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Space Shuttle Case Studies: Challenger and Columbia

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Abstract

The two Space Shuttle tragedies, Challenger and Columbia, have led to many papers on case studies on engineering ethics. The Challenger disaster in particular is often discussed due to the infamous teleconference that took place the night before the launch in which some engineers tried to postpone the launch. However, the space shuttle program itself is worthy of study as it relates to the engineering design process, and the details of the Challenger and Columbia disasters are worthy of discussion as they relate to a variety of sub-disciplines, including material science, thermodynamics, fluid mechanics, and heat transfer. This paper summarizes the major technical findings of the Rogers Commission and the Columbia Accident Investigation Board (CAIB). An overview of the history of the space shuttle program, going back to the end of the Apollo program, is presented, including some of the design compromises that were made in order to get political support for the space shuttle program. A detailed bibliography is given that will aid instructors in finding additional material they can tailor to their particular class needs.

Introduction

The Space Shuttle was one of the most complex devices ever engineered, containing more than 2,500,000 individual parts and 1,200,000 ft of wiring, with 1,440 circuit breakers.[1] Unfortunately, this complexity proved difficult to manage, resulting in the loss of 2 shuttles and 14 astronauts in 135 missions, a failure rate of 1.5%, which is much higher than that of commercial passenger airlines, which incur equivalent fatal loss events at a rate of about 0.00005%, or 0.5 per million flights.

Even expressed as death rate per billion passenger miles, which gives an advantage to the shuttle due to the long distance each mission covered, its loss rate of around 4 fatalities per billion passenger miles is still higher than the 0.9 deaths per billion passenger miles of commercial airlines (though lower than the rate for automobiles, which is 12 deaths per billion passenger miles). As evidenced by the Challenger and Columbia disasters, takeoff and landing were the most dangerous parts of the shuttle's flight path, as there was relatively little danger while orbiting in space.

This paper presents several ways in which case studies of the space shuttle can be used in undergraduate engineering courses, including engineering ethics[2-6], the engineering design process, failure modes and effects analysis (FMEA), forensic engineering, thermal sciences, materials science, and communications.[7,8] There is a large body of quality technical literature on the space shuttle published by NASA that is publically available, including publications by the NASA History office.[9,10] Additionally, technical publications on specific topics can be found on the NASA Technical Reports Server (NTRS).[11]

Space Shuttle Program Origins

The National Aeronautics and Space Administration (NASA) was formed from the National Advisory Committee for Aeronautics (NACA) in 1958. In 1961 President Kennedy issued the goal for NASA to send a man to the moon by the end of the decade, and congress approved the funding for the moon mission (see Figure 1 for historical NASA funding levels). In 1969 Apollo 11 landed on the moon, and the last manned lunar mission was Apollo 17 in 1972.

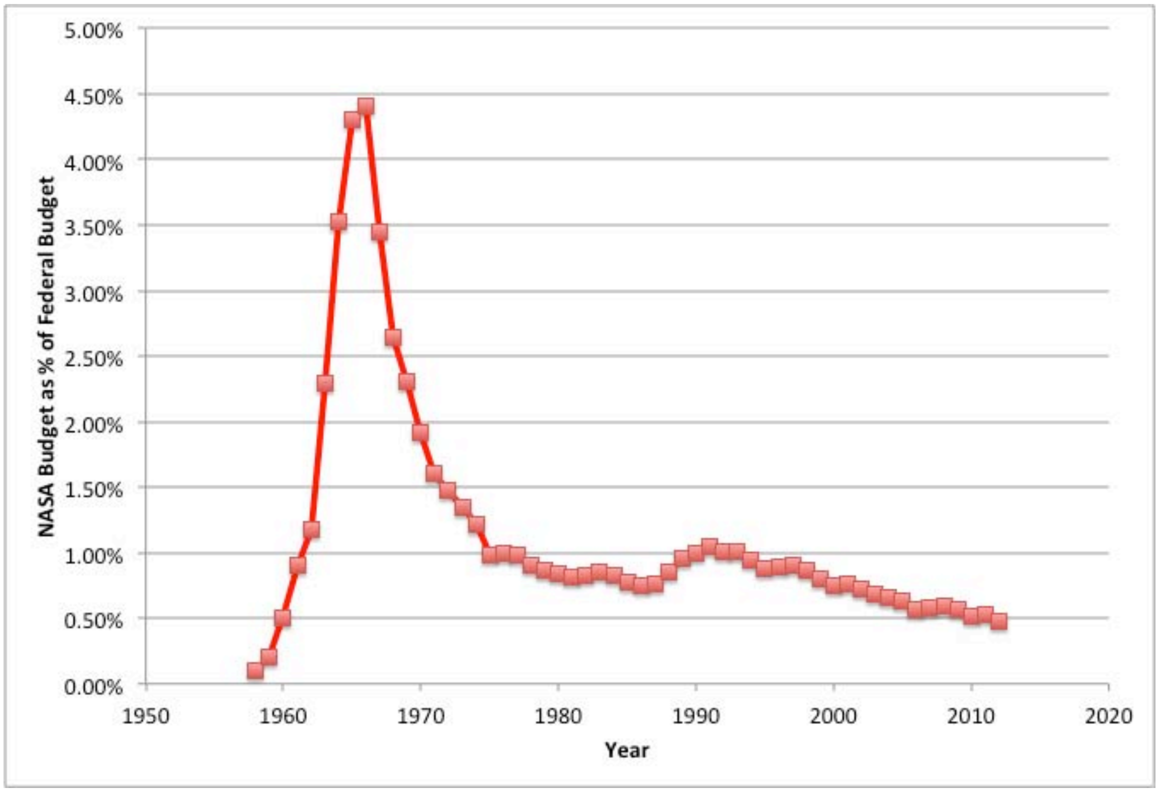


Figure 1: NASA budget as percent of total federal budget, based on a figure originally appearing in the Augustine Report[12] in 1990, and using data from NASA History office.

