CONCEPTUAL DESIGN OF SPACE EFFICIENT TANKS

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ABSTRACT

For spacecraft propellant tank applications, an all-metal spherical pressure vessel is always the most mass-efficient construction. However, on board spacecrafts where available space is limited, spherical tanks or tanks with spherical heads are not the most efficient packaging solution. This paper summarizes some of the space-efficient tank designs currently being employed or considered by the aerospace industry, including tanks with ellipsoidal heads, common bulkhead tanks, and nested tanks. We will also touch upon the feasibility of Propellant Management Devices (PMDs) within these tanks. Due to the summary nature of this paper, no design details are provided.

INTRODUCTION

For decades, spacecraft hardware development had focused on mass. Thousands of pressure vessels were designed and manufactured with a primary purpose of minimizing mass. The reason is simple – the cost of delivering hardware into space is enormous. The industry uses $25,000 to $30,000 per pound as a rough guide. Under this cost pressure, the primary focus during pressure vessel design has been on mass. Although miniaturization of other spacecraft components has achieved the goals of reducing both occupied space and mass, space saving features during pressure vessel design is usually a secondary concern unless specifically required by the customer.

In recent years, however, spacecraft packaging has gained more attention. Now more emphasis are being placed on designing light weight pressure vessels that also maximizes the use of available space as the industry has found that space on a spacecraft, as well as mass, is at a premium.

TRADITIONAL TANKS

The all-titanium spherical tank is the most common satellite pressure vessel configuration. Thousands of spherical tanks have flown since the inception of the space age. The spherical geometry offers the best pressure performance and therefore provides the most mass-efficient pressure vessel design. By taking advantage of the high mechanical properties of solution treated and aged (STA) titanium, some titanium spherical tanks have been designed with membrane thickness as thin as 0.017 inch. Spherical tanks are also easy to manufacture, requiring two hemispherical heads joined together by a single girth weld. They are lightweight, high-performance, and have been the workhorse of the satellite age for many decades. Figure 1a is an illustration of a spherical tank. Spherical tanks can be designed with various different mounts, including girth tabs, continuous flange, or polar bosses. Figures 1b and 1c provide examples of various mounting features of a spherical propellant tank.

Figure 1a: A spherical pressure vessel

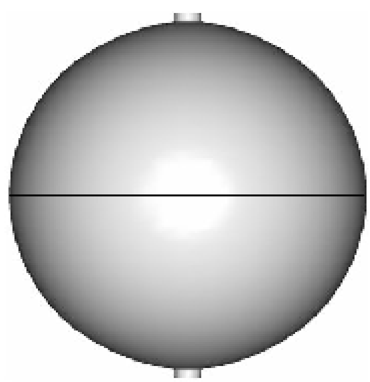
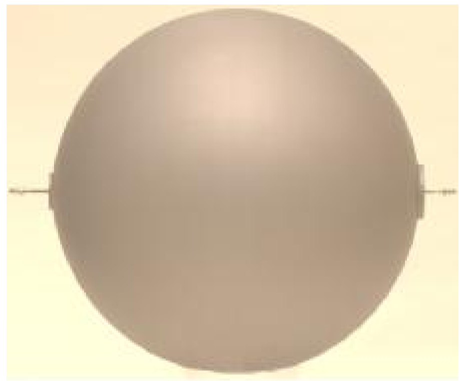


Figure 1b: Spherical Propellant Tank with Girth Tabs

Figure 1c: Spherical Propellant Tank with Polar Bosses



The increasing demand for larger spacecraft with longer mission life created the need for more on board propellant and thus larger propellant tanks. However, due to the size limitation of launch vehicles, satellites and, therefore, satellite propellant tanks, can only grow in length rather than girth[1]. This is often accomplished by adding a cylinder section between two hemispherical heads as illustrated in Figure 2a. Although the hemispherical heads can be designed as thin as practical, the cylinder section is typically thicker due to its less pressure efficient configuration. A cylindrical pressure vessel also has multiple girth welds which add mass to the tank. This type of pressure vessel design is still mass efficient as long as the cylinder section is within a reasonably length. Cylindrical tanks are widely used in recent years, and hundreds of cylindrical tanks with hemispherical heads have been delivered. In fact, more cylindrical tanks were delivered in the last 10 years than spherical tanks.

