National Aeronautics and Space Administration

System Failure Case Studies

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FIRE IN THE COCKPIT

A seminal event in the history of human spaceflight occurred on the evening of January 27th, 1967, at Kennedy Space Center (KSC) when a fire ignited inside the Apollo 204 spacecraft during ground test activities. The 100% oxygen atmosphere, flammable materials and a suspected electrical short created a fire which quickly became an inferno. Virgil Grissom, Edward White II, and Roger Chaffee (the prime crewmembers for Apollo mission AS-204 – later designated Apollo 1) perished in the flames before the hatch could be opened.

Figure 1: Grissom, White and Chaffee.

BACKGROUND: THE SPACE RACE

In October of 1957, at the height of the Cold War, the Soviet Union launched the Sputnik satellite providing a global display of Soviet technological prowess and sending shock waves throughout the "free world." This marked the very public beginning of the "space race." Over the next four years the USA and the Soviet Union space programs evolved, learning from failures and celebrating successes. Then, in 1961, newly elected President John F. Kennedy declared that the USA would land on the Moon and safely return by the end of the decade – thus initiating the Apollo Program and the race to the moon.

Mercury/Gemini Success – Overcoming Design & Quality Control Issues

Project Mercury was the United States' first human space flight program and accomplished six missions safely between May of 1961 and May of 1963 with a one astronaut crew. Historical records indicated that the Mercury Project struggled with design and quality issues associated with spare parts, batteries, improper soldering, improper installation of valves, and dirty regulators. Mercury was followed by the Gemini Project (two astronaut crew), which accomplished ten missions safely between March of 1965 and November of 1966. Notable design and quality issues included an electrical short on Gemini VIII in the control circuitry that caused early termination of the mission and a landing in a secondary recovery area. The Apollo Program accomplished the first manned missions in 1968 after seven years of component design, development and testing.

Apollo Spacecraft 204

AS-204 was built by North American Aviation (NAA) and shipped to KSC in August, 1966, despite the fact that there was still open work. That work and other engineering changes would be completed at KSC. The Command

A Tragic Fire Took the Lives of Three Astronauts Aboard Apollo 1.

Proximate Cause:

- A spark caused by an electrical short in a 100% oxygen atmosphere set fire to an abundance of flammable material

Underlying Issues:

- Vulnerable design and material choices for wiring, atmosphere, cabin materials, and hatch door
- Poor quality control and workmanship
- Inadequate provisions for emergency response
- Budget and schedule pressures resulted in the over-prioritization of speed

Module (CM) was received at KSC on August 26th and mated to the service module in September. More tests, reviews, and engineering changes ensued until January 6th, when the CM was removed from the test facility and mated with the launch vehicle on Pad 34.

Single vs. Two Gas Design

Competing design concepts included tradeoffs between the single gas (oxygen) versus two gas (nitrogen and oxygen) options, including: mass (500 pound weight penalty for tanks, tubing, and instrumentation for the two gas option); complexity and reliability (fewer failure modes with single gas design); vulnerability to the "bends" (nitrogen bubbles that could form in the body's tissues in the event of a micro-meteoroid impact / decompression event); physiological problems associated with a 100% oxygen atmosphere (eye irritation, hearing effects, clogged chest); and increased fire hazard in a 100% oxygen atmosphere (to be mitigated through careful restriction of flammable materials). NASA had used the single gas design on Mercury and Gemini missions (over 1,000 hours of flight time) and on thousands of ground tests without a fire incident. The single gas option seemed a reasonable choice at the time.

Hatch Design

The CM was known as a "Block 1" design. One significant change from previous spacecraft designs was the hatch. Earlier hatches had opened outward, but the experience with premature release of a hatch on the Mercury MR-4 mission led to a redesign. The new hatch system was comprised of three sections, which required the removal of six bolts and opened inward. It was estimated that it took about 90 seconds to remove and stow the hatch and egress the crew.

WHAT HAPPENED?

The Fire

On January 27th, 1967, the Apollo 1 crew entered the spacecraft to perform an important launch countdown rehearsal test. The test commenced at 2:42 pm with hatch installation and subsequent oxygen cabin purge. For the next three hours, the crew and ground personnel performed tests. The countdown checklist continued to the point planned at 6:20 pm (T-10 minutes) when ground personnel would "pull the plugs" and the spacecraft would go into a simulated fuel cell environment. Awaiting clearance for this event, another hold was called. From 6:20 to 6:30 pm, there was routine troubleshooting of communications problems, and no events occurred that appeared to be related to the subsequent failure.

