National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Spektr of Failure

On June 25, 1997, a manually controlled rendezvous and docking test between a Progress automated supply vehicle and Space Station Mir became a threat to crew survival. The Mir crew controlled the Progress remotely, but loss of telemetry data crippled their efforts to steer a spacecraft they could not see. By the time the Progress spacecraft entered their line of sight, it was moving too fast to control. Progress slammed into a solar array and ricocheted into the Spektr module, sending the station into a slow tumble. The impact punctured Mir's hull and resulted in the first decompression on board an orbiting spacecraft.

Background

Shuttle-*Mir* Partnership

When Russia emerged from the collapse of the Soviet Union in 1991, its fragile economy threw its space program upon harder times. The Russian Space Agency (RKA) suffered an 80% budget reduction, and only Space Station *Mir* survived subsequent project cuts. While Russia struggled to keep its space program alive, the United States sought new goals for its own space initiatives. The Space Council, which U.S. President George H.W. Bush had reestablished in 1989, advocated a cooperative venture with Russia. In 1992, leaders of both nations signed a "Joint Statement on Cooperation in Space." This agreement evolved into the Shuttle-*Mir* collaboration, eventually known as Phase 1 of the International Space Station Program. Phase 1 would last from 1995 to 1998. During those years, astronauts would spend three to four-month increments on board *Mir* (Figure 1). During each increment, one astronaut would join two cosmonauts to conduct life science, microgravity, and environmental research.

Progress: From *Kurs* to TORU

Unmanned cargo spacecraft named Progress periodically visited the space station to deliver fresh supplies and collect accumulated rubbish. These vehicles docked with *Mir* using an automated system called *Kurs*, which had been developed by a government owned company in Kiev. When the Soviet Union fragmented, Kiev became the capital of newly independent Ukraine, which steadily raised the system's price. Before long, Russia witnessed a 400% increase in *Kurs* costs, leading RKA to consider phasing out use of the *Kurs* equipment in favor of the backup manual system known as TORU (Teleoperated Rendezvous Control System).

By 1997, only one Progress vehicle had been successfully docked with *Mir* using TORU. In March of that year, the Russian Federal Space Agency Mission Control Center (TsUP) ordered *Mir*'s crew to

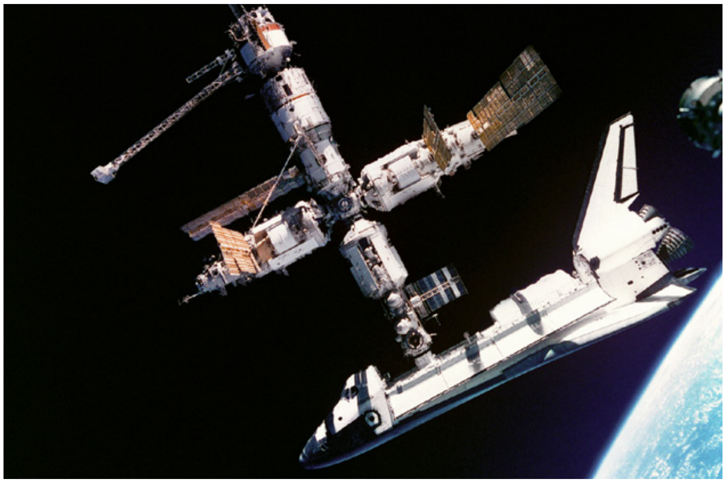

Figure 1: Space Shuttle Atlantis docks with Mir.

test the TORU system again on Progress-M 34. TsUP would maneuver the Progress to a position approximately 7 kilometers above *Mir*, then transfer control to cosmonaut crew commander Vasiliy Tsibliyev, the TORU operator. To maneuver Progress toward *Mir*'s docking node, Tsibliyev would manipulate joysticks controlling movement and orientation while watching a television feed transmitted from a Progress-mounted camera (Figure 2). Progress' trajectory began above the station, so Tsibliyev's screen would display *Mir* and its docking node with Earth in the background. During the March test, the screen remained blank, forcing Tsibliyev to fly the Progress blind and abort the docking. The result: Progress missed the station by a slim 200 meter margin.

Three months later, in June of 1997, TsUP ordered Tsibliyev to perform another TORU test. TsUP attributed the visual feed malfunction to the *Kurs* antenna, which delivered telemetry data to *Mir*. Ap-

Automated supply vehicle collides with Space Station *Mir*

Proximate Causes:

- Preplanned braking maneuvers were insufficient to slow the spacecraft's momentum.
- Absence of telemtry led crew to misjudge spacecraft's speed and position.

