APPLICATION

THE SPACE SHUTTLE *CHALLENGER* AND *COLUMBIA* ACCIDENTS

The NASA Space Shuttle Disasters

The space shuttle is one of the most complex engineered systems ever built. The challenge of lifting a space vehicle from earth into orbit and have it safely return to earth presents many engineering problems. Not surprisingly, there have been several accidents in the U.S. space program since its inception, including two failures of the space shuttle. The disasters involving the space shuttles *Challenger* and *Columbia* illustrate many of the issues related to engineering ethics as shown in the following discussion. The space shuttle originally went into service in the early 1980s and is set to be retired sometime in 2011 or 2012.

The Space Shuttle *Challenger* Disaster

The explosion of the space shuttle *Challenger* is perhaps the most widely written about case in engineering ethics because of the extensive media coverage at the time of the accident and also because of the many available government reports and transcripts of congressional hearings regarding the explosion. The case illustrates many important ethical issues that engineers face: What is the proper role of the engineer when safety issues are a concern? Who should have the ultimate decision-making authority to order a launch? Should the ordering of a launch be an engineering or a managerial decision? This case has already been presented briefly, and we will now take a more in-depth look.

Background

The space shuttle was designed to be a reusable launch vehicle. The vehicle consists of an orbiter, which looks much like a medium-sized airliner (minus the engines!), two solid-propellant boosters, and a single liquid-propellant booster. At takeoff, all of the boosters are ignited and lift the orbiter out of the earth's atmosphere. The solid rocket boosters are only used early in the flight and are jettisoned soon after takeoff, parachute back to earth, and are recovered from the ocean. They are subsequently repacked with fuel and are reused. The liquid-propellant booster is used to finish lifting the shuttle into orbit, at which point the booster is jettisoned and burns up during reentry. The liquid booster is the only part of the shuttle vehicle that is not reusable. After completion of the mission, the orbiter uses its limited thrust capabilities to reenter the atmosphere and glides to a landing.

The accident on January 28, 1986, was blamed on a failure of one of the solid rocket boosters. Solid rocket boosters have the advantage that they deliver far more thrust per pound of fuel than do their liquid-fueled counterparts, but have the disadvantage that once the fuel is lit, there is no way to turn the booster off or even to control the amount of thrust produced. In contrast, a liquid-fuel rocket can be controlled by throttling the supply of fuel to the combustion chamber or can be shut off by stopping the flow of fuel entirely.

In 1974, NASA awarded the contract to design and build the solid rocket boosters for the shuttle to Morton Thiokol. The design that was submitted by Thiokol was a scaled-up version of the Titan missile, which had been used successfully for many years to launch satellites. This design was accepted by NASA in 1976. The solid rocket consists of several cylindrical pieces that are filled with solid propellant and stacked one on top of the other to form the completed booster. The assembly of the propellant-filled cylinders was performed at Thiokol's plant in Utah. The cylinders were then shipped to the Kennedy Space Center in Florida for assembly into a completed booster.

A key aspect of the booster design are the joints where the individual cylinders come together, known as the field joints, illustrated schematically in Figure 1.1a. These are tang and clevis joints, fastened with 177 clevis pins. The joints are sealed by two O-rings, a primary and a secondary. The O-rings are designed to prevent hot gases from the combustion of the solid propellant from escaping. The O-rings are made from a type of synthetic rubber and so are not particularly heat resistant. To prevent the hot gases from damaging the O-rings, a heat-resistant putty is placed in the joint. The Titan booster had only one O-ring in the field joint. The second O-ring was added to the booster for the shuttle to provide an extra margin of safety since, unlike the Titan, this booster would be used for a manned space craft.

Early Problems with the Solid Rocket Boosters

Problems with the field-joint design had been recognized long before the launch of the *Challenger.* When the rocket is ignited, the internal pressure causes the booster wall to expand outward, putting pressure on the field joint. This pressure causes the joint to open slightly, a process called "joint rotation," illustrated in Figure 1.1b. The joint was designed so that the internal pressure pushes on the putty, displacing the primary O-ring into this gap, helping to seal it. During testing of the boosters in 1977, Thiokol became aware that this joint-rotation problem was more severe than on the Titan and discussed it with NASA. Design changes were made, including an increase in the thickness of the O-ring, to try to control this problem.

