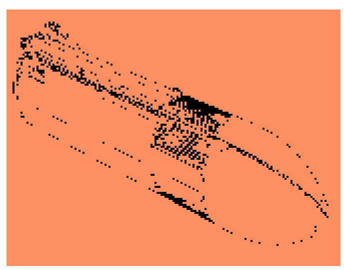
This document contains excerpts from the SLWT Independent Assessment Report (title page shown below). Only those sections which relate to the PBMA element **Hardware Design** are displayed.

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

1.4 SLWT Safety and Risk Management Activity

Hazard Analysis

Michoud Space Systems' Hazard Analysis process consists of identifying potential hazardous conditions, developing controls to prevent the hazards, verifying the controls are in place, and documenting the results. The involvement of systems safety personnel in all phases of SLWT development and operation ensures timely identification and elimination/control of potential risks to personnel, property, and the environment within the constraints of cost, schedule, and program requirements. SLWT hazard analysis process relies on the established Space Shuttle Hazard Analysis process. SLWT hazards have been reviewed by the System Safety Review Panel and will be entered into the ET Hazard Analysis Report following PRCB approval. Also, the current version of the Space Shuttle Critical Items List (CIL) includes SLWT items.

Design Safety Checklist

Michoud Space Systems' Design Safety Checklist is a practical and effective technique for the application of safety experience to the design and operation of hardware systems and equipment. The Design Safety Checklist assists all disciplines in the application and retention of lessons learned. It provides a management tool to coordinate the safety program; places safety in the mainstream of events; provides educational benefits to all disciplines; and provides a systematic method to identify hazards that can be used independently or in support of more sophisticated hazard analysis methodologies.

2.0 Background - Introduction to the SLWT

SLWT Risk Quantification Using Probabilistic Risk Assessment Techniques

As part of a larger project to develop the NASA Quantitative Risk Assessment System (QRAS), in 1997, MSFC SMA worked with the ET Project Office and consultant Bob Mulvihill to update the 1995 SAIC probabilistic risk assessment (PRA) of the ET. The current LWT version of the ET was remodeled. The results of this most recent work, in terms of the ET's estimated contribution to the risk of a Space Shuttle catastrophic accident (on a per mission basis), yield a lognormal probability density having a median value of 1/7246, a 5th percentile of 1/12,629 and a 95th percentile of 1/4158. Comparing median values, among the Shuttle elements, the ET contributes less than 3% of the overall Space Shuttle risk of catastrophic accident of 1/205. Over the next 3-4 months, the SLWT will be quantitatively modeled by MSFC. In the January-February 1998 time frame, it will be possible to compare the estimated risk of the two versions of the ET.

3.0 Major Safety and Risk Management Issues, Mitigation Approaches and Independent Assessment

The following paragraphs identify major SLWT program safety and risk management issues, describe principal risk management approaches and discuss the independent review and assessment activity associated with the particular issue.

Independent Assessment

The SLWT program has had the benefit of extensive independent assessment activity. The program has been very responsive to suggestions and has benefited accordingly. Appendix A present a chronology of IA activity along with key events and milestones in program development. It is important to note that three types of IA input has supported the program. First, the program has had continuous ("real time") IA participation by the "Verification Team", established early in the program. Secondly, the program has been the focus of periodic (yearly) "snapshot" IA review from such teams as the Independent Annual Review, and the Aerospace Safety Advisory Panel (ASAP). Thirdly, there have been a series of one-time reviews, such as the early (1993) Jim Odom, Bob Ryan, and Rick Davis independent assessment reviews. (These reviews established the design verification framework that was ultimately implemented.) Other examples include the 1994 OSMA (Mulville) Review.

All of the IA input and activity has been integrated by the SLWT program and has been continuously monitored by members of the Verification Team. Typically the snapshot and one-time reviews built upon, and in some cases expanded and reinforced, issues that were actively under the review and scrutiny of the Verification Team.