Figure 2a: Cylindrical Tank with Hemispherical Heads

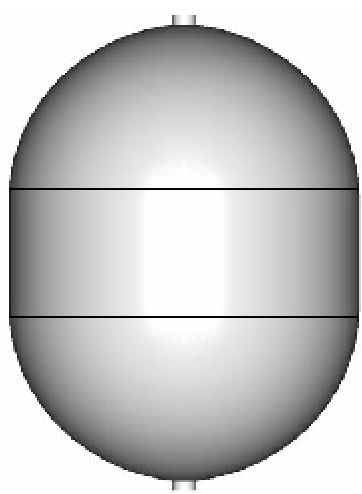


Figure 2b shows the MESSENGER propellant tank[2] which is the most recent addition to the all-titanium cylindrical tank family. The MESSENGER tank design was the result of an extensive trade study whose main focus was to minimize tank mass. The criticality of a minimum mass tank for the mission to Mercury dictated the need for hemispherical heads. However, as tank volumes increase and tank cylinders grow longer, it becomes increasingly difficult for all-metal tanks to meet the tank frequency requirements. Other factors also come into play, such as manufacturability and cost. For very long tanks, fiber reinforcement of the metal cylinder becomes necessary in order to meet the stiffness requirements[1]. An example of this type of "hybrid tank" is shown in Figure 2c.

Figure 2b: All-Metal Cylindrical Tank with Hemispherical Heads

Figure 2c: Hybrid Cylindrical Tank with Hemispherical Heads and Composite Wrapped Cylinder Section

There is a great deal of "dead space" around a hemispherical head that contributes to poor packaging efficiency. As satellite integrators try to pack more instruments and payloads onboard satellites, a tank with ellipsoidal heads becomes a more attractive option. For all-metal designs, ellipsoidal heads are inherently less efficient than hemispherical heads. Therefore, although this approach better utilizes available space, it is done at the expense of mass efficiency. Figure 3a is an illustration of a cylindrical tank with ellipsoidal heads. The actual length of cylinder section may vary, depending upon the propellant volume requirements. Figure 3b shows two tanks with the same ellipsoidal heads but different cylinder lengths.

Figure 3a: A Cylindrical Tank with Ellipsoidal Heads

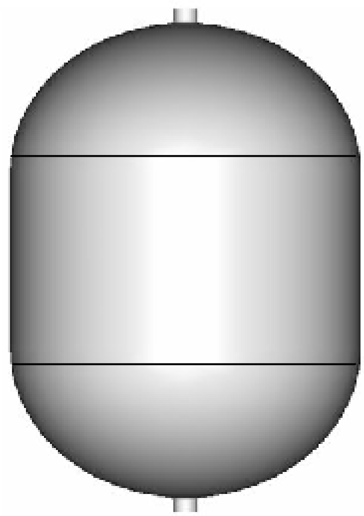


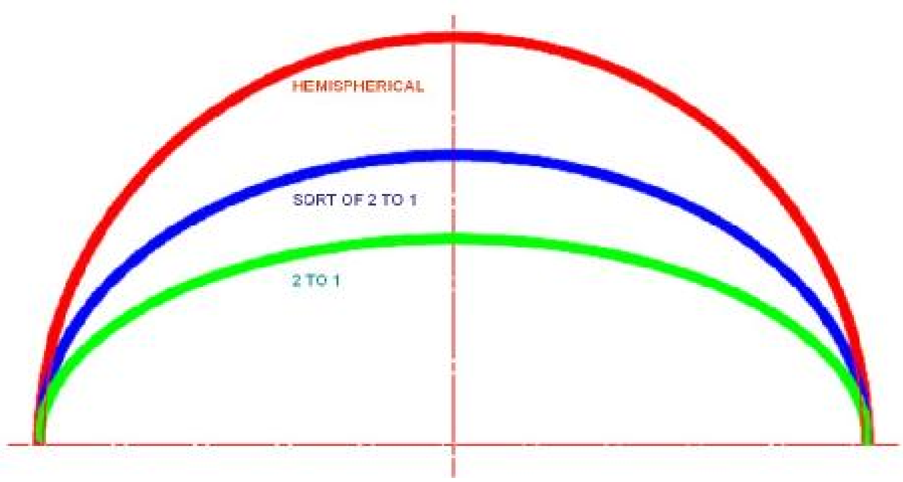
Figure 3b: Examples of Tanks with Ellipsoidal Heads

