SPACE SHUTTLE MAIN ENGINE
THE FIRST TEN YEARS

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Part 7 – Main Oxidizer Valve Fire, Main Fuel Valve Fracture, Nozzle Feed Line Failures

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Main Oxidizer Valve Fire

Engine 2001, Test 901-225, was scheduled for a 520 second flight mission simulation test on December 27, 1978. The test ended with a major fire when the HPOTP discharge duct ruptured at 255.63 seconds. Abnormal operation was apparent in the data for about 0.120 seconds before the failure, showing an rapid increase in LOX side power which culminated in exceeding the redline value for the HPFTP turbine temperature. The failure progressed too rapidly for the redline to provide protection and the high pressure LOX duct ruptured simultaneously with the engine shutdown command. The resulting fire caused sufficient damage to the engine control system, such that an engine-controlled shutdown was not possible; and propellant flow was ultimately terminated by closing the facility prevalves. The investigating team concluded that a fire had started in the MOV and created a flow blockage downstream of the HPOTP main pump discharge. Since the boost pump supply line is upstream of the MOV, the blockage caused a significant diversion of LOX to the boost pump and subsequently to the two preburners. This, in turn, created a drastic increase in power to both high pressure turbines, which led to the overpressurization of the main oxidizer duct in just over one-tenth of a second [30].

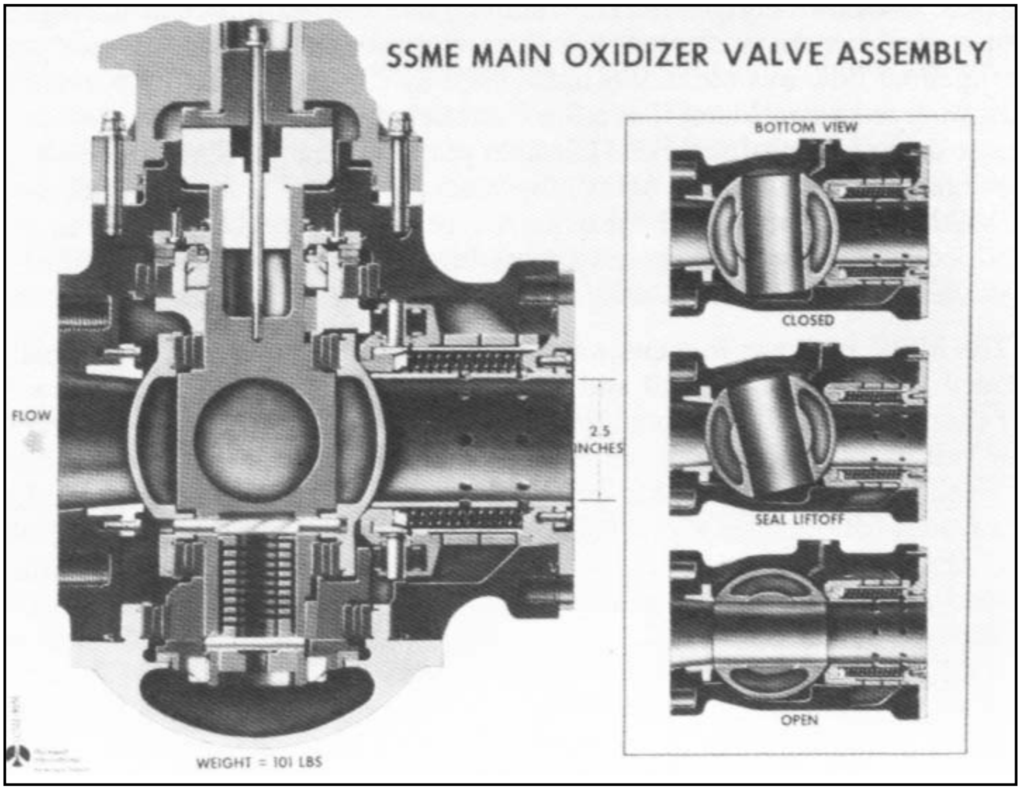

Figure 20. Main Oxidizer Valve (Photo No. LC301-865E)

