

PART IV. EXTERNAL TANK

Introduction

The external tank (ET) was the largest element of the STS and the only non-reusable major component. The complete ET structure measured approximately 154' in length, more than 30' longer than the orbiter. Since it was expendable, the ET was designed "to minimize active or moving parts."¹²²⁵ The ET contained and delivered approximately 1.6 million pounds of propellants (fuel and oxidizer) for the three SSMEs. The LO2 oxidizer was held in a forward tank, while the larger, rear tank contained the LH2 fuel. A structural connector called the intertank separated the two propellant tanks. In addition to serving as the shuttle's "fuel tank," the ET also was the backbone structure for attachment of the orbiter and SRBs. It accommodated the stresses created by both its own weight and that of the orbiter prior to launch, as well as the stresses generated by the SSMEs and SRBs during launch.

The ET was designed by the Martin Marietta Corporation, and manufactured and assembled by the Lockheed Martin Space Systems Company¹²²⁶ at NASA's government owned - contractor operated Michoud Assembly Facility (MAF) in New Orleans, Louisiana.¹²²⁷ The ET program was managed by the ET Project Office at MSFC. Lockheed Martin had approximately 2,000 subcontractors and suppliers located across the United States who provided materials for the ET. Historically, the suppliers included the Aluminum Company of America for SRB attachment fittings, ball forgings, longerons, forward ogive forgings and diagonal struts; both Reynolds Metals and Kaiser Industries Corporation for machined aluminum for LH2 tank barrel panels; Kaman Aerospace for slosh baffle segments; Aerochem for LO2 tank barrel panels; and Aircraft Hydroforming, Inc. for gore and ogive panels, as well as outer, inner and intermediate chords.¹²²⁸

Historical Overview

Early Design Concepts

The tank design concepts developed in the late 1960s for the USAF Flight Dynamics Laboratory foreshadowed the Shuttle ET designs of the early 1970s. Both Lockheed and McDonnell Douglas submitted their early designs, prepared for the USAF, to NASA as part of the Phase A

¹²²⁵ Martin Marietta Corporation, *System Definition Handbook, Space Shuttle External Tank (Lightweight Model), Configuration & Operation Volume I*, (New Orleans, LA: Martin Marietta Corporation, August 1980), III-5, MSFC History Office, Huntsville.

¹²²⁶ In March 1995, the Martin Marietta Corporation and Lockheed Corporation merged to form the Lockheed Martin Corporation.

¹²²⁷ MAF was previously used for building the first stage of the Saturn IB and Saturn V rockets for the Apollo Program.

¹²²⁸ Edward H. Kolcum, "Space Shuttle Lightweight Tank Production Begins," *Aviation Week & Space Technology*, November 16, 1981: 135.

Space Shuttle competition.¹²²⁹ The Star Clipper vehicle concept developed by Lockheed included two 23.67'-diameter fuel tanks that formed a "vee" around the orbiter's nose. This represented the first major concept that moved part of the propellants (LH2 fuel) externally into expendable tanks.¹²³⁰ The Model 176, developed by McDonnell Douglas for the USAF study, used parallel fuel tanks with both LH2 fuel and LO2 oxidizer tanks located external to the orbiter. The two 150'-long x 24'-diameter fuel tanks were mounted on either side of the orbiter, and the 73'-long oxidizer tanks were attached on the orbiter's top and bottom.¹²³¹

NASA augmented the Phase B Space Shuttle study efforts in April 1971, with the addition of an analysis of an external hydrogen tank for the orbiter of a fully reusable shuttle.¹²³² As a result, a new task was added to the existing McDonnell Douglas and North American Rockwell Phase B study contracts, as well as to the Lockheed Phase A Alternate Shuttle Concepts contract. A final report for the expendable LH2 tank prepared by each contractor was submitted between June 25 and June 30, 1971.¹²³³

In May 1971, NASA had made the decision to put both the LO2 and LH2 tanks outside the orbiter airframe. "As with all shuttle components, cost was of primary importance in tank design."¹²³⁴ The intended consequence was to reduce total Shuttle development costs by half, and within the range considered supportable by Congress.¹²³⁵ An expendable ET allowed the orbiter to be smaller and lighter, and with less costly TPS materials.¹²³⁶

The original design requirements for the ET were written by Rockwell International, NASA's orbiter and systems integration contractor. At this time, the program mission model called for 445 flights at the rate of sixty per year. According to Myron Pessin, former Chief Engineer for the External Tank Project at MSFC, the RFP developed by the ET Project Office, headed by James Odom, was based on the requirements prepared by Lockheed. Accordingly, "because of the high build rate envisioned, major attention was given to features to encourage low cost production approaches."¹²³⁷ Additionally, "ET design and processes had to be optimized for high rate production."¹²³⁸

¹²²⁹ Jenkins, *Space Shuttle*, 68-69.

¹²³⁰ Jenkins, *Space Shuttle*, 68.

¹²³¹ Jenkins, *Space Shuttle*, 69.

¹²³² Whalen and McKinley, "Chronology," 11.

¹²³³ Whalen and McKinley, "Chronology," 13.

¹²³⁴ Dunar and Waring, *Power to Explore*, 292.

¹²³⁵ Dunar and Waring, *Power to Explore*, 283.

¹²³⁶ Jenkins, *Space Shuttle*, 140.

¹²³⁷ Myron A. Pessin, "Lessons Learned From Space Shuttle External Tank Development – A Technical History of the External Tank," (technical history, NASA MSFC, October 30, 2002), 2.

¹²³⁸ Myron A. Pessin, interview by Rebecca Wright, *NASA STS Recordation Oral History Project*, June 30, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/PessinMA/PessinMA_6-30-10.htm.

Contract Awards

The ET was the third major procurement for the STS, following the award of initial contracts for the orbiter and the SSME. Following a series of reviews and presentations for prospective contractors, held at MSFC on September 7, 1972, December 12, 1972, and March 6, 1973, the RFP for the DDT&E of the Shuttle ET was released to industry on April 2, 1973.¹²³⁹ This procurement included the manufacture of three ground test tanks (Structural Test Article, Propulsion Test Article, and Dynamic Test Article) and six developmental flight tanks (ET-1 through ET-6), with the last delivery in 1979.¹²⁴⁰

Four companies were invited to bid: the McDonnell Douglas Astronautics Company of Huntington Beach, California; the Boeing Company of Seattle, Washington; the Chrysler Corporation Space Division of New Orleans, Louisiana; and Martin Marietta Aerospace, Denver Division.¹²⁴¹ Because it had been selected by NASA as the prime orbiter contractor, Rockwell was prohibited from proposing on the ET contract. However, this firm teamed with Chrysler to provide a joint bid.¹²⁴² In March 1973, appointments were made to the Space Shuttle ET Project Source Evaluation Board, which was co-chaired by Robert E. Lindstrom, Director of the Shuttle Office at MSFC, and James R. Odom, ET Project Manager.¹²⁴³ By the end of May, NASA received a proposal from each contractor team.

On August 16, 1973, NASA announced the selection of Martin Marietta for the ET DDT&E contract.¹²⁴⁴ A letter contract was executed on September 1, 1973. The period of performance for this initial contract (No. NAS8-30300), valued at roughly \$40.5 million, ran through December 16, 1974. A letter contract extending the period of performance through January 31, 1975, with no increase in price, was approved by NASA Headquarters on November 25, 1974.¹²⁴⁵ By January 1975, NASA and the contractor “agreed on terms for a \$156.565 million cost-plus-award-fee contract.”¹²⁴⁶ Martin Marietta subcontracted the manufacture of the intertank aluminum panels to Avco Corporation’s Aerostructures Division of Nashville, Tennessee. The \$3.2 million contract between Martin Marietta and Avco was signed on June 11, 1975. Work was

¹²³⁹ Whalen and McKinley, “Chronology,” 22-24; “Shuttle Tank Effort,” *Marshall Star*, March 14, 1973, 2; “Space Shuttle External Tank Proposals Released,” *Marshall Star*, April 4, 1973, 1, 4.

¹²⁴⁰ “Martin-Marietta to develop Space Shuttle Tank,” NASA News Release No. 73-163, August 16, 1973, Folder: Space Shuttle-External Tank #1 1972-1973, MSFC History Office, Huntsville.

¹²⁴¹ “NASA Asks Proposals for Shuttle ET,” NASA News Release No. 73-64, April 2, 1973, Folder: Space Shuttle-External Tank #1 1972-1973, MSFC History Office, Huntsville.

¹²⁴² Jenkins, *Space Shuttle*, 187.

¹²⁴³ James B. Odom, interview by Rebecca Wright, *NASA STS Recordation Oral History Project*, July 20, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/OdomJB/OdomJB_7-20-10.htm.

¹²⁴⁴ “Martin Marietta to develop Space Shuttle External Tank,” *Marshall Star*, August 29, 1973, 2.

¹²⁴⁵ “Letter contract extension,” no date, Programs/Projects: Space Shuttle, Drawer 23, Folder: Shuttle-External Tank August-December 1974, MSFC History Office, Huntsville.

¹²⁴⁶ Dunar and Waring, *Power to Explore*, 302.

slated to begin during the latter half of 1975 on ten intertank units, with delivery scheduled for late 1978.¹²⁴⁷

At the time of RFP release, the shuttle systems requirements, including the orbiter tile design, had not been finalized. Later, as the systems requirements matured, design changes to the ET were needed, especially to the TPS materials and their locations.¹²⁴⁸ The Space Shuttle ET Project Requirement Review Board, chaired by Mr. Odom, met at MSFC in early February 1974, to define the program and technical requirements for subsequent design and development. All aspects of the STS hardware interfaces, ET subsystems, test and verification, and flight operations were addressed.¹²⁴⁹ A major discussion point at this time was the proposal to increase by 1,000 pounds the ET control weight of 75,000 pounds. In a note to Dr. William R. Lucas, Director of MSFC (1974-1986), Shuttle Program Manager Robert (Bob) Lindstrom reported that “The loads situation of Shuttle continues to be serious – our most recent ET loads will give us a few hundred pounds impact plus a cost and schedule penalty.”¹²⁵⁰ Robert Thompson, Manager of the Space Shuttle Program Office at JSC (1970-1981), expressed concern for all shuttle element weights. As a result, the “Level II management reserve at MECO of 7,000 pounds” was established “to be used to implement new requirements or tradeoffs among element weight . . .”¹²⁵¹ Reducing the weight of the ET to enable increased payload capacity was a continued concern throughout the SSP.