A tank with ellipsoidal heads does have an added advantage of a lower center of gravity as compared to a tank with hemispherical heads and identical volume. There are also other reasons that make an ellipsoidal head attractive which are unrelated to packaging. One such tank was designed to prevent damage during ground handling and testing by allowing a fully revered diaphragm to rest against the ellipsoidal head. See Figure 4. However, in order to operate this tank, an external pressurant tank must be added to the satellite propulsion system. This is a good example of a design philosophy where a weight penalty is paid to eliminate potential mishaps during ground handling and testing.

Figure 4: A Diaphragm Tank with an Ellipsoidal Head

There is a range of ellipsoidal head shapes. When space is available, the preference is to use configurations as close to hemispherical as possible to minimize mass. As the head becomes "flatter", or the ratio of radius to head height becomes larger, the mass penalty increases. Figure 5 shows three typical head configurations. The hemispherical head, with a radius to height ratio of 1 to 1, is the most mass efficient design. A $\sqrt{2}$ to 1 head is still somewhat mass efficient. However, a 2 to 1 head becomes very mass inefficient. Our experience base indicates that the mass penalty on the 2 to 1 head design is very high, and satellite integrators must fully understand the potential mass impact (by conducting a trade study) before committing to this type of head design.

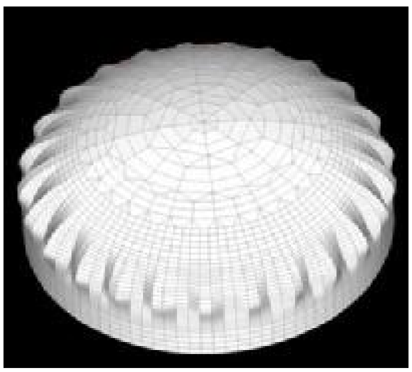
Figure 5: Various Head Shapes



Relatively few all-metal pressure vessels with ellipsoidal heads have been developed. Most of these tanks have $\sqrt{2}$ to 1 heads. Although all the composite overwrapped pressure vessels developed by ATK has ellipsoidal heads, they were designed to geodesic isotensoid shape[3] to facilitate composite overwrap.

The primary reason for increased mass on flat heads is buckling. As the head contour becomes "flatter", it becomes increasingly susceptible to forces that cause buckling. See Figure 6. To compensate, more material is needed to strengthen the tank shell, and the thicker wall results in increased mass. The acceptability of the increased mass is determined by the customer based on many different factors such as mass budget allocation, choice of launch vehicle, etc., that cannot be easily controlled by the tank manufacturer.

