National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Trial by Fire

On February 24, 1997, six crew members on Mir Space Station faced significant danger when fire ignited in the solid fuel oxygen generator. The searing flame, which erupted from a fuel cartridge, cut off access to one of two Soyuz escape capsules. The module's narrow space made it difficult to fight the fire, but with teamwork and composure, the crew prevailed. Although the incident would raise tensions between the teams on the ground and on orbit, both sides would learn valuable lessons applicable to the design of the International Space Station.

Background

Shuttle-*Mir* Partnership

In 1986, the Soviet Union launched Space Station *Mir*'s core module (base block) into earth orbit, beginning a tour that would last 15 years. From 1986-1990, the Soviet Union expanded the base block with three additional modules: *Kvant*-1, *Kvant*-2, and *Kristall*. But not long after *Kristall* launched, the Soviet Union collapsed and economic chaos ensued. The space program struggled financially, and maintaining *Mir* became a serious challenge.

Help came in 1991, when U.S. President George H.W. Bush and Russian President Boris Yeltsin signed an agreement that evolved into collaboration between the Space Shuttle and *Mir* programs. The United States paid Russia $400 million to send its astronauts to *Mir* (Figure 1). This partnership saw seven astronauts spend 1-4 month increments with a cosmonaut crew from 1995-1998. Their goals were to work with international partners, identify risks in developing and assembling a space station, gain experience on long-duration missions, and conduct life science, microgravity, and environmental research programs. Funds from the partnership allowed Russia to add three more modules to *Mir*: *Spektr* (1995), Space Shuttle Docking Module (1995), and *Priroda* (1996).

Oxygen Generator

Two Elektron units supplied *Mir* with enough oxygen to support a three-man crew. However, periods of transition could require up to six individuals to reside in the station at once.

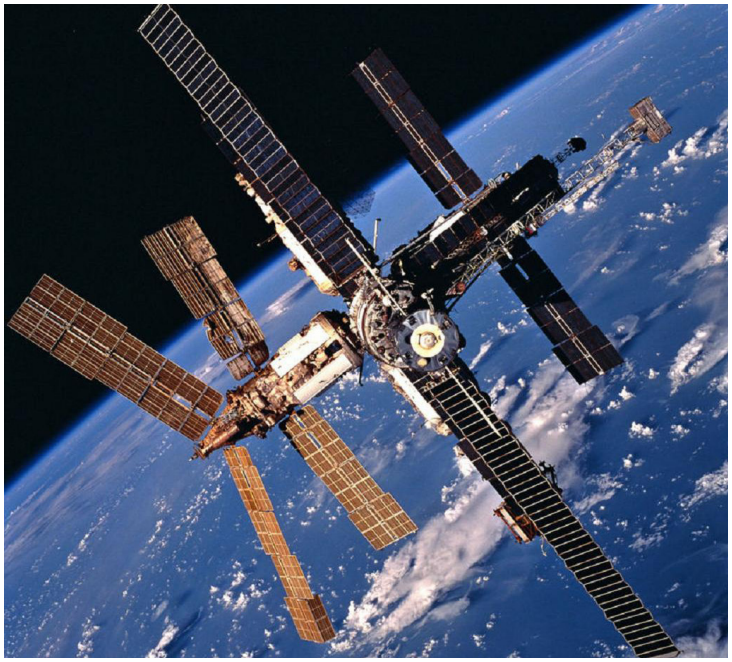

Figure 1: Space station Mir orbited Earth for fifteen years.

During times of increased occupancy, crew members activated the Solid Fuel Oxygen Generator (SFOG) in *Kvant*-1 (Figure 2). The SFOG worked by burning cassettes containing Lithium Perchlorate ($LiClO_4$) at temperatures exceeding 750° F. The heat decomposed the $LiClO_4$, which gave off a by-product of oxygen in the process. The SFOG infused *Mir* with this supplement. One cassette provided enough oxygen for one person for 24 hours, and the cosmonauts typically burned three such canisters daily.