As can be seen in Figure 1, even before the end of the manned moon missions in 1972, NASA's budget was being pared down. At the same time, NASA was developing plans for post-Apollo missions, including plans for space stations in orbit and on the moon. These space stations would require a "space shuttle" to service them. After much negotiation, NASA finally gained approval from the Nixon administration to build the Space Shuttle, but not the space station. Further, there were no remaining Saturn V rockets to lift the major components for a proposed space station into orbit. (A modified Saturn V rocket had put Skylab into orbit in 1973). The space shuttle program was approved in 1972 with a budget of a $5.5 billion and a goal of completion in 1978, 6 years later. The first launch was not actually achieved until 1981, but the total cost overrun was only 15%, which is pretty good by government standards where 40% of NASA Space Programs had cost overruns of 100% or more, and some projects have cost overruns up to 400%.[13]

While the space shuttle program was approved, there was not sufficient funding for a space station. So now what would a shuttle do? NASA still had to justify the shuttle to congress to get funding for the project. NASA's ambitious plan for the Shuttle included launching all government satellites, including those from the department of defense, and commercial satellites, as well as NASA’s own satellites and other missions. Also, to garner additional political support for the space shuttle, NASA sought partnership with the Air Force. The Air Force’s requirements resulted in some design changes for the space shuttle, including larger wings to increase the cross-range landing capabilities, a larger cargo bay, and the addition of a second launch facility at Vandenberg Air Force base in California for classified launches. Early NASA space shuttle plans called for a two-stage launch to orbit vehicle.[9] This was not possible with the funding and technology available at the time. As a result two additional booster rockets had to be added to the design in order to actually get the space shuttle to orbit. As noted in the Columbia Accident Investigation Board (CAIB) report, “These sometimes-competing requirements resulted in a compromise vehicle that was less than optimal for manned flights.”[1] In a 1982 interview, a range safety officer stated, “the space shuttle gives the best configuration for a large explosion.”[14] In 2005, NASA Administrator Mike Griffin said of the shuttle, “It was a design which was extremely aggressive and just barely possible,” and that the shuttle was “inherently flawed.”

“When combined, commercial, scientific, and national security payloads would require 50 Space Shuttle missions per year. This was enough to justify – at least on paper – investing in the Shuttle.”[1] NASA was so confident in its ability to achieve routine access to space through the shuttle that it planned to phase out of expendable launch vehicles (ELV’s) such as the Atlas, Titan, and Delta rockets. In reality, NASA only achieved 135 shuttle launches over the duration of the program (1981-2011), an average of 4.5 flights per year, an order of magnitude less than what was planned, and after the Challenger disaster of 1986, ELV production was rapidly resumed.

The space shuttle orbiters were built in Palmdale, CA. The orbiters ended up costing $1+ billion each. The flight of Columbia in 1981 with two test pilots aboard was the first U.S. space flight since the last Apollo mission in 1975 (which was the Apollo-Soyuz test project). After the fourth flight in June 1982, the Agency declared the Shuttle system “operational,” meaning that the spacecraft and propulsion system had passed their flight tests, and could carry the full crew of 7 astronauts. The final space shuttle mission, STS-135, ended July 21, 2011 when Atlantis landed at NASA's Kennedy Space Center. The complete roster of orbiter vehicles is:

- Enterprise (Approach and Landing Testing in 1977)
- Columbia - 1981 - 2003
- Challenger - 1983 - 1986
- Discovery - 1984 - 2011
- Atlantis - 1985 - 2011
- Endeavour - 1992 – 2011

The total shuttle stack (orbiter, external fuel tank, rocket boosters) when fully loaded with fuel has a mass of 2.05 million kg (4.5 million lbm). The orbiter can carry a payload of 38,000 to 56,300 lbs to orbit, depending on the orbit, which represents about 1% of the total mass at liftoff. The main engines generate 2,000,000 N of thrust each, and the solid rocket boosters (SRBs) produce 14,700,000 N each, so that the boosters generate 85% of the thrust at liftoff.

The external fuel tank holds 719,000 kg (2,000,000 L) of fuel. The liquid oxygen is kept at -297 °F (-183 °C) and the liquid hydrogen at -423 °F (-253 °C or 20 K). The aluminum structure of the tank is covered in insulating foam that reduces the boil off of the cryogenic propellants while the shuttle stack is sitting on the launch pad and also protects the tank from aerodynamic heating during launch. The external fuel tank is 154 ft (47 m) long and is also used structurally to transmit the thrust force of the boosters to the orbiter. In orbit the shuttle travels at 17,500 mph (7800 m/s) and must decelerate to a speed of 220 mph (100 m/s) at landing. During re-entry, the nose and leading edges of the wings experience temperatures as high as 3000 °F (1650 °C).[1]

One of the major decisions to be made during the shuttle development was the design for the booster rockets. Options included using liquid or solid-fueled boosters, and whether the boosters would be expendable or reusable. NASA believed that solid rocket boosters would be less expensive to develop, even though they had had higher projected operational costs than liquid boosters. The shuttle was the first manned spacecraft to use solid rockets.[1] There is some speculation that the Air Force pressured NASA to use solid fuel boosters because they wanted to develop the technology further for their own missiles. While liquid rockets generally have a higher specific impulse than solid rockets, solid rockets have the advantage that they can be stored a long time without worrying about the fuel boiling or evaporating. At the time, solids were seen as a proven technology, based on the USAF Minutemen ICBMs. To reduce costs, NASA planned to recover and refurbish the metal booster casings for future flights. The vendor selected by NASA, Morton Thiokol, was based in Utah, and there was no way for the large booster rockets to be shipped whole to the launch site in Florida, so the boosters had to be build in segments and shipped by rail to Florida, where they were assembled, with O-rings to seal the joints between the segments. The solid rocket boosters use a fuel that is a mixture of ammonium perchlorate, aluminum, and polybutadiene acrylic acid acrylonite. A brief discussion of the evaluation of the original bids for the booster rockets is included in an appendix in Vaughan's book.[15] One problem encountered with the SRBs in practice is that the booster segments would often end up distorted, not round, due to impact on the ocean during recovery. Additional information on the development of the Space Shuttle can be found in Heppenheimer's book *The Space Shuttle Decision,*[9] while *Wings on Orbit*[10] provides an overview of all the space shuttle missions.

