Lessons Learned

From Space Shuttle External Tank Development

- A Technical History of the External Tank -

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Table of Contents

Preface

Madison Research Corporation, under NASA Marshall Space Flight Center contract NAS8-00021, is providing subject matter expert (SME) support to the Second Generation Reusable Launch Vehicle Program Office's Space Launch Initiative (SLI) effort. This report details the technical history of developing the Space Shuttle External Tank and documents lessons learned during that effort. Development is chronicled beginning with the pre-proposal phase, then the proposal phase, through early design and test programs, continuing through Lightweight External Tank development, Challenger impacts, environmental effects, and finally ending with development of the Super Lightweight Tank.

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A Technical History of the External Tank

1.0 Pre Proposal Phase

When the Shuttle program was started, a contract was issued to Orbiter and systems integration contractor, Rockwell International, to develop the requirements for the External Tank (ET). Initiation of the ET contract was delayed one year to permit the requirements to mature before starting the program.

At that time the program mission model consisted of 445 flights at a rate of 60 per year. Therefore, the ET design and processes had to be optimized for high rate production. Facilities and tool planning also had to support this rate.

In order not to waste the one-year delay, studies were done on the Saturn vehicle to determine which of the components were high cost and long lead time items. The five potential contractors -- Boeing, Chrysler, Martin, McDonnell-Douglas, and General Dynamics -- were invited into Marshall Space Flight Center (MSFC) to tell how they would build these high cost items, and in part, the whole ET, cheaply. The only constraint was that nothing they told MSFC would be considered "proprietary." Since NASA's Michoud Assembly Facility (MAF) had been selected as the manufacturing site for the ET, those contractors who were not familiar with MAF were given office space at MAF, and free run of the complex, to bring themselves to the same level as the Saturn contractors Boeing and Chrysler.

In addition to the efforts by the potential contractors, extensive effort was undertaken by NASA, both MSFC and other centers, to investigate low cost production. As an example, the dome gores of the S-IC were hydraulically bulge formed in a T3 temper. The parts were then chemically milled in a T3 temper, the fittings for dome penetrations were welded in, and the parts aged in a restraining fixture to a T8 temper. This created many problems since this aluminum alloy, Al 2219, does not chemically mill well in a T3 temper. Age straightening the parts after fitting welding was manpower intensive and the hydraulic bulge forming was also expensive.

Among the techniques investigated were peen forming by a Canadian company, explosive forming based on work done by Langley Research Center, and stretch forming using the Boeing 750-ton stretch press. None of these techniques worked out although stretch forming by a subcontractor using custom modified tooling was eventually selected.

An effort which was very successful, however, was the spiral wrap (barber pole) Thermal Protection System (TPS) application technique developed by MSFC's Manufacturing Engineering Laboratory. This technique was based on some early work done by Rockwell on the SII and was developed into a production process by MSFC. The process was displayed to all potential contractors during the pre proposal period and was selected by Martin for their proposal.

Another activity by MSFC with the potential contractors was the determination of which surplus equipment and tooling at Seal Beach (SII) and Huntington Beach (SIVB) should be sent to MAF. By having the contractors review these pieces of equipment in place at Seal Beach and Huntington Beach, many of these items were surplused on the West Coast, saving shipping costs to Michoud.

2.0 Proposal Phase

Based on the design requirements developed by systems integration during the preproposal phase a request for proposal (RFP) was developed by the ET Project Office headed by Jim Odom and his deputy, Lowell Zollar. Because of the high build rate envisioned, major attention was given to features to encourage low cost production approaches. Another unique feature was the insistence by NASA Headquarters that NASA evaluate the contractor engineering and production management systems and, if acceptable, to use those rather than insisting on doing things "NASA's" or "MSFC's" way. It was believed that this would result in lower non-recurring costs, and, where the contractors' systems were more efficient than "NASA," in lower recurring costs. "Design-to-Cost" was the moniker attached to the cost containment campaign.

Proposals were received from Martin, Boeing, Chrysler, and McDonnell-Douglas. General Dynamics bid as a subcontractor to Boeing. The RFP called for a bare-bones minimal government involvement program. Martin responded to the RFP as written. The other bidders, because of the long involvement with NASA and MSFC, believed that NASA and MSFC would never change their ways, and so, bid a "business-as-usual" approach. Thus, Martin's proposal was significantly lower both in non-recurring as well as recurring costs. Because this was what the selection officials in Washington were looking for, Martin was awarded the contract. Chrysler threatened to protest because they claimed Martin "bought-in" with an unrealistically low bid. Following discussions with NASA Headquarters, they chose not to protest.

The MSFC Source Evaluation Board (SEB) was chaired by Bob Lindstrom with Jim Odom as his deputy. There were representatives from NASA Headquarters, Kennedy Space Center (KSC) and Johnson Space Center (JSC). The SEB provided their evaluation to Headquarters which made the selection. Prior to RFP release, the size of the ET had floated depending on the system studies, but this was frozen at RFP release. At the time of RFP release the Orbiter tiles had not been finalized, so there were no restrictions on ice formation on the ET.

Thus, the Martin proposal called for small amounts of ablator on the tank where high heating was expected, ablator on the intertank where the shock waves from the Orbiter and Solid Rocket Boosters (SRB) would impinge, ablator on the struts and brackets, ablator on the LH_2 aft dome, and foam on the LH_2 sidewalls and forward dome. Large areas of ice and frost would be expected to be formed, as was seen on Saturn, but this had not been identified as a concern.

3.0 Early Design

The early design phase resulted in a number of design changes to the ET as the system requirements matured. Among these were the following:

a. As noted previously, the design of the Orbiter tiles matured to the point where it became necessary to preclude the formation of ice anywhere on the ET forward of the 2058 ring frame. This was done by covering all metal structures that would get below freezing with a Spray on Foam Insulation (SOFI) or, in the case of the pressurization lines, by using a heated purge. Certain liquid oxygen (LO_2) feedline brackets, which required extensive movement to compensate for the relative thermal contraction, could not be fully insulated without motion breaking the insulation. Therefore, ice formation on these brackets was accepted by the Program Office as unavoidable.

b. The ET proposal configuration used BX 250 foam on the liquid hydrogen (LH_2) sidewall and forward dome, SLA561 ablator on the aft dome, and SLA561 on the intertank and LO_2 tank in the area of high heating. For those protuberances that saw extremely high heating and did not have cryogenic backface temperatures MA25S was baselined. The Orbiter tile issue drove design changes to cover the entire tank with BX 250, except for the aft dome. Ablator was still necessary under the foam in the high heating areas because of the poor high heating capability of BX 250. The aft dome insulation remained SLA561.

   The original ET concept used irridite chemical conversion coating on the whole ET outer surface. Testing by Dr. Jim Stuckey showed that the bond between the aluminum and the irridite would be the weak link in the bonding chain when ablator was bonded onto the cryo surfaces. This chain consisted of aluminum, irridite, 0.010-inch epoxy primer, 0.0005-inch silene primer, 0.100-inch GX 6300 adhesive, and the ablator panels topped by foam. Because Dr. Stuckey's tests showed the aluminum/irridite bond to be significantly weaker than the others, the irridite coating was deleted from the propellant tanks. The system selected relied on the epoxy primer for corrosion protection -- a reliance which turned out to be mistaken when the Main Propulsion Test Article (MPTA) was tested. After MPTA, strontium chromate and carbon black were added to the primer which changed it from yellow to green and increased its corrosion resistance.

c. MSFC's Science and Engineering (S&E), Dr. Stuckey, then approached the project with CPR 421, a commercial product with much better high heating capability. This product had been investigated during the last days of the Saturn program but was not available in a sprayable foam. When Martin developed it to be sprayable, it virtually fell off of the tank wall until it was discovered that it had to be sprayed onto a heated tank wall with heated foam and an elevated ambient environment. The above are just two examples of Dr. Stuckey's many contributions to the ET TPS system. The design was changed to use CPR 421 on the sidewalls and aft dome. Areas of high heating still required an ablator underlayer. Because of the difficulty of predicting interference heating a ground rule was established, for all bracketry, that ablator was required one foot from the bracket under the foam. The change to CPR 421 had a significant impact on the processing requirements with resultant tooling and facilities. BX 250 foam required a relative humidity (RH) below 40% for application, which could be satisfied with a chilled water/reheat system. The change to CPR 421 required an RH less than 30%, which required the addition of a chemical dryer, and a heated tank wall (on the order of 135 to 150 °F), which required passing hot gas through the tank while it was being rotated for the "barber pole" TPS application mode. Preliminary testing of CPR 421 for the aft dome environment indicated that it would be adequate without an ablator underlayer.

d. About this time Professor Einhorn of the University of Utah ran some environmental tests of CPR 421 in which he pyrolized the material, captured the effluent in a cryogenic trap and tested its toxicity on rats. He then published his data showing that this material had a potential toxicity problem. Based on this CPR withdrew CPR 421 from the market. The toxic product was a chemical compound called TMPP with one of the Ps being phosphorus. ET had CPR reformulate this foam without phosphorus. This was identified as CPR 488. This material performed well on the sidewalls but when subjected to the combined environment tests of the aft dome at Wyle Laboratories, the material ignited and burned to the substrate. The combined environment test was a unique test developed by Lockheed Martin, Wyle Laboratories, and MSFC. This test, performed at Wyle Huntsville, consisted of a flat aluminum plate, machined to match the aft dome stress levels. The plate was attached to a cryostat filled with liquid helium and then strained with hydraulic jacks to the flight biaxial stress levels. Radiant heat lamps were installed to match the radiant heating from the Solid Rocket Motor (SRM) plumes, and an acoustic horn blasted the test setup at 165 dB. This simulated the aft dome environment as well as possible. The test was repeated on the Super Lightweight Tank (SLWT) with two failures, which will be discussed under section **8.0 Super Lightweight Tank (SLWT)**. Therefore, it became necessary to underlay 800 sq ft of the aft dome with 0.4 inch of ablator, covered by CPR 488; the CPR for cryo insulation on the pad; and the ablator for thermal protection in flight. To provide the capability to spray the ablator TPS cells M&N were built at MAF. Cell P was built as part of the package to clean and prime the LH_2 tank before ablator application.

e. To save the weight of this ablator and its associated cost, the ET Project then had North Carolina Foam Industries (NCFI) develop an NCFI foam which would be adequate for the aft dome environment without ablator. This material was validated in the combined environment tests at Wyle Labs. The NCFI aft dome foam was phased in during the early flight program after several flights with ablator/CPR 488.

f. Because the LO_2 tank is pressurized with autogenous oxygen bled from the Space Shuttle Main Engine (SSME) heat exchangers and the gaseous oxygen is subjected to aeroheating on the bare pressurization line, the gas enters the LO_2

tank at a temperature of about 500° F. There was a concern that this would raise the wall temperature above the allowable foam bond line limits. Therefore, to protect the foam bond line, a layer of ablator was put onto the ogive nose for several feet down, under the foam. Ablator can tolerate a higher bond line temperature than foam. As the program progressed the ogive skin temperature became better defined and the allowable foam bond line temperature was increased; therefore, the ablator was deleted and the foam applied directly to the ogive on subsequent flights.

g. The original design of the ET front end had a conical nose with a bulbous hemispherical cap over the vent and relief valve. This was changed to an ogive shape with a biconic spike in the 1972 - 73 timeframe. The change to an ogive shape had significant ramifications to the manufacturing process. It was previously planned to roll the conical shape on tapered rolls, a common manufacturing process, but the ogive required a new process. The first option looked at was the approach used in the S-1C, hydraulically bulge formed gores. This had proved to be a very expensive process on Saturn. Also, the large ogive size would drive expensive tooling. The next option was to stretch form the gores using Boeing's 750-ton stretch press, the largest in the country. However, this was going to load the press to its limit and, because the press was essential to the B-747 program, Boeing was unwilling to take the risk of damaging their press. Shot peen forming, and explosive forming, an approach Langley had been investigating, were considered and ruled out. When Martin approached the industrial market, they discovered a supplier named Aircraft Hydroforming (AHF) who owned a large stretch press, although not as big as Boeing's. AHF was able to adapt their equipment to make the forward and aft ogive gores as well as the dome gores. A trade study was run to evaluate the relative benefits of a one- vs. two-piece ogive, but the manufacturing, tooling and facility issues ruled out the one piece despite its engineering advantages.

h. In looking at the domes, which were a very high cost item on the S-1C, it became apparent that the numerous penetrations of the various gores in the S-1C, with the necessity for welded fittings at each penetration, was not the way to go. Accordingly, Martin chose to collect all the penetrations into a very large cap for each dome which would permit the dome gores to be clear window panes. Only one gore, in the aft LH_2 dome, had the LH_2 feed line and the LH_2 recirculation line penetration. This was necessary because the very high heating in the center of the dome and the difficulty of routing the feed line and recirculation line on the outside up to the Orbiter interface precluded a low point drain. This necessitated the use of a siphon in the bottom of the LH_2 tank with the higher unusable propellant than a bottom drain would have provided.

