Soyuz investigation lands with a thud

With a "pop" that was barely audible outside the test chamber, a small Russian explosive bolt was detonated successfully in Moscow last January, punctuating the end of a two-year investigation into a consecutive pair of near-disastrous Soyuz landings. By functioning normally, the bolt—removed by spacewalking cosmonauts last summer from a manned Soyuz docked to the ISS—refuted the last surviving theory on why two such bolts had failed to fire during earlier missions.

Fortunately, according to a NASA study released on February 20, the hardware and software countermeasures already implemented to accommodate that failure mode are probably good enough to provide adequate crew safety should the problem recur. And recur it might, since the pyrobolt glitch now joins a long list of "unexplained anomalies" generated by the hypercomplex ISS.

Beyond the apparently satisfactory ending to these life-threatening anomalies, the bigger issue is how neither U.S. nor Russian engineers expected these failures to occur at all. That such near-fatal breakdowns can continue to blindside space operators and flight crews, even after decades of experience and vastly improved modeling tools, is worrisome. To the degree the incident dispels any overconfidence and complacency among space workers, it can serve as an important contribution to future spaceflight safety.

After all, in October 2007 and April 2008 the fireworks had been much more intense than the squib's small pop in Moscow. On both occasions, Soyuz landing modules, carrying a trio of returning space travelers, had tumbled out of control during reentry, enveloping their lightly shielded forward surfaces in flame. Smoke filled the cabins and emergency-level *g*-forces tossed the crewmembers around in their seats.

Locating the source

Both crises were later traced to a separation bolt's failure to release the crew's descent module from its spent propulsion module just before hitting the atmosphere. Unable to turn its protected bottom into the airstream, each Soyuz swerved into a nose-forward orientation under aerodynamic forces. As temperatures soared on the capsule's forward end (which contained the landing parachutes and an exit hatch), turbulent buffeting built up and soon tore the two multiton modules apart just before the point where serious—even lethal—damage could have been inflicted.

When two consecutive Soyuz missions ended in near-disaster, their landing modules tumbling out of control amid flames on reentry, the problem was traced to bolts that failed at the same location in both spacecraft. Russian officials initially pointed to U.S. actions as the root cause of the failures; however, a fuller investigation refuted those claims. After some troubling revelations, this anomaly remains unexplained.

Both ships landed hundreds of miles short of their aim point because the planned "lifting" entry had been impossible. For a lifting entry, the descent module uses roll thrusters to point its small lift vector left or right to steer toward a target point while stretching the descent and thus doing most deceleration in the thinner upper layers of the atmosphere. All attitude control propellants had become exhausted when the descent module's autopilot struggled to orient itself while dragging the propulsion module along. By the time the modules tore free, the descent module was falling like a rock ("ballistic mode," the Russians call it), and only its offset center-of-mass was enough to turn its heat shield into the proper forward direction. But with guidance messed up by the tumble, the autopilot's last-ditch control mode was to create a constant roll that averaged out the lift vector and thus nulled its cumulative steering force on the plummeting spacecraft.

The separation bolts are installed in pairs at five points along the circumference of the module interface. After the bolt assembly at one of these locations failed on two consecutive missions, Russian space officials decided to retrieve the bolt placed at that same spot in the Soyuz that was then in space. By lucky coincidence, movable ladders near the vehicle's docking port could support cosmonaut access to only one of the five bolt locations—and the suspect location was that one. In July 2008 the bolt was removed and packed into a metal cylinder to be returned to Earth for analysis.

The Russians had theorized that some feature of the space environment, associated with the station's growing size and electrical power generation capability, had physically damaged the previous bolts, perhaps by repelling the explosive slurry away from the internal ignition wire. But several weeks of nondestructive testing on the retrieved bolt revealed nothing unusual, and when hit with the minimum-level voltage early this year, the bolt fired exactly as designed—probably to the surprise and dismay of the investigators.