Underlying Issues:

- Flawed Docking Procedure
- Economic Pressure
- Absence of Telemetry Data
- Insufficient System Knowledge

parently, RF radiation emitted through the antenna interfered with the camera signal. TsUP addressed this issue simply by turning off the emitter. This left Tsibliyev without telemetry of speed, range and range rate data. Ground control instructed astronaut Michael Foale and cosmonaut Aleksandr Lazutkin to manually calculate the speed, range and range rate using a handheld laser rangefinder and a stopwatch. American engineers were not consulted or informed of this fallback measure until after the mishap.

Figure 2: The TORU Docking System.

What Happened

Collision

At 11:43 am on June 25, the crew began the TORU test under remote control conditions for which they had not trained. If all proceeded as planned, Progress would dock at 12:08 p.m. Lazutkin and Foale stationed themselves in Base Block and *Kvant*-1 (Figure 3), prepared to gauge distance with laser rangefinders. Tsibliyev fired Progress' thrusters, relieved that this time, his screen displayed Progress' camera feed overlaid with a checkerboard grid. Tsibliyev discerned a small dot representing *Mir* from the background of Earth's swirling clouds, but worried that Progress was advancing too slowly. Foale and Lazutkin could not see the approaching vessel from any of the portholes, and the crew spent some minutes waiting to sight the Progress, unsure of whether to brake or accelerate.

At 12:03, *Mir* filled approximately 0.8-0.9 squares on Tsibliyev's grid, and with this information, he estimated the range at approximately 5.5 km. Still, nobody could see Progress from the windows. At 12:04, Tsibliyev applied 53 seconds of continuous, preplanned braking. Tsibliyev then applied an additional 52 second braking impulse. At 12:06, *Mir*'s hull filled four entire squares on his display. Knowing the spacecraft should now be within visual range, Foale and Lazutkin anxiously searched for it again, but Progress was nowhere to be seen.

Ninety seconds remained before the final docking time when Lazutkin saw the Progress emerge suddenly, looming from behind one of *Mir*'s solar arrays. Urgently, he commanded Foale to flee to the *Soyuz* and prepare for evacuation. Suddenly learning of Progress' proximity, Tsibliyev clamped down the braking lever, but despite his commands, Progress coasted past the docking node over Base Block at high relative speed (three meters per second). *Mir*'s hull now filled Tsibliyev's entire screen. Then, Progress slammed into a solar array and ricocheted into the *Spektr* module, rocking the entire station (Figure 4). The crew felt the pressure change in their ears almost immediately and heard a loud hissing noise. Progress had punctured the hull somewhere on *Spektr*. If the crew did not act quickly, they would suffocate.

Recovery

Lazutkin raced to the hatch of *Spektr* Module and rapidly disconnected the numerous cables that snaked through the opening. If he could seal off *Spektr*, the crew, the station and overall mission could be saved. Foale, who had been preparing the *Soyuz* for crew evacuation, quickly joined him. Two cables lacked disconnect fittings near the hatch, so they severed both cables with a knife. Tiedowns and air escaping through *Spektr*'s heavy, open hatch prevented them from pulling it inward, but Lazutkin and Foale found an external hatch cover that could effectively seal the opening. They untied and popped it into place, sealing off the leak. But disconnected cables left *Mir* with only 40% power. Progress' impact sent the station into a slow tumble that turned solar arrays away from the sun, draining battery reserves and shutting down the main computer. Experiments and personal items inside the *Spektr* module, now depressurized, were lost – but the crew and the station survived.

As Lazutkin and Foale isolated the leak, *Mir* made it into communications range with TsUP. Tsibliyev radioed the list of critical events: collision, depressurization, power loss, tumbling station attitude. TsUP instructed the crew as to which systems to shut down in order to save power and asked them to determine the spin rate. Using his thumb as a reference point, Foale analyzed the stars' wobble and determined the station's spin rate to be approximately 1° per second. He relayed this information to ground controllers who fired *Mir*'s engines based on that data to control the spinning. Then, based on his thumb measurements, Foale shouted instructions to Tsibliyev to fire the attached *Soyuz* thrusters to orient *Mir* so that its solar panels again faced the sun. Four and a half hours later and almost thirty hours since the collision, *Mir*'s solar panels faced the Sun again. The crew could finally rest.

