Structural Verification of the Space Shuttle's External Tank Super LightWeight Design
- A Lesson in Innovation -

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Introduction

The Super LightWeight Tank (SLWT) team was tasked with a daunting challenge from the outset: boost the payload capability of the Shuttle System by safely removing 7500 lbs. from the existing 65,400 lb. External Tank (ET). Tools they had to work with included a promising new Aluminum Lithium alloy, the concept of a more efficient structural configuration for the Liquid Hydrogen (LH2) tank, and a highly successful, mature Light Weight Tank (LWT) program.

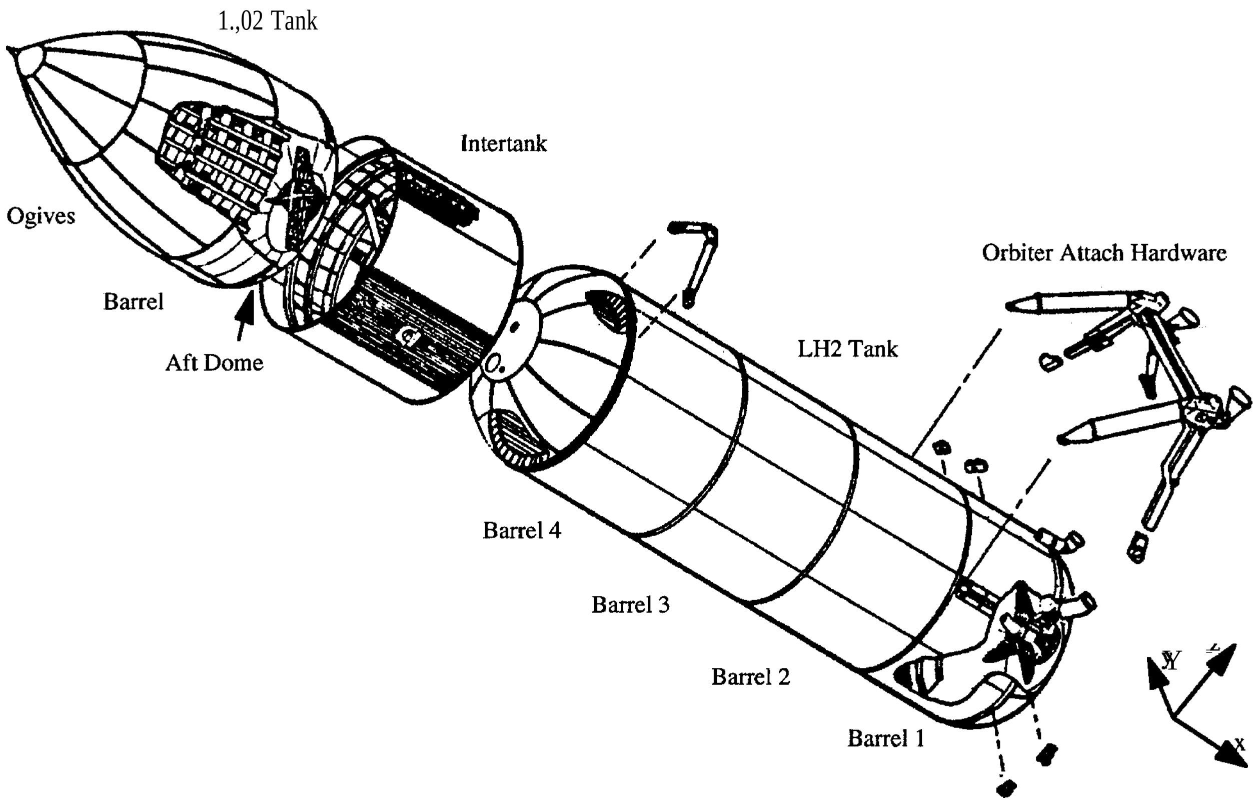

Figure 1. External Tank

The 44 month schedule which the SLWT team was given for the task was ambitious by any measure. During this time the team had to not only design, build, and verify the new tank, but they also had to move a material from the early stages of development to maturity, The aluminum lithium alloy showed great promise, with an approximately 29% increase in yield strength, 15% increase in ultimate strength, 5°/0 increase in modulus and 5°/0 decrease in density when compared to the current 2219 alloy, But processes had to be developed and brought under control, manufacturing techniques perfected, properties characterized, and design allowable generated. Because of the schedule constraint, this material development activity had to occur in parallel with design and manufacturing. Initial design was performed using design allowable believed to be achievable with the Aluminum Lithium alloy system, but based on limited test data. Preliminary structural development tests were performed with material still in the process of iteration. This parallel path approach posed obvious challenges and risks, but also allowed a unique opportunity for interaction between the structures and materials disciplines in the formulation of the material.

While the change from 2219 Aluminum to 2195 Aluminum Lithium for the pressure vessels, i.e. liquid hydrogen (LH2) and liquid oxygen (LO2) tanks, was the primary weight savings tool, it was not sufficient by-itself. Additional changes made in order to achieve the required weight savings included: use of Aluminum Lithium 2090 for the mechanically fastened skin-stringer panels in the Intertank, optimization/machining of the Thermal Protection System (TPS) foam, optimization of the monocoque thickness on the LO2 tank barrels and ogives and the LH2 tank forward and aft domes, optimization of the LO2 aft dome, and, the most significant structural design change, redesign of the LH2 barrel panels from a skin-stringer configuration to an orthogrid stiffened configuration.

Structural Verification Approach

These changes presented the structural verification team with the challenge of defining a structural verification program which protected the flight safety of the Shuttle program, yet met the program's stringent cost and schedule constraints. The team had established the ground rule that all structural verification would be tied to either a test, or flight history of the current LWT. Obviously the technical ideal was a program similar to the original ET verification program, with dedicated structural test articles (STA's) for each major element, i.e. LH2 tank, LO2 tank and Intertank. This approach however, was not feasible given the program's constraints. The question then became, "What tools do we have available for verifying the structure, and how can we make the best use of them?". This question led the team into one of the most innovative structural verification programs ever defined.