   The large cap also permitted one-piece dome gores as opposed to the two-piece gores of the S-IC. MSFC had been performing some R&D on forming a premachined cap using hydraulic bulge foaming. This approach was selected and a contract awarded to General Dynamic (GD), San Diego for 27 caps. GD delivered these but not to the drawings. All had to be bought on MRBs. While the weld tooling had enough muscle to force the parts into alignment, the residual stresses were more than the stress or welding people desired. When the RFPs went out for the second buy, GD "no bid" so it was necessary to find a new contractor. A new manufacturing approach was also selected. It was decided to spin the full plate thickness caps to contour in a T3 temper, age up to the T8 temper and then to chemically mill the weld land patterns. PMS Fansteel was selected as the contractor. The approach worked very well. The 140-inch cap size was selected because the largest plate Alcoa could roll was 154 inches and spinning across a weld was not considered feasible. Because the bulkhead is an ellipsoid rather than a hemisphere, the amount of draw the spinning operation required was about 10 inches even though the cap is a circular arc.

i. Another difficult forming problem encountered in the early design and fabrication stages was the manufacture of the intertank thrust panel. Avco was the contractor initially selected for the intertank. They were able to produce the skin/stringer panels but when they tried to make the thrust panels, they failed. They tried to machine the thrust panels flat in a T8 temper and bump form them very locally (about a 1-foot square area) into the proper contour. After Avco had broken a number of panels, Martin changed the process to machine the panels flat in a T3 temper at Avco and to ship the panels to Martin Denver to be bump formed. After forming, the parts were aged to a T8 temper and returned to Avco. Avco would then machine the ends on a big skin mill as they did on the skin/stringer panels. This insured that the ends of the panels were parallel and in a continuous plane. A problem that came up on the first part was the lack of realization that, in aging 2219 from a T3 to a T8, the material grows about 0.05%. This resulted in the flanges at the end of the first panels being machined below drawing tolerances. Because these were for the Main Propulsion Test Article ground test tank, the panels were bought on MRB. Following the first 20 panels used for the Design, Development, Test, and Evaluation (DDT&E) articles, subsequent buys of this part were from LTV and then Learjet.

j. The LH_2 propellant tank barrel panels were machined flat on big skin mills at Reynolds, NCI, Avco, and several other vendors. Martin procured all of the aluminum and drop shipped it to the machining houses. At this time, several problem areas surfaced.

   1) The aluminum rolling industry was saturated with aircraft orders. Accordingly, they established a priority system based on previous orders, i.e., you could only order what you had bought the previous year. Since ET was a new program, there were no prior-year orders. Also, the price of aluminum was quoted as "price at time of delivery." Since the orders were typically placed one to two years before delivery, budgeting for aluminum delivery was virtually impossible.

   2) When the aluminum could be obtained, the contractors with big skin mills were also saturated with an extensive waiting list.

3) 2219 aluminum, with its high copper content, tended to contaminate the aluminum industry casting furnaces. Thus, they limited the casting of this alloy to once a year. If an order missed that window, there was a year wait.

Martin procurement management, using the leverage of Martin Corporate, was able to obtain the needed aluminum to support the program.

4.0 Test Program

The ET Test Program, as laid out at the start of the program, consisted of five elements:

- *Materials*
- *Components*
- *Major Ground Test Program*
  - *Structural Tests*
  - *Dynamic Tests*
  - *Propulsion Tests*

4.1 *Materials*

The material test program was primarily focused on the thermal protection materials. The aluminum alloy used for the majority of the Standard Weight ET and later for the Lightweight Tank (LWT) was 2219, a well-characterized material documented in MIL-HBK-5. The initial welding process, tungsten inert gas or TIG, had been used on S-IC with this alloy. Thus, there was as extensive data base at MSFC. Martin had also used this material on portions of the Titan II & III, so they had in-house experience at their Denver operations. One area where this experience was invaluable was in the weld tool design. MSFC had had a long running argument regarding whether weld tooling should be optimized for parts handling or for torch attitude. The tool designers wanted to minimize the parts handling while the welding people wanted to optimize torch attitude. Based on the Denver experience Martin voted with the welding people and optimized torch attitude (vertical up or downhand) as opposed to the 3 o'clock horizontal torch position which was heavily used on the S-1C.

To get back to TPS, it was necessary to characterize both the ablator material and the foams for the heating rates expected for ET. This was done primarily using the wind tunnels at Arnold Engineering Development Center (AEDC). AEDC was originally very reluctant to test foam in their wind tunnel where chunks of foam could come off and go down the tunnel. George Hobson of MSFC worked with AEDC to implement radical modifications to the tunnel to provide a unique capability to test critical ET materials under realistic flight conditions. A number of the samples were tested at varied heating rates (q dot). The measured recession data was then plotted against q dot and a 2σ band was established to bound the recession rates. The ablator, which had been developed for the Mars Viking Lander, was tested in the plasma arc at Ames Research Center which could deliver higher heating rates. AEDC anchored the lower end. For the SOFI testing AEDC could only reach heating rates of around 10 BTU/sq ft/sec, so this was selected as a cut off on foam recession. At predicted heating rates above 10 it was assumed that the foam would disappear so the foam had to be underlaid with ablator. Also, the surface within one foot of a protuberance had to have ablator because of the uncertainty of predicting heating rates near protuberances. Later modification to the tunnels at AEDC allowed the foam to be tested above 10 BTU/sq ft/sec which permitted extensive ablator to be removed on the sidewalls. Better understanding of the flow fields around the protuberances permitted the one-foot ablator rule to be dropped on later ETs. Thus, the current design has no ablator on the cryogenic sidewalls. Another interesting and unique test was the testing of SOFI on a 10-foot diameter tank in the environmental hanger at Eglin Air Force Base. The insulated tank was filled with liquid nitrogen (LN_2) and subjected to various rain, wind, humidity and temperature conditions to determine the rate of ice growth. These data were then reduced to an ice/frost nomograph by Rick Bachtel, and a Lockheed Martin thermal engineer converted the nomograph to a computer program known as Surf/Ice which is used at KSC to predict whether unacceptable ice will form during tanking or exist prior to launch.

In addition to the above tests, tests were run on mini tanks to develop application techniques; cryoflex tests were run to verify substrate adhesion; and strength, density, and crush tests were also run.

4.2 *Components*

Individual structural tests were run on such components as attach fittings, bi-pod assembly and yoke, slosh baffles, etc. Structural tests were split between MSFC and MAF depending upon where the capability existed. The largest component test was of the ET/Orbiter complete aft interface structure run at MAF. A complete load frame was built up to encapsulate the aft Orbiter attach structure. This load frame was able to simulate the loads on the aft attach structure from the Orbiter. The load frame, although self-equilibrating except for dead weight, was assembled at MAF on the load tie-down floor installed by Boeing for the S-IC. The floor structure has since been removed to make room for production tool foundations so it would be expensive to exactly replicate the test set-up today.

Component tests on functional items such as the vent and relief valves were run by the suppliers in the standard qualification mode, i.e., repeated cycles at cryogenic conditions, vibration, high and low temperature, etc. Because the level sensors in the propellant tanks were government furnished equipment (GFE) from JSC for the first nine ETs, they were qualified by Rockwell. Since Orbiter was to furnish the signal conditioners, the program gave them the responsibility of the sensors also. Following the flight of STS-7 Martin took over the procurement of the sensors from the supplier, Simmons. These sensors, which use a 0.0005-inch platinum wire in a warm wire mode, were an outgrowth of the SII stage sensor. The current supplier is Goodrich.

The ET/Orbiter disconnects, one LO_2 and one LH_2, were also GFE from JSC/Rockwell. The program’s position was that Rockwell would have to develop the Orbiter half of the disconnect, so it would be technically and cost efficient for Rockwell to develop both halves. It was planned for Martin to take over the procurement and assembly of the tank halves after the DDT&E flights. However, after the DDT&E phase Rockwell was not finished with the disconnect qualifications, so Martin's assumption of the role was delayed. Following Rockwell's qualification Martin, who had been under contract from MSFC to study the disconnects, recommended that Rockwell keep the design responsibility and that Martin would only have the fabrication and procurement responsibility. In light of this recommendation Level II chose to keep the whole package at Rockwell and to GFE the tank halves.

One test which Rockwell ran has had a strong impact on the subsequent program. This test of a LO_2 disconnect at Wyle Labs with water, with the flapper deliberately misrigged, resulted in a mechanical failure of the valve allowing it to slam shut. Should this happen in flight, all three SSME LO_2 pumps would be unloaded and all three turbines would run away and disintegrate. Also, the water hammer would probably rip the LO_2 feedline off the side of the ET. Because this indicated the criticality of the flapper rigging, Rockwell instituted a practice of checking the rigging at the launch site before mating to the Orbiter. Since there is only one test tool, used both in California and Florida, this requirement limits the number of launches per year. Shipping the tool cross country many times a year increases the probability of its being lost or damaged putting the whole program at risk. ET Project has recommended several times that a second tool be fabricated but, to date, this has not happened.

Another system which was furnished as GFE was the range safety system (RSS). The command receiver/decoder, the batteries, the antennas, the confined detonating fuse (CDF) and the range safety distributor were GFE from the SRB project and were qualified by them. The only portion of the RSS procured by ET was the linear shape charge (LSC) which was different from SRB. This was qualified by the vendor. One of the qualification tests required that it cut a four-inch Al 2219 plate. This had to be repeated as a part of the lot acceptance for each lot of material, as well as the testing to extend the lot shelf life. Acceptance was later changed to require that the four-inch plate be broken but not necessarily cut. This was a much easier test.

John Young, among others, had been fighting the need for the RSS on the ET from the time the ejection seats were removed from the Orbiter and was finally successful in obtaining Range concurrence. The entire system was removed several years ago with the resultant deletion of a number of Criticality I failure modes.

One item of instrumentation on the ET, which has been an area of concern, has been the LO_2 and LH_2 tank ullage pressure transducers. These transducers measure the pressure within the ullage or gaseous volume in the LO_2 and LH_2 tanks. The ET pressurization system consists of three single strings from LO_2 and LH_2 ET transducers, Orbiter power supply and signal conditioner, Orbiter flow control valve, and SSME heat exchanger. Each SSME provides high temperature, high pressure oxygen or hydrogen to an Orbiter flow control valve. The ET ullage pressure transducer senses the pressure in the ET propellant tanks and sends a signal to the Orbiter, which cycles the appropriate flow control valve. There are four transducers in the LH_2 system and there were four on the LO_2 system until a change which will be discussed later. These transducers are pot-wiper type transducers with the potentiometer wound of 0.0005-inch platinum wire. The first time these were tested in actual use was on MPTA, and it was noted that the LO_2 wipers were dithering on the pot and smearing the platinum wire causing several windings to short out. This caused the calibration of the transducer to shift. Because the four transducers had different length sense hoses, Martin developed a family of acoustic snubbers which when mated with the hoses detuned the organ pipe acoustic mode and solved the problem on the LO_2 side. However, the requirement to maintain an internal pressure within the LO_2 tanks of 1.7 psig when the LO_2 was over the 2% level created another problem. The 0-30 psig transducers were not sensitive enough to control the 1.7 psig blanket pressure. As a solution, two commercial off-the-shelf (COTS) transducers of a different design were added. These were Tavis variable reluctance, 0-5 psig transducers and used 28-volt, four-wire power vs. the 5-volt, three-wire system the flight transducers used. Because there was no 28-volt power supplied from the Orbiter, the Tavis devices were ground powered through the intertank umbilical. Two of these units have flown on every ET with 100% success, despite their being COTS items rather than EEE Level S as all other Shuttle electrical systems require. The use of COTS was acceptable since these are redundant, were only active prelaunch, were not flight critical, and were ground powered.

With the snubbing system on the LO_2 side the LO_2 flight transducers performed well. A later change to the pressurization system was made to immobilize the Orbiter flow control valves in a constant flow position, in essence a fixed orifice system. Thus, the LO_2 tank flight transducers became only critical during prelaunch where only two were necessary. Accordingly, one of the expensive transducers has been removed from the LO_2 side leaving three and a dummy installed to maintain the mass distribution on the bracket, thus avoiding a total requalification. During prepressurization the LO_2 tank is pulsed with helium. As the helium cools from contact with the LO_2 surface, the pressure falls and causes the second transducer to fall out of the prepressurization control band which signals the ground prepressurization valve to initiate another helium pulse. Since it is the second transducer which controls, only three are needed to maintain redundancy should one of the first two fail.

The original design had four transducers on both LO_2 and LH_2. The Orbiter power supplies only powered three with the fourth being a spare. A control system on the Orbiter would sample the three active transducers shortly before launch (currently T minus 10 seconds) and switch in the spare if necessary. The spare can be (and is) switched on from the ground to check it. This system is still active on the LH_2 tank, which uses a closed loop control system, but the LO_2 system operates open loop so three transducers are sufficient.