Proximate Cause

The obvious proximate cause (loss of control and impact of Progress) led to controversy. The Russian press reported that Energia Space Rocket Corporation's investigation as delivered to Russian President Boris Yeltsin blamed crew commander Vasiliy Tsibliyev and flight engineer Aleksandr Lazutkin for the collision. However, five of Russia's best space pilots from the cosmonaut training center at Star City, Russia, reportedly simulated the TORU docking test using the same maneuvers TsUP had given Tsibliyev. All five simulations reportedly produced the same result…collision with *Spektr* at the same location. Meanwhile, Vladimir Utkin, Director of the Central Scientific Research Institute of Machine Building and NASA astronaut Thomas Stafford headed an investigation (known as the Stafford Commission) whose findings showed *Mir*'s crew had done all that it could. The Stafford Commission emphasized the hazards of performing the maneuver outside of radio contact with the ground, making it impossible for TsUP to use its controls or data readings to assist the crew. Additionally, TsUP's plan forced Tsibliyev to fly the Progress not only without telemetry, but also without the proficiency that can only come from practice. *Mir* was not equipped with docking simulators, so Tsibliyev had not rehearsed the docking in more than four months, leaving his docking skills degraded. Further, poor lighting conditions resulting from Progress' camera angle made it difficult to discern *Mir* from the background of Earth's clouds. The Stafford Commission also discovered that Progress-M 34 had been overloaded, thus displacing its center of gravity. The spacecraft's response to Tsibliyev's commands therefore differed from the responses TsUP had predicted. Months later, as the Commission's investigation drew to a close, Energia admitted the flaws

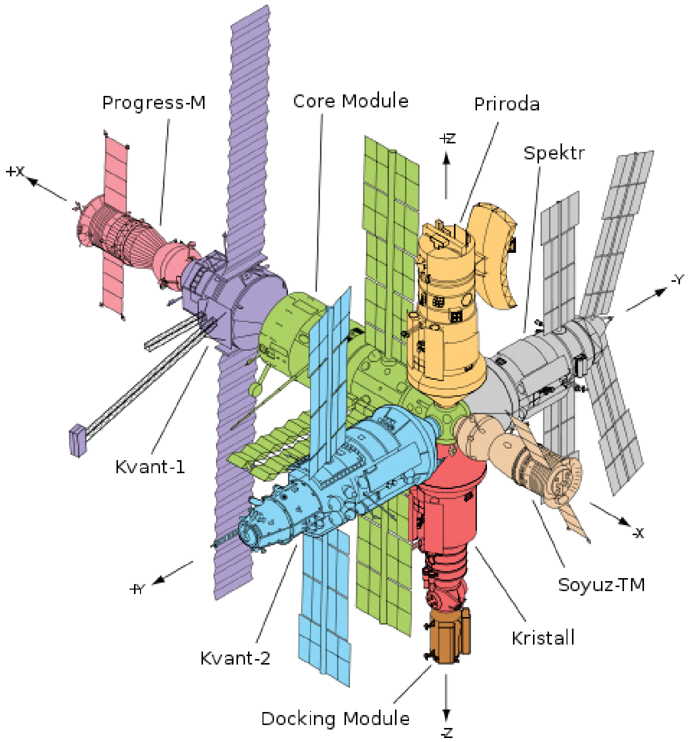

Figure 3: Core Module (Base Block) is shaded in green. Progress should have docked to Kvant-1. Instead, it collided with Spektr.

in the docking test. Generals from the cosmonaut training center in Star City also admitted that they could have done better in training Tsibliyev. These admissions supported the Stafford Commission's conclusions that many factors conspired to undermine crew efforts to dock the Progress safely - it was a system failure as opposed to flight crew error.

Underlying Issues

Economic Pressure

RKA required an alternative to the *Kurs* docking systems for it could not afford to pay Ukraine's steadily rising prices. Program leaders had already cut Progress launches from six per year to three. A successful TORU test would liberate funds dedicated to *Kurs* and restore Progress flights to their original frequency. With these objectives in mind, TsUP hastily added the June 1997 test that would end in collision.

Tsibliyev, however, was under significant physiological stress from cumulative lack of sleep, and psychological stress from knowledge of the aborted March TORU test when collision had been averted. A sleep study had dominated the weeks preceding the test, leaving him irritable and quarrelsome. Ground controllers knew this, but still pushed the schedule forward.