Challenger

Challenger was the third Orbiter built (OV-099), and the second to fly in space, after Columbia. On its final flight (STS-51L) on January 28, 1986 it carried a full crew of 7 astronauts. STS-51L was the 25th overall shuttle flight and it carried two satellites: one for NASA communications, the other to observe Halley's Comet. STS-51L had originally been scheduled for July 1985. On January 28, 1986, the space shuttle Challenger exploded 73 seconds after launch. The timeline of the accident is:

- Puffs from leaking O-ring within first 1.0 s of flight
- 59 s - Visible flame from O-ring
- 64 s - External fuel tank breached
- 72 s - booster begins to rotate and fuel tank collapses due to structural failures
- 73 s - explosion and destruction of STS. Traveling Mach 1.92 at 46,000 ft (14,000 m) altitude at that time.
- The Range Safety Officer activated the auto-destruct systems on both SRBs 110 s after launch (36 s after explosion).

Note that these times after launch corresponds to the time of “max q”, where q is the commonly used symbol in aerospace engineering for the dynamic pressure:

$$q = \frac{1}{2}\rho V^2$$

While the space shuttle continues to accelerate as it reaches orbit until its fuel is burned out, the atmospheric density, ρ, decreases with increasing altitude, so that there is a unique point where q, and the total aerodynamic loading on the shuttle, is maximized.

The Presidential Commission on the Space Shuttle Challenger Accident (commonly known as the Rogers Commission) was formed on February 3, 1986. The mandate of the Commission was to:

1. Review the circumstances surrounding the accident to establish the probable cause or causes of the accident.
2. Develop recommendations for corrective or other action based upon the Commission's findings and determinations.[16]

Led by the visual evidence, the investigation focused on seal in joint between lowest segments of right SRB. Pictures shortly after launch (see Figure 2) showed a black puff of smoke emanating from the lowest field joint on the right solid rocket booster one second after liftoff.

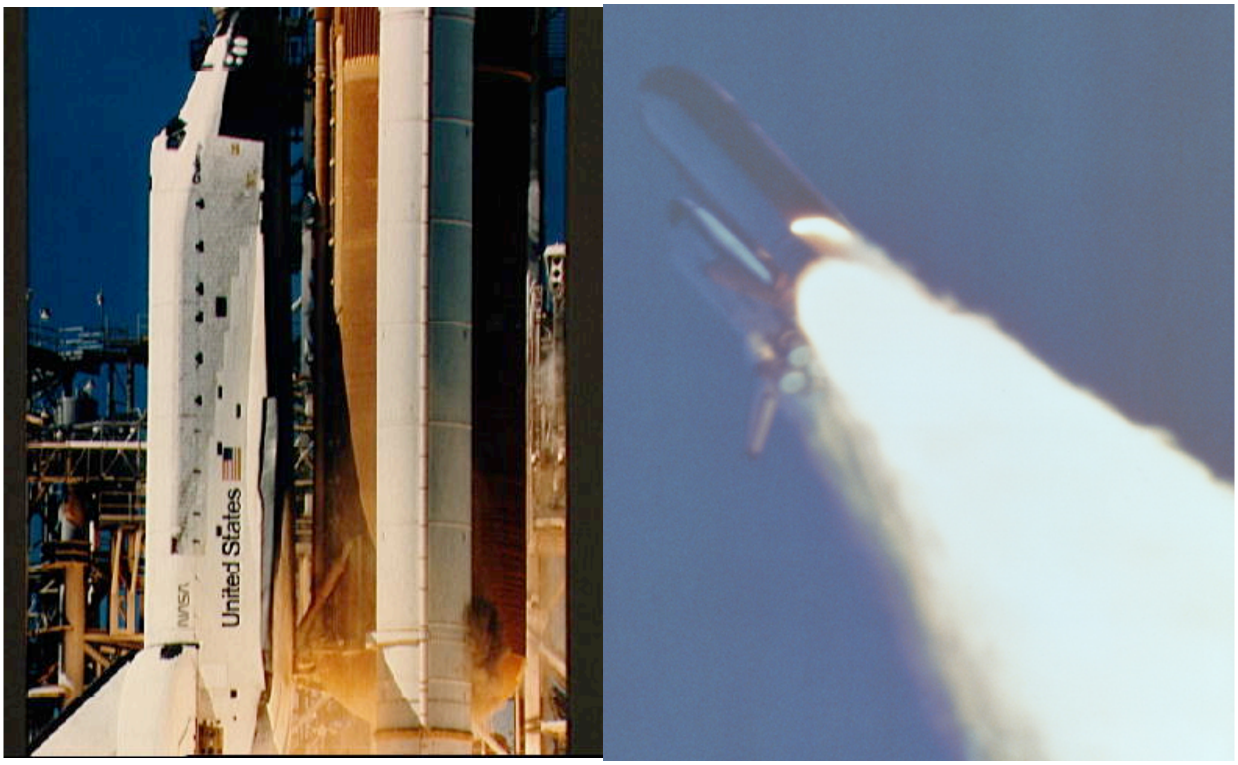


Figure 2: Picture of black puff of smoke emitted from right SRB at liftoff, and flame emanating from same location later in the flight.

The probable cause of the accident is as follows: As the boosters were ignited and rose to operating pressure of 1000 psi (70 bar) the segments of the booster moved, causing the lower field joint on the right booster to rotate open. Due to the cold temperatures the O-rings were not resilient enough to expand into the opened groove and seal the joint, allowing combustion products to escape from the gap. Some of the combustion products, mostly aluminum oxide, coalesced into a plug that temporarily sealed the hole and prevented the shuttle from exploding on the launch pad. As the shuttle travelled through the period of "max q", it also experienced wind shears at that altitude. The aerodynamic forces caused the aluminum oxide plug to break free, allowing hot combustion gases to escape through the hole in the booster. The hot jet weakened the lower strut connecting the booster to the external fuel tank, allowing the booster to rotate about the upper strut. Further damage to the external fuel tank released the liquid oxygen and hydrogen fuel, causing the explosion that ripped the Challenger apart.

