The Space Shuttle *Challenger* Explosion in 1986

Main reference documents: Report on the Presidential Commission on the Space Shuttle Challenger Accident 1986, Feynman 1988, Vaughan 1996, Jensen 1996, Dunar & Waring 1999, Chiles 2002, Feldman 2004, Chernov & Sornette 2016, www.nasa.gov,Wikipedia.

1. Background

NASA Space Transportation System, first envisioned in 1968-1969 - before the Project Apollo landed on the moon - was supposed to provide the Unites States an easy and convenient access to space. The original purpose of the system was twofold: to reduce the cost of spaceflight by replacing the current method of launching "capsules" on expendable rockets with reusable spacecraft; and to support ambitious follow-on programs including permanent orbiting space stations around the Earth and Moon, and a human landing mission to Mars. The Shuttle was to be able to ferry cargo as well as passengers.

The Space Transportation System was marketed as a routine bus-like transportation to space with one flight every week. The selling argument for the program at NASA was “safe, cost-effective and routine access to space”.

NASA had settled on the basic layout of the Space Shuttle in 1972. It would consist of two solid rocket boosters and three main engines burning hydrogen and oxygen for the eight minute flight to orbit. The fuel and the oxidizer for the main engines were to be stored in an external fuel tank attached to the orbiter. The orbiter would be the manned and winged shuttlecraft that would return to earth (see Figure 1 for the layout of the Shuttle).

Solid rocket boosters (SRBs) operate in parallel with the main engines to provide the additional thrust needed for the Orbiter to escape the gravitational pull of the Earth. Boosters use solid fuel, thus the name Solid Rocket Boosters. Because the fuel is solid, after ignition it is impossible to control them or shut them off before they have burned out. Solid rocket boosters typically burn for about two minutes, raising the shuttle up to 60 kilometres. After this the booster rockets are separated from the shuttle by small explosive charges. The booster will then splash into the ocean with parachutes for recovery and reuse. The external tank was designed to fall off later, on the way to the orbit, burning and disintegrating on the way down.

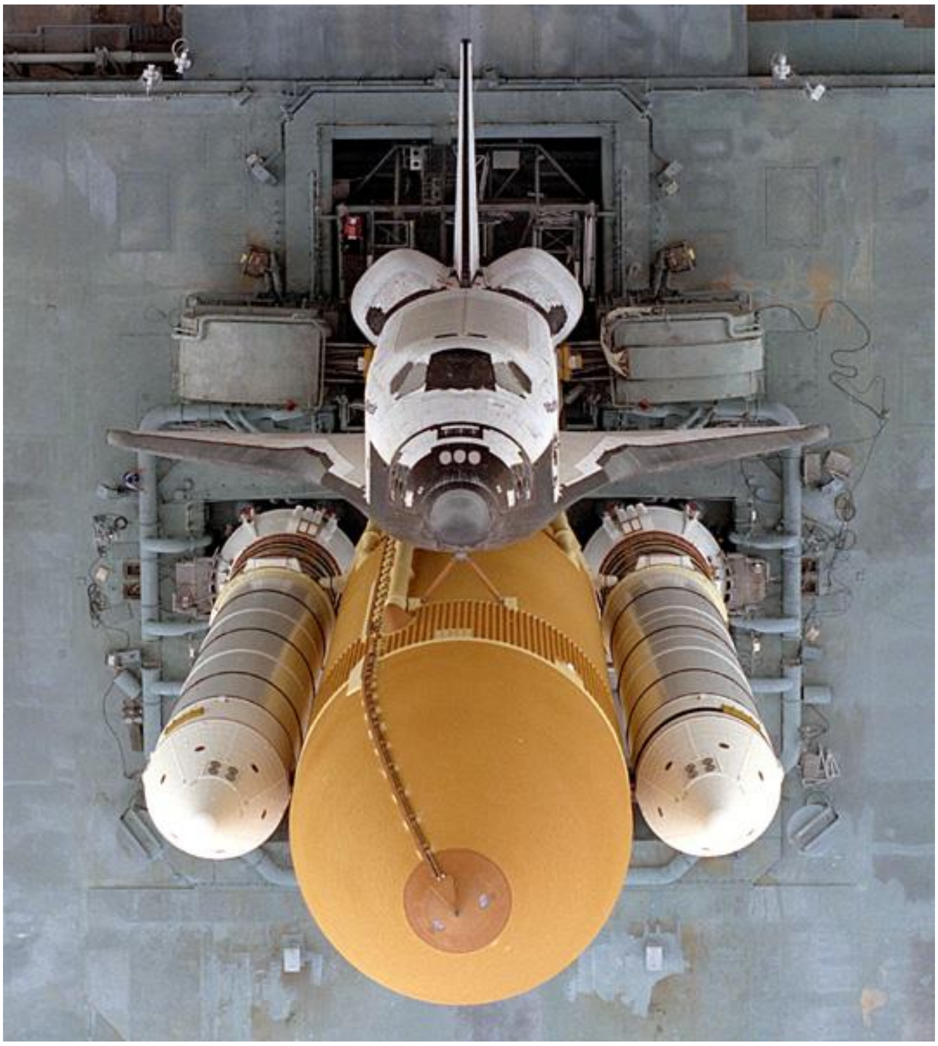


Figure 1. Space Shuttle Atlantis, sister shuttle of Challenger, with its solid rocket boosters (SRB) and external fuel tank, resting on the launch pad (www.nasa.gov).

The Space Shuttle was to be the first manned flight in the United States to use solid rockets. NASA scaled up the Titan 3 heavy-lift satellite launcher's solid rocket motors and added an extra O-ring to each field joint to increase the margin of safety. The solid rocket motor of the Space Shuttle is the largest solid propellant motor ever developed for space flight. The huge motor is composed of a segmented motor case loaded with solid propellants, an ignition system, a movable nozzle and the necessary instrumentation and integration hardware. Each SRB held 450-550 tons of propellant, basically inserted into a long steel tube, sealed on one end with a nozzle on the other. The SRBs were manufactured in Utah by Morton Thiokol, the main supplier of Titan rocket family to the U.S. Air Force.

Because a fully assembled booster was too big to move across land in a single piece, each rocket motor travelled to Kennedy Space Center in Florida by railroad, broken into four main cylindrical segments. Workers at Kennedy stacked the segments together vertically and topped the stack with a nose cone, making up a full-length booster. These connections between segments were called field joints, since these temporary "field joints" are sealed before each flight "in the field" (outside the manufacturing plant, that is) at the Kennedy Space Center.

