ET Physical and Functional Descriptions

ETs by the Numbers

A total of 136 flight ETs were manufactured and assembled by Lockheed Martin at NASA's MAF. This included six SWTs, eighty-five LWTs, and forty-five SLWTs. In accordance with data from Lockheed Martin, as provided in the table that follows, the peak period of ET manufacture was between 1983 through 1986.[1380] A total of thirty-five tanks were delivered to KSC during these years, averaging eight to nine tanks per year. The years 1984 and 1985 were distinguished by the delivery of ten and eleven tanks, respectively. Beginning in 1987, in the aftermath of the *Challenger* accident, and continuing through 1993, only three or four ETs were delivered each year. Subsequently, production increased, and from 1994 through 2002, deliveries averaged six tanks per year. The *Columbia* accident in 2003 stopped all ET shipments to KSC until 2006, and as a result, by the end of 2007, only four tanks were delivered to KSC.[1381]

Lockheed Martin did not assign the numbers ET-7 and ET-95 to any completed and operational external tank.[1382] According to Pessin, ET-7 "was never completed," and the pieces were "never assembled."[1383] In accordance with the Lockheed Martin numbering sequence, both ET-7 and ET-95 marked the transition from the SWT to the LWT, and from the LWT to the SLWT, respectively. ET-94, a LWT, was used as a spare and housed at MAF. In 2010, it was used for studies of a Shuttle-derived vehicle; it was not in flight configuration.

Four tanks were delivered to Vandenberg before they were redelivered to KSC: ET-23, -27, -33, and -34. ET-27, which flew on STS-34, was originally scheduled for the first Shuttle flight from Vandenberg.

In addition to the flight tanks, Lockheed Martin fabricated three test articles that were never flown. These were the Structural Test Article (STA); the GVT-ET, and the MPTA-ET.

[1380] Lockheed Martin, "Flight Info."
[1381] Following Hurricane Katrina in August 2005, MAF was out of production for about one year. Bartolone, interview.
[1382] The numbering sequence used by Lockheed Martin differs from that used by NASA and others (e.g., Jenkins 2001). Thus, while Lockheed Martin did not use ET-7, NASA lists ET-7 as the sixth standard weight tank (SWT-6), which flew on STS-7. Jenkins designates the MPTA-ET as ET-1.
[1383] Pessin, "Lessons Learned," 19, 20.

Deliveries of Flight External Tanks to the Kennedy Space Center.[1384]

Year	Total	Tank Numbers (ET-#)	SWT	LWT	SLWT
1979	1	-1	1		
1980	0		0		
1981	2	-2, -3	2		
1982	4	-4, -5, -6, -8	3	1	
1983	7	-9 through -15		7	
1984	10	-16 through -25		10	
1985	11	-26 through -36		11	
1986	7	-37 through -43		7	
1987	4	-44 through -47		4	
1988	3	-48 through -50		3	
1989	4	-51 through -54		4	
1990	4	-55 through -58		4	
1991	3	-59 through -61		3	
1992	4	-62 through -65		4	
1993	4	-66 through -69		4	
1994	5	-70 through -74		5	
1995	6	-75 through -80		6	
1996	7	-81 through -87		7	
1997	4	-88 through -91		4	
1998	6	-96 through -101			6
1999	7	-92, -102 through -107		1	6
2000	5	-93, -108 through -111			5
2001	6	-94, -112 through -116			6
2002	6	-117 through -122			6
2003	1	-123			1
2004	0				0
2005	0				0
2006	1	-124			1
2007	2	-125, -126			2
2008	4	-127 through -130			4
2009	5	-131 through -135			5
2010	3	-136 through -138			3
Totals	136		6	85	45

Note: ET-122 originally was delivered on November 21, 2002, subsequently brought back to MAF for modifications, then returned to KSC in 2010 for flight.

[1384] Data compiled from Lockheed Martin, "Space Shuttle Flight Info," March 2010, 100-103, accessed August 2011, http://www.lockheedmartin.com/data/assets/ssc/michoud/.

General Description and Coordinate System[1385]

The ET (Figure No. D-17) measured 153.8’ in length, 27.6’ in diameter, and had a propellant capacity of approximately 1.6 million pounds (535,000 gallons). The inert weight of the SLWT was roughly 58,500 pounds. The ET was comprised of three primary structures: two separate propellant tanks and an intertank section located between them (Figure Nos. D-18, D-19). The upper tank held LO2 at minus 297 degrees F. The lower tank contained LH2 at minus 423 degrees F. Flanges at the top and bottom of the ribbed intertank connected the three elements. All power, pressure, and purges were received from either the orbiter or ground facility. The only active components on the ET were the vent/relief valves.[1386]

The SLWT was made of aluminum-lithium and steel alloys and titanium. A SOFI material approximately one inch thick was applied to the exterior of the entire tank, with 282 square feet of underlying ablators to prevent ice build-up and to protect the tank from engine and aerodynamic heating.[1387] Overall, the ET contained 481,450 parts, 38 miles of electrical wiring, 1,000 feet of insulated sleeving, 50 feet of coaxial cable, 4.7 miles of tape, 7,000 feet of safety wire, and 4,000 pounds of thermal protection materials. It required more than one-half mile of welding to join together the aluminum panels that formed the tank.[1388]

The baseline description of the SLWT contained in the following sections is from Lockheed Martin’s *Space Shuttle External Tank System Definition Handbook SLWT*, dated December 1997. Upgrades and improvements which post-date 1997 have been incorporated, to the extent possible. The physical and functional descriptions are organized by major ET system. Included are descriptions of the structures system, propulsion system, electrical system, and TPS, as well as interface hardware.

For the purposes of clarity and consistency, references to stations within the ET coordinate system have been minimized. The ET coordinate system used three reference planes. The “Y” reference plane intersected the ET (and attached orbiter) longitudinal centerline. The “Z” reference plane was parallel to the longitudinal centerline of the ET and the attached SRBs, and was arbitrarily located 400” from the ET longitudinal centerline in a direction opposite the attached orbiter. The “X” reference plane was nominal to the Y and Z planes, and was arbitrarily located 2,058” forward of the center of the two aft ET-to-orbiter structural attach points. Fore and aft distances along the longitudinal ET axis were designated ET “Stations,” and were measured as positive (+) distances from the X reference plane. Right and left designations are in the +Y and –Y directions, respectively, coinciding with the orbiter pilot’s right and left

[1385] This description focuses on the SLWT because it was the end state ET for the SSP.
[1386] Lockheed Martin, *Space Shuttle External Tank, System Definition Handbook SLWT, Layout Drawings Volume II* (New Orleans, LA: Lockheed Martin, December 1997), 4-2.
[1387] Lockheed Martin, “Fact Sheet Space Shuttle External Tank,” July 2011, accessed August 2011, http://www.lockheedmartin.com/data/assets/ssc/michoud/FactSheets/ETFact Sheet.pdf.
[1388] Lockheed Martin, “Space Shuttle External Tank Statistics and Comparisons,” June 2011, accessed August 2011, http://www.lockheedmartin.com/data/assets/ssc/michoud/FactSheets/ETStatistics.pdf.

perspective, when the orbiter was attached to the ET. Angular measurements around the circumference of the ET (within an X plane) were referenced to 0 degrees in the +Z direction (toward the orbiter); positive angles were clockwise looking forward.[1389]

Structures System

Three primary elements comprised the ET structures system: the LO2 tank, located in the forward position; the aft-positioned LH2 tank; and the unpressurized intertank, which connected the two propellant tanks. The intertank housed instrumentation and processing equipment, and provided one of the attachment structures for the SRBs. The LH2 tank was approximately twice as large as the LO2 tank. The basic structure was made of aluminum alloys 2024, 2195, 2219, and 7075.