Further testing revealed problems with the secondary seal, and more changes were initiated to correct that problem. In November of 1981, after the second shuttle flight, a postlaunch examination of the booster field joints indicated that the

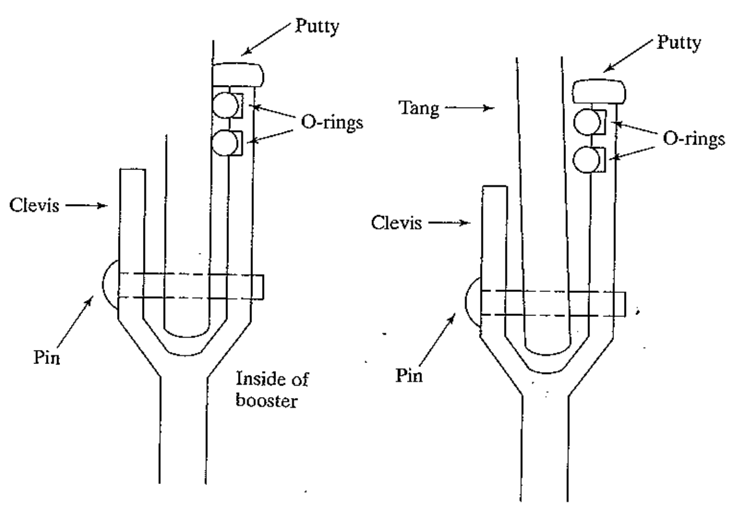


Figure 1.1

(a) A schematic drawing of a tang and clevis joint like the one on the *Challenger* solid rocket boosters.

(b) The same joint as in Figure 1.1a, but with the effects of joint rotation exaggerated. Note that the O-rings no longer seal the joint.

O-rings were being eroded by hot gases during the launch. Although there was no failure of the joint, there was some concern about this situation, and Thiokol looked into the use of different types of putty and alternative methods for applying it to solve the problem. Despite these efforts, approximately half of the shuttle flights before the *Challenger* accident had experienced some degree of O-ring erosion. Of course, this type of testing and redesign is not unusual in engineering. Seldom do things work correctly the first time, and modifications to the original design are often required.

It should be pointed out that erosion of the O-rings is not necessarily a bad thing. Since the solid rocket boosters are only used for the first few minutes of the flight, it might be perfectly acceptable to design a joint in which O-rings erode in a controlled manner. As long as the O-rings don't completely burn through before the solid boosters run out of fuel and are jettisoned, this design should be fine. However, this was not the way the space shuttle was designed, and O-ring erosion was one of the problems that the Thiokol engineers were addressing.

The first documented joint failure came after the launch on January 24, 1985, which occurred during very cold weather. The postflight examination of the boosters revealed black soot and grease on the outside of the booster, which indicated that hot gases from the booster had blown by the O-ring seals. This observation gave rise to concern about the resiliency of the O-ring materials at reduced temperatures. Thiokol performed tests of the ability of the O-rings to compress to fill the joints and found that they were inadequate. In July of 1985, Thiokol engineers redesigned the field joints without O-rings. Instead, they used steel billets, which should have been better able to withstand the hot gases. Unfortunately, the new design was not ready in time for the *Challenger* flight in early 1986 [Elliot et al., 1990].

The Political Climate

To fully understand and analyze the decision making that took place leading to the fatal launch, it is important also to discuss the political environment under which NASA was operating at that time. NASA's budget was determined by Congress, which was becoming increasingly unhappy with delays in the shuttle project and shuttle performance. NASA had billed the shuttle as a reliable, inexpensive launch vehicle for a variety of scientific and commercial purposes, including the launching of commercial and military satellites. It had been promised that the shuttle would be capable of frequent flights (several per year) and quick turnarounds and would be competitively priced with more traditional nonreusable launch vehicles. NASA was feeling some urgency in the program because the European Space Agency was developing what seemed to be a cheaper alternative to the shuttle, which could potentially put the shuttle out of business.