SLWT Verification Team

The Verification Team monitored and assisted in the implementation of the 1993, Odom/Davis Independent Assessment recommendations and served throughout the program life-cycle as the arbitrator of technical safety and risk management issues related to design, parent material and manufacturing issues. The initial Odom/Davis review provided the verification "compass" that has guided the SLWT verification activity. The membership of the original SLWT Verification Team is shown below:

Robert Ryan	NASA/MSFC	Co-chair
Dennis Deel	LMC/MAF	Co-chair
Frank Boardman	NASA/MSFC	
Neil Otte	NASA/MSFC	
Glenn Miller	NASA/JSC	
Dr. Michael Nemeth	NASA/LaRc	
Gale Copeland	LMC/MAF	
Michael Quiggle	LMC/MAF	
Robert Morra	LMC/Retired	

Dr. Jackie Bunting LMC/Astronautics

Independent Annual Reviews (IAR)

IAR's chartered by the Program Management Council, were conducted in 1994, 1995, 1996, and 1997. The IAR forum served to elevate safety and risk management concerns to the Deputy Administrator, the AA/OSMA as well as other senior NASA officials throughout the SLWT development. The IAR maintained a balanced review of both schedule and budget concerns as well as technical safety and risk management issues.

Aerospace Safety Advisory Panel (ASAP)

ASAP conducted status reviews in 1993 and 1994, and in-depth technical reviews in 1995, 1996, and 1997. The ASAP team provided independent review of safety and risk management issues throughout the development of the SLWT. The ASAP team focused on safety of flight issues and provided numerous recommendations concerning parent material qualification as well as welding and design verification. The SLWT technical assessment and evaluation activity of ASAP was spearheaded by:

- Melvin Stone, former Director of Structures at Douglas Aircraft Company,

- Kenneth Englar, former Chief Engineer of Mc Donnell Douglas Corporation and Chief Design Engineer for the Delta Launch Vehicle, and

- Dr. Seymour Himmel, former Associate Director of the NASA Lewis Research Center, and active in aerospace engineering since 1948 when he joined the National Advisory Committee for Aeronautics.

Individual Technical Expert Reviewers of the SLWT Development Activity

Another dimension of the independent assessment assurance role is "degree of independence." That is, from how far "outside the circle" of program development activity does the expert reviewer bring his or her perspective? The challenge is to find individuals knowledgeable enough in relevant technical areas but still outside the cultural influence of the project team driving to meet program cost and schedule goals. The SLWT program has been fortunate to have numerous expert reviewers from outside the project team environment as shown in Appendix B of this document.

3.3 Issue: Design Verification Elements And Complexity

Design verification concerns have been at the center of SLWT safety and risk management activities and have been a principal focus of independent assessment activity. The following paragraphs provide a summary of design verification approaches used for each of the principal SLWT elements.

The SLWT design verification approach operates from a bottom-up assessment of component failure modes and requires capability demonstration of each component, by test or linked to test data. In very few cases (e.g. LOX tank barrel, LOX tank aft ogive, and aft end of intertank thrust panel)) this ground rule cannot be satisfied and design verification must be demonstrated through a combination of analysis, test, heritage (existing flight and test data), and simulation modeling. These three cases represented design and material changes where verification "by testing" was deemed unrealistic. The technical complexity and physical requirements of the test would have required time and resources unavailable to the SLWT program. For these cases, the safety factor was increased to 2.0 and a second, independent analysis was required. While extraordinarily rigorous, the "combination verification" sometimes complex rationale creates a dependency on fidelity of analyses, goodness of modeling assumptions, absence of unknown synergistic effects and applicability of component testing data. This concern is mitigated by the use of conservative considerations in analysis and test. This body of conservative practice is also summarized below.

3.3.1 Mitigation Approaches

As mentioned above, the SLWT program design verification program is test-based. Every effort has been made to build verification rationale on demonstrated test data, either unique to the SLWT program, or through applicable testing performed for the existing Light Weight Tank program.

LO2 Tank Design Verification: Complementary Elements:

The LO2 tank was verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness. Component testing to failure was initiated for multiple sub-systems, such as the slosh baffle beaded web. The fidelity of several LO2 tank design elements was independently verified by analyses conducted at the Langley Research Center. The LO2 tank aft dome stability was verified in the Aluminum Lithium Test Article (ALTA) program. Other important elements in the overall design verification included the work to characterize the parent material properties and develop welding and weld repair allowable data bases.

