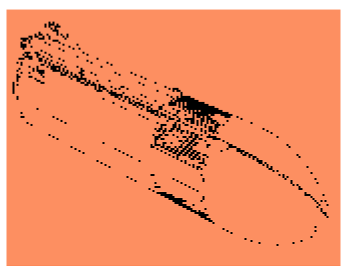
This document contains excerpts from the SLWT Independent Assessment Report (title page shown below). Only those sections which relate to the PBMA element **Manufacturing** are displayed.

The complete report is available through the PBMA web site, Program Profile tab.

Space Shuttle Super Lightweight Tank (SLWT) Independent Assessment of Risk Management Activities



NASA Office of Safety and Mission Assurance
December 12, 1997

SLWT - Summary of Major Changes from LWT

optimize TPS application

2195 Al-Li for 2219 Al

2090 Al-Li for 2024 and 7075 Al
Intertank thrust panels remain 2219, a decision based on the knowledge that thick plate , 2 1/2 to 3 inches, (2219 or 2195) is intrinsically difficult to work with. Decision to maintain status quo eliminated potential cost/schedule & technical risk

2195 Al-Li for 2219 Al

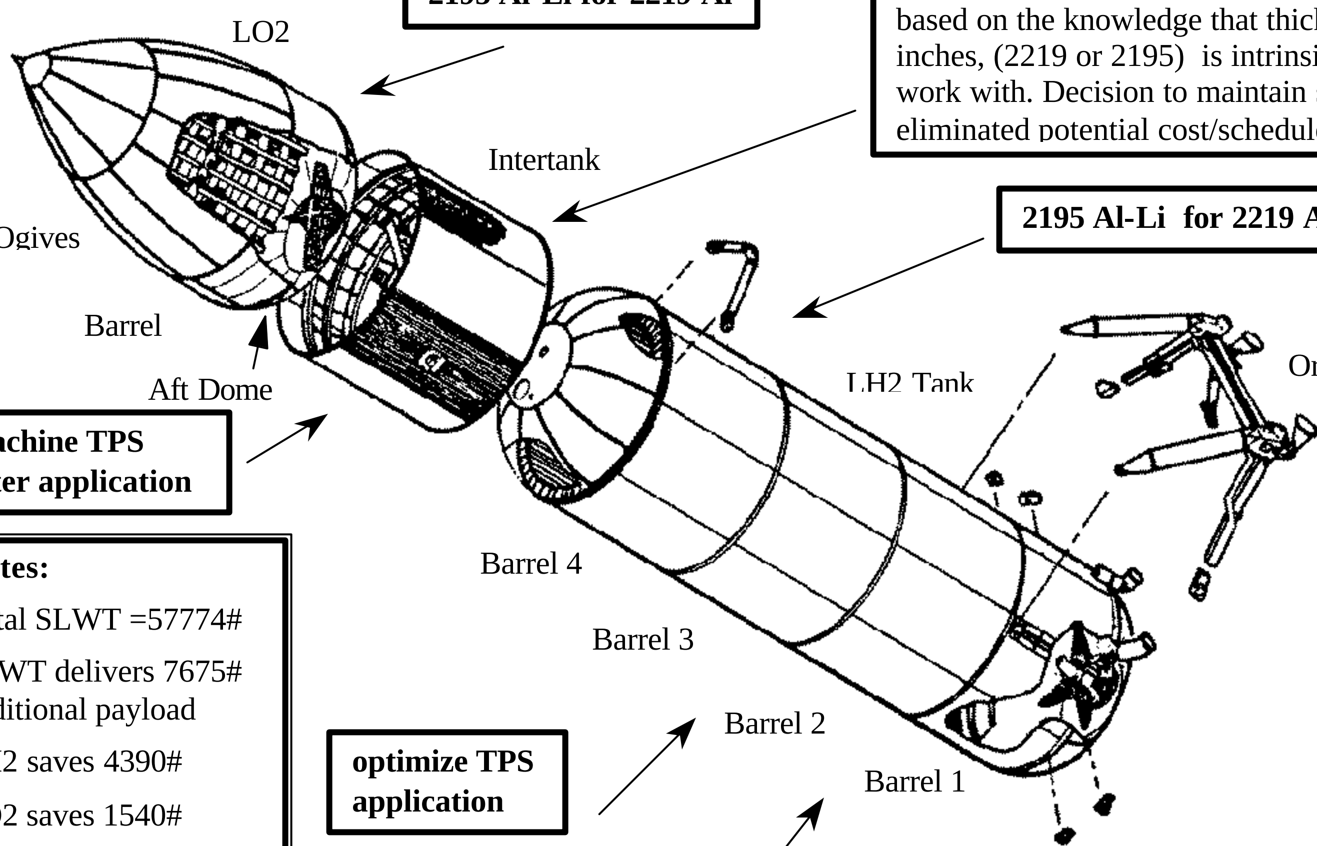


Figure 2.1

machine TPS after application

Notes:

Total SLWT =57774#

SLWT delivers 7675# additional payload

LH2 saves 4390#

LO2 saves 1540#

Intertank saves 669#

TPS saves 699#

Misc savings 377#

optimize TPS application

orthogrid structure replacing skin & stringer construction

Welds
3000 feet of welding on each tank
Weld land thickness from t=0.140” to 1.00”

3.1. Issue: Parent Material Properties

Comparatively limited knowledge of 2195 material characteristics and weldability (including repair) created a challenging development program. It was necessary to confront and address one technical issue after another, in parallel with design and manufacturing development activity. Parent material issues included manufacturing variation and instability, fracture toughness and lowered properties in the short transverse direction.

3.1.1 Mitigation Approaches

Acceptance Testing

Rigorous material acceptance testing approaches have been implemented which incorporate ultrasonic testing (particularly important for detecting laminar flaws, i.e. volumetric flaws parallel to surface) of all material raw stock, as well as strength, conformity (to specification requirements) and fracture acceptance testing on every lot.

Fracture Control (Testing to Verify Flaws Will Not Propagate)

Each lot of 2195 aluminum lithium undergoes "simulated servicing testing" in which a flaw of known size (length and cross-section) is introduced into a standard ASTM, four inch coupon and subjected to tensile loading as follows; 1) load to 100% proof stress (just short of yield) at room temperature, 2) load to tanking/pre-launch stress levels for seven cycles at cryogenic temperatures (liquid nitrogen bath), at 85% of proof stress, 3) load to flight stress levels at cryogenic temperatures (to demonstrate cryogenic strength enhancement) at 104.8% of proof, 4) repeat items 2) and 3) three more times. The sample is then pulled to failure and must pass the specification requirements. This procedure reflects the requirement for the SLWT to be capable of four full mission lives.

Inspection

In addition, a requirement was imposed for dual inspector dye-penetrant inspection of all parent material and formed parts, conducted by Level III inspectors (highest qualification). The inspection procedure for parent material was subsequently eliminated based on extensive inspection history that failed to identify any defects that would represent a safety of flight concern. The decision to eliminate this particular inspection was reviewed and approved by the MSFC Fracture Control Board.

3.1.2 Independent Assessment of Mitigation Approaches

Aerospace Safety Advisory Panel

The ASAP provided periodic oversight of SLWT program developmental issues. The following paragraphs provide insight to the rigor of the ASAP review activity.

ASAP 1996 Annual Report Finding 16 / Recommendations 16a-c

Finding 16

The 2195 aluminum-lithium alloy used in the tank walls and domes of the new SLWT has lower fracture toughness at cryogenic temperatures than was anticipated in the design. To compensate for this potentially critical shortcoming, NASA has limited the pressure used in the full tank proof test and has recognized that the acceptance of each SLWT for flight is highly dependent on the far more stringent quality control of the material and processes used to manufacture the SLWT than is required for the current external tanks.

Recommendation #16a

Assure that the acceptance tests for the 2195 material and the quality control procedures used in the manufacture of each SLWT continue to be sufficiently stringent, clearly specified, conscientiously adhered to and their use unambiguously documented.

NASA Response

The Space Shuttle Program (SSP) and MSFC will continue to ensure that material acceptance testing and quality control procedures used in manufacturing of SLWT's are of sufficient quality to validate that each tank is fully in compliance with all program requirements and is safe to fly.

Recommendation #16b

The criticality of these quality control operations makes it mandatory for NASA to retain buyoff of the results of those fabrication operations and tests that are essential in determining SLWT safety.

NASA Response

The SSP and MSFC will retain approval of the quality control program and changes to that baseline.

Recommendation #16c

As quality control data on the size of flaws detected in 2195 materials are collected, they should be used in an updated analysis of the SLWT structure, because it may permit the verifiable spread between flight limit stress and proof stress to be raised above that presently reported.