The MOV is shown in a cutaway representation in Figure 20. It is a ball valve fabricated with an integral ball and shaft. The valve is rotated by a hydraulic actuator (not shown) spline-coupled to the shaft at the top of the valve assembly. The hollow ball is approximately 5 inches in diameter with a 2.5 inch tubular flow passage. At the FPL flow rate of 850 pounds per second, the fluid velocity through the valve exceeds 350 feet per second. The ball seal is a machined plastic ring which is loaded against the inlet side of the ball by a bellows. The shaft has two integrally machined cams which push against a cam follower mechanism which lifts the seal from the ball during the first six degrees of valve rotation. The LOX flow for the MCC ASI is supplied from a port immediately downstream of the seal and begins to flow as soon as, the seal is lifted. To minimize turbulence, a 2.5 inch diameter inlet sleeve is bolted to the valve inlet, isolating the bellows from the flow environment and aligning the flow stream with the ball tubular flow passage in the open position. The sleeve was positioned to a fixed gap between the ball and sleeve by using a stack of 0.002 inch thick stainless steel shims under the bolted inlet flange.

Disassembly of the MOV from the incident test revealed that the bellows had been burned away and the inlet sleeve was 50 percent consumed. (see Figure 21) A dynamic analysis using two-dimensional and three-dimensional models, showed that the inlet sleeve had a fundamental natural frequency of about 1,900 Hz, which corresponded to a high energy vibration generated by the HPOTP (four times pump speed). This was augmented by data obtained from a simulated LOX feed system test facility set up by NASA at MSFC to study flow under controlled laboratory test conditions [31]. It was shown that the energy generated by the HPOTP was enough to excite the sleeve frequency and loosen the preload on the bolts attaching the sleeve to the valve inlet flange. The team concluded that excessive vibration in this loosened condition caused the very thin steel shims to ignite, causing the fire. Disassembly of valves from prior engines confirmed this potential by showing evidence of fretting and broken shims.

Figure 21. MOV Inlet Sleeve After Test 9001-225. (photo No. 307-971)

Several design changes were incorporated, the most important being replacement of the shims with a single ‘machined spacer having a minimum 0.040 inch thickness. To change the natural frequency of the sleeve assembly, the material was changed from 21-6-9 CRES to INCO 718 and the wall thickness was increased by about 75 percent. To minimize the potential for fretting, the sleeve diameter was increased to be an interference fit; the spacer material was changed from 302 CRES to INCO 718; and the attaching screws were countersunk with cup washers to provide positive locking.

These changes were made to the OPOV and the FPOV as well as the MOV. Testing was resumed utilizing the new LOX valves with Engine 0201 on January 30, 1979, after a total downtime of 33 days.

Main Fuel Valve Fracture

In April 1978, at the NASA/NSTL test site, a test series was initiated on a simulated Space Shuttle orbiter aft section, including a cluster of three main engines. This combination of hardware was known as the Main Propulsion Test Article (MPTA) and was used by NASA to conduct full-up system tests of the entire orbiter propulsion system. On July 2, 1979, MPTA Test SF06-01 was scheduled for a 520 second flight mission simulation test. At about 18 seconds, the MFV housing on Engine 2002 developed a major fracture which allowed hydrogen to leak into the enclosed aft compartment. The loss of fuel in the engine caused both turbine temperatures to increase; and the HPFTP turbine temperature exceeded its redline value, which caused engine shutdown to be commanded for all three engines. During this time the pressure in the aft compartment increased as a result of vaporizing the hydrogen. Almost at the same time as the shutdown command, the aft compartment pressure reached 3.2 psi [32], which exceeded the structural capability of the aft compartment heat shield supports. Figure 22 shows how the heat shields around each engine were blown off. Major structural damage was sustained in the aft section of the MPTA. An external fire ensued which caused minor damage, mostly to instrumentation wiring; but there was no fire, damage inside the aft compartment.

The MFV is similar in construction to the MOV (Figure 23). It is the same size as the MOV, but it operates at 50 percent higher pressure, 100 R colder temperature, and three times the fluid velocity. Three major differences between the valves are due to the higher pressure and colder temperature. The forged MFV housing is made from an alloy of titanium instead of INCO 718 in order to withstand the high pressure with a minimum weight valve. Because titanium has a significant gain in strength at very low temperature, the MFV was turned around with the bellows-loaded seal at the valve outlet rather than the valve inlet. This orientation allows the valve to be thoroughly chilled before engine start, thereby assuring maximum strength prior to being subjected to the operating pressure. The third difference is insulation The LH2 temperature is below 40 R, which is well below the boiling point of liquid nitrogen. To preclude the formation of liquid nitrogen on the valve surface, the housing is covered with an insulator.

