National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Tough Transitions

March 1981: Twelve years had passed since astronauts first landed on the moon, six years had passed since the legendary Apollo program had come to a close, and a new chapter in human spaceflight was about to begin. Space Shuttle Columbia, the first reusable launch system and orbital spacecraft, would soon embark upon its maiden voyage. The Space Shuttle had been in development since the early 1970's, and its initial test flight, STS-1, was over two years behind schedule. As ground crews worked diligently to prepare for the launch, a group of technicians collapsed inside Columbia's nitrogen-filled aft compartment after a countdown demonstration test on March 19. STS-1 Pilot Bob Crippen recalled that day: "About a month before the first flight, John (Young) and I were at the Kennedy Space Center doing a Terminal Countdown Demonstration Test, which is pretty much a dry run of what actually goes on when you go launch a Shuttle. The test went great. John and I climbed out of the cockpit, went back to the crew quarters at the O&C Building, and we were patting each other on the back and said 'Hey, we're getting pretty close to flight.' That was when we got the bad news. There had been an accident at the Pad." Nitrogen exposure would claim three of the technicians' lives.

Background

Space Shuttle Program

NASA had been developing early designs for the space shuttle years before Apollo's first lunar landing in 1969. When President Richard Nixon authorized the development of reusable space exploration vehicles three years later, those designs became a springboard from which NASA launched the project known officially as the Space Transportation System (STS) and unofficially as the Space Shuttle Program. The Space Shuttle grew into a significantly more complex system than earlier human spaceflight programs. The vehicle's intricate launch and reentry configurations challenged flight crew safety considerations, and the decision to fly astronauts on the first (or any) launch rested upon successful test and quality control processes.

In June 1974, Rockwell International (now owned by The Boeing Company) began work on the first orbiter, which NASA named Enterprise in response to a massive write-in campaign by *Star Trek* fans. Enterprise never left the atmosphere, but flew approach and landing tests to help verify the reliability and redundancy of the Space Shuttle's design.

Figure 1: Space Shuttle Columbia prior to the STS-1 launch.

STS-1 Mission Objectives

The first operational orbiter, Columbia, arrived at Kennedy Space Center (KSC) atop a modified 747 in March 1979. On STS-1, its first mission, Columbia would carry a Development Flight Instrumentation package as its only payload. This package contained sensors and measuring devices that would record orbiter performance and log stresses encountered during each stage of the flight profile. The flight's primary mission objectives were to safely ascend into orbit, check all systems, and return to Earth landing as an unpowered glider.

Three Technicians Die Before Space Shuttle Columbia's Inaugural Launch

Proximate Cause:

- **Oxygen-deficient environment in aft compartment renders workers unconscious and hampers rescue efforts.**

Underlying Issues:

- **Unclear and Incomplete Procedures**
- **Communications Breakdown**
- **Inadequate Controls and Recovery Systems**
- **Competing Operations Philosophies**
- **Failure to address recurring causes of earlier mishaps**

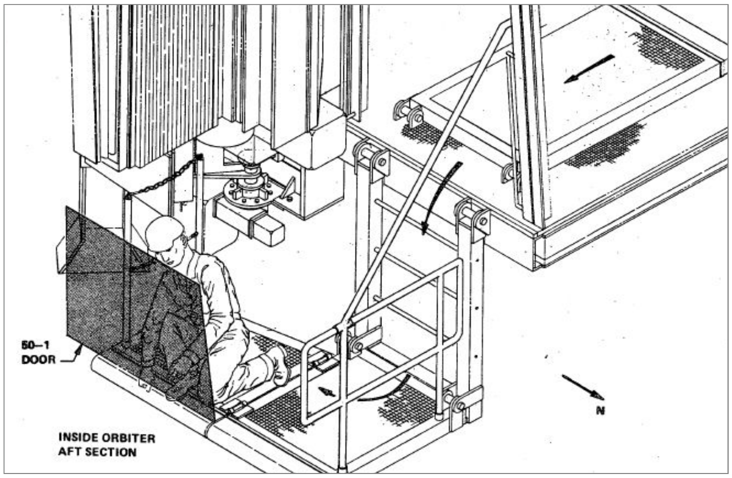

Figure 2: The curtained 50-1 door granted access to the shuttle's aft crew compartment.