On August 28, 1974, NASA awarded a \$26,453,600 contract to Martin Marietta for ET contract support through August 31, 1978. This four-year facilities contract provided for the acquisition of plant equipment at MAF, rehabilitation of existing facilities, and construction, modification, maintenance, and repair of facilities.¹²⁵² This contract was amended on February 17, 1977, with the provision of approximately \$3.7 million to fund construction of one new facility plus the addition of Cell D to the Vertical Assembly Building. The amended facilities contract also provided for the continuation of previously authorized facility work.¹²⁵³ According to James Odom, “the buying and the designing of the tooling was extremely crucial to the success of the program.”¹²⁵⁴ He estimated NASA’s original investment in specialized tooling at about \$900 million.

¹²⁴⁷ “Nashville Firm Gets \$32 Million Shuttle Contract,” *Marshall Star*, June 18, 1975, 4.

¹²⁴⁸ Pessin, “Lessons Learned,” 3.

¹²⁴⁹ “Shuttle ET Review Being Held Here,” *Marshall Star*, January 30, 1974, 1, 2.

¹²⁵⁰ Bob Lindstrom to Dr. Lucas, December 23, 1974, Programs/Projects: Space Shuttle, Drawer 23, Folder: Shuttle-External Tank Aug-Dec 1974, MSFC History Office, Huntsville.

¹²⁵¹ Robert F. Thompson to Manager, Shuttle Projects Office, MSFC, August 14, 1974, Programs/Projects: Space Shuttle, Drawer 23, Folder: Shuttle-External Tank Aug-Dec 1974, MSFC History Office, Huntsville.

¹²⁵² “MSFC Awards Support Contract to Martin Marietta,” NASA MSFC News Release No. 74-157, August 28, 1974, Programs/Projects: Space Shuttle, Drawer 23, Folder: Shuttle-External Tank Aug-Dec 1974, MSFC History Office, Huntsville; Whalen and McKinley, “Chronology,” 30.

¹²⁵³ Whalen and McKinley, “Chronology,” 46-47.

¹²⁵⁴ Odom, interview.

NASA's second major contract with Martin Marietta, valued at \$230 million, was awarded in July 1980, for the beginning of full-scale flight tank production to support Shuttle operations. It covered delivery of seven ETs, and provided long lead time procurement for components and subassemblies for five additional tanks and raw material for nineteen more units.¹²⁵⁵ Effective to this contract, NASA's MSFC applied its amendment to the existing ET DDT&E contract with Martin Marietta to add more than \$42.9 million to cover weight reduction redesign and development efforts and to modify tooling to be used in future production. The redesign was in accordance with NASA's plan to reduce the weight of the ET by 6,000 pounds to permit increased payload carrying capacity. Under this new contract, the first lightweight ET was expected to be delivered in the summer of 1982.¹²⁵⁶

Production Buys 2 through 4 (Contract No. NAS8-33708) for fifty-four operational flight tanks and related launch site and flight support, covered the period between June 30, 1980 and June 3, 1991. The value at the end of this contract was \$2,225.9 million. Production Buy 5 (Contract No. NAS8-36200) was for the manufacture, assembly, test, checkout, and delivery of thirty-five lightweight tanks plus twenty-five super lightweight tanks. The \$3,773.0 million contract covered the period between November 2, 1984, and September 30, 2002. Production Buy 6 (Contract No. NAS8-00016, Schedule A), valued at \$908.3 million, covered thirty-five flight tanks plus support for the period of September 27, 1999 through January 29, 2006. Following the *Columbia* accident, this contract was replaced by Schedule F, which called for the manufacture, assembly, test, checkout and delivery of nineteen tanks, between January 30, 2006, and September 30, 2010. The production portion of this contract was valued at \$996.9 million.¹²⁵⁷ Cumulatively, Lockheed Martin's ET contract with NASA was valued at approximately \$11 billion. Approximately 70 percent of the funds committed to the external tank went to subcontractors, most of whom supplied materials to Lockheed Martin.¹²⁵⁸

ET Test Programs

In his technical history of the ET, Myron Pessin described five types of development test programs. These included materials testing, components testing, structural tests, dynamic tests, and propulsion tests. A summary of each follows.

¹²⁵⁵ "ET Production Contract Let," *Marshall Star*, July 2, 1980, 1; "NASA Awards Martin Marietta \$230 Million Contract for Production of Shuttle External Tanks," NASA News, MSFC, Release No. 80-90, Programs/Projects: Space Shuttle, Drawer 23, Folder: ET 1979 and 19809, MSFC History Office, Huntsville.

¹²⁵⁶ "External Tank to be Lightened," *Marshall Star*, July 2, 1980, 1.

¹²⁵⁷ NASA MSFC, Transition Project Office, "STS Stack Recordation Data Package," June 15, 2009.

¹²⁵⁸ Dunar and Waring, *Power to Explore*, 303.

Materials and Components Tests

According to Pessin, the primary focus of the materials test program was the thermal protection materials, including foam insulation and ablators.¹²⁵⁹ Foams were tested under realistic flight conditions in wind tunnels at the USAF's Arnold Engineering Development Center in Tennessee, and ablators were tested in the plasma arc jets at Ames. Unique tests of spray-on foam insulation (SOFI) were conducted at Eglin Air Force Base in Florida. SOFI testing at Eglin made use of a 10'-diameter tank filled with liquid nitrogen and "subjected to various rain, wind, humidity and temperature conditions to determine the rate of ice growth."¹²⁶⁰ These data were later incorporated into a computer program used at KSC to predict whether ice would form during tanking or would exist prior to launch.

During 1976, MSFC engineers used an aluminum "mini-tank" to test the TPS for the LH2 tank. Thirteen tanks, each coated with SOFI, were tested to evaluate the ability of the insulation to withstand various types of stress during launch and flight. Acoustic environment tests exposed the insulation to sound levels averaging about 170 decibels. These tests were conducted to insure that the insulation would not be cracked by sound vibrations created by the SRBs and the SSMEs. The test series also included vacuum tests designed to detect any air pockets between the aluminum tank surface and the foam due to poor bonding. Such air pockets, in a space vacuum, could expand and result in rupturing of the insulation. A third type of mini-tank test examined three kinds of LH2 conditions: pressure, boil off, and hold. The pressure tests helped the NASA engineers determine if the insulation had enough elasticity to expand when the tank was filled and pressurized. Boil off tests, which measured the loss through evaporation, calculated the efficiency of the foam TPS. The objective of the hold tests was to determine the effects of a seven-hour idle period on the insulation system of a full LH2 tank. The knowledge gained during the mini-tank tests was used in the further development of a durable and efficient spray foam TPS for the ET's LH2 tanks.¹²⁶¹

Tests of individual ET components, such as attach fittings and slosh baffles, were performed at both MSFC and MAF. The largest component test was of the ET/orbiter complete aft interface structure, which was run at MAF. For this test, a load frame was built at MAF to simulate the loads from the orbiter.¹²⁶²

Structural Tests

The structural qualification program, according to Odom, was designed "to really understand the capability of literally every square foot on the tank."¹²⁶³ The static structural tests were

¹²⁵⁹ Pessin, "Lessons Learned," 7.

¹²⁶⁰ Pessin, "Lessons Learned," 8.

¹²⁶¹ "Shuttle External Tank Tests Being Conducted at Marshall," *Marshall Star*, August 4, 1976, 4.

¹²⁶² Pessin, "Lessons Learned," 8.

¹²⁶³ Odom, interview.

performed to simulate the loads in the critical areas of prelaunch and flight. Four structural test articles, a LH2 tank, a LO2 tank, and two intertanks, were manufactured and assembled at MAF during 1977.¹²⁶⁴ The two flight-type intertanks differed in TPS materials and instrumentation. Intertank 1 lacked TPS materials, and its instrumentation configuration reflected the requirements for the two standard and one modal test. Intertank 2 featured TPS materials in the vicinity of the LH2 tank interface, and its instrumentation supported the requirements for one test only, the LH2 static test.¹²⁶⁵ A key element of the ET testing program, according to Odom, was that all the test articles were built on exactly the same tooling as the flight articles.”¹²⁶⁶ Testing at MSFC was scheduled to verify the structural integrity of the ET components prior to the first static test firing of the shuttle’s main propulsion system at SSC.¹²⁶⁷ The structural test program was conducted by MSFC’s Test Lab, part of the Center’s Science and Engineering Directorate. Three configurations were tested: the actual intertank with a LO2 tank simulator above and LH2 tank simulator below; the actual intertank and LO2 tank simulator; and the actual intertank and LH2 tank simulator.

The intertank structural test article was shipped from MAF by barge on February 25, 1977, and arrived at MSFC on March 11.¹²⁶⁸ Also transported were a LH2 tank simulator, a LO2 tank simulator, and a LO2 tank modal ring. The intertank and two tank simulators were used in the first series of structural tests, which were completed successfully in mid-November 1977.¹²⁶⁹ During the tests, loads as high as 4.35 million pounds were applied to the intertank test article to verify its capability to withstand the stress of Space Shuttle launch and powered flight. Forces were exerted to induce bending and twisting effects, as well as straight up-and-down loads.¹²⁷⁰

The second phase of ET structural testing focused on the LO2 tank, attached to the intertank.¹²⁷¹ Initially, the LO2 tank was tested with the tank empty, but under internal pressure. Next, testing was performed with the tank filled with barium sulfate (“driller’s mud”) and water to simulate the acceleration effects of the LO2 in flight. The tests simulated both liftoff and maximum acceleration conditions of flight. The final series in this test phase was conducted to verify the structural stability of the tank for LO2 loading during prelaunch operations.¹²⁷²

¹²⁶⁴ “Shuttle ET Test Articles Near Completion at MAF,” *Marshall Star*, July 6, 1977, 2.