<u>Liquid Oxygen Tank</u>

The LO2 tank was an ogive-shaped aluminum monocoque[1390] structure, which was designed to reduce aerodynamic drag and aerothermodynamic heating (Figure Nos. D-20, D-21). It was composed of a fusion-welded assembly of preformed chemically-milled gores and panels, and machined fittings and ring chords. The LO2 tank had a volume of approximately 19,463 cubic feet designed to contain approximately 1.38 million pounds (145,000 gallons) of oxidizer. The empty weight was approximately 12,000 pounds. The LO2 tank measured 27.6’ in outside diameter and 54.6’ long, and operated in a pressure range of 20 to 22 pounds per square inch, gauge (psig). Vortex and slosh baffles were mounted in the LO2 tank to minimize liquid residuals and damp fluid motion. A 17”-diameter feedline conveyed the LO2 from the LO2 tank through the intertank, then outside the ET to the aft right-hand ET/orbiter disconnect umbilical. The LO2 flowed through the feedline at approximately 2,787 pounds per second, with the SSMEs operating at 104 percent, or a maximum flow of 17,592 gallons per minute. The LO2 tank’s nose cone, which contained electrical system components, functioned to reduce drag and heating, and also acted as a lightning rod.[1391]

Aluminum alloys (2024, 2195, and 2219) were used exclusively in the fabrication and assembly of the LO2 tank structure. Compared with the LWT design, the weld lands in the SLWT were increased by up to 0.25” in thickness.[1392] The “robust weld lands” connected the ogive to ogive, barrel panel to barrel panel, dome gore to dome gore, and dome cap to dome body.

[1389] Martin Marietta, *Handbook, Configuration & Operation*, III-5.
[1390] Monocoque is a type of construction in which the outer skin carries all or a major part of the stresses, as distinguished by an internal frame or truss system.
[1391] USA, *Crew Operations*, 1.3-2; Lockheed Martin Corporation, “External Tank,” 2010, accessed August 2010, http://www.lockheedmartin.com/ssc/michoud/ExternalTank/index.html.
[1392] Lockheed Martin, *Handbook (SLWT),* 6-3.

The **major assemblies** which comprised the LO2 tank were the nose cone and cover plate, the forward and aft ogive sections, the cylindrical barrel section, the slosh baffle, and the LO2 aft dome (Figure No. D-22). A description of each follows.

A **nose cone** and a flat removable **cover plate** topped the ogive nose section. The conical-shaped **nose cone**, mounted on the ogive, was 2.54' long and was constructed of 0.252"- to 0.336"-thick epoxy graphite composite. The design for the original SWT nose cone used over 1,000 fasteners to assemble multiple sheet metal pieces. It was covered with TPS materials. In June 1989, MSFC and Martin Marietta began developing a new advanced nose cone constructed from a high-temperature resistant composite. The new composite nose cone was manufactured by the MSFC Productivity Enhancement Center from eighteen to twenty-one sheets of graphite phenolic cloth inside a graphite mold. The new design could withstand temperatures in excess of 900 degrees F, thus eliminating the need for the TPS. The composite nose cone resulted in a weight savings of 21 pounds.[1393]

The forward end of the nose cone featured a cast aluminum lightning rod, which protected the entire Space Shuttle vehicle at the pad. The lightning rod, which measured 13.34" long, was attached to the nose cone by six 0.25"-diameter bolts. The nose cone featured provisions for two stainless steel louvers that were part of the oxidizer vent system. It also had a penetration for the electrical cable tray and the LO2 pressurization line. The nose cone was attached to the nose cone brackets by twenty-nine 3/8"-diameter bolts.[1394]

The removable **cover plate** provided a location for mounting propulsion system components. Machined from 2219 aluminum plate, it measured 39" in diameter, 0.35" thick, and weighed 79 pounds. The cover plate incorporated machined stiffeners, and was joined to the ogive forward ring by ninety-two 5/16"-diameter bolts. A pressure seal of Naflex provided a gastight joint. Removal of the plate provided a 36"-diameter access opening to the LO2 tank.[1395]

The 612"-radius **ogive section** was formed by welding a forward fitting, eight forward gores, and twelve aft gores. The forward fitting was a one-piece, machined forging that included the cover plate mating-and-sealing surface. It was butt welded to the forward ogive gore assembly. The forward ring contained a 1.4" penetration for the electrical feed-through connector.[1396]

One forward and one aft gore section had locally thickened skin pads and weld tabs for the attachment of support brackets for the LO2 pressurization line and electrical cable tray. The skin pads and weld tabs continued over the adjoining barrel section.[1397] All ogive gore panels were

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[1393] Jenkins, *Space Shuttle*, 423. Two non-production units were tested in January 1994, and the first production unit was used on ET-81.
[1394] Lockheed Martin, *Handbook (SLWT)*, 6-6.
[1395] A Naflex seal is a metallic seal with a redundant sealing feature; it was created by North American Aviation, Inc. Lockheed Martin, *Handbook (SLWT)*, 6-7, 6-16.
[1396] Lockheed Martin, *Handbook (SLWT)*, 6-7.
[1397] Lockheed Martin, *Handbook (SLWT)*, 6-8.

chemically-milled on both sides, and edge trimmed and butt welded during assembly to form the ogive section. An extruded "T" ring frame was butt welded to the aft edge of the ogive section and to the forward edge of the barrel section of the LO2 tank. This frame provided for the forward attachment of the slosh baffle and contributed to the tank's stability. The frame was pre-formed to a circular shape in four, ninety degree segments. The four segments were butt welded together to complete the frame.[1398]

Mounted to the forward ogive gore panel was the mast for the LO2 level and temperature sensors. The mast measured approximately 82.8" long, with a 3.1" outside diameter and a wall thickness of 0.083".[1399] Also attached to the forward ogive gore, by means of butt welding, was a fitting made from a single piece of machined 2219 aluminum. This fitting provided attachment and sealing features for the nose cone and the cover plate.[1400]

The **cylindrical barrel section**, which measured approximately 98.2" in length, was fabricated from four chemically-milled and formed panels of 2219 aluminum plate welded together. Skin thicknesses on the two side panels were tailored in grid fashion to accommodate SRB thrust loads. The other two panels were identical except for three thickened skin pads and weld tabs on one panel. These tabs supported the cable tray and GO2 pressure line extending over the barrel.[1401]

The **LO2 slosh baffle assembly**, fabricated in two sections, consisted of aluminum rings tied together with longitudinal stringers and tension straps. The main stabilizing ring frame served as the aft baffle support ring at the juncture of the barrel section and the LO2 tank dome. This ring was comprised of thirty-two machined forgings alternating with thirty-two stiffened webs, plus aluminum chord. The webs of the frames, web stiffeners, and stringers were riveted, while the tension straps were pin joined.[1402] The baffle assembly, primarily made of 2024 aluminum sheet, was designed to prevent fluid slosh.