A problem, which showed up in early launch attempts on the LH_2 side, was called stiction or sticky friction where the transducer would hang up and then jump. This was fixed on STS-3 by adding a slow ramp rate test at the supplier to screen out stiction sensitive units. Although the problem has not recurred, John Young, in his famous top ten Shuttle risk letter published after the Challenger accident, listed stiction as a significant risk.

Because of the early pot-wiper transducer problem and the good success of the COTS unit, the ET Project Office approached Tavis about supplying the high range COTS units to use in flight. This change was taken to the Level II Program Requirements Change Board (PRCB) who directed ET to move out and directed Orbiter to furnish 28-volt, four-wire power and signal path to the ET. After several years Orbiter went back to the PRCB and had the change cancelled because of difficulty in furnishing the ET power.

On the LH_2 side the most common problem was one of transducer output dropout during the long period when the LH_2 tank was sitting filled with the vent valve open, a phase called replenish. This several-hour period was included in the flow to allow the LH_2 to boil and become denser. Over the years the cause of these dropouts was never positively traced, but they became accepted because as soon as the pressure changed, the units began working normally. Just closing the vent valve and letting the tank start to self pressurize has always been enough to get the transducers back to normal. On only one flight has the Orbiter system switched in the spare prelaunch. During the Flight Readiness Firing (FRF) of Orbiter 104 three of the four ET LH_2 transducers experienced shorted windings. Since this was an FRF, the failed parts could be removed. The failed transducers were from different lots and had the correct sense hoses and snubbers. Extensive lab testing was unable to reproduce the problem. A complete set of new transducers was installed on the ET for the flight with one of them experiencing shorted windings prelaunch. The Orbiter control system switched that one out at 10 seconds and the flight proceeded normally. This has never been explained nor has it recurred in 60-70 flights since then.

After the Challenger accident, because of Mr. Young's letter, the ET Project Office presented the transducer issue to the Level II PRCB and was directed to have the Tavis variable reluctance transducers redesigned to operate on a 5-volt, three-wire system. Requalification was done to EEE Level S standards and raised the cost of the transducers substantially. A charge-amp within the unit was only available for minimum lots of 100, so Martin had Tavis build 50 of each LO_2 and LH_2 and requalify them. Because the LO_2 was flying open loop, Gerry Ladner, then ET Project Manager, chose to incorporate the LO_2 units to gain flight experience before going closed loop on the LH_2 side. The LO_2 units have performed perfectly but, with the sixth ET buy when Lockheed Martin considered changing the LH_2 side, the pot-wiper vendor dropped his price and the variable reluctance supplier raised his drastically. Lockheed Martin, who was under a strong cost incentive on the sixth buy, chose to stay with the pot wiper. The 40 variable reluctance units on the shelf at MAF are periodically retested to detect long term drift, but they have been fine.

4.3 ***Major Ground Test Program***

4.3.1 ***Structural Tests***

Besides the materials and components tests, there were three "all-up" test series: the Structural Test Articles (STA), the Mated Ground Vibration Test (MGVT), and the Main Propulsion Test Article (MPTA).

The **STA** consisted of four test articles: a LO_2 tank, a LH_2 tank, and two intertanks. The Intertank STA was the first of the structural tests and was performed in building 4696 Load Annex. It demonstrated the ability of the Intertank to introduce and redistribute thrust loads from SRBs. The LO_2 tank was tested with barium sulfate (drillers' mud) and water in MSFC building 4619. Both a modal test and a standard capability test were run with good results, with one exception. The LH_2 tank was tested, with an intertank attached, with LH_2 loaded and was taken to 140% of design limit loads for three different conditions. This LH_2 tank test and the LO_2 tank test confirmed the analytical models used by Martin in their analysis with one exception each. When the LH_2 tank was loaded with LH_2, with the aft attach points constrained as they would be by the Solid Rocket Motors (SRMs), the insulation on the aft dome failed. This was traced to the cryo shrinkage of the metal frame and dome. With the $\pm$ y attach points constrained, the frame and dome elongated in the y direction. Dome deflection caused a local buckle near the load attach point which cracked and debonded the foam. To resolve this problem the first six ETs, called the standard weight tanks, went through a unique stacking sequence to reduce the "pinch loads" on the aft bulkhead attach frame, known as the 2058 frame.

The stacking sequence involved attaching the ET at the forward SRB attach points, then mechanically pulling the SRBs apart to attain a predetermined displacement at the aft struts using hydraulic jacks anchored to the Vertical Assembly Building (VAB) columns while the SRBs were hard attached to the launch mount. This actually bent the SRM cases elastically. The aft ET/SRB struts were installed and lightly torqued into position. The SRBs were then released putting the struts and the tank 2058 frame into compression. The required 46,000 ± 3,000-lb strut preload (each side) was achieved on the second attempt on each vehicle preloaded. When the cryogenic propellant was loaded and the tank chilled, the compressive strain had to be overcome before the 2058 frame would go into tension. Strain gages were installed on the struts to measure load and were calibrated using the test rig at MSFC prior to installation. To verify the amount of pretensioning each tank could take, ET-3 through ET-6 standard weight tanks were taken to incipient failure during proof test. Since the gores at that time were clean "window panes," the buckles were elastic and did no permanent damage. The practice of bending the SRBs entailed certain risks. Therefore, when the ET was redesigned to the "lightweight tank" (LWT), over 400 pounds of aluminum were added to the aft dome in the form of circumferential ribs on the dome gores to stiffen them. This increased the capability of the ET to the point where the strut precompression was no longer required. In addition to stiffening the dome, an attempt was made to slightly preload the 2058 ring frame in compression by torquing the SRB struts. It was discovered by United Space Boosters, Incorporated (USBI) that torque in excess of a preload of about 1000 lbs. would gall the struts so that they were not reusable. Accordingly, the stacking procedure was modified to torque the struts to the 1000-lb. level to take up freeplay in the system, resulting in a significant drop in the applied load.

The SLWT further redesigned the aft dome to remove the ribs while maintaining the stiffness. This eased TPS application on the aft dome.

4.3.2 *Dynamic Tests*

The next major structural test program was the **Mated Ground Vibration Test (MGVT)**. This consisted of a flight-like ET, a set of empty SRB/SRMs, a set of loaded SRB/SRMs with inert grain, and Orbiter 101. This stack was assembled in the MSFC GVT tower, suspended on air bearings and shaken. The program was to establish the vehicle bending modes and nodal crossing points. These data were used to validate the ET and system analyses and were necessary for the design of the flight control systems and to locate the rate gyros and the accelerometers used by this system.

The test also revealed a critical design weakness, the weakness noted previously, on the ET LO_2 tank during an activity which was an integral part but not an objective of the test.

To get the weight into the LO_2 tank for the test, it was filled with water since the MGVT tower was not supplied with a cryogenic storage capability. While filling the LO_2 tank with water, a large (5-10 feet) buckle appeared in the ogive portion of the tank. The tank was unpressurized at this time. The Martin stability model had predicted that the tank wall should have been stable under this condition. After much investigation, it was determined that, although the analysts had evaluated the model with a commanded pressure of zero gage, the model had erroneously predicted a pressure enhanced allowable. When the model was corrected to reflect the zero pressure, it predicted an instability. Since the fabrication of the first flight tank was well along and material had been processed for six standard weight ETs, a decision was made to finish these tanks with the material on hand and to put an operational constraint on the launch site to maintain a minimum of 1.7 psig any time propellant levels were greater than 2%. To verify the new model assessment, the STA LO_2 tank, which had finished its test program, was carefully measured to insure that it was within drawing tolerances, and filled with water while unpressurized. It behaved exactly as the GVT LO_2 tank and buckled almost identically in size and location. The LO_2 tank had been filled with water earlier during proof test without buckling. However, during the proof test it is supported uniformly rather than by an Intertank resting on two points at the SRB attachments.

Maintaining the 1.7 psig pressure during fill was not a significant problem for the launch site, but not being able to vent the tank when full caused a higher LO_2 saturation temperature with the resultant less dense LO_2 and lower propellant load and payload reduction. When the Lightweight ET was redesigned, Martin looked at beefing up the whole LO_2 tank to take zero psig during the whole fill cycle, but the weight penalty was 800 lbs. A compromise was reached to beef up the forebody with 200 lbs. of aluminum which could permit venting the tank with propellant levels above 98%. This allowed the LO_2 to stabilize at a lower temperature, after a boil off hold period of 4-5 hours, and to regain the propellant load. The Operations and

Maintenance Requirements and Specification Document (OMRSD) currently requires 1.7 psi between 2% and 98% which is built into the propellant loading software.

The MGVT program provided vital design information for the guidance and control system design.

4.3.3 *Propulsion Tests*

Another major test program was the **Main Propulsion Test Article**. This consisted of an ET, three SSMEs, and an Orbiter boat tail structure containing and supporting main propulsion hardware. The program was laid out as an 18-month program, so ET delivered a flight weight tank with flight type insulation. The tank was actually in the test stand, exposed to the Mississippi coastal environment with a number of firings, many propellant loadings and proof tests, for over seven years. For a program of that duration, a battleship tank should have been used but the program schedule had predicted only 18 months. At the time the tank was manufactured at MAF (the first), the MAF TPS spray facilities could not support the later flight TPS (CPR 488). CPR 488 requires a heated substrate and an RH below 30%. Since the change to CPR was made fairly late in the development cycle, the spray facilities had not had the chemical dehumidifier installed at the time MPTA was processed.

BX 250, a foam which did not require a heated substrate and only RH below 40%, was used. Because foam would not stick to bare aluminum, the tank was covered with an epoxy primer. The MPTA used the first generation primer which, while providing a suitable under layer for foam adhesion, provided minimal corrosion protection. The combination of non-protecting primer and weather exposure far beyond predictions resulted in massive corrosion problems. This was aggravated by the LH_2 which froze any gas at the tank surfaces causing negative pressure relative to ambient. This caused the outside air to be cryopumped through microscopic cracks in the foam. As the moisture in the outside air was drawn through this foam, it leached chlorides from the foam blowing agent which resulted in a chlorine rich liquid at the metal surface. Since Al 2219 is prone to surface corrosion, the ET propellant tanks suffered extreme corrosion, in one case 87% of the thickness of the aluminum. Martin developed a new primer with chromates replacing some of the inert filler materials. The corrosion damage was measured and assessed. Then the tanks were stripped in the test stand, the corrosion was cleaned from the pits with dental picks, the pits filled with undiluted primer, and the tanks primed and recovered with BX 250. This had to be done at least twice during the MPTA program. The most extreme area of corrosion, near the cable tray support, was repaired using a through-the-wall single bolt patch. Because of this loss of material it was necessary to proof test the propellant tanks with gas pressure in the test stand. It finally reached a point where the ET Project could not support any more firings and recommended that the tank be replaced with a new one if the test program was to go on. Because of the cost, the lack of SSMEs qualified to fire at 109%, and funding, the MPTA test program was cancelled.

Although the Shuttle flies with the SSME at 104% (now 104.5%), the MPTA was only tested at 102% because of structural limitations on the test stand. The stand had been modified for 3 SSMEs at 109% but the lack of engines kept delaying this test until the program was terminated. After cancellation the boattail was sent to Huntsville where all of the components were removed for Rockwell engineering examination or were shipped to KSC as maintenance training aids. The boattail structure was used for Shuttle C structure and is still in the “boneyard” at MSFC. The MPTA tank was converted to a display article and now resides at the U. S. Space and Rocket Center.

There were several lessons learned from the Main Propulsion Test Article (MPTA) effort. The main benefit of MPTA was to prove the concept where the ET was mounted along side of the Orbiter and the propellant was delivered through a cross feed system. At the start of the concept studies there was some concern whether a cross feed system could maintain net positive suction head (NPSH) as necessary. The MPTA also demonstrated the integration of the SSME into the Orbiter; provided a mechanism to qualify the propellant delivery lines since there was no test facility which could flow LH_2 at the Shuttle flow rates; provided data for the structural and POGO dynamic models; and developed the propellant loading software and procedures. NASA and contractor KSC personnel were temporarily assigned to MPTA to develop these procedures and to ensure their transfer to KSC.

A stratification cable running the length of each propellant tank with appropriately located temperature sensors was able to provide data to evaluate potential stratification and to assess the geysering suppression system, which eventually led to the deletion of the anti-geysering line with a resultant cost and weight savings. The location of the various loading sensors and the baffles necessary for their proper operation were also demonstrated on the MPTA. The level sensors were government furnished property (GFP) from the Orbiter supplier, Rockwell, who had the responsibility for their electronic boxes, but the loading sensors were cross checked against continuous capacitance probes built at MSFC by John Hamlet of the Guidance and Control Lab.