Each of the pair of solid-fuel boosters was made from four separate segments that bolted end-to-end-to-end together. Although the obvious solution of making the boosters of one long segment (instead of four short ones) was later suggested, long solid fuel boosters have problems with safe propellant loading, with transport, and with stacking for launch — and multi-segment solids had had a good track record with the Titan-3 military satellite program. See Figure 2 for an assembly of the SRBs.

Figure 2. In a Vehicle Assembly Building high bay, an aft center segment of a Solid Rocket Booster is lowered toward a segment already in place. Credit: NASA

During the design, construction and testing of the new space shuttle, majority of attention was devoted to two large problems. The first problem concerned the orbiter and its thirty-one thousand reusable, protective tiles that it needed on its belly and wing edges to survive the heat of re-entry into the earth atmosphere. The other problematic area was the space shuttle main engine (SSME). A shuttle needed three SSMEs, each of which was supposed to pack more power in less space than any rocket motor had ever before been able to. And the engine system needed to be reusable, since the orbiter was designed to land after mission. Engine tests were started in 1975, and lasted for four years before a reliable engine functioning was obtained in late 1979, delaying the maiden flight of the Space Shuttle by two years.

Space Shuttle *Challenger* (NASA Orbiter Vehicle Designation: OV-099) was the second in its class. Its sister shuttle, Columbia, the first shuttle to commence operations, made its maiden flight in April 1981, after the problems with SSME and the protective tiles had been solved in late 1979. Challenger's maiden flight was on April 4, 1983, and it completed nine missions before its fatal last mission, STS-51-L on January 28, 1986. The mission, 51-L, tenth for Challenger, was the 25th launch of the STS into space.

2. Description of the event

Challenger exploded 73 seconds after launch. All of its seven crew members were killed. The cause of the accident was found to be a leak in the O-ring, which failed at least partly due to excessively cold temperature. The accident led to a two-and-a-half year grounding of the shuttle fleet, with missions resuming in 1988 with the launch of Space Shuttle Discovery on mission STS-26. Challenger itself was replaced by the Space Shuttle Endeavour, which first launched in 1992.

The commission that was set up to investigate the disaster established the technical cause behind the loss of Challenger: A combustion gas leak through the right Solid Rocket Motor aft field joint initiated at or shortly after ignition eventually weakened and/or penetrated the External Tank, initiating vehicle structural breakup and loss of the Space Shuttle Challenger during STS Mission 51-L (Report, 1986).

The gas leak was caused by failure in the O-rings of the booster (see Figure 3). The shuttle had several O-rings, made of a rubber compound, which were used to seal the Solid Rocket Booster field joints. The Solid Rocket Boosters are made in sections. There are two types of joints to hold the sections together: the permanent “factory joints” are sealed at the Morton Thiokol factory in Utah; the temporary “field joints” are sealed before each flight - at the Kennedy Space Center in Florida (Feynman, 1988). The O-rings measured 146 inches in diameter and were just 0.280 inch thick. Each one was moulded in one piece to span the entire circumference of the booster. Each solid rocket booster had three field joints, and the shuttle had two solid rocket boosters.

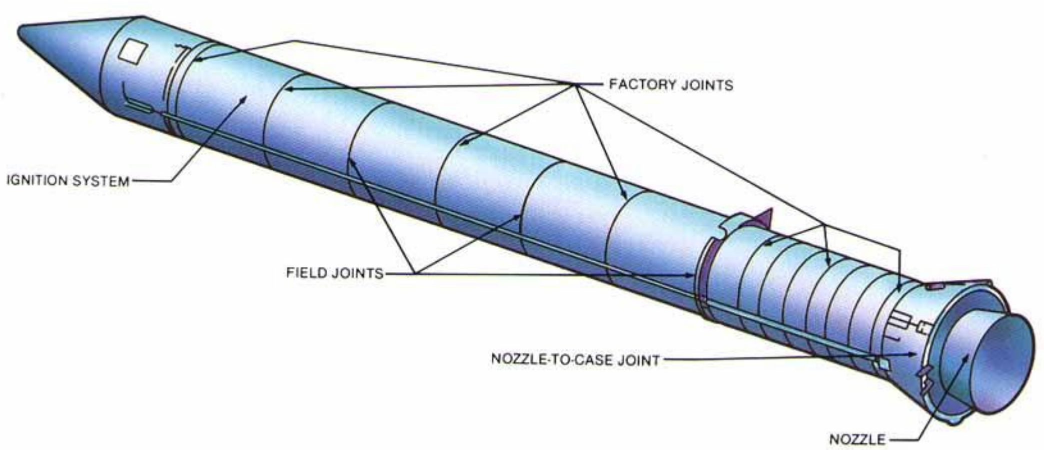


Figure 3. Solid Rocket Booster. NASA used to tell the press that the enormous power turned out by the booster matched the combined power of all the engines on seventeen 747 airliners at full thrust.

The official report describes the beginning of the chain of events in the following way: “Just after liftoff at .678 seconds into the flight, photographic data shows a strong puff of gray smoke was spurting from the vicinity of the aft field joint on the right Solid Rocket

Booster ... increasingly blacker smoke was recorded between .836 and 2.500 seconds ... The black colour and dense composition of the smoke puffs suggest that the grease, joint insulation and rubber O-rings in the joint seal were being burned and eroded by the hot propellant gases." At 64 seconds into the flight, flames from the right Solid Rocket Booster ruptured the fuel tank and resulted in an explosion 73 seconds after launch (Report on the Presidential Commission on the Space Shuttle Challenger Accident 1986, www.nasa.gov).

The weather on launch day was exceptionally cold (36 F, ≈ 2°C), 15 degrees F lower than that measured for the next coldest previous launch. Ice had formed on the pad during the night. The durability of the O-rings had not been tested at such temperatures and some worries about the effect of temperature to the ability of the O-rings to seal effectively were expressed. Thus, before the launch a teleconference was held between NASA and Morton Thiokol, where the dangers of launching at cold temperature were discussed. After the teleconference a decision to launch was made.

3. Causes and contributing factors

3.1 Design of the O-rings and experience feedback on their use

Post-accident investigations found that the resiliency of the O-rings was directly related to the temperature. The colder the ring, the slower it returns to its original shape after compression. Further, O-rings had caused problems for a longer period of time in the space shuttle program. The first erosion damage (0.053 inch, about one-fifth of the O-ring diameter) was detected in the field joint of the solid rocket boosters used on Columbia's second flight in 1981. However, no clear reason for the erosion could be determined. The worst possible erosion (0.090) was calculated at this point and tests were carried out to determine how much erosion the primary O-ring could tolerate. Tests put this value at 0.095. The *safety margin* was set at 0.090.