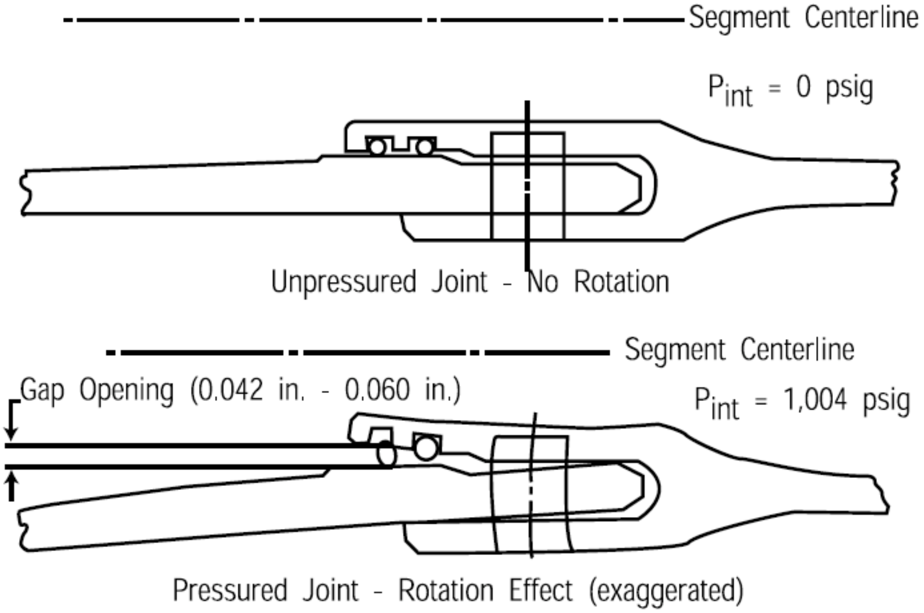


Figure 3: Schematic of SRB joint showing rotation.[17]

While it is commonly believed that the astronauts died in the explosion, the crew cabin remained intact and the astronauts survived alive during the descent of the crew cabin until it hit the ocean, when they died from blunt force impact. At least some of the astronauts were likely conscious during the entire descent. NASA may have encouraged the public to believe that the astronauts died during the explosion to deflect criticism of their decision to build the space shuttle without an escape system.

As with any accident investigation (see for example the books by Chiles[18] or Dawson[19]), it became clear after the fact that there were plenty of warning signs that there were problems with the design of the O-ring seals for the segments of the solid rocket boosters. These warning signs are recorded by Dunar and Waring:[17]

- 1977 – During a hydroburst test, failure occurred in the joint seals. Both the primary and secondary O-rings leaked. These tests indicated some joint opening, contrary to joint designers' expectations.
- 1980 - NASA's Space Shuttle Verification/Certification Propulsion Committee was concerned about leaks in the joints. They designated the joint as criticality 1R (redundant hardware, total element failure of which would cause loss of life or vehicle.) It was also noted that it was "not known if the secondary O-ring would successfully re-seal if the primary O-ring should fail."
- 1981 – The launch of STS-2 resulted in blow-by through the putty around the O-ring in the joint. There was one scorched primary O-ring.
- 1984 - Primary O-rings eroded in 3 joints on STS-41B. The erosion on one case-to-case joint O-ring was 0.050" of the 0.250" diameter.
- 1985 - STS-51C experienced the coldest launch to date at 53 ˚F (12 ˚C). Two primary O-rings in case-to-case field joints had erosion, and primary rings in two field and both nozzle joints had soot blow-by.
- 1985 - Morton Thiokol performed bench tests to evaluate the effects of temperature
  - At 100 ˚F (38 ˚C) the O-ring maintained contact with the metal sealing surface
  - At 75 ˚F (24 ˚C) the O-ring lost contact for 2.4 seconds.
  - At 50 ˚F (10 ˚C) the O-ring did not re-establish contact in ten minutes at which time the test was terminated

It was known that colder temperatures would make the O-rings harder and less resilient. It would also make the putty stiffer and thicken the greases. All of these factors would reduce the O-rings ability to expand into its groove, increasing the probability that complete seal would not be obtained, which would allow hot gases to blow by the O-rings, and could also cause hot gases to impinge on the O-rings, causing erosion of the rings.[17] It is also worth nothing that an ice team member on the launch pad had measured a temperature of 8 ˚F (-13 ˚C) on the lower portions of the right SRB with an infrared instrument earlier in the morning before the Challenger launch, though this information was not relayed to shuttle management. While some other references have ascribed this to a faulty measurement, as the air temperature was 36 ˚F (2 ˚C) at launch time, McDonald[20] presents an analysis that shows the area of the booster that failed was in fact at that low temperature of 8 ˚F prior to launch.

With all these warning signs, the Rogers Commission was also interested in finding out why shuttle managers had decided to launch despite a known problem. NASA had a goal of 24 shuttle flights per year (note this is already down from predictions of 50 flights per year used to justify the shuttle program) but had only launched 9 flights in 1985. STS-51L was the "Teacher in Space" mission, for which the launch was broadcast live to many schools, and it was planned to have school teacher Christa McAuliffe broadcast experiments from the shuttle to schools during the mission. There was a large manifest of DOD and commercial satellite launches backlogged, and upcoming launches of probes to other planets and Halley's comet had limited launch windows during which they could be performed. Further, the flight of STS-51L had already been postponed the day before due to high winds. In short, there was intense pressure on NASA managers to maintain their launch schedule. Of particular interest to the Rogers Commission was a teleconference between Morton-Thiokol and NASA that took place the evening before the Challenger launch. Vaughan[15] gives in a thorough account of this teleconference.