The ball strut tie rod assemblies (BSTRA) in the internally constrained lines were demonstrated on the MPTA using an alloy named STOODY 2 for the balls. However, MSFC M&P insisted that the flight hardware be changed to Inconel 718. Orbiter, which had the same vendor, has retained the STOODY 2 alloy.

The stratification sensors were able to demonstrate that helium bubbling would control geysering without the need for the anti-geysering (A/G) line, a 4-inch line which was installed parallel to the LO_2 feed line. Its original intent was to provide a downcomer for the cold LO_2 while the helium bubbling in the feed line would carry the warm LO_2 back to the tank. By varying the heat leaks in the different lines, it was planned to set up a thermal pumping cycle which would continue to re-circulate the LO_2 without further inputs once it had been started. Helium bubbling on MPTA showed that bubbling alone would be adequate permitting the removal of the line at a saving of several hundred pounds and considerable cost. When the A/G line was deleted, the bracketry used for the anti-geyser line was used for the gaseous hydrogen (GH_2) pressurization line permitting the removal of the GH_2 pressurization line bracketry and greatly simplifying the TPS design. On subsequent tanks the bracketry was optimized. The A/G line was deleted on ET-4, and on ET-8 (the first of the LWTs) the GH_2 line was moved and the cabletrays were reduced in size. Another issue which came up before the first flight was the realization that the Orbiter tiles were so fragile that an ice cube dropped four inches would crack the tile glass coating. This caused a rethinking of the ET TPS design. Level II gave the ET Project Office a weight target of approximately 500 lbs. and told them to start at the tank nose and to protect the Orbiter tiles from ice back to the 2058 ring frames. All of the bracketry which gets cold enough to grow ice was to be insulated. Rather than insulate the pressurization lines ET chose to use a heated purge prelaunch with bare lines. Thus, these lines would serve as lightning paths to conduct lightning restrikes back to the SRB exhausts where the charge would be bled off. At this time Martin had test data showing that a lightning strike on foam-covered aluminum would leave a crater in the foam, but the aluminum would not be punctured. However, later testing with a pressurized mini tank loaded with LN_2 showed that these tests were wrong and that a lightning strike on a pressurized cryogenic tank would cause a leak. The foam protection of the various ramps and brackets became known as the “blue streak” ramps.

The loads the External Tank used for design were furnished by the integration contractor, Rockwell International. These static loads were based on the assumption that the flow traveled down the Shuttle , i. e. along the X axis. About the time the first ET was being finished, MSFC conducted a series of oil flow tests in the MSFC 14-inch wind tunnel. These oil flow tests, on a 0.4% model, consisted of blobs of viscous colored oil on the model. The tunnel was then run to a particular Mach number and photographed. The tunnel was then run to a higher Mach number and photographed and so forth over a range of Mach numbers. These photos showed the flow swirling around the ET in the transonic regime rather than flowing down the tank as had been supposed. While this had little effect on the static loads, the traverse flow across the cable trays raised a concern for aerodynamically excited torsional flutter (Tacoma-Palmyra Bridge). Because the MSFC tests only showed the flow on the surface, Rockwell built a 3% model, instrumented with hypodermic needles as total and static pressure pickups at the scaled elevations on the vehicle. This model was tested in the wind tunnels at Ames Research Center. These tests confirmed the MSFC data. This test series was identified as IA190. A second model, which scaled the cable tray/feed line area to a larger scale, was also run at Ames with good confirmation. This test series was identified as IA191. While structural analysis of the cable tray structure indicated that the flutter would have a limit cycle of about 1 degree, the repeated cycling could cause a fatigue problem on the cable tray brackets. Martin tried several fixes in a variable angle of attack wind tunnel at the University of Ottawa but reshaping the cable trays or stiffening the trays was unsuccessful. Filing the gap under the trays stopped the flutter excitation but the differential thermal expansion between the trays and the tanks would have caused the foam to come out on loading the cryogenic propellants. The final solution selected was to build ramps upwind of the cable trays to force the flow over the trays.

These ramps became known as PAL ramps, for protuberance air loads ramps, even though the problem was not an air load issue but an unsteady aerodynamic issue. Because the first tank had been delivered by this time, Martin installed the foam ramps onto the first ET in the VAB at KSC. Since that time the ramps have been installed at MAF as part of the basic manufacturing process. A test series has been run at AEDC with full scale cable trays and feed lines to see if the ramps could be deleted but the results did not provide enough confidence to support the change.

After the anti-geyser line was removed, the hydrogen pressurization line was rerouted from its interface at the ET/Orbiter disconnect to the other side of the ET to use the LO_2 pressurization line brackets. This caused the hydrogen line to be placed in front (upstream) of the aft ET/Orbiter crossbeam. This raised the possibility of periodic vortex shedding (Von Karman flagpole theory) which could excite a resonance in the line and cause its failure. While there were questions whether a line immediately in front of a flat crossbeam could sustain periodic vortex shedding in a continually changing velocity flow field with the line clamped at several places, the safe approach of shielding the line with a metal fairing was selected and is still flying.

Among the other things learned on the early tests was that the instrumentation island design, to verify the induced environment, was defective and that the ablator application process used at MAF was also defective. With regard to the instrumentation island design, last minute testing, after ET-1 had been delivered to KSC, showed that the islands could fall off when cryogenic propellants were loaded. It became necessary for Martin to remove all but one of the islands in the VAB and to patch the foam. The only island not removed was the one in the center of the aft manhole of the LH_2 tank which was attached to a welded clip. The others had all been bonded. Martin came up with a new design using welded clips on ET-2 through ET-6.

The ablator bonding problems resulted in about 400 square feet of ablator becoming debonded the first time an ET was loaded with LH_2. While the failure analysis was inconclusive, it appeared that the design process was acceptable but the Martin production people tried to bond too large an area and did not get the ablator panels under vacuum before the adhesive pot life ran out. The reworked process was demonstrated on ET-2 which was taken to Stennis Space Center and installed in the MPTA stand. This ET was tested successfully and the MAF crews were sent to KSC to rework ET-1. Although John Yardley, the Associate Administrator for Manned Space Flight, was willing to bet that ET would delay the first launch, this was not so. Orbiter problems provided a schedule umbrella for the ET.

Following the ablator bonding problem, caused by process deviation, analysis was intensified regarding the ablator/aluminum bond line. This analysis showed that the higher coefficient of thermal expansion of the ablator binder, compared to the aluminum, would cause the ablator to try to shrink and introduce biaxial tension in the ablator and corresponding shear forces at the bond line near any edges, discontinuities, or cracks. Then, when the tank was pressurized, the tank growth from pressure would compound this shear force possibly causing the bond line to fail. Martin arrived at the approach of prepressurizing the LH_2 tank to higher than tank pressures to stretch the ablator when it was warm and highly elastic. The GX 6300 adhesive used to bond the foam was found to undergo a "phase change" and essentially froze into a solid at –165 ^oF and was not compliant without cracking. The "freezing" of the adhesive then occurs after the thermal strain has developed and is in proportion to its stiffness in fluid state, not frozen state. As an additional precaution the ablator panels were serrated in selected areas to allow flexure of the metal panels without the development of bending stresses in the SLA and the attendant transverse stress at the bond line.

Loading against the higher back pressure slowed the LH_2 fill rate, but the LO_2 tank has always taken considerably longer than the LH_2 tank to fill so this is not a problem. Later, when the ablator was all removed from the LH_2 tank sidewall, KSC was asked whether they wanted to change the loading system, but that would have involved software and hardware changes so the system was left alone.

Because early test data showed the tank insulation could be adversely affected by ultra violet light, the first several ETs were painted white with a fire retardant latex (FRL) paint. Parallel ambient exposure testing of foam samples on the roof of MAF showed the damage to be so shallow that it was insignificant. The paint was deleted on acreage on ET-3 and on machined surfaces on ET-5 at a total weight savings of 580 pounds and at significantly lower labor costs.

Another test finding from MPTA was the observation that the vented LO_2 would form ice on the vent louvers on the nose cone. This ice, which was above the Orbiter's windows, could fall and damage the Orbiter's thermal protection system and windows. To preclude this, an interface was added at the launch pad consisting of a purged cap called a "coolie hat" with inflatable dock seals called "grubworms," which directed the cold gas away from the Shuttle to the stand. However, when this was tried at KSC on STS-1, the pressure surge, when the vent and relief valves opened, unseated the "grubworm" and the cold gas blowing by the seals eroded the insulation on the ET forebody. This surge occurs when the vent valve opens wide and rapidly allowing the pressure surge to overcome the internal pressure in the dock seals. A mechanical stroke limiter was placed inside the LO_2 vent and relief valve to limit the former 2-inch stroke to 1.1 inches. The smaller opening throttled the pressure surge and fixed the problem, at a small loss in performance because of the higher LO_2 tank vent system back pressure. This raised the saturation temperature of the LO_2 thus lowering its density. FRL paint is still applied under the "grubworm" footprints to provide a wear surface.

5.0 Lightweight External Tank

With the coming of the Galileo mission Shuttle needed more payload launch capability. Therefore, the ET Project Office was given an action to reduce the dry weight of the tank by 6,000 lbs. The mission model called for this to happen on ET-28. With the various slides to the Shuttle schedule but the fixed astronomic date of Galileo, the first effectivity kept moving up and ended up on ET-8, the first of the operational Lightweight Tanks. (ET-7 was never completed).

In order to meet the weight reduction goals, a variety of weight reduction and performance improvement options were selected.

1. Margin reduction – Where the analysis models and the structural test program showed excessive margins, the parts were redesigned to reduced margins. This was possible because the thousands of measurements on the STA confirmed the structural models and load paths.

2. Mixed factor of safety – The standard weight ETs were designed to a constant factor of safety of 1.4 against all loads. The redesign of the LWT was based on applying a factor of safety (FS) of 1.4 to all not well-defined loads, such as aerodynamics or vibratory loads, and a factor of safety of 1.25 for well-defined loads such as thrust or pressure. Since the actual loads on each part typically are a mix of well-defined and not well-defined, the FS on each part will range from 1.25 to 1.4. Since Rockwell furnished well-defined and not well-defined loads at each interface point, Martin was then forced to flow these loads down to each part with the percentage contribution from each loading point. The Load Indicators furnished to JSC for the Day-of-Launch I-Load Update (DOLILU) system illustrate these load mixes.

3. Materials replacement – Certain materials used in the initial design, such as 7079 Al and 5-2.5 titanium, were generally superceded by 7050 Al and 6-4 titanium. The appropriate parts were redesigned using the properties of these new materials.

4. Pressurization system – The ET LH_2 tank pressurization system was originally designed so that one failure of a flow control valve, either open or closed, would cause the LH_2 Tank ullage pressure to fall outside of the control band. Thus, a single failure could cause the LH_2 Tank to reach relief pressure. This made it necessary to proof test the LH_2 Tank to the top side of the relief band, approximately 3 psi above the control band. This forced the tank to be designed to this higher pressure. A combined effort between the ET project and JSC Systems Integration resulted in the pressurization system being redesigned so that a single failure would result in pressure staying within the control band. Since the tank structural design is based on “fail ops” (i.e. being tolerant of a single failure), the proof pressure was dropped to the top side of the control band and the tank was proofed 3 psi lower. This enabled a substantial reduction in LH_2 tank weight.

The weight savings from deleting the anti-geysering line and deleting the paint were also booked to the lightweight ET reduction of 10,000 lbs. (vs. the target of 6,000 lbs.). Removal of the developmental flight instrumentation (DFI) was also booked as part of the LWT since it now coincided with the first LWT. If the program schedule had not slipped, this change, the A/G line and the paint reduction would have been in place on ET-7 and the first LWT would have been ET-28. But since the schedule slipped the LWT to ET-8 (the pieces of ET-7 were never assembled), all of these changes were booked to the LWT.

There were two weight increases associated with the LWT which were made to enhance operations.

a) As noted before, the LO_2 tank ogive would collapse if a blanket pressure of 1.7 psi were not maintained during fill and after the tank was full. This higher ullage pressure raised the LO_2 saturation temperature and reduced the loaded mass. The LWT added 200 lbs. of aluminum structure to the forward ogive to permit the topping and replenish flows to take place with the vent and relief valve open to the 1.1-inch stroke. This resulted in an ullage pressure of 0.8 psig at saturation, reducing the LO_2 bulk temperature, increasing the LO_2 density and its loaded mass. Adjusting the mixture ratio (minor software change on the engines) to burn this additional LO_2 resulted in a performance gain which more than offset the increase in tank weight.

b) The aft dome was reinforced as discussed in **4.3.1** ***Structural Tests***.

Although the LWT was scheduled for ET-8, certain of the material replacements were not available for this effectivity and were introduced when available. Most significant were the titanium castings used for the interface hardware tank attachment fittings which were delayed until LWT 23.