What Happened

Test Modifications

After a flight readiness firing on February 20, 1981, ground teams suspected a gaseous nitrogen (GN_2) leak in Space Shuttle Columbia's aft service compartment. One month later, the issue prompted engineers to conduct a special test to check for the leak during a scheduled countdown demonstration test (CDT). The CDT included a GN_2 purge that would replace the air in the orbiter's aft compartment with gaseous nitrogen. Test teams agreed that extending the duration of the GN_2 purge would allow them to investigate the suspected GN_2 intrusion. Operators discussed and approved this deviation at a pre-task meeting, but the written deviation only included the steps, not the time required to do the extended purge. The deviation was not recognized as one that affected a hazardous operation because the box that indicated an increased hazard level was marked "no." Therefore, neither contractor nor NASA Safety reviewed the deviation. Because the time requirement was missing, the deviation was processed as though the purge would be completed during the existing planned period and the GN_2 purge extension did not appear on the integrated schedule. This was one of 500 approved deviations for the CDT.

Access Controls Dropped

Rockwell International (RI) technicians John Bjornstad, Forrest Cole, and William Wolford arrived at the shuttle access point on the 130-foot level of the rotating service structure (RSS) and checked in at the monitor station at 9:15 am. The orbiter aft compartment was located behind the curtained 50-1 door (Figure 2), and Bjornstad entered first. Cole followed, and Wolford entered third.

At 9:21 am, RI technician Jimmy Harper arrived at the 50-1 door to discover Wolford and Bjornstad unconscious inside the compartment (Figure 3). Harper entered to help the fallen men, but in doing so collapsed backward onto the service platform just outside the 50-1 door. RI technician Nick Mullon and RI quality inspector W. Corbitt arrived at the threshold as Harper fell. Spotting the unconscious technicians through the door, Mullon was able to drag Wolford out of the compartment while Corbitt called for help.

At 9:22 am, Harper regained consciousness and notified the compartment control monitor that ammonia or hydrazine could be present in the aft section of the orbiter and that workers in the area were blacking out. Upon hearing this, the control monitor contacted the pad leader and called rescue teams to the accident site. Meanwhile, Corbitt and Mullon removed Bjornstad from the compartment. Mullon passed out before rescue crews arrived.

At 9:24 am, the systems engineer running the GN_2 purge overheard the emergency calls and initiated the switchover from GN_2 to air. It would take two minutes before the Launch Processing System (LPS) would indicate airflow to the orbiter's mid/aft fuselage.

At 9:28 am, fire and rescue crews removed the last technician, Forrest Cole, from the aft compartment. Rescuers engaged resuscitation efforts and rushed Bjornstad, Cole, Mullon, Harper, and Wolford to the hospital within 30 minutes of rescue. John Bjornstad, who had been exposed to GN_2 for approximately 6-10 minutes, was never resuscitated and died within 3 hours of the exposure. Forrest Cole, who had been exposed to GN_2 for approximately 14 minutes, died 13 days after the incident. Nick Mullon died several years later from complications resulting from the GN_2 exposure. The other technicians recovered from their injuries. Columbia was undamaged.

Proximate Cause

After subsequent investigations, it became apparent that the injuries and deaths occurred because the technicians entered a pure nitrogen atmosphere. Analysis found that the men were exposed to this hazard because the test conductors, the NASA Test Director (NTD), and other involved personnel lacked formal communication regarding the extended GN_2 purge. As a result of the miscommunication, pad personnel dropped access controls prematurely.

Underlying Issues

Unclear and Incomplete Procedures

When operators agreed to perform the intrusion test, they formulated Operations & Maintenance Instruction (OMI) Deviation 13-20. The CDT procedure included a GN_2 to air transfer, and the deviation was inserted just prior to that step. The CDT procedure also did not include steps for opening the pad for work after completion of the test. The deviation delineated steps for carrying out the test, but it did not discuss procedures to close the launch pad for the hazardous GN_2 condition or to reopen it once the purge was complete. Deviation

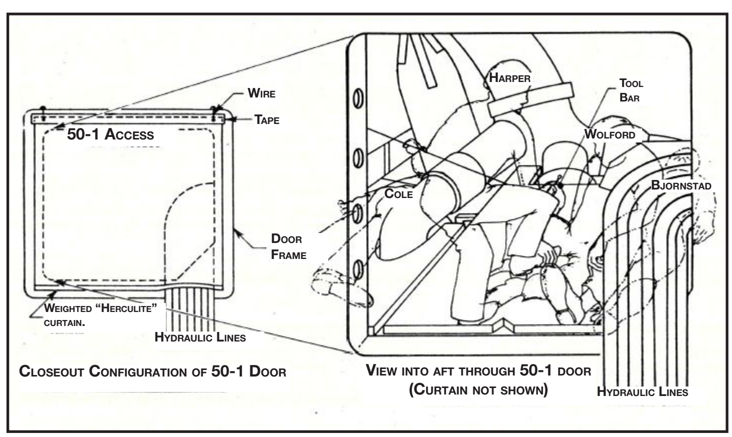

Figure 3: View into aft compartment from the platform outside the 50-1 door depicting approximate locations of fallen technicians at around 9:21 am.