Figure 6a: 2 to 1 Head Buckling Mode



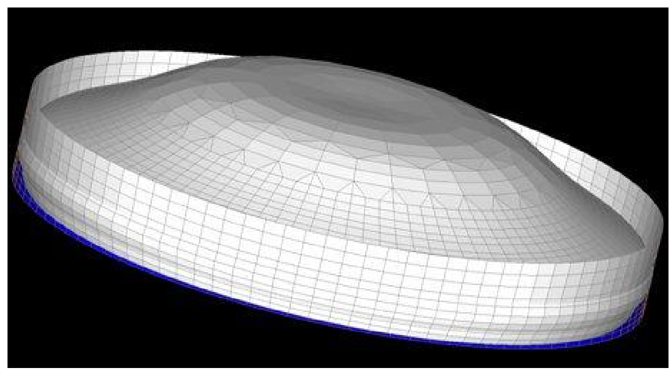
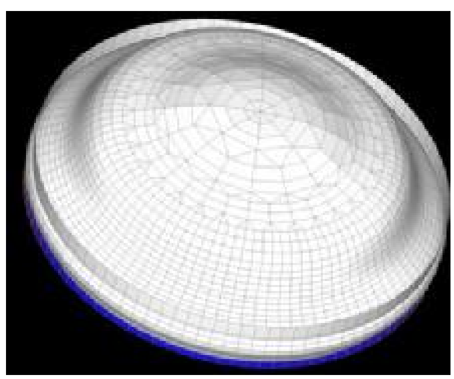


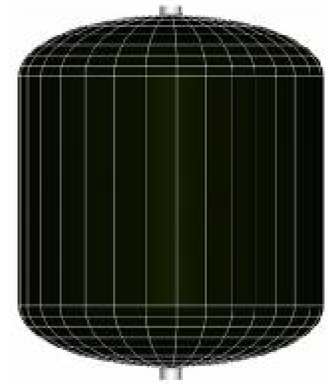
Figure 6b: Square Root of 2 to 1 Head Buckling Mode



<u>COPV PROPELLANT TANK</u>

As the head becomes flatter and the mass increase on an all-titanium shell becomes unacceptable, other tank shell constructions become more attractive. One of the options is adopting a fully wrapped propellant tank design, as shown in Figure 7.

Figure 7: A Composite Overwrapped Propellant Tank with Very Flat Heads

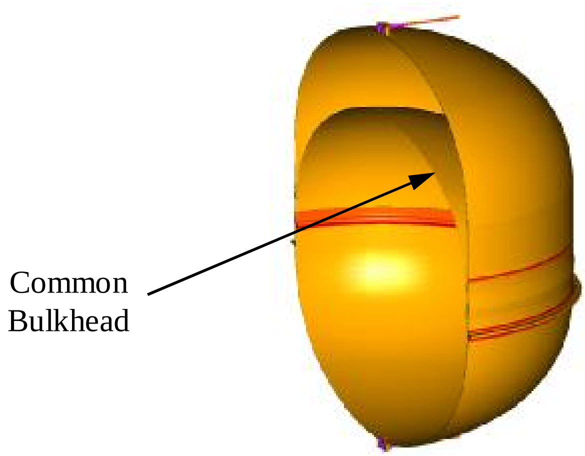


Composite Overwrapped Pressure Vessels (COPVs) are now widely used in the aerospace industry for high pressure (i.e. 4,500 psi) xenon or pressurant tank applications[3,4,5,6]. The COPV design takes advantage of the superior strength of carbon fiber which is ideal for high pressure applications. However, COPV is usually unnecessary for low pressure (i.e. 250 psi) propellant tank applications when all-titanium construction can be equally or more competitive. In recent years some customers have expressed interest in low pressure COPV propellant tanks. However, our trade studies have shown that unless the heads must be extremely flat, there are no valid reasons to justify the development of a COPV propellant tank. Thus far we are unaware of any flight of a low pressure COPV propellant tank.

COMMON BULKHEAD TANK

If space is severely limited on a bi-propellant propulsion system, one of the best packaging solutions is to utilize a single tank with a common bulkhead,.as shown in Figure 8.

Figure 8: A Pressure Vessel with Common Bulkhead



A common bulkhead tank consists of two independently pressurized compartments, one for fuel and one for oxidizer. The excellent packaging efficiency of a common bulkhead tank is self evident. The two tank heads can be spherical or ellipsoidal, as allowed by mass and envelope constraint. In this respect the common bulkhead tank shell is no different than any other tanks described thus far. The common bulkhead, or the common wall shared by both compartments, must also be designed following the rules of pressure vessel design. The configuration of the common bulkhead can be hemispherical or ellipsoidal and is independent of the head shape of the tank, although hemispherical common bulkhead is always attractive due to its low mass.