Feldman (2004, p. 700) emphasises that the engineers were not sure why the erosion had been 0.053 the first time. They only stated this to be the case based on measurements. The safety margin was a kind of compromise achieved in the crossfire of different demands and groups: engineers, managers, high-level NASA officials, political decision makers and 'stubborn technology', which had already been developed and could not be significantly modified within the given time limit (Feldman, 2004, p. 700). NASA seems to have introduced the safety margin concept so that the demands of different parties could be discussed using shared terminology. This (seemingly) did away with the conflicts in the demands since the parties could now use a neutral (objective) quantitative concept.

In 1983, heat was found to reach the primary O-rings in both nozzle joints. Since no erosion was detected, the engineers decided that the problem was *within the experience base* - that is, it was not a new threat to safety. By this time, 14 flights (by either Challenger or Columbia) had been made, 3 of which had exhibited problems with O-rings. Neither the safety margin nor the experience base could explain the problem or shuttle operations. In other words, the concepts were of no use for predicting operations. The parties also did not use experience accumulated from other shuttle programmes or aeroplane design. The safety margin and experience base offered NASA measurable concepts for use in quantifying moral judgement (Feldman 2004, p. 701).

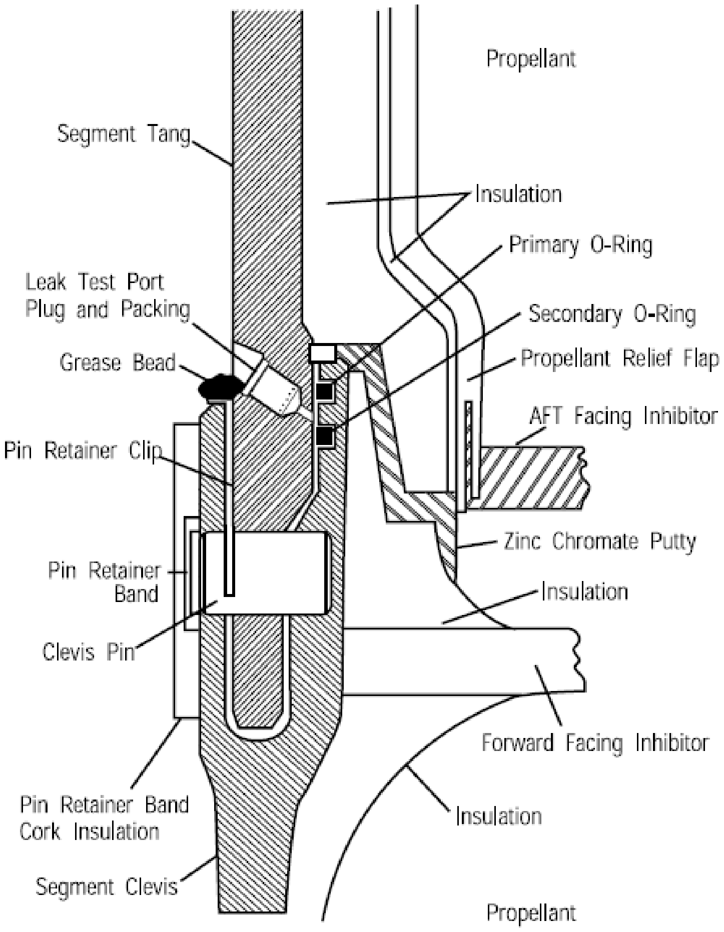


Figure 4. Cross section of SRM field joint (Dunar & Waring 1999, p. 342)

New issues related to the O-rings were detected in the following years. In 1984 the primary seal was endangered for the first time when soot was blown by the primary O-ring to the nozzle joint. Erosion was also detected in two primary O-rings. In the 1985 mission 51-C, lubricating oils burned in both the primary and secondary O-rings. This was the first time heat reached a secondary O-ring. However, based on their experiments, NASA researchers determined erosion to be a self-limiting phenomenon, which would thus not endanger shuttle safety. The new incidents did nothing but strengthen this ‘belief’. In addition, both incidents and the erosion in the primary and secondary O-rings came under the experience base and the safety margin. The engineers at Morton Thiokol said: "the condition is not desirable but it is acceptable" (Vaughan, 1996, p. 156). According to Feldman, it was still unknown when and where the erosion took place, although previous investigations had already shown that gas eroded the O-ring through putty. In Feldman’s view, interpreting the phenomenon as a self-limiting one was not plausible in view of the new evidence. Damage to the secondary O-ring should have raised doubts as to the redundancy of the rings. This, however, was not the case (Feldman, 2004, p. 706).

The hypothesis that erosion was caused by cold weather was presented for the first time during the 1985 mission 51-C flight. On that flight, the temperature on launch day had been 51 °F (10.6 °C), the coldest to date for a launch of the space shuttle. However, since there was no quantitative support for this hypothesis it received hardly any attention in NASA's internal investigations - despite it being a 'known fact' that the rubber used for the O-rings hardens in cold weather, so reducing the effectiveness of the seal. According to the official accident report (Report 1986), four out of 21 flights had shown damage to the O-ring when the temperature on launch day had been 61 °F or higher. However, all flights in lower temperatures showed heat damage to one or more O-rings (Report 1986). Further, since Mission 51–C had experienced very rare weather, the "worst case temperature change in Florida history", cold weather was dismissed as a general cause for concern.

Roger Boisjoly, an aerodynamicist at Morton Thiokol, wrote a memo warning about the faulty design of the O-rings and send in to his superiors in July 1985, after mission 51-C. The memo had no immediate effect, but eventually a Seal Task Force was assembled in August 1985 with Boisjoly in charge. However, the task force did not have any authority to make major decisions concerning the design of the SRBs. By the end of August the task force had proposed 63 possible joint modifications, including 43 for the field joints. New steel case segments that incorporated some of the modifications were actually ordered by NASA, but these were not yet in use at the time of the accident. Further, the decision to change the field joints did not have an effect on the launch schedule of the shuttles using the old joints.