¹²⁶⁵ Martin Marietta Corporation, *System Definition Handbook, Configuration and Operation, Space Shuttle External Tank* (Huntsville, AL: MSFC History Office, November 1975), XIII-8.

¹²⁶⁶ Odom, interview.

¹²⁶⁷ “Shuttle Structural Hardware Shipped to Marshall Center,” NASA News, MSFC, Release No. 77-30, February 25, 1977, Programs/Projects: Space Shuttle, Drawer 23, Folder: ET 1977, MSFC History Office, Huntsville.

¹²⁶⁸ “ET Intertank Test Article To Arrive at MSFC March 11,” *Marshall Star*, March 9, 1977, 1, 4.

¹²⁶⁹ “Major Tank Test Article Shipped,” *Marshall Star*, March 2, 1977, 3; “ET Test Hardware Arrives,” *Marshall Star*, March 16, 1977, 4; “1977 Was a Busy Year for Marshall,” *Marshall Star*, December 21, 1977, 3; “External Tank Segment Successfully Tested,” NASA News, MSFC, Release No. 77-212, November 11, 1977, Programs/Projects: Space Shuttle, Drawer 23, Folder: ET 1977, MSFC History Office, Huntsville.

¹²⁷⁰ “External Tank Structural Testing Begins at MSFC,” *Marshall Star*, August 24, 1977, 1.

¹²⁷¹ “Intertank Passes Tests,” *Marshall Star*, November 16, 1977, 1.

¹²⁷² “Structural Testing of Liquid Oxygen Tank Begins Here,” *Marshall Star*, July 18, 1979, 1, 2.

During the next test phase, the LH2 tank, attached to the intertank, was loaded and taken to 140 percent of design limit loads for three different conditions (Figure No. D-1). Testing entailed filling the LH2 tank with nitrogen at 42 psi for fourteen hours and applying hydraulic loads as high as 600 tons at the SRB attach points.¹²⁷³ The tank was loaded with LH2, and the aft attach points were constrained as they would be by the SRMs. During this test, the tank buckled near the attach point and foam was debonded and shed. According to Pessin, this failure resulted from “cryoshrinkage” of the metal frame and dome.¹²⁷⁴

A modal test performed on the LO2 tank closed out the structural test program (Figure No. D-2). According to Chuck Verschoore, former MSFC Test Laboratory lead for structural testing, the modal test evaluated the dynamic nature of the structure.¹²⁷⁵

Main Propulsion Test Program

The Main Propulsion Test Program was critical in demonstrating the performance of the ET from a propulsion perspective. The first ET, designated as the Main Propulsion Test Article External Tank (MPTA-ET), was rolled out at MAF on September 9, 1977 (Figure No. D-3). It was a flight weight tank with flight type insulation. Following a brief ceremony, the ET was loaded on a barge and shipped to SSC (then, NSTL) for installation on the test stand and subsequent static test firing of the three main engines.¹²⁷⁶ The first static firing of the MPTA was on April 21, 1978. Previously at SSC, the first ET tanking test was conducted on December 1, 1977. The purpose of this test was to verify that the MPTA, as well as the test facility, could withstand the super-cold LH2 and LO2 used to fuel the SSME. In the test, the ET was filled with LH2 and LO2, and these propellants were flowed through the connecting piping to the three main engines. The test results validated that the engines could be cooled down to their operating temperature. Several days earlier, the ET had been filled with a 40 percent load of LO2 and vibrated to provide information on the natural frequencies of the MPTA.¹²⁷⁷

According to Pessin, the MPTA program resulted in many important contributions. It proved the concept for delivery of propellant through a cross feed system; provided a mechanism to qualify the propellant delivery lines; developed the propellant loading software and procedures; demonstrated the location of the various loading sensors and the baffles necessary for their proper operation; and demonstrated that the anti-geysering line could be removed.¹²⁷⁸

¹²⁷³ Whalen and McKinley, “Chronology,” 49; “First Liquid Hydrogen Tank Completes Test,” *Marshall Star*, May 11, 1977, 1.

¹²⁷⁴ Pessin, “Lessons Learned,” 12.

¹²⁷⁵ Chuck Verschoore, Interview by Sarah McKinley, June 27, 1988, *Oral Interviews: Space Shuttle History Project Transcripts Collection, Report No. MHR-16*, NASA MSFC, December 1988.

¹²⁷⁶ “1st Shuttle ET Set For Rollout Sept. 9,” *Marshall Star*, September 7, 1977, 1, 2.

¹²⁷⁷ “ET’s Tanking Test at NSTL Is Successful,” *Marshall Star*, January 11, 1978, 4.

¹²⁷⁸ Pessin, “Lessons Learned,” 15.

The MPTA-ET was actually in the test stand at SSC for more than seven years, during which time it was used in many test firings, propellant loadings, and proof tests. Given the long period of exposure, the test article experienced massive corrosion problems, resulting, in part, from the use of a non-protecting primer. To maintain its usefulness, the test tank was stripped, cleaned, primed, and recovered with foam while in the test stand at least twice during the MPTA program.¹²⁷⁹ After cancellation of the program, the MPTA-ET was modified for display at the U.S. Space and Rocket Center in Huntsville, Alabama.

Ground Vibration Test Program

Following completion of the ALT program (See Part IA, Historical Context), the orbiter prototype *Enterprise* was flown to MSFC for a series of Ground Vibration Tests (GVT) to determine the structural integrity of the shuttle vehicle. The test program, initiated in May 1978, and completed in February 1979, simulated the period of flight just prior to SRB separation.¹²⁸⁰

Three basic test configurations were used to match conditions during the various phases of an actual flight. The first phase of the test series, started in late May 1978, used the GVT-ET test article (Figure No. D-4) mated to the *Enterprise*. The LO2 tank contained deionized water and the LH2 tank was pressurized but empty. The combined orbiter-ET was suspended by a combination of air bags and cables on a truss structure attached to the top of the Structural Dynamic Test Facility (Building 4550) at MSFC. This configuration was used to simulate the high altitude portion of ascent after SRB separation.

During filling of the test article's LO2 tank with water, the forward dome "buckled." This "critical design weakness" was similar to the problem revealed during the structural tests.¹²⁸¹ To solve this problem, pressure was applied to the tank during loading.¹²⁸² Following the recommendation to resume testing using existing hardware, the Test Readiness Review Board gave permission on May 23, 1978.¹²⁸³

In August 1978, following modifications to Building 4550, the second series of vibration tests added a set of SRBs containing inert propellant to simulate lift-off conditions. "This marked the first time that a complete set of dimensionally correct elements of the Space Shuttle had been assembled together."¹²⁸⁴ This phase of testing ended on December 2, 1978.

¹²⁷⁹ Pessin, "Lessons Learned," 14.

¹²⁸⁰ Dunar and Waring, *Power to Explore*, 314.

¹²⁸¹ Pessin, "Lessons Learned," 13.

¹²⁸² Odom, interview.

¹²⁸³ A.A. McCool, *Final Report on MVGVT Lox Tank Incident*, May 31, 1978, Programs/Projects: Space Shuttle, Drawer 23, Folder: ET 1978, MSFC History Office, Huntsville.

¹²⁸⁴ Jenkins, *Space Shuttle*, 213.

The third and final phase of testing, initiated in January and completed in late February 1979, used a configuration similar to the second series, except that the SRBs were empty. It simulated the configuration of the Shuttle just prior to the burnout and separation of the SRBs. As a result, among other findings, “new insight into the reaction of attach points between the tank and the boosters was gained.”¹²⁸⁵

Following the completion of the GVT program, in March 1979, the ET was transported by barge to KSC for use in fit checks at the VAB and for training personnel in stacking operations. Later, the GVT-ET was returned to MAF for evaluation and refurbishment.¹²⁸⁶ Plans to refurbish and recycle it into a production ET were never realized.

ET Evolutionary Development

Beginning in early 1975, NASA’s MAF was made ready for manufacture of the ET. More than 300 special tools, including thirty-four major fixtures, were required to build and assemble the ETs, including fitting, trimming, welding, and the application of TPS materials. Roughly half of the special tooling was completed by October 1975, and expected to be ready in the spring of 1976.¹²⁸⁷ At roughly the same time that assembly of the first test tank was initiated, in late July 1976, over 1,298 tons of material for tooling and fixtures had arrived at MAF.¹²⁸⁸

The ET was developed in three evolutionary stages. From the original Standard Weight Tank (SWT) to the third-generation Super Lightweight Tank (SLWT), the changes reflected successive efforts to increase Shuttle payload capacity, incident to the assembly of the ISS, by lightening the weight of the tank. In general, every pound reduced from the ET resulted in another pound that could be taken to orbit. ET weight reductions also enabled the Shuttle to go to a higher orbit.

The original SWT, manufactured until 1983, weighed approximately 76,000 pounds (Figure No. D-5). To provide more payload launch capacity, in 1980, MSFC began a two-year tank redesign program to trim 6,000 pounds from the weight of the original SWT.¹²⁸⁹ The Lightweight Tank (LWT), in production from 1981 through 1998, weighed roughly 10,000 pounds less, or about 66,000 pounds, while the SLWT, which debuted in 1998, weighed approximately 58,500 pounds. Following the *Columbia* accident in 2003, the SLWT underwent a series of additional improvements, including the incorporation of friction-stir welding to the manufacturing process.

¹²⁸⁵ “Vibration Tests Provide Valuable Data on Shuttle,” *Marshall Star*, March 7, 1979, 1, 4.

¹²⁸⁶ “Test ET Leaves MSFC Enroute to Kennedy,” *Marshall Star*, March 21, 1979, 1.

¹²⁸⁷ “Shuttle Tank Tooling-up Underway at New Orleans,” *Marshall Star*, July 28, 1976, 1.

¹²⁸⁸ “Michoud Plant Nearing ET Production Capability,” NASA News, MSFC, Release No. 76-60, August 6, 1976, Programs/Projects: Space Shuttle, Drawer 23, Folder: ET 1976, MSFC History Office, Huntsville; Whalen and McKinley, “Chronology,” 42.