NASA Response

The simulated service database has been developed from data collected on fracture specimens with flaws that are 0.175 inch long. The data verify a 2.9 percent positive spread between the flight and proof-test conditions. Using the demonstrated flaw detectability level for our nondestructive evaluation dye penetrant process (0.086 inch long) would increase the spread to approximately 14 percent. Because of uncertainties, it is NASA's standard policy to use a factor of two on our flaw detectability limit. This methodology provides the proper risk allocation between nondestructive evaluation capability and proof test levels. The use of a flaw size of 0.175 inch for the simulated service test is conservative for the SLWT.

The ASAP report continues: "NASA is taking extra precautions to assure that errors in manufacture can be detected. For example:

- Each sheet and plate of procured 2195 aluminum lithium material is inspected by ultrasound at the vendor, where flaws as small as 0.047 inch can be detected, and a flaw of 0.078 inch is cause for rejection. (<u>OSMA Note:</u> Any detectable flaw is cause for rejection).

- Before and after forming, (<u>OSMA Note:</u> As mentioned above dye penetrant inspection is now performed only after forming) the entire surface of each tank element is subjected to dye penetrant inspection with two pair of experienced and qualified eyes looking for flaws. Flaws as small as 0.086 inch have been shown to be detectable. Any detected flaw is cause for rejection."

All ASAP recommendations have been fully implemented and members of the ASAP team supporting the SLWT Design Certification Review on September 28, 1997 expressed satisfaction that the design is safe and the program is prepared to proceed. It is worth emphasizing that ASAP has consistently voiced concern that the SLWT program must remain vigilant in assuring flight critical manufacturing process control (1996 Annual Report):

"Obviously, strict adherence to established procedures is required at every step of this process. Once successful, complacency cannot be tolerated in the production of subsequent tanks"

<u>Verification Team</u>

The Verification Team has also been heavily involved in parent material issues. Chapter 2 of the Odom Report, ("Final Report of the Super Lightweight Mission Success Team" report, July 1994) is devoted to issues associated with parent material properties, in particular demonstration of Fracture Toughness Ratio (FTR); the ratio of cryogenic fracture toughness to room temperature fracture toughness. The Verification Team activity, extending from the Odom report, incorporated close partnership with the LM Fracture Control Board and the MSFC Fracture Control Board. These independent teams of technical experts provided close examination and rigorous scrutiny of all material acceptance rationale. The Verification Team documented and tracked safety and risk management issues and assured closure of any item affecting flight safety.

3.2 Issue: Manufacturing (Weld & Weld Repair)

As mentioned above, every SLWT has over 3000 feet of welding. The weld land thickness ranges from t=0.140” to 1.00”. Three welding techniques are employed: (Gas Tungsten Arc Welding (GTAW), Variable Polarity Plasma Arc (VPPA), and “Soft” Plasma Arc (SPAW). With 3000 feet of weld, it is essential to assure that welds are free of defects that could become safety of flight issues.

3.2.1 Mitigation Approaches

The SLWT program has implemented a rigorous series of demonstration requirements for welding and weld repair processes involving the production of verification panels to demonstrate manufacturing capability and the fidelity of the completed weld or weld repair.

Weld Repair Strength Verification

Weld repairs are frequent. The first SLWT will have on the order of 600 weld repairs. This is comparable to the number of repairs on the early 2219 External Tanks. The current weld repair rate on the 2219 tanks is on the order of 150 repairs per tank.

Initially, weld repair strength verification testing was conducted with one inch wide coupons (cut from the five inch long repair weld) pulled to failure to determine ultimate strength. As the SLWT development program evolved, other test data revealed that repair welds actually did not have the strength observed in the one-inch coupon tests. Indeed, it was determined that residual transverse forces were “stored” in the weld due to solidification shrinkage, resulting in the weld repair being weaker than the initial weld. The one-inch wide coupons, in effect, released the residual stress and consequently did not show degraded strength performance. In late 1994, the SLWT program initiated efforts to more accurately evaluate the global effects of a local repair. Subsequently, an effort was undertaken to increase the strength of the repair weld and establish a methodology and criteria for identifying acceptable weld repairs.