The Teleconference

- Morton Thiokol engineers Roger Boisjoly & Arnie Thompson in Utah were concerned about the damage sustained by the O-rings on STS-51C, which had been the previous coldest launch to that point in time, and about the predicted cold temperatures for the Challenger launch the next day.
- Thiokol asked for a teleconference with NASA later that evening (January 27) to discuss the issue of O-ring sealing in cold temperature.
- The teleconference started at 8:45 p.m. EST and connected NASA Marshal Space Flight Center (MSFC) officials in Alabama and Florida with Morton-Thiokol in Utah. (Morton Thiokol manager Al McDonald was also in Florida). Viewgraphs were sent via fax from Utah to Alabama and Florida. See Tufte[7] for a copy of the viewgraphs.
- Thiokol engineers recommended not to launch unless air temp was at least 53 ˚F (the temperature for STS-51C) since they did not want to exceed their previous experience base for cold temperature launches with O-rings, while the predicted temperature at launch was 29 ˚F
- A MSFC project manager responded by saying "When do you want me to launch, next April?"
- When challenged, Thiokol engineers admitted they lacked statistical analysis to show the correlation of Temperature and O-ring damage (shuttle spec of 40-90 ˚F also noted)
- MSFC asked Thiokol for go/no-go recommendation
- At this point (after more than 1 hr of telecon) a Thiokol VP in Utah took them offline for 30 minutes to discuss the no-launch recommendation. The Thiokol engineers repeated their warning not to launch in cold. Another Thiokol VP said, "Take off your engineering hat and put on your management hat."
- The Telecon resumed at 11:00 p.m. A Thiokol VP said the data was inconclusive and the company recommended to launch
- MSFC official asked for dissent - none given. Al McDonald refused to sign the launch authorization on behalf of Thiokol due to his own concerns about the cold temperatures, so a Thiokol official in Utah had to sign off on the launch and fax the authorization to Florida.

There were many consequences of the Challenger disaster. It would take 32 months until the next shuttle mission was launched in September 1988. In addition to re-designing the joints of the solid rocket boosters, there were new main engines and a crew escape system was added to the shuttle. It was decided that the Shuttle would no longer launch commercial satellites, the Shuttle-Centaur program cancelled, and the secondary launch site at Vandenberg abandoned. The Department of Defense planned to make future launches on ELVs. NASA had the Endeavour built as a replacement for Challenger in 1991. It was estimated that the recovery from Challenger cost $12 billion.[1]

Among the Rogers' Commission's findings were, "The nation's reliance on the Shuttle as its principal space launch capability created a relentless pressure on NASA to increase the flight rate ... NASA must establish a flight rate that is consistent with its resources."[16] Commission member Richard Feynman, the Nobel Prize winning physicist, noted, "The argument that the same risk was flown before without failure is often accepted as an argument for the safety of accepting it again. Because of this, obvious weaknesses are accepted again and again, sometimes without a sufficiently serious attempt to remedy them or to delay a flight because of their continued presence." In Feynman's appendix to the report of the Rogers Commission,[16,21] he estimates that the failure rate of solid-fuel rockets to be about 1 in 50. It is worth noting that the Challenger was the 25th shuttle launch, and there are two solid rocket boosters in each shuttle stack.

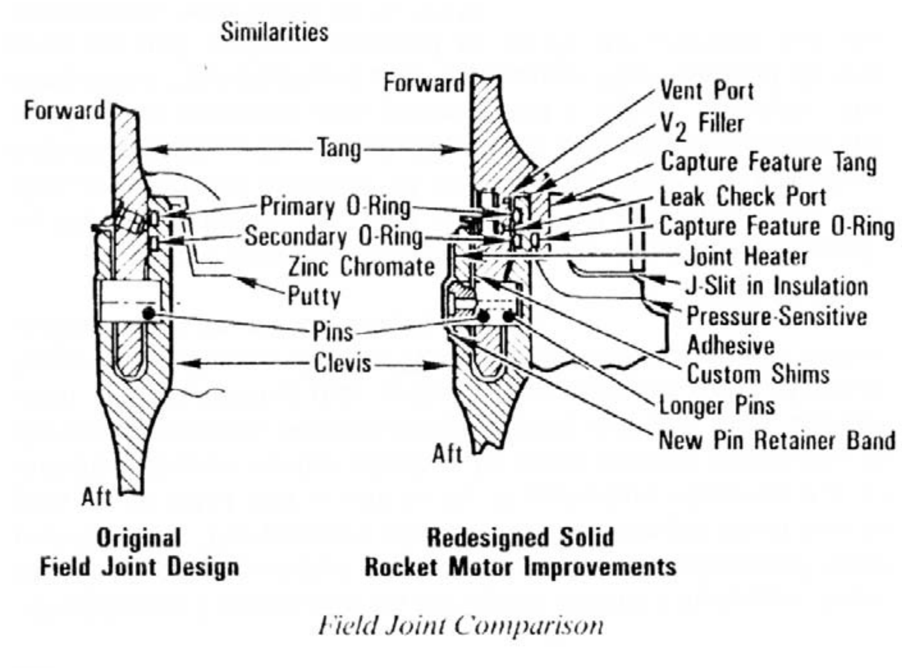


Figure 4: Re-designed SRB joint.

Columbia

On February 1, 2003, the space shuttle Columbia broke up during re-entry at the end of its mission that had started on January 16, 2003. The Columbia Accident Investigation Board (CAIB) was formed on February 12, 2003. STS-107 was the 113th Shuttle flight, and the 28th flight for Columbia.

The investigation found that a piece of insulating foam broke off of the left bipod ramp of external fuel tank and struck the wing of the orbiter 81.7 seconds after launch. At that time the shuttle was at an altitude of 65,800 ft (20,000 m) and travelling at 1650 mph (Mach 2.46). This is past the point of "max q" but still during the period when aerodynamic loads on the shuttle are high. The piece of foam was estimated to be around 24 by 15 inches in size, with a mass around 1 kg. This debris strike was not detected until the day after launch when the video and photography was reviewed. It was estimated that the piece of foam struck the shuttle with a relative velocity over 500 mph (225 m/s). The time of 81.7 s after launch is significant, as at that time the level of the cryogenic fuel in the external fuel tank would drop below the location of the bipod ramp. Thus the foam at the location goes from being surrounded by extremely cold liquid to be surrounded by the relatively warm atmospheric air. Any vapors trapped in voids in the foam will then expand as the temperature rises, providing the necessary force to loosen a piece of foam, which is then blown downwards in the aerodynamic slipstream. Figure 5 shows a picture of the shuttle on the Launchpad with the location of the left bipod ramp (where the shuttle attaches to the fuel tank) marked, as well as the location on the left wing where the foam impacted. Even though the mass of the insulating foam was very small, its relative velocity at the time of impact was high enough that the kinetic energy was sufficient to create a hole in the reinforced carbon composite sections of the leading edge of the shuttle wing.