During flight 51-B in the spring of 1985, the primary nozzle joint O-ring burned and the secondary O-ring was seriously damaged. The primary O-ring had not sealed as expected. Erosion was also detected on the secondary O-ring for the first time. The primary erosion was 0.171, clearly exceeding the safety margin (0.090). According to Vaughan (1996), erosion and O-ring redundancy became related technical issues after this flight. The investigations into the 51-B incident determined that the primary O-ring could only have eroded this badly if the incident had taken place within the first milliseconds of ignition. This, in turn, was only possible if the primary seal had been in the wrong position from the start. According to the NASA investigators, had the joint itself leaked, all of the six joints should have leaked identically. The investigators attributed the problem to inspections overlooking the incorrectly installed seal, and to a change in the quality of putty due to a change in manufacturer. A faulty leak check procedure had thus masked a faulty primary O-ring. With a working procedure, the incorrectly installed O-ring would have been noticed and corrected before lift-off. Conclusion was that with a change in the putty used in the O-rings, a leak check pressure of 100 psi was too low. Based on the report, the pressure used for seal checks was increased to 200 psi. Furthermore, a launch constraint was placed on the solid rocket boosters.

According to NASA requirements, a formal constraint prevented flight until a technological problem was fixed or verified safe. Flights continued, however, because SRB project manager at NASA filed formal waivers lifting the constraint for each of the six flights preceding the fatal flight of 51–L. NASA required review and approval of each waiver by organizations responsible for project management, engineering, and quality. After the Challenger accident, however, several NASA and Thiokol officials claimed ignorance of the formal constraints and waivers.

3.2 Safety, Reliability and Quality Assurance

As part of the safety, reliability and quality assurance effort, components of the Shuttle system are assigned to criticality categories as follows:

Criticality 1	Loss of life or vehicle if the component fails.
Criticality 2	Loss of mission if the component fails.
Criticality 3	All others.
Criticality 1R	Redundant components, the failure of both could cause loss of life or vehicle.
Criticality 2R	Redundant components, the failure of both could cause loss of mission.

The assignment of criticality follows a highly detailed analysis of each Space Shuttle component to determine the effect of various ways the component could fail. This analysis always assumes the most adverse conditions with the most conservative assumptions. Any component that does not meet the fail-safe design requirement is designated a Criticality 1 item and must receive a waiver for use. A Critical Items List (CIL) is produced that contains information about all Criticality 1 components. This list contained the data and actions taken for each item to preclude their failure. The CIL included more than 700 shuttle items before the accident.

During the official accident investigation witnesses repeatedly referred to redundancy in the Solid Rocket Motor joint and argued over the criticality of the joint. While the field joint has been categorized as a Criticality 1 item since 1982, most of the problem reporting paperwork generated by Thiokol and Marshall listed it as Criticality 1 R, perhaps leading some managers to believe-wrongly-that redundancy existed. The Problem Assessment System operated by Rockwell contractors at Marshall, which routinely updates the problem status (for FRRs, see below) still listed the field joint as Criticality 1R on March 7, 1986, more than five weeks after the accident. In fact, during the time of the accident, the Solid Rocket Boosters nozzle joints were classified as Criticality 1Rs, but the field joints were classified into Criticality 1 category.

Also NASA’s flight readiness review (FRR) practices, where the CILs are reviewed, seemed to have contributed to the accident. FRR is the final, formal review in the launch preparation taking place about two weeks before launch. The goal is to determine that the shuttle is ready to fly and to fly safely (Vaughan 1996, p. 82).

There were four levels of reviews (IV-I), with the fourth and third level being the ones conducted by the contractors in charge of the solid rocket boosters, as well as the programs for the main engine and the external fuel tank. After the third and fourth level reviews, the items that were raised in the Marshall Space centre reviews (levels II and I) were considerably compressed. According to Vaughan (1996, p. 94), one of the main official criteria for inclusion of items in the level II review was a so-called Delta review concept. It was informally called “management by exception”, and it meant that the Project Managers were required to report at the level II and I reviews “any change, or deviation, from what was previously understood or done”. Thus the formal procedure implied that, in terms of flight readiness and safety, only those issues that indicated a change were important. Known and recurring “problems” or deviations were not problems in terms of safety. This social process affected information flow up the hierarchy in a critical way. Vaughan (1996, p. 247) argues that, in addition to its technical functions, the FRR process also had “ritualistic, ceremonial properties with latent consequences that also reduced ambiguity, affecting the perceptions of risk held by work group members”. According to her, “negotiating in FRR, creating the documents, making the engineering analysis and conclusions public, and having them accepted in an adversarial review system contributed to the persistence of the cultural construction of risk” (Vaughan, 1996, p. 247). The public and open nature of the review process generated commitment to its outcomes and legitimated the results in the minds of both engineers and managers.

Also the NASA internal investigation agreed that the Level I flight readiness reviews adopted a built-in bias that limited the flow of information. Since the Shuttle had proven flight worthy and was designated “operational,” and the experts in lower levels had already certified flight readiness, the Level I review became increasingly ritualistic. Reviews were often short and key officials failed to attend. This was also the case in the flight readiness review preceding the Challenger’s last flight. Two weeks earlier, in the Flight Readiness Review, Thiokol had certified in writing that the SRBs were flight-ready.

3.3 Testing the O-rings and making judgements on their safety

The joints had to be checked for leaks before liftoff since the integrity of the joints was a crucial design factor (Jensen, 1996, p. 277). As the problems with the joints began to crop up, the pressure used in the tests was increased from 50 psi to 100 psi and, finally, to 200 psi. There were some concerns about the effect of the prelaunch pressure test on the seals. If the pressure from the test broke through the primary ring, it would blow tiny pinholes in the putty, which could then be used by flames [coming from the inside of the rocket] moving in the opposite direction (Jensen, 1996, p. 277). Thus, the joint design created a conundrum; the engineers wanted high-pressure tests to verify O-ring assembly, but verification of the O-rings could create dangerous gaps in the putty, which could jeopardize the O-rings (see Figure 4). Further challenge was created by a change in the manufacturer and subsequently the quality of the putty that was used. The change was due to the old manufacturer discontinuing the product. The new putty, taken into use in 1983, proved more difficult to pack in the joint during assembly and less able to provide thermal protection during launch. However, the new putty could also withstand low pressure leak checks done previously, requiring the raising of pressure.

Feldman (2004, p. 711) points out that after the events of spring 1985, the significance of the safety margin had gradually (and probably without any explicit decision) changed to mean the durability of the secondary O-ring. Similarly, the experience base referred to events prior to spring 1985 and did not include the primary ring burn-through experienced in the previous flight (because it could be explained by an error made during the installation of the seal and not by the technical features of the seal). The finding was that an increase in the check pressure would cause erosion in the primary O-ring but should eliminate all erosion in the secondary O-ring. This convinced all parties that both redundancy and safety margins were in order.