These pressures led NASA to schedule a record number of missions for 1986 to prove to Congress that the program was on track. Launching a mission was especially important in January 1986, since the previous mission had been delayed numerous times by both weather and mechanical failures. NASA also felt pressure to get the *Challenger* launched on time so that the next shuttle launch, which was to carry a probe to examine Halley's comet, would be launched before a Russian probe designed to do the same thing. There was additional political pressure to launch the *Challenger* before the upcoming state-of-the-union address, in which President Reagan hoped to mention the shuttle and a special astronaut—the first teacher in space, Christa McAuliffe—in the context of his comments on education.

The Days Before the Launch

Even before the accident, the *Challenger* launch didn't go off without a hitch, as NASA had hoped. The first launch date had to be abandoned due to a cold front expected to move through the area. The front stalled, and the launch could have taken place on schedule. But the launch had already been postponed in deference to Vice President George Bush, who was to attend. NASA didn't want to antagonize Bush, a strong NASA supporter, by postponing the launch due to inclement weather after he had arrived. The launch of the shuttle was further delayed by a defective microswitch in the hatch-locking mechanism. When this problem was resolved, the front had changed course and was now moving through the area. The front was expected to bring extremely cold weather to the launch site, with temperatures predicted to be in the low 20's (°F) by the new launch time.

Given the expected cold temperatures, NASA checked with all of the shuttle contractors to determine if they foresaw any problems with launching the shuttle in cold temperatures. Alan McDonald, the director of Thiokol's Solid Rocket Motor Project, was concerned about the cold weather problems that had been experienced with the solid rocket boosters. The evening before the rescheduled launch, a teleconference was arranged between engineers and management from the Kennedy Space Center, NASA's Marshall Space Flight Center in Huntsville, Alabama, and Thiokol in Utah to discuss the possible effects of cold temperatures on the performance of the solid rocket boosters. During this teleconference, Roger Boisjoly and Arnie Thompson, two Thiokol engineers who had worked on the solid-propellant booster design, gave an hour-long presentation on how the cold weather would increase the problems of joint rotation and sealing of the joint by the O-rings.

The engineers' point was that the lowest temperature at which the shuttle had previously been launched was 53°F, on January 24, 1985, when there was blow-by of the O-rings. The O-ring temperature at *Challenger's* expected launch time the following morning was predicted to be 29°F, far below the temperature at which NASA had previous experience. After the engineers' presentation, Bob Lund, the vice president for engineering at Morton Thiokol, presented his recommendations. He reasoned that since there had previously been severe O-ring erosion at 53°F and the launch would take place at significantly below this temperature where no data and no experience were available, NASA should delay the launch until the O-ring temperature could be at least 53°F. Interestingly, in the original design, it was specified that the booster should operate properly down to an outside temperature of 31°F.

Larry Mulloy, the Solid Rocket Booster Project manager at Marshall and a NASA employee, correctly pointed out that the data were inconclusive and disagreed with the Thiokol engineers. After some discussion, Mulloy asked Joe Kilminster, an engineering manager working on the project, for his opinion. Kilminster backed up the recommendation of his fellow engineers. Others from Marshall expressed their disagreement with the Thiokol engineers' recommendation, which prompted Kilminster to ask to take the discussion off line for a few minutes. Boisjoly and other engineers reiterated to their management that the original decision not to launch was the correct one.

A key fact that ultimately swayed the decision was that in the available data, there seemed to be no correlation between temperature and the degree to which blow-by gasses had eroded the O-rings in previous launches. Thus, it could be concluded that there was really no trend in the data indicating that a launch at the expected temperature would necessarily be unsafe. After much discussion, Jerald Mason, a senior manager with Thiokol, turned to Lund and said, "Take off your engineering hat and put on your management hat," a phrase that has become famous in engineering ethics discussions. Lund reversed his previous decision and recommended that the launch proceed. The new recommendation included an indication that there was a safety concern due to the cold weather, but that the data were inconclusive and the launch was recommended. McDonald, who was in Florida, was surprised by this recommendation and attempted to convince NASA to delay the launch, but to no avail.