The **LO2 aft dome** section was comprised of the aft (dome-to-barrel) ring frame, twelve identical gore segments, and a 140"-diameter dome end-cap. The end-cap included the LO2 contoured feed outlet, a 36"-diameter manhole access, and a 1.28"-diameter penetration for the aft LO2 low-level sensor electrical feed-through connector. The dome was assembled by welding together three pre-formed and chemically-milled gore skins and a quarter section of the extruded ring frame to form a dome quarter panel. The quarter panels were welded together, after which the dome end-cap was welded onto the assembly. The aft ring frame served as the weld juncture

[1398] Lockheed Martin, *Handbook (SLWT)*, 6-9.
[1399] Lockheed Martin, *Handbook (SLWT)*, 6-15.
[1400] Lockheed Martin, *Handbook (SLWT)*, 6-16.
[1401] Lockheed Martin, *Handbook (SLWT)*, 6-10.
[1402] Lockheed Martin, *Handbook (SLWT)*, 6-10, 6-17.

between the barrel section and the dome. The outer flange was mated to the intertank with 194 bolts of 9/16”-diameter.[1403]

The variable skin thickness of the dome gore panels was accomplished by chemical milling. Panel members were reinforced by a series of circumferential bands. The spherical dome cap was spun formed and then chemically milled on both sides. The cap featured cutouts for the contoured LO2 outlet/inlet fitting and the manhole fitting, and for an electrical feed-through connector. The outlet/inlet fitting was welded to the dome cap.[1404]

A **vortex baffle** was installed to the end-cap, internal to the tank. The baffle served to reduce fluid swirl resulting from the Coriolis effect, and prevented entrapment of gasses in the delivered LO2. The 160”-diameter vortex baffle was attached to the dome cap at four locations, with two fasteners at each location. The assembly included four webs with upper and lower caps, and vertical stiffeners stabilized with diagonal straps. The webs and caps were joined at the center with a splice plate at the bottom and a splash plate on top. The 0.02”-thick webs contained a total of 124 holes which served to both lighten the structure and reduce the slosh locally. A four-segment, 800-micron filter screen, which helped to anchor the baffle assembly, was mounted to the lower caps of the vortex baffle.[1405]

A 45”-diameter manhole fitting, welded to the dome cap, provided a 36”-diameter clear access to the tank interior. The fitting featured ninety-two attachment points for mating to the machined aluminum manhole cover. The fifty-seven pound manhole cover measured 40.32” in overall diameter and 0.185” thick at the center. It provided an interfacing sealing surface with the manhole fitting, as well as a means for making a leak check of the primary seal.[1406]

Intertank

The intertank was a semi-monocoque, cylinder-shaped structure comprised of external stringers and internal frames (Figure No. D-23). It connected the two propellant tanks, housed instrumentation and processing equipment, and provided the attachment structure for the forward end of the SRBs. Flanges on the bottom and top ends of the intertank attached with the LO2 and LH2 tank assemblies. The intertank measured 270” (22.5’) long, 331” (27.6’) in diameter, and weighed approximately 12,100 pounds. Aluminum alloys were used exclusively in the intertank structure, with the exception of fasteners and the SRB fitting socket inserts, which were steel.[1407] The primary functions of the intertank were to receive and distribute all thrust loads from the SRBs, and to provide structural continuity. The intertank also provided a carrier plate assembly

[1403] Lockheed Martin, *Handbook (SLWT)*, 6-11.
[1404] Lockheed Martin, *Handbook (SLWT)*, 6-12.
[1405] Lockheed Martin, *Handbook (SLWT)*, 6-13.
[1406] Lockheed Martin, *Handbook (SLWT)*, 6-14.
[1407] Lockheed Martin, *Handbook (SLWT)*, 7-3.

that interfaced with the fluid, electrical, and pneumatic systems ground facilities.[1408] The major structural elements of the intertank included two thrust panels, six stringer-stiffened panels, ring frames, and the SRB beam (intertank crossbeam) (Figure No. D-24).

The two **thrust panels** were rough machined from 2219 aluminum plate, and formed to cylindrical segments with a radius of approximately 165”. They were final machined to a finished size of 2.06” by 130” by 270.35”. Skin thickness was variable, depending on the location. Each panel was comprised of twenty-six external parallel ribs. These, in addition to seven circumferential ribs, were designed to prevent buckling of the intertank. Rib thickness ranged between a minimum of 0.17” to 1.05” near the SRB fittings; circumferential rib thickness varied from 0.5” at the center of the panel to 0.18” at the outer edge.[1409] Two longerons of extruded aluminum were mechanically fastened to each thrust panel, one on each side of the SRB fitting, to provide added stability. The longerons measured 114” long, 3” wide, and 5” high, with a maximum thickness of 0.22”. They extended through the two smaller ring frames, and ended near the LO2 tank attachment flange ring.[1410]

Each of the six **skin/stringer panels** was made of two 2090 aluminum sheet skins mechanically spliced using longitudinal butt straps. Skin doublers, also of 2090 aluminum sheet, provided reinforcement for areas where the skin was penetrated for the ET intertank carrier plate assembly, the access door opening, venting, and the entry of cables and lines. Additional skin reinforcing doublers were located adjacent to the thrust panels and the LO2 tank attachment flange ring. The skin doublers were located both internally and externally. Eighteen external stringers were equally spaced around each panel to provide buckling and flutter resistance, to distribute loads to the attachment flanges, and to provide for the attachment of mounting brackets for propulsion and electrical subsystem lines and cable trays. The aluminum stringers were mechanically fastened to the skin panels and flanges.

The intertank featured one **main ring frame**, which distributed SRB loads to the intertank skin, and four **intermediate ring frames**, which provided intertank skin panel stability. The main ring frame adjoined the SRB thrust fitting. It was constructed of four quadrant subassemblies, each built of outer and inner tee chords machined from 7075-T73511 aluminum extrusions and joined to webs to form an I-beam measuring 20” deep. The outer chords were fastened to the cylindrical skin panels. The width of each outer chord was 6” for a length of 53” at the end which fastened to the SRB fitting, 6” for a length of 54” adjacent to the access door in one quadrant, 3.8” at the end spliced to the adjacent chord, and 3.2” wide for the remainder of its length. The inner chord was a uniform 3.86” wide. The web thickness varied from 0.180” to 0.05” with increasing distance from the SRB fitting.[1411]

[1408] Lockheed Martin, *Handbook (SLWT)*, 7-2.
[1409] Lockheed Martin, *Handbook (SLWT)*, 7-4, 7-5.
[1410] Lockheed Martin, *Handbook (SLWT)*, 7-6.
[1411] Lockheed Martin, *Handbook (SLWT)*, 7-7.

