interface fitting, which weighed 530 pounds, was a near mirror image of the aft left fitting. The thrust strut-to-ball interface fitting, the thrust struts, and the vertical struts, also were near identical.[1462]

The **ET/orbiter Crossbeam** was a rectangular-shaped aluminum structure measuring 176" long. It was comprised of extruded channel sections and integral forgings welded together to form a single assembly. It was bolted to the right ball interface fitting by twenty-four 5/8"-diameter bolts. The right end of the crossbeam contained two bulkhead forgings that supported the LO2 feedline elbow; the left end contained two integral bulkhead forgings that provided the attachment for the LH2 feedline hinge brackets.[1463]

The ET, like the orbiter, had half of the 17" LH2 feedline disconnect that served as the structural support for an **umbilical assembly**. This assembly contained the 2" GH2 pressurization line disconnect, the 4" recirculation line disconnect, and pullaway ET/orbiter and orbiter/SRB electrical disconnects, all mounted in a single cluster plate. This plate was mechanically attached to the ET side of the interface.[1464] The right umbilical assembly was similar to the left assembly, except for the absence of the 4" fluid disconnect. With the ET mated to the orbiter, the disconnect halves were held together by 2-1/4"-diameter umbilical separation system bolts.

ET/Ground Facilities Interfaces

The ET intertank was equipped with fluid and electrical interfaces with the ground facility pressurization, vent and electrical systems. The umbilical system consisted of a hardline subassembly which terminated with a GUCA. The GUCA interfaced with the ET intertank carrier plate assembly (ETCA). Each of these carrier assemblies contained their respective sections of the disconnect component for the electrical or gas system. A pyrotechnic bolt attached the GUCA to the ETCA.[1465]

ET Process Flow

Throughout the SSP, all ETs were built, assembled, and acceptance tested by contractor Lockheed Martin Space Systems Company at NASA's MAF in New Orleans, Louisiana, then transported by barge to KSC for inspections, integration with the orbiter and SRBs, and launch. A summary of this process follows.

[1462] Lockheed Martin, *Handbook (SLWT)*, 12-21.
[1463] Lockheed Martin, *Handbook (SLWT)*, 12-22.
[1464] Lockheed Martin, *Handbook (SLWT)*, 12-24, 12-25.
[1465] Lockheed Martin, *Handbook (SLWT)*, 12-33, 12-34.

Manufacture and Assembly

According to Mark Bryant, vice president of the External Tank Program for Lockheed Martin Space Systems, the length of time required to build a tank was affected by several factors. Generally, the LWT used to take about two years to build, while the SLWT with the post-*Columbia* modifications and process controls took more than three years, start to finish.[1466]

Overview

The components of the ET were manufactured in Building 103 at MAF (Figure No. D-29). The process began with three concurrent manufacturing and assembly tracks – one for the LO2 tank, one for the intertank, and one for the LH2 tank. The LO2 tank and intertank were combined in Cell J of Building 114; the LH2 tank and the LO2 tank/intertank were assembled into the finished ET in Cell A of Building 110.[1467] Pressure testing of both propellant tanks was conducted in Building 110 and Structure 451. The ET components were cleaned and sprayed in Buildings 110, 114, and 131, and ablator was applied to elements of the ET in Building 318. Final approval and purchase of the ET by NASA took place in Building 420.[1468]

The manufacturing approach for the LO2 tank and LH2 tank assemblies entailed welding structural components into subassemblies such as domes, ogives and barrels, and then performing mechanical, propulsion, and electrical system installations at the subassembly level, to the extent possible. After completion of these processes, each tank was proof tested.[1469] Next, the LH2 tank was cleaned, iridited,[1470] primed and mated to the intertank to form the LO2/intertank stack and TPS application was completed. The LO2/intertank stack was joined to the LH2 tank in the vertical attitude and TPS closeout was performed. The mated ET assembly was then moved to the horizontal final assembly area for completion.[1471]

LO2 Tank Assembly

The LO2 ogive nose section was fabricated in two sections: forward and aft. The forward section consisted of eight gore panels and a forward ring fitting. The eight gores were welded in a vertical trim and weld fixture, first into four quarter panels, and then into two half-body assemblies, and finally into one assembly. The forward ring fitting was welded on next. All