A rush to judgment

The Russians had blamed U.S. power arrays for other Russian hardware failures in the past, when later investigation found actual causes much closer to home. In June 2007, for example, the triply redundant Russian control computer system began experiencing fatal errors and eventually shut down completely. True, this happened during the installation of a third power array to the station by a visiting shuttle, and the coincidence was an obvious place to begin the search for a cause-and-effect chain. But the enthusiasm with which Russian officials jumped to the verdict against NASA was overwrought.

Early on, top officials announced their conclusion that NASA was at fault. Russian Space Agency head Anatoliy Perminov, through news agency Interfax, declared on June 18, 2007, "In our opinion, the computer failure resulted from a [powerful and sudden] static surge related to the installation of new [American] solar panels." And on June 18, ITAR-TASS, the official Russian news agency, reported: "An Energia official told ITAR-TASS that a fivefold overvoltage resultant from the unfolding of extra U.S. solar batteries caused the computer failure."

A few days earlier, Agence France-Presse in Moscow had attributed almost exactly the same words to Irina Gomenyuk, spokesperson for the spaceship vendor, Energiya Space and Rocket, in Korolev, northern Moscow. In hindsight, all of these knee-jerk "blame the Americans" announcements not only were inaccurate, but also could have harmed the progress of the authentic investigation.

Weeks later, troubleshooting by the station crew determined that moisture contamination and subsequent corrosion and mold in-

The Soyuz TMA-11 spacecraft (opposite page, lower right corner) lands next to a burning field April 19, 2008, in central Kazakhstan carrying NASA astronaut Peggy Whitson, Expedition 16 commander; Russian Federal Space Agency cosmonaut Yuri Malenchenko, flight engineer and Soyuz commander; and South Korean spaceflight participant So-yeon Yi. Photo: NASA/Reuters/Pool.

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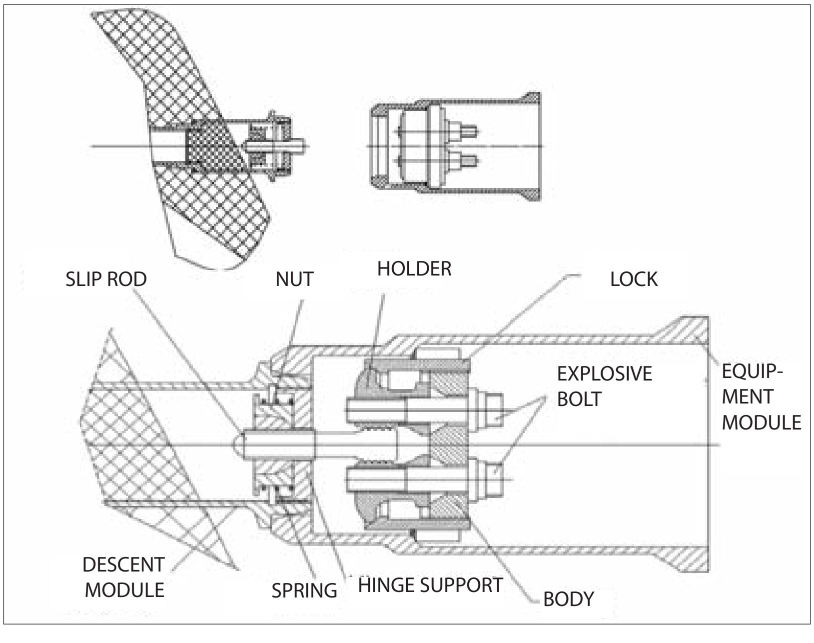
side the Russian hardware was the true cause—the electrical power was innocent. "Upon removal of the old unit, the crew reported that there was cold condensate behind it," notes an internal NASA ISS status report for August 12. "Drops of humidity and mold were discovered. The unit itself is humid."

A later NASA report says the damage "presumably" was "the result of repeated emissions of condensate from the air separation lines" of a nearby dehumidifier. Airflow and power usage were supposed to keep the computer cables warm enough to prevent water from condensing on them, but the dehumidifier had been malfunctioning, and its frequent on-off cycles led to surges of water vapor. Also, a stream of cold air from another location on the dehumidifier helped drive the cable temperatures occasionally below the dew point.