Intertank Design Verification: Complimentary Elements

The intertank was also verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness, thrust panel material and SRB beam design. Component testing to failure was initiated for multiple sub-systems, such as the skin stringer/joint, the beaded web, and the thrust panel. It is worth noting that early tests of the skin-stringer assembly resulted in skin buckling (prior to the required level), and led to design improvements which eliminated the problem. Independent analyses were conducted using the MSFC finite element stability model to verify aft thrust panel performance.

The overall design was also supported by use of MIL-HANDBOOK 5 materials allowables information.

LH2 Tank Design Verification: Complementary Elements

Buckling rather than strength represents the biggest challenge for structural designers. Buckling and the resultant orthogrid delamination result from shear and compression loading of a structure with insufficient stiffness.

The LH2 tank was verified using a combination of test and analysis. In order to mitigate potential tank buckling concerns designers decided to maintain the current structural ringframe stiffness. Component testing to failure was initiated for multiple sub-systems, such as the orthogid panel cryoflex tests in which bi-axial loads were introduced to assess stress concentrations and validate cryogenic performance of the NASTRAN structural design model. The ALTA program demonstrated the stability requirements for most of the LH2 tank barrels with the remainder being demonstrated by protoflight testing. In order to verify the design and production fidelity of LH2 tanks, the SLWT program will subject every production tank to a protoflight testing regimen which will demonstrate longeron stability and aft dome stability. Supporting the LH2 design verification is the previously cited work performed in parent material characterization and development of welding and weld repair allowables.

Tanking/Detanking Test at KSC

A test plan has been developed to tank/detank the first SLWT with the primary function of providing a propellant loading demonstration. The resulting temperatures and pressures will be monitored by KSC, including LM engineers. The results will be correlated to the analytical Main Propulsion System predictions and the historical database. The six ET/SRB struts will be strain gauged to allow correlation of the "pinch load" values.

Conservative Assumptions and Philosophy to Offset Design Verification Complexity

Analysis assumptions were made in a safety-conservative fashion employing the following:

- Maximum loads were combined with maximum pressures to achieve a worst case;
- Used limit/load pressures for pressure relieving scenarios, used limit minimum pressures for stability calculations;
- Used MIL HANDBOOK 5 "A Basis" assumptions (or NASA/MSFC) material property values;
- Used minimum pressure vessel thickness for pressure vessel failure modes;
- Used maximum drawing peaking/mismatch for generic weld analysis;
- Used verified "equivalent cylinder", which is conservative versus NASTRAN non-linear analysis for failure modes;

- Used maximum principal stress and not "Hencky Von-Mises" strength failure theory for flight analysis. (Henky Von-Mises theory projects an increase in ultimate tensile strength when a structure is loaded in a bi-axial fashion)

Other examples of Conservative Design Engineering and Analysis

- SLWT "Durability and Damage Tolerance" approach, set out in the MIL-Q-1530 specification assumes a flaw exists in every structural component at a size just below the detection threshold of NDE capability with assumed worst case location and orientation.

- Tank is designed for 3-engine 106% power rating (as well as two engines at 109% for abort cases) aerodynamic and structural load environment.

- Factor of Safety (FOS)

    - FOS = 1.25 for areas on the tank where the load environment is well understood;

    - FOS = 1.40 for areas of the tank where the load environment is less well understood;

    - FOS = 2.0 for structural areas of the tank not verified by test.

- 2195 aluminum lithium has approximately a 10% increase in stiffness at cryogenic temperature and a fracture toughness ratio greater than 1.0.

- The 115% structural verification protoflight test is conducted at ambient temperatures for each tank.

- 6'x6' flat plate cryogenic load testing is a "worst case" delamination scenario, as a curved section would have greater resistance to orthogrid delamination.

Verification of Analytical Models and Methods

The success and safety of the SLWT is dependent on the accuracy and margin contained in analytical models and methodologies employed in the design process. The models and methods have been verified through, 1) comparison of model or method predicted structural response with measured structural responses from numerous test programs, 2) comparison of primary design model predicted response with predictions from other independent analytical models.