The four intermediate ring frames were of similar construction, forming an I-beam measuring 12” deep. However, there were two significant differences among the four intermediate ring frames. The ring frame adjacent to the access door had a locally wider outer chord section. Secondly, the two ring frames located in the forward half of the intertank had the outer chords cut and portions of the webs notched to straddle the two longerons.[1412]

The **SRB beam assembly** was a rectangular box beam consisting of top and bottom chords, stiffened webs, stability bulkheads, and SRB thrust fittings, all mechanically joined. It measured 42.95” deep at the center and tapered to 26” (at the ends) by 15” wide. The SRB beam spanned 345” between the centerlines of the two SRB thrust fittings which formed the ends of the assembly. The top (forward) chord was an extruded and machined 7075-T86 aluminum channel with extensions for attaching web members. The bottom chord was similar to the top, and both were fastened to the SRB fitting. Side webs of 7075-T6 aluminum sheet were joined to the top and bottom beam chords. The webs located in the area of the ring frame junction with the SRB fitting were reinforced with tee and angle stiffeners. Two skin doublers provided further structural strength at this location. The two intertank SRB thrust fittings, of machined aluminum (7050-T73) forgings, were mechanically fastened to the chord ends of the SRB beam, the machined gusset fittings, the main frame outer chord, and the thrust panel.[1413]

Two **vent openings**, each with an area of 6 square inches, were provided at the forward end of the intertank. They were for venting during preflight environmental conditioning and for equalization of internal/external pressures in flight. Each **pressure vent** consisted of an elliptical-shaped tube which was installed on the intertank skin.[1414]

The intertank featured an **access door** made of composite graphite polyimide material, with sixteen plies on the skin and eight plies on the stringers. The door, recessed from the intertank stringer tops, was attached to the intertank with forty-four bolts.[1415]

Four **aerodynamic fairings** enclosed the penetrations for the LO2 feedline, the gaseous hydrogen pressure line, and at the two electrical cable tray locations. The fairings were fastened to the tops of the stringers immediately fore and aft of the penetration openings. In addition, supports for the cable trays and propulsion lines were fastened to the stringers by formed-sheet and machined brackets that bridged the stringer gaps.[1416]

[1412] Lockheed Martin, *Handbook (SLWT),* 7-8.
[1413] Lockheed Martin, *Handbook (SLWT),* 7-9, 7-10.
[1414] Lockheed Martin, *Handbook (SLWT),* 7-10.
[1415] Lockheed Martin, *Handbook (SLWT),* 7-11.
[1416] Lockheed Martin, *Handbook (SLWT),* 7-12.

Liquid Hydrogen Tank

The cylindrical-shaped LH2 tank was a semimonocoque structure fabricated exclusively of aluminum alloys (Figures No. D-20, D-25, D-26). It was comprised of welded barrel sections and ring frames, and was capped on both ends by modified ellipsoidal domes. The LH2 tank measured 331” (27.6’) in outside skin diameter and 1,160” (96.7’) long. It had a volume of 52,371 cubic feet, and held approximately 231,000 pounds (390,000 gallons) of propellant fuel, which included a 3 percent ullage.[1417] The empty weight was approximately 29,000 pounds.[1418] The LH2 tank was roughly two-and-one-half times larger than the LO2 tank, but weighed only one-third as much when filled. This was because LO2 is sixteen times heavier than LH2. The LH2 tank contained an anti-vortex baffle and siphon outlet to transmit the LH2 from the tank through a 17” line to the left aft umbilical. The LH2 feedline flow rate was 465 pounds per second with the SSMEs at 104 percent, or a maximum flow of 47,365 gallons per minute. The operating pressure range was 32 to 34 psia.

A frame located at the juncture of the forward dome and the forward barrel contained a flange for joining the LH2 tank to the intertank. This frame also provided the structure for the ET/orbiter forward attach point. A frame at the juncture of the aft dome and aft barrel contained the structure for the ET/SRB aft attachment, as well as for the aft ET/orbiter attachment.[1419]

The **major assemblies** which comprised the LH2 tank were the forward and aft domes, the cylindrical barrel sections, and the major ring frames (Figure No. D-27). A description of each follows.

The **LH2 forward dome** was a welded assembly of twelve gore segments and a dome cap, all fabricated from 2195-T8A4 and 2219-T87 aluminum plate. The dome shape and manufacturing techniques were the same as for those used for the LO2 tank. Gore skin thickness was tapered to maintain stress uniformity and each gore was chemically milled on both sides to equalize skin stresses. Thickness varied from a minimum of 0.066” near the aft edge of the gore to 0.084” near the dome cap. The membranes were reinforced by a series of circumferential chemically milled bands. The dome cap measured 140” in diameter and was 0.092” thick, with the exception of the weld lands. It was machined to accommodate installation of the LH2 vent valve, the LH2 pressure line fitting, the electrical feed-through fitting, the forward manhole fitting, and the LH2 tank manhole covers.[1420]

[1417] Ullage is defined as: 1. the amount of liquid within a container that is lost, as by leakage or evaporation; 2. The amount by which a container falls short of being full; and 3. The free space above the liquid contained in a barrel, drum, or tank, provided to accommodate the expansion of the liquid. http://www.the freedictionary.com/ullage; www.businessdictionary.com/definition/ullage.html.
[1418] USA, *Crew Operations*, 1.3-3; Lockheed Martin Corporation, “External Tank.”
[1419] Lockheed Martin, *Handbook (SLWT),* 5-2.
[1420] Lockheed Martin, *Handbook (SLWT),* 8-5.

The **LH2 tank aft dome** was similar in shape and construction to the LH2 tank forward dome and the LO2 tank domes. The major difference between it and the LH2 tank forward dome was the provision for the mounting of fittings. Provisions for tank access were incorporated in the aft dome cap, and the manhole fitting was similar to those on both the LO2 tank domes and the LH2 tank forward dome. Unlike the LWT design, the SLWT did not have a second manhole cover.[1421] The fitting for the LH2 feedline was unique because of the angle at which it penetrated the dome, and because of the compound curve of its flange. A vortex baffle assembly was located at the LH2 feedline siphon outlet just above the aft dome. This assembly was comprised of four identical baffle webs formed of 2024 aluminum. Outer frame chords of extruded tee-shaped aluminum were riveted to each web. The webs contained fluid damping holes and stiffeners.[1422]