Planishing Weld Repair

The program used the process of hammering (peening) or cold forming, referred to as "planishing" to flatten the weld repair geometry in a way that residual stresses were redistributed, thus eliminating localized areas of high residual tensile stresses. The program established a 70% to 110% target for recovery of shrinkage as an indicator of strength recovery. It was also observed that planishing "work hardened the joint" further increasing strength.

Weld Repair Sensitivity Study and Weld Allowable Data Base

Recognizing the inadequacy of one-inch coupons, the SLWT program conducted a sensitivity study involving 150 to 200 "wide panel" tests each test using 19 inch wide panels, of a given thickness (variable), which were repair welded a certain number of times (variable), then planished to a particular degree of recovery (variable). Based on the sensitivity testing a "standard repair" was defined as a testing norm for use in developing the "weld allowable" data base. The standard repair was defined as a five inch long, "R5" (where R5 indicates five repair welds, each one over the previous), in plate 0.32 inch thick and planished to a recovery value in the range 70% to 110%.

The weld design value ("weld allowable") program tested on the order of 600 to 700 wide panels, including specimens representing all thicknesses of welds in the tank and testing to failure for both room temperature and cryogenic test conditions. The baseline "standard repair" was uniaxially loaded to failure for statistical samples of 30, for room temperature, and 20 for cryogenic temperatures. These tests provided a reasonable statistical knowledge of the variation of repair weld strength performance (one standard deviation on the order of 2 ksi). Additional tests were then conducted with other thickness material with reduced sample sizes (n=5 to 10). This body of testing forms the "weld allowable data base".

Out of Family Weld Repair

Weld repairs do not always conform to the criteria of "standard repair." In some cases many more repairs are necessary or the length of the repair is longer than five inches, or planishing recovery is less than 70%. In such cases a sample of three wide panels are tested to failure to determine whether or not strength performance is within the range of the weld allowable data base. If this limited sample demonstrates similar strength values to the well characterized "weld allowable" population, and the lowest test strength value meets or exceeds the appropriate weld allowable, typically on the order of 30 ksi (room temperature), then the weld repair is considered an in-family repair that is acceptable and safe.

Wide Panel Testing

Wide panel testing used a fracture screening process similar to that employed in the parent material acceptance process. The testing protocol is designed to demonstrate that a detectable crack or flaw will not propagate under the stress of four simulated life cycles of tensile loading as described below:

1) load to 100% proof stress (just short of yield) at room temperature, 2) load to tanking/pre-launch stress levels for seven cycles at cryogenic temperatures (liquid nitrogen bath), at 85% of proof stress, 3) load to flight stress levels at cryogenic temperatures (to demonstrate cryogenic strength enhancement) at 104.8% of proof, 4) repeat items 2) and 3) three more times. The sample is then pulled to failure and must pass the specification requirements. This procedure reflects the requirement for the SLWT to be capable of four full mission lives. This testing demonstrates the ability of the panel to provide limit-load (plus margin) strength performance without cracking, with an induced reference flaw size.

Reproof / Re-Inspect After Repair Weld

Figure 3.1 provides a flow of the steps involved in assuring the fidelity of welds and repair welds on the SLWT. It is important to note that all repair welds are subjected to intense evaluation. Each repair weld is x-rayed at three different angles, and subjected to dye penetrant NDE inspection. Following these tests, the pressure vessel is proof tested to verify the acceptability of the tank. Then a final "targeted" x-ray inspection is conducted for historic problem areas, areas of the tank not fully loaded during proof tests, all weld repairs, and all weld intersections to verify that the proof test did not "open up" any defects that were below the NDE threshold of detectability. Any out of specification condition is recorded in a Non Conformance Document (NCD) which requires material review board (MRB) disposition. The disposition must have the concurrence of NASA S&MA and NASA S&E. The weld repair risk mitigation process builds confidence that the completed SLWT has no unacceptable defects and is acceptable for flight..

As seen in the figure 3.1, the SLWT program uses the "Defect Knowledge Base" as the central authority for deciding whether or not an observed defect is: 1) acceptable "as is", 2) meets rigorously defined criteria to permit "in family repair", or 3) represents something "out of family", which requires testing and analysis sufficient to define a new weld repair protocol. The "Defect Knowledge Base" is then coupled to a multi-step verification process to assure the fidelity of weld repairs.