The team began by looking at each structural subassembly and their failure modes. An example of this would be barrel 4 of the LH2 tank which exhibits the following critical failure modes: strength in proof, stability of the +Z axis during liftoff and post-staging, stability of the $\pm$ Y axis during liftoff, and stability of the -Z axis during prelaunch. Each of these failure modes had to be verified by a test. As the team worked their way through the structural subassemblies, a program took shape which included a variety of elements: subassembly component testing, maintaining Standard Weight Tank (SWT) or LWT thickness and design, independent structural analysis, proof testing of the LO2 and LH2 tanks, protoflight testing of the LH2 tank, and testing of a dedicated Aluminum Lithium Test Article (ALTA).

Existing Data Base and Design Ground Rules

The obvious advantage that the SLWT verification team had was the wealth of test and flight data from the original SWT and the current LWT. Although many things were changing for the SLWT, many things remained the same. Outer mold line, interface hardware, and load introduction points were unchanged. And although some loads did increase due to other performance enhancements on the Shuttle System - most notably the change from 104°/0 thrust to 106°/0 for the Space Shuttle Main Engines (SSME's) - the load mix was not significantly changed. The team utilized this data base in developing the verification plan. An example of this was the ground rule for maintaining equal or greater stiffnesses in the LH2 tank ringframes. The testing that was performed on the SWT showed that the ringframes were large enough to enforce nodes, and that general stability of the LH2 tank across ringframes was not a critical failure mode. Although some chords were changed from 2219 to 2195 and some web thicknesses reduced, the chord and frame geometry's were maintained, resulting in equivalent or, taking into account the increased modulus of 2195, greater frame stiffnesses than in the LWT. This allowed the team to concentrate on panel stability of the orthogrid design vs. general instability of the LH2 tank. The team also fell back on the existing data base in areas where a test was not feasible. An example of this was the LO2 tank aft ogive regions critical for flight stability. The only technically adequate test for these regions would be a test of a complete LO2 tank; a prohibitive test from both the cost and schedule standpoint. In these regions the membrane thicknesses were maintained at the LWT thicknesses, even though analysis showed that a reduction in thickness was possible. In this way the capability of the SLWT LO2 tank for this failure mode was maintained at better than the LWT capability because of the increased modulus of 2195.