The four **cylindrical barrel sections** were fabricated of 2195-T8M4 aluminum plate. Each section was a welded assembly made from eight orthogrid stiffened skin panels. Two basic orthogrid pocket configurations were used throughout the skin panels. The skin membrane thickness varied from panel to panel, from a minimum of 0.084” to a maximum of 0.555”. The thickness of the weld lands at the edges of each panel was generally 0.325”. The skin panels included provisions for mounting support fittings for propulsion system lines and electrical cable trays. Two longerons, made from 2219-T6 aluminum forgings, were butt welded into the skin panels of the aft barrel section. The longerons measured approximately 181.75’ long by 32.496” wide.[1423]

Five **major ring frames** joined the dome and barrel sections together. These frames were I-Beam-shaped with varying depths and chord configurations. With one exception, the frames were fabricated in 90-degree segments at the subassembly level. They were then spliced by circumferential weldments along the outer chord, and by mechanically attached splice plates and angles at the web and inner chord. The outer chord was made from extruded 2195-T8A3 and 2219-T8511 aluminum; the inner chord was fabricated of extruded 2024-T8511 aluminum. The webs were made of 2024-T81 sheet and plate aluminum.[1424] The forward and two aft major ring frames were stiffened by radially-oriented web stiffeners. The other two frames required no web stiffening. Each major ring frame was stabilized by struts which tied the frame inner chord to the barrel orthogrid at circumferential locations.[1425]

Propulsion System

The ET contained all the fuel and oxidizer to feed the orbiter’s three main engines (Figure No. D-28). These propellants were delivered between the tanks and orbiter interface through **17”-diameter feedline disconnects.** The complete ET propulsion system was comprised of the LO2

[1421] This feature was eliminated on the aft dome as a weight saving measure.
[1422] Lockheed Martin, *Handbook (SLWT)*, 8-14, 8-15.
[1423] Lockheed Martin, *Handbook (SLWT)*, 8-6, 8-7, 8-19.
[1424] Lockheed Martin, *Handbook (SLWT)*, 8-4, 8-9.
[1425] Lockheed Martin, *Handbook (SLWT)*, 8-9 through 8-13.

and LH2 feed systems; the LO2 and LH2 tank pressurization and vent/relief systems; the intertank and tank environmental control systems; and the ET intertank carrier plate assembly.

Feed Systems

Each ET contained five **propellant umbilicals** which fueled the main engines. Two umbilicals were for the LO2 tank (one for LO2 and one for GO2) and three were for the LH2 tank (two for LH2 and one for GH2). These lines carried the fuel, oxidizer, gases, electrical signals, and power between the tank and the orbiter.

Eight **propellant depletion sensors**, designed for propellant loading control, were located inside the ET, four each for the fuel and the oxidizer. The LO2 oxidizer sensors were initially mounted on the LO2 feedline manifold (later relocated to the oribiter side of the feedline), and the LH2 fuel sensors were mounted on the bottom of the LH2 tank. The orbiter's onboard computers monitored the mass of the Shuttle vehicle, which lessened as the fuel was depleted. If any two of the fuel or oxygen sensors read a dry condition, the engines would be shut down and the ET jettisoned. The location of the sensors allowed the maximum amount of oxidizer to be consumed, while allowing sufficient time to shut down the engines before the oxygen pumps ran dry (known as "cavitation"). In addition, 1,100 pounds of LH2 were loaded over and above that required by the 6:1 oxidizer/fuel engine mixture ratio to assure that when the main engine cutoff occurred, the propellant mixture was fuel rich. Otherwise, oxidizer-rich engine shutdowns could cause burning and severe erosion of the engine components.[1426]

The **LO2 feed system** consisted of the LO2 feedline and the helium inject line. The LO2 feedline was a 17"-inner diameter insulated pipe made of aluminum and corrosion-resistant steel. It ran up the side of the LH2 tank through a slotted port in the intertank skin to a joint on the outlet of the LO2 tank.[1427]

The LO2 feedline assembly consisted of nine sections, including the forward flexible assembly, the flexible elbow, four straight sections, an aft flexible assembly, an aft elbow, and the ET/orbiter disconnect assembly. These sections were joined with bolted flanges which contained seals to control leakage. The forward flexible assembly was located entirely within the intertank. The elbow assembly penetrated the intertank skin and ran down the side of the ET a distance of approximately 108". The four straight sections ran down the side of the LH2 tank from the flexible elbow to the aft flexible assembly, a distance of approximately 840". The upper section was 247.7" long, the middle two sections were 246.7" long, and the lower section was 102.5" long. The aft elbow joined the 76.6"-long aft flexible assembly to the ET half of the LO2 disconnect at the right ET/orbiter umbilical disconnect plate. The straight sections were made of

[1426] NASA KSC, "The Lightweight Space Shuttle External Tank," NASA Fact Sheet (Florida: Kennedy Space Center, February 1983), Sweetsir Collection, Box 50E.3, Folder 125, Kennedy Space Center Archives, Florida; USA, *Crew Operations*, 1.3-3, 1.3-4.
[1427] Lockheed Martin, *Handbook (SLWT)*, 9-9.

2219 aluminum and the aft elbow was a casting of A357T6 aluminum. The flexible sections were fabricated of 347 stainless steel, 21-6-9 stainless steel and Inconel 718. The feedline had flexible joints in five places which allowed for fabrication and installation tolerances, thermal expansion, and relative motion during liftoff and flight. Seven supports secured the LO2 feedline to the tank structure, including five pivoting supports located along the length of the LH2 tank.[1428]

The helium inject line, made of 3/8" outer diameter stainless steel tubing ran through the intertank, down the LH2 tank, inside the cable tray, and into the LO2 aft elbow. This line introduced a controlled flow of helium into the aft end of the LO2 feedline to prevent geysers during propellant loading and hold before launch. It was not operational during flight.[1429]

The **LH2 feed system** consisted of the LH2 feedline and the LH2 recirculation line. The LH2 feedline was a 17"-inner diameter pipe made of aluminum and corrosion-resistant steel. The internal/external configuration ran from the ET half of the LH2 disconnect through a flanged port on the upper LH2 tank aft dome, to near the bottom of the dome. The uninsulated internal feedline section consisted of a 35"-long articulated bellows segment and a bell-mouth siphon segment. The LH2 internal feedline assembly was fabricated from 304L and 321 stainless steel. The 42"-long external feedline section, fabricated of 321 and 347 stainless steel, 21-6-9 stainless steel, and Inconel 718, contained an articulated bellows assembly with an insulation jacket to prevent the formation of liquid air during countdown and launch operations.[1430]

The LH2 recirculation line measured 4" in diameter by approximately 60" long. It was constructed of 21-6-9 stainless steel and insulated with SS-1171 and SLA-561. The line connected the 4" disconnect valve in the ET/orbiter umbilical assembly with the LH2 tank. It carried warm LH2 from the engine back to the ET during propellant loading and hold. The recirculation line incorporated two free bellows assemblies with argon gas-filled jackets, similar to the LH2 feedline.[1431]

Tank Pressurization and Vent/Relief System

The pressurization and vent relief system, which regulated the tank pressure, incorporated the LO2 and LH2 tank pressurization subsystems and the LO2 and LH2 tank vent/relief subsystems.

