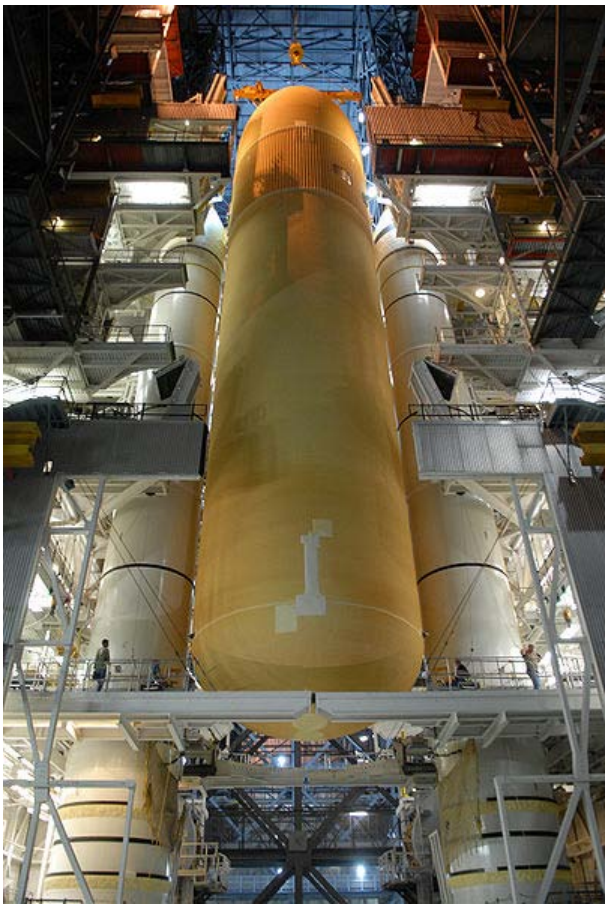
Super Lightweight Tank Risk Management Case Study



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Introduction to: "Super Lightweight Tank: A Risk Management Case Study"

Mass reduction to optimize performance has always represented a goal in the design of transportation systems from bicycles to automobiles to aircraft and especially space systems. For the Space Shuttle Program (SSP), mass reduction was a significant goal throughout the design, development, and operations of nearly every element. Mass is critical because it is directly coupled with lift capability. Lift capability determines *when* the Shuttle can launch, *where* it can go, and *what* it can carry. Less mass in the system means increased performance through increased lift or increased Shuttle payload. This case study explores the development of the Super Lightweight Tank (SLWT) and challenges participants to identify, analyze, and develop mitigation plans for the risks facing the management team on this project.

Background: Global Political Factors Set the Stage

In June 1993, amidst serious consideration by the United States (U.S.) Congress to cancel the almost decade-long space station program, the Vest Committee, chaired by MIT's Charles Vest, and chartered by the White House to explore redesign options, urged that the station be launched into a "world orbit" so that that Russian, Japanese, and Chinese launch vehicles and spacecraft could reach the station. On September 2, 1993, representatives from the U.S. and Russia officially signed the *Joint Declaration on Cooperation in Space*, paving the way for a massive, unprecedented partnership to complete and operate the International Space Station (ISS) in an orbital plane tilted 51.6 degrees from the equator. Implicit in this agreement was the assumption that the Space Shuttle would find a way to achieve a significant increase in lift capability.

Increased Lift Capability Necessary

Beginning in December 1997, the primary objective of the SSP was to support the assembly of the ISS. Of the 34 planned primary SSP payloads, 27 were ISS-related. The increased lift capability needed for the Space Shuttle to reach the higher orbital inclination of the ISS was estimated at 13,500 pounds according to the most up-to-date calculations (at the time) from the SSP Office.

Both the Orbiter and the External Tank (ET) were primary targets for mass reduction efforts because a pound saved would translate directly to a pound of payload gained. On the other hand, since the Solid Rocket Boosters [(SRBs) while by far the heaviest component] only participate in the first 2 minutes of launch, it takes 10–11 pounds of savings to gain 1 pound of payload. The ET was the clear choice for the needed weight reduction.

The ET Project team had previously identified a number of optimizations that would reduce mass by several hundred pounds. The ET, however, needed a mass reduction in the thousands of pounds dictating consideration of a redesign.

Standard Weight Tank (SWT)

The first flight-ready ET was the Standard Weight Tank (SWT) that weighed 77,100 pounds dry and flew in April 1981 on STS-1, the first Space Shuttle mission (see Figure 1). The ET on STS-1 was also referred to as SWT-1. Weight-saving measures were already going into effect by STS-3, which flew less than a year after STS-1. SWT-3 saved 600 pounds by simply not painting the tank white, leaving its "natural" orange-brown color. SWT-4 saved another 600–700 pounds by eliminating the anti-geyser line used to expedite filling the Liquid Oxygen (LO2) Tank.

Figure 1. STS-1

Lightweight Tank (LWT)

In truth, NASA had never actually stopped looking for weight savings on the ET. In 1979, before even the first Shuttle flight, NASA had already identified the future need for increased payload launch capability for the Galileo mission. NASA returned to Martin Marietta, who designed and constructed the SWT, and commissioned them to build a Lightweight Tank (LWT) to be 6,000 pounds lighter for $45 million. In September 1982 (and one day ahead of schedule), Martin Marietta delivered the LWT for use on STS-6 in April 1983, having reduced more than 10,000 pounds for only $43 million. Table 1 summarizes the LWT modifications. The reductions were so successful that the LWT actually included hundreds of pounds of added structural support to the LO2 Tank and aft dome to enhance overall performance.