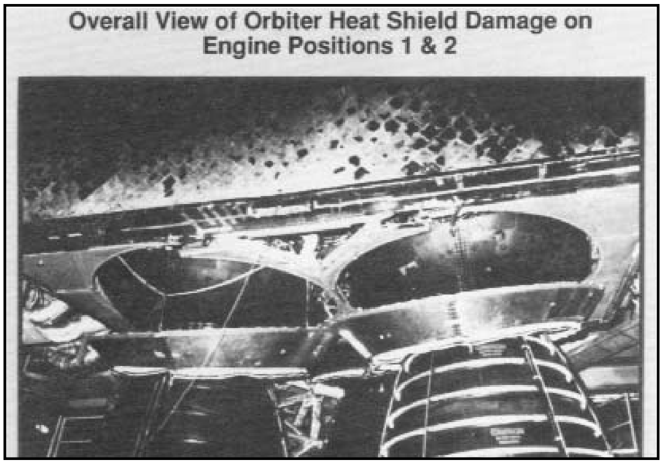

Figure 22. MPTA Heat Shield Failure (Phtot No. SC89C-4-1010)

Because the incident involved a fracture in the titanium housing, the investigating team was expanded to include fracture specialists and experts in the characteristics of titanium. Nine consultants were employed from nine different research centers around the country [33]. The investigators conducted a thorough visual inspection of the fracture surface using magnifying glass, light microscope and scanning electron microscope (SEM). Most of the fracture surface exhibited the characteristics of a simple ductile-type failure due to overload. The SEM analysis clearly indicated the fracture origin to be at the location of a cutout in the housing designed for the ball seal retraction cam follower (see Figure 23). There was no evidence of material or forging defects, and the microstructure was normal for this titanium alloy. The material composition was verified to be correct by chemical analysis. Proper mechanical properties were verified by testing forging samples which were made as extensions on the housing in the original forging and then using sample bars machined from the fractured housing. Although SEM analysis identified areas in the originating fracture surface that indicated propagation by fatigue, other features identified by the SEM were indistinguishable from stress corrosion, hydrogen embrittlement, or low amplitude fatigue. Fractography was unable to identify the exact failure mechanism [33].

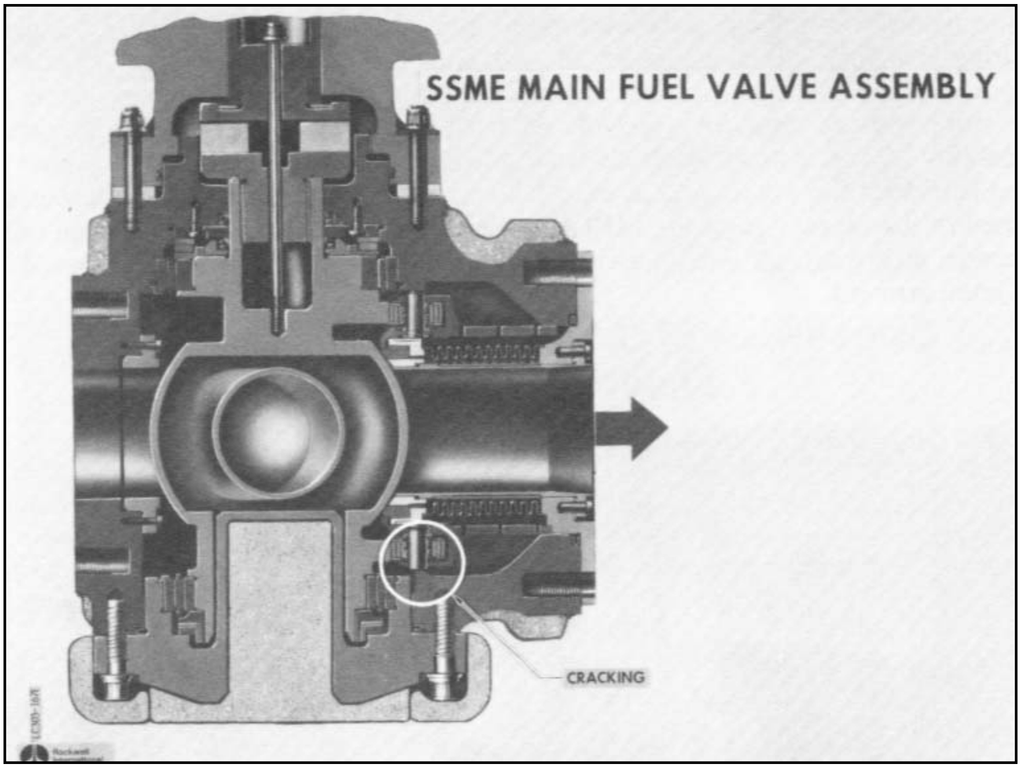

Figure 23 Main Fuel Valve (Photo No. LC303-167E)