Figure 5: Picture of Columbia shuttle stack with locations of foam and impact marked.

The shuttle crew continued their two-week mission unaware of the significance of the damage to the orbiter. On the morning of February 1, 2003, the shuttle prepared to return to earth. The timeline is as follows (all times Eastern Standard Time):

8:15 - De-orbit burn of 158 s duration to slow orbiter down from 17,500 mph (7800 m/s) at altitude of 175 miles (280 km)
8:44 - Earth atmosphere entry interface. Leading edge temperature 2500 °F (1400 °C)
8:48 - First abnormal data reading in left wing strain gage (flight recorder only)
8:49 - Speed is Ma = 24.5, Columbia rolls to right as planned
8:53 - Columbia crossed CA coast during peak heating period

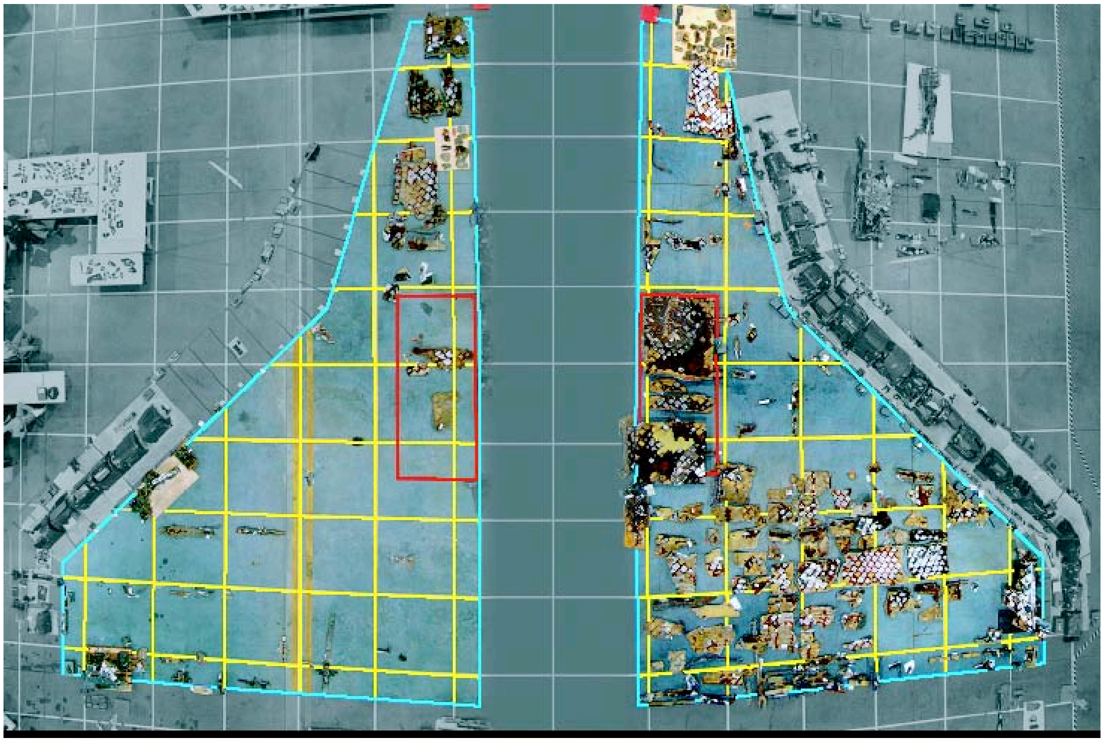
8:54 - Signs of debris shed. Altitude of 230,000 ft (70,000 m). First abnormal readings at Mission Control
8:58 - Thermal tile shed (most westerly piece of debris recovered)
8:59 - Last communication from orbiter
9:00 - Orbiter observed breaking up

The shuttle never made it to the landing site in Florida. During re-entry the breach in the RCC panel allowed hot gases (temperatures up to 5000 °F) to enter the inside of the wing. These hot gases melted the internal aluminum truss structure of the wing. The deformed wing caused increased drag on the left side of the orbiter. The automatic control systems attempted to keep the shuttle flying straight. Eventually the left wing collapsed, and the orbiter spun out of control, and the resulting aerodynamic forces broke it apart. There was no chance of crew survival at the speed (over 10,000 mph) and altitude the shuttle was travelling.[1]

The Columbia Accident Investigation board analyzed forensic analysis of debris from Columbia, in-flight data relayed to ground, and recovered data stored on the orbiter flight recorder in their analysis. They also employed computer simulations to verify their hypotheses of what happened during Columbia's launch and re-entry. Figure 6 shows a picture of the debris recovered from the shuttle wings. All pieces of the shuttle that were found by searchers were taken to a warehouse in Texas where the pieces were laid out in a grid, with each grid square corresponding to a particular location on the shuttle. Workers recovered about 38 percent of the Orbiter, totaling 84,000 pieces. It can be seen at a glance of Fig. 6 that there was clearly more damage to the left wing than the right one.