Fire Ignites Aboard Space Station *Mir*

Proximate Causes:

- Piece of latex glove contaminates Lithium Perchlorate canister during assembly on the ground
- Hydrocarbons from latex material increase risk of anomalous ignition in Lithium Perchlorate canister

Underlying Issues:

- Emergency preparation and planning
- Post-crisis communication
- Early warning signs

The $LiClO_4$ cassettes were cylindrical sealed containers. Replacing a canister in the SFOG was as simple as breaking the seal, opening the lid, and sliding it into the generator. Cosmonaut flight engineer Sasha Lazutkin compared the process to "jamming a mullet ball into an old-fashioned musket." Each $LiClO_4$ canister contained a percussive primer and an igniter tablet. Once a crew member loaded the canister and activated the SFOG, the generator's firing pin struck the percussive primer, initiating a chemical reaction in the igniter tablet that caused the $LiClO_4$ to decompose.

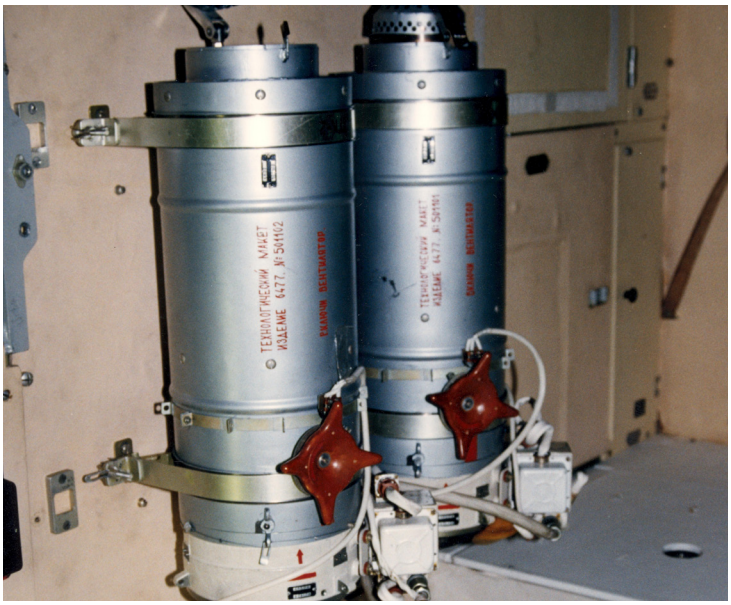

Figure 2: The solid fuel oxygen generator in Mir's Kvant-1 module appeared similar to the ones pictured here. Turning the red knob on the SFOG exterior activated a chain reaction that caused the lithium perchlorate in the canister to decompose.

What Happened

Crew Replacement

On January 22, 1997, U.S. Astronaut Jerry Linenger rode Space Shuttle Atlantis to Space Station *Mir*, joining cosmonaut commander Valery Korzun and cosmonaut flight engineer Aleksandr Kaleri. Linenger would replace astronaut John Blaha and begin NASA's fourth increment aboard the station. On February 13, 1997, a *Soyuz* capsule carried cosmonaut Vasily Tsibliyev, cosmonaut Aleksandr Lazutkin (replacements for Korzun and Kaleri), and German astronaut Reinhold Ewald to *Mir*. Approximately two weeks later, Korzun, Kaleri, and Ewald would use that capsule to return to Earth. Until their departure, *Mir* would hold a full complement of six crew members.

Cartridge Replacement

Constant demands to maintain *Mir*'s systems while sustaining a rigorous experiment schedule prevented the crew from relaxing together often. February 23 was an exception. In observance of Army Day, the six crew members gathered in *Mir*'s base block where they enjoyed a meal that included sausages, cheese, lemons, and caviar—rare delicacies for a crew accustomed to far simpler fare. After dinner, the crew lingered in base block, chatting, while Linenger headed toward *Spektr* to set up a sleep experiment.

It was customary to replace the SFOG cartridge before bedtime, so as the social hour concluded, resident commander Korzun asked the crew's junior member, Lazutkin, to replace the cassette in the SFOG. This maneuver had been executed without incident on thousands of other occasions—1500 times on the ground and 2500 times on *Mir*—and no one had reason to believe that this one would be different.

After floating into *Kvant*-1, Lazutkin pulled a cylindrical cartridge from storage and shoved it into the oxygen generator. Then, after activating the container through an external dial, he turned back toward base block. Lazutkin described, "I was ready to fly back. It was the normal procedure. No one ever worries whether it is working." But then Lazutkin heard an unfamiliar, quiet hissing. As he turned to investigate, a jet of bright orange flame erupted from the generator. Lazutkin recalled that for some seconds, he stared, frozen at the fire, "A small, tiny, baby volcano." Ten feet away, in Base Block, Ewald reacted first. "*Pozhar*!" he exclaimed. '*Pozhar*' is the Russian word for fire.

