National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Tragic Tangle

On April 23, 1967, the Soviet Union launched the Soyuz-1 spacecraft to achieve a new and elaborate docking capability. Multiple malfunctions on orbit forced ground crews to abort the mission. In a crippled spacecraft with rapidly draining power reserves, cosmonaut Colonel Vladimir Komarov heroically maneuvered the craft for re-entry to Earth. Upon re-entry, the vehicle's drag and backup parachutes entangled. With no means of braking, Soyuz-1 struck the ground at 90 miles per hour, and the most experienced cosmonaut of the Soviet space program was killed upon impact.

BACKGROUND

The Space Race

The Soviets' launch of Sputnik in 1957 heralded the dawn of modern space exploration. On May 25, 1961, after the USSR sent Yuri Gagarin into Earth orbit and back, U.S. President John F. Kennedy declared that America would commit itself to landing a man on the moon before the end of the decade. The Space Race was on, national security and prestige were at stake, and two powerful space programs came to symbolize the Cold-War struggle between two nations.

Although the Soviets led the race early in the decade, the U.S. surged ahead in 1965 and 1966 following ten Gemini missions where astronauts pioneered many techniques that would later be used en route to the Moon. The Soviets had yet to claim a successful cosmonaut flight since *Vostok* 6 in 1963. The Soviet's Central Design Bureau of Experimental Machine Building (TsKBEM) planned a challenging 1967 mission for its new *Soyuz* spacecraft. *Soyuz*-1, carrying one cosmonaut, would launch first (Figure 1). *Soyuz*-2 would carry three cosmonauts and launch the next day. *Soyuz*-2 would dock with *Soyuz*-1 on orbit, and two crewmembers would transfer from *Soyuz*-2 to *Soyuz*-1 via spacewalk. After the transfer, both vehicles would return to Earth.

Test Failures

Prior to the *Soyuz*-1 launch, the government created a new State Commission called the "State Commission for Flight-Testing of the *Soyuz* Spacecraft." The State Commission planned two unmanned test flights. The first flight launched

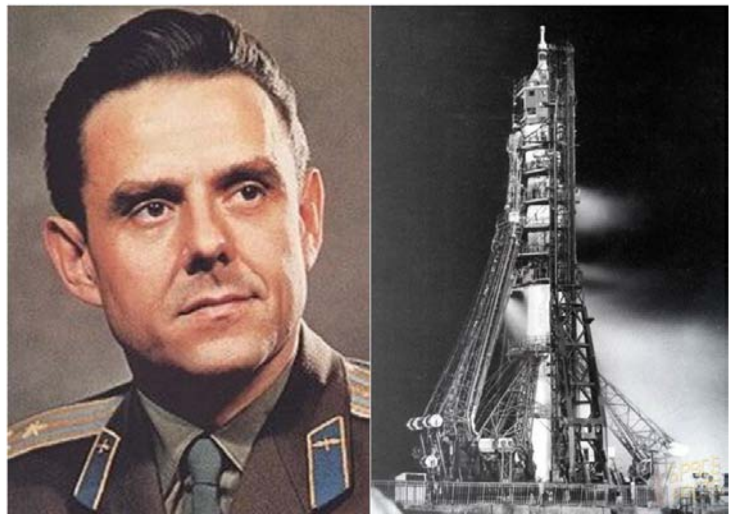

Figure 1: Cosmonaut Colonel Vladimir Komarov (left) was the lone crewman of Soyuz 1 (right)

successfully on November 28, 1966. The *Soyuz* vehicle had multiple propulsion system problems; it could not orient properly upon re-entry and a self-destruct charge automatically destroyed the spacecraft over the Pacific. The second test flight (delayed only three weeks to December 14) aborted automatically on the pad when the IIA5II launch vehicle first stage failed to ignite on command, but the second stage 'strap-on' boosters did ignite. Hurriedly, the Commission added a third unmanned test flight, launching on February 7, 1967. An American space program tragedy ratcheted up the pressure on January 27, when three astronauts perished in the Apollo-1 (204) fire. Now there was incentive to capitalize on a U.S. failure. Communication problems plagued the third *Soyuz* test flight, affecting

Soyuz-1 crashes due to parachute malfunction, crewman killed.

Proximate Cause:

- During the descent, drag and main parachutes malfunctioned, entangling the backup parachute as it deployed.

Underlying Issues:

- Manufacturing Oversight
- External Political Pressures
- Inadequate Preparation

navigation on orbit and during re-entry. The vehicle re-entered and was recovered from the Aral Sea, but a hole had burned through the bottom of the vehicle on re-entry; a human would have died if onboard.

Political Pressures

Remarkably, despite a 100% failure rate in the preceding *Soyuz* test flights, TsKBEM leaders convened in February and March of 1967 to consider the feasibility of sending a manned crew on the next mission. Engineers presented TsKBEM with more than 200 design faults. Several cosmonauts voiced concerns over the newly reinforced but not flight-tested heat shield. After intense discussion, a majority of the engineers reportedly expressed confidence in the heat shield and supported crewed flight. TsKBEM gave the order to proceed with the docking mission.

Was there a looming political deadline as well? There is evidence that the Soviet Central Committee wanted the rendezvous mission to commemorate May Day, a holiday considered immensely important. Such influence would affect TsKBEM's decision to push forward.

What Happened?

Primary and Backup Failures

On April 23, 1967, *Soyuz*-1, carrying Cosmonaut Colonel Vladimir Komarov (Figure 1), lifted off successfully and entered orbit without incident; however, it was not long before problems arose. Short-wave radio failure reduced communications to a brief line-of-sight period each orbit. More significant was the left solar panel, which would not open (Figure 2). Then came even worse news: an inoperable solar-stellar attitude control sensor robbed the vehicle of its primary maneuver control system. If he could not maneuver, Komarov could not dock to *Soyuz*-2 (a major mission objective). But the more immediate problem was survival. If unable to expose his good solar panel to sunlight, his vehicle's power supply would be gone about 28 hours after launch, in just 19 orbits.

Komarov had two backup maneuvering systems: an ionic orientation system and a manual system. During the 3rd and 5th orbits, Komarov experimented with the manual system but was unable to move his good solar panel into sunlight.

Mission Aborted

On the ground, debate broke out: abort the mission, or proceed with the launch of *Soyuz*-2? Assuming that the orientation sensor could still be fixed, the State Commission ordered the continuation of *Soyuz*-2 launch preparations. A plan emerged for two *Soyuz*-2 spacewalking cosmonauts to manually unfurl the solar panel. Komarov meanwhile radioed that cabin temperature changes now accompanied his rapidly draining power reserves. When he reported that attempts to use the ionic orientation system had failed, a unanimous decision was made to cancel the *Soyuz*-2 launch and bring Komarov home. Six orbits remained.

Re-entry Plan Changes

While engineers considered the effects of an imbalanced vehicle under manual control, Komarov reported he believed the ionic system now would work. On the 17th orbit, a main engine burn command was initiated, but the onboard computer correctly sensed low ion concentration in the system and prevented the burn. The 19th orbit would be the last re-entry chance.

To maneuver using only manual controls, Komarov needed an outside reference (Earth's horizon was best). Controllers devised a procedure for Komarov to turn the vehicle before entering Earth's shadow, transfer attitude control to *Soyuz*-1's gyroscope system, and make manual adjustments after emerging again. No one had trained for this procedure before. With amazing skill, Komarov executed the entire sequence and made his re-entry window.

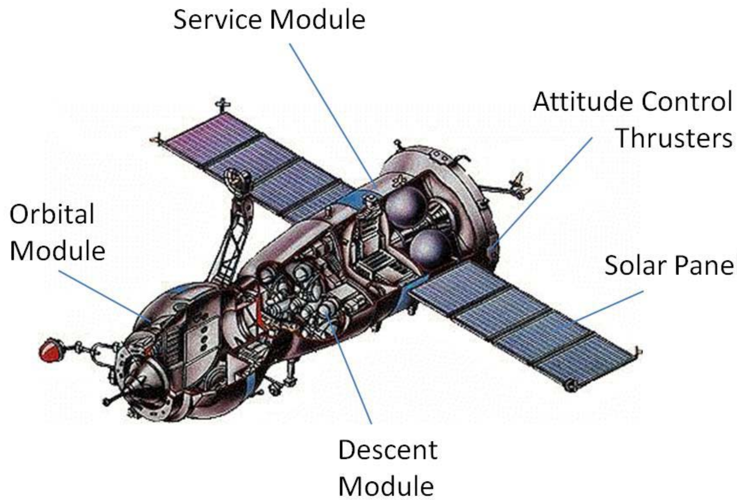

Figure 2: Diagram of a Soyuz space vehicle

Tumble and Impact

As *Soyuz*-1 began to enter the atmosphere, it may have tumbled due to the stuck solar panel. The drag parachute deployed to slow the spacecraft enough for the main parachute to open without shredding; however, the main parachute was jammed inside its container. Sensors detected *Soyuz*-1's increased velocity and activated the backup system. The backup system was programmed to eject both the drag and main parachutes before deploying the backup parachute; however, since the main parachute was stuck in its container, the primary apparatus remained attached to the spaceship. The drag chute remained flapping above the craft, and when the system deployed the backup parachute, the drag chute prevented it from unfurling. Without any means to reduce its tremendous speed, *Soyuz*-1 slammed to the Earth at 90 miles per hour. Impact velocity would have been fatal. Fire consumed the spacecraft (Figure 3).

Proximate Cause

Although *Soyuz*-1 encountered several in-flight malfunctions, none of them were a direct cause of this tragedy. *Soyuz*-1's destruction resulted from a failure in the primary parachute's deployment, which subsequently caused the backup system to malfunction. The tangled parachutes never opened, hurtling *Soyuz*-1 towards Earth and killing Vladimir Komarov upon impact (Figure 3).

Underlying Issues

Manufacturing Oversight

After the accident, an investigation team comprised of engineers, top officials, and program leaders determined the main parachute failed to deploy because of the pressure difference between the interior of the parachute container and the atmosphere.

It was later found that TsKBEM's manufacturing technicians had committed a grave mistake while *Soyuz*-1 and *Soyuz*-2 were under construction. To prepare the ships for flight, technicians coated them with a thermal protectant. The ships were then baked in a high-temperature test chamber to polymerize the coating, but the parachute containers did not have their covers during this process. Consequently, masses of hard resin built up inside the containers and impeded the chutes' ability to deploy.

The gravest implication of this oversight is that *Soyuz*-2, had it been launched, would have encountered the same malfunction. If the mission had not been aborted, the Soviets could have ultimately lost four cosmonauts that day instead of one.

Historians have also postulated that if the asymmetric vehicle tumbled and unshielded hull areas were exposed to high temperatures before parachute deployment, crew survival would have been unlikely.

Schedule Pressure

Much has been written of the stress that U.S. engineers endured during the Space Race. They were not alone. Vasily Mishin, chief designer at TsKBEM, stated in a 1990 interview about the *Soyuz*-1 mission that "Truly, there was never a time when we worked in peace, without being hurried or pressured from above…high-ranking bureaucrats believe that they are fulfilling their duties if they are shouting 'Let's go, let's go!' at people who don't even have time to wipe the sweat off their brows." Schedule pressure served to inhibit, rather than promote solid engineering design.

Aftermath

Colonel Komarov's death was the first in-flight fatality of space exploration. After the accident, all Soviet space flights were cancelled while the Soviet space program was put on hold for 18 months.

Figure 3: The charred remains of Soyuz-1

Given the time that was needed before, engineers rebounded from the tragedy with the emergence of a much-improved *Soyuz* program. Over 230 *Soyuz* craft have been constructed in 40 years, and they are now known as one of the most dependable and efficient launch vehicles ever designed. International crews have relied on the *Soyuz* spacecraft to travel to the International Space Station and return to Earth since November of 2000 (Figure 4). Since then, the Space Station has constantly carried a *Soyuz* 'life raft' in the event that the Station's crew should need to return to Earth in an emergency.

For Future NASA Missions

Ultimately, the *Soyuz*-1 failures can be traced to an environment where the stakes for mission success tipped the balance against crew safety. Pressured to match a competing nation, decision-makers gambled.

Although recent decades have exhibited more collaborative worldwide efforts to advance space exploration, external pressures to achieve remain. Fortunately, the crushing time constraints of the Space Race can be viewed with the perspective of history instead of an immediate threat. Today, schedule remains an important element of any agenda, but we cannot let schedule define our flight test program. Instead, flight testing should be defined by risk and technical performance: we must allow for the possibility that another automated flight may be necessary before we "go operational." Unfortunately, sending a system through numerous testing iterations will not guarantee mission success. This mishap and our own Apollo 13 mission abort show us that our knowledge and understanding of our systems must be to such an extent that our flight and ground teams can react to and handle unplanned contingencies when they occur.

The old design philosophy of "Fly-Fix-Fly" relies on time and testing to learn from failures and improve the system. While supercomputers and software allow us to model cause and effect with impressive speed and complexity, the old external pressures and human biases still affect our entering assumptions; will we just look at known single-point failure points, or take more time to examine less likely but catastrophic failure modes? How much time does the schedule allow? Despite the unsuccessful test flights, the *Soyuz* Chief Designer insisted, "Not a single supervisor for any of the *Soyuz* systems would have given the 'go-ahead' to the flight if he were not certain of that system's satisfactory operation." We have learned to live with the certainty that we're uncertain to some degree about how any system will perform under actual conditions. Quantifying that uncertainty in a way leaders can understand can turn a gamble into a calculated and acceptable risk.

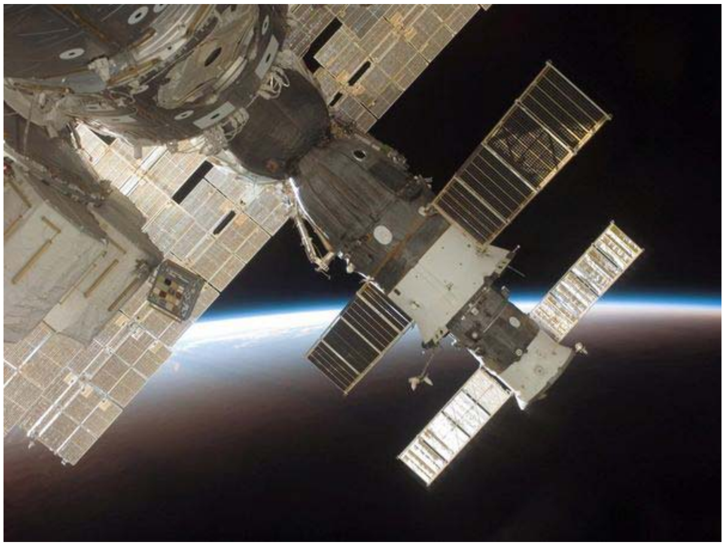

Figure 4: Soyuz-13 docked at ISS

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Questions for Discussion

- Are there external factors that put your program or projects at risk? How do you mitigate these factors?
- What processes does your project use to determine the need for testing?
- How does your organization adapt to time-critical events that affect mission or safety risk?
- How does your organization prepare for time or budget demands?

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NSC
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Executive Editor: Steve Lilley steve.k.lilley@nasa.gov

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