The CAIB analysis took five analytical paths – aerodynamic, thermodynamic, sensor data timeline, debris reconstruction, and imaging evidence – and all five independently arrived at the same conclusion. However, there was resistance from Marshall Space Flight Center to accept the conclusion that a piece of lightweight foam could have destroyed the space shuttle, so the CAIB took an active role in developing one final test – a piece of foam matching the size and velocity seen from the launch video would be propelled using an air gun at a mockup of the shuttle wing. The foam poked a large hole in the shuttle wing, as can be seen in the videos available from NASA.[22]

As with the Rogers Commission, the CAIB was also interested in understanding the decisions surrounding the Columbia mission. At the time of the Columbia mission, NASA was under intense pressure, largely self-imposed, to complete the construction of the International Space Station (ISS). Construction of the ISS had begun in 1998 (5 years earlier). It currently has a mass of 924,700 kg. Its solar arrays generate 84 kW of power, and it orbits at an altitude of nearly 420 km (260 miles) above the earth. The CAIB report noted, "Nearly every shuttle flight undertaken between 1999 and 2003 was in support of the *ISS*." As at the time of Challenger, NASA was trying to increase its launch rate. STS-107 was unique in that it was one of the few shuttle missions not going to the ISS. Because it was the first orbiter built, and designed in the 70s with less reliance on computer tools than today, Columbia was built to a more conservative engineering standard than the other orbiters and was heavier as a result. Thus it could not take as much cargo to the ISS as the other shuttles. Columbia was not equipped with an ISS docking system. For STS-107 the cargo bay was loaded with the SPACEHAB module for conducting science experiments in microgravity.


Lower Left wing debris

Lower Right wing debris

Figure 6: Top view of recovered debris from Columbia's wings.[1]

The CAIB also explored other incidents of foam shedding from the external fuel tank on previous shuttle missions. Of the 112 previous shuttle missions, there was quality imagining available for 79 of those missions. There was evidence of foam shedding in 65 of those 79 missions (82%). In particular, they found evidence of foam loss from the left bipod area on 10% of flights. The CAIB report also notes the original shuttle design requirements:

"*The Space Shuttle System, including the ground systems, shall be designed to preclude the shedding of ice and/or other debris from the Shuttle elements during prelaunch and flight operations that would jeopardize the flight crew, vehicle, mission success, or would adversely impact turnaround operations… No debris shall emanate from the critical zone of the External Tank on the launch pad or during ascent except for such material which may result from normal thermal protection system recession due to ascent heating.*"

Even though the shuttle requirements called for no foam to be shed from the external tank during liftoff, and engineers were aware of the problem of foam shedding on previous flights, they accepted the flight risk. This is an example of the "Normalization of deviance" described by Vaughan[14] when analyzing why the shuttle continued to fly with known problems in the SRB field joints at the time of Challenger.

The Augustine Committee[12] had noted, “And although it is a subject that meets with reluctance to open discussion, and has therefore too often been relegated to silence, the statistical evidence indicates that we are likely to lose another Space Shuttle in the next several years, probably before the planned Space Station is completely established on orbit. This would seem to be the weak link of the civil space program: unpleasant to recognize, involving all the uncertainties of statistics, and difficult to resolve.”

More specifically, the CAIB report noted a 1989 study, “Shuttle reliability is uncertain, but has been estimated to range between 97% and 99%. If the Shuttle reliability is 98%, there would be a 50-50 chance of losing an Orbiter within 34 flights. The probability of maintaining at least three Orbiters in the Shuttle fleet declines to less than 50 percent after flight 113.” With the losses of Columbia and Challenger in the first 113 shuttle flights, the actual data very closely matched the prediction of 98% reliability.

The CAIB also made a challenge to NASA, in the style of Apollo 13, of what could have been done to rescue the Columbia astronauts if they had realized the severity of the problem at the time. The response they received from NASA is that the most viable course of action would have been rescuing the STS-107 crew by launching Atlantis. “Atlantis would be hurried to the pad, launched, rendezvous with Columbia, and take on Columbia’s crew for a return. It was assumed that NASA would be willing to expose Atlantis and its crew to the same possibility of External Tank bipod foam loss that damaged Columbia.”[1] The limiting factor for how long the crew of Columbia could have stayed in space would have been the buildup of CO_2 in the orbiter.

After the loss of Columbia, the next Shuttle launch was in 2005, two and half years later. When the shuttle Discovery was launched on the return-to-flight mission in July 2005, a piece of foam of similar size to the one that doomed Columbia was captured on video falling from the external tank. This piece of foam did not strike Discovery, and occurred later in the launch when aerodynamic forces were less. In spite of all the modifications made since Columbia, the foam-shedding problem had not been solved. The shuttle fleet was grounded once again, until Discovery flew again in July 2006.

Plans were made for the Shuttles to be retired in 2010 (actual retirement in 2011). A new vehicle was to be developed names Orion with an Ares launch vehicle. The Ares launch vehicle program was later cancelled. In September 2011 a new Space Launch System (SLS) was announced with a planned development cost of $35 billion.

Ethical Considerations

There are previous publications that provide ready-to-use ethics case studies, mostly relating to Challenger.[2-5] Some additional questions that could be suitable for starting an in-class discussion or for homework include:

- If you were in the place of Roger Boisjoly or Al McDonald and were convinced it was not safe to launch Challenger, what would you have done?
- Would you have gone outside the chain of command to inform higher-level NASA management of your concerns?

- What do you think the consequences of that action would be?
- How effective were the memos that had been written about earlier problems with the O-rings?
- What would you have done if you were the engineer whose manager denied the request for further imagery of damage to Columbia?

Communication Skills

The authors of the CAIB report noted that when they asked NASA for specific information, more often than not they would receive a copy of PowerPoint slides, leading to the following observation: "The Board views the endemic use of PowerPoint briefing slides instead of technical papers as an illustration of the problematic methods of technical communication at NASA."[1] Edward Tufte analyzed the viewgraphs that were used in the teleconference the night before the Challenger launch[7] as well as how results from some analysis of potential damage to Columbia was presented[8] while Columbia was still in orbit with a chance to save the astronauts. This provides a good starting point to discuss with the students the most effective ways of presenting information to other engineers and to management. Some specific activities that could be requested of students:

- How could Thiokol engineers have presented their case better on the effects of cold weather on the O-rings?[7]
- How could the analysis from the Crater model predicting damage from the piece of foam on shuttle thermal tiles been presented?[8]
- What are the merits of PowerPoint Presentations vs. Technical Reports written in Microsoft Word?