Table 1.1 Space Shuttle *Challenger* Accident: Who's Who

	Organizations
NASA	The National Aeronautics and Space Administration, responsible for space exploration. The space shuttle is one of NASA's programs
Marshall Space Flight Center	A NASA facility that was in charge of the solid rocket booster development for the shuttle
Morton Thiokol	A private company that won the contract from NASA for building the solid rocket boosters for the shuttle
	People
NASA	
Larry Mulloy	Solid Rocket Booster Project manager at Marshall
Morton Thiokol	
Roger Boisjoly Arnie Johnson	Engineers who worked on the Solid Rocket Booster Development Program
Joe Kilminster	Engineering manager on the Solid Rocket Booster Development Program
Alan McDonald	Director of the Solid Rocket Booster Project
Bob Lund	Vice president for engineering
Jerald Mason	General manager

The Launch

Contrary to the weather predictions, the overnight temperature was 8°F, colder than the shuttle had ever experienced before. In fact, there was a significant accumulation of ice on the launchpad from safety showers and fire hoses that had been left on to prevent the pipes from freezing. It has been estimated that the aft field joint of the right-hand booster was at 28°F.

NASA routinely documents as many aspects of launches as possible. One part of this monitoring is the extensive use of cameras focused on critical areas of the launch vehicle. One of these cameras, looking at the right booster, recorded puffs of smoke coming from the aft field joint immediately after the boosters were ignited. This smoke is thought to have been caused by the steel cylinder of this segment of the booster expanding outward and causing the field joint to rotate. But, due to the extremely cold temperature, the O-ring didn't seat properly. The heat-resistant putty was also so cold that it didn't protect the O-rings, and hot gases burned past both O-rings. It was later determined that this blow-by occurred over 70° of arc around the O-rings.

Very quickly, the field joint was sealed again by byproducts of the solid rocket-propellant combustion, which formed a glassy oxide on the joint. This oxide formation might have averted the disaster had it not been for a very strong wind shear that the shuttle encountered almost one minute into the flight. The oxides that were temporarily sealing the field joint were shattered by the stresses caused by the wind shear. The joint was now opened again, and hot gases escaped from the solid booster. Since the booster was attached to the large liquid-fuel booster, the flames from the solid-fuel booster blow-by quickly burned through the external tank. The liquid propellant was ignited and the shuttle exploded.

The Aftermath

As a result of the explosion, the shuttle program was grounded as a thorough review of shuttle safety was conducted. Thiokol formed a failure-investigation team on January 31, 1986, which included Roger Boisjoly. There were also many investigations into the cause of the accident, both by the contractors involved (including Thiokol) and by various government bodies. As part of the governmental investigation, President Reagan appointed a blue-ribbon commission, known as the Rogers Commission, after its chair. The commission consisted of distinguished scientists and engineers who were asked to look into the cause of the accident and to recommend changes in the shuttle program.