Following this things went fairly smoothly with minor refinement to the TPS as a better understanding of the foam high temperature properties and the thermal environments permitted the removal of much of the ablator. This resulted primarily from modifications to the wind tunnel at AEDC which permitted testing the ET materials at high heating rates. Because the AEDC tunnel could only reach rates of 10 BTU/sq ft/sec, an assumption had been made that the foam disappeared and that ablator had to be applied under it above this level. When the tunnel could test at higher heating rates and the recession rates were established, much of this ablator could be removed.

Fingerprinting

In the early 1980s, Martin received a shipping lot of TPS primer in which the wrong solvent reducer had been shipped, even though the can was labeled with the correct material and the shipping paper showed that the correct material had been shipped. This two-part primer, consisting of a pigment and a solvent/reducer, is flight critical in that it provides the binder which permits the urethane foam to bond to the aluminum substrate. The lot of incorrect material cleared the simple receiving acceptance testing in use at that time and was released to the factory floor where a technician sprayed a 1,000 sq ft tank dome. However, the technician noted that the material did not behave normally. When investigated, the wrong solvent was found and the dome area had to be cleaned by hand sanding and scrubbing with Scotch Brite and a solvent.

Although the problem was caught by an alert technician, a major concern was raised within both NASA and Martin as to how to tell if a supplier had made a change, either deliberately or accidentally. Since most of the non-metallic materials include materials from several tiers of subcontractors, many of whom have no idea where or how their materials are used or the criticality of their changes, changes to non-metallic materials are not uncommon. Upjohn, the CPR foam manufacturer at one time, changed the trace iron content of their isocyanate from less than 5 parts per million to less than 2 parts per million. This made the foam lighter in color which helped their market for picnic coolers, but forced ET to spend $1 million at AEDC recertifying the new chemistry. When asked if they would make any further changes, they responded that ET used 5% of their capacity and that changes which could increase the marketability of the remaining 95% of capacity would be made. They did promise to tell us beforehand. With this attitude by primary suppliers the risk of changes down to the third and fourth tiers of suppliers is enormous.

Bob Lynn, MSFC lab lead for the Materials and Processes Laboratory, taking note of the recent availability of computer controlled chemical analysis instruments, approached Martin about setting up a laboratory to sample incoming non-metallics and comparing them to previous lots to detect possible changes. Martin hired an expert in this field who helped to develop a plan and an equipment list. NASA purchased the equipment for Martin and put it in place. The spectral output of each type analysis instrument was called its signature and was digitized and stored in a computer. The sum of the signatures of the various instruments was called the fingerprint and compared to previous lots of material. After several lots had been sampled, the normal variance had been established and this screening tool became very effective.

Although this process was set up initially as a receiving screen, Martin has expanded it to, in most cases, determine what has changed and what effect the change will have on the product. Martin makes this capability available to their suppliers to help them solve problems with ET materials and even to assist the suppliers in developing new products necessitated by environmental regulation changes.

Fred Gregory, then Associate Administrator for Safety and Mission Success, gave ET Project funding to contract with Lockheed Martin to write a fingerprinting manual. Mr. Gregory then sent copies to all NASA contractors. The SRM contractor, who is extremely dependent on non-metallics, has implemented a major fingerprinting effort.

After the introduction of the LWT, the ET Project was relatively stable until Joe Sexton of MSFC's M&P Lab was alerted by friends at Boeing Seattle to a new welding product, known as a Variable Polarity Plasma Arc (VPPA) welder, being introduced by Hobart. Plasma arc welding was common in steel welding but deposits building up on the electrode would come loose and contaminate the weld when used for aluminum. The variable polarity, where the positive and negative current would reverse about 5% of the time, served to clean the electrodes and provide a new "state of the art" in aluminum welding.

Following a visit to Boeing Seattle, Joe prevailed on the ET Project Manager, over the reluctance of the project production engineer (me), to spend about a quarter of a million on a Hobart VPPA unit and a computer controller. Following results totally outside the historical world of aluminum welding, the Project bought Martin a similar package with similar results.

Martin then developed a plan to divide the production tools into three families (easier to implement, next, and hardest) and submitted Engineering Change Proposals (ECPs) to modify family one. Following the completion of these tools the next family was authorized. The third family was never incorporated but those tools which were modified resulted in a substantial improvement in quality, reduction in repairs, and reduction in manufacturing manhours.

The VPPA process, by its nature, required far less preweld cleaning and edge preparation, and, because it blew contaminates out of the backside of the weld, was subject to much less porosity. An interesting sideline of this process was the appearance of the "phantom enigma," a white line which sometimes ran the length of the weld. For some time this was only found in a production weld and could not be repeated in the laboratory. Finally, MSFC M&P Lab learned how to make these indications in the lab, and examination by x-ray crystallography at Vanderbilt University showed that this was a unique crystalline pattern which appeared in x-rays but had no effect on the properties of the weld. However, Martin was always afraid that this x-ray indication could hide a linear lack of fusion so they would perform a manual ultrasonic scan as insurance.

VPPA became the baseline welding process for all but downhand welds until the aluminum lithium super lightweight tools came along. This welding process change is addressed in **8.0 Super Lightweight Tank (SLWT)**.

6.0 Challenger Impacts

Following the introduction of VPPA welding, External Tank deliveries went fairly smoothly with the production rate building toward 18 ETs per year, although this was at the start of the build cycle with deliveries never reaching that rate. The event which caused this delivery rate to drastically slow down was the Challenger accident.

The events leading up to and causing the accident are well documented elsewhere (see the Rogers Commission Report) so this discussion will be limited to the ET implications. At the time of the accident Jack Nichols was S&E ET Chief Engineer and the position of Chief, Project Engineering Branch was vacant. Porter Bridwell was Project Manager and Hal Coldwater, head of MSFC Test Lab, led the ET Contingency Team. Billy K. Davis of the ET Chief Engineer's Office became the MSFC Representative to the photo interpretation team at KSC.

Several issues where the tank was suspect were resolved and the tanks cleared as the root cause. When the SRM gas jet with a heating rate of over 700 BTU/sq ft/sec impinged on the tank insulation, which had been shown to withstand heating rates of 15 BTU/sq ft/sec for only a short time, the insulation failed. Then the tank wall failed and the tank, which is pressure stabilized in flight, lost pressure and structural stability, and the accident proceeded from there. Thus, tank structural failure was an effect rather than the root cause.

Among the tank issues investigated were the IR (infrared) gun readings carried by the Red Team. These IR readings were significantly below those predicted from the ambient thermal model for both the ET and SRM hardware. Further investigation showed the IR gun would read low when taken from a warm environment, such as indoors, to a cold environment, as outside. This was known to the Red Team who took the gun to their truck several hours before they were to make the readings. The insidious thing was that the IR gun carrying case was heavily insulated with foam to protect the gun from handling damage. This also provided thermal protection for the gun and prevented it from cooling down. Tests at MSFC using the Red Team timeline reproduced their temperature exactly and proved that a hydrogen leak was not responsible for the lower temperatures. The tests and data were presented to and accepted by the Rogers Commission.

There was also a suggestion that a burning hydrogen leak from the ET could have overheated the SRM joints. This was tested by subjecting a simulated motor joint with its insulation to various hydrogen leakage burn rates. It became clear that a hydrogen fire of sufficient size necessary to burn the joint insulation would cause such intense smoke from the burning motor joint insulation that it would have been impossible not to see on the dozens of cameras. These data and pictures of the smoke were presented to the Rogers Commission who accepted them as proof that a tank hydrogen leak had not caused the motor hot gas leak.

Immediately after the accident, MSFC reviewed every MRB and Weld Repair Record on the subject tank with no discrepancies found. Martin also updated MSFC's copy of the ET stress analysis report to the latest changes. These 17-volume reports were reviewed in depth, with a two- to three-man team of stress analysts assigned to each volume of the stress analysis report. No design deficiencies were discovered which could have contributed to the accident.

During the MRB reviews Martin also re-read all of the weld X-rays. This was done three times, once by the production technician, once by Martin's Quality Group, and third, by Martin's Material Engineers. On one weld the quality control (QC) representative reported a 0.4-inch crack, well below the critical flaw size. The Martin Materials engineer read this as fuzziness on the film, but once it was called a crack, it became a major concern. Since MSFC's Level III radiographer had just retired, the Shuttle Projects Office asked Rockwell to hire him as an independent consultant. He found the noted x-ray indication at the end of a gore-to-gore dome weld but, when viewing the x-ray of the weld which welded a chord to this location, he found nothing. During this chord-to-gore weld the area under question gets re-melted, and those x-rays showed nothing. The culmination of this effort was the recovery of this piece of the ET from the ocean bottom with no sign of any damage or cracking. In summary, the tank was cleared of any responsibility in the cause of the Challenger accident.

Following the accident there were no significant ET redesigns but the original design and manufacturing processes were re-evaluated. The major issues growing out of this were the new Failure Modes and Effects Analysis/Critical Item List (FMEA/CIL) and Hazards Assessments and the revisited weld non-destructive evaluation (NDE) acceptance criteria.

Following the accident Martin re-did the FMEA/CIL using new ground rules from JSC. Rockwell was contracted by MSFC to perform a completely independent FMEA/CIL. The ET Chief Engineer then played these two documents against each other with participation by both parties to arrive at a final version. In conjunction with this all of the ET Hazard Reports were re-opened and revisited as necessary. Also, JSC established a task force to re-evaluate all of the Launch Commit Criteria and the Flight Mission Rules. ET participated in these re-writes involving the ET and the Main Propulsion System (MPS). All of the OMRSDs were re-evaluated and MSFC and Martin were put into the review and approval loop of the Operational Maintenance Instructions (OMI) which were rewritten. After they were re-issued, MSFC backed out but Martin, through the Launch Support Services (LSS), remained active in the review. One of the actions committed by JSC to the Rogers Committee was the development of a System Integrity Assurance Plan (SIAP) which was published as Vol. XII of NSTS 07700. MSFC was requested to participate in the preparation of these documents, although virtually all of MSFC objections were overridden. Finally, the ET and SSME representatives were sent home and the MSFC Shuttle Systems Office took over. Part I of SIAP was implemented but, when the impact of implementing Part II was submitted to the PRCB, the MSFC costs were so high JSC refused to fund them. Bob Marshall, MSFC Shuttle Projects Manager, then refused to implement Part II into the MSFC Projects without adequate funding.

The SIAP program was intended to be a massive data base at JCS to collect and analyze all Shuttle part failures down to the lowest build levels and lowest tier subcontractor. This presented a massive problem to MSFC since NASA's contracts with their primes and the primes with their subs on down required reporting at the Acceptance Test Procedure (ATP) level for FMEA Criticality I, IA, and II failures.

Adding the extensive reporting levels for all levels down to the lowest piece part would have imposed an enormous cost on the MSFC projects, which were still building parts. It was also planned to enter these reports into JSC's Problem Reporting and Corrective Action (PRACA) System. Since MSFC had accepted their contractors' reporting formats to save money, all of the contractor reporting systems would have had to be replaced with PRACA compatible formats. To preclude this Bob Moorehead, JSC SIAP Manager, said that MSFC could report in their own format and the JSC would develop computerized conversion systems. In the 15 years since SIAP started this has not happened. MSFC S&MA has a contractor who manually converts all project reports to PRACA format. Lockheed Martin reports all ATP or later failures on Criticality I, IA, or II hardware in their Corrective Action Process Summary (CAPS) system. They also submit CAPS, as requested by the NASA Project Manager, on any other failures. Closure of CAPS requires the NASA Project Manager's signature. To insure NASA visibility of critical factory-build problems below the CAPS reporting level the MSFC Chief Engineer representative at MAF has to approve all fracture critical part MRBs, and the ET S&MA representative has to approve all MRBs. This system has worked very well.

Another action which resulted from Challenger was a "Blue Ribbon" review of Martin's fracture control practices and NDE rules. This committee was convened by Bob Ryan, but to ensure that there was no MSFC bias, the chairman was picked from Northrop Aviation. There were members from the USAF at Wright Patterson, Ohio State University, NASA Lewis, NASA Langley, and NASA JSC with Paul Munafo representing MSFC. In general, they confirmed Martin's practices but they did add a post-proof x-ray requirement on all repairs, regardless of whether they had been fully proofed. Other welds which were fully proofed to 105 % of the flight limit load (corrected for the fracture toughness ratio) did not require post-proof x-ray. They also cancelled Martin's crack acceptance manual and required all cracks, or crackline indications either pre or post proof, to go to MRB.

Following this re-assessment the ET Project was fairly quiet with only the normal loads changes, thermal changes, and propulsion issues. The changes included going to a fixed orifice pressurization system on the LO_2 tank and failing to implement one on the LH_2 tank because of the difficulty in maintaining adequate pressurization for some engine-out cases. Somewhere during this time period, the range safety system on the ET was deleted. John Young had been trying to do this for a long time but finally the JSC Range Safety Working Group convinced the USAF Range people that this could be done. This resulted in a small weight saving to the ET but a significant cost saving to the SRB project that furnished the active components as GFP. It also enabled removal the high temperature (MA25S) ablator from the cable tray segments where the LSC was located. A number of FMEA/CIL Criticality I failure modes were removed.