It is evident that the problems concerning the Solid Rocket Boosters were known from the beginning. Some safety engineers had proposed redesigning the entire SRB hardware well before the accident took place. Instead, a decision was made to test and correct the old design. The decision was influenced by cost and schedule considerations. Vaughan (1996, p. 116) writes: “Engineering decisions are biased toward making existing hardware and designs work, as opposed to scrapping it and coming up with a better design. But safety concerns also contributed to this bias. In the engineering profession, changes are often considered as negative things, something to be avoided. In the short run, a new design brings new uncertainties, not greater predictability. Because designs never work exactly as the drawings predict, the learning process must start all over again. A change introduced in one part of a system may have unpredicted ramifications for other parts. In the interest of safety, the tendency is to choose the evils known rather than the evils unknown.”

3.4 The teleconference

The weather on Challenger’s final launch day was exceptionally cold. Citing cold weather, the engineers recommended that the launch be postponed to the next day. Engineers at Morton Thiokol, the subcontracting manufacturer of the Solid Rocket Booster and the O-rings, also had their doubts about the cold tolerance of the rings. They expressed their doubts in a teleconference held the evening before launch.

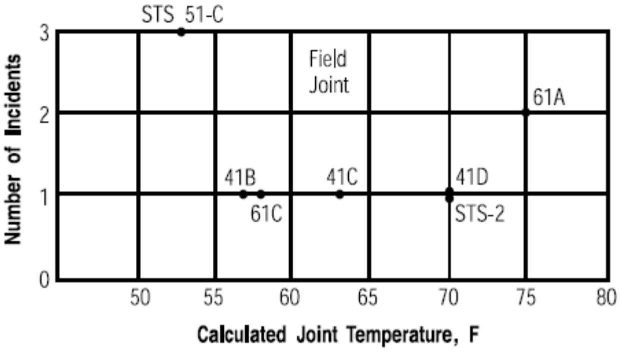
The teleconference connected Wasatch, Utah, (Morton Thiokol) and Huntsville, Alabama, (NASA officials, e.g. George Hardy, the deputy director for Science and Engineering) with the launch site at Cape Kennedy, Florida, (e.g. NASA SRB project manager Mulloy, Stanley Reinartz, the NASA Shuttle Projects manager, and Allan McDonald, Thiokol’s SRM project director). At the beginning of the conference, the engineers from Morton Thiokol presented their view that launching in cold weather proposed a risk for the field joints.

Marshall’s officials immediately questioned Thiokol’s proposal. George Hardy said later that he was “appalled” by the contractor’s reasoning. Stanley Reinartz observed that the recommendation violated the Shuttle requirement that the motor operate between 40 and 90 degrees. Mulloy noted that NASA had no launch commit criteria for the joint’s temperature and that the eve of a launch was a bad time to invent a new one. He asked, “My God, Thiokol, when do you want me to launch, next April?”

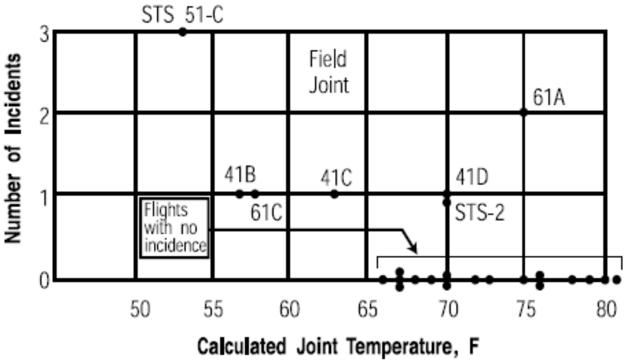
At the teleconference, engineers from Morton Thiokol presented their concern over the effect of temperature on the ability of the O-rings to seal, and concluded that they could not recommend a launch at a temperature below 53°F (≈12°C). NASA disagreed with the data and the launch delay recommendation the Morton Thiokol engineers (not unanimously though) presented. Managers at NASA used strong words in expressing their different opinion and in pointing out the flaws in Morton Thiokol’s reasoning. However, they said they would not launch against a recommendation from a contractor. Morton Thiokol asked for a “caucus”, where they went through the data they had and made a management decision (meaning that only the four managers (out of 14 participants at Morton’s end) present expressed their final opinion). The teleconference resumed after a 30-minute break, during which the NASA participants were already preparing to call the launch off.

However, to NASA’s surprise, when Morton Thiokol called back, they were represented by their vice president of the booster program and they were now recommending a launch without any temperature constraints. The personnel at NASA’s end of the line were not aware that anyone at Thiokol still objected to the launch, and they were not aware of the decision-making process that eventually led to the change of recommendation. A critical piece of information - that the decision was a management decision made against the somewhat inconsistent and ambiguous analyses and worries of engineers - was lost. The reason for changing the representative of Thiokol for the second part of the teleconference was due to the original representative declining to sign the voucher recommending the launch during the 30 minute hiatus.

In the teleconference in which the fate of the Challenger was decided, the engineers at Morton Thiokol were trying to prove that temperature was a decisive factor affecting the O-ring damage. The problem was that their data was inconclusive. O-ring damage had happened at temperatures ranging all the way from 53° F to 75° F. Obviously, temperature could not be the only factor, if it was a factor at all, in contributing to O-ring damage. And what would be the effect of temperature in terms of numbers; how did it affect the O-rings, and which temperature level would suffice? For these questions there was no hard empirical evidence. The investigation board points out that if the engineers would have looked at all the flights, not only those with O-ring damage, a clearer picture would have emerged (see Figure 5). Only three instances of thermal damage to O-rings had been observed on the twenty flights made in temperatures of 66° F or more. All four flights staged at 63° F or below had shown O-ring damage. The engineers were more used to rapid corrective actions than trending and analysis.



Plot of flights with incidents of O-ring thermal distress as function of temperature.



Plot of flights with and without incidents of O-ring thermal distress.

NOTE: Thermal distress defined as O-ring erosion, blow-by, or excessive heating.

Figure 5. Plot of flights with and without O-ring incidents shows that looking for linear correlation between temperature and the number of incidents was difficult when only the problematic flights were considered. However, if NASA or Thiokol would have looked at all flights, a pattern where the lack of incidents was explained by higher temperatures would have emerged. (figure from Dunar & Waring 1999, p. 359)

It is also worth remembering that the tele-meeting facilities at that time comprised basically of a phone and speakers. There were no flat screens and moving cameras. Karl Weick has been considering that had the meeting taken place face to face the NASA managers might have realized the anguish of the Thiokol engineers and taken them more seriously. Such subtle signals were lost over the phone.