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[1466] Roy, "External Tank."
[1467] M. Todd Cleveland, *Evaluation of Resources Associated with the Space Shuttle Program, Michoud Assembly Facility, New Orleans, Louisiana* (survey report, MAF, TRC, May 2007), 19.
[1468] Cleveland, *Evaluation of Resources*, 19.
[1469] Proof testing was done to screen for critical flaws in the structure. It was performed on each LH2 tank and LO2 tank to demonstrate the strength of each tank pressure wall to 113 percent or greater of the limit load. Ryan, "Aerospace Problems."
[1470] Iridite is a chemical film which provides a barrier medium to prevent corrosion on aluminum surfaces, and enhances adhesion of paints and primers.
[1471] Lockheed Martin, *Handbook (SLWT)*, 14-2.

edges were custom-trimmed prior to welding. The aft ogive section consisted of twelve gore panels. The operations were the same as for the forward ogive, except there was no forward fitting. Four extruded segments comprised the T-frame which made the transition from ogive section to barrel section. These were welded together in a trim and weld fixture. The four pre-formed panels which formed the barrel section were welded together.[1472]

Fabrication of the LO2 dome began with the dome gore/gore welded assembly. The longitudinal abutting edges of the gore panels were saw-trimmed and welded. The completed quarter panel and the mating chord abutting edges were trimmed and welded. Next, the abutting edges of the quarter panel-chord assemblies were welded to produce a half dome body. The two half dome assemblies were brought together and the abutting edges trimmed and welded together to form a dome body. The completed dome body was then routed to the dome body/cap weld fixture for welding into a completed dome. The dome cap was welded to the dome body in a rim and weld fixture. Both the dome body and the dome cap were trimmed, then welded together on the dome body/cap weld fixture.[1473]

The LO2 forward slosh baffle individual ring segments and truss assemblies were joined, and then fabricated into a three-level baffle assembly. The LO2 tank major weld was accomplished in a horizontal rotational weld fixture. The major tank components were welded together from forward to aft. The slosh baffle was installed into the ogive/barrel assembly prior to welding on the aft dome. Next, the aft dome weld, which was the tank closeout weld, was made using an expanding mandrel. The completed LO2 tank was proof tested in the hydrostatic test facility using demineralized water to which a chromate corrosion resistant solution was added (Figure No. D-30). A vacuum was drawn on the aft dome to provide the required proof pressure gradient. After proof testing, the LO2 tank was X-rayed, then routed for cleaning and TPS application.[1474]

Intertank Assembly

The structural assembly of the intertank began with the splicing of the intermediate and main frame 90 degree segments into 180 degree segments. The 180 degree frame segments were loaded and aligned into a half section tack station along with the three stringer panels. Here, approximately 409 of the total panel to frame fasteners were installed. The panel to panel butt splices were tack fastened and the rollties were installed. The intertank -Z half section was positioned on the automatic riveter and the +Z half section was started on the tack section station. While on the automatic riveter, the remaining panel to frame butt splice fasteners were drilled and installed. The -Z half section was then moved to the finish/inspect station where the fasteners, installed by the automatic riveter, were inspected, and all systems substructure was installed. Operations were repeated for the +Z half section. Splice details and closure panels for the SRB beam were pre-drilled in a pre-assembly fixture. The pre-aligned SRB beam was placed

[1472] Lockheed Martin, *Handbook (SLWT)*, 14-2.
[1473] Lockheed Martin, *Handbook (SLWT)*, 14-2, 4-3.
[1474] Lockheed Martin, *Handbook (SLWT)*, 14-3.

in the assembly fixture. The half sections were then loaded in, and their frames spliced at the +Y axis. Thrust panels were then installed. Longeron tie ins and thrust panel butt straps and rollties were installed. The forward and aft interface flange holes patterns also were drilled. After removal of the intertank from the assembly fixture, it was placed in a fixture for installation of propulsion and electrical systems. The intertank was then moved to Cell G or H for SOFI application to the sidewalls using an automotive gun spray system. After completion of SOFI rim operations, the intertank was moved to Cell J for LO2 tank stacking.[1475]