Also, during this period Martin gradually implemented VPPA into the rest of the tool family except for a couple of downhand torch attitude tools where VPPA did not work very well.

In the analysis world Martin developed a family of Load Indicators which established a relationship between external loads and design capabilities of the ET components. These were used for development of design loads and later for assessment of loads resulting from "day-of-launch wind measurements." Thus, when the wind measuring balloons predicted that the load limit would be exceeded, it could quickly be determined whether there was a tank problem. Eventually these were refined down to indicators which could be loaded in the day-of-launch Loads Programs, DOLILU and DOLILU II, to assess the effect of upper atmosphere winds on the tanks without Martin requiring a team of loads and stresses analysts to be on standby.

7.0 Environmental Effects

During this period a major environmental issue arose which had more impact on the ET than any other change. The Environmental Protection Agency (EPA) determined that the Freon blowing agent, used to make the foam insulation rise, was damaging the ozone layer of the atmosphere with resultant potential health effects to people and the environment. Regulations were issued which banned the manufacture of CFC-11 Freon, a major constituent of the ET foam family CPR 488, NCFI, BX 250, and PDL.

There were several years advance notice and, in anticipation, ET had developed a foam formulation lab in the MSFC Productivity Enhancement Center (PEC) operated by Lockheed Martin. Because of the tremendous usage of this material (auto air conditioners, etc.) virtually every chemical manufacturer in the U. S. and elsewhere started a major effort to find a replacement. Martin and MSFC M&P Lab (Scotty Sparks) went into a major effort to obtain and sample all of the products being developed. While many products would work for the standard commercial foams (upholstery) or for air conditioning, the ET requirements were totally unique. Dow Chemical, who had bought Upjohn, who had bought Chemical Products Research (CPR), showed little interest in modifying their foam because ET was a tiny part of their market. Fortunately, Gus Cavalaris, NASA Sub-system manager for ET TPS, had Martin develop and qualify a second source for the sidewall foam (CPR 488) with NCFI, the aft dome foam supplier. When this foam was reformulated with HCFC 141b blowing agent, it was able to meet all known ET requirements. Unfortunately, this blowing agent had an ozone depletion rating of 15% (15% as bad as Freon). Because of this EPA, has required that this material be phased out in 2003/2004. NASA is currently attempting to get a waiver to continue to use this material until 2010. Another blowing agent, HCFC 134a, has a zero ozone depletion potential (ODP) but it will not work successfully in the ET foam system. Martin and MSFC have a continuing effort on going to find a "third generation" blowing agent but, at this time, there appear to be no "drop-in" replacement materials.

The new sidewall foam, NCFI 24-124 with HCFC 141b, was qualified for the critical properties identified in the previous development and test program, i.e., adherence to a cryogenic substrate and high temperature ablation. Test methods developed over the years, primarily cryostrain and the MSFC hot gas facility, were used to certify this material for the flight environments.

The first usage of this new foam on the tank sidewalls was phased in over three tanks starting with STS-85 with no noticeable problems. However, when the Orbiter from STS-86 landed, there was extreme tile damage to the Orbiter wing in a unique pattern along the wing chines. Rereview of the tile damage on STS-85 showed the same pattern, although not as severe. Calculated debris trajectory analysis confirmed this. Analysis by the Boeing debris people indicated that this damage was probably caused by foam from the sides (± y axis) of the ET intertank. This was totally unexpected since the intertank has a heated purge prelaunch, the foam never sees cryogenic substrate condition, and the heating rates are very low, well below the rates shown to cause foam damage. Review of the hand-held camera images taken by the crew to photograph the tanks after separation showed significant loss of foam from the intertank. For the next several flights the foam was hand-machined down to minimum drawing tolerance to reduce the outer fiber stress on the foam under bending and to reduce the mass and rigidity of foam hitting the Orbiter if some foam did come off. SRB mounted a video camera in the SRB forward skirt behind a window to observe the ET intertank. These cameras, which provided outstanding coverage, clearly showed a phenomenon called “popcorning” in which small pieces of the foam surface would spall off.

A massive Fault Tree was established to resolve this problem. Tests in a thermal/vacuum chamber as well as tests in the MSFC hot gas facility were able to reproduce the noted “popcorning.” The thermal/vacuum testing program was developed to analyze and develop a resolution for this problem. Apparently, the higher vapor pressure of the HCFC 141b combined with the lower yield strength of the new foam, in conjunction with the propensity for this foam to fail on slip planes parallel to the intertank ribs, caused small chunks of foam to come off. A fix, validated in the hot gas facility, appears to have resolved the immediate problem. The fix consists of punching 0.030-inch holes into the foam on 0.300-inch centers in the areas where an aerodynamic transport mechanism existed to carry the foam from the ET to the Orbiter. This, however, adds a considerable workload to the factory tank build. To resolve this, Lockheed Martin has started a development program to modify the foam chemistry and process to spray thinner and less susceptible foam on the ET to preclude “popcorning.” This is being worked in conjunction with a foam re-qualification program necessitated by the vendor change of the isocynate source from Spain to Texas. The change in foam chemistry also eliminates a flame retardant that is no longer available. The development of a “third generation chlorine-free foam” is a longer-term effort and will not be addressed here.

8.0 Super Lightweight Tank (SLWT)

Before addressing the Super Lightweight External Tank (SLWT) a brief discussion of aluminum-lithium (Al-Li) alloys is appropriate. During the 1950s, Alcoa developed an Al-Li alloy, Al 2020, which North American Aviation used in a high supersonic attack bomber role for the Navy. This carrier-based aircraft was called A5J. However, around the time it went into service, the strategic role was taken away for the Navy and the A5J was converted into a reconnaissance aircraft used extensively in Vietnam. Although the aircraft performed well, the Al-Li material had significant problems believed to be in the fracture and fatigue areas. No further use of this alloy has been found.

Although the U.S. dropped the use of Al-Li, the Russians continued extensive development and are using it in the MIG-29. In the early 1990s, NASA sent Dr. (to be) Fred Bickley to Russia for several weeks to explore their usage. He found Al-Li used extensively in aircraft, but its use in welded structure was limited. On the MIG-29 if more than two weld repairs were required at a given location, the part was scrapped rather than trying further repairs. The Russians reported that they had developed a weldable Al-Li alloy for cryogenic usage, but at the time Dr. Bickley was there, it had not been made for several years. Dr. Bickley's findings were borne out when the Russians visited MSFC before the MIR (Russian Space Station) missions. They were given briefings on the MSFC Shuttle Elements. The only question asked of the ET presenter when it was mentioned that a lighter weight ET was under development using Al-Li was, "Do you have trouble welding Al-Li?" The presenter answered "yes" and went on to the next chart. However, the Russians visited the Materials Lab the next day for extensive discussions.

In the 1980s, U.S. aluminum manufacturers realized that the increasing use of composites for aircraft structures would soon impact their sales for aircraft, so they resurrected the Al-Li work they had done in the 1950s. Alcoa developed an alloy called Al 2090, which showed good aircraft properties but limited weldability. This alloy was also not available in the thicker plate gages, which ET needed to hog out their tank skins. The Al 2090 is believed to be used in the C-17 transport aircraft.

Martin, as part of their corporate empire, at one time owned an aluminum company. They sold the company but retained the R & D Labs in Baltimore. This group began working on developing a high strength, weldable, cryogenic friendly Al-Li alloy. They called this alloy "Weldalite," which actually covered a family of Al-Li alloys.

Now the ET comes into the picture. Martin, now Lockheed Martin, obtained samples of the "Weldalite" alloy under an Independent Research and Development (IRAD) program and had three dome gores and a quarter of the chord, which attaches the dome to the barrel, formed. These were welded into what the ET calls a "quarter dome."

Forming the Al-Li into dome gores was a learning experience. The forming process for the previous Al-Cu alloy (Al 2219) gores is done by starting with plate in the T3 temper (minus the cold work), cutting the gore to shape from flat stock, stretch forming in a stretch press, which adds cold work to satisfy the T3 temper requirements, aging to T8 temper, and chemical milling to the final configuration.

When this was tried on the Al-Li, the material was so stiff in the T3 temper that it broke the gore supplier's (Aircraft Hydroforming's) stretch press. The energy release was so violent that the roof almost came off the building, and the films looked like an earthquake was occurring. Martin and AHF worked out an approach which involved the aluminum supplier delivering the plate in a T0 temper. AHF would then bump form the flat gore stock in one axis, solution heat treat to 985°F, quench in 10 seconds (which gave them a T3 temper minus some of the cold work), and then stretch form to the final contour. This stretch forming supplied the cold work necessary to get to a T3 temper. The panels were then aged to a T8 temper and chemically milled to final contour. Because the aging time/temperature for Al 2219 resulted in over-aged material for Al-Li, another test program was necessary to establish the optimum aging cycle. Post delivery solution heat treating and quenching these large curved panels required new ovens and quench tanks since this is usually done on flat plate at the rolling mills.

Lockheed Martin then approached the ET project with an offer to develop an 8,000-lb lighter ET. When the Project Manager approached Level II at JSC regarding Lockheed Martin's offer, he was told that the Shuttle required no additional payload (ET weight reductions play off pound-for-pound in payload improvement) and that Shuttle landing weight limitations on abort already limited the payload which could be carried on a "due East" mission. Subsequently, when ET had some money left at the end of a fiscal year, the project again asked JSC for permission to use some of this money to purchase Al-Li material so as to get familiar with it if performance was needed at some later time. JSC again responded that they had no need for additional performance and could not use additional performance if it were available. They refused to authorize the use of Shuttle funds for unneeded payload.

Things rocked along without significant action until the Space Station made the decision to change their orbital inclination to 57°, so that the Russians could fly directly to the station. The inclination change cost Shuttle 13,500 lbs. of payload capability, which put it well below the Station needs. Since the Advanced Solid Rocket Motor (ASRM) Program had already been cancelled, this left it to the External Tank to make up a significant portion of the payload loss. To be conservative the ET Project proposed to reduce the dry weight of the ET by 7,500 lbs. using the aluminum-lithium alloy developed by Lockheed Martin under the Weldalite banner. JSC convened a "Non-Advocate Review" team chaired by Bob White, JSC Systems Engineering, and representatives from Langley Research Center and MSFC to evaluate the Lockheed Martin plan. Lockheed Martin proposed delivering the first "Super Lightweight ET," to be called SLWT, in 48 months after go ahead. This was considered reasonable since Lockheed Martin had delivered the first ET, the Main Propulsion Test Tank, in 48 months starting from scratch with no design, an empty plant, and no work force. JSC accepted the 48-month schedule, but waited four months before starting the project and left the end date the same. This brought the span time down to 44 months. Because the Space Station schedule and NASA's reputation were riding on the ET, the ET Project Office accepted the challenge.

The first step after turn-on was to purchase some of the Al-Li material. Although Lockheed Martin Labs had developed the material, Reynolds Aluminum had bought the production rights. When Reynolds mixed up their first batch of production material, its behavior, particularly in the fracture area, was not the same as Lockheed Martin's lab material. When Reynolds could not explain or resolve the differences, Lockheed Martin Labs, Lockheed Martin Michoud, and MSFC M&P Labs joined in setting up a Taguchi design of experiment (DOE) program. Because Reynolds had no experience in this type of program, Lockheed Martin Huntsville, who had used it extensively in the TPS development programs, taught Reynolds how to perform the DOE. Reynolds was finally able to make the material, but the room temperature/cryogenic temperature fracture toughness ratio for the thick plate was erratic from plate to plate. The resolution of this will be discussed later. To aid Reynolds and to insure good material Lockheed Martin, MAF, and MSFC M&P co-located Ph.D. metallurgists at Reynolds for several years.

The next "gotcha" occurred when Lockheed Martin used the IRAD quarter dome to practice straightening "oil cans" induced by weld repairs in the doubly curved dome welds. The effects of weld shrinkage in these weld repairs had been well known on both the S-IC and the ET. This shrinkage would cause a flat spot or even a reverse curvature in the vicinity of the repair. For Al 2219 the magnetic hammer developed at MSFC or planishing of the weld repair had been used to correct the "oil can." To provide a test practice article Lockheed Martin chose to induce "oil cans" into the IRAD dome by making multiple (6 or 8) repairs at the same location. Fine cracks in the weld repair at the location of the repair were not unknown on Al 2219. However, when the multiple repairs were tried on Al-Li, the repair area cracked open so widely that a newspaper could be read through the opening. When Bob Schwinghamer, Deputy Director of S&E, saw these cracks, he immediately assigned Fred Bickley to the ET Chief Engineer's Office as Czar of Al-Li weld repair. After examination of the repaired area, it was found that welding Al-Li caused a crystalline structure called an equiax zone of extremely brittle material surrounded by a continuous secondary phase. Repeated repairs caused this zone to grow until the residual stress from the weld shrinkage exceeded the strength of the brittle weld repair causing it to fail. This raised several issues.