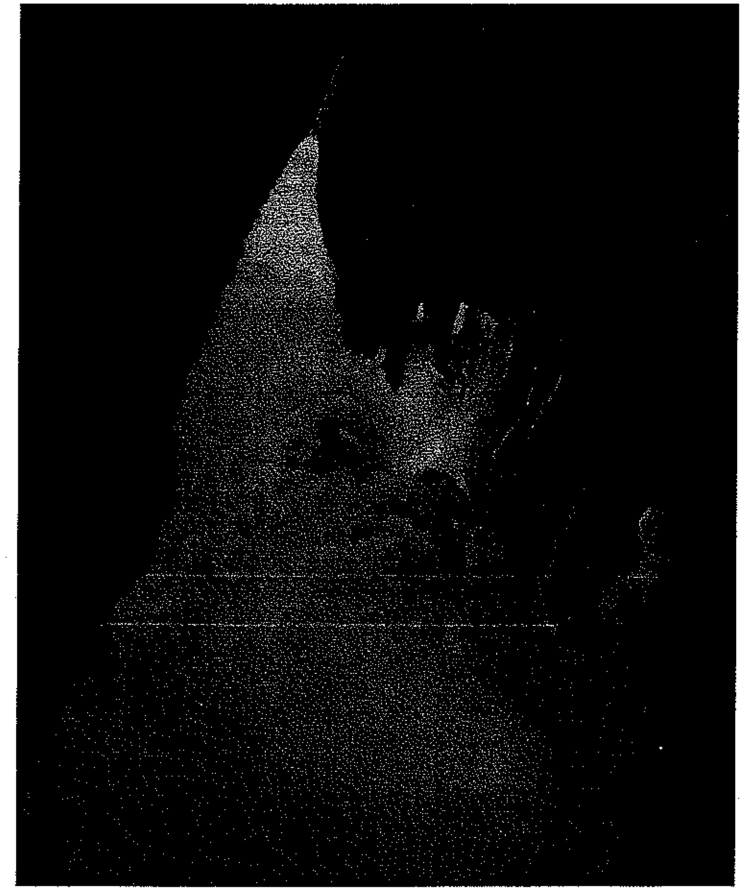
One of the commission members was Richard Feynman, a Nobel Prize winner in physics, who ably demonstrated to the country what had gone wrong. In a demonstration that was repeatedly shown on national news programs, he demonstrated the problem with the O-rings by taking a sample of the O-ring material and bending it. The flexibility of the material at room temperature was evident. He then immersed it in ice water. When Feynman again bent the O-ring, it was obvious that the resiliency of the material was severely reduced, a very clear demonstration of what happened to the O-rings on the cold launch date in Florida.

As part of the commission hearings, Boisjoly and other Thiokol engineers were asked to testify. Boisjoly handed over to the commission copies of internal Thiokol memos and reports detailing the design process and the problems that had already been encountered. Naturally, Thiokol was trying to put the best possible spin on the situation, and Boisjoly's actions hurt this effort. According to Boisjoly, after this action he was isolated within the company, his responsibilities for the redesign of the joint were taken away, and he was subtly harassed by Thiokol management [Boisjoly, 1991, and Boisjoly, Curtis, and Mellicam, 1989].

Eventually, the atmosphere became intolerable for Boisjoly, and he took extended sick leave from his position at Thiokol. The joint was redesigned, and the shuttle has since flown numerous successful missions. However, the ambitious launch schedule originally intended by NASA was never met. It was reported in 2001 that NASA has spent $5 million to study the possibility of installing some type of escape system to protect the shuttle crew in the event of an accident. Possibilities include ejection seats or an escape capsule that would work during the first three minutes of flight. These features were incorporated into earlier manned space vehicles and in fact were in place on the shuttle until 1982. Whether such a system would have saved the astronauts aboard the *Challenger* is unknown, and ultimately an escape system was never incorporated into the space shuttle.

The Space Shuttle *Columbia* Failure

During the early morning hours of February 1, 2003, many people across the Southwestern United States awoke to a loud noise, sounding like the boom associated with supersonic aircraft. This was the space shuttle *Columbia* breaking up during reentry to the earth's atmosphere. This accident was the second loss of a space shuttle in 113 flights—all seven astronauts aboard the *Columbia* were killed—and pieces of the shuttle were scattered over a wide area of eastern Texas and western Louisiana. Over 84,000 individual pieces were eventually recovered, comprising only about 38% of the shuttle.



Explosion of the space shuttle *Challenger* soon after liftoff in January 1986. NASA/ Johnson Space Center

This was the 28th mission flown by the *Columbia*, a 16-day mission involving many tasks. The first indication of trouble during reentry came when temperature sensors near the left wheel well indicated a rise in temperature. Soon, hydraulic lines on the left side of the craft began to fail, making it difficult to keep control of the vehicle. Finally, it was impossible for the pilots to maintain the proper positioning of the shuttle during reentry—the *Columbia* went out of control and broke up.