At least one ground controller questioned the wisdom of this decision. Tsibliyev's weariness and struggle with the TORU controls was clearly audible to Sergei Kirkalev, the first cosmonaut to fly aboard the shuttle in 1994. Kirkalev formally contested the decision to fly the June test. He later stated, "I was against it, but I was not heard...my feeling was they were not comfortable with this operation, this test. Just listening to the crew, you could feel they were uncomfortable. In my experience, if a pilot doesn't feel comfortable to fly, it's better not to fly…many specialists were against the test, but they would not speak out." Tsibliyev lacked any incentive to veto the test, as his flight bonus pay would have been reduced or rescinded for failure to follow TsUP instructions.

RKA physicians had the power to rule that Tsibliyev's psychological strain inhibited his performance, but they signed off on the test despite the crew commander's obvious fatigue. Rostislav Bogashevsky, an RKA senior psychologist, later admitted that he withheld "grave doubts" about Tsibliyev's ability to carry out the docking maneuver, for he believed that almost nothing would stop TsUP from pushing forward.

Flawed Docking Procedure

The rush to implement the TORU system likely influenced how TsUP dealt with the EMI problem with the *Kurs* antenna and TORU television display. Russian design and test methods at the time did not uncover EMI hazards until actual flight—and then fixed problems on subsequent flights. Intent on completing this test, TsUP turned off the precise telemetry data that had enabled the *Kurs* to reliably dock the Progress, and assumed the crew could spot Progress and use manual observations and calculations to substitute for the telemetry data needed until the video feed could be used for the close proximity work. In the haste of adapting to the EMI problem, TsUP failed to plan for the hazard that *Mir*'s solar arrays could block crew line of sight to Progress, rendering the rangefinder useless.

The RKA docking protocol made the lack of telemetry data particularly hazardous because it used a method known as the "hot approach," which allowed the docking vessel to advance at high speeds (meters per second vs. inches per second) until the last minute, when the TORU operator would apply maximum possible braking thrust. RKA feared that if it did not use the hot approach to finish the docking quickly, then the navigation system would accumulate errors. Thus, the hot approach was necessary because in essence, the docking process was a race to dock before cumulative navigation drift error made docking impossible. Given the danger the hot approach imposed upon the crew, a better option would have been to redesign the docking system rather than to formulate docking instructions based on a system known to be faulty.

TsUP's instructional memo directed Tsibliyev to keep the Progress rotating during its approach so the camera would remain centered on *Mir*. In order to do so, Tsibliyev had to adjust its pitch downward. A basic orbital dynamics principle states that "the steeper a spacecraft's downward path, the faster it will fall toward Earth," so Tsibliyev's commands had the unforeseen effect of increasing Progress' velocity. This resulted in an approach that was even faster than expected. With the telemetry antenna switched off and with the Progress obscured from line of sight, Tsibliyev had no way to foresee this occurrence. Furthermore, since Progress' center of gravity changed when ground crews overloaded it, the vehicle did not respond to Tsibliyev's commands as expected. When the Progress entered visual range, the crew realized too late that braking thrust had been insufficient.

Insufficient Test Knowledge

Neither NASA nor the U.S. crew member Michael Foale had been briefed about the TORU test. Although Foale did his best to glean information about the maneuver, the cosmonauts' reluctance to discuss the docking was clear. Upon learning of the test after the collision, NASA engineers stated they would have called for ground simulations prior to the flight test. A ground simulation could have shown that Progress' actual center of gravity differed from that which had been programmed into spacecraft guidance. A ground simulation could also have shown the risks of the hot approach method, and revealed the blind spots created by the station's modules and solar panels.

Aftermath

In the days immediately following the accident, Tsibliyev, Lazutkin, and Foale worked hard to restore and maintain power on *Mir*. By 30 hours post-collision, the crew had restored full continuous power to the base block. Approximately one week after the collision, ground control devised a plan for the cosmonauts to perform an IVA (Intravehicular Activity) inside the sealed-off *Spektr* to reconnect power cables. However, Tsibliyev exhibited poor health and Lazutkin committed a serious fundamental error that sent the station powerless and spinning once again. It forced the crew to repeat grueling efforts to restore power, and ground control realized they were pushing too hard. TsUP postponed the IVA for the next pair of cosmonauts on August 22.

