Death On Orbit: Extreme Environmental Conditions and the Deaths of American Astronauts

Craig T. Mallak

ABSTRACT

When the Space Shuttle Columbia was lost in 2003, the investigation presented many unique challenges, including numerous findings that had never been observed by forensic pathologists. The previous two major space shuttle fatality incidents also presented unique and complex issues. The causes of these incidents are now identified and the environmental impacts on the astronauts were a major contributor to the tragedies. Even with the improvements learned from the losses of Apollo 1 (1967), the Challenger (1986), and the Columbia (2003), space flight continues to be one of the most dangerous professions and environmental factors are significant contributors to this threat. While many have now been explained, the myriad of environmental insults to the crew continues to be a source of interest for those involved in space flight. Most forensic pathologists will never be involved in a death investigation of astronauts at the edge of outer space, on a mission, or during training, yet the findings are nevertheless of interest in the field of environmental death. *Acad Forensic Pathol.* 2018 8(1): 112-118

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INTRODUCTION

There have been over 40 astronauts/cosmonauts killed either in flight or during training (1, 2). The three major National Air and Space Administration (NASA) fatality incidents in American space flights: Apollo 1, the Challenger, and the Columbia were all associated with environmental conditions that resulted in 17 fatalities. While there were other factors involved, without the specific environmental conditions, the fatalities may have not occurred. All three missions were investigated by the forensic pathologists of the Armed Forces Institute of Pathology (AFIP), with the Columbia incident investigated under the auspices of the formalized Armed Forces Medical Examiner System as part of the AFIP. While the autopsy reports have never been released to the public, there is still significant information to learn about how the environment contributed to the deaths.

DISCUSSION

Apollo 1 (1967)

The original designation for this scheduled space flight was AS-204. Long after the fatal incident, it was renamed Apollo 1; there was never an Apollo 2 or an Apollo 3 mission. Mission planners decided to emphasize the “Apollo” part of the mission, hence the abbreviation changed from “SA” to “AS.” The launch vehicle/service and command module had been tested, without a crew, 12 times prior to this mission. The command module was mounted on a Saturn IB rocket, the smaller predecessor to the Saturn V that eventually made the missions to the moon (3).

The command module for Apollo 1 arrived at the Kennedy Space Center in August of 1966 with 113 engineering changes left incomplete (4). The module went through several tests, noting well over 100 deficiencies including one that involved spilling glycol coolant on the electrical circuit panels where it dried. On January 6, 1967, after most of the repairs were made, the vehicle was moved to Launch Complex 34 (LC-34) for additional testing. There continued to be problems with the testing and a quality control engineer from North

American Aviation, Thomas R. Baron, made so many complaints that his superior, John Hansel, eventually fired him for violating procedural requirements and disregarded most of the discrepancies he noted (5).

The primary crew for Apollo 1 consisted of Gus Grissom, Edward White, and Roger Chaffee. They had participated in command module tests for several months without significant incident. On January 27, 1967, they were scheduled to perform a “plugs-out” test during which the rocket would be disconnected from launch pad power, relying solely on battery power to simulate the use of fuel cells. Included in this series of tests were simulated emergency egresses from the command module (6). The hatch required over 40 latches to open inward. There was also an emergency crank above the latch that required five turns before it opened. This operation took 70 seconds to accomplish under ideal conditions. The rocket was not fueled and the test was considered nonhazardous. There were no fire extinguishers or fire suppression systems in the module (7).

At 1 pm on the 27th of January, the crew, dressed in their flight suits, entered the command module for the plugs-out test. The latch was sealed and the module was pressurized with pure oxygen at 115 kilopascal (kPa) (864 mmHg), 14 kPa (105 mmHg) above earth’s atmospheric pressure of 101 kPa (758 mmHg). The decision to use pure oxygen was based on 1) weight considerations to maintain air-like atmosphere, 2) a previous pilot who lost consciousness when nitrogen seeped into his suit, and 3) concern about the possibility of nitrogen narcosis if the crew had to make emergency egress after being under pressurized nitrogen for an extended period of time (8). A pure oxygen environment had been used in the ten Gemini (1962-1966) missions and the six Mercury (1958-1963) missions without any problems. The high pressure simulated the pressure they would be exposed to in space, about 34 kPa (259 mmHg). This was also the pressure in their suits (9).