3.5 The power of one man against the organization

Participating in that teleconference was Roger Boisjoly, a rocket engineer working for Morton Thiokol. He was also the leader of a Seal Task Force assembled in August 1985 to find a quick solution to the field joint problems. This Task Force was assembled after Boisjoly sent an internal memo to Morton Thiokol top management in July 1985 expressing his severe concern over the design of the SRBs and calling for their immediate redesign. The top management allegedly asked him to keep silent on these worries as they were "too sensitive to release to anybody". The management perhaps also realised the amount of work involved in Boisjoly's proposal and the effect it would have on schedules. Indeed, after the accident, it took Morton Thiokol over 32 months to redesign the SRBs.

Boisjoly had strong preservations about launching in such a cold weather and after the conference he spoke to many other people about his worries concerning the launch. Boisjoly, who died in early 2012, suffered severe psychological distress after the accident and spent a majority of his later career by considering engineering ethics and talking about that fatal meeting where he was unable to stop the accident from happening. He argued that the caucus called by Morton Thiokol managers, which resulted in a recommendation to launch, "constituted the unethical decision-making forum resulting from intense customer intimidation” (Boisjoly 2006).

Boisjoly later affirmed that “this was a meeting where the determination was to launch, and it was up to us to prove beyond a shadow of a doubt that it was not safe to do so. This is in total reverse to what the position is in a preflight conversation.” The fact that he failed to do so haunted him for the rest of his life.

Boisjoly was awarded the AAAS Scientific Freedom and Responsibility Award in 1988 “For his exemplary and repeated efforts to fulfill his professional responsibilities as an engineer by alerting others to life-threatening design problems of the Challenger space shuttle and for steadfastly recommending against the tragic launch of January 1986.” (archives.aaas.org).

3.6 Pressure to launch

The management team eventually decided to go through with the launch, even after hearing the critical comments from Morton Thiokol. During the telemeeting, obviously frustrated with the Thiokol engineers reservations about launching, NASA booster manager Larry Mulloy shouted the famous lines “My God, Thiokol, when do you want me to launch, next April?”.

The management at NASA was under a lot of pressure to make the launch the next day. The launch had already been postponed four days due to poor weather and a technical fault (unrelated to the field joint leak leading to the disaster). In addition, NASA was behind the planned launch schedule (twelve planned flights in 1986). Further, there was a civilian onboard, as part of the “teacher in space program” and her entire class had arrived to see the launch and hear her lecture from space. And ever more, President Reagan was supposed to address the nation in his state of the nation speech the next day and the successful launch of Challenger with the first ever teacher in space was supposedly high on his priorities of things he wanted to say. Postponing the launch would have ruined that opportunity. There had also been repeated mockery on the television news of previous scrubs and the NASA management was probably not keen on being a topic of yet another TV joke.

NASA had originally promised sixty launches per year, a schedule that was far too optimistic. The highest rate ever achieved by the shuttle program was nine flights in 1985. The promise of fast and routine access to space proved impossible to keep. Seeking this access were multiple communications and space technology companies wishing to use the shuttle program to lift their satellites and probes to orbit. In May 15th 1986, the Challenger was supposed to carry a space probe called Ulysses into orbit. The planet Jupiter was about to make a close flyby of earth, and Ulysses had to be in orbit to make the rendezvous with the magnetic effects of that flyby – a gravitational boost. Ulysses would then study the north and south poles of the sun. Thus, the "teacher in space" flight was in an urgent need of completion in order to reserve adequate time for prepping Challenger to flight status again. These later flights were impossible to postpone because they needed to be launched during a specific time window.

For the first time in its history, NASA was in a position where it was not able to set its own launch schedule. Now it had several customers who each had their say in the schedule. High usage rates were critical to the Shuttle's economy because its huge development costs needed to be recouped within a reasonable amount of time. This was especially so in light of NASA's diminishing budget and the underestimated costs of a single launch.

3.7 Budget constraints

As a federal agency, the National Aeronautics and Space Administration (NASA) receives its funding from the annual federal budget passed by the United States Congress. As Figure 6 shows, NASA's budget peaked in 1964-1966, when the Apollo program was fully under way. The Apollo program culminated in the moon landing in 1969, and marked the U.S. victory of the space race.

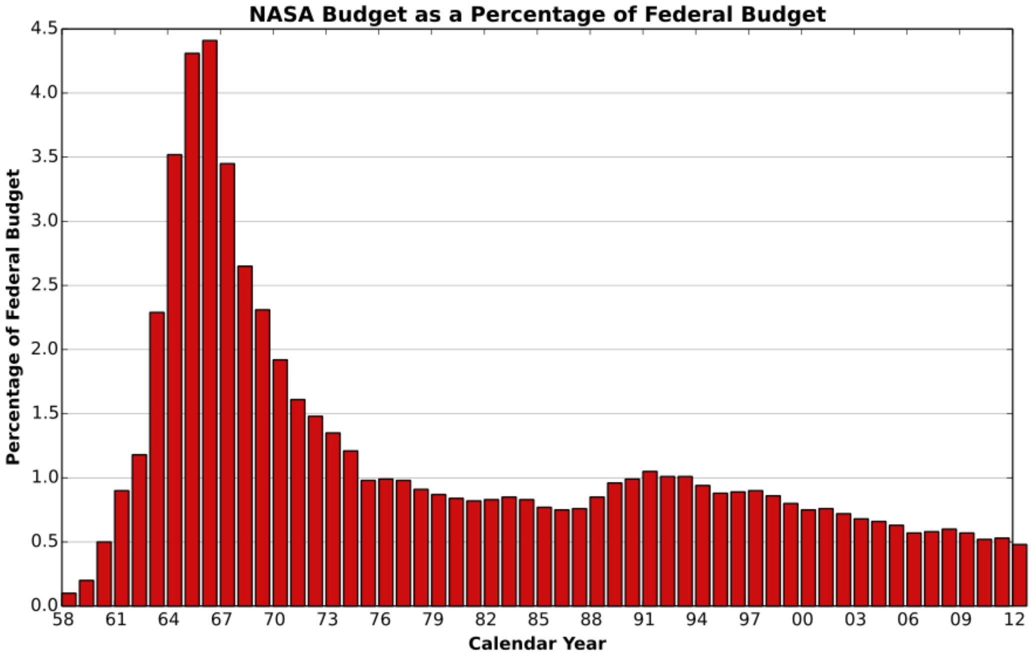


Figure 6. NASA budget as a percentage of Federal budget

Paradoxically, the Space Race victory of the U.S. over Soviet Union proved detrimental to NASA's budget (see Figure 6). After the perceived threat of Soviet Union landing yet another victory after Sputnik 1 in 1957 (first satellite) and Yuri Gagarin (first human in space) in 1961 subsided, NASA was unable to sustain political support for its vision of an even more ambitious Space Transportation System entailing reusable Earth-to-orbit shuttles, a permanent space station, lunar bases, and a manned mission to Mars. Only a scaled-back Space Shuttle was approved. Several compromises had to be made because of the reduced budget, including the involvement of the military and the choice of cheaper re-usable solid rocket boosters.