The bottom of the space shuttle is covered with ceramic tiles designed to dissipate the intense heat generated during reentry from space. The destruction of the *Columbia* was attributed to damage to tiles on the leading edge of the left wing. During liftoff, a piece of insulating foam on the external fuel tank dislodged and struck the shuttle. It was estimated that this foam struck the shuttle wing at over 500 miles per hour, causing significant damage to the tiles on the wing over an area of approximately 650 cm^2. With the integrity of these tiles compromised, the wing structure was susceptible to extreme heating during reentry and ultimately failed.

Shuttle launches are closely observed by numerous video cameras. During this launch, the foam separation and strike had been observed. Much thought was given during *Columbia*'s mission to attempting to determine whether significant damage had occurred. For example, there was some discussion of trying to use ground-based telescopes to look at the bottom of the shuttle while in orbit. Unfortunately, even if it had been possible to observe the damage, there would have been no way to repair the damage in space. The only alternatives would have been to attempt to launch another shuttle on a dangerous rescue mission, or attempt to get the astronauts to the space station in the hopes of launching a later rescue mission to bring them back to earth. In the end, NASA decided that the damage from the foam strike had probably not been significant and decided to continue with the mission and reentry as planned.

This was not the first time that foam had detached from the fuel tank during launch, and it was not the first time that foam had struck the shuttle. Apparently numerous small pieces of foam hit the shuttle during every launch, and on at least seven occasions previous to the *Columbia* launch, large pieces of foam had detached and hit the shuttle. Solutions to the problem had been proposed over the years, but none had been implemented. Although NASA engineers initially identified foam strikes as a major safety concern for the shuttle, after many launches with no safety problems due to the foam, NASA management became complacent and overlooked the potential for foam to cause major problems. In essence, the prevailing attitude suggested that if there had been numerous launches with foam strikes before, with none leading to major accidents, then it must be safe to continue launches without fixing the problem.

In the aftermath of this mishap, an investigative panel was formed to determine the cause of the accident and to make recommendations for the future of the shuttle program. The report of this panel contained information on their findings regarding the physical causes of the accident: the detachment of the foam, the damage to the tiles, and the subsequent failure of critical components of the shuttle. More significantly, the report also went into great depth on the cultural issues within NASA that led to the accident. The report cited a "broken safety culture" within NASA. Perhaps most damning was the assessment that many of the problems that existed within NASA that led to the *Challenger* accident sixteen years earlier had not been fixed. Especially worrisome was the finding that schedule pressures had been allowed to supercede good engineering judgment. An accident such as the *Challenger* explosion should have led to a major change in the safety and ethics culture within NASA. But sadly for the crew of the *Columbia,* it had not.

After the *Columbia* accident, the space shuttle was once again grounded until safety concerns related to foam strikes could be addressed. By 2005, NASA was confident that steps had been taken to make the launch of the shuttle safe and once again restarted the launch program. In July of 2005, *Discovery* was launched. During this launch, another foam strike occurred. This time, NASA was prepared and had planned for means to photographically assess the potential damage to the heat shield, and also planned to allow astronauts to make a space walk to assess the damage to the tiles and to make repairs as necessary. The damage from this strike was repaired in space and the shuttle returned to earth safely. Despite the success of the in-orbit repairs, NASA again grounded the shuttle fleet until a redesign of the foam could be implemented. The redesign called for removal of foam from areas where foam detachment could have the greatest impact on tiles. The shuttle resumed flight with a successful launch in September of 2006 and no further major accidents through early 2011.

SUMMARY

Engineering ethics is the study of moral decisions that must be made by engineers in the course of engineering practice. It is important for engineering students to study ethics so that they will be prepared to respond appropriately to ethical challenges during their careers. Often, the correct answer to an ethical problem will not be obvious and will require some analysis using ethical theories. The types of problems that we will encounter in studying engineering ethics are very similar to the design problems that engineers work on every day. As in design, there will not be a single correct answer. Rather, engineering ethics problems will have multiple correct solutions, with some solutions being better than others.

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Columbia Accident Investigation Board, Information on the investigation including links to the final report can be found at the board's website, caib.nasa.gov, or on the NASA website, www.nasa.gov.