Al-Li had to be welded with an inert gas purge on the backside of the weld rather than only on the front side, as was common on all other aluminum. An approach to repair the weld cracks in Al-Li was to make alternate side repairs, for example, make repairs by grinding from the backside to grind out the equiax zone, and to make the repair from the backside. If a succeeding repair were needed, then sides were again swapped. Since all of Lockheed Martin's high production rate tools were designed to weld and repair for the one side, this meant building a new group of repair fixtures. It was also found that Al-Li could not tolerate as much heat as Al 2219. For Al 2219 repairs, which were made manually, the welds were carefully controlled to a torch speed of 4 inches/minute. The repair welders were trained and certified to move their torch at precisely 4 inches/minute. Al-Li could not tolerate this much heat and required torch speeds of 10 inches/minute. The very experienced repair welders had an extremely difficult time retraining their muscles, and it turned out the younger, new welders became more adept at repairing Al-Li than the senior people. Lockheed Martin solicited help from all of the other Martin Divisions, MFSC, Langley, JSC, USAF at Wright-Patterson AFB, and the Edison Welding Institute (EWI). EWI includes membership from virtually everyone in the U.S. welding business. They are also tied into The Welding Institute (TWI) in Cambridge, England and constitute virtually all of the welding smarts in the free world. Their (“Edison’s”) conclusion was that we would never learn to repair this material. When asked whether a change of weld wire from Al 2319 would help, their response was that changing weld wire would not help. Thus, 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.

The next gate to be passed was whether the material could be welded in the first place. The baseline ET used VPPA welding for most of its welding. Developing tools which could furnish the inert gas backside purge with the plasma torch blowing through the material, a characteristic of VPPA, caused enormous tool design issues with several purge boxes being cut up by the plasma torch.

The tooling for the long LH_2 tank barrels (20 ft), which were welded horizontally to permit off loading the tool under a 36-ft crane height, used the standard TIG weld process. This had worked well on Al 2219, but major problems were encountered on the Al-Li. These welds were made in a down hand torch attitude, an attitude where VPPA was not effective. The plasma torch would blow the weld puddle out of the seam. A new technique was needed.

Lockheed Martin at MSFC developed a Soft Plasma Arc Weld (SPAW) system to resolve this problem. This was another example of the MSFC Productivity Enhancement Center providing the solution to a real-time critical program issue. Although Babcock and Wilcox had developed a similar system for welding the steel ASRM cases, the Lockheed Martin MSFC people developed their aluminum SPAW system totally independently.

It was also found that welding with the 4043 weld wire vs. 2319 was more forgiving. However, the 4043, a high silicon wire, was not as strong as 2319 or the parent Al-Li (now known as Al 2195). On multiple weld repairs the concentration of 4043 would gradually build up until the puddle was almost pure 4043. This brought the strength of the repairs down to about 32 ksi when the test data was processed per MIL-HBK-5 statistical practice. The weld lands on the parent material had to be sized for this weld strength. This of course added weight.

When reflecting on this, NASA and Lockheed Martin questioned whether the method used to develop weld allowables was giving the welds adequate credit. The classical method was to weld a test panel, make a repair of approximately 6 inches, and cut a 1- to 2-inch test specimen out of the center of this repair. Thus, the test specimen was testing entirely repaired material. However, on the real hardware, as the repair yielded, the loads would redistribute and the original weld would pick up some of the load. It appeared that this test method was short changing the weld repair. To test this, a series of 17-inch wide panels was coated with a photo stress coating which would show the stress pattern under ultraviolet light. Pat Rogers of MSFC's Structures and Dynamics Lab developed a computer program to display these stress fields also, with excellent correlation to the photo stress images. When tested on Al 2219, the results were exactly as predicted. The repair yielded, the loads redistributed, and the panel pulled well over the minimum allowable value. But, when this was tried on Al-Li 2195, the material yield strength was so high the loads remained concentrated in the repair. Instead of the 32 ksi obtained previously, the welds were failing around 18 ksi. Since extensive parts had been machined with weld lands sized for 32 ksi repair capability, this had the potential to be a real show stopper. In tracking down the cause of the discrepancy, it was determined that the repair weld shrinkage stress was trapped in the joint and this reduced the joint capability. An approach was developed to planish the weld bead, forcing it back into the joint and spreading the joint to get rid of the shrinkage stress. This requires scribing and measuring the joint before every repair, making the repair, and planishing the bead to eliminate the shrinkage. Planishing of weld beads is not a precisely controlled process and frequently forms other cracks leading to additional weld repairs as high as R19. This need to planish all repairs was a major driver in selecting the 4043 weld wire since it was easier to planish. Because of the difficulty in making and planishing multiple repairs, a verification ground rule was established that every "first repair of its kind" had to be replicated on three 17-inch wide panels, which were then tested on a universal test machine, either at room temperature or cryogenically depending on where the critical stress condition existed. This rule, as well as others relating to the fracture characteristics of the material, was staffed through both the Lockheed Martin Fracture Control Board and the MSFC Fracture Control Board. To illustrate the difficulty in making some of the repairs, the first 17-inch wide test panel on an R17 repair (17 repairs overlapping) took 800 man-hours to prepare. Actions taken to reduce the need for planishing are addressed in the weld wire replacement discussions at the end of this section.

Another of Lockheed Martin's weight saving approaches was to abandon the hogged out longitudinal "T" stiffeners with mechanically fastened ring frames and to machine a rectangular waffle pattern directly into the skin panels of the LH_2 tanks. This waffle, called an orthogrid, provided almost half of the SLWT weight saving. McDonnell Douglas had flown a triangular pattern called an isogrid but orthogrids had not been used before on propellant tanks although some payload fairings had used this approach. McDonnell Douglas, however, published some research in iso- and orthogrids which turned out to be very useful to Lockheed Martin. One problem with the orthogrid is forming to the circular arc without crippling the vertical legs.

Lockheed Martin and MSFC did extensive development in the MSFC PEC to investigate forming techniques. The classic method of forming this type of configuration is to machine flat in a T3 temper, fill the pockets with a low melting alloy, roll, and melt the filler material out and then age to a T8 temper. To find a lower cost approach, rolling the flat machined material, both with and without a soft aluminum cap sheet, and bump forming with contoured shoes on a numerically controlled press were also tried. When Lockheed Martin competed the part to industry, the bump forming with the numerically controlled press was selected. This has performed very well. After forming, the plate is aged to a T8 temper in a restraining fixture to insure final contour. To certify the integrity of these skin panels, the plate is ultrasonically scanned at the rolling mill. After the panels are formed and aged, they are inspected with a Type III penetrant (ultrasensitive) by two totally independent sets of eyes. Each inspector has a matrix to follow to insure that every pocket is scanned. Previously, on the Al 2219 tanks for both Boeing S-IC and ET the machined skins were penetrant inspected with a Type II penetrant for a number of skin panels. This post-machining inspection was dropped when nothing was found over a large number of samples. Machined plates are always ultrasonically scanned at the rolling mill and are still scanned for Al 2219 deliveries.

Because of the thick plate necessary to hog out the ET skins, it is necessary for the stress analysis to be performed in three dimensions. For the Al 2219 isotropic material conventional analysis tools were available. However, Al 2195 tends to be anisotropic in that the properties through the material (short transverse direction) are somewhat weaker than the long or long transverse directions. It thus became necessary to modify analysis tools, by both Lockheed Martin and MSFC, to design and analyze these parts. The material behaves almost like a composite which has only the strength of the resin in the short traverse direction. The analysis tools developed for composites were adapted for Al-Li.

It was mentioned earlier that the cryogenic/room temperature fracture toughness ratio of the Reynolds Al-Li was erratic from plate-to-plate with each plate being a furnace lot. Since the ET propellant tanks are proof tested at room temperature and flown cryogenically, the ratio is most important. Al 2219 is approximately 10% tougher at cryogenic condition than at room temperature. This provides that flaws, which are just below critical at room temperature, have room to grow at flight temperatures. The whole issue of the ET fracture-based designs is beyond this paper, but Don Bolstad of Lockheed Martin has published several papers. However, the erratic nature of this ratio was most critical to the SLWT. To resolve it a decision was made to perform a simulated service test on every plate. Failure of this test resulted in the plate being re-melted and re-processed.

The simulated service test consisted of cropping two specimens from the end of each plate. Electro deposition machining (EDM) notches were machined in each sample. The first sample was stressed to failure during development; the second was stressed to the stress level expected during proof test at room temperature. The sample was then stressed 13 times to the level expected during loading of propellants at cryo temperatures, then stressed to maximum expected flight stress at cryo temperature. This cycle of loading stress and flight stress was repeated three times to meet the four life program requirements with the exception that on the fourth cycle the sample was broken and had to exceed a predetermined % of the failure stress of the first sample. This is still being done on all 32 barrel plates of every LH_2 tank.

Since the orthogrid panel had never been flown in this application, the stress community desired a repeat of the original ET structural test program. However, neither the test fixture used for LH_2 tank test nor the funding was available for this level of testing. A test requirements panel consisting of the Lockheed Martin Chief Engineer, retired Martin Corporate Chief Engineer, MSFC ET Chief Engineer with MSFC Lab support, and Bob Ryan of MSFC arrived at an approach which was called ALTA (Aluminum Lithium Test Article). Since the failure mode of concern in the orthogrid was compression buckling, the ALTA was structured to verify this mode. It consisted of a single ET barrel with a forward LH_2 dome and an aft LO_2 dome (more on this later). Because there were four orthogrid patterns on the SLWT, each was repeated over a 90° arc. An old S-II test fixture at MSFC was modified with hydraulic jacks so the short tank could be loaded in compression. Before the test could start, a welding arc strike was noted on the tank, probably from a test stand welder although no one would "fess up." A major MRB was convened to determine if this arc strike would impact the integrity of the tank. Extensive work and analysis by MSFC M&P materials people to examine and replicate this condition showed it to be acceptable.

A second failure mode was also tested on the test article. The ET LO_2 tank aft dome has a stability failure mode when the LO_2 is only in the center of the dome near the end of flight. LO_2 at 3gs tends to punch out the center of the dome while pulling inward on the upper part of the dome. This condition was tested on the Standard Weight ET using barium sulfate solution (driller's mud) during the ET structural test program. However, the aft dome of the SLWT was extensively redesigned by removing the ribs and adding thickness. Therefore, the ALTA aft dome was tested with a dense solution (steel shot in a viscous medium) before the side wall testing took place. The test involved contracting with several cement mixers to keep the shot in suspension, pumping it into the dome, and immediately pumping to out when the test condition had been met. Although the dome passed, a number of cement mixer drivers concluded that NASA had lost their minds.

On the sidewall test the tank was pressurized to minimum flight limit pressures and the jacks loaded to induce design ultimate compression load in the tank wall. The pressure was then gradually decreased until the tank failed. It failed explosively at over 200% of design limit internal net load, well over the requirement of 140%. This certified the orthogrid concept for compression stability.

Although ALTA was able to test and verify the three LH_2 tank upper barrel configurations, the aft barrel, with its welded-in longerons, could not be adequately tested for in-flight stability. After much evaluation the test requirements team recommended that, rather than trying to take one barrel to 140% of design load, as was usually done, every SLWT should be tested as part of its proof test to 115% in this area. The first test was heavily instrumented to verify the structural model and load paths, and all subsequent SLWTs have repeated this test, although without instrumentation. It may be remembered that for Orbiter 099 the structural test vehicle was only tested to 120% and then converted to a flight vehicle, Challenger.

The verification committee, headed by Bob Ryan and Bob Mora, also established that, when a change could not be tested and was a change from the previous flight configuration, it had to be verified by two independent analytical models with a Factor of Safety greater than 2.0. For the LO_2 tanks ogive stability, Lockheed Martin used an analytical tool called equivalent cylinders. To obtain a second validation, Dr. Mike Nemeth of Langley Research Center was asked to build a STAGS (Structural Analysis of General Shells) nonlinear stability model of the ogive. As noted earlier, the ogive of the MGVT buckled while filling with water, a precursor to the MGVT testing. The data from this failure was fed into the Langley model which predicted the failure precisely without Dr. Nemeth knowing about the MGVT failure. This, of course, added credence to the model which was used to support the redesign. The same approach of independent models was also used on the SLWT intertank where Lockheed Martin used the model developed for the original ET, while MSFC Structures and Dynamics Lab developed a totally independent model.

Another area of long-standing concern for the ET has been the joint where the deeply cryogenic LH_2 tanks joined the warm intertank. This was verified by test on the original Structural Test Program for the Standard Weight ET. The joint concept was not changed on either the Lightweight ET or the Super Lightweight ET, so the analysis tools developed for the Standard Weight ET remained valid for the later variants.