While a liquid-fueled booster design provided better performance, lower per-flight costs, less environmental impact and less developmental risk, solid boosters were seen as requiring less funding to develop at a time when the Shuttle program had many different elements competing for limited development funds. Finally, the Shuttle was developed with the original development cost and time estimates given to President Richard M. Nixon in 1971, at a cost of $6.744 billion in 1971 dollars versus an original $5.15 billion estimate. The operational costs were higher than anticipated, however. Thus, the financial pressures did not dissipate when the Shuttle became operational. One launch of the Shuttle cost about 1.5 billion dollars in 2010 currency.

4. Investigations of the accident

4.1 Official investigations and Diane Vaughan’s study

The Challenger accident has been investigated by various groups of people. The official investigation by the Presidential Commission (1986) found numerous rule breakings and deviant behaviour at NASA prior to the accident. They also accused NASA of allowing cost and schedule concerns to override safety concerns. Many blamed the accident on a fundamental design error in the O-rings. Vaughan (1996) shows in her analysis of the same accident how most of the actions that employees at NASA conducted were not deviant in terms of the culture at NASA. She also shows how safety remained a priority among the field-level personnel and how the personnel did not see a trade-off between schedule and safety (Vaughan, 1996). They perceived the pressure to increase the number of launches and keep the schedule as a matter of workload, not a matter of safety versus schedule. The decisions made at NASA from 1977 through 1985 were “normal within the cultural belief systems in which their actions were embedded” (Vaughan, 1996, p. 236).

An example of secrecy that the commission found was the finding that NASA Levels II and I were not aware of the history of problems concerning the O-ring and the joint. They concluded that there appeared to be “a propensity of management at Marshall to contain potentially serious problems and to attempt to resolve them internally rather than communicate them forward” (Presidential Commission, 1986a, p. 104). The U.S. House Committee on Science and Technology later submitted its own investigation of the accident, and they concluded that “no evidence was found to support a conclusion that the system inhibited communication or that it was difficult to surface problems”. (U.S. Congress, 1986)

If communication or intentional hiding of information were not to blame, then what explains the fact that the fatal decision to launch the shuttle was made? The U.S. House Committee on Science and Technology disagreed with the Rogers Commission on the contributing causes of the accident: “the Committee feels that the underlying problem which led to the Challenger accident was not poor communication or underlying procedures as implied by the Rogers Commission conclusion. Rather, the fundamental problem was poor technical decision-making over a period of several years by top NASA and contractor personnel, who failed to act decisively to solve the increasingly serious anomalies in the Solid Rocket Booster joints." On the other hand, Vaughan argues in her study (1996) that the actions that were interpreted by the investigators as individual secrecy and intentional concealing of information, or just bad decision making, were in fact structural, not individual, secrecy. Structural secrecy means that it is the organizational structures that hide information, not individuals.

Vaughan (1996, 409–410) summarises: "The explanation of Challenger launch is a story of how people who worked together developed patterns that blinded them to the consequences of their actions. It is not only about the development of norms but also about the incremental expansion of normative boundaries: how small changes – new behaviors that were slight deviations from the normal course of events – gradually became the norm, providing a basis for accepting additional deviance. No rules were violated; there was no intent to do harm. Yet harm was done." The organization gradually drifted to a state in which it no longer operated safely. Earlier danger signals had become part of 'normal' work and they were no longer noted.

The Nobel Prize winner theoretical physicist Richard P. Feynman was part of the Commission. He eloquently explains in his book (Feynman, 1988) how he practically conducted his own investigation in parallel to the Commission (while simultaneously taking part in the Commission), and wound up disagreeing with some of the Report's conclusions and writing his own report as an Appendix to the Commission Report. The Appendix was called "Personal Observations on the Reliability of the Shuttle". In the report he questions the management's view on the reliability of the shuttle as being exaggerated, and concludes by reminding managers of the importance of understanding the nature of risks associated with launching the shuttle: "For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled" (Feynman, 1988, p. 237).

4.2 Secondary source investigations

Jensen (1996) provides a narrative of the accident based on secondary sources, which emphasises the influence of the political and societal factors. For example, he points out how the firm responsible for designing the solid rocket boosters was chosen based on political arguments and how the original design of the space shuttle by NASA did not include booster rockets using solid fuel but rather a manned mother plane. A manned mother plane carrying the orbiter proved too expensive in the political climate where NASA had to fight for its budget and justify the benefits of its space program (see Section 3.7). Reusable rocket boosters were cheaper. As the rocket boosters were designed to be reusable after being ditched into sea water on each flight, NASA did not want to consider what "all the pipes and pumps and valves inside a liquid-fuel rocket would be like after a dip in the ocean (Jensen, 1996, p. 143)". Thus it was decided that solid fuel instead of liquid should be used. Solid rocket motors had never been used in manned spaceflight since they cannot be switched off or "throttled down" after ignition. Moreover, the fact that the design had field joints at all had –at least partially – to do with Morton Thiokol wanting to create jobs at their home in Utah, 2500 miles from the launch site. There was no way of building the booster in one case in Utah and shipping it to the Kennedy Space Center (Jensen, 1996, p. 179). Jensen also considers the network of subcontractors and NASA's deficient ability to control the quality of their work. Morton Thiokol, for example, signed subcontracts with 8600 smaller firms (Jensen, 1996, p. 156).