¹²⁸⁹ Dunar and Waring, *Power to Explore*, 320.

Standard Weight Tank

Fabrication of the first flight ET began in 1977, and during 1978, the first six flight ETs were in various stages of component fabrication, assembly, and acceptance testing. ET-1 moved to the checkout area at MAF for inspection, final painting over the SOFI, and acceptance reviews during the last week of June 1979.¹²⁹⁰ It was rolled out and delivered to NASA on June 29, 1979, then barged to KSC for flight on STS-1.¹²⁹¹

ET-1 through ET-6, used for development flight tests, contained additional DFI to confirm the ET design and to provide for diagnostic analysis in case of flight anomalies. The DFI was an independent system designed as an add-on to the operational instrumentation system. It was designed to “leave minimal scars upon its removal.”¹²⁹²

The SWT weighed 73,415 pounds empty, according to the contractor’s 1975 *System Definition Handbook*.¹²⁹³ The basic structure of the original SWTs was made of aluminum alloy 2219; aluminum alloys 2024 and 7075 also were used. Tank sections, comprised of many thicknesses of aluminum sheeting, were assembled by gas tungsten arc welding.¹²⁹⁴ The second flight tank, ET-2, weighed about 200 pounds less than the first.¹²⁹⁵ ET-3 was the first tank which did not feature a coat of white latex paint. Originally added for atmospheric protection, elimination of the paint resulted in a 600 pound weight reduction.¹²⁹⁶ It also provided almost 600 pounds of extra shuttle payload carrying capacity, and saved about \$15,000 in manufacturing costs.¹²⁹⁷ The first unpainted, rust-colored ET was launched on March 22, 1982, with STS-3. The anti-geysering line, used to circulate LO2 in the LO2 fill system, was found to be unnecessary and deleted on ET-4, resulting in weight and cost savings.¹²⁹⁸ The last of the total six SWTs was delivered to KSC on July 26, 1982. ET-6, flown on *Challenger’s* STS-7 mission, was the last flight SWT used.

¹²⁹⁰ “ET-1 Moves to Final Checkout,” *Marshall Star*, June 20, 1979, 4.

¹²⁹¹ “First Flight ET Is Ready for Rollout,” *Marshall Star*, June 27, 1979, 1; “MSFC’s Elements For First Shuttle Delivered to KSC,” *Marshall Star*, August 8, 1979, 1.

¹²⁹² Martin Marietta, *Handbook, Configuration & Operation*, XII-2. Removal of the DFI coincided with the first LWT. Pessin, “Lessons Learned,” 20.

¹²⁹³ Martin Marietta, *Handbook, Configuration & Operation*, I-3.

¹²⁹⁴ Carl R. Weymueller, “King-size fuel tank boosts spacemen into orbit,” *Welding Design & Fabrication* (May 1979): 177-178.

¹²⁹⁵ Kolcum, “Lightweight Tank,” 133.

¹²⁹⁶ The foam was susceptible to ultraviolet light, and started to deteriorate when on the pad. To avoid deterioration, the first two ETs were painted. Odom, interview.

¹²⁹⁷ NASA MSFC, *Shuttle Color Change*, NASA Fact Sheet (Huntsville, AL: George C. Marshall Space Flight Center, March 1980), MSFC History Office, Huntsville.

¹²⁹⁸ Pessin, “Lessons Learned,” 16; “Assembly Now Underway To Lighten External Tank,” *Marshall Star*, December 10, 1980, 2.

Lightweight Tank

Assembly of the first LWT, ET-8¹²⁹⁹ (Figure No. D-6), began in November 1980, with work on the aft dome of the LH2 tank. The tank arrived at KSC on September 8, 1982, and launched with STS-6 in April 1983. The eighty-fifth and final LWT was delivered to KSC on April 19, 1999, and flew on STS-99. The second generation ET (Figure No. D-7) weighed approximately 10,000 pounds less than the SWT.¹³⁰⁰ To accomplish the weight reduction, the thickness of many of the aluminum skin panels was reduced. Selected stringers in the LH2 tank were eliminated, and fewer ring stiffeners were used in the barrel assemblies. Major frames in the LH2 tank were modified, and the slosh baffle in the LO2 tank was redesigned, resulting in a 600 pound reduction.¹³⁰¹ Dome caps, which were chemically milled on only one side, were now milled on both sides to reduce thickness and weight without reducing strength.¹³⁰² Beginning with ET-8, the GH2 pressurization line was relocated and the cable trays were reduced in size. This change allowed for the elimination of ablator from a section of the tank.¹³⁰³ A titanium alloy which was stronger, lighter, and less expensive than the previous material, was used for the aft SRB attachments. Specifically, all 5A1-2.5 titanium alloy fittings were changed to 6A1-4V titanium alloy, and all 7075-T73 aluminum hardware was changed to 7050-T73 aluminum.¹³⁰⁴

Like the SRBs, the original SWT contained a RSS capable of destroying the vehicle. The ET package consisted of linear-shaped charges on both the LO2 and LH2 tanks. Beginning with ET-80, the ET RSS was eliminated; the RSS was retained in the SRBs.¹³⁰⁵ Elimination also enabled removal of the high temperature ablator, MA25S, from the cable tray segments where the linear-shaped charges were located, thus resulting in a small weight savings to the ET.¹³⁰⁶ STS-78/ET-79 was the last to carry the ET RSS; STS-79/ET-82 was the first flight without it.

According to Pessin, in order to enhance operations, two modifications were made which increased the ET weight. Approximately 200 pounds were added to the LO2 tank “to permit the topping and replenish flows to take place,” and over 400 pounds of aluminum were added to the LH2 tank aft domes in the form of circumferential ribs to stiffen the gores.¹³⁰⁷

New welding techniques made LWT production more labor and cost efficient. Beginning in 1984, MSFC adopted Variable Polarity Plasma Arc welding. This method required less preweld

¹²⁹⁹ Martin Marietta did not assign the number ET-7 since the tank was never completed.

¹³⁰⁰ The weight savings from deleting the anti-geysering line and the white paint, both effected during SWT production, as well as the removal of DFI, were “booked” to the LWT reduction. Pessin, “Lessons Learned,” 20.

¹³⁰¹ Martin Marietta, “First Lightweight Propellant Tank to Fly on Shuttle Tomorrow,” n.d., Sweetsir Collection, STS-6C, Folder 125, Kennedy Space Center Archives, Florida.

¹³⁰² Kolcum, “Lightweight Tank,” 133; Martin Marietta, “Propellant Tank.”

¹³⁰³ Pessin, “Lessons Learned,” 16.

¹³⁰⁴ Jenkins, *Space Shuttle*, 422.

¹³⁰⁵ Jenkins, *Space Shuttle*, 434.

¹³⁰⁶ Pessin, “Lessons Learned,” 25.

¹³⁰⁷ Pessin, “Lessons Learned,” 12, 20.

cleaning and edge preparation, and also minimized weld defects. Plasma Arc welding became the baseline process until the SLWT tools came along.¹³⁰⁸

Super Lightweight Tank

The SLWT, introduced in 1998, weighed 7,500 pounds less than the previous LWT, and allowed the Space Shuttle to carry heavy components for assembly of the ISS (Figure No. D-8).¹³⁰⁹ The primary difference between the LWT and the SLWT was a change in material; no changes were made to the basic components. Aluminum alloy 2219 was replaced with aluminum-lithium (Al-Li) alloy 2195 in most of the major structures. This alloy was part of the Weldalite family developed and patented by Lockheed Martin Laboratories in Baltimore, Maryland. Al-Li alloy 2195 is composed of 1 percent lithium, 4 percent copper, 0.4 percent silver, 0.4 percent magnesium, and 94.2 percent aluminum. It is 30 percent stronger and 5 percent less dense than the original 2219 aluminum alloy.¹³¹⁰ Pre-production laboratory tests showed that Al-Li alloy 2195 could be welded, and could withstand a temperature of minus 423 degrees F, the temperature at which LH2 is stored. Originally, Reynolds Metals in Chicago, Illinois, provided the Al-Li material for SLWT production. After the company was sold to Alcan, located in Ravenswood, West Virginia, Alcan became the supplier.¹³¹¹ While this aluminum-lithium alloy had superior qualities, NASA and Lockheed Martin engineers experienced many difficulties as they learned to form, weld and repair this new material.¹³¹² As Pessin noted, “we were starting a program with a squeezed schedule, one on which the whole reputation of NASA was riding, and we could not make the material and could not make the repairs in it.”¹³¹³ Weld repairs were a significant challenge for production of the SLWTs using the new Al-Li alloy 2195.

In the LH2 tank, the Al-Li 2195 replaced aluminum alloy 2219 in the dome cap and eleven of the twelve gore panels; the major ring frame outer chord at Station 1129;¹³¹⁴ the barrel panels; the ring frames; and the forward dome gore panels. Material replacement in the LO2 tank included the aft dome cap and gore panels; the Station 852 outer chord; the forward and aft ogive gores; the barrel panels; and the Station 745 T-ring outer chord.¹³¹⁵ The LH2 aft dome gore was left as 2219 aluminum “to eliminate the need to develop the weld processes in aluminum lithium.”¹³¹⁶

¹³⁰⁸ Pessin, “Lessons Learned,” 22; Dunar and Waring, *Power to Explore*, 321.

¹³⁰⁹ Lockheed Martin Corporation, “External Tank,” 2010, <http://www.lockheedmartin.com/ssc/michoud/ExternalTank/index.html>; NASA MSFC, “Super Lightweight External Tank,” April 2005, http://www.nasa.gov/centers/marshall/pdf/113020main_shuttle_lightweight.pdf.

¹³¹⁰ Lockheed Martin, “External Tank,” NASA MSFC, “Super Lightweight External Tank.”

¹³¹¹ Lockheed Martin Space Systems Company, “Space Shuttle Super Lightweight External Tank,” July 2010, <http://www.lockheedmartin.com/data/assets/9166.pdf>.

¹³¹² Pessin, “Lessons Learned,” 28-30.

¹³¹³ Pessin, “Lessons Learned,” 31.