Analytical Models and Methods

The SLWT program employed a finite element analysis NASTRAN program to predict and analyze structural load distributions. Other analytical methods were used to predict buckling and ultimate failure (closed form or standard structural analysis techniques). The SLWT NASTRAN model is the same pedigree as models used throughout the external tank program life. NASTRAN model analyses correlated well with strain gauge data acquired in previous external tank development programs (Standard Weight Tank and Light Weight Tank). Building on this heritage of safety and mission success, the SLWT program set out to demonstrate the model's ability to predict the load distribution throughout the redesigned tank structure for various loading cases and, most importantly, (along with other techniques described above), predict where and when a structure will fail for a given loading scenario.

The SLWT NASTRAN modeling code and analysis techniques have been validated through extensive correlation of strain gauge measurement information acquired during 1) the Aluminum Lithium Test Article (ALTA) program, 2) during protoflight tests conducted with each LH2 tank, and 3) in component testing.

Model/Method Verification through Test: ALTA

In the case of the ALTA, over 700 strain gauges were deployed to acquire load distribution information through the various ALTA test scenarios including ultimate failure. The NASTRAN predicted load distribution correlated well with observations, falling within 5 % of measured strain gauge values in the regions of the test objectives. This conformity is considered excellent within the norm of structural design activity. The closed form cylinder analysis technique predicted the failure with an appropriately conservative margin. The model predicted failure at 126.5% of limit load, ultimate failure actually occurred at an equivalent load factor of 218%, following a period of extensive skin buckling and non-linear behavior. This degree of conservatism is appropriate when considering the non-linear and less well behaved mechanics of stability failure.

Model/Method Verification through Test: SLWT-1

In the case of the SLWT-1 LH2 tank, loads were introduced for two protoflight loading scenarios, and 5 proof testing scenarios. Again, 700 strain gauges were deployed and measured induced loads which correlated extremely well with NASTRAN predictions, showing correlation within 5%.

Model/Method Verification through Test: Cryogenic Performance Test

The cryogenic test panel behaved as predicted by the NASTRAN model, achieving agreement within 5% between strain gauge measurements and predicted response.

Model/Method Verification through Test: Component and Coupon Testing

Component testing "to capability", was performed on 13 different subassemblies having either a design or material change, (e.g. intertank skin/stringer-joint compression tests, frame beaded web tests, and the "cryoflex" (cryongenic environments test). In each test, results showed article failure strength was well predicted by analytical techniques with some conservatism (e.g. 20-40% for beaded webs, 2-3% for intertank skin-stringer tests). There was however one test where the test article skin buckled which required a design change that subsequently passed the test. Welding and material qualification (pull to failure) testing results were also shown to agree well (20% conservatively) with BOSOR (buckling of shells of revolution) analytical predictions.

Model/Method Verification through Comparison: Langley Research Center (LaRC) Finite Element Model

Independent analytical models were used to validate the NASTRAN results in the three cases where combination analysis and coupon testing was used to verify structural integrity. A LaRC finite element model was used to validate the NASTRAN results for the LO2 tank barrel section and the LO2 tank aft ogive assuring in each case, a Factor of Safety greater than 2.0.

Model/Method Verification through Comparison: MSFC Finite Element Model

The MSFC finite element analysis model was employed to verify predicted loads and capability of the intertank aft thrust panel. The two models (NASTRAN and MSFC finite element) agreed well and predicted structural Factors of Safety greater than 2.0.

Environmental Loads Model (Load Sets)

Space Shuttle Program Level II (Johnson Space Center) provides the SLWT program with Boeing North American (Rockwell) generated load sets. The SLWT program worked in an iterative process with Level II (i.e., sending the SLWT structural model to Downey to support system level loads calculations, receiving back the overall Shuttle system load environment, then refining the design as necessary to provide design margin, then sending the revised structural model back to Downey to support the next round of environmental load simulation.) The pedigree of the Level II environmental loads/ systems loads model is based on actual flight Orbiter strain gauge data, and early wind tunnel testing information.

3.3.2 Independent Assessment of Mitigation Approaches

Verification Team Reviews

Three principal technical review teams evaluated the early SLWT test and verification strategy. To a large extent, their activities were conducted in parallel which provided for constructive interaction and eventual synthesis of technical issues.