A common bulkhead tank can be orientated with the oxidizer compartment either at the top or at the bottom of the tank, as shown in Figures 9 and 10. Each compartment must have its own pressurant inlet and propellant outlet ports. The ports can be located either on the bosses or through the tank membrane. Because the location of the inlet and outlet ports will affect the design of the Propellant Management Devices (PMDs), the design of the tank shell and the PMDs must be closely coordinated.

Figure 9: A Common Bulkhead Tank with Upper Oxidizer Compartment

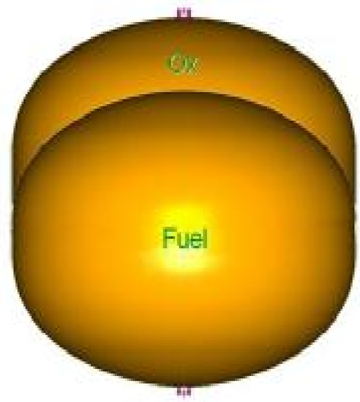
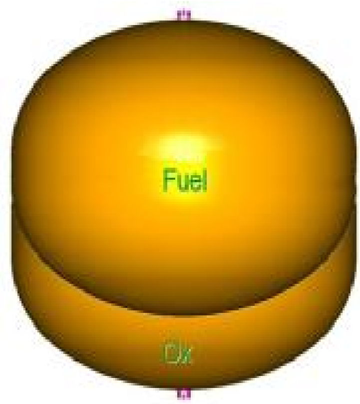
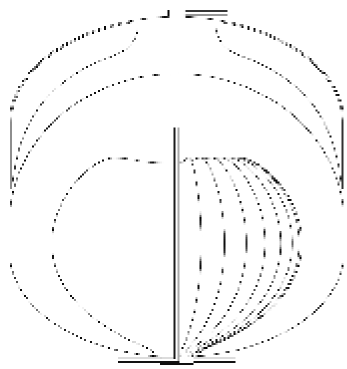


Figure 10: A Common Bulkhead Tank with Upper Fuel Compartment



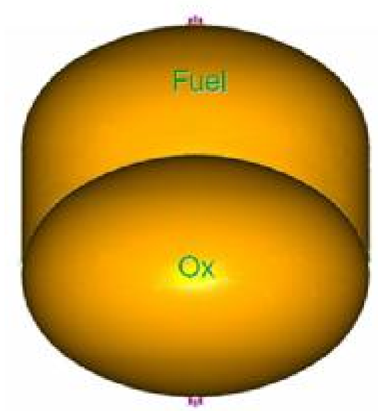
Two separate and distinct Propellant Management Devices (PMDs) for the two compartments must be custom designed for the spacecraft mission. The process of designing PMDs for a common bulkhead tank is no different than any other PMD development, and must consider inlet and outlet tube locations, ground handling and ground drain, manufacturability, as well as launch and spacecraft operations, among others. It is possible to mount a PMD on the common bulkhead, but not preferred because it adds to the complexity of the bulkhead design. Figure 11 shows a possible tank design with both PMDs mounted on the polar bosses.

Figure 11: PMD Concept for a Common Bulkhead Tank



A tank shell and PMD trade study is always recommended whenever tank and PMD solutions are not readily apparent. For example, the PMD for the upper fuel compartment of the tank shown in Figure 10 may be problematic, but the problems can be alleviated by reversing the common bulkhead for a smaller oxidizer compartment as shown in Figure 12. A properly conducted trade study will examine the many possible design variations to adequately address the challenges of designing tank/PMDs that are simple to manufacture, easy to operate, and meet all the mission requirements.

