled with liquid natural gas (LNG), also called liquid methane. A Beech Aircraft Sundowner was converted to run on LNG. 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.

Figure 5. Liquid Natural Gas Fueled Sundowner Light Aircraft

7. Helicopter LNG Dewar Fuel System
Under a Concept Evaluation program for the US Army at Ft. Rucker, Alabama, Beech Aircraft developed a liquid natural gas fuel system for the TH-55 training helicopter. The system consists of two fuel tanks, the transfer system, including instrumentation, a heat exchanger to vaporize the fuel and an air-gas mixer (carburetor). The fuel system was vibration tested and operated extensively on a test stand to generate engine performance curves. A helicopter with an LNG fuel system was first flown in October 1984. Evaluation testing was completed in May 1985.

8. Beech aerospace cryogen acquisition by Ball
In December 1986, Ball acquired some of the cryogenic assets of Beech Aircraft including the contracts for 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. There was no relocation needed by the staff as Beech Aircraft and Ball are in the Boulder area.

9. Phantom Eye HALE aircraft
The Phantom Eye High Altitude Long Endurance aircraft (HALE) is an unmanned vehicle system being built by The Boeing Company Phantom Works that will be used for long term persistence. The first phase is a propeller-driven demonstrator that is 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 were as follows:

- 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. Several different overall tank geometries were considered. These included 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.

It was decided that sprayed-on foam insulation (SOFI) would be 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 ad 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

10. UUV- IRAD Development Dewar

For several decades, unmanned underwater vehicles (UUV) 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 as given in Table 1.

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.

Table 1. ONR LEUVP Broad area announcement threshold and objective metrics

	Threshold	Objective
Nominal Power Density (Watts/liter)	10	20
Energy Section Length	76.2 cm (30’’)	76.2 cm (30’’)
Energy Volume (liter) 47.0 cm (18.5’’) (ID) x 76.2 cm (30’’)	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.

11. Summary

The table below 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.

Table 2. 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	Sc H2	29	N/A	298	1.8
UUV O2	2013-2014	1	LO2	16	N/A	298	7.3

12. 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.

References

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