SLWT Weld Defect - Risk Management Flow

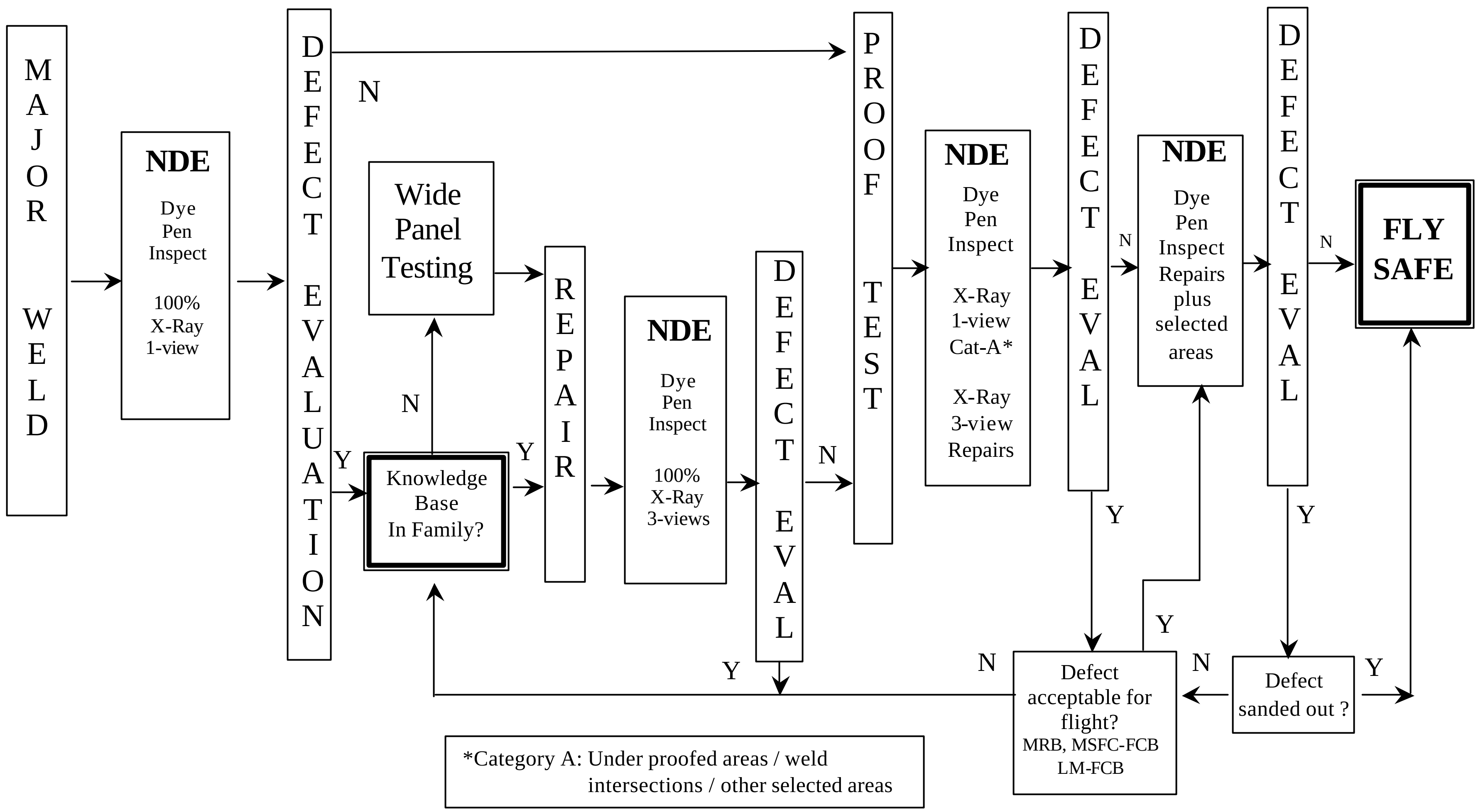


Figure 3.1

Weld Repair Risk Management Example

An example of the rigor of the SLWT analysis and review process is the approach taken when two very small subsurface flaws (0.030" and 0.045") were detected by X-ray on the ET97 LH2 tank after its final proof test. Repair and retest were considered, but the risk of two additional heat repairs was considered greater than the acceptance of these flaws. Before the flaws were considered for acceptance, a rigorous analysis was performed which showed that these flaws would survive over one thousand mission lives of seven propellant loading cycles and one flight loads cycle. For conservatism, the apparent radiographic flaw length was doubled for the analysis to compensate for the uncertainty involved in sizing flaws by X-ray. Since the program requirement is to be good for four mission lives, the capability of these flaws was more than 250 times the requirement. Further, the critical initial flaw size in the areas of each of the flaws is more than 10 times the apparent flaw length and this analysis was performed using a surface flaw rather than an imbedded flaw which is a more conservative approach. This determination was approved by the SLWT material review board, the LMC Fracture Control Board, and the MSFC Fracture Control Board that included representation from a JSC fracture control expert (Glen Ecord). The MSFC Fracture Control Board findings were documented to the project in their letter ED21 (ED25-97-73) dated October 30.