Fifteen hypothetical failure modes were investigated in detail. Extensive testing and analysis at Rocketdyne, MSFC and the various research centers managed to disprove 11 of them; however, the available evidence was insufficient to narrow the failure cause down further than the remaining four hypothetical failure modes. Therefore, positive action was taken to eliminate all of them for future valves. Aside from process changes, the cam follower cutout area was reworked on all existing housings to provide generous radii for up to 30 percent reduction in stress concentration. In addition, for long-term recurrence control, the valve housing was redesigned to reduce the peak strains to 80 percent of yield.

Engine start transient testing was resumed on July 6, 1979 with Engine 0007; and mainstage testing beginning on July 12, 1979, ten days after the incident, with Engine 2007.

Nozzle Feed Line Failures

Engine 0201 Test 750-041 was scheduled for a 100 second test on May 14, 1979, at the Rocketdyne Santa Susana Field Laboratory (SSFL). The test was terminated at 4.27 seconds by the redline monitor for the HPFTP turbine gas temperature for a reason not associated with the major incident which followed. During the shutdown transient, when the MCC combustion chamber pressure dropped a little over 50 percent, a nozzle fuel coolant feed line ruptured close to the nozzle exit in a section of 1.625 inch diameter tubing known as the “steerhorn”, which it resembles [34]. The massive fuel leak caused the engine to operate LOX rich, which caused significant hardware burning in both preburners, both high pressure turbines, the main injector, MCC and the nozzle. The external hydrogen fire caused damage to the engine control system and the facility instrumentation.

The nozzle is a regeneratively cooled extension bolted to the MCC which completes the combustion gas expansion from a 5 to 1 expansion ratio to a 77.5 to 1 expansion ratio. It has the contour of an optimized 80.6 percent bell nozzle (80.6 percent of equivalent 15 degree cone length) to minimize overall engine length. Figure 24 shows a cutaway representation of the nozzle with the configuration that was used through the first five flights. The nozzle is ten feet long, almost eight feet wide at the exit and weighs about 1,000 pounds. The tubular construction consists of 1,080 stainless steel (A286) tubes brazed together and to a surrounding structural jacket with coolant manifolds welded to each end of the tube assembly. The MFV is mounted on the nozzle inlet manifold which receives all of the MFV fuel flow.

Immediately, 20 percent of the LH2 is re-routed to the MCC coolant circuit. One half of the remaining LH2 is routed through the CCV (see Figure 3) to the two preburners. The remaining 40 percent of the fuel is distributed equally among three fuel transfer ducts (downcomers) for delivery to the nozzle aft manifold. Less than a foot from the end of the nozzle, the downcomers terminate in a tee fitting, which splits the flow into two tubes, each perpendicular to the downcomer. Each tube is then routed though ninety degree turns to enter the aft manifold at one of six equally spaced inlets around the circumference, creating three inverted