The training lasted several hours, with NASA and the astronauts troubleshooting numerous issues. A simulated countdown started at 6:31 pm. Within seconds, one of the astronauts announced a cockpit

fire. Within 12 seconds, the pressure had exceeded 144.78 kPa (1086 mmHg), making it impossible to open the inward-opening latch. The last transmission from an astronaut occurred 17 seconds after the fire was first reported. At the same time, the command module ruptured, spreading flames throughout the area. Shortly after rupture, the fire in the module extinguished itself after the consumption of the oxygen in the module and the hatch was opened by ground personnel within five minutes (10). The surrounding fire continued and there was concern at one point that the launch pad may collapse.

In addition to the pure oxygen, a major environmental danger was what was described as flammable “wall to wall Velcro,” nylon seats, and 30 kg of other flammable materials (8). While the exact cause of the fire was never determined, there was evidence of several electrical arcs, an exothermic reaction from previously spilled glycol coolant reacting with silver wire, and a recorded power surge were all considered possible sources of ignition (11).

The astronauts were seated, from left to right: Roger Chaffee, Edward White, and Gus Grissom. There was corresponding burning of the spacesuits with Grissom at 70%, White at 25%, and Chaffee at 15%. The investigative board used this finding to conclude that the fire spread from the wiring under Grissom’s seat to the left (12).

While the autopsy reports were never released to the public, the investigation reports that followed stated the factors leading to death included high temperature, overpressure, and hypoxia with inhalation of products of combustion. It was estimated that consciousness was lost within 15-30 seconds after the breach of the spacesuits. The chance of resuscitation was lost by four minutes after the fire started (13).

In the aftermath of the fire, there were several investigations both within NASA and other government agencies such as the United States Senate. After months of investigation and testing, several recommendations were made and subsequently implemented. There were 11 recommendations with the most

significant addressing the environmental issues in and around the astronauts (14).

The first finding was the elevated 100% oxygen ambient environment within the command module, with a recommendation that for lift-off the atmosphere within the module be 40% nitrogen and 60% oxygen. After launch, the module would be vented and replaced with pure oxygen at 34 kPa (259 mmHg). The lower kPa is adequate as the other gases are not needed to sustain life in the closed environment. The atmosphere within the space suits is also maintained under these conditions. The lower kPa would help prevent fires (8). In microgravity of space, pure oxygen is less of a hazard as there is no air convection and any fire would spread slowly and be easily extinguished (9).

Another major finding was the abundance of flammable materials in the command module, with a recommendation that all materials within the crew space were to be made from fire-resistant materials. In line with this recommendation was a separate finding about the use of various fluids in the mechanical operation of the module. All fluids for future flights were not flammable and did not produce exothermic reactions when in contact with other components of the command module. This practice continues to this day.

The astronauts were not able to egress the module due to the over pressurization of the cabin in combination with the inward opening hatch. Future flights and tests were undertaken with the pressure in the module being no higher than that of the ambient pressure, and the hatches opened outward on all future spacecraft.

The astronauts had no back-up source of oxygen and inhaled toxic fumes when the primary oxygen supply system failed during the first minute. All subsequent missions provided the astronauts with a backup source of oxygen that could be activated manually, automatically, or via command sent from mission control.

Challenger STS 51-L (1986)

The Challenger was the second fully functional space shuttle. The first mission took place in 1983 and the

Challenger made eight more flights before the fatal mission in 1986. The designation of “STS 51-L” was one of several, ever-evolving flight term designators. The term STS is the abbreviation for Space Transportation System (15). The “5” designated the fiscal year of the mission. The “1” indicated that the mission was to launch from Cape Canaveral, whereas a “2” would have represented a launch from Vandenberg Air Force Base in California. No shuttle missions were ever launched from California and the project to establish the launch site was terminated after the loss of the Challenger. The “L” is to track the number of launches planned that year, in this case number “12” (16). Many of missions were never launched for a variety of reasons but the planning took years and designators stayed the same whether the launch took place or not.

The crew of the Challenger for this January 28, 1986 mission consisted of five astronauts: Mission Specialist Judith A. Resnik, Commander Francis R. Scobee, Mission Specialist Ronald E. McNair, Pilot Michael J. Smith, and Mission Specialist Ellison S. Onizuka. There were also two designated Payload Specialists, Payload Specialists Christa McAuliffe, designated as the first “Teacher in Space” chosen for a mission, and Gregory B. Jarvis, representing the Hughes Aircraft Corporation (17).