Subassembly Component Testing

The subassembly component tests allowed the team to target a specific design or material change with a test. An example of a subassembly component test was the Intertank skin-stringer/j oint compression tests. Two of these articles representative of different areas of the Intertank were tested; both having .080" thick 2090 Aluminum Lithium skins, but one demonstrating the .063" thick 2090 formed stringers and the other demonstrating the .080" thick 2024 extruded stringers. The test articles were 137.5" long and 33.24" wide and included the skin panel, five hat stringers, two end chords, and two intermediate frames. The articles were mounted in a test fixture and the aft ends deflected radially .625" to simulate the cryogenic shrinkage of the LH2 interface. The aft end was chilled with LN2 to -320° F and an axial compressive load was applied. The articles were loaded to failure, and in both cases, successfully carried the required ultimate load. In all, 13 different subassembly tests were performed, many with two or more articles of different configurations. Additional examples are: Intertank intermediate frame beaded web tests - one with ,025" thick web and one with .032" thick web, LO2 slosh baffle web test, and a cryogenic environments test which subjected a section of the LH2 barrel panel design to hi-axial stresses at -423° F.

The subassembly component testing also highlights an important philosophy which was implemented on the SLWT structural test program. This was: all structural testing which utilized a dedicated test article would be performed to failure in order to find the true capability of the hardware. Test to failure was considered important for a number of reasons. First it protected the program in the event of loads increases, If load increases were proposed, and analytical margin was available which would allow the higher loads to be accepted, the hardware would still be adequately test demonstrated. Second, the data from the instrumentation and final failure load could be used to correlate and refine analysis methods. This had implications not just for the SLWT program but also for future programs. And third, it was recognized that with new designs, and particularly with a new alloy, failure modes and characteristics may be different, It was deemed important to know not just the load at with the structure would fail, but also the manner in which it would fail. This is particularly true given the laminar nature of the short transverse direction of the aluminum lithium alloys. Strict attention was given to looking for any coupling of failure modes.

Independent Analysis

The ground rule was to base all structural verification of the SLWT on test. However this ground rule was deviated from in two areas. The deviations were allowed on a case by case basis, and with additional requirements imposed. The structures which deviated from the ground rule were required to maintain an analytical factor of safety of 2.0 versus the normally required factor of safety of 1.25 to 1.4 for the SLWT. An additional, independent analysis of the hardware was also required. The two areas which were allowed to deviate from the test ground rule were the LO2 tank aft ogive and barrel in areas critical for unpressurized pre-launch stability, and the aft end of the intertank thrust panel which is critical for staging stability. In both cases the original LWT design and thicknesses resulted in high factors of safety, and the structures team was confident that the thicknesses could be reduced safely, The structure was resized by Lockheed Martin (the External Tank prime contractor) maintaining a factor of safety of 2.0. Independent analyses were then performed by Marshall Space Flight Center (MSFC) for the Intertank thrust panel, and by Langley Research Center (LaRC) for the LO2 tank, to verify the analytical factors. Confidence in the analyses was gained by correlation to test data. The aft end of the Intertank thrust panel was tested to failure under axial loads. This data was used to correlate the models and provided complimentary rationale for verification of the redesign. The LO2 analysis was correlated by analyzing the buckling of the LO2 tank forward ogive which occurred during testing of the original SWT Ground Vibration Test Article (GVTA). The analysis accurately predicted the location of the buckle, at the proper load level with a reasonable imperfection.