Tragedy struck at 6:30 pm, about 5 ½ hours after the start of the simulated countdown, when a significant transient in the AC Bus 2 voltage was observed. The transient indicated a major short circuit somewhere in the CM wiring. At 6:31:04.7, a crew member, speculated to have been Grissom, exclaimed "Fire! We've got a fire in the Cockpit!" At 6:31:16.8, another voice, thought to have been Chaffee, whose job it was to maintain communications in an emergency, said "We've got a bad fire – let's get out. We're burning up!" Before he could finish his sentence, the pressure inside the spacecraft had built up to more than two atmospheres. The spacecraft ruptured, and the cabin filled with toxic fumes. By 6:31:22, all voice and data transmissions had stopped.

Rescue efforts were hampered by the fire and smoke. Visibility in the environmentally controlled close-out room was essentially nonexistent. In all, 27 men were treated for smoke inhalation in fighting the fire. Efforts to remove the three-part hatch system began about one minute after the report of the fire, and the hatches were all removed by about 6:36 pm. By then, it was too late.

PROXIMATE CAUSE

The report of the Review Board stated that "the fire was most probably brought about by some minor malfunction or failure in equipment or wire insulation… This failure, which most likely will never be positively identified, initiated a sequence of events that culminated in the conflagration." The most likely scenario, identified in the exhaustive evaluation and findings of the Review Board, is reproduced in-part below.

Electric Arcs: Teflon has excellent fire resistance, but low resistance to cold flow (see "Cold Flow" inset). The Teflon covering on the wire used in Apollo 204 could also be damaged easily or penetrated by abrasion. In addition, the Board found numerous examples in the wiring of poor installation, design, and workmanship. If a power conducting wire experiences penetration of its insulation by the metal structure of the spacecraft or spacecraft components, an instantaneous

Figure 2: Wires where the fire was suspected to have started.

short to ground is created at the point of conductor contact. An arc or a series of arcs between conductor and structure will result. Circuit breakers and other practical circuit interrupting devices cannot act rapidly enough to prevent an arc. Thus, arcs cannot be eliminated as a potential source of ignition energy. As noted previously, there were strong data indications of an abrupt, short-duration voltage decrease. This is consistent with a quickly terminated arc.

Cold Flow: Cold flow (or creep) deformation involves the insulation gradually separating or flowing apart from a pressure point, such as in the case of a foot resting on exposed wire that is held against a metal edged structure.

UNDERLYING ISSUES

Design & Material Issues

Both wiring and plumbing installation designs were faulted by the accident Review Board – "unprotected vulnerable wiring carrying spacecraft power and vulnerable plumbing carrying a combustible and corrosive coolant." The choice of Teflon as the wire coating may have been a good choice from the standpoint of fire resistance but the wrong choice for wires that were directly exposed to the cabin environment.

The selection of a 100% oxygen atmosphere was made despite the potential hazard. The decision was an accepted risk. The absence of a mature systems safety process was demonstrated by the presence of extensive combustible materials in the cabin, even though the intention to limit such material was the rationale and basis, in-part, for approving the 100% oxygen atmosphere.

Figure 3: Commemorative patch.

In addition, the hatch design which opened inward did not provide the means to quickly egress the crew in the event of a fire, as the pressure buildup inside the cabin creates massive forces against opening the door.

Quality Control

Issues concerning NAA personnel management, equipment, parts, procedures, workmanship, and contamination were released to the press in 1966 by KSC quality inspector Thomas Baron in a 55 page report. At the time, NAA analyzed the accusations and denied most of them, although later the company admitted that about half of them were valid. Mr. Baron was called to testify before Congress after the accident.

Emergency Preparedness

The Review Board cited inadequate provisions for emergency response or rescue as a contributing cause. Also, the fire and medical teams were not initially present when the fire started.

Budget and Schedule Pressures

The Apollo 1 fire took place in the charged environment of Cold War national urgency – speed was imperative. In addition, NAA was under intense scrutiny and criticism from NASA over cost overruns and schedule delays in the years prior to the mishap. These concerns led to an investigation by Apollo Program Director Major General Samuel C. Phillips in late 1965. In retrospect, time and budget pressures could be viewed as contributing factors to the design, manufacturing, and quality control