The **LO2 Tank Pressurization Subsystem** consisted of a GO2 pressurization line fabricated of Inconel 718 corrosion-resistant steel tubing. The 2"-outer diameter line extended from the GO2 pressurization disconnect on the aft right ET/orbiter umbilical, up the exterior of the LH2 tank, intertank, and LO2 tank, and terminated at the LO2 tank forward cover plate. The pressurization

[1428] Lockheed Martin, *Handbook (SLWT)*, 9-10 through 9-12.
[1429] Lockheed Martin, *Handbook (SLWT)*, 9-14.
[1430] Lockheed Martin, *Handbook (SLWT)*, 9-15 through 9-17.
[1431] Lockheed Martin, *Handbook (SLWT)*, 9-18.

line was comprised of nine separate line assemblies: the upper flex line assembly, the upper curved line assembly, the upper transition line assembly, the mid flex line assembly, four straight assemblies, and the lower flex line assembly.[1432] All line sections were mated to each other and to their interfaces with flanged joints. Naflex Inconel 718 seals were used at each mechanical joint. A leak-test port was located at each joint to provide access between the primary and secondary sealing surfaces. The pressurization line was supported by thirty-three sliding supports and two fixed supports. The latter were located at the aft end of the intertank and at the forward end of the LO2 tank.[1433] A cylinder-shaped diffuser, located at the GO2 pressurization line outlet, was secured internally to the LO2 tank.

The **LH2 Tank Pressurization Subsystem** consisted of a 2”-outer diameter tube made of corrosion-resistant steel. The line extended from the GH2 pressurization disconnect on the aft left umbilical, to the LH2 tank, up into the intertank, and terminated at the cover plate mounted to the LH2 tank forward dome cap. A cylindrical-shaped GH2 diffuser was mounted to the cover plate inside the LH2 tank. The GH2 pressurization line consisted of an upper flex assembly, a straight line assembly, a lower flex assembly, a straight line section, and an aft flex assembly. The subsystem also included eleven flexible joints, two supports for the line upper assembly located within the intertank along the LH2 tank dome, and other sliding and fixed supports.[1434]

The **LO2 Tank Vent/Relief Subsystem** consisted of a two-stage GO2 vent/relief valve, a vent manifold, and two louver assemblies. This dual-function valve could be opened by ground support equipment for the vent function during prelaunch, and during flight when the ullage pressure of the LH2 tank reached 36 psig, or the ullage pressure of the LO2 tank reached 31 psig.[1435] The valve inlet was bolted to a port on the LO2 tank forward bulkhead cover plate. The outlet connected to the vent manifold. The inner manifold contained a bellows assembly. GO2 was discharged on opposite sides of the nose cap through the louvers.[1436]

The **LH2 Tank Vent/Relief Subsystem** included a single vent/relief valve inlet bolted to a fitting welded into the LH2 tank forward dome. The outlet was bolted to a vent duct, which in turn bolted to the vent disconnect on the intertank umbilical disconnect plate. The vent duct was bolted to the vent valve. A steel vent valve actuation line led from a 3/8”-diameter disconnect at the intertank umbilical carrier plate to an actuation port on the valve. The line followed and was attached to the side of the vent duct.[1437]

[1432] Lockheed Martin, *Handbook (SLWT)*, 9-19, 9-20.
[1433] Lockheed Martin, *Handbook (SLWT)*, 9-21.
[1434] Lockheed Martin, *Handbook (SLWT)*, 9-23, 9-24.
[1435] USA, *Crew Operations*, 1.3-3.
[1436] Lockheed Martin, *Handbook (SLWT)*, 9-26, 9-27.
[1437] Lockheed Martin, *Handbook (SLWT)*, 9-30.

Environmental Conditioning System

The ET environmental conditioning system consisted of an intertank purge and a hazardous gas detection system. These served to purge the intertank, the nose cap, and propellant tanks, as well as to sample the intertank environment for gas composition during propellant loading operations. The intertank was purged with dry, heated GN2 during propellant loading to prevent condensation of moisture, to preclude air ingestion through the intertank vents, and to avert a buildup of hazardous gases.[1438] Similarly, heated GN2 purged the ET nose cone cavity to provide an inert atmosphere and to minimize the ice/frost formation that would be caused by cold vent gas. The gas flow rate was approximately 13.5 pounds per minute.[1439]

ET Intertank Carrier Plate Assembly

The ET intertank carrier plate assembly was where the ground umbilical carrier assembly (GUCA) and the facility lines mated. The flight half of the ET/ground umbilical interface provided for the servicing of the pressurization and vent system, hazardous gas detection system, operational instrumentation system, and electrical power.[1440] The plate assembly was machined from aluminum alloy 2219 plate, and mechanically fastened to the skin panel by four flanges.[1441]

Electrical System

The ET's electrical system provided operational instrumentation, cabling, electromagnetic compatibility, and lightning protection. All electrical power was supplied by the orbiter, except for heater power which was provided by the ground facilities.

Operational Instrumentation

The operational instrumentation for the ET electrical system included thirty-five flight systems and ground systems sensors, as well as switches and the ice/frost heating subsystem. Of the sensors, four gas temperature sensors and two LO2 ullage pressure sensors were ground measurements; the others were flight measurements. The instrumentation provided status data to the orbiter, or to the launch facility, regarding temperature, pressure, and liquid levels prior to launch. After the *Columbia* accident, ground temperature measurements were added to control the bipod heaters.

The **thirty-five sensors** included the following:

- Two resistant-type transducer ullage temperature sensors, one for LO2 and the other for LH2;

[1438] Lockheed Martin, *Handbook (SLWT)*, 9-31.
[1439] Lockheed Martin, *Handbook (SLWT)*, 9-34.
[1440] Lockheed Martin, *Handbook (SLWT)*, 9-34.
[1441] Lockheed Martin, *Handbook (SLWT)*, 7-12.

- Four resistant-type transducer gas temperature sensors, including two in the intertank and two mounted on the nose cone plate;
- Four potentiometer-type, absolute-pressure transducer LH2 pressure sensors, of which one was for backup purposes only;
- Three variable reluctance-type, differential pressure transducer LO2 ullage pressure sensors;
- Two variable reluctance-type, pressure transducer LO2 ullage loading pressure sensors;
- Twenty liquid level and depletion sensors which indicated the presence or absence of LO2 or LH2.[1442] The LO2 depletion sensors were located in the orbiter while the LH2 depletion sensors were located in the ET.

