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Design and Fabrication Techniques for a Large Titanium 15-3-3-3 Propellant Tank

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Abstract

THE titanium industry has had only limited success in fabrication and assembly using the titanium alloy 15-3-3-3. Presented are the results of a program to design, fabricate, assemble, and test a large propulsion tank made from titanium 15-3-3-3. The propulsion tank, 75 in. in diameter and 106 in. in length, contains approximately 15,000 lb of propellants. The propellants are separated by a common bulkhead designed to be nonpressure-supported and to have no communicating welds to ensure no leakage between the fuel (monomethylhydrazine) and the oxidizer (mixed oxides of nitrogen). The propellant tank is the core structural component of a liquid stage envisioned for spacecraft using the space transportation system (STS) launch vehicle. The fabrication of the tank end domes and common bulkhead presented the greatest challenge. Different fabrication techniques considered for these domes were super plastic forming, closed hot die forging, cold spin forming, and explosion forming. Subscale pilot programs were conducted for explosion forming and spinning. A hot spinning operation was selected as the fabrication technique. This program has advanced the state-of-the-art and use of the titanium 15-3-3-3 alloy. The successful completion of the structural tests demonstrated structural adequacy and confirmed that titanium 15-3-3-3 could be used for large propulsion tank structures.

Contents

The central propellant tank, shown in Fig. 1, is composed of two cylindrical sections joined by an elliptical-separating bulkhead and capped on both ends by an elliptical-shaped dome.[1] The dome shapes are an ellipse with a dome height to radius ratio of $\sqrt{2}$. The $\sqrt{2}$ to 1 ellipse was chosen over spherical or other elliptical designs because it minimizes tank length thereby reducing STS launch costs. Furthermore, the $\sqrt{2}$ to 1 shape gives a constant pressure loading on the dome structure.[2,3] The radius of 37.5 in. (75-in. diam) and the cylinder lengths chosen accommodate 15,300 lb of propellant. For increase or decrease of propellant weight, only the cylindrical lengths need to be increased or decreased. Studies show the versatility of this design concept that allows for tank lengths for capacities ranging from 8000 to 23,000 lb.

The common bulkhead design was chosen by a study of different tank designs having a constant envelope.[2] Three different design concepts—common bulkhead, double bulkhead, and two separate tanks—were considered. The common bulkhead provided a clear advantage of delivering payload to orbit; the double central bulkhead resulted in 6% less payload to orbit, while the two separate tank concept resulted in 26% less.

The tank end-dome design has manhole covers to allow access into each tank for cleaning the inside and assembling baffles. (The baffles prevent fuel slosh in either a spinning or nonspinning mode.) The manhole covers are screwed onto the domes by using a new unique thread design as shown in Fig. 1, view A. To complete the tank, various propellant lines are required, such as outlets and gas ports, for the fuel and the oxidizer. Views B and C of the figure show the concepts for the common bulkhead and end dome weldments.

Material tradeoff studies for the central tank design among aluminum, stainless steel, and titanium showed a clear advantage to using titanium.[2,3] A review of potential fabrication techniques to be used on the domes and central bulkhead showed that titanium 15-3-3-3 was preferable because of its heat-treatable properties and its projected ultimate strength of approximately 180,000 psi. The heat-treatable property was attractive since after solution anneal, a liquid quench would not be necessary to achieve superior mechanical materials properties. The primary drawback of this material was that it has not been used much in industry, except in sheet metal applications, and, therefore, was relatively an unknown alloy. Therefore, forming, welding, machining, and defining mechanical properties would be a new experience.

One advantage of this tank design is that the end domes and the common bulkhead can be fabricated by the same technique. Final machining is used to distinguish the end domes from the common bulkhead. The fabrication methods investigated were super plastic forming, explosive forming, spin-

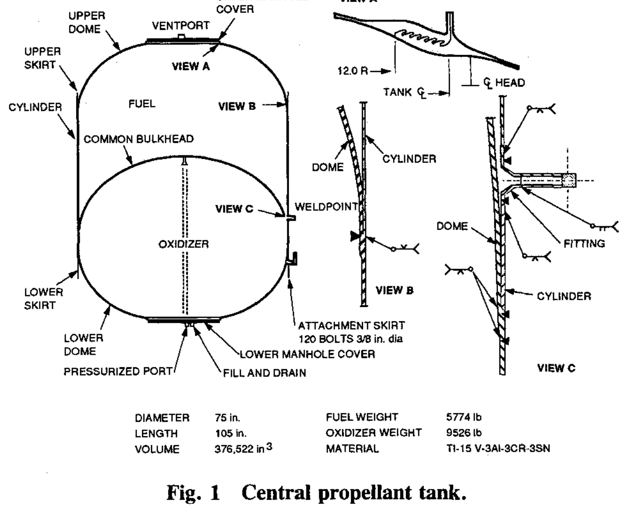

Fig. 1 Central propellant tank.