The space shuttle at the time of liftoff was composed of the orbiter, a large hydrogen/oxygen tank that supplies fuel to the engines on the shuttle, and a solid rocket booster on each side of the large fuel tank. The solid fuel booster provided the primary thrust for the first two minutes after which they were jettisoned and recovered from the ocean to be re-used (18).

The solid rocket boosters were composed of several cylindrical segments that were stacked on top of each other and attached through an intricate combination of fasteners. The propellant lined the inner ring of the cylinder with the center of the rocket motor open from near the top cone to the thrust/vector opening at the bottom. When assembled, the booster was 45.4 m in length, 3.7 m in diameter, and weighed 590 000 kg (19). The segments were sealed by use of two O-rings and covered by a zinc-chromate

putty. The rings compressed and decompressed rapidly in response to weight of the booster and thrust during use. During their change in configuration, they did not completely seal the two segments. The 0.711 cm in diameter rings were seated in a groove that was 0.787 cm in width. The putty was designed to be driven against the O-rings by the thrust force and provide a fire tight seal. The putty would boil and burn, but the risk of burning through to the O-ring during the two minutes of use was considered highly improbable and an acceptable risk. The O-rings were manufactured by Morton Thiokol Corporation and were rated for use above 11.67°C (19); they had never been tested at low temperature.

On the morning of January 28, 1986, the launch was cleared for 11:38 am. The temperature was 2°C, 15 degrees colder than any previous shuttle launch. Morton Thiokol Engineer Roger Boisjoly warned NASA not to launch due to the possibly of the failure of the O-rings under these environmental conditions. The NASA manager ignored the warning and moved forward with the launch (20). The mission started at 11:38 am with the ignition of the main engines and boosters. Within the first second, puffs of black smoke were seen coming from the aft/medial aspect of the lower seam of the right rocket booster. It was later determined that the aft section of the booster was in the shade of the shuttle assembly and the temperature was -2°C. There were eight more increasing puffs of smoke from this same location before 2.5 seconds into the launch; the smoke then stopped. The shuttle experienced the worst wind shear of any mission to date between 37 and 64 seconds of the flight. At 58 seconds, the first flame was seen at this same location on the right booster, and as the flame grew it was deflected against the external hydrogen/oxygen tank. The tank was breached at 64 seconds and almost a million kilograms of oxygen and hydrogen explosively burned at the 72 second mark, resulting in termination of the flight. The shuttle was travelling 2400 km/hour at a height of 14 km when it broke apart and fell into the ocean (21).

During the investigation that followed, multiple theories were considered as the cause of incident. They

settled on the O-ring and putty as the primary cause. Management's failure to listen to Morton Thiokol was also listed as contributory to the disaster. During the investigation, the O-rings underwent numerous tests. They were designed to afford flexibility to the rocket to take the stress off metal segments as well as seal the seams between the segments. When compressed, they would block the medial and lateral walls of the ring groove preventing blow-by of the gases from the thrust. When stress was off the joint, the superior and inferior wall were blocked by the ring. During the transition, one of the two rings was always blocking opposing walls, blocking escape of the gases. The time for recovery of the ring from the compressed configuration to round is far less than one-tenth of a second at 15°C. At -2°C, the resiliency was slowed by a factor of five, allowing an opening for the gases to escape. The putty inside the rings hardened with the decrease in temperature and one test performed between 28°C and -7°C saw the delay on the putty sealing any leaks was increased from 500 milliseconds to 1.9 seconds (22). The O-rings changed configuration about three times a second when the rocket was in operation. The puffs of smoke noticed at the time of ignition and thereafter represented burning of the rings and putty escaping through the joints. This blow-by was initially sealed by the products of oxidation of the aluminum in the propellant. The extreme wind shear broke these seals, allowing the burning propellant to escape through the opening of the now burned-through O-rings (23). While there was failure at several steps of the processes in this launch, it ultimately was the extreme environmental factors that caused this accident. Several improvements were made to correct the deficiencies (24), but there was still one more shuttle to be lost due to the environment.

Columbia STS 107 (2003)

The Columbia was the first operational shuttle. The first shuttle, the Enterprise, was essentially a glider used to test whether it could land from a high altitude without power. In 1979, the Columbia was moved from Palmdale, California to the Kennedy Space Center in Florida. It would take two more years to complete construction and prepare the orbiter for test

flights (25). The shuttle would fly 27 times before STS 107. The missions included repairing satellites and the Hubble telescope.

