Asynchronicity: The Near Loss of the Apollo-Soyuz Test Project Crew

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Background

- July 17, 1975: In an exercise of United States and Soviet Union cooperation, Apollo-Soyuz Test Project (ASTP) astronauts and cosmonauts shook hands between their docked, orbiting spacecraft.
- July 21, 1975: The Soyuz and crew undocked and landed in Russia.
- July 24, 1975: The Apollo descended toward the Pacific Ocean.
  - The crew did not activate the Earth Landing System at the correct altitude.
  - As a result, toxic propellant fumes entered the capsule through the open cabin pressurization valve before splashdown.

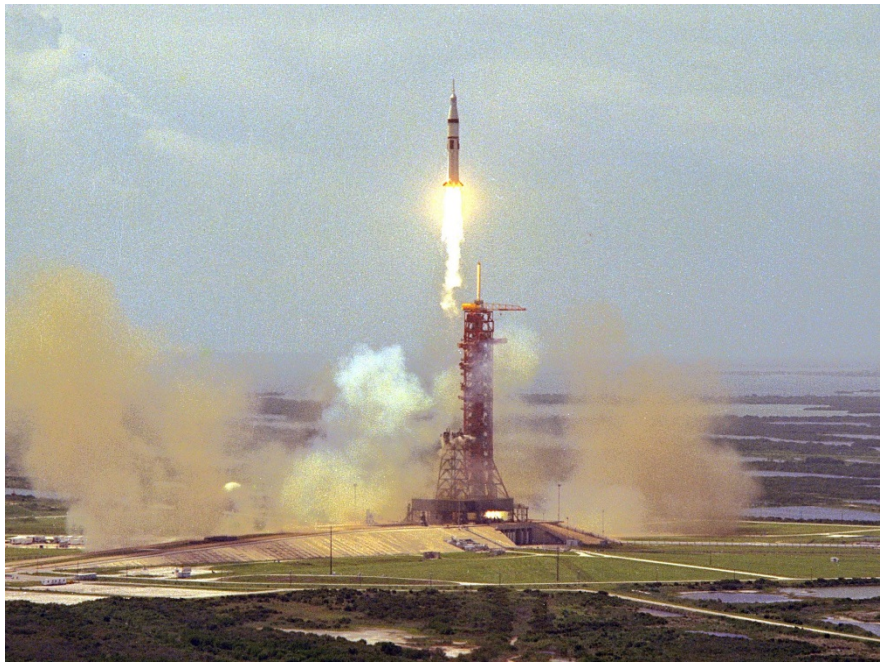

Figure 1. The Apollo crew of the ASTP mission lifting off in a Saturn IB launch vehicle
Source: NASA

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Earth Landing System (ELS) Design Change

Figure 2. The ASTP CM during splashdown
Source: NASA

- During re-entry, pyrotechnics devices were use to jettison the apex cover, deploy and release the drogue parachutes, and deploy the main parachutes. The ASTP re-entry procedure required the crew to arm the ELS pyrotechnic buses at an altitude of 50,000 feet. Then, at 30,000 feet, the crew was to arm the automatic ELS sequencer itself by positioning two ELS switches to "LOGIC" and "AUTO."
- Nov. 23, 1970: **Engineers had marked both ELS switches for elimination. They were presented as Single-Point Failures (SPFs)** that could prematurely arm the system during the time-critical re-entry.
- Dec. 8, 1970: New wiring added redundancy to the ELS pushbutton switches, apex cover jettison and both parachute deployments in Apollo 15 and later spacecraft. This allowed the pyro buses to remain armed after Command Module (CM)/Service Module (SM) separation, removing the need to manually arm the ELS during the re-entry sequence.
- If armed, the ELS applied power to baroswitches, which would close at 24,000 feet to activate the ELS relay, disabling the Reaction Control System (RCS) and enabling timer relays to release the apex cover and deploy both sets of parachutes sequentially down to 10,000 feet. Manual switches could disable the RCS and deploy chutes if the redundant automatic system failed.
- Separate from the ELS, the cabin pressure release valve opened automatically during descent at 24,000 feet to equalize cabin pressure with ambient pressure outside. The ELS was designed to disable the RCS by that point. The entire ELS sequence lasted only 26 seconds in AUTO.

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What Happened

- Prior to flight, the mission Commander (CDR), who had flown Apollo 10, insisted they would use the original Apollo procedure and they would remember to manually arm the pyrotechnic buses at 50,000 feet and the ELS sequencer at 30,000 feet.
- However, during descent, the CM Pilot (CMP) armed the ELS pyrotechnic buses 20 seconds late at 37,000 feet. Then, the CMP did not acknowledge the CDR's checklist command or arm the two automatic ELS sequencer switches (A and B in photo) when the Docking Module Pilot (DMP) called them out at 30,000 feet. Had they been armed in time, the crew would not have been exposed to N2O4.