Figure 12: A Common Bulkhead Tank with a Smaller Oxidizer Compartment at the Bottom of the Tank



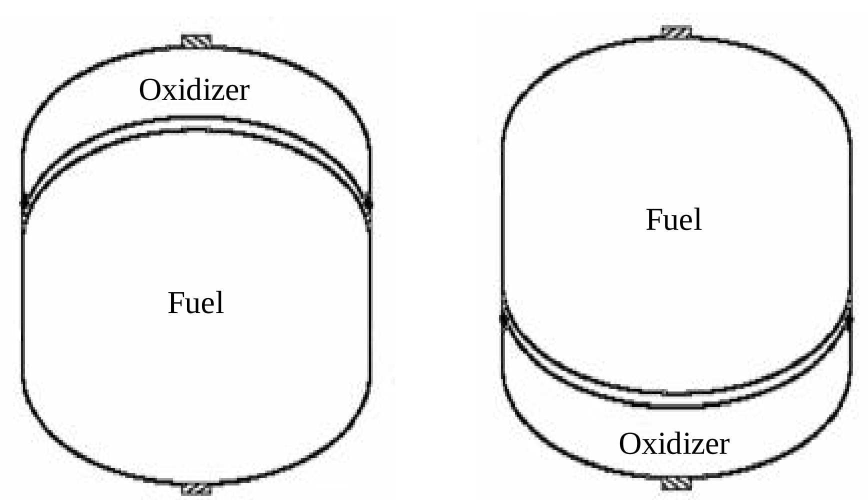
Because both compartments are pressurized, the primary design challenge of the common bulkhead is to prevent buckling, which will lead to a catastrophic failure of the satellite. The common bulkhead will be thick based on spacecraft pressure vessel standards. To reduce weight, isogrids that are extensively used on aircrafts and spacecraft structures are incorporated into the bulkhead structure. The technology does exist to design a common bulkhead that will not buckle. As in any spacecraft pressure vessel design activity, the real challenge is to generate a tank design with sufficient safety margin but without excessive mass penalty.

Common bulkhead tanks are in use for short duration launch vehicle flights. However, we are not aware of any common bulkhead tanks on long duration spacecraft missions. Although analytical techniques and manufacturing technologies are mature, the satellite industry is still unable or unwilling to accept the perceived risk of a common bulkhead tank for hypergolic propellants. The resistance to fly common bulkhead tanks based on "perceived risk" is not scientifically sound. As scientists and engineers, we must rely on experiment results and test data to make logical decisions. It is the authors' opinion that a common bulkhead tank can be designed and manufactured to the highest performance and reliability using the latest analytical tools and the current state-of-the-art manufacturing and inspection techniques, and its acceptance supported by qualification and acceptance testing.

NESTED TANKS

When the "perceived risk" of a common bulkhead tank is not acceptable but the severe height and space limitations remain a requirement, a nested tanks approach is one of the last remaining options. Nested tanks are two separate and distinct tanks nested in close proximity to each other, as shown in Figure 13. Although the two tanks do not share a common wall as in the common bulkhead tank, the heads adjacent to each other do share a similar contour. The two tanks can be integrated mechanically or welded together.

Figure 13: Nested Tanks



Nested tanks consist of a "typical" tank and an "irregular" shaped tank. The design and manufacture of the "typical" tank presents no new challenges. The design of the "irregular" tank with a concave head is similar to the design challenge of the common bulkhead. Similarly, the PMD design challenges are no different from those of the common bulkhead tank.

The combined mass of the nested tanks will be significantly higher than a common bulkhead tank of equivalent volume. The extra mass is contributed by the fourth head and the features required to integrate these two tanks. The nested tanks approach, however, does overcome the perceived high risk of the common bulkhead tank.

CONCLUSION

The three tank concepts discussed here – COPV propellant tank, common bulkhead tank, and nested tanks – are new tank solutions to some age-old spacecraft packaging problems. In this new age where tank packaging efficient is becoming more critical, the advancements in tank design and analysis tools and manufacturing and inspection technologies will enable us to design tanks that are compact, light weight, as well as reliable. Our true challenge today is to move beyond heritage and conventional approaches to solve the new difficulties facing the industry.

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