13-20 also failed to specify that the GN_2 purge would be extended to accommodate the intrusion test, so controllers processed the activity as though it would take place during the planned GN_2 hazard period. The box on the deviation used to indicate an increased hazard level was marked "no." The change, therefore, had no apparent impact on the CDT schedule or personnel hazards. Neither NASA nor contractor safety reviewers had to examine Deviation 13-20 as written. If the deviation had specified the time required to extend the GN_2 purge or the hazard level had been correctly marked, reviewers may have identified the conflict—that technicians were scheduled to work inside the orbiter while the purge was still ongoing.

Communications Breakdown

Test conductors should have had opportunities to clarify the circumstances surrounding the GN_2 purge during pre-task meetings, but Deviation 13-20 was only one of more than 500 deviations applied to the CDT. Hence, the large number of late deviations processed along with Deviation 13-20 inhibited adequate discussion and coordination before the CDT took place.

While the CDT was ongoing, briefings during shift changes made no mention of the purge extension, and at the end of the simulated launch, staffing levels in the Firing Room dropped significantly. As a result, operational discipline and control relaxed even while the hazardous GN_2 flowed through orbiter aft compartment. During this transitional period from CDT to processing work, the Firing Room crew, though aware of the ongoing GN_2 flow, knew nothing of the technicians scheduled to work in the aft compartment as soon as the pad reopened, and the "all clear" announcement was made.

Inadequate Safety Controls and Recovery Systems

The GN_2 purge displaced oxygen in the aft compartment and created an atmosphere of pure nitrogen, which human senses cannot detect. Inhaling an oxygen-deficient atmosphere can result in unconsciousness without any warning symptoms after only a few breaths. Given this hazard, continuous use of partial-pressure oxygen monitoring equipment could have precluded entry into the aft compartment. Such systems are equipped with flashing lights that could have provided a visual indication of the oxygen deficiency.

Once the workers collapsed, the distance to the storage lockers containing temporary air packs prevented rescuers from enlisting their aid. Without an oxygen source, rescuers themselves fainted inside the confined space. The Accident Investigation Board also found that the access platform's design hindered rescuers burdened with incapacitated personnel.

KSC Safety documents lacked requirements or effective procedures to control access to work areas exposed to an inert gas environment despite significant asphyxiation risk. A "hazard warning" sign, which would have secured the area, should have been posted outside the confined space. Instead, an "access control" sign, which can be removed from an area without concurrence from Safety personnel, was placed near the orbiter interior (Figure 4). The access control procedure should also have included atmosphere checks to verify a safe environment within the compartment prior to sign removal, just like the checks performed for hazardous gases elsewhere (booster and engine nozzles, and areas surrounding GN_2 plumbing).

Competing Operations Philosophies

At the time, two different philosophies regarding integrated operations—strict control through the Firing Room chain of command versus dispersed control and responsibility at the work site—governed labor at the launch site. Firing Room staff and on-site technicians and engineers suffered an acute disconnect that hampered communications: Firing Room personnel attempted to impose control over integrated operations, but the on-site workforce sought to accomplish as much work as possible without the seeming encumbrance of Firing Room oversight. This autonomy led ground teams to make decisions and accomplish work without communicating with the Firing Room first. Therefore, on the morning of March 19, the RI technicians proceeded with their scheduled work without the Firing Room team's knowledge.

Failure to Address Recurring Causes of Earlier Mishaps

The STS-1 Official Accident Investigation Board reviewed the findings of the 1967 Apollo-1 accident in which three astronauts lost their lives in a capsule fire. The Board found that many of the problems leading to the STS-1 confined space accident paralleled the problems that led to the Apollo-1 tragedy: the pure oxygen atmosphere in the Apollo capsule was not identified as hazardous, contingency plans and equipment were incomplete, emergency teams were not present for the tests, and structural design made swift egress difficult. Although fourteen years separated the two incidents, the STS-1 Accident Investigation Board determined that as of 1981, KSC failed to comply with a 1967 Congressional request to establish a solution to review operational checkout procedures in a timely manner.

Figure 4: Access control signs (left) can be removed without concurrence from Safety Personnel. After the accident, personnel were required to use the sign depicted at right for GN_2 purges.