Jensen argues that the NASA spokesmen emphasised that the space shuttle did not require any new innovations, except for the main engines, for political reasons. Too heavy emphasis on the need for experimentation and risks associated with technological innovations would have made Congress wary of providing the necessary funding (Jensen, 1996, p. 158). The personnel at NASA were surprised by that kind of attitude at the management level when the engineer level was tackling a wide range of never-before-tried technical solutions. When the space shuttle finally became operational, Jensen (1996, p. 202) argues that "every single breakdown was regarded as an embarrassing exception, to be explained away and then be corrected, under wraps, as quickly as possible - so as not to damage the space shuttle's image as a standard piece of technological equipment". Jensen also tackles the long working hours and work stress that was due to the production pressures, and the bureaucratic accountability as a substitute for the professional accountability of the early NASA culture (Jensen, 1996, p. 363).

5. Other identified contributing factors to the accident

5.1 The nature of the problem

One of the challenges affecting decision making was that the problem with the O-rings was multidisciplinary. Still, both Morton Thiokol engineers as well as NASA engineers had very special, and narrow, fields of expertise. Expertise from both the Materials and Properties Lab (on the effect of temperature on the rubber O-ring) and the Structures and Propulsion Lab (on joint dynamic) were needed in order to understand how resiliency affected redundancy in the field joints' primary and secondary two O-rings. (Vaughan, 1996, p. 360)

Further, the problems with the O-rings were infrequent and a different cause was found each time there was erosion in an O-ring. This affected how the solid rocket booster work group made sense of them. Vaughan (1996, p. 149) writes: "The infrequent occurrence and the irregular pattern created a temporal sequence that was extremely important in shaping the construction of meaning in the work group: an incident would occur, followed by flights with no erosion, causing the group to conclude that they had correctly identified and corrected the problem. The effectiveness of the remedy affirmed their diagnosis."

5.2 Testing of the Solid Rocket Boosters

Seven test firings were made in Utah before the shuttle program was commenced. One of the test firings was done in cold temperature (36 F). However, the test firings were not made in actual launch conditions where the rocket boosters would be connected to the orbiter and the external fuel tank. There were at least two physical phenomena in the launch that contributed to the leak that were not anticipated in the test firing phase. The first phenomenon was called the “twang”, a bending of the whole shuttle stack after the main engines lit but before the boosters came on. It caused the whole craft the bend backward about one metre, measured at the nose, and then rebound forward. This momentum put a lot of pressure on the field joints. The second phenomenon acting to pry the joints open was the stress accumulating at the struts attaching the boosters to the shuttle’s external fuel tank. Each booster had two lower struts, each mounted to a steel ring around the rocket’s circumference. The lower strut numbered P-12 was just about 30 centimetres from the leak point.

The testing procedure requested by NASA did not specify that actual launch conditions need to be recreated. Thus, Morton Thiokol did the test firing according to their understanding of the physical phenomenon that might threaten the integrity of the field joints. One phenomenon that they paid attention to was the “joint rotation”, the slight bulging of the steel case upon ignition. The bulging might ease open the seals at the field joints if not properly taken into account.

Testing of solid rocket boosters is also very expensive compared to testing liquid engines. This fact might have contributed to the quite small number of test firings. Further contributing fact probably was the success of the tests and the amount of experience from Titan boosters that convinced the Thiokol engineers of the functioning of the SRB design.

5.3 Contracting

Jensen has considered NASA’s deficient ability to control the quality of the subcontractor network’s work as a contributing factor to the accident. Morton Thiokol, for example, signed subcontracts with 8600 smaller firms (Jensen, 1996, p. 156). Further, political decisions might have influenced the choice of some contractors.

It has also been pointed out that the contract between NASA and Morton Thiokol offered the corporation no incentives to spend money to fix problems believed unlikely to cause mission failure. “The incentive fee, rewarding cost savings and timely delivery, could total as much as 14 percent of the value of the contract; the award fee, rewarding the contractor’s safety record, could total a maximum of 1 percent. No provisions existed for performance penalties or flight anomaly penalties. Absent a major mission failure, which entailed a large penalty after the fact, the fee system reinforced speed and economy rather than caution. (Dunar & Waring 1999, p. 365)” Due to the nature of the contract, preparations for upcoming missions had higher priority than redesign activity at Thiokol and work on flight hardware came before work on test hardware. The company paid the costs of the redesign activities without additional money from NASA. To get the extra money necessary to speed progress for the O-ring task force, Thiokol would have had to submit an engineering change request and thus acknowledge the failure of its design.

5.4 A “can do” attitude

In the official Challenger investigation, it was concluded that a “can do” attitude at NASA contributed to the accident by creating overconfidence in the organization’s ability to perform for the personnel. Vaughan (1996, p. 234) discussed it with the project members from the Solid Rocket Booster project and they agreed that such an attitude existed and that it affected their decision making by reinforcing their belief in their technical analysis.

Vaughan writes: “Describing it, several work group members stated, ‘We believed in our people and our procedures.’ They were assured in their decisions because they had ‘long-term personnel with a history of hands-on hardware design that lead to experience and first-hand knowledge’ … because ‘we followed every procedure’; because ‘the FRR [Flight Readiness Review] process is aggressive and adversarial, examining every little knit’; because ‘we went by the book’; and because ‘we did everything we were supposed to’.” The Challenger was not supposed to explode. The risks were supposed to be acceptable. Even in hindsight, for many at NASA it was hard to see the risk as nothing but acceptable and their actions as justified.

References

Boisjoly, R. (2006). Ethical Decisions - Morton Thiokol and the Space Shuttle Challenger Disaster. Available from: http://www.onlineethics.org/CMS/profpractice/ppessays/thiokolshuttle.aspx

Chernov, D. & Sornette, D. (2016). Man-made catastrophes and risk information concealment. Springer.

Chiles, J.R. (2001). Inviting disaster. Lessons from the edge of technology. New York: HarperCollins.

Dunar, A.J. & Waring, S.P. (1999). Power To Explore -- History of Marshall Space Flight Center 1960-1990. U.S. G.P.O., Supt. of Docs.

Feldman, S. P. (2004). The culture of objectivity: Quantification, uncertainty, and the evaluation of risk at NASA. Human Relations, 57, 691–718.

Feynman, R. P. (1988). What Do You Care What Other People Think?": Further Adventures of a Curious Character. W.W.Norton.

Jensen, C. (1996). No downlink. A dramatic narrative about the Challenger accident and our time. New York: Farrar Straus Giroux.

Starbuck, W.H. & Milliken, F.J. (1988). Challenger: Fine-tuning the odds until something breaks. Journal of Management Studies, 25, 319-340.

U.S. Congress. House. Committee on Science and Technology. (1986). Investigation of the Challenger accident: Report. House Report 99-1016. Washington, D.C.: Government Printing Office.

Vaughan, D. (1996). The Challenger launch decision. Chicago: University of Chicago Press.