An in-house, Martin Marietta review was conducted by former MMSS President Rick Davis during spring-summer 1994. Rick Davis, strongly recommended conducting a full-up cryogenic test. Concurrently, a team led by Jim Odom was chartered to "assess the feasibility" of the overall SLWT development program. A NASA MSFC Engineering review was conducted during the summer of 1994 by Bob Ryan. This team developed an approach combining analysis and testing with rigorous modeling of performance. The Bob Ryan team interacted with both the Rick Davis and Odom teams, and worked closely with the SLWT program management team to develop the ultimate SLWT test and verification approach. An OSMA review led by Dan Mulville was conducted in the summer-fall 1994. The OSMA report concurred with the recommendations from the Odom and Davis teams to expand the planned structural verification activity.

The "Verification Team" (follow-on for the Davis/Odom review activity) provided ongoing, in-depth technical review capability to the SLWT program. Based on a review of the proceedings of Verification Team presentations and discussions it was evident that the SLWT program is systematically involved in risk identification, risk ranking, and risk mitigation. An example (Verification Team meeting, May 18-19, 1994) is provided below:

<u>Ranked Safety of Flight Issues (a quantitative ranking methodology was employed)</u>

- LH2 Barrel 1 Panels at Longeron--Stability Failure Modes
- LH2 Barrel 2 Panels at Longeron--Stability Failure Modes
- LH2 Tank Barrel 4 Panels--Stability Failure Modes
- LH2 Barrel 3 Panels--Stability Failure Modes
- LH2 Barrel 2 Panels--Stability Failure Modes
- Forward Ogive Gores--Stability Failure Modes
- LO2 Tank Barrel Panels--Stability Failure Modes
- Skin Stringer Panels--Stability Failure Modes
- LO2 Tank Dome Gores--Stability Failure Modes

For each safety of flight risk area, "ideas for risk reduction were collected and actions assigned to expand upon all ideas with promise." The SLWT "Verification Philosophy" was hammered home time and time again. The philosophy was:

- "Verify by test, for each structural element, the integrity of the structure;
- Test can demonstrate structure will withstand ultimate loads, or test can demonstrate structure will withstand limit load and validate analysis accuracy and conservatism used to extrapolate to ultimate load;
- Test can be omitted if FS greater than or equal to 2.0 (generally applied to secondary structure);
- Test not required if a similar, more critical, structural element has been test verified (i.e., gore panels, barrel segments);
- Test completion is precursor to flight or critical design condition (e.g., stacking, pre-launch, etc.);
- Test articles will be built on production tooling with production processes;
- Test articles will be fabricated from material acceptable for production hardware Deviations from above philosophy may be acceptable based on quantifiable rationale."

Verification Team meetings were thorough in their coverage of SLWT structural safety-of-flight issues, well documented, had clear conclusions and action items, and good follow-through from one meeting to the next. As discussed in introductory remarks concerning IA activity, the Verification Team has been a real time risk management participant identifying and assuring satisfactory closure of issues.

OSMA (Mulville) Review 1994

OSMA was asked by the Program Management Council to conduct an independent assessment of the SLWT design verification activity in mid-1994, leading to a report in November of that year. This report concluded that the current SLWT protocol met the intent of NASA policy but strongly urged that additional testing be incorporated to reflect structural performance at cryogenic temperatures. In a December 9, 1994 letter to Acting Deputy Administrator, the AA/OSMA said,

“Although a full-up structural test article is not required, the opportunity to better demonstrate the performance of ‘as welded and repaired’ structure as proposed by the engineering change proposal now under consideration will further reduce program risk. Consequently we support the engineering change proposal’s (ECP) acceptance.”

The OSMA review team concluded the SLWT project test and verification plan would be acceptable “upon closure” of:

A. Material characterization
B. Weld characterization
C. Successful correlation of analytical modeling with:
   1. Component coupon test data
   2. Sub-assembly, Aluminum Lithium Test Article performance data (140% proof test, then test to failure)
D. Proof testing of the LO2 and LH2 tanks: a room temperature pressure proof test at an analytically equivalent (adjusted) pressure of 105% of fracture basis limit load (production verification test)
E. Protoflight testing of the LH2 tank: 115% static loads applied to Orbiter and Solid Rocket Booster attach points (production verification test)
F. Resolution of cryogenic loading concerns

The review team recommended that the Shuttle program evaluate the ‘desirability’ of instrumenting the first SLWT to determine pre-launch and/or flight loads. This non-safety-of-flight recommendation was considered but ultimately set aside. The program decided against implementation based on strong confidence in the knowledge of the expected load environment and a belief that analytical modeling and tests have provided equivalent insight into flight load response.