Aftermath

After the pre-STS-1 tragedy, NASA implemented many changes to strengthen safety practices related to procedural deviations and access control. These included constraints on deviation traffic, requirements for atmosphere sniff checks, barrier placement and removal, use of warning lights, and placement of standby emergency officers. NASA provided GN_2-specific warning signs for areas affected by GN_2 purges and installed an oxygen deficiency monitoring system in its Shuttle Processing facilities. Temporary air packs were staged in enclosed compartments within the spacecraft in addition to nearby access platforms. Mandatory training on the use of the air packs was implemented as a part of the area access training.

After the mishap, a consistent operations philosophy emerged, resulting in tighter operations control from the Firing Room. The Firing Room became the final authority in all pad operations, and ground teams were required to participate in schedule and work briefings or reviews during each shift and test. Local operations control still existed, but work was now verified and approved through Firing Room Test Team personnel.

For Future NASA Missions

Tragedy has marred the start of every human spaceflight program since the Apollo-1 fire in 1967: Russians grieved the loss of Cosmonaut Commander Vladimir Komarov when his spacecraft, *Soyuz*-1, plummeted to Earth after a parachute deployment failure; NASA's space transportation system endured an inauspicious beginning when three of its contractors died preparing STS-1 for launch; and the first commercial spaceflight suffered an alarming setback when three Scaled Composites employees perished while performing a cold flow nitrous oxide test.

Many of the factors that led to earlier tragedies recurred in subsequent mishaps. Schedule pressure, poor emergency response provisions, or poor communications continue to play roles in the complex chains of events leading to failures—especially early in a program. As inaugural missions approach, it is critical for workers to follow established processes while guarding against "tunnel vision." Hands-on personnel are the last line of defense. If they perceive an unsafe condition, they must act as capable to lower the risk (stop work, alert management). Ask 'what can go wrong?' to uncover unexpected hazards; then pursue options to mitigate exposure to their effects.

Henry Petrosky, author of *To Engineer is Human*, stated, "No one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art." As both successes and failures chronicle the strides of an advancing aerospace industry, the list of lessons learned lengthens—but complacency threatens to reduce and eliminate safety margins. On November 18, 2010, external tank repairs for STS-133 led to a close call resulting from a GN_2 purge in a temporary enclosure. Circumstances surrounding the incident echoed those which led to the pre-STS-1 tragedy on the same launch pad three decades earlier, including the absence of an oxygen deficiency monitoring system.

During an interview marking the 30th anniversary of the historic STS-1 launch, astronaut Bob Crippen stated, "if we want to go beyond Earth orbit to the moon or asteroids or Mars or wherever, we're going to have to get over being so risk-averse." Surgeon, journalist, and Harvard Medical School professor, Atul Gawande, wrote "it isn't reasonable to ask that we achieve perfection. What is reasonable is to ask that we never cease to aim for it." Like healthcare and like dozens of other industries, human spaceflight carries enormous risks. If it is to aim for perfection, NASA must identify and eliminate needless risks during design and operational processes. NASA must spare no effort to address the Agency's systemic safety issues such as the ones that led to the pre-STS-1 tragedy.

Questions for Discussion

- What are some unique challenges during the initial operational (start-up) phase of a program? During transitions between programs?
- What types of complex chains of events, chains of contributing factors/causes can lead to mishaps? How can the overall organizational system be improved to break these chains and proactively reduce the risks of serious mishaps?
- What are safety risks associated with ground crew safety during flight hardware processing? How can improving ground crew safety also improve flight crew safety?

References

Crippen, Bob. "Shuttle Workforce Message from Bob Crippen." NASA Kennedy Space Center, 2010. < http://www.youtube.com/watch?v=5vfyZtVPvfs>.

Dean, James. "30 Years Later, Space Shuttle's Maiden Trip Remains a Marvel." Florida Today. 11 April, 2011.

Gawande, Atul. Complications: A Surgeon's Notes on an Imperfect Science. Macmillan, 2003.

National Aeronautics and Space Administration. Significant Incidents and Close Calls in Human Spaceflight. JSC S&MA Flight Safety Office.

National Aeronautics and Space Administration. LC 39A Mishap Investigation Board Final Report. John F. Kennedy Space Center, 1981.

Petrosky, Henry. To Engineer is Human. Vintage Books, 1992.

Space Walk of Fame Foundation. "In the Line of Duty." CollectSpace.com. 7 Oct 2010. < http://www.collectspace.com/ubb/Forum23/HTML/002596.html>

U.S. Chemical Safety and Hazard Investigation Board. "Hazards of Nitrogen Asphyxiation." 2003 < http://www.csb.gov/assets/document/SB-Nitrogen-6-11-03.pdf>

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