Conclusions

Even after their retirement, the Space Shuttles still evoke a great deal of interest from students. Studies of the shuttles can be used to stimulate students' interest in their technical studies, as well as touching on ABET outcomes such as ethics (f) and lifelong learning (i). Additional activities for in-class discussion or homework/project investigation include:

- How would you re-design the joint seals on the SRB?
- What escape options could you make for the shuttle crew?
- What different configuration of the shuttle stack could have been used that would be safer?
- Compare the advantages of different possible spaceship designs for low-earth orbit (LEO), including the shuttle, a lifting-body configuration, or a single-stage launch-to-orbit vehicle (such as X-33)?
- What are the advantages of manned space flight compared to unmanned spaceflight?
- How should the experiences with the shuttle affect future designs for space vehicles?
- What are the merits of hydrogen fuel vs. RP1 or other fuels?

Further reading that could be assigned to the students includes books on general engineering disasters,[23-24] and references specifically on space systems disasters.[25-27]

Notes on Bibliographic Sources

Students should also be challenged to perform a critical evaluation of sources, including analyzing biases of the authors. It is highly recommended that students are assigned to read the CAIB report.[1] It provides a great deal of technical information and analysis, presented at a level easy for undergraduate engineering students to understand. Vaughan's book[15] focuses on the process of "normalization of deviance" that led to acceptance of continuing to fly with the flight risks poised by the O-rings. One of the Appendices also gives a brief description of the original competition for the booster contract. Engineering students will likely prefer reading McDonald's book[20] to other accounts of the Challenger disaster. In the Appendix, co-author Hansen[20] gives his comments on the books written about Challenger prior to that time, in particular noting the authors of Power to Explore[17] take a revisionist approach, attempting to exonerate Marshall Space Flight Center from some of the blame for the Challenger launch decision.

Bibliography

1. Columbia Accident Investigation Board (CAIB) Report. (2003) Government Printing Office. http://www.nasa.gov/columbia/caib/html/start.html
2. Brocato, J. (2009) Two Ways of Using Case Studies to Teach Ethics. Proceedings of the 2000 ASEE Conference. AC 2009-1565.
3. Evers, C.T. (2011) A Case Study-based Graduate Course in Engineering Ethics and Professional Responsibility. Proceedings of the 2011 ASEE Annual Conference. AC 2011-1501.
4. Hoffman, T.J., Shooter, S.B., Zappe, C.J., and O'Donnell, M.R. (2002) A Study of Risk Communication in Engineering and Management Curricula. Proceedings of the 2002 ASEE Annual Conference.
5. Hoover, K. & Fowler, W.T. (2006) "Studies in Ethics, Safety, and Liability for Engineers: Space Shuttle Challenger". The University of Texas at Austin and Texas Space Grant Consortium. http://www.tsgc.utexas.edu/archive/general/ethics/shuttle.html and http://ethics.tamu.edu/Portals/3/Case%20Studies/Shuttle.pdf
6. Niewoehner, R., Steidle, C., and Johnson, E. (2008) The Loss of the Space Shuttle Columbia: Portaging the Leadership Lessons with a Critical Thinking Model. Proceedings of the 2008 ASEE Conference. AC 2008-539.
7. Tufte, E.R. (1997) Visual Explanations. Graphics Press. (pp. 38-53 discuss Challenger)
8. Tufte, E.R. (2006) The Cognitive Style of PowerPoint. Graphics Press.
9. Heppenheimer , T.A. (2002) Space Shuttle Decision, 1965-1972 (History of the Space Shuttle, Volume 1) Smithsonian Institution Scholarly Press. http://history.nasa.gov/SP-4221/sp4221.htm
10. Hale, W., Lane, H., Chapline, G., Lula, K. (2011) Wings in Orbit: Scientific and Engineering Legacies of the Space Shuttle, 1971-2010. NASA SP-2010-3409 http://www.nasa.gov/centers/johnson/wingsinorbit/index.html
11. NASA (2013) NASA Technical Reports Server (NTRS). Ntrs.nasa.gov
12. Augustine Report - Report of the Advisory Committee On the Future of the U.S. Space Program. December 1990. http://www.history.nasa.gov/augustine/racfup1.htm
13. Wolsko, T.D. (1980) A Preliminary Assessment of the Satellite Power System (SPS) and Six Other Energy Technologies. Argonne National Laboratory Report ANL/AA-20.
14. Esch, K. (1986) How NASA Prepared to Cope with Disaster. *IEEE Spectrum*, March 1986, pp. 32-36.
15. Vaughan, D. (1997) The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA. University of Chicago Press.
16. Report of the Presidential Commission on the Space Shuttle Challenger Accident (1986). Available at http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/table-of-contents.html or http://history.nasa.gov/rogersrep/51lcover.htm
17. Dunar, A.J. and Waring, S.P. (1991) Power to Explore: History of Marshall Space Flight Center 1960-1990. NASA SP-4313. (Chapter 9 deals with Challenger) http://history.msfc.nasa.gov/book/chptnine.pdf
18. Chiles, J. R. (2008). Inviting Disaster: Lessons from the Edge of Technology. HarperCollins Publishers.
19. Lawson, D. (2004) Engineering Disasters: Lessons to be Learned. ASME Press.

20. McDonald, A. and Hansen, J.R. (2012) Truth, Lies, and O-Rings: Inside the Space Shuttle Challenger Disaster. University Press of Florida.
21. Feynman, R.P. (1988) What do You Care What Other People Think? (1988). Norton publisher.
22. Columbia Accident Investigation Report, Volume 1: Movie Clips. (2003) (6 videos total available) http://www.nasa.gov/columbia/caib/html/movies.html
23. Petroski, H. (1992) To Engineer Is Human: The Role of Failure in Successful Design. Vintage Press.
24. Schlager , N. (1994) When Technology Fails: Significant Technological Disasters, Accidents, and Failures of the Twentieth Century. Gale Research.
25. Harland, D., and Lorenz, R. (2005) Space Systems Failures: Disasters and Rescues of Satellites, Rocket and Space Probes. Springer Praxis Books.
26. Newman, J. (2001) Failure Space: A Systems Engineering Look at 50 Space Systems Failures, *Acta Astronautics*, Vol. 48, pp. 517-527.
27. Tomei, E.J., and Chang, I.S. (2009) 51 Years of Space Launches and Failures. 60th International Astronautics Conference. pp. 7117-7129.