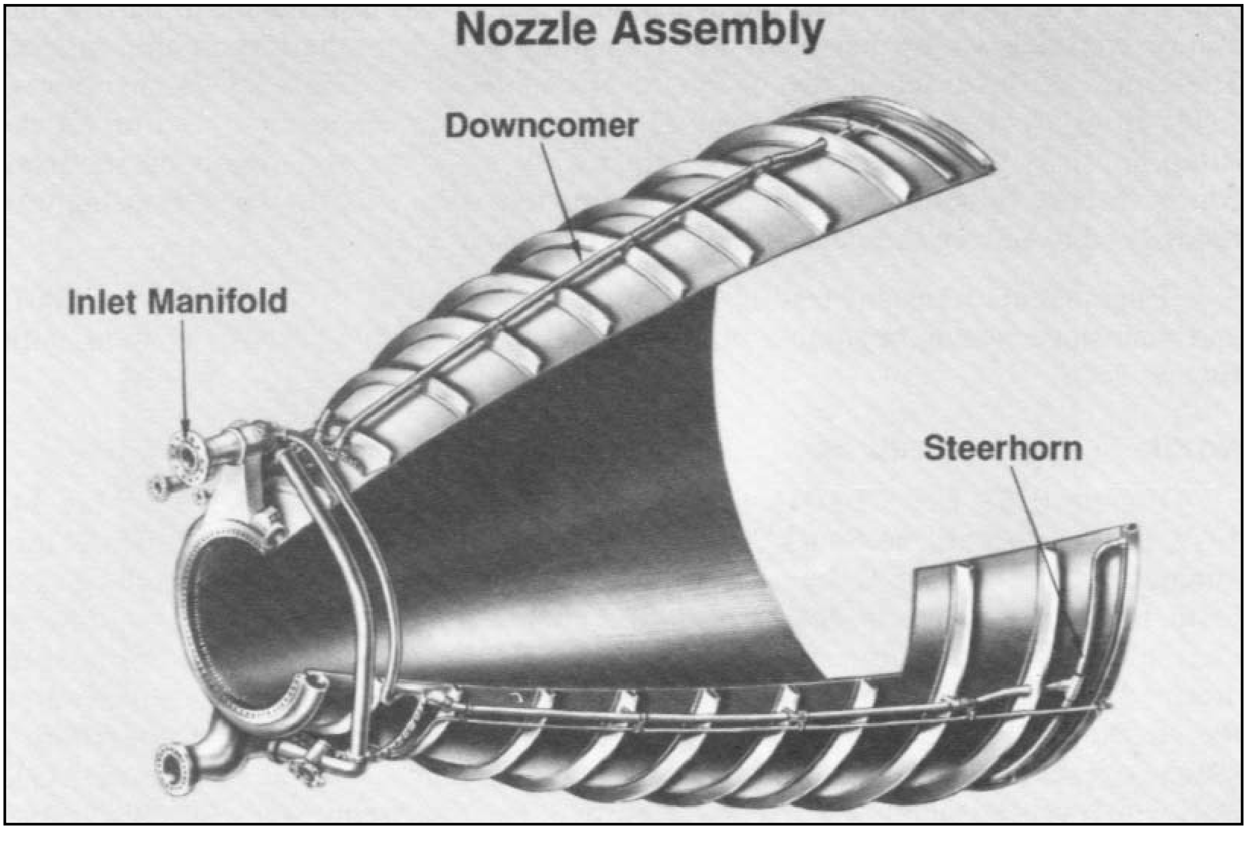

Figure 24 SSME Flight Nozzle (Photo No. SC89c-4-1012)

"steerhorns". The LH2 flows from the aft manifold into each of the 1,080 tubes and provides nozzle wall cooling while flowing forward to the outlet manifold. After exiting the outlet manifold, the fuel is mixed with the outlet flow of the CCV prior to combustion in the preburners.

The failure occurred in the number one steerhorn, which is directly beneath the MFV. The entire right-hand section of tubing had broken off from the nozzle, between the welds at the tee fitting and the aft manifold. Most of the tube was recovered as a single piece; however, extensive fragmentation had taken place at both ends, and some of the fragments were not found. Metallurgical analysis of the recovered pieces disclosed that most of the fracture surfaces were indicative of simple ductile failure due to overload. It was concluded that the fracture at the end of the tube started at a low cycle fatigue crack 0.003 inch deep by 0.75 inch long located in the heat affected zone adjacent to the tee weld. Fracture initiation the manifold end was uncertain because not all of the fragments were recovered although no fatigue indications were evident in the fragments that were found. No material deficiencies or fabrication defects were found in any of the recovered pieces.

The nozzle had previously been subjected to 45 tests on other test facilities; however, this was the first test on the SSFL A-3 test stand with a full size flight nozzle. All the prior tests on A-3 had been conducted with a stub nozzle like the one used on the ISTB. Because of the concern that some test facility interaction contributed to the failure, two investigating teams were formed [35]. One team concentrated on facility effects while the other investigated the nozzle structural capability and engine dynamics for potential causes of the fatigue failure. The facility was eventually cleared.