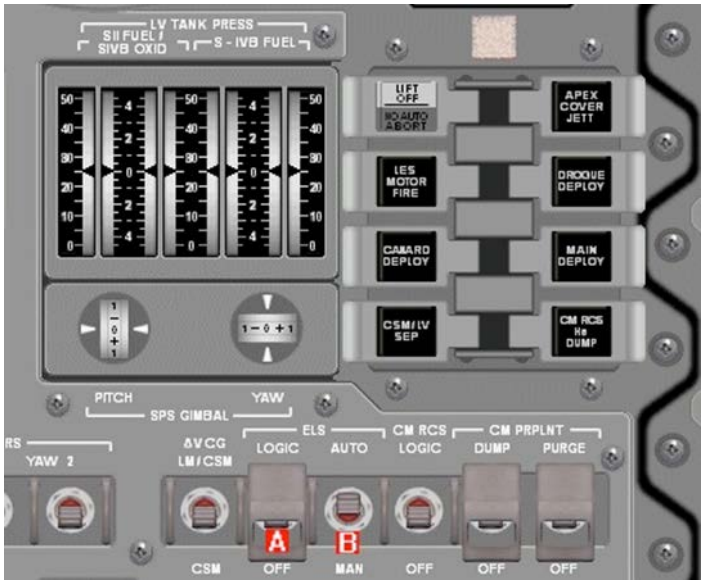

Figure 3. ELS sequencer switches
Source: NASA

- At 24,000 feet, the CMP realized that the apex cover was still attached; the drogue parachutes had not deployed. He switched to cue card backup procedures, jettisoned the cover and deployed the drogues manually. At approximately 16,000 feet, the CDR stated he had the Propellants OFF (RCS isolation valves closed). However, the RCS was still enabled because the automatic ELS function had not been armed, and the manual RCS Command switch had not been thrown to OFF. The CDR then realized the ELS was not in AUTO and switched LOGIC and AUTO (RCS commands disabled) at 9,600 feet. The CMP manually deployed the main parachutes at 7,150 feet.

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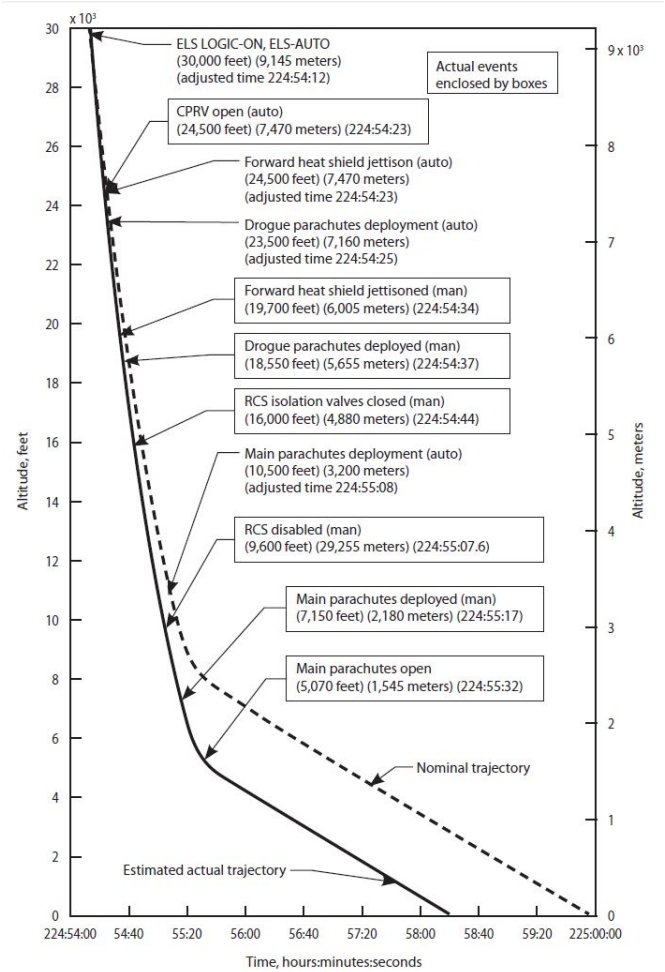

Figure 2. Comparison of actual and nominal ASTP descent sequences
Source: NASA

- At 24,000 feet, the CMP realized that the apex cover was still attached and the drogue parachutes had not deployed. He switched to cue card backup procedures, jettisoned the cover and deployed the drogues manually.

- At approximately 16,000 feet, the CDR stated he had the Propellants OFF (RCS isolation valves closed). However, the RCS was still enabled because the automatic ELS function had not been armed, and the manual RCS "CMD" (Command) switch had not been thrown to OFF. The CDR then realized the ELS was not in AUTO and switched LOGIC and AUTO (RCS commands disabled) at 9,600 feet. The CMP manually deployed the main parachutes at 7,150 feet.

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What Happened (cont.)