Secrets and lies

Another troubling aspect of instinctive Russian performance in the ISS partnership, and its effect on NASA's publicity policies, appeared at the very beginning of the pyrobolt crisis. The first occurrence of the failure mode, aboard Soyuz TMA-10 in October 2007, did not involve a U.S. passenger and was never publicly acknowledged by the Russians. However, NASA was privately informed, and it warned its astronauts then aboard the space station that the same problem could occur inside the Soyuz they would eventually ride back to Earth. (The warning was correct—the same failure did recur.)



A cross-section of a separation bolt shows how firing of either of two independent pyrobolts would free the module attach bolt. On two successive Soyuz landings both pyrobolts at one of five attach points failed to fire. A Russian investigation concluded that in both incidents, both bolts in one pair were rendered defective by electrostatic charges.

But this information was withheld from the U.S. public, and even congressional oversight committees, even though it involved a significant safety issue for a Russian spaceship. NASA has not answered any questions about how this could have happened, nor has the agency described any other Soyuz safety-related issues it may have been told about but did not disclose.

When the second near-disaster occurred, in April 2008, it was a private Russian source who broke the story to the news wires. "It was very lucky that all members of the crew survived," the unnamed space engineer told the Interfax news agency in Moscow. "Everything could have ended much worse. It was a very narrow escape." He provided additional technical details that enhanced his credibility: "As a result of excessive thermal overloads, the hatch was significantly burnt. Besides, the transmitter antenna melted and the contact was lost. The exterior part of the pressure equalization valve was burnt," he continued. In conclusion, he warned, "There is no guarantee that the crew of the next Soyuz capsule landing six months from now will not face the same problems."

Official Russian reaction followed, in the form of bland denials and insinuations of sinister motives. "The reports about the threat to the life of astronauts do not stand up to scrutiny from the technical point of view and generally harm the Russian space industry," stated the head of the space agency's press service, Aleksandr Vorobyov. "The information which was published with a reference to an unnamed and highly incompetent source was nothing but a dirty trick. [It] was wrong from a technical point of view."

Only in the days and weeks that followed did NASA officials acknowledge that the original Russian rumors were accurate.

A pattern of blame

The Russians' approach to the pyrobolt problem has clear parallels with their initial blame-NASA position following the 2007 computer failure, and may still be interfering with an accurate assessment of the root cause.

According to "NASA's Assessment of the Soyuz Anomalies," a February 20 report by ISS chief engineer Chris Hansen to a flight readiness review panel, NASA engineers remain unconvinced that Russian experts have correctly identified what led to the two pyrobolt-caused Soyuz separations. They also dismissed subtle Russian attempts to blame them on U.S. actions.

The Russian results blame both the descent failures on damage to an explosive bolt in their Soyuz spacecraft, a conclusion that is not in dispute. That failure, they say, was caused by "long-term exposure to electrical discharges resulting from the difference in potential between the station hull and the surrounding [ionized] plasma." The Russian conclusion adds that this electrical charge increased in magnitude as each new NASA solar power wing was added. Thus they indirectly blame the U.S. for their spacecraft's inability to tolerate space "static electricity" effects.

The problem with this conclusion is that when cosmonauts brought one of those bolts back to Earth, it looked—and operated—as if it were completely undamaged by this effect. Whatever effect had "dudded"—crippled the effectiveness of—the previous two bolts in that position had no discernible effect on the third one that was manually retrieved via spacewalk. But the cosmonauts had retrieved it halfway through their mission, meaning that its exposure to the presumably damaging environment was much less than on previous missions that had seen pyrobolt failures.

Based largely on the absence of evidence that such damage is even real, NASA's experts concluded (in the February 2009 report), "The ISS environments team does not feel that [the] plasma environment caused [an] electrical potential issue." In other words, NASA rejected any idea that its raising the station's power capacity caused the Russian problem. It is "unlikely in our experience," the report added.

"But," it continued, "with [an] improperly grounded system, [a] failure of the type predicted is possible." The report also called the idea of dudding the explosive bolt "possible, but low probability."