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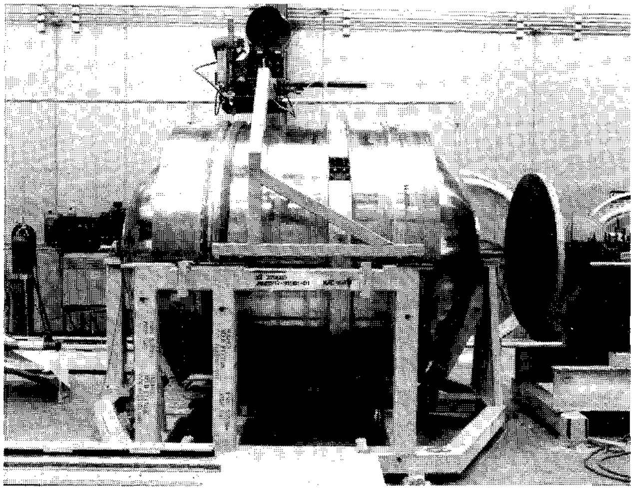

Fig. 2 Completed tank in weld fixture.

ning, spin forging, and forging for domes; and roll and longitudinal welding and roll-ring forging for cylinders.

Fabrication of the dome, because of its 75-in. diam, presented the greatest challenge. The advantages and disadvantages of the different fabrication techniques were investigated. The technical paper has some discussion on these techniques. The most promising techniques proved to be explosive forming and spinning: the hot spinning process was chosen for the dome fabrication.

The material for the full size tank required the use of the largest flat-rolled plates of titanium 15-3-3-3. The plates were 112–115 in. wide and required two thicknesses: 1) $\frac{3}{8}$ in. for the end domes and cylinders, and 2) $\frac{1}{2}$ in. for the common bulkhead. The plates were rolled and preliminary mechanical properties of the plates showed a grain size of 5, ultimate strength of 182,000–192,000 psi, and elongation of 9%. The plate material was cut into a disk of greater than 75 in. and placed on a spinning mandrel for the dome fabrication. The spinning process consisted of three separate steps. Each step entailed heating the disk and mandrel to a temperature in excess of 1200°F, while the machine tool was forcing the titanium material over the mandrel to make the required dome contour. After some trial and error, two full-scale domes were fabricated. The domes were trimmed and cleaned and then cut at various locations to make material property specimens.[4] Material properties and a weld program are discussed in the technical paper.

In the final tank assembly, the end domes were first welded to the fuel and oxidizer cylinders. The welds were X-rayed and dye-penetrant inspected. The brackets to hold the baffles for fuel slosh management were welded to the inside and outside of the common bulkhead and the inside of the fuel and oxidizer tanks. A cone assembly was also welded to the common bulkhead.

The next task was to clean the fuel and oxidizer tanks and the common bulkhead subassemblies. The fuel tank and the common bulkhead were then placed into the weld fixture and a closure weld fixture was installed in the common bulkhead. The third weld was to tack weld only the fuel cylinder to the common bulkhead. The fourth weld provided a complete closure weld of the oxidizer tank. The fifth weld completed the weld of the fuel tank to the common bulkhead. The completed tank in the weld fixture is shown in Fig. 2.

Upon completion of the tank assembly, the manhole covers were threaded onto the end domes and helium leak tests were conducted for the oxidizer tank welds and inside fuel tank for leakage through the common bulkhead. Finally, a leak test of the fuel tank was conducted. The tank assembly was then given a final age heat treatment. After aging, the aft skirt was trimmed and all skirt holes used to hold the tank to the liquid stage were drilled. The tank was then ready for testing.

A hydrostatic test of the completed tank was performed in August 1989. The tank was loaded with 1,640 gal (13,685 lb) of water. A trial run with 100 psig pressure in both the oxidizer and fuel tanks was successful. It was decided to go further to 150 psig. At approximately 140 psig, a manhole cover seal weld cracked, causing some water leakage (the manhole cover is held in the tank end dome with spherically designed teeth to take pressure loads and sealed to prevent leaking by an external weld). Since neither the fuel nor oxidizer tank had lost pressure, it was decided to proceed to the design maximum expected operating pressure of 260 psig. As the pressure was increased in each tank, the end dome and manhole cover teeth engaged to the point in which no leakage was evident. The tank reached 260 psig pressure without incident. A 5-min hold at 260 psig also elapsed without pressure drop. It was then decided to proceed to 275 psig. This, too, was accomplished and the pressure was held for 5 min. This ended the hydrostatic pressure tests since proof pressure and burst pressure tests were considered beyond the scope of this test program.

A separate collapse pressure test of the common bulkhead was also performed in the hydrostatic test configuration. The common bulkhead was subjected to its design pressure of 30 psig without incident. Further testing on this common bulkhead was accomplished without incident up to 45 psig. At that point, no further testing was done.

The successful completion of the above tests demonstrated the structural adequacy of the central tank design, manufacture, welding, and assembly.

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