- Closure of the propellant isolation valves allowed the oxidizer trapped between valves and thrusters to boil off and reddish-brown nitrogen tetroxide (N_2O_4) flooded the cabin when the cabin pressure relief opened. The gas irritated the crew's skin and eyes and they began coughing — impeding intercom communication within the CM and to ground control.
- Upon splashdown, the CM flipped over, suspending the three crewmen upside down in their harnesses. The CMP hung unconscious while the CDR freed himself to retrieve the emergency oxygen masks, which were inaccessible during descent.
- The crew donned masks, actuated the spacecraft's uprighting system, and opened the vent valve to clear the toxic cabin fumes.

Figure 4. The uprighted ASTP CM during recovery in the Pacific Ocean. Source: NASA

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Proximate Cause

Toxic gas entered the cabin for 30 seconds from manual deployment of the drogue parachutes to the disabling of the RCS. Crew exposure was estimated to last nearly five minutes.

Underlying Issues

Instead of relying on the new redundant wiring change, the crew did not follow the procedure to arm the pyrotechnic buses at 50,000 feet and to enable the automatic ELS at 30,000 feet.

Oxidizer Boiloff

- When the CDR closed off the propellant isolation valves, the oxidizer — trapped between the isolation valves and the thruster solenoid valves — began to boil off as the thrusters operated for another 23 seconds (before the RCS was inhibited by the RCS disable relay).
- The cabin pressure relief valve opened automatically at 24,500 feet to equalize cabin pressure but was located two feet downwind one of the positive RCS roll thrusters. Designers had not addressed the potential for the valve to open with the thruster still firing.
- N2O4 reacted with the air and formed nitrogen dioxide (NO_2) and nitrogen trioxide (N_2O_3). The CDR observed a dark reddish-brown cloud in the cabin (apropos of N_2O_3). The crewmen were exposed to an average concentration of NO_2 of approximately 250 parts per million over a period of four minutes and 40 seconds.

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Underlying Issues (cont.)

Time-Critical Manual Switching

- The ELS was designed to operate automatically, with manual backup. The change was effective for Apollo 15 and subsequent flights; but the crew procedure to leave the pyrotechnic buses armed after CM/SM separation was made for Apollo 16 and subsequent missions.
- Yet, the ASTP crew did not trust the redundant ELS wiring and reverted to the Apollo 10 procedure of arming the buses at 50,000 feet manually during their descent (Apollo crews had flown in AUTO or MANUAL regardless of mission procedure until Apollo 15). As a result of that decision, the crew had to perform several crucial manual functions within a few seconds before reaching 24,000 feet for the ELS to operate as designed; however
  - Spacecraft control was not returned to the proper mode at 90,000 feet.
  - The pyrotechnic buses were not armed at 50,000 feet.
  - The RCS was not disabled “RCS CMD-OFF” at 24,000 feet.
  - The two switches that arm the ELS sequencer were thrown 55 seconds after the intended 30,000-feet mark.
- The Apollo Soyuz Mission Anomaly Report concluded that timely performance of any one of the missed functions would have prevented the entry of toxic gases.

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Underlying Issues (cont.)

Procedure Conflict

- RCS CMD-OFF was listed on the CMP's entry cue card as a normal function rather than being flagged with asterisks denoting a backup function as on the checklist. The DMP's entry cue card was simplified six months prior to launch; most manual backup tasks, including RCS CMD-OFF, were omitted. In training, the RCS CMD switch was never turned off unless the CDR did so when using manual backup procedures. If there was communication breakdown, the capability for the DMP to take over or assist the real-time callout of entry procedures during the time-critical earth landing sequence was restricted by the major change to his cue card, which deleted the RCS CMD-OFF and other backup tasks. The conflict between the cue card and checklist may have contributed to the RCS not being manually disabled.
- The CMP stated that he threw the proper switches as the CDR read from the entry checklist.

Emergency Oxygen Masks

- The emergency oxygen masks were designed for use as a backup in case of smoke or contamination in the cabin, but were stowed during descent. The crew's exposure may have been minimized had the masks been accessible from the restrained crew position during entry and landing.

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Aftermath

- Warm public reception of ASTP astronaut and cosmonaut goodwill tours in both countries meant that the descent incident had not detracted from the overall success of ASTP.

Relevance to NASA

- The ASTP re-entry incident sent a message: increasingly complex spacecraft design drove the need for crew comprehension of the systems behind the latest procedures — and no discretion to revert to older procedures. In August 1978, the director of operations for the new Space Shuttle Program wrote that astronauts "would not be permitted to either change or deviate from well-established procedures," a new NASA requirement. Already rigorous training added a dimension of standardization. Today, that tradition continues on board the International Space Station.
- Further, the importance of redundant design in critical electrical controls was demonstrated. The effects of a failure to follow a time-critical procedure in a tightly coupled system should be addressed in training and documentation such that the operator understands system function in both nominal and off-nominal states. Then, if the automatic behavior does not match the operator's expectation of correct function, manual backups can be used — if time allows — to maintain safety and mission success.

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