The NASA assessment stressed that "this analysis is based on multiple assumptions and an incomplete knowledge of the entire system and other potential failure modes." The reason for this handicap did not have to be spelled out—the Russians simply did not tell NASA these sorts of "trade secrets."

Another motivation for NASA's skepticism was that the theory had essentially become accepted even before the hypothetical plasma environment had actually been measured in the vicinity of the Soyuz vehicles. It was not until December 23, 2008, that a pair of spacewalkers from the station installed a small Langmuir probe on the Russian end of the station. The instrument measures the electric potential of plasma flowing across the station's outer surface as well as the effect of electrical current generated by the station's solar power panels.

Such effects are real and have been measured by U.S. instruments. As a safety measure, to prevent "grounding shock" during spacewalks, NASA early on installed two small ion generators at the U.S. end, to provide a safe electrical potential balancing between the station's outer hull and the thin ionosphere through which it orbits. And within a few weeks of installation, the new probe did (according to NASA officials) confirm the existence of similar effects at the Russian end.

Russian officials welcome astronaut Peggy Whitson, cosmonaut Yuri Malen-chenko, and South Korean spaceflight participant So-yeon Yi (out of frame) at the Chkalovsky airport, Star City, after their bumpy ride home aboard TMA-11. Photo Credit: NASA/Bill Ingalls.

Remedial measures

While stating that the separation failures should still be categorized as unexplained anomalies, the report describes in detail how changes in hardware (to protect against electrical effects) and software (to shake the modules free even if the bolts fail again) will provide adequate safety levels should this sort of problem recur.

The two bolts that failed were in the same position around the waist of the Soyuz and, because of the coincidental overlay of an aerodynamic shroud attach point, were not only isolated but also grounded differently (and apparently inadequately) from the other four pyrobolts. The fabrication of the pyrobolt support structure was modified, and command cables were rerouted, with increased EMI shielding, for the Soyuz launched in October 2008. When it returned to Earth early in April it landed safely and smoothly.

But in case the pyrobolts had failed to

Russian search and rescue forces and medical personnel assist the crew of the Soyuz TMA-13 (which had the safety modifications) after its safe landing on April 8, 2009. Photo credit NASA/Bill Ingalls.

On entry, the first Soyuz in 1969 separated safely only after smoke filled the cosmonaut cabin; recent events closely resembled this.

fire, Russian designers added another safety feature. They programmed the autopilot of the propulsion module to wait a few seconds after the nominal separation time, and then initiate a pattern of gyrations—rolls and pitches—designed to overload the module attach couplings (especially as they were weakened by entry heating) and to break them loose from mechanical stress. The first flight test of this shake-and-break maneuver took place last October, but it occurred halfway through descent, while still out of range of Russian radio tracking stations.

This situation finally explained why last fall the Russians had made an urgent request that NASA send a team of radio telemetry experts to Athens, Greece, to record data from the returning Soyuz as it passed overhead on its way to landing in Kazakhstan. It was not clear at the time why this was even required (or why the Russians could not do it for themselves), since the descent module had a recorder to preserve all its performance data. It turned out that the desired radio signal was coming from an autopilot computer in the soon-to-burn-up propulsion module, not from the descent module at all. The data to be retrieved would indicate how well the new "shake-loose" backup plan was being implemented by that module's thrusters. The successful receipt of these signals did confirm the proper performance of the maneuver; however, attempts to record the April 2009 telemetry (by a NASA team in Tel Aviv and by a receiver newly installed on the ISS) apparently both failed.

NASA's assessment concluded that whatever the root cause of the pyrobolt failures was, if the problem recurs, the hardware and software changes now in place should be adequate to prevent loss of vehicle and crew. "Independent reentry analysis indicates [the] truss will *likely* fail prior to hatch or parachute compartment failure," it stated. This would lead "to successful reentry" and a safe landing of the crew, albeit far off course.

As to the two alarming landing mishaps that started the investigation, the report's conclusion still reflected NASA's skepticism concerning the Russian results: "The separation failures," it stressed, "are still unexplained anomalies."