LH2 Tank Assembly

The LH2 forward and aft domes were fabricated in the same manner as the LO2 dome. The LH2 aft barrel section was welded. The three LH2 forward barrel sections were welded in a horizontal barrel weld fixture (Figure No. D-31). The panels were sequentially loaded and welded. The three LH2 T-ring frames were welded in the same fixture used for the LO2 T-ring. The LH2 tank major weld was accomplished in a horizontal rotational weld fixture similar to that used for the LO2 tank. The LH2 tank assembly sequence began with the loading of the aft dome into the weld fixture followed by the loading of the aft barrel section. After the mating edges had been prepared, the circumferential weld was made. The remaining barrel sections and ring frames that comprised the LH2 tank were prepared and welded in like manner. The welded assembly, less the forward dome, was then removed from the fixture and loaded into another fixture where X-rays and mechanical installations were performed. The assembly was then moved to another fixture where the final circumferential weld of the LH2 tank was made between the forward dome and the forward barrel section. Welding of the forward dome to the barrel section completed the LH2 tank assembly (Figure No. D-32). The completed LH2 tank was then routed to proof test, which combined a pneumatic GN2 pressure test with a hydraulic local test. While the tank was pressurized, loads were applied to simulate the loads from the SRBs and the orbiter. Completion of the proof test was followed by a leak test, then transport to Building 103 for proof X-ray operations.[1476]

TPS Application

After completion of proof testing and X-rays, the LO2 tank was cleaned and iridited internally and cleaned externally. Internal installations were made, welds were iridited and external surfaces primed, and SOFI was then applied to the aft dome using an automated sprayer. The LO2 tank was then mated and spliced to the intertank, the LO2 feedline was mechanically hooked-up, the feedline brackets were installed, and SLA handpack operations were performed (Figure No. D-33). The LO2/intertank stack underwent an automated application of SOFI, and mechanical installations were performed. Closeout/trim of flange and cable tray brackets was completed and the LO2 stack was ready for mating to the LH2 tank.

[1475] Lockheed Martin, *Handbook (SLWT),* 14-3.
[1476] Lockheed Martin, *Handbook (SLWT),* 14-4.

After proof testing and X-ray, the LH2 tank was cleaned, primed, and covered with an application of TPS. The first steps were external cleaning, prime and mechanical installations. The LH2 tank was then internally cleaned and iridited. Internal installations in the aft dome were completed, followed by the application of SOFI to the barrel section areas and the forward dome. SLA panels were bonded to the apex aft dome area, and then SOFI was applied to the aft dome. Next, the LH2 tank was mated with the LO2 tank/intertank assembly (Figure No. D-34), and TPS closeout of the splice area was performed. SRB attachment fittings were installed and alignments were verified prior to final assembly, performed in Building 103. This entailed the installation of electrical and mechanical hardware, including feedline, cable tray, interface hardware, and electrical wiring, as well as ET/orbiter interface hardware. TPS closeouts followed.[1477]

Test and checkout, performed in Building 420, started with a wiring integrity test, followed by mechanical joint leak tests, subsystem testing, and finally, an All Systems Test which simulated the flight profile (Figure No. D-35). Pack and ship activities also were completed in Building 420. Next, the LO2 and LH2 tanks were purged with GN2, and pressurized to 6 psig with dry GN2 prior to shipment.[1478]

Transportation and Delivery

Each completed ET was loaded onto the covered barge *Pegasus* at MAF (Figure No. D-36), then towed to Gulfport, Mississippi, where retrieval ship *Liberty Star* or *Freedom Star* joined the barge to make the approximate 900 mile journey to KSC (Figure No. D-37).[1479] It typically took about seven to ten days for the tank to travel through the Mississippi River, out to and across the Gulf of Mexico, then up through the Straits of Florida to Cape Canaveral, through the port, up the Banana River, and on to the Barge Terminal Facility at KSC located near the VAB (Figure No. D-38).[1480]

At KSC, each ET was offloaded from the barge (Figure No. D-39) and moved atop a transporter to the transfer aisle of the VAB (Figure No. D-40). The ET was rotated to vertical (Figure No. D-41), and placed in a checkout cell for visual inspection by a team of engineers, technicians and quality inspectors. While in the checkout cell, the ground umbilical carrier plate was installed and the aft hardpoint TPS closeout was performed. Nitrogen, which filled both the LH2 and LO2 tanks, was replaced with helium, mainly to keep moisture out and to allow for pressure monitoring. Propulsion system leak checks and limited electrical checks were performed, as well as a pneumatics checkout to make sure the valves were functioning properly.[1481] The umbilicals