¹³¹⁴ See page 314 for a definition of “station.”

¹³¹⁵ R.S. Ryan, “A History of Aerospace Problems, Their Solutions, Their Lessons,” NASA Technical Paper 3653 (Huntsville, AL: MSFC History Office, September 1996), 112, 114.

¹³¹⁶ Pessin, “Lessons Learned,” 36.

Many of the mechanically fastened materials in the intertank, skins, stringers, and doublers were changed to Alcoa's Al-Li 2090.

Compared with the LWT, membrane thickness in the SLWT was resized in the LH2 tank dome cap and eleven gores, as well as the LH2 aft dome cap, gore panels, and barrel panels.¹³¹⁷ Many SLWT weld lands were increased in thickness by up to 0.35" to allow more margin for potential weld repairs. These robust weld lands included the longeron to barrel panel; barrel panel to barrel panel on Barrel No. 2 forward of the longerons; Frame 1623 and 1377 chord to chord aluminum 2195 welds; LH2 forward and aft dome gore to dome gore; LH2 forward and aft chord to gore; LH2 aft dome cap to dome body; and LH2 aft manhole and siphon plate.¹³¹⁸

In addition to the change in material, the SLWT's structural design was improved. The SLWT featured a new orthogonal waffle grid design (called an orthogrid) to improve strength and stability. The new design replaced the LH2 tank T-stiffeners, and provided almost half of the SLWT weight savings. Weight savings also were made by machining off the excess foam on the entire intertank, resulting in a reduction of approximately 270 pounds of foam. Additionally, the thickness of the foam applied to the LH2 barrel section was controlled, saving about 55 pounds on the SLWT.¹³¹⁹ Seven Z frames were eliminated in the LH2 tank barrel panels, and one baffle tray was removed from the LO2 tank.¹³²⁰

The first SLWT, ET-96, arrived at KSC in February 1998. It flew with *Discovery's* STS-91 mission, launched on June 2, 1998. ET-138, the last production SLWT, flew on STS-135 (July 8, 2011), the final mission of the SSP (Figure No. D-9).

Prior to the STS-91 mission, between February and September 1996, a special Aluminum Lithium Test Article (ALTA) was used in a series of SLWT certification and capability tests at MSFC. The test article consisted of a single ET barrel with a forward LH2 dome and an aft LO2 dome. It measured 40' long and 27' in diameter.¹³²¹ Reynolds Metals Company cast the Al-Li 2195 ingots for the ALTA.¹³²² To verify the structural integrity of the LH2 tank's new orthogonal waffle-like design and new aluminum lithium material, the test article was exposed to loads and pressures to simulate the conditions while at the pad, at liftoff, and when the SRBs separated from the shuttle. Following completion of the certification test series, the test article underwent a series of capability tests, including testing the article to the point of failure. While

¹³¹⁷ Ryan, "Aerospace Problems," 112, 114.

¹³¹⁸ Lockheed Martin, *Space Shuttle External Tank, System Definition Handbook SLWT, Layout Drawings Volume II* (New Orleans, LA: Lockheed Martin, December 1997), III-5, MSFC History Office, Huntsville.

¹³¹⁹ Pessin, "Lessons Learned," 32, 36, 37.

¹³²⁰ Ryan, "Aerospace Problems," 112, 114.

¹³²¹ Pessin, "Lessons Learned," 34; Ed Campion and June Malone, "Super Lightweight External Tank Certification Testing to Begin," February 1996, http://findarticles.com/p/articles/mi_pasa/is_199602/ai_901012153.

¹³²² Martin Marietta Manned Space Systems, "Tank weld assembly team prepares for test schedule," *Mission Success Bulletin* (Huntsville, AL: MSFC History Office, August 23, 1994), 2.

not required to certify the tank for flight, these tests provided valuable data about the SLWT's structural capability.¹³²³

A “second generation” of SLWTs used a lighter, stronger alloy (Al-Li 2297) in the intertank thrust panels, resulting in a significant weight savings. Following on this change, although adding weight back, all of the dome gores and ogive gores were converted back to 2219 aluminum, which was easier to weld, and which drastically reduced repairs.¹³²⁴

The final enhancement to the SLWT was the introduction of friction stir welding. This process was selected by ET project managers because it produced stronger welds that were easier to make on the lighter-weight Al-Li 2195 alloy. Friction stir welding also had “significantly fewer process elements to control,” compared with fusion welding, used in the manufacture of the earlier tanks.¹³²⁵ Additionally, the process variables were highly repeatable, and minimized the risk of weld defects.¹³²⁶ NASA and Lockheed Martin initially demonstrated the effectiveness of the friction stir welding process in 1998 using a 27.5'-diameter simulated LH2 tank with six barrel panels. Two subsequent special studies were completed between 1999 and 2001, and friction stir welding was implemented into production in 2001. Eight longitudinal weld joints on the LH2 barrel and four longitudinal welds on the LO2 barrel were welded using this process, totaling approximately 700' of weldments on each ET.¹³²⁷

ET-132 was the first ET to fly (STS-132, launched on August 28, 2009) with a friction stir weld.¹³²⁸ It featured longitudinal friction stir welds on two of the LH2 tank barrels. ET-133, flown with *Atlantis* in November 2009, also featured friction stir welds on two barrels. ET-134, the 130th tank Lockheed Martin fabricated for the SSP, and which flew on *Endeavour's* STS-134 mission, was the first flight ET to feature longitudinal friction stir welds on all four LH2 tank barrels and the single LO2 tank barrel.¹³²⁹ ET-134 also featured lighter aluminum lithium material on the intertank thrust panels and on the LO2 tank aft ogive panels.¹³³⁰

¹³²³ Michael Braukus and June Malone, “Shuttle Super Lightweight Fuel Tank Completes Test Series,” July 1996, http://findarticles.com/p/articles/mi_pasa/is_199607/ai_238988282.

¹³²⁴ Pessin, “Lessons Learned,” 37.

¹³²⁵ NASA MSFC, “Friction Stir Welding,” 2001, http://www.nasa.gov/centers/Marshall/pdf/104835main_friction.pdf.

¹³²⁶ Jeff Ding, et al., “A Decade of Friction Stir Welding R&D At NASA's Marshall Space Flight Center and a Glance into the Future,” NASA MSFC, no date, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080009619_2008009118.pdf.

¹³²⁷ Ding, et al., “Friction Stir Welding.” Each ET has approximately one-half mile of total weldments.

¹³²⁸ Lockheed Martin, “Flight Info.”

¹³²⁹ “External Tank Flies with Improved Welds.” ET-134 also debuted improved intertank, thrust panels constructed of Al-Li 2297, a lighter material, which replaced AL-Li 2219, used on all previous intertanks.

¹³³⁰ Lockheed Martin, “Flight Info,” 97. Aluminum 2219 was substituted with Aluminum 2297, which has lower density (7 percent) with similar mechanical properties. This change resulted in an approximate 226 pound reduction in structural weight. Chris Bergin, “STS-132 FRR approves May 14 launch date – External Tank Boost,” May 5, 2010, <http://www.nasaspaceflight.com/2010/05/sts-132-frr-approve-may-14-external-tank-boost/>.

Thermal Protection System Changes

“Of all the changes other than the weight reduction – which is by design,” James Odom stated, “the changes to the TPS was [sic] probably the most difficult and probably cost us the most money.”¹³³¹ Every time a component in a foam was changed, the foam needed to be recertified. Porter Bridwell, former ET Program Manager, agreed that the TPS materials represented a major change to the tank.¹³³² Compliance with new federal environmental regulations was a key driver of change in NASA’s use of ET TPS materials, particularly affecting the use of certain types of insulating foam.

On September 16, 1987, leaders from the U.S. and other world nations signed the “Montreal Protocol on Substances that Deplete the Ozone Layer.” Under this international environmental treaty, Class I ozone-depleting compounds, such as chlorofluorocarbons (CFCs), were to be phased out of production by the end of 1995. The Environmental Protection Agency (EPA) set a date of January 1, 1996, for the total phase out of CFCs.¹³³³ CFC-11, a Freon-based blowing agent, was a major constituent in foams used for the ET, including those in the CPR, NCFI, BX, and PDL families.¹³³⁴ Production of this compound after 1995 was allowed only by special exemption, and with Montreal Protocol approval. After extensive testing, NASA’s ET Project proposed to replace CFC-11 with the hydrochlorofluorocarbon (HCFC) HCFC-141b for applying the NCFI foams.¹³³⁵ At the same time, the EPA allowed NASA to continue use of stockpiled supplies of CFC-11 until HCFC-141b was certified for use on the Space Shuttle and phased in.

Provided with several years of advance notice, according to Pessin, NASA and Lockheed Martin worked to develop and qualify a second source for the sidewall foam. When this foam was reformulated with the HCFC-141b blowing agent, it was able to meet all known ET requirements.¹³³⁶ The new foam, NCFI 24-124 containing HCFC-141b, was certified for flight, and phased in over three tanks. It was first used on the LH2 tank aft dome of ET-82 which flew with STS-79 in 1996. In 1997, beginning with ET-88/STS-86, the HCFC-141b-containing foam was applied on the tank’s acreage.¹³³⁷

In 1999, the EPA expanded its ban on ozone-depleting substances. As a result, BX-250, a polyurethane foam containing CFC-11, was banned. NASA’s request for an exception was

¹³³¹ Odom, interview.

¹³³² Porter Bridwell, interview by Jessie Whalen and Sarah McKinley, December 18, 1987, *Oral Interviews: Space Shuttle History Project Transcripts Collection*, NASA MSFC, December 1988, 37.

¹³³³ U.S. EPA, “Montreal Protocol on Substances that Deplete the Ozone Layer,” no date, http://www.epa.gov/ozone/downloads/MP20_FactSheet.pdf.

¹³³⁴ CPR denotes Chemical Products Research (which was bought by Upjohn, which, in turn, was purchased by Dow); NCFI is the North Carolina Foam Industries; PDL denotes Product Development Laboratory.

¹³³⁵ The HCFCs were later targeted for phase-out by the EPA. U.S. EPA, “Montreal Protocol.”