Proof Tests

Both the LO2 and LH2 tanks have always undergone proof tests on the SWT and LWT programs, and proof testing will continue for the SLWT program. The LO2 tank proof test is a room temperature hydrostatic test with the addition of a vacuum under the aft dome to increase the delta pressure on the dome. The LH2 tank proof test is a room temperature GN2 test with mechanical loads applied to the Orbiter and SRB attach points at the aft end of the tank. These loads are reacted by a load head at the front of the tank. Because the proof pressures and loads are determined based upon fracture mechanics considerations, and the strength increase is greater then the fracture toughness increase for cryogenic flight temperatures, the room temperature proof tests result in a strength demonstration above limit load. The verification team determined that the minimum test demonstrated factors of 1.12 for every LH2 tank and 1.17 for every LO2 tank, adequately verified the strength of the pressure vessels.

LH2 Tank Stability Verification

The major change for the SLWT occurred in the LH2 tank. Although the ringframe stiffnesses and the longerons which transfer the Orbiter loads into the tank were unchanged, both the configuration of the barrel panels and the material were changed. The material was changed from 2219 to 2195, and the design from a skin-stringer stiffened structure to an orthogrid. The orthogrid design also varied around the circumference of the tank, with different pocket sizes and rib heights resulting in three basic panel designs. The loading of the LH2 tank also varies; including axial load, bending moment, and shear, as well as concentrated loads from the Orbiter and Solid Rocket Boosters (SRB's). While the strength of the LH2 tank was adequately demonstrated in the proof test, stability of the LH2 tank's various panel configurations with the appropriate load profiles also had to be verified. Two test programs were used to verify the stability of the LH2 tank: protoflight testing of each LH2 tank, and a dedicated Aluminum Lithium Test Article (ALTA).

Protoflight Testing

Protoflight testing consists of two test conditions. One protoflight test case was configured to demonstrate stability of the longeron regions in barrels 1 and 2. The testing is performed in the proof test facility, which has the capability of imposing mechanical loads into the tank at the Orbiter and SRB attach points. As an ultimate demonstration of stability is not possible without over stressing the tank and making it unusable for flight, the testing is performed to 115% of flight limit load. In addition to the protoflight test case for stability of barrels 1 and 2, a test case for stability of the aft dome is also performed. The critical load case for the aft dome is driven by the "pinch" loads induced by the rigidly held SRB's as the LH2 tank is filled and the tank attempts to shrink to a smaller diameter. One hundred and fifteen percent of these "pinch" loads are applied during the protoflight testing. The protoflight stability tests will be performed on every LH2 tank.

The protoflight testing highlights another philosophy incorporated by the verification team. Additional risk to the Shuttle during flight was not an option. Confidence in the structural integrity of the vehicle had to be secured in the verification program. The protoflight testing for the SLWT does represent some additional risk to the program when compared to the LWT testing; that being increased risk of losing the LH2 tank and proof facility. But the risk is confined in the ground testing.

The ALTA

The most innovative element of the SLWT structural verification program was the ALTA. The primary purpose of the ALTA was to demonstrate the ability of the orthogrid panel configurations to withstand the SLWT ultimate loads. However the team pushed far beyond that basic goal.