3.2.2 Independent Assessment of Mitigation Approaches

Office of Safety and Mission Assurance

OSMA supported all IAR activity and engaged the SLWT program in discussions concerning technical safety and risk management issues throughout the program life cycle. One example of OSMA involvement in the area of weld repair was the SLWT consideration of options for addressing the problem of intersection cracks (IC) observed in certain weld configurations, a topic of review at the 1997 IAR. Based on OSMA concerns and the need for better understanding the intersection crack phenomena, a review was held at NASA Headquarters in June of this year. At the same time the SLWT program's ongoing IC elimination initiative identified a potential solution. Testing showed that intersection cracking can be eliminated, almost entirely, through the substitution of 2219 ring frames for 2195 ring frames, and modifications to the welding techniques (dual cover vs. single cover weld passes and vertical, up oriented VPPA welding).

Ongoing Challenges and Problem Solving in the Welding Arena

Because of ongoing challenges in development of welding techniques and processes, the once-a-year independent assessment activities of the IAR and ASAP were not able to provide "real time" input to problem identification and resolution activity. Rather the team of LM, Reynolds Aluminum, MSFC, the LM and MSFC Fracture Control Boards and the Verification Team were all involved in assessing and addressing welding techniques and the goodness of the resulting weld.

3.4 Issue: Production Verification

In addition to the manufacturing process development issues identified above, and given the sensitivity of critical manufacturing processes, it is evident, that full scale production verification testing is important to assure the individual tank is free of defects.

3.4.1 Mitigation Approaches

Production Verification Testing

LH2 Protoflight Test

- Each production LH2 tank receives a prototype test which imposes 115% static limit load. The test verifies buckling stability. The loads are introduced at the Orbiter and Solid Rocket Booster attach points using worst case static load values.

- Each LH2 and LO2 tank undergoes a room temperature pressure proof test at an analytically equivalent (adjusted) pressure of 105% of fracture basis limit load. These tests provide an even higher strength verification and a flaw screen (fracture control acceptance test). The test process verifies weld integrity, fracture strength, and addresses workmanship issues. All welds not subject to operational load are x-ray inspected.

Non Destructive Evaluation

The SLWT program uses x-ray and dye penetrant testing and inspection (along with proof testing) as a means to verify the integrity of each SLWT pressure vessel. Process requirements are the most stringent possible.

Parent Material

Parent material NDE includes ultrasonic testing of all raw stock.

LO2 Tank

LO2 NDE activity includes: penetrant inspection of pressure vessel membrane, visual inspection, X-ray and penetrant of welds pre-proof, and X-ray of selected welds, weld intersections, and all weld repairs post proof.

Intertank

Intertank NDE includes: penetrant inspection of all formed parts, and visual inspection of assembled hardware.

LH2 Tank

LH2 NDE involves: penetrant inspection of pressure vessel membrane, visual inspection, X-ray and penetrant of welds pre-proof, and X-ray of selected welds, weld intersections, and all weld repairs post proof.

3.4.2 Independent Assessment of Mitigation Approaches

Production verification independent assessment activity involved all of the various groups discussed above and overlapped in part with material acceptance activity and design verification as well as welding and weld repair. This specific area does provide an opportunity to highlight another key partner in the independent assessment process, the MSFC Science and Engineering Directorate.

MSFC Science and Engineering Directorate

Previous discussion of the MSFC Fracture Control Board recognized, in effect, the significant role of numerous experts in metallurgy, material properties, fracture mechanics, and test and evaluation. The nature of their "independence" was based in their professional adherence to their science, and unyielding technical rigor. Another "inside" but independent technical forum was the NDE community at MSFC. NDE issues were worked very hard at milestone reviews and were in fact outstanding issues of discussion, and eventual resolution, at the Design Certification Review.