¹³³⁶ Pessin, “Lessons Learned,” 26.

¹³³⁷ NASA MSFC, *External Tank Thermal Protection System*, NASA Facts, (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/114022main_TPS_FS.pdf.

granted by the EPA, and subsequently, NASA developed BX-265 foam, applied with HCFC-141b, as a replacement. In December 2001, BX-265 first flew as a replacement of BX-250. However, tanks already insulated with BX-250 continued to be flown as BX-265 was implemented through the manufacturing process.¹³³⁸

Post-Columbia Modifications to the ET

Historical Background

On January 22 and 24, 1981, the LH2 and LO2 tanks of ET-1 were loaded with 1.6 million pounds of propellants in preparation for STS-1. A few days later, *The Huntsville Times* reported that engineers at KSC were inspecting damaged foam insulation on *Columbia's* ET. Two sections of foam insulation had come loose in the area of the bipod that attached the orbiter's nose to the tank. The cause was believed to be related to the slight shrinkage of the aluminum tank as the supercold LH2 and LO2 were loaded.¹³³⁹ Repairs began on March 8, and *Columbia* was launched on April 12, 1981, marking the beginning of the Space Shuttle flight program.¹³⁴⁰ While the STS-1 mission was a success, about 300 orbiter tiles needed replacement due to damage from ET foam impacts.

The foam "liberation" on the Shuttle's first flight ET foreshadowed the events ahead, culminating with the *Columbia* accident, when foam debris struck the orbiter's wing leading edge, resulting in the loss of the STS-107 shuttle crew and vehicle. As underscored in the report of the CAIB, "the shedding of External Tank foam – the physical cause of the *Columbia* accident – had a long history. Damage caused by debris has occurred on every Space Shuttle flight, and most missions have had insulating foam shed during ascent."¹³⁴¹ The CAIB report also noted that of the seventy-nine missions for which photographic imagery was available, there was evidence of foam shedding for sixty-five of the missions.¹³⁴²

In the aftermath of the tragedy, the CAIB recommended that NASA initiate an aggressive program to eliminate all ET TPS debris-shedding at the source (Figure No. D-10). In response, NASA developed and implemented a three-phase approach. Phase 1, implemented prior to RTF, focused on already built tanks. Tests and analyses were conducted to understand the root causes of foam shedding. As a result, structural changes were made to the LH2 tank ice/frost ramps; the LO2 feedline brackets; the forward ET/orbiter attach fitting, called the bipod; and the LO2 tank feedline bellows.

¹³³⁸ NASA MSFC, *Thermal Protection System*.

¹³³⁹ Whalen and McKinley, "Chronology," 79.

¹³⁴⁰ Whalen and McKinley, "Chronology," 81.

¹³⁴¹ CAIB, *Report, Volume I*, 121.

¹³⁴² CAIB, *Report, Volume I*, 122.

In addition to these modifications, enhanced process controls were implemented to improve safety and to reduce instances of liberated foam. These included test panels, video review of spray applications, increased inspections, and more refined engineering requirements. Beginning with the first RTF mission, STS-114, an enhanced finishing procedure was implemented to improve foam application to the stringers, or intertank ribbing, and to the upper and lower area of the LH2 intertank flange.¹³⁴³

Phase 2 efforts, not considered mandatory for RTF, focused on continuous improvement, such as practical debris elimination enhancements that could be incorporated into production. Phase 3 encompassed long-term development activities that would eliminate TPS foam on the vehicle. The Phase 3 changes were never implemented, due to the retirement of the SSP.¹³⁴⁴

NASA conducted two RTF missions to validate the effectiveness of the changes made to meet the recommendations of the CAIB: STS-114/ET-121 in July 2005, and STS-121/ET-119 in July 2006. ET-120 was the first tank to be modified with new safety improvements mandated by the CAIB. It shipped from MAF on December 31, 2004, and was scheduled to fly with *Discovery* on the first RTF mission, STS-114, originally set to launch on May 22, 2005.¹³⁴⁵ However, when the results of a tanking test indicated ice build up on the LO2 feedline bellows, a problem that could not be addressed on the pad, *Discovery* was returned to the VAB where ET-120 was swapped out with ET-121. On July 26, 2005, at 127 seconds into the flight, a piece of foam, measuring about 36" long and 11" wide, detached from the tank. The location of the foam loss was approximately 15' below the flange that joined the intertank to the LH2 tank, or about 20' from the top of the LH2 Protuberance Air Load (PAL) ramp. Thus, despite significant modifications to reduce the possibility of foam loss, STS-114 experienced foam liberation during ascent; the foam did not impact the orbiter.

After STS-114, in October 2005, NASA shipped both ET-119 and ET-120 back to MAF for destructive evaluation and non-destructive evaluation (NDE) to determine the most probable cause of the foam losses, and "to redesign, test, and eliminate those causes."¹³⁴⁶ Subsequently, in October 2005, ET-120 was used as a dissection test article during an investigation at MAF to better understand the foam loss on the PAL and ice/frost ramps during the STS-114 mission.¹³⁴⁷ Dissections revealed TPS cracking at the LH2 PAL ramp and LH2 ice/frost ramp locations of ET-120. Unlike ET-120, which had been through two tanking and thermal cycles, ET-119, which

¹³⁴³ NASA MSFC, *Space Shuttle External Tank ET-128, STS-124*, NASA Facts, (Huntsville, AL: George C. Marshall Space Flight Center, 2008), http://www.nasa.gov/centers/marshall/pdf/228641main_8-368946_28229.pdf.

¹³⁴⁴ NASA, *NASA's Implementation Plan*, 1-4.

¹³⁴⁵ NASA, *STS-120, Harmony: A Global Gateway* (Washington, DC: NASA, October 2007), 68, http://www.nasa.gov/pdf/192725main_STS-120_Shuttle_Press_Kit.pdf.

¹³⁴⁶ NASA, *Implementation Plan*, xiii.

¹³⁴⁷ Following its use in the foam loss investigation, ET-120 was repaired to return it to flight status. Repair work began in October 2006, and ET-120 supported the launch on need effort for *Endeavour's* STS-118 mission, launched in August 2007. Later, ET-120 flew with *Discovery's* STS-120 mission, launched on October 23, 2007.

had not been through these cycles, did not have cracks in the LH2 tank's PAL ramp foam. The cracks most likely occurred during thermal cycling, it was concluded, "and similar cracks were the most likely cause of the foam loss on STS-114/ET-121."¹³⁴⁸

PAL ramps (Figure No. D-11) were manually sprayed wedge-shaped layers of foam. Originally, they were designed as a safety precaution to protect the pressurization lines and cable tray along the side of the ET from airflow during ascent. Prior to their elimination, each ET had two PAL ramps. One was located near the aft end of the LO2 tank, just above the intertank, and the other was below the intertank, along the upper end of the LH2 tank. Both ramps extended about 5' into the intertank area. The LO2 PAL ramp was 13.7' long and the LH2 PAL ramp was 36.6' long. Prior to STS-114, PAL ramp foam loss had been observed on STS-4/ET-4 and STS-7/ET-6. The likely causes of these losses were believed to be repairs and cryo-pumping (air ingestion) into the ablator panels under and adjacent to the PAL ramps.¹³⁴⁹

Following nearly three years of studies and testing, NASA determined that eliminating the PAL ramps was the best means of reducing the risk of foam debris. Removal of the PAL ramps reduced the weight of the ET foam by about 37 pounds.¹³⁵⁰ ET-119, flown on the second RTF mission, STS-121, which launched on July 4, 2006, was the first to fly without PAL ramps.¹³⁵¹ The tank featured small, foam ice/frost ramp extensions, which had been added to the ice/frost ramp locations where the PAL ramps were removed. A total of nine extensions were added, six on the LH2 tank and three on the LO2 tank. Each weighed 0.10 pounds.¹³⁵² This mission demonstrated that removal of the PAL ramp was successful in reducing the debris risk. As a result, the PAL ramps were removed from all future tanks. ET-128, launched with STS-124 on May 31, 2008, was the first tank to fly with all RTF improvements incorporated during production instead of being added after manufacturing was complete.¹³⁵³

Description of Structural Changes

Beginning with RTF, several elements of the ET were the focus of redesign and structural modifications which generally aimed at mitigating foam loss. These key areas included the ice/frost ramps, the LO2 feedline brackets, the LO2 feedline bellows, the LH2 tank/intertank flange region, the forward bipod fitting, and the +Z aerovent. In addition to these changes, a new observation camera system was implemented, in accordance with the CAIB recommendations. A summary of these modifications follows.

¹³⁴⁸ NASA, *Implementation Plan*, 1-4.

¹³⁴⁹ NASA, *Implementation Plan*, 1-2.

¹³⁵⁰ NASA MSFC, *Return to Flight External Tank, ET-119*, NASA Facts, (Huntsville, AL: George C. Marshall Space Flight Center, June 2005), http://www.nasa.gov/centers/marshall/pdf/150034main_Shuttle_ET-119_FS.pdf.

¹³⁵¹ Lockheed Martin, "Flight Info," 89; NASA MSFC, *ET-119*; NASA, *STS-120*, 68.

¹³⁵² NASA MSFC, *Preparing the External Tank, ET-118*, NASA Facts (Huntsville, AL: George C. Marshall Space Flight Center, August 2006), http://www.nasa.gov/centers/marshall/pdf/155290main_shuttle_et118_fs.pdf.

¹³⁵³ NASA MSFC, *Tank ET-128*.

Ice/Frost Ramps: The ET main propulsion system pressurization lines and cable trays were attached along the length of the tank at several locations by metal support brackets. These brackets were protected against ice and frost formation during tanking operations by thirty-six foam protuberances called ice/frost ramps (Figure No. D-12). Twelve of these ramps were located on the LO2 tank, seven on the intertank, and seventeen on the LH2 tank. The size and design of the ramps depended on location. The ramps on the LO2 tank were approximately 1.5' long by 1.5' wide by 5" high and weighed about 12 ounces. The ramps on the LH2 tank were larger, measuring approximately 2' long by 2' wide by 1' high, with a weight of 1.7 pounds each.