Figure 2. shows the basic configuration of the ALTA. The barrel is representative of barrels 3 and 4 in the LH2 tank and contains the three basic orthogrid configurations. These orthogrid configurations are also representative of the panels on the -Z axis of barrels 1 and 2 (the opposite side of the tank from the longerons). Therefore, between the protoflight test and the ALTA, the entire LH2 tank is demonstrated. Also included on the ALTA was an aft dome from the LO2 tank. The SLWT team had identified the possibility of additional weight savings from the LO2 tank aft dome if a test could be performed. However, a test of the type needed had never been performed before. The LO2 aft dome is stability critical during the end of flight when the Shuttle is accelerating

at 3 g's and the LO2 surface level is falling through the dome, This induces hoop compression in the dome and drives the critical stability margins. To test the dome to the required ultimate condition required a fluid with a specific gravity of 4.2, or 35 lb./gal. This fluid would have to be pumped into the tank against the stabilizing pressure and then flow back out of the tank. A fluid which would meet these requirements had never been made before. After preliminary conversations with people in the oil drilling industry, the challenge was accepted and a lighter redesigned LO2 tank aft dome was included on the ALTA. The ALTA pressure vessel was completed with a 2219 LWT LH2 forward dome. With the ALTA the team had designed a test article which verified major portions of not just one, but two of the SLWT pressure vessels, as well as accepting the challenge to push the boundaries of test technology.

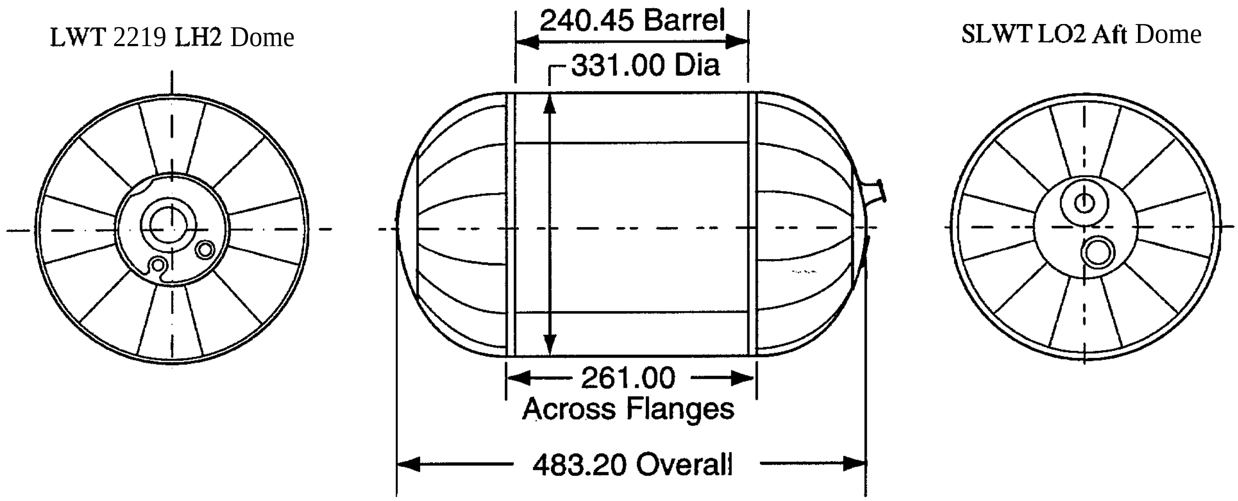

Figure 2. ALTA configuration

The team knew that the program had only one dedicated structural test article, and that they had to glean all the information possible from it. Therefore, the testing of the ALTA was designed not just to qualify the hardware, but to maximize the knowledge gained. The testing started with a pneumatic proof test performed at the Michoud Assembly Facility (MAF) in New Orleans where the ET's are built. The ALTA was then sent to the Marshall Space Flight Center (MSFC) for structural testing. The testing was performed in a refurbished Saturn test stand which was capable of applying axial loads, bending moments, and shears, as well as pneumatic pressurization. The ability to fill the LO2 aft dome with water and the High Density Fluid (HDF) was also provided.

Structural testing was performed over a period of three months and started with the application of influence loads. Axial load, bending moments, and shears were applied one at a time to check that the response of the structure was as predicted, and to verify the instrumentation. A radial load was also applied to the barrel panel at the LO2 feedline support fitting to verify the transverse stiffness of the barrel panel. Application of limit load cases were then started.