The review team also recommended considering a cryogenic impact assessment test proposed in a Martin Marietta ECP. This test involved bi-axial loading of a 6'x6' flat orthogrid plate at cryogenic temperatures. This test was designed to verify the performance of 2195 in the as-welded and as-repaired configuration, as well as to verify adhesion of SOFI thermal insulation. Completion of this test was deemed desirable in order to reduce the risk associated with incorporation of new materials, design and fabrication methods in the SLWT.

The cryoflex panel testing was, in fact, implemented and, as discussed above, showed excellent agreement between the NASTRAN predicted load distribution and strain gauge measurements. All of the OSMA recommendations were implemented or accepted by OSMA as closed.

ASAP Findings and Recommendations / SLWT Program Response

The ASAP, led in it's technical evaluation by Melvin Stone, took exception (1995 report) with the LO2 tank aft dome design verification approach: "The liquid oxygen tank aft dome gore panel thickness of the SLWT has been reduced significantly on the basis of analyses. To stiffen the dome a rib was added. The current plan to verify the strength of the aft dome involves a proof test to only limit load. Buckling phenomena cannot be extrapolated with confidence between limit and ultimate load." ASAP recommended that "the SLWT aft dome should either be tested to ultimate loads or its strength should be increased to account for uncertainties in extrapolation."

NASA agreed with the recommendation and added an aft dome test to the ALTA test program (successfully completed).

Appendix A

Chronology of Milestones and Independent Reviews

- Nonadvocacy Review-January 20, 1993
- Aerospace Safety Advisory Panel (ASAP) - May 12, 1993
- MMC Mission Success Review - October 1993
- S&E Review - February 23, 1994
- NASA / Martin Marietta Independent Reviews - April 17-23, 1994
- 1994 Independent Annual Review - May 18-19, 1994
- Verification Team Independent Review - May 18-19, 1994
- Preliminary Requirement Review (PRR) - June 1994
- NASA / Martin Marietta Independent Reviews - June, 1994
- Aerospace Safety Advisory Panel - June 29, 1994
- ALTA Design Review - August 1994
- NASA / Martin Marietta Independent Review Report - October 1994
- Preliminary Design Review - November 1994
- MSFC Fracture Control Board - January 1995
- Start Fabrication of ALTA - February 1995
- Blue Ribbon NDE Review - April 3-4, 1995
- 1995 Independent Annual Review - April 10, 1995
- Verification Team Independent Review Follow-On - April 10-11, 1995
- NASA / Martin Marietta Independent Review Followup - May 30-June 1, 1995
- Start Fabrication of SLWT 1- June 2, 1995
- Space Shuttle Program Review - June 15, 1995
- Aerospace Safety Advisory Panel - June 14-15, 1995
- Critical Design Review - June 28, 1995
- Verification Team Independent Review Followup - August 1995
- Brewster Shaw Review - June 14-15, 1995
- Production Readiness Review - December 1995
- ALTA Proof Test - January 1996
- ALTA DD-250 - January 1996
- Verification Team Independent Review Followup - February 1996
- Tommy Holloway Review - April 19, 1996
- Aerospace Safety Advisory Panel - May 9, 1996
- 1996 Independent Annual Review - May 15-16, 1996
- NASA Independent Review of Extrusions - July 1996
- ALTA Ultimate Tests Complete - July 1996
- ALTA Capability Test Complete - September 6, 1996
- LH2 Tank Pre-proof Review - November 12-14, 1996
- Verification Team Independent Review Followup - November 25-26, 1996
- Review with Aerospace Safety Advisory Panel - March 20, 1997
- SLWT-1 LH2 and LO2 Tank Proof Test - March 25, 1997
- Space Shuttle Program Review - April 28, 1997
- 1997 Independent Annual Review - June 23-24, 1997

- Design Certification Review Phase I - June 24-26, 1997
- Design Certification Review Phase II - September 1997
- SSP Performance Enhancements DCR - October 22, 1997
- Lead Center Performance Enhancements DCR - November 13, 1997
- SLWT-1 DD250 - January 6, 1998
- First SLWT Launch - May 29, 1998