The LH2 tank incorporated two vent valve position indicator **switches** to denote OPEN or CLOSED positions prior to launch; the LO2 tank had a CLOSED position only. These three vent valve switches were integral parts of the valve assemblies.[1443]

The **ice/frost heating subsystem** consisted of two calrod heaters mounted on each of the forward bipod spindle assemblies. These functioned to minimize ice accumulation on the bipod fitting. The heaters were powered and regulated by the launch facility.[1444]

Cabling

Both ET and Orbiter/SRB interface cabling were components of the electrical system. The **ET cabling system** provided hardware connections between the ET electrical components and orbiter interfaces. The system consisted of wiring, connectors, protected wire splices used in areas where connectors were not required, cabling, and disconnect panels located in the intertank that held bulkhead connectors. External cabling on the ET was routed through protective aluminum cable trays. The cable trays had removable covers and were protected by TPS on the external surfaces. The primary tray ran along the right shoulder of the ET. Twelve **orbiter/SRB interface cables** were located on the ET. The cables, which did not connect into the ET electrical system, ran through protective cable trays.[1445]

Lightning Protection

The primary lightning protection feature for flight was the nose spike located on the nose cone, described previously.

[1442] Lockheed Martin, *Handbook (SLWT)*, 10-2 through 10-6.
[1443] Lockheed Martin, *Handbook (SLWT)*, 10-7.
[1444] Lockheed Martin, *Handbook (SLWT)*, 10-8.
[1445] Lockheed Martin, *Handbook (SLWT)*, 10-9, 10-10, 10-14.

Thermal Protection System

The exterior surface of the ET featured a multi-layered thermal protection coating approximately 1" thick. SOFI for high insulation efficiency, and premolded ablator materials for dissipating heat were the primary tank constituents. The system also included phenolic thermal insulators. These were needed for the LH2 tank attachments to preclude air liquefaction and to reduce heat flow into the LH2 tank. The TPS prevented super cold LO2 (-297 degrees F) and LH2 (-423 degrees F) from forming ice on the outside surfaces of the ET; protected the skin surface from the aerodynamic heat of ascent as well as radiant heat from the engines; and maintained the propellants at an acceptable temperature. The SOFI had several property requirements. It had to adhere to the tank; had to withstand the cryogenic temperatures at the surface; had to withstand atmospheric stresses; had to keep the ET surface above 32 degrees; and had to be lightweight. The TPS weighed roughly 4,823 pounds.[1446]

The original SWTs featured a 1"-thick layer of two primary TPS materials: CPR-421, a fluorocarbon-blown, rigid-foam system applied to almost all exterior cryogenic surfaces, and SLA-561, an ablator used in areas of high aerodynamic heating.[1447] As previously noted, from the SWT to the SLWT, the constituent elements of the ET's TPS underwent several changes. The end-state SLWT featured four insulating foams: NCGI 24-57, NCFI 24-124, PDL 1034, and BX-265. SLA 561 was the primary ablator, with MA25S used for highly heated local areas.[1448] Each main element of the ET had its own TPS requirements, as summarized in the following table.

[1446] USA, *Crew Operations*, 1.3-3.
[1447] Martin Marietta, *Handbook, Configuration & Operation*. According to Lockheed Martin's *System Definition Handbook* , CPR-421 was adversely affected by sunlight and water, and thus, required a protective coating to protect it against ultraviolet radiation and moisture.
[1448] Lockheed Martin, *Handbook (SLWT)*, 4-4.

External Tank Thermal Protection.[1449]

TPS TYPE	MATERIAL: CHARACTERISTICS	ET LOCATION
Spray-on Foam Insulation (SOFI)	***NCFI 24-57***: A polyiso-cyanurate foam applied with blowing agent HCFC-141b. Has higher temperature stability than conventional urethane foams.	LH2 Tank Dome
	NCFI 24-124: A polyiso-cyanurate foam applied with blowing agent HCFC-141b. Has higher temperature stability than conventional urethane foams	LH2 Tank Barrel Intertank acreage LO2 Tank Ogive/Barrel
	BX-265: A polyurethane foam. Used for select closeout areas, primarily to protect against ice/frost and air liquefaction. May be sprayed or molded-in-place. In high heating locations when a BX-265 closeout is used, a SLA-561 underlayer is required.	LH2 Tank Apex Closeout LH2 Tank Aft Interfaces/Cable Tray Covers/Fairings LH2 Tank Longeron LH2 Tank Aft Struts LO2 Feedline Bipod Closeouts Intertank/LH2 Tank Flange Closeout Intertank/LO2 Tank Flange Closeout
Pour-on Foam Insulation (POFI)	***PDL 1034***: Used for ice/frost closeout applications and as a repair foam for small damaged areas. Suitable for filling difficult- shaped cavities.	LO2 Feedline LH2 Tank Aft Interfaces/Cable Tray Covers/Fairings LH2 Ice/Frost Ramps LO2 Ice/Frost Ramps Intertank/LH2 Tank Flange Closeout Bipod Closeouts Nose Cone
Molded Ablators (MA)	***MA 25S***: Used in areas of the ET/orbiter interface, and where heating rates exceed the capability of SLA-561. Can be used as a sprayable or bonded ablator.	Bipod Struts Nose Cone
Hand-packed Ablators	***SLA-561***: Used in areas of high heating. May be sprayed or used in molded form.	LH2 Tank Apex Closeout LH2 Tank Aft Interfaces/Cable Tray Covers/Fairings LO2 Feedline Fairing LO2 Cable Trays and Fairings

[1449] USA, “Vehicle Assembly Building External Tank Processing,” (presentation, KSC, no date), 7.

The ET derived its distinctive color from the insulating foam. When first applied, the foam was light tan in color. Then, exposure to ultraviolet rays darkened or reddened the foam over time.[1450]

SOFI is a low-density, closed-cell foam which was used on the tank acreage to keep the propellants at optimum temperature while preventing a buildup of ice on the outside of the tank. It is a polyurethane-type foam composed of five primary ingredients: polymeric isocyanate, a flame retardant, a surfactant, a blowing agent, and a catalyst.[1451] The SOFI was applied over the SLA when both highly efficient insulation and high heating capability were required.[1452]

The larger sections of the tank were covered in NCFI 24-124. This SOFI type accounted for 77 percent of the total foam used on the ET. NCFI 24-57 was used on the aft dome of the LH2 tank. Both NCFI 24-124 and NCFI 24-57 were mechanically sprayed foams. PDL 1034, a hand-poured foam, was used for filling odd-shaped cavities. BX 265 foam was manually applied, or hand-sprayed, in the closeout areas, and applied mechanically on the feedlines and domes inside of the intertank.[1453]

The SLA is a denser composite material made of silicone resins and cork that dissipates heat by eroding. It was used on areas that were subjected to extreme heat, including the aft dome and the cable trays. The ablator thickness was defined primarily by the ascent mission phase.[1454] MA25S, a high temperature ablator, was developed by Lockheed Martin.

During the application process, TPS materials were subject to the formation of small voids caused by encapsulated air in the foam. This was especially the case around uneven areas, such as joints. To reduce the likelihood for voids, strict process controls for both automated and manual foam applications were implemented. Typically, foam was hand-applied around complicated areas.[1455]

Interface Hardware

The ET contained hardware for attachment and interface with the two SRBs, the orbiter, and with the ground launch facilities. The interfaces were both structural connections to the other stack elements, as well as umbilicals for the transfer of fluids and electrical power. The **ET/SRB**

1450 Steve Roy, "Last Shuttle External Tank Rolling Out on July 8," July 7, 2010, http://www.nasa.gov/connect/chat/last_tank_rollout2.html.