As stated previously, barrel 4 of the LH2 tank was subject to 4 failure modes. The strength failure mode had already been tested during the proof test at MAF. The three stability cases were tested on the ALTA at MSFC. By applying the appropriate combinations of axial, shear, and moment, the critical load cases were tested for the +Z, -Z, and ±Y axis panels. First, all three cases were tested to limit flight loads, and then all three were performed to the ultimate flight loads. With the conclusion of the ultimate flight cases the LH2 orthogrid barrel panels - with the exclusion of the barrel 1 and 2 longeron region which are verified in the protoflight testing - were fully verified.

With the verification of the LH2 barrel completed, testing was performed on the LO2 aft dome. The dome was first filled with water to simulate a proof test fill condition. The dome was then tested with the HDF. This test was believed by many to be the riskiest test performed in the SLWT program, not from a SLWT structure viewpoint but from the viewpoint of the ability to perform the test. The Baroid Company was under contract to provide the fluid, pump it into ALTA and then drain it. The fluid used was a mixture of water, a polymer suspending agent, and steel fines. Challenges encountered with the fluid were: the mechanism needed to mix the fluid, the equipment needed to pump it, and it's ability to flow out of the tank. Working together, NASA, Lockheed Martin, and the Baroid Company met these challenges with the use of concrete trucks, a concrete pump, and the injection of air into the drain line. With these challenges met, the HDF test of the LO2 aft dome was successfully performed. Both the dome and the test set-up performed as expected.

With the completion of the barrel panel tests and the LO2 dome test, the ALTA had performed it's function of verifying the appropriate SLWT hardware. However, the verification team maintained its commitment to gain all the information possible, and to test to failure. In fact, not just one, but three capability tests were performed on the ALTA barrel panels. The liftoff capability test was performed first and the ability of the barrel panel to both carry additional mechanical body loads, and remain stable with decreased pressure was demonstrated, The mechanical body loads were first increased to 125% of the ultimate ,or 175% of the limit, design loads. The body loads were then decreased to the ultimate loads and the pressure decreased. Next, the prelaunch capability test was performed. As the prelaunch case was an unpressurized condition, the case consisted of demonstrating the mechanical loads to 125% of the ultimate, or 162°/0 of the limit, load case. The final capability case was the Post Staging load case. The mechanical loads were first increased to 11 5°/0 of the ultimate, or 146°/0 of the limit, design load condition - the capability of the test stand. The mechanical loads were then decreased to ultimate and the pressure decreased from the design pressure of 31.8 psi. The structure performed linearly until approximately 20 psi, at which time non-linearity was observed in the strain gage readings. Final collapse occurred at ultimate loads and 9 psi pressure. The testing proved the robust design of the orthogrid barrel panels, as well as providing insight into the failure mechanisms of the 2195 Aluminum Lithium. Table 1 shows the load conditions which were tested to capability.

Flight Condition	Design Ultimate Load Condition		Capability Load Condition	
	Pressure (psi)	% of Limit Body Loads	Pressure (psi)	% of Limit Body Loads
Liftoff	17.6	140	17.6 9.6	175 140
Prelaunch	0.0	129.5	0.0	162
Post Staging	31.8	126.5	31.8 20.0 * 9.0 **	146 126.5 126.5

* Denotes approximate condition at which non-linearity was observed in" the gages.
** Denotes condition at which final collapse occurred.

Table 1. ALTA capability conditions

Conclusion

The SLWT verification team was handed the challenge of assuring the adequacy of the SLWT structure to safely perform it's mission. They met that challenge and more. They demonstrated the ability to bring together a verification program utilizing a combination of current data bases, design ground rules, analysis, component testing, protoflight testing, and innovative, cost effective, dedicated structural test articles. They pushed the state of the art of test technology. They looked beyond the current program requirements and expanded the data base in structures technology, They looked to the future and squeezed all the information possible out of each test. They performed their task and more.