Lockheed Martin recognized, when starting the SLWT, that the conventional serial design process would not support the SLWT schedule. They chose to go to the Product Development Team approach. This involved breaking the design effort into a family of design packages such as intertank, domes, hydrogen barrels, etc. Teams consisting of design engineering, stress engineering, materials engineering, process engineering, manufacturing engineering, manufacturing planning, quality engineering, and material procurement personnel were convened for each design package. The product of these teams was complete packages of drawings, process specifications and procedures, manufacturing planning packages, and purchasing requirements. NASA Chief Engineer's representatives were assigned to each team to insure real time coordination of issues or concerns. The performance of these teams varied with the personnel working in the team but, on the whole, they were valuable in meeting the very tight SLWT schedule.

The approach of having a high level independent team review and develop the verification program ground rules and content proved very valuable both from a content standpoint and in selling the adequacy of the program to outside reviewers.

One such reviewer was an Aerospace Safety Advisory Panel consultant who expressed extreme concern in the fracture-based design of the propellant tanks. Neil Otte, then S&E, and Don Bolstad from Lockheed Martin spent many hours proving the soundness of the ET approach. This effort forced ET personnel to re-look at their assumptions and analytical practices to prove the project was going in the right direction. Their major finding was "Don't relax on the extra care required for 2195 Al."

In an attempt to insure material availability and to bring the cost down, Lockheed Martin had Alcoa qualify as a second source for Al-Li 2195. Although Reynolds considered their process proprietary and would not release details to Alcoa, Alcoa was able to replicate the material independently and was qualified as a second source for the thin plate from which the dome and ogive gores and LO_2 tank barrel panels were made. However, Alcoa was not qualified for the thick plate for which the LH_2 barrel panels were machined. Reduced build rate made it impractical to contract with the second 2195 supplier.

Thus, the Super Lightweight External Tank ended up with aluminum-lithium ogive gores (14), LO_2 panels (4), LH_2 barrel panel (32), LO_2 tank aft dome gores (12), LH_2 tank forward dome gores (12), and LH_2 aft dome gores (11). The LH_2 aft dome gore into which the big machined forgings for the LH_2 feed line and the LH_2 recirculation line were welded was left as 2219 aluminum to eliminate the need to develop the weld processes in aluminum lithium.

Many of the thin-gage mechanically fastened materials in the intertank, skins, stringers, doubler, etc. were changed to Alcoa's aluminum-lithium 2090. This went well with no significant problems.

The final weight savings was made by reducing the amount of foam TPS on the ET. This was done by two approaches. The foam on the intertank, because of the application method and the irregular surface of the intertank, was far thicker in many areas than was necessary for ice protection, ascent heating, or thermal protection during re-entry. To eliminate the surplus foam a massive machining tool was developed to machine the foam on an entire intertank to the thermal requirements. This eliminated approximately 270 lbs. of foam from the finished ET. Thinner foam also proved of value when the "popcorning" problem discussed earlier occurred on the intertank.

The second foam weight savings approached the issue from the other direction; that is, rather than machining off excess foam as was done on the intertank, the amount of foam applied was controlled. This was done on the LH_2 barrel section where the required foam thickness was greater on the side facing the Orbiter than on the side away for the Orbiter. Lockheed Martin and MSFC in the Foam Formulation Lab of the Productivity Enhancement Center developed the Variable Output Proportioning System (VOPS). The sidewalls of the LH_2 tanks were foamed by rotating the tank while the spray gun transversed up the tank. The VOPS permitted the foam output to be modulated as the tank rotated, thus controlling the thickness. This saved approximately 55 lbs. on the SLWT.

In summary, despite a large number of problems in materials and manufacturing process, the Lockheed Martin and NASA team delivered the first SLWT on a schedule which supported the first International Space Station schedule, within budget, and meeting the performance goals.

Although the first SLWT, ET-96, met the program objectives, its producibility deficiencies would have made continued manufacturing of this tank risky from a schedule standpoint and overly costly. Therefore, Lockheed Martin and NASA established a program for a second generation Super Lightweight External Tank to resolve these issues. The first step was to find other weight saving candidates so weight could be put back into the hard-to-build areas. Lockheed Martin, in their manufacture of the F-16 fighter at Fort Worth, had adopted another aluminum-lithium alloy, 2297, for the major bulkhead of the aircraft. This part was machined flat from thick plate in its final temper and was not welded. While this application was foreign to most ET applications, the thrust panels in the intertank come close. These thrust panels are machined flat in a T3 (softer) temper, bump formed to the circular radius, and aged to final configuration. Lockheed Martin and the MSFC Materials Lab started a development program to investigate whether the use of this lighter, stronger alloy (2297) was possible in this application. Because Lockheed Martin was on their fifth supplier of these difficult to form parts, there was some apprehension in the NASA Project Office. However, they were able to prove that it could be done with a significant weight saving.

Changing the thrust panels opened the door to several producibility changes whose weight increases were offset by the thrust panel. All of the dome gores and ogive gores could be converted back to Al 2219, which Lockheed Martin was comfortable welding. Because of advanced modeling and analysis techniques since the LWT was designed in 1978, these parts are somewhat lighter than the LWT, but heavier than the SLWT. With the new thrust panels and the further optimization of the dome gores, ogive gores, and orthogrid LH_2 barrel panels, the tank still met its weight goals. Welding of these second generation domes and ogives has drastically reduced the repairs and MRBs.

A second producibility enhancement was the introduction of a new welding process developed by TWI. Several United States aerospace manufactures had been working with the MSFC Productivity Enhancement Center to develop this process call Friction Stir Welding. Friction Welding has been used for some time, particularly in oil well drill pipe and in the assembly of the injectors on the SSME. Friction stir welding, while similar, uses a rotating spindle, which heats the material to be joined well short of melting, as opposed to arc welding, and joins material in a semi-molten state. It is often called solid state welding.

This is not the place for an extensive discussion of this process, but a number of papers have been published, particularly by Jeff Ding of MSFC Materials Laboratory, and are available on the internet, or directly from Jeff. Lockheed Martin has adapted this process for longitudinal welds in both the LH_2 barrels and the LO_2 barrel. Martin and their suppliers had developed the process and built two production tools which have the capability for the 8-ft. LO_2 barrels, the 15-ft. aft ET barrel, and the three 20-ft. forward barrels. The two tools have been installed in a pit at MAF to provide offload clearance under the bridge cranes and are undergoing final check out. A full diameter, shorter length training tool is at MAF for operation training and certification. While use of this process will not result in any further weight savings, all indications from the development program are that it will yield nearly perfect welds consistently. First production parts from this process are due in 2003. Continuing producibility efforts are underway to further bring down manufacturing cost and build time and to improve quality.

Another technology being implemented into the ET manufacture is the use of digital x-ray. Martin and MSFC started working on this in the late 1970s, but a large mainframe computer was needed to process the results. Since that time sensor technology and computer capability have now made this viable with a considerable savings in manpower for x-raying weld repairs and elimination of environmentally undesirable materials in the processing of film. Since ET has 0.6 miles of welds, just the x-ray film and filing systems are a significant cost. At this time Lockheed Martin has completed the certification of digital x-ray on one tool and progressing towards a second. Plans are in place to completely convert all x-ray positions to digital. This is particularly useful in repairs because the repair technician can see his grind out and repair process as he goes along rather than taking a picture, waiting until it is processed, then grinding some more, taking another picture, and so forth. Also, since the pictures are digital, they can be computer enhanced, enlarged, or focused to provide better visibility.

8.1 *Lessons Learned from SLWT Effort*

1. Thoroughly research and develop changes before they are committed to the program. We jumped into aluminum lithium before we understood it.

2. Researching changes in the laboratory only is insufficient. They must be tried in the production environment before committing them to the program.

3. For long duration programs expect and prepare for vendor changes.

4. Document and obtain title to qualification test procedures and unique equipment. The next vendor will need them.

5. If at all possible, follow Deming's guidelines to select suppliers based on capability rather than cost. Work with your supplier to get his quality up and cost down. Recompeting for price only is inviting disaster.

6. Particularly in the area of non-metallics, qualify back-up suppliers with independent sources of materials because, over time, you are going to lose some of your initial suppliers and key material sources.

7. Design, as much as possible, so that no entry is required at the launch site, but put access panels where they may be needed and where accessible from existing work stands. Hanging people from a crane in a boatswain chair is not a good way to go. The two rollbacks instituted by ET at KSC were caused by woodpeckers and hail damage to the ogive which is inaccessible from the launch stand.

8. Finally, no NASA Project Manager can be successful if he does not have an outstanding contractor. Lockheed Martin deserves 60% of the credit for the ET success, MSFC Labs and S&MA 25%, and the Project 15% (that may be high for the Project Office). However, at the start of a project the Project Office contribution in setting up an efficient management structure and establishing effective management processes can be a most significant contribution.

APPENDIX A

Acronyms and Abbreviations

A/G	anti-geyser
AEDC	Arnold Engineering Development Center
AHF	Aircraft Hydroforming (Company)
Al	Aluminum
ALTA	Aluminum Lithium Test Article
ASRM	Advanced Solid Rocket Motor
ATP	Acceptance Test Procedure
BSTRA	Ball Strut Tie Rod Assemblies
BTU	British thermal unit
B&W	Babcock and Wilcox
BX 250	a foam insulator
CAPS	Corrective Action Process Summary
CDF	Confined detonating fuse
CFC	Chlorofluorocarbon
COTS	Commercial of-the-shelf
CPR	Chemical Products Research
CPR 421	a CPR foam
CPR 488	a CPR foam
Cu	Copper
DDT&E	Design, Development, Test, and Evaluation
DFI	development flight instrumentation
DOE	Department of Energy
DOLILU	Day-of-Launch I-Load Update
ECP	Engineering Change Proposal
ED Lab	MSFC Structures and Dynamics Laboratory
EDM	electro deposition machining
EPA	Environmental Protection Agency
ET	External Tank
EWI	Edison Welding Institute
FMEA/CIL	Failure Modes and Effects Analysis/Critical Item List
FRF	Flight Readiness Firing
FRL	flame retardant latex
ft	feet or foot
FS	factor of safety
g	gravity force
GD	General Dynamics
GFE	Government Furnished Equipment
GFP	Government Furnished Property
GH_2	gaseous hydrogen
GVT	Ground Vibration Test
HCFC	Hydro-Chloro-Fluoro-Carbon
IA190	a wind tunnel series
IA191	a wind tunnel series
Inconel 718	a high nickel alloy
IR	Infrared
IRAD	Independent Research and Development

JSC	Johnson Space Center
k	thousand
KSC	Kennedy Space Center
ksi	thousand pounds per square inch
lb	Pound
lbs	Pounds
LH_2	liquid hydrogen
Li	Lithium
LN_2	liquid nitrogen
LO_2	liquid oxygen
LSC	linear shape charge
LSS	Launch Support Services
LTV	Ling-Temco Vought (Company)
LWT	Lightweight Tank
M&N	MAF work stations
M&N cells	MAF work stations
M&P Lab	MSFC Materials and Processes Laboratory
MA25S	a Martin-developed high temperature ablator
MAF	Michoud Assembly Facility
MGVT	Mated Ground Vibration Test
MIR	Russian Space Station
MPS	Main Propulsion System
MPTA	Main Propulsion Test Article
MRB	Material Review Board
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCFI	North Carolina Foam Industries
NDE	nondestructive evaluation
NPSH	net positive suction head
NSTS	National Space Transportation System
ODP	ozone depletion potential
OMI	Operational Maintenance Instructions
OMRSD	Operations and Maintenance Requirements and Specification Document
P cell	a MAF work station
PAL	protuberance airloads
PDL	Polymer Development Laboratories – a Martin supplier
PEC	Productivity Enhancement Center
POGO	a dynamic condition
PRACA	Problem Reporting and Corrective Action
PRCB	Program Requirements Change Board
psi	pounds per square inch
psig	pounds per square inch gage
QC	quality control
qdot	heating rate
R&D	research and development
RFP	request for proposal
RH	relative humidity
RSS	range safety system
σ	sigma or standard deviation
S&E	Science and Engineering
SEB	Source Evaluation Board
sec	second

SIAP	System Integrity Assurance Plan
SLA561	a foam insulator
SLWT	Super Lightweight Tank
SOFI	Spray On Foam Insulation
sq ft	square feet
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
STA	Structural Test Article
STAGS	Structural Analysis of General Shells
STOODY 2	a very hard alloy
STS	Space Transportation System
T0, T3, etc.	aluminum temper levels
TIG	tungsten inert gas
TMPP	a complex product of combustion
TPS	Thermal Protection System
TWI	The Welding Institute
USAF	United States Air Force
USBI	United Space Boosters, Inc.
VAB	Vertical Assembly Building
VOPS	Variable Output Proportioning System
VPPA	Variable Polarity Plasma Arc