1451 The surfactant controlled the surface tension of a liquid, and thus, cell formation. "The blowing agent, HCFC 141b, created the foam's cellular structure by making millions of tiny bubbles or foam cells." NASA MSFC, *Thermal Protection System*.

1452 Lockheed Martin, *Handbook (SLWT)*, 11-2.

1453 Closeouts were TPS applications conducted after final assembly and checkout; a minimum number were made at the launch site. They were most critical on areas where the insulation was applied on surfaces subjected to cryogenic temperatures. Lockheed Martin, *Handbook (SLWT)*, 11-2.

1454 Lockheed Martin, *Handbook (SLWT)*, 11-2.

1455 NASA, *Implementation Plan*, 1-1.

interfaces included four structural attach points plus electrical connections, per SRB. Of these, one forward attach point was located on the intertank, and three attach points were fitted on the aft LH2 tank section. The **ET/orbiter interfaces** included one forward and two aft connections. A **ground facility interface,** located at the intertank, provided ground services to purge the intertank and to actuate vent valves for prelaunch operations. In addition, the ET included interface provisions for the connection to transportation and handling support equipment.

ET/SRB Interfaces

The structural interfaces between the ET and the two SRBs consisted of eight attachment points, four on each side (left and right) of the ET. These included two forward interfaces (left and right) for SRB attachment and thrust transmission, and six aft stabilization interface points (three left and three right). The latter were connected to the ET aft major ring frame. In addition, two ET/SRB electrical interfaces (left and right) were located on the aft top stabilization struts. All ET/SRB interface attachment hardware was SRB-provided and consisted of a frangible bolt at each of the forward interfaces, and a shear pin at each of the aft strut/tank interfaces.[1456]

The two identical **ET/SRB forward thrust interfaces** consisted of permanently fixed, 5"-radius spherical seats machined from AMS-5629 corrosion-resistant stainless steel, and housed in large machined/forged 7050 aluminum alloy thrust fittings. Each of the thrust fittings weighed approximately 400 pounds. An SRB-provided frangible bolt was installed through each fitting. The thrust fittings also included provisions for attachment of the ET forward hoisting fittings.

The six **ET/SRB aft structural attachments** included upper top, upper bottom, and lower attachments, each with a left and a right. Each fitting, made from annealed titanium alloy (Ti6AL4V) castings, was attached to the ET major ring frame by shear pins and tension bolts. The upper fitting (top and bottom) measured 7" wide at the base, was 26" in length, and weighed approximately 75 pounds. It was attached to the ring frame with eight 3/4"-diameter and six 5/8"-diameter tension bolts, a 3-3/4"-diameter shear pin, and a shaped key. The lower fitting measured 6.5" wide at the base, was 19" in length, and weighed approximately 50 pounds. It was configured similar to the upper fitting, featuring a monoball interface with the SRB stabilization strut. Each of the 3.25"-diameter monoballs was manufactured of Inconel 718. Each lower fitting was attached to the aft major ring frame with twelve 3/4"-diameter tension bolts, a 2"-diameter shear pin, and a 1" x 0.5" platform key.[1457]

ET/orbiter Interfaces

ET/orbiter structural interfaces included two aft-positioned points located at the ET aft major ring frame and the LH2 tank longerons, as well as a forward attachment supported from the LH2 tank forward ring frame. The right aft support was a tripod, making it fixed. The other two

[1456] Lockheed Martin, *Handbook (SLWT),* 12-6.
[1457] Lockheed Martin, *Handbook (SLWT),* 12-9 through 12-11.

interfaces were bipods, with the left aft permitting lateral pivot motion and the forward allowing fore/aft motion. All ET/orbiter structural interface attachment hardware was orbiter-provided, and consisted of a frangible bolt and hex nut at the forward interface, and a frangible nut and tension bolt at each of the two aft points. Fluid and electrical interfaces were located at two aft umbilical assemblies, positioned adjacent to the two aft structural interfaces. These two umbilical assemblies, supported by brackets, consisted of clustered disconnects that mated with the ET fluid lines and electrical cables.[1458]

The **ET/orbiter Forward Attachment** hardware was a bipod weighing approximately 190 pounds. It was canted at 0.5 degrees forward when mated to the orbiter. The primary elements of the forward attachment were the identical left and right struts, the yoke fitting, the upper end and lower end fittings, and the spindle assembly. The latter, comprised of operating mechanisms within a titanium housing, provided attachment of the struts to the LH2 tank forward ring frame structure.[1459] The two hollow, aluminum struts measured 60" long and featured flanges on each end. The orbiter end of the left strut was attached to a yoke fitting that mated with the orbiter. The yoke fitting was a large machined titanium (Ti-6AL4V) casting that formed a 74 degree apex angle between the two struts, and which encased the orbiter-provided frangible bolt. The ET end of both struts was flanged identically to mate with the flanged lower end fitting. One end fitting was cast titanium and the other was Inconel 718.[1460]

The **ET/orbiter Aft Left Attachment** hardware consisted of a bipod structure. When the tank was unloaded, the bipod was canted 18 degrees inboard. The structure was attached to the orbiter by an orbiter-housed 2.5"-diameter tension bolt coupled with a frangible nut. The components of the aft left structure included a ball interface fitting, thrust strut, thrust strut end fitting, vertical strut, vertical strut end fitting, and vertical strut tank fitting. The ball interface fitting, made of forged 7050 aluminum alloy, weighed approximately 530 pounds. It joined the thrust and vertical struts. The thrust strut, also of 7050 aluminum alloy, was 120" long, with a 16.6" inner diameter. The thrust strut end fitting, made of 2219 aluminum, was connected to the LH2 tank left longeron by a 4"-diameter stainless steel shear pin inserted through a 5-3/4"-diameter stainless steel monoball. The approximately 60"-long vertical strut, of 7050 aluminum alloy, was connected to the ball interface fitting by a 4"-diameter steel shear pin. Sixteen 7/8"-diameter steel tension bolts connected the vertical strut to the 2219 aluminum strut end fitting. The vertical strut tank fitting was made of titanium (Ti-6AL4V) casting. Six 5/8"-diameter and four 7/8"-diameter steel bolts, and a 3-3/4"-diameter integral shear pin attached the fitting to the ring frame.[1461]

The **ET/orbiter Aft Right Attachment** was a tripod structure. It originated from two points on the aft major ring frame and from the forward end of the right longeron. The aluminum ball

[1458] Lockheed Martin, *Handbook (SLWT)*, 12-15.
[1459] Lockheed Martin, *Handbook (SLWT)*, 12-17.
[1460] Lockheed Martin, *Handbook (SLWT)*, 12-18.
[1461] Lockheed Martin, *Handbook (SLWT)*, 12-19, 12-20.

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.

<u>ET/Ground Facilities Interfaces</u>

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.