The *Kurs* and TORU equipment were later installed in the International Space Station. Crews conduct regular practice with TORU in coordination with Mission Control. On July 4, 2010, the Progress 38 vehicle docking approach to ISS (under *Kurs* command) had to be aborted due to EMI from the TORU TV transmitter. The *Kurs* system switched the Progress to a safe flyby path as programmed."

For Future NASA Missions

The late, award-winning science writer Sir Arthur C. Clarke addressed the difficulty of predicting future events as falling into two categories, called 'failure of imagination' (the inability to imagine that which is technically possible but not yet present), and 'failure of nerve' (failure to extrapolate a trend to its logical consequences). Predicting, and thus planning for off-nominal scenarios involving complex flight systems takes time, a systematic approach and effective communication to overcome both predictive pitfalls. "Test-while-you-fly" for the sake of efficiency and economy alone is a failure of nerve from a technical safety risk viewpoint.

One of the signal achievements of international spaceflight partnership since the *Mir* project has been agreement to share that information mutually identified as essential to mission success and safety of flight. As commercial companies compete for government-sponsored spaceflight work, it would be a failure of nerve to ignore the risks posed by information considered both proprietary and essential to flight safety. Technology and research that increases safety margin merits the ultimate accolade of becoming 'open source.' To proceed otherwise will incur costs far beyond those required to repair *Mir* as a result of this incident.

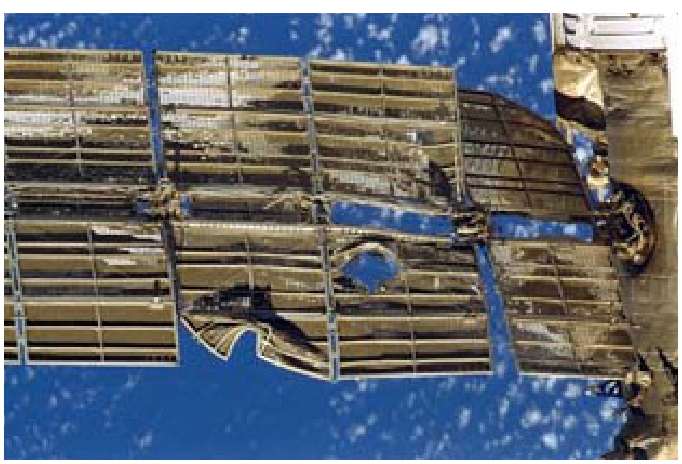

Figure 4: Mir solar array with collision-induced damage

Questions for Discussion

- What kind of pressure is your organization currently facing, and how is it affecting your projects?
- What steps have you taken to ensure thorough and adequate communication between teams on your project?
- What measures have you enacted to ensure that your teams receive sufficient and recurrent training?
- Are you certain that your solutions to current problems do not introduce new failure modes?

References

"Atlantis Docked to *Mir*." Online Image. 4 July 1995. 9 Sept 2010. Great Images in NASA. <http://grin.hq.nasa.gov/ABSTRACTS/GPB-2000-001315.html>.

Burrough, Bryan. Dragonfly: NASA and the Crisis aboard *Mir*. Harper Collins, New York: 1998.

Haines, Lester. "ISS crew capture robotic spacecraft." The Register. <http://www.theregister.co.uk/2010/07/05/progress_docks/>.

"*Mir* Diagram." Online Image. 9 Sep 2010. National Aeronautics and Space Administration. <http://www.spaceflight.nasa.gov/history/shuttle-mir-multimedia/diagrams>.

Petty, John Ira. "History of Shuttle-*Mir*." National Aeronautics and Space Administration. Dismukes, Kim. 4 Apr 2004. <http://spaceflight.nasa.gov/history/shuttle-mir/index.html>

Report on Docking Accident, Moscow Izvestiya, 30 Sep 97 and Moscow ITAR-TASS, James E. Oberg E-mail October 2, 1997

Russian Space Agency, Rocket Space Corporation Energia, WG-2/RSC E/2007-7, 17 Sept-1997, " *Mir* Station Safety Assurance Mission Readiness Report for the Joint Mission with the Space Shuttle (3.5M), Shuttle-*Mir* Flight STS-86"

Shayler, David. Disasters and Accidents in Manned Spaceflight. Springer, New York: 2000.

"Solar Array." Online Image. 9 Sep 2010. National Aeronautics and Space Administration. <http://spaceflight.nasa.gov/history/shuttle-mir/history/h-flights.htm>.

"TORU Docking System on Display." Online Image. 9 Sep 2010. High TechScience. <http://www.hightechscience.org/toru.htm>.

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