Table 1:	Light Weight Tank (1983 - 1998) Modifications
Design	Pressurization system redesigned so a single valve failure would no longer raise the pressure above the control band, allowing a thinner LH2 Tank.
	Exterior was no longer painted white.
Materials	7079 Aluminum (Al) upgraded to 7050 Al.
	5-2.5 Titanium (Ti) upgraded to 6-4 Ti.
Functional	Removed anti-geyser line.
Margins	Reduced margins on structural, load bearing parts.
	Instead of using a universal Factor of Safety (FoS) of 1.4, FoS was reduced to 1.25 where possible.

Super Lightweight Tank (SLWT)

When LWT was delivered, the ET was considered to be about as lean as possible, with only a few hundred pounds of optimization left. But not long afterwards, Martin Marietta produced an unsolicited proposal for an even lighter ET based on a few major redesigns. This redesign was called the Super Lightweight Tank (SLWT). Figure 2 shows a summary chart of this proposal. The most significant suggestion was the replacement of the traditional aluminum-copper (Al-Cu) alloy with an experimental aluminum-lithium (Al-Li) alloy that had been demonstrated to be both lighter and stronger. This single upgrade was predicted to save 4,889 pounds. Second was the use of a novel orthogrid structure in the design of the Liquid Hydrogen (LH2) Tank panels. The orthogrid is a waffle-like pattern allowing selective reinforcement to specific areas that require more strength while paring down the areas that do not. This orthogrid would save an additional 2,747 pounds. A Variable Output Proportioning System (VOPS), which modulates the foam spray, combined with Thermal Protection System (TPS) machining used to control the thickness of the foam would reduce a final 367 pounds. In total, this amounted to slightly more than 8,000 pounds of proposed weight savings on a new ET.

Martin Marietta's Proposal for the Super Light Weight Tank

	(ET-71)*	Proposed Weight-Saving Changes				*(predicted)*
Part(s)	LWT	Al-Li	VOPS	Machined TPS	Orthogrid	SLWT
LO2 Tank	12,667	-1,700	-16	--	-75	10,876
Intertank	12,885	-479	--	-271	-179	11,956
LH2 Tank	29,458	-2,710	-80	--	-2,493	24,175
Other	10,439	--	--	--	--	10,439
Total Dry Weight	65,449	-4,889	-96	-271	-2,747	57,446

**Martin Marietta's proposal was based on a predicted ET-71 weight allocation. The actual ET-71 flew at 65,767 lb.*

Figure 2. Proposed weight-savings (in pounds) for each component of the LWT's upgrade to the SLWT.

Al-Li Advantages and Technology Readiness

At about 2.5 times the cost, the Al-Li (Al 2195) was predicted to be 40% stronger and 10% less dense than the Al-Cu (Al 2219) currently in use. Laboratory tests have also shown Al 2195 to exhibit anisotropic mechanical behavior compared to isotropic Al 2219, meaning that Al 2195 may behave more like a composite at times than a homogenous material. It would put the ratio of the ET structural weight to the weight it carries at about 1:27. The standard weight-to-cargo ratio for a pickup truck is 3:1.

An important development was the invention of Weldalite® in 1986, a weldable, cryogenic friendly Al-Li alloy. Previously, the combination of these two elusive properties was unattainable by Al-Li projects in the U.S. that had been abandoned multiple times as far back as 1950. Encouraged by this development, Martin Marietta successfully welded a prototype ET "quarter dome" out of three dome gores and a chord (which attaches the dome to the barrel) made of Al 2195, one of the formulations of Weldalite®. A subsequent Marshall Space Flight Center (MSFC) study analyzed these results and concluded that the use of Al-Li to construct the ET seemed possible.

At the same time, MSFC investigated the use of an orthogrid design (a waffle-like grid) for use in tank panels. MSFC hoped to leverage research conducted by McDonnell Douglas on a similar isogrid design (triangular-shaped grid), which they had flown successfully. The upgrade from Al 2219 to the higher strength Al 2195 would allow the use of the orthogrid resulting in a weight savings when compared with either the current "T stiffener" or isogrid designs.

While there were still risks involved with the VOPS and TPS machining processes, both of these techniques were well-understood, and the ET team seemed unconcerned with any threats to the success of those modifications. The proposal offered delivery in 48 months, which would coincide exactly with the December 1997 target deadline. That proposed delivery date did not leave any room for schedule slip, but Martin Marietta had been able to produce the very first SWT from scratch on a similar schedule. Overall, the ET team expressed confidence in the SLWT plan.

Design Verification Complexity

The aerospace engineering / systems engineering best practice is to verify new designs by test whenever possible. This philosophy extends from components to subsystems to major elements to the integrated system. This paradigm is codified in the principle of Test-Like-You-Fly (TLYF), formally adopted by most aerospace system developers. In cases where verification-by-test is not feasible, alternative methods are used. The SLWT program was compelled to employ alternative methods for system-level verification and also in three subsystem cases (e.g., LO2 tank barrel, LO2 tank aft ogive, and aft end of inter-tank thrust panel). Verification methods included a combination of analysis, subscale test, heritage (existing flight and test data), and simulation modeling. It is important to note that "alternative method verification" always includes embedded risks where one is dependent upon: 1) fidelity of analyses, 2) goodness of modeling assumptions, 3) absence of unknown synergistic effects, and 4) applicability of component testing data.

Case Study Challenge

As the ET Project manager, you must present your plans for mass reduction to the SSP Office by the end of the month, and currently the SLWT is your only option. You will be expected to provide a rigorous assessment of risks that may be associated with the ET design modification considering, as a minimum, material availability, production quality, manufacturing issues, and most importantly – design verification approaches.