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[1477] Lockheed Martin, *Handbook (SLWT),* 14-5.
[1478] Lockheed Martin, *Handbook (SLWT),* 14-5.
[1479] There were instances when a chartered ship was used to pull the barge instead of a SRB retrieval ship when the ships were engaged in other operations. Bartolone, interview.
[1480] Bartolone, interview.
[1481] Lockheed Martin, *Handbook (SLWT),* 3-3.

located on the bottom end of the ET, built by Boeing as matched sets to the orbiters, were balanced, adjusted, repaired (if necessary), and prepared for orbiter mate by a Boeing team.[1482] Normal processing in the check-out cell took about eighteen days.

After verification of ET integrity, the transport equipment and instrumentation were removed, and the ET was hoisted by a large overhead crane (Figure No. D-42) and moved to the VAB integration cell (High Bay 2 or 4) for storage prior to stacking. The ET was lifted out of the high bay via overhead crane and moved into High Bay 1 or 3 for mating.

Integration and Launch

After the SRBs were stacked on the MLP in VAB High Bay 1 or 3, the ET was lowered into position and mated to the SRBs (Figure No. D-43). The ET/SRB forward support fittings were attached, followed by mating and securing of the aft fittings. All ET/SRB interface system connections were made. Next, the orbiter was moved into the integration cell and attached to the ET at one forward attachment point and two aft points. The orbiter was rotated forward and jacked into final position for attachment to the ET bipod. Umbilicals between the ET and orbiter were connected.

Following the move of the complete Space Shuttle vehicle from the VAB to the launch pad, facility servicing lines were mated through the ET intertank carrier plate assembly. The facility LO2 and LH2 systems were purged, and both ET tanks were purged with helium to assure an inert atmosphere for propellant loading.[1483] At T-5 hours and 50 minutes, the launch processing system initiated the SSME LH2 chill-down sequence in preparation for LH2 loading.

Both propellants were loaded simultaneously, starting with a slow flow rate to precondition the lines, tanks, and engines. At the 2 percent level, the flow rates were increased to a maximum of 12,000 gallons per minute for LH2 and 5,000 gallons per minute for LO2 until 98 percent capacity was reached. The flow rate was reduced again to provide a topping flow rate to 100 percent capacity, followed by a still slower replenish rate to maintain 100 percent propellant levels. This flow continued until the automatic sequence started at T-9 minutes.[1484] Vapors from each propellant were vented during the loading and conditioning process.

The fuel system purge began at T-4 minutes. At T-2 minutes and 55 seconds the LO2 tank was pressurized to 221 psi, and almost one minute later, the LH2 tank was pressurized to 42 psi. At T-9.5 seconds, the engine chill-down sequence was complete. The main fuel valve and the main oxidizer valve in each engine were opened. Between the time of valve opening and MECO, LH2 and LO2 flowed out of the ET through the disconnect valves, and into the feedline manifolds, from where they were distributed to the engines.

[1482] Bartolone, interview.
[1483] Lockheed Martin, *Handbook (SLWT),* 3-4.
[1484] Lockheed Martin, *Handbook (SLWT),* 3-5.

The ET fed approximately 535,000 gallons of LO2 and LH2 propellants to the three SSMEs during the first 8.5 minutes of flight, at a rate of 1,035 gallons per second.[1485] The ET was jettisoned within ten to fifteen seconds after MECO, at an altitude of about 70 miles (Figure No. D-44). Separation of the ET from the orbiter was initiated by the firing of a pyrotechnic valve located in the nose cap that broke the attachment hardware links.[1486] Following separation, the residual LO2 contained in the tank was gasified, which imparted a tumbling action to the ET. Tumbling provided for better fragmentation and a more predictable area of impact. The ET broke up into fragments as it fell back to Earth. Almost the entire tank burned up during re-entry. Any debris that did not burn fell into a predetermined area of the Pacific or Indian Ocean.

[1485] Lockheed Martin, "Statistics and Comparisons."
[1486] NASA KSC, "Lightweight External Tank."