Beginning with modifications to ET-120, changes to the LH2 tank ice/frost ramps were made at fourteen locations. Also, changes were made at four locations on the LO2 tank ice/frost ramps. After analyses revealed cracked base foam in the ice/frost ramps of ET-120, NASA approved a complete ramp redesign to reduce the probability of ice/frost formation and possible debris.¹³⁵⁴ ET-128, which flew on *Discovery's* STS-124 mission, debuted the redesigned ice/frost ramps on the LH2 tank. The redesign changes were incorporated into all seventeen ice/frost ramps on the LH2 tank. Specific changes included the replacement of PDL and NCFI foam in the ramps' base cutout by BX hand-spraying to reduce bonding and cracking.¹³⁵⁵ This replacement foam material also was applied in bracket pockets to reduce voids. Pressurization line and cable tray bracket feet corners were rounded to reduce stresses, and shear pin holes were sealed to reduce leak paths. Also, isolators were primed to promote adhesion, and isolator corners were rounded to help reduce foam stresses.¹³⁵⁶

Liquid Oxygen Feedline Brackets: The 70' long by 17"-diameter LO2 feedline carried LO2 oxidizer to the orbiter, where it was distributed to the SSMEs. The feedline was attached to the ET with five brackets. The brackets allowed for movement of the feedline during fueling on the pad, during detanking in flight, and to compensate for thermal expansion and contraction. The original brackets, manufactured from aluminum, were primed, then covered with ablator, over which a 1"-thick layer of BX-250 foam was sprayed on. An interim modification was made to the foam configuration of ET-120's LO2 feedline brackets. The BX foam insulation and ablator were removed from the upper portion of four brackets. The foam insulation was later reapplied without the Super Light Ablator (SLA). Elimination of the SLA reduced the TPS mass for each bracket by about 0.12 pounds.¹³⁵⁷

Beginning with ET-128/STS-124, new titanium brackets replaced aluminum brackets at four locations to minimize ice formation in under-insulated areas. Titanium is seventeen times less

¹³⁵⁴ NASA, *STS-120*, 69; Lockheed Martin, "Flight Info," 89.

¹³⁵⁵ PDL is the acronym for Product Development Laboratory, the original supplier of ET foam. This hand-poured foam was used for filling odd-shaped cavities. NCFI is the acronym for North Carolina Foam Insulation. This foam was used on the bottom (aft dome) of the liquid hydrogen tank. NASA MSFC, *Tank ET-128*.

¹³⁵⁶ NASA MSFC, *Tank ET-128*.

¹³⁵⁷ NASA, *ET-120*.

thermally conductive than aluminum, and therefore, does not conduct cold or heat as well. Thus, the tank required less TPS material, and the amount of foam required for insulation on the ET could be reduced. In addition, Teflon material was applied to the upper outboard monoball attachment to eliminate ice adhesion, and additional foam was added to the feedline to minimize cold spots and reduce ice.¹³⁵⁸ Along with the modification to the LH2 tank ice/frost ramps, the redesign of the foam in the area of the LO2 feedline brackets greatly reduced the potential for liberated foam during the initial phase of launch. Post-flight analysis indicated no observed foam loss from either the feedline brackets or the ramps of ET-128. All subsequent tanks incorporated this redesign.

Liquid Hydrogen Tank/Intertank Flange Area: Flanges located at the bottom and top of the intertank provided attachments for the LH2 tank and the LO2 tank, respectively. After the tanks were joined, the flange regions were insulated with foam. ET separation imagery had shown repeated losses of the foam overlying the LH2 tank/intertank flange. Analyses indicated that “when the GN2 [gaseous nitrogen] used as a safety purge in the intertank came into contact with the extremely cold hydrogen tank dome, the GN2 condensed into LN2 [liquid nitrogen].”¹³⁵⁹ The LN2 seeped into the intertank joints, fasteners, vent paths, and other penetrations into the foam, filling voids in the foam. During ascent, the LN2 returned to a gaseous state, pressurized the voids, and caused the foam to detach.

A simplified, enhanced close-out, or finishing, process was implemented to reduce the risk potential for TPS debris from the flange region. Assessments of the tank had indicated that voids, or spaces, sometimes developed in the foam sprayed on the flange. To reduce the number of voids, the new procedure entailed an improved foam application to the intertank ribbing (stringer area), and to the upper and lower area of the flanges. The enhanced process also included real-time surveillance to detect any imperfections so they could be repaired immediately. A related improvement was the reversal of the flange bolts that connected the LH2 tank and intertank, such that the nut ends were enclosed by the intertank’s stringers. The stringers were then filled using a new mold-injection procedure. In addition, the spraying process on the intertank’s thrust panel was changed to assure a smooth spray, and a sealant was added to the threads on the flange bolts to reduce the risk for foam debris.¹³⁶⁰

Forward Bipod Fitting: Each ET had two bipod fittings, made from titanium, which connected the tank to the orbiter through two forward attachment struts. The fittings were coated with ablator, over which foam was sprayed and allowed to dry. The foam was then shaved into a ramp shape. Historically, the shape of the bipod ramp changed over time. ET-1 through ET-13

¹³⁵⁸ NASA MSFC, *Tank ET-128*.

¹³⁵⁹ CAIB, *Report, Volume I*, 1-10.

¹³⁶⁰ NASA MSFC, *External Tank Liquid Hydrogen Tank/Intertank Flange*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/113323main_Flange_Fact_Sheet.pdf.

featured ramps with a 45 degree angle. Beginning with ET-14, the ramp angle was changed to between 22 and 30 degrees, and a slight modification was implemented on ET-76 and later tanks.

NASA began developing redesign concepts after foam came off the left bipod ramp area during the October 2002, launch of *Atlantis* on the STS-112 mission. A similar loss during *Columbia's* STS-107 mission in January 2003 prompted the agency to redesign the bipod ramp during RTF efforts.¹³⁶¹ The old design used wedge-shaped foam ramps to prevent ice from building up on the fitting (Figure No. D-13). Each ramp measured approximately 30" long, 14" wide, and 30" high. The ramps were applied by hand spraying BX-250/265 foam over the bipod fittings during the final stages of the tank's preparation, and then finished by hand carving the foam to the required dimensions. Analysis during the STS-107 investigation indicated that hand spraying was prone to produce internal voids and defects in the foam; it was shown that such voids and defects contributed to foam loss during ascent.¹³⁶²

While the fittings proper were not changed, the redesign removed the insulating foam ramps (Figure No. D-14). To prevent the formation of ice build up from the subzero (cryogenic) LH2 fuel, the new design added four rod heaters below each forward bipod fitting in a new copper plate to reduce heat loss.¹³⁶³ The cartridge-type heaters were 0.25" in diameter and 5" in length. Each could produce up to 300 watts of power when operated at 120 volts ac. Designed to function only during pre-launch, the heaters were powered and monitored through connections in the ground umbilical carrier plate. Related modifications to the original bipod fittings included the elimination of the bipod spindle heater elements, and the addition of a smaller end cover made from Inconel 718 to withstand higher temperatures. The new bipod design also required additional cabling to operate the heating system. It included eight circuits, four for each bipod. The circuits ran from the external tank ground umbilical carrier plate to the heaters which were under the bipod fittings.¹³⁶⁴

Imagery from STS-114 documented a missing piece of foam near the tank's left hand bipod attachment fitting. Subsequent analyses indicated the probable cause was "cryoingestion," whereby increased pressure of gases under the foam may have resulted in the liberation of foam. The leak path for the gas could have been through the heater or temperature sensor wiring harness. Voids found in the material used to bond the wire harnesses to the substrate were identified as another potential contributor to the problem. To correct these problems, electrical harnesses that serviced the bipod heaters and temperature sensors were removed and replaced with improved versions. Void spaces beneath the cables were eliminated by using an improved bonding procedure.¹³⁶⁵

¹³⁶¹ Earlier, bipod foam losses were observed on STS-7 (1983), STS-32 (1990), STS-50 (1992), STS-52 (1992), and STS-62 (1994). CAIB, *Report, Volume I*, 1-83.

¹³⁶² NASA MSFC, *External Tank Forward Bipod Fitting*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/114020main_ET_Bipod_FS.pdf.

¹³⁶³ NASA MSFC, *Bipod Fitting*; NASA MSFC, *Tank ET-128*.

¹³⁶⁴ NASA MSFC, *Bipod Fitting*; NASA MSFC, *Tank, ET-119*.

¹³⁶⁵ NASA MSFC, *Tank, ET-119*.

Liquid Oxygen Feedline Bellows: The ET featured five LO2 feedline bellows, which were part of the LO2 feedline assembly. Two of the bellows were located inside the intertank. The other three were located at joints along the feedline on the outside of the LH2 tank, with two near the aft end and one near the top. These accommodated thermal expansion and contraction, allowing the feedline to move or flex. Only the bellows located near the top of the LH2 tank, near the LO2 feedline fairing, was viewed as a significant debris concern (Figure No. D-15). The bellows were protected by a rain shield covered with BX-265 foam. However, because they were designed for movement, the bellows proper, unlike the rain shield, were not covered with insulating foam. As a result, ice and frost could form, presenting a potential source of debris. To reduce the formation of ice, the foam on the bellows' cover was reshaped to include a "drip lip" that allowed moisture to run off. The original configuration of the thermal protection on the bellows was angled, which allowed condensate to contact the feedline rain shield and freeze.¹³⁶⁶

In addition to the new drip lip configuration, a 0.5"-wide, copper-nickle alloy strip heater was added to the topmost bellows located near the LO2 feedline fairing to further reduce the amount of ice and frost formed prior to launch. The heater was installed in the bellows cavity, and bonded to the bellows rain shield and convolute shield. Heater wire was routed under the foam to the LO2 feedline fairing penetration in the intertank.¹³⁶⁷ The heater was added after new information from debris studies showed that ice forming on the bellows posed a significant debris concern.