The nozzle structural analysis with the predicted thermal, pressure, and dynamic environments indicated a safety factor at ultimate of greater than two for the transient loads and predicted that no fatigue damage would be incurred from the start, operation and shutdown cycle (infinite life). The failure occurred during shutdown at a chamber pressure that corresponds to the maximum nozzle deflections due to internal asymmetric jet separation, the phenomenon known as side loads. A two-inch nozzle diametric ovalation was observed in the Test 750-041 motion picture coverage, but this was no more than that which was expected and which the design allowed. A laboratory test was performed to measure the actual strains with this amount of displacement, and it verified low stresses (45,000 psi or less versus the material capability of over 180,000 psi). With the material properties and the structural analysis clearly in conflict with the failed hardware, it had to be concluded that the predicted design loads were in error because the operating environment was not properly defined. To define this environment the engine test program was resumed eight days after the incident on Engine 2004, with special instrumentation on the nozzle to measure steerhorn strains and vibration.

Over the next six months, strain gage and accelerometer data were gathered from 41 tests on nine engines. From these data it was discovered that at the sideload conditions corresponding to the failure, high amplitude strains existed at the tee in the 200 to 400 Hz regime. This was determined to be a shock pulse with a few cycles of high amplitude strain, significantly higher than predicted levels, that could explain a low cycle fatigue failure [36]. Although there was considerable variation in the peak strain from test to test, the maximum recorded peak-to-peak strain was almost 20,000 microinches per inch. This was not high enough to cause failure in a single test, but it was high enough to sustain fatigue damage that would lead to a failure in a predictable number of tests. A fatigue damage model was developed from the strain gage data that predicted a fatigue life of 48 tests for the nozzle that had failed in 46 tests.

The failed steerhorn had a 0.049 inch wall thickness. A previous producibility design change had increased this dimension to 0.080 inch, and nozzles with the thicker wall had already started engine test and were committed for the flight configuration. The fatigue damage model predicted a life of 80 tests for the thick-wall steerhorn. It was judged acceptable to continue testing both the thin-wall and the thick-wall steerhorn configurations by establishing a life limit at which they would be removed from service. The life limits were set based on the fatigue damage model, using a factor of two for single engine tests and a factor of four for flight and MPTA tests. A redesign of the nozzle feed lines was undertaken which reduced the peak stresses in the steerhorn by at least 40 percent. The major contributor to the stress reduction was the inclusion of a. "steam loop" in the downcomers, to absorb longitudinal thermal contraction. Because of the required lead time for this type of change, the steam loop nozzle was not incorporated into the flight program until the sixth shuttle flight.

MPTA Test SF6-003 was scheduled for 510 second duration on November 4, 1979. The test was prematurely terminated at 9.7 seconds when an HPOTP seal redline was exceeded on the number three engine (0006), and all three engines were shutdown. During the shutdown, the number one engine (2002) experienced a steerhorn failure which caused major internal engine damage and significant damage to the MPTA instrumentation systems. The previous investigating team was reconvened with a situation that seemed to contradict their previous findings. The nozzle on Engine 2002 had thin-wall steerhorns with a calculated life of 48 tests, yet it failed on the eighth test. In addition, the nozzle was instrumented with strain gages and the data showed that the maximum recorded strain magnitude -was not enough to cause failure [37].

Metallurgical examination of the fracture surfaces showed a dimpled texture typical of a tensile overload, with no indications of fatigue striations. A microhardness survey of the fracture surface revealed that the welds at the tee were much softer than they should have been. Further examination, using an electron microprobe X-ray analyzer, indicated that the material was probably Inconel 62 rather than Inconel 718, as required. This finding was very significant because Inconel 62 has only one-half the strength of Inconel 718. An inspection method was developed using an electrolytic oxalic acid etch that would allow instant recognition of this material in other welds. Etching all the welds on the failed nozzle disclosed that eight of them were soft welds. Extending this inspection to all other nozzles showed that most of them had some soft welds. A survey of weld filler wire at Rocketdyne found two lots of wire with the wrong material, and they were both from the same vendor [38]. A review of 16,360 welds on 349 different parts revealed that 3,359 welds had been made using the filler wire from the suspect lots. Each of these were analyzed for possible corrective action. All weld wire (7,000 pounds) was, removed from service and reverified prior to use. Stringent controls were put into place at Rocketdyne and then extended to 31 vendors.

Two actions were taken with the flight nozzles as a result of the soft weld wire incident. First, the remaining nozzles with thin-wall steerhorns were removed from service. Secondly, all nozzles with soft welds at the steerhorn tee were reinforced by electrodeposited nickel plating over the welds. This increased the strength of the weld by a factor of three.