The flight was scheduled for 17 days working the "SpaceHab," a module in the cargo bay, to test how well the crew could carry out science experiments in preparation for work aboard the International Space Station. The flight was delayed over three years for various reasons and finally commenced on January 16, 2003. The crew consisted of Rick Husband, the Commander; William McCool, the Pilot; and Mission/Payload Specialists Michael Anderson, David M. Brown, Kalpana Chawla, Laurel Clark, and Ilan Ramon from the Israeli Defense Forces (26).

The shuttle sat on launch pads through several severe rainstorms and water accumulated in the open spaces in the insulation. When the liquid hydrogen and oxygen tanks filled the day before launch, the water froze and most likely weakened the insulation as the ice expanded. At 57 seconds into the mission, the Columbia experienced severe wind shear to the left side of the boosters, tank, and orbiter. The nose of the shuttle is attached to the liquid fuel tank by a bipod. The tank was sprayed with 2.5-5.0 cm of insulating polyurethane foam to slow the loss of the liquid hydrogen and liquid oxygen. In areas such as the bipod, the foam was hand applied. At 81 seconds of flight, the foam came off the base of the left tripod and struck what NASA believes is the eighth tile on the leading edge of the left wing at a speed relative to the orbiter of over 1000 km/hr, puncturing it and exposing the contents of the wing. Speed of the foam was calculated as a combination of the slowing of the foam and acceleration of the shuttle (27). The crew was unable to see the damage as there were no spacewalks planned and there was no robotic arm on this mission. The flight continued to orbit at 281 km above the earth.

While the foam strike was known by NASA, it was decided to continue the flight profile. On February 1, 2003, the Shuttle began the procedures for a normal return to earth with a planned landing at Kennedy Space Center in Florida. Where "outer space" begins and atmosphere ends is unknown. It is known that at an altitude of 609

600 km, the atmospheric pressure is 4.8×10^{-10} kPa (36×10^{-10} mmHg). The arbitrary altitude for outer space is 100 km, known as the Kármán Line (28, 29).

As the shuttle approached the 70 000-60 000 m altitude, the air pressure would have been less than 2.2×10^{-2} kPa (0.165 mmHg), but at a speed of Mach 24.1 or 29 524 km/hr, there would be enough air resistance to heat the leading edge of the wings to 1537°C. The heat entered the defect on wing and over the course of less than six minutes, from 8:48 am to 08:54 am, all the sensors in the wings and the landing gear were destroyed and the shuttle started to shed debris, first noticed over California. The last transmission was a single word at 08:59 am (30).

The shuttle lost the left wing, and now out of control over eastern Texas, the cabin depressurized within a minute, the shuttle broke up, and the astronauts separated from the craft and fell somewhere lower than a height than 60 km, travelling around 10 000-18 500 km/hr. The investigation team performed numerous calculations based on the debris that was recovered, but the exact point where crew-craft separation occurred remains an estimate.

The first call to the AFIP came in before 10:00 am. Initial discussion was that NASA did not believe there would be any need for assistance due to the height and speed at which the astronauts lost contact with the shuttle. By shortly after 1:00 pm, that decision was reversed and a multidisciplinary forensic pathology investigation was undertaken over the next ten days at three different locations.

The autopsy reports have never been released to the public. There is only one definitive finding ever released, which was that all the Columbia astronauts had microscopic evidence of ebullism (31). Ebullism, as evidenced by bubbles in the soft tissue, occurs when the human body is exposed to altitudes greater than 19.2 km when the body is not protected in a pressurized suit or environment to prevent exposure to the extremely low air pressure 6.21 kPa (46.6 mmHg) (32). Numerous other injuries of unidentified crew members are discussed publicly with possible mecha-

nisms, but given the numerous forces applied to them during this event, the exact mechanism is uncertain (33). Far less information was ever made public about the postmortem examinations in the Challenger and Apollo 1 accidents.

CONCLUSION

Accidents such as the three described are very complex, with multiple factors leading to the incidents. Everything from mechanical failures to the NASA culture was discussed extensively; however, the environmental stressors placed on and around the astronauts played a large contribution to the deaths. The Apollo and the Shuttle programs both underwent extensive changes in design and operating procedures in the aftermath of each incident, but NASA can't change the environment and it continues to be an issue in the current space programs.

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