Observation Camera System: Among the recommendations made by the CAIB was that NASA provide a capability to obtain and downlink high resolution images of the ET after it separated from the orbiter vehicle. Prior to RTF, the Space Shuttle had two on-board high-resolution cameras that photographed the ET after separation. However, the images were not downlinked to the Mission Control during the mission. As a result, no real-time imaging of the ET was available to check for potential debris.¹³⁶⁸

Beginning with STS-114, the Space Shuttle was newly equipped with three video cameras which provided views of the orbiter's underside and the ET prior to tank separation. One camera was located on the ET and the other two were installed, one each, on the two SRBs. The ET camera was mounted inside the LO2 feedline fairing, a metal covering that protected the area where the fuel feedline penetrated the intertank. The video camera, a Sony XC-999, was the same type that flew on STS-112/ET-115 in October 2002.¹³⁶⁹ The ET-mounted camera provided a field of view of about 100 degrees, and included the vicinity of the bipod attachment area and a portion of the bottom side of the orbiter. The camera's battery pack and transmitter were contained in an

¹³⁶⁶ NASA MSFC, *External Tank Liquid Oxygen Feedline Bellows*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, May 2005), http://www.nasa.gov/centers/marshall/pdf/119015main_revLOX_FS.pdf.

¹³⁶⁷ CAIB, *Report, Volume I*, 1-10.

¹³⁶⁸ NASA, *NASA's Implementation Plan*, 1-59.

¹³⁶⁹ The camera flown on STS-112/ET-115 was the first to provide "live shots." The camera specifications were developed by Lockheed Martin, who also integrated the camera into the tank system and developed the camera housing.

electronics box mounted on top of the SRB crossbeam inside the ET. The camera also had two S-band antennas located on the opposite side of the tank from the orbiter. The complete camera system weighed thirty-two pounds. The camera system was activated about three minutes prior to launch, and operated for fifteen minutes following liftoff. The video was downlinked during flight to several NASA data receiving sites. Lockheed Martin Space Systems developed the camera specifications and camera housing, and integrated the camera into the ET system.¹³⁷⁰

+Z Aerovent: The final post-*Columbia* modification, which debuted with ET-135/STS-131, was the removal of foam-over-foam around the +Z aerovent near the forward flange of the intertank. This change was implemented to reduce the potential for crack formation. The successful first flight of the +Z aerovent TPS redesign underscored the lessons learned from ongoing investigations of foam loss events. Contamination on the intertank structure, prior to the application of foam, it had been observed, resulted in bond adhesion failures, which caused foam shedding during ascent. In response, changes in production procedures were implemented at MAF, which resulted in more effective substrate cleaning and TPS application on the intertank.¹³⁷¹

Other Challenges: Return to Flight to Final Mission

ET foam debris shedding continued throughout the SSP, but diminished in frequency as the result of the redesign efforts. Reportedly, the last few flights were the “cleanest.” Other problems related to the ET challenged NASA up until the near close of the SSP. These included continued difficulties with the LH2 engine cutoff (ECO) sensors, as well as stringer cracks in the intertank.

LH2 ECO Sensors

Four ECO sensors were mounted on a single carrier plate approximately 4’ from the bottom of the LH2 tank (Figure No. D-16). Designed to activate in an emergency situation, they indicated when the ET was about to run out of propellant. In preparation for the STS-114 RTF mission, a tanking test on ET-120 resulted in an ECO sensor anomaly. The sensors indicated “wet” when there was no propellant in the tank. Because of another problem that could not be fixed at the pad, *Discovery* was rolled back to the VAB and the orbiter was mated to another stack, originally intended for the next mission, STS-121. *Discovery* was returned to the launch pad with its new stack about one month before the targeted launch. During pre-launch check-outs on the day of launch, the LH2 ECO sensor on the new tank falsely indicated “wet,” resulting in a launch scrub. As a result, NASA conducted a more thorough investigation of the anomaly. *Discovery* eventually launched successfully on July 26, 2005, and no false indicators were received from the LH2 ECO sensors.

¹³⁷⁰ NASA MSFC, *Space Shuttle External Tank and Solid Rocket Booster Camera Systems*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/114016main_ET_SRB_Cam_FS.pdf.

¹³⁷¹ Chris Bergin, “STS-132 FRR.”

In December 2007, another issue with the ECO sensors was indicated during tanking, preventing the launch of STS-122/ET-125. That month, while the ET remained at the launch pad, components of ET-125's ECO sensor system feed-through assembly were taken to MSFC and subjected to failure analysis. ECO sensor system modifications were designed, tested, certified and retrofitted to ET-125 between December 2007, and February 2008. STS-122 launched on February 7, 2008; the ECO sensor LH2 feed-through connector on the LH2 tank of ET-125 was modified on the launch pad.¹³⁷² According to Anthony Bartolone, Lead Project Engineer, ET and SRB Processing at KSC, ultimately, the cause of the problem was determined to be contamination in a connector that went through the wall of the hydrogen tank.¹³⁷³ The connector, a set of pins embedded in glass, was not functioning properly due to contamination by the lubricant used to install the connector. Specifically, the contaminant prevented the electrical connection to go through the wall of the external tank, which was being interpreted as a loss of the signal or failure of the sensors. To resolve the problem, the connector was removed from subsequent ETs. The pins were welded or soldered to their sockets to prevent contamination from creating an open circuit. From that point on, there were no more problems with the ECO sensors.

Intertank Stringer Cracks

A hydrogen vent line leak discovered during fueling for *Discovery's* final mission (STS-133/ET-137) in November 2010 resulted in a launch scrub.¹³⁷⁴ During the final inspection (from camera views) of the detanking and draining process, small cracks were found in two of the stringers in the wall of the ET's intertank. Exhaustive tests and analyses at both MSFC and MAF followed to understand the root cause. Engineers concluded that the cracks were caused by temperature-induced stress near the tops of the stringers as the LO2 tank, exposed to minus 297 degree F propellant, contracted during fuel loading. This contraction pulled the tops of the stringers away from the bottom of the LO2 tank. Although the tank was designed to accommodate such a contraction, the metallurgy of the tank came into question. The problem was traced to the stringer material, 2090 aluminum, manufactured by Alcoa, which lacked sufficient fracture toughness. The alloy was discovered to be from a lot which was more brittle than usual, and more susceptible to fractures. To resolve the problem, a "radius block modification" was made.¹³⁷⁵ Structural doublers were riveted in place over 105 of the 108 rib-like stringers to

¹³⁷² NASA MSFC, *Tank ET-128*.

¹³⁷³ Anthony P. Bartolone, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, July 5, 2011, http://www.jsc.nasa.gov/history/oral_histories/STS-R/BartoloneAP/BartoloneAP_7-5-11.htm.

¹³⁷⁴ This was the third recurrence of the hydrogen leak since RTF. The problem was solved by a change of the flight seal design, and modifications to the alignment of the ground umbilical carrier plate's feet on the tank. Chris Bergin, "SCRUB: Weather delays Endeavour 24 hours – ET-134 sports final tank mods," February 6, 2010, <http://www.nasaspaceflight.com/2010/02/live-sts-130-attempt-1-tank-mods/>.

¹³⁷⁵ The thin reinforcing strips of aluminum added to provide increased strength were called radius blocks.

provide additional strength and to make them less susceptible to stress-relief fractures.¹³⁷⁶ Foam insulation was reapplied after the modifications to the stringers were made.¹³⁷⁷

The Final Flight Tanks

The last two ETs to fly out the SSP were ET-122 and ET-138. **ET-122** originally was scheduled to serve as the “Launch on Need” tank for STS-134 when this mission was the last planned flight of the SSP. Fabrication of ET-122 was completed nine years earlier, in November 2002. At that time, because there was no room at KSC to store the tank, it was placed into storage at MAF. During RTF operations following the *Columbia* accident, ET-122 was modified by the removal of ramps, bipod fittings, and the tank flange closeout between the intertank and the LH2 line. Also, ice frost ramp extensions were added to the LH2 PAL ramps, and an ET camera system and internal electrical harnesses were installed. Subsequently, ET-122, still undergoing modifications in Cell A of the Vertical Assembly Building at MAF, was damaged when Hurricane Katrina hit the facility on August 29, 2005. NASA approved a plan to restore the tank to flight configuration in November 2008. Repairs were made to the LO2 tank and the intertank, and damaged foam was removed and replaced. ET-122 rolled out at MAF on September 20, 2010, and arrived at KSC aboard the *Pegasus* barge on September 28, 2010. It flew with STS-134 (*Endeavour*), launched on May 16, 2011.

Thirty-one years after the first flight ET was delivered to KSC, the last newly manufactured production tank, **ET-138**, arrived at KSC in July 2010, following its roll out on July 8, 2010. Originally scheduled to fly with STS-134 (*Endeavour*), it was later reassigned to STS-135 (*Atlantis*). ET-138 featured the modifications that had been made to ET-137. Specifically, to provide additional strength, radius block doublers were installed to the tops of the rib-like stringers all the way around the upper end of the intertank.¹³⁷⁸ The last flight tank featured artwork in the form of a commemorative logo painted on a 3’-high by 5’-wide intertank access door near the top of the tank. The logo was designed by Blake Dumesnil, an engineer at JSC, and hand-painted on the door by Lockheed Martin graphic artist Jon Irving. The logo depicted the Space Shuttle flanked by the U.S. flag, fourteen stars to commemorate the astronauts lost aboard *Challenger* and *Columbia*, and the shuttle fleet.¹³⁷⁹

¹³⁷⁶ William Harwood, “Shuttle fueling test to check Atlantis’ external tank,” June 15, 2011,

<http://www.spaceflightnow.com/shuttle/sts135/110615tanking/index.html>; Bartolone, interview.

¹³⁷⁷ Steven Sicheloff, “Spotlight on external fuel tank draws Facebook questions,” *Spaceport News*, January 28, 2011, 3, 6.

¹³⁷⁸ Harwood, “Shuttle fueling test.”

¹³⁷⁹ Linda Herridge, “Last external fuel tank arrives for STS-134 mission,” *Spaceport News*, October 1, 2010, 1;

NASA, “Atlantis’ External Tank to Feature Commemorative Logo,” June 9, 2011,

http://www.nasa.gov/mission_pages/shuttle/flyout/flyout_shuttle_logo.html.