Fire Fighting Effort

Startled, commander Korzun peered inside *Kvant*-1 where three-foot flames spewed from the SFOG. Molten metal flew across the module and spattered into the opposite bulkhead. Already, Lazutkin was shrouded in black smoke. Korzun was at his side in an instant. Lazutkin attempted to douse the flame jet with a soaked towel, to no avail. Urgently, Korzun commanded Lazutkin to leave the module then ordered the crew to get fire extinguishers, don oxygen masks, and travel in pairs. As Tsibliyev, Ewald, and Kaleri scrambled, the flames grew larger, inching toward the opposite bulkhead in *Kvant*-1. If the fire breached the metal panels and pierced the hull, they would die. Cosmonaut Kaleri hurriedly began printing coordinates for evacuation and reentry to Earth through the *Soyuz* capsules. There was one problem: the two escape capsules were on opposite ends of the station, and the fire blocked the only path to one of them. If the six crew members could not extinguish the blaze, three could escape in one capsule, but the other three would be left to die.

Meanwhile, smoke filled the module and spilled into the base block where it reached a smoke detector and triggered the master alarm. The alarm jolted Linenger from his work, and he darted toward base block where Ewald and Tsibliyev, donning oxygen masks, confirmed a real emergency. Linenger lunged toward *Kvant*-1, but its limited space did not allow anyone to assist Korzun as he fought the fire alone. Three of the crew stood by, prepared to pass fire extinguishers to Korzun through the hatchway. The others prepared the accessible *Soyuz* for evacuation.

Foam from three fire extinguishers eventually doused the flames, and Korzun recalled that spraying foam on the walls and surrounding equipment prevented the fire from spreading.

Proximate Cause

The fire consumed most of the SFOG and most of the oxygen canister, making it difficult to determine the exact cause of ignition (Figure 3). Almost two years after the incident, NASA scientists found that hydrocarbons in the Lithium Perchlorate canister increased the risk of problems. Using this information, Russian investigators reviewed production processes for a source of such contaminants. They zoned in on latex working gloves. In July 1999, tests showed that inserting four square centimeters of a latex glove in a SFOG cassette was enough to reproduce the blaze, finally leading investigators to a cause that had eluded them for nearly two years.

Underlying Issues

Emergency Preparation

After his return to Earth, Astronaut Linenger debriefed NASA on his stay aboard *Mir*. During that discussion, Linenger highlighted lessons learned from the fire regarding emergency preparedness and crew safety, particularly in terms of warning systems and training drills.

Mir's master alarm served several functions that ranged from innocuous events such as wake-up calls to real emergencies such as the fire that occurred on February 24. Linenger reported that the master alarm could ring four or five times in one day, essentially desensitizing the crew to crucial notifications. Linenger stated, "The master alarms became so common that I got to the point of ignoring them...after awhile a person might assume that real emergency was not occurring…the constant alarms made you feel a little complacent about them which was bad." Linenger went on to emphasize the need for separate, distinct alarms for fire and for depressurization—the most serious events that could occur on a space station. More effective warning systems could save crew members several seconds of reaction time, which, in a crisis, could differentiate success and failure.

Safety Drills

The crew did not practice dry runs or emergency drills simulating response to a fire. Astronaut Linenger highlighted this omission as a weakness partly because of the unexpected difficulties they encountered when a real emergency arose. For instance, launch brackets still fastened the fire extinguishers to the walls, and the crew needed screwdrivers and pliers to detach them. This set up a time-consuming, sub-optimal circumstance that practice might have eliminated. However, Linenger also pointed out that the fire extinguishers' design made practice runs difficult: physically pulling the extinguishers from the wall activated a chemical that pressurized the extinguisher, but once it pressurized, the extinguisher would last only three months. If a fire were to occur beyond that span of time, the extinguishers would have diminished efficacy.

Figure 3: The charred remains of the solid fuel oxygen generator

Safety drills could also have identified difficulties in evacuating *Mir* had evacuation become necessary. In one of his debriefs, Linenger stated, "What I learned is that you need to [be] on the right side of the fire so that you have your back to the rescue vehicle...instead we have six people on the wrong side of the fire, and then if that fire goes uncontrolled in *Kvant*, then nobody can get out." With access to only one *Soyuz*, the crew would have faced difficult decisions if the fire had not been extinguished. The cosmonauts later identified a second problem with their escape plans: both *Soyuz* vehicles would have used the same reentry coordinates, so a scenario in which both capsules evacuated the station could have resulted in a collision between the spacecraft during reentry. Linenger pointed out the importance of establishing more detailed emergency protocols prior to the accident: "I think you need very straightforward procedures and they need to be debated, thought out, and come up with the best solution and then make the crew abide by those proceedings."

Post-Crisis Communication

Astronaut Linenger encountered difficulty conversing with the ground during the communication passes immediately following the fire. As a physician, crew health became one of his foremost concerns after the fire, and he feared that air on *Mir* might now contain dangerous, unknown contaminants. When he sought further information about the contents of the SFOG containers, he discovered that Russian mission control placed emphasis on different priorities. A similar lapse in communication occurred when NASA management did not learn about the fire until more than twelve hours after it had occurred, and Russian mission control limited the facts it would publicly disclose.

Early Warning Signs

NASA's contract with the Russian Space Agency dictated that NASA would ensure cosmonaut safety aboard the Shuttle and Russia would assume responsibility for astronaut safety aboard *Mir*. Because of this arrangement, NASA had not implemented a structure to analyze *Mir* since the Russians were responsible for crew safety aspects. In his book, *Dragonfly: NASA and the Crisis aboard Mir*, Brian Burrough writes, "NASA . . . was forced to admit in the wake of the fire [that it]

knew next to nothing about *Mir*'s inner workings. No one had attempted anything like a basic safety assessment of the station before the White House first announced the Shuttle-*Mir* missions in 1993." Burrough surmises that more comprehensive knowledge of the Russian systems might have brought fire hazards to light and allowed NASA to further investigate earlier instances of fire in space. However, international cooperation at the time had not yet reached a level that would have made this possible.

Aftermath

Immediately after the fire, astronaut Linenger thoroughly examined the crew for ill effects from smoke inhalation. As a safety precaution, the crew continued wearing oxygen masks for several hours after the incident. All of them escaped the ordeal without suffering serious injuries.

After an interagency commission deemed the SFOG cartridge fire an isolated occurrence, it allowed continued use of the Lithium Perchlorate cartridges. However, safety measures surrounding cartridge activation were tightened: cosmonauts had to store cartridges in special containers, visually inspect each cartridge prior to installation, place gas masks and fire extinguishers near the SFOG, and cover all skin surfaces during cartridge activation. After discovering the probable cause, Russian officials required SFOG assembly workers on the ground to turn in their gloves for inspection at the end of each shift.

The fire also had a long-term impact on the International Space Station's (ISS) design. Engineers developed a new oxygen generator and new SFOG cartridges. These cartridges would be activated by an electrical initiator rather than a percussive primer and igniter tablet. Oxygen canisters for the ISS became subject to stricter quality control and now include containment shields.

For Future NASA Missions

Mir's on-board fire was not the first of its kind, but was the worst that had ever occurred in space travel. Fortunately, all six crew members survived a situation that could have spiraled into a disaster. Not only did the crisis emphasize the importance of practicing safety drills and formulating emergency procedures, but it also highlighted areas for design improvement. Developers did not hesitate to apply these lessons to the newest technological advancement - the ISS.

As NASA begins a new journey toward deeper regions of the galaxy, it must not allow new difficulties and dangers to upset an established pattern of learning and application. International partnerships must include a common knowledge of shared equipment and facilities. Different organizations—international and commercial—have different cultures and understandings. Because cultural differences can give rise to communication lapses, NASA must find ways to overcome these differences to prevent weaknesses from creeping into joint systems and processes. NASA must continue rising to the challenge of truly learning from mistakes to prevent close calls and failures from falling into the void of wasted opportunity.

Questions for Discussion

- In what areas of your project do communication weaknesses exist?
- What areas of your project have been affected by a close call, and how did your project improve because of that situation?
- What are specific situations related to your project that could benefit from a pre-determined, step-by-step emergency protocol?

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Responsible NASA Official: Steve Lilley Developed by: ARES Corporation
steve.k.lilley@nasa.gov

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