National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Descent into the Void

On June 6, 1971, three cosmonauts rose to orbit aboard Soyuz-11 to dock with Salyut, the world's first space station. During the next three weeks, the crew performed more than 140 science experiments, captivating the Soviet public with televised reports. Acclaim awaited the crew as they began re-entry on June 30. Teams deployed to the descent site in Kazakhstan, arriving in time to observe an apparent flawless landing. Upon opening the Soyuz' hatch, rescuers found all three crewmembers still in their seats, lifeless. The national outpouring of grief reportedly matched U.S. sorrow following President Kennedy's assassination in 1963.

BACKGROUND

Salyut

The year 1971 completed the first decade of human spaceflight. American excitement over the Apollo lunar missions receded as the Vietnam War escalated; U.S. space program funding was re-allocated while long-term exploration goals lost support. Human space flight projects in the USSR, however, moved forward. Intending not only to reach the moon but to colonize it, Soviet engineers designed a long-duration lunar base including habitation modules, lunar rovers, and power plants. Building toward long-duration lunar missions meant launching an orbital space station to conduct science and test engineering concepts as a launch point for missions to the moon and to Mars.

On April 19,1971, the Soviets launched the world's first space station, *Salyut*. Ground controllers soon discovered that *Salyut*'s OST-I telescope cover failed to jettison properly, limiting achievement of critical scientific objectives. With new non-astronomy objectives hastily assigned, three cosmonauts blasted off aboard *Soyuz*-10 on April 23 to dock with and spend a month on the station (Figure 1). Unfortunately, the *Soyuz*-10 docking apparatus suffered damage during unsuccessful docking maneuvers, and ground control aborted the mission. To compensate, program leaders planned two more June 1971 flights to *Salyut*.

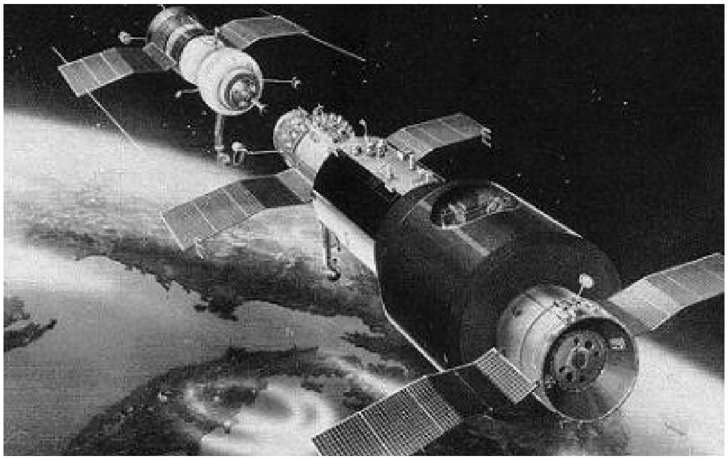

Figure 1: Artist's impression of a Soyuz spacecraft (left in picture) docking with Salyut

Crew Changes

The *Soyuz*-10 backup crew was selected as the primary crew for *Soyuz*-11. However, only three days before the launch, medical examiners discovered swelling on the right lung of Valeriy Kubasov, the primary crew's flight engineer. Suspecting that the swelling was an early symptom of tuberculosis, doctors unanimously ordered his removal from the mission. According to the rules of the Ministry of Health, if one crew member fell ill, then the entire crew had to be

Capsule Decompression Kills Three Cosmonauts

Proximate Causes:

- Ventilation valve on the spacecraft opened at an altitude of 105 miles instead of the intended 2.5 miles.
- Cabin pressure leaked into space, killing all three cosmonauts.

Underlying Issues:

- Absence of open-valve warning system
- Absence of emergency valve-choking system
- Absence of structural shock testing to worst-case levels

Figure 2: Cosmonauts Dobrovolskiy, Patsayev, and Volkov were last-minute replacements for the primary crew.

replaced – not just the ailing cosmonaut. On June 4, 1971, Georgiy Dobrovolskiy, Viktor Patsayev, and Vladislav Volkov became the primary crew (Figure 2). Ironically, Kubasov later discovered that his malady was merely an allergic reaction - not tuberculosis. He and his crewmates would be spared as a result.

What Happened?

Success aboard *Salyut*

On June 6, 1971, the *Soyuz*-11 crew launched into Earth orbit and docked with *Salyut*. They began an ambitious science experiment schedule, exercised, and appeared to enjoy their weightless environment. For the first time, Soviet citizens could watch televised reports from the crew, who showed high morale and collected pioneering data. While on orbit, the cosmonauts performed cardiovascular experiments, tested visual acuity, and measured radiation exposure. Biological experiments involved tadpoles, flies, and algae as well as maintaining plants in a small greenhouse built into *Salyut*. In addition, the crew used gamma-ray telescopes to collect data from celestial bodies and performed studies pertaining to weather and Earth resources. In total, the cosmonauts finished more than 140 experiments, the most ever conducted on a Soviet space mission. Yet all was not well; discord grew between individual crewmembers as glitches and emergencies challenged them. Earthbound cosmonaut capsule communicators mediated several authority clashes between the three men. Stress intensified on June 16 when a strong smoke odor broke out on *Salyut*, and the cosmonauts jostled to act independently or assert authority. The smoke was traced to an electrical cable fire; backup power was selected and the smoke abated. The crew remained concerned enough to request ending the mission and returning to Earth. Yet ground control judged *Salyut* to be safe. They ordered the station ventilated and experiments resumed. The extended mission and onboard stress affected crew performance; mission doctors expressed concern for the crew's physical and mental health. The men now rarely used exercise equipment meant to maintain muscle conditioning, and had abandoned *Salyut*'s exercise track because its use shook solar panels and antennas. Volkov, in particular, became increasingly irritable and exhibited mental errors. Ultimately, the State Commission ordered the mission shortened by six days. *Soyuz*-11 would now return home 24 days after launch on June 30th. Despite difficulties, the mission thus far was considered a huge success. The cosmonauts had collected more scientific data than any other mission to date, became the first crew to dock with and inhabit a space station, and surpassed the 18-day world record for continuous spaceflight.

Descent and Depressurization

On June 29, the three cosmonauts transferred mission materials from *Salyut* to *Soyuz* in preparation for the return to Earth. After the crew closed the hatch between the descent vehicle and the orbital compartment, the "hatch open" caution and warning panel light did not turn off. Tired and worried, Volkov radioed to ground control, "The hatch isn't pressurized, what should we do, what should we do?" Once the descent module separated from the rest of the spacecraft, that hatch would be exposed to open space (Figure 3). A cosmonaut capsule communicator instructed, "Don't panic. Open the hatch, and move the wheel (to engage the hatch latches) to the left to open. Close the hatch, and then move the wheel to the right 6 turns with full force." Finally after several attempts and exceeding 6 wheel turns, the light went out. The crew then lowered the pressure on the other side of the hatch in the orbital module to verify the hatch was sealed. After completing the tests, Dobrovolskiy undocked the ship and navigated around *Salyut* for photographs. Three Earth orbits later, he announced to ground control that the 'Return' indicator light was on. Ground control replied, "Let it be on. It's correctly on. Communications are ending. Good luck!" Communications would never be regained. The engine was programmed for a seven-minute retrofire. Automatic re-entry began as ground control lost radio communications with the crew; their fate would be discovered by landing site rescue teams.

The rescue squads that deployed to the assigned landing site observed the vehicle's flawless landing, but when they opened the hatch, they found the three cosmonauts had died.

Unanswered Questions

Crew autopsies revealed that each man had blood in the lungs, nitrogen in the blood, and hemorrhages in the brain – signs that somehow, the capsule had depressurized and the cosmonauts had suffocated. When recovery teams examined the descent vehicle, they noted the radio transmitter was manually switched off and all cosmonauts had unfastened their shoulder straps. One of two ventilation/equalization valves was found open 10 mm and pyrotechnic powder traces were found in the throat of the valve, supporting the theory that the capsule rapidly depressurized, asphyxiating the crew. A test was performed at the landing site to check the hermetic seal of the cabin. Pressure tests of the cabin show a slight loss, but it took 1.5 hours for the cabin to fully depressurize with the valve closed. What had forced the valve to open too soon? At approximately 723 seconds after retrofire, the descent module separated from the service compartment and orbital module. This orbital/descent module separation exposed the ventilation/equalization valves and the pressure relief valve to vacuum. Then, contrary to design intent, the 6 pyrotechnic-cartridges and the 6 pyrotechnic bolts used to separate the orbital module from the descent module fired simultaneously instead of sequentially with a delay between the bolts and cartridges. The resulting off-nominal separation shock to the descent module opened on of the two ventilation/equalization valve and pressure regulator outlets to vacuum.

The on-board memory device (a magnetic tape system ironically named *Mir*) and voice tapes proved invaluable as investigators strove to reconstruct crew reaction to the leak. According to the memory device, separation of the descent vehicle from the orbital module and service compartment occurred at a 105-mile (170 km) altitude. Upon separation, pressure dropped to a near vacuum in just 112 seconds with a steadily increasing whistle. The crewmembers did not wear pressure suits (per three-cosmonaut design volume constraints) and would have been immediately aware of the escaping air. From the evidence of crew positions and spacecraft controls, it is theorized that the crew would have had a caution and warning panel light, "Leakage," come on with a corresponding audio alarm. Additionally, the crew would have felt and heard the rapid depressurization rate. The crew would have unstrapped to check that the manually operated orbital/descent module equalization valve and hatch overhead were closed. The men switched off the radio transmitters, probably to locate the hissing leak. Dobrovolsky was found tangled in his straps in the attempt to hold a crew checklist over the display panel. It was the best he could do; behind that panel and beneath his commander's seat, unreachable and uncontrollable by the crew, sat the failed, leaking ventilation/equalization valve (35 mm opening). Biomedical sensors showed that 4 seconds after the depressurization began, Dobrovolsky's breathing rate shot from 16 per minute to 48 per minute. Asphyxiation began and death occurred within 40 seconds of pressure loss.

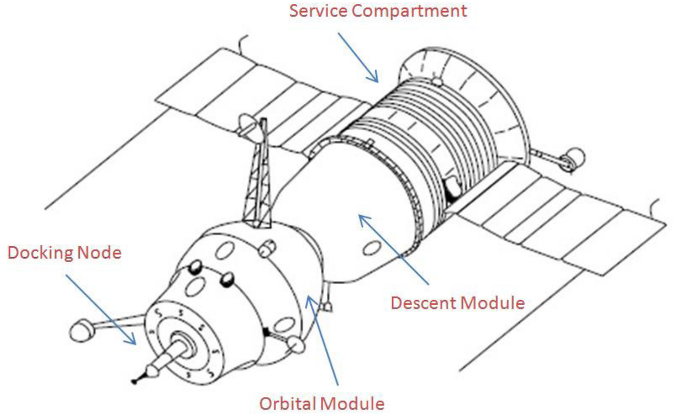

Figure 3: The descent module nominally separated from the other compartments when 12 explosive bolts fired sequentially.

Proximate Cause

Pressure inside the descent module leaked into the vacuum of space when a pyrotechnic ventilation/equalization valve designed to open when the vehicle reached an altitude of 2.5 miles (4 km) instead opened at a height of 105 miles (170 km). In an effort to determine what caused the valve to open early, engineers simulated varying loads on the valve, and deduced that the pyrotechnic fasteners that should have fired sequentially during capsule separation from the orbital module and descent module fired simultaneously instead. The resultant force jarred a ball joint in the pyrotechnic valve mechanism loose. This forced the valve open and depressurized *Soyuz*-11. Other pyrotechnics blew a valve seal clear at about 4 km altitude per design intent to equalize cabin pressure with the atmosphere—but the prematurely open valve had already done so in vacuum. Analysis of automatic attitude control system thruster firings made to counter the force of escaping cabin pressure, along with the pyrotechnic powder traces found in the throat of the valve determined when the valve had malfunctioned, causing the depressurization.

Underlying Issues

Design Flaws

Once the equalization valve opened, the cosmonauts lacked a backup procedure or control mechanism to close it. They were aware of a pressure leak seconds after it began, but surrounding distractors would have slowed their search for its cause. Noise from the transmitters obscured the leak's telltale sound, and the earlier "hatch open" warning light could have misled them into thinking the frontal hatch seal was involved. The designers included a warning light to notify crewmembers when the hatch seal was insecure. The two ventilation valves (one for air in and one for air out), also paths to vacuum, lacked both a warning system and a closure mechanism. Designers may not have conceived of a failure mode forcing either valve to open and prematurely rupture the seal. Verification testing did not include the higher shock of simultaneous pyrotechnic fastener firing.

Aftermath

The deaths of the cosmonauts were felt by those who had already mourned the loss of cosmonaut Komarov in *Soyuz*-1, and reverberated worldwide across government space programs. While the Soviets were at first reticent to reveal the technical causes of the accident, a Soviet design engineer provided his NASA counterpart with key details in 1973 during preliminary meetings for the Apollo-*Soyuz* Test Project, which would launch two years later in 1975. NASA, in turn, provided information on the Apollo 13 mishap. This vital exchange of hard-won engineering knowledge began collaboration toward international partnership and mission successes that continue today.

In the near term, missions to *Salyut* were grounded. The *Soyuz* spacecraft was redesigned with increased valve reliability versus shock loads. Emergency pressurization equipment was added to the spacecraft. A manually operated valve, accessible to the crew, was placed in series with the pyrotechnic valves in both the ventilation inlet and outlet (Figure 4). Cosmonauts were issued and required to wear pressure suits for launch and landing; *Soyuz* crews were reduced to two to account for the additional equipment volume. Later, redesigned space suits occupied less space and allowed a *Soyuz* to be flown with three suited crewmembers. In October of 1971, *Salyut* was no more; its on-board supplies expired, the first human space station was commanded to a destructive re-entry over the Pacific Ocean.

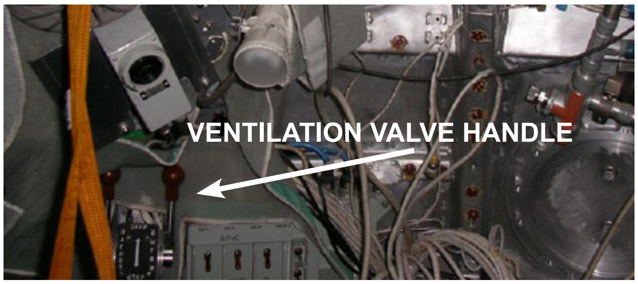

Figure 4: Manual ventilation valve handles were added to the Soyuz spacecraft.

For Future NASA Missions

The *Soyuz*-11 story tells of a failure mode that a design team did not foresee. Years of experience with high-altitude pressurized aircraft did not prepare them to test critical components versus off-nominal pyrotechnic shock events to uncover single-point failures. We lack documentation of how extensively the Soviets tested the valves on the spacecraft flown for the *Soyuz*-11 mission, but the absence of emergency equipment such as oxygen masks or alarms seems to indicate design intent to make the system failsafe. Twenty years later, Chief Designer Mishin maintained such an approach was preferable to pressure suit use: "in multi-seat spaceships it is necessary to ensure collective safety, which can better be ensured by duplicating the systems that pressurize the entire Descent Apparatus…spacesuits required additional complex devices, thus increasing weights and volumes." More recent experience with *Soyuz* and Space Shuttle re-entry has shown not only that pressure suit availability is critical, but that usability is important as well. A key recommendation from the Columbia Crew Survival Report said: "Future spacecraft must fully integrate suit operations into the design of the vehicle and provide features that will protect the crew without hindering normal operations."

It is necessary to ensure comprehensive human understanding of any design, but complex systems can defeat the attempt. As a system moves from concept toward fabrication and operation, transitions between project life cycle phases allow involved engineers, technicians or operators to miscommunicate or misinterpret the designer's original intentions, resulting in an end product that does not perform as conceived. Conversely, the designer's failure to imagine a valid and critical failure mode may be more challenging for hazard analysts to uncover than quantifying already known or assumed scenarios.

Questions for Discussion

- Are your teams prepared to deal with time-critical emergencies?
- Have you compared your project's design to the physical realities to which it will eventually be subjected?
- Are you aware of the sensitivities of your design? Are you aware of the type and magnitude of the effects that small design changes may have on your system?
- How do you address risks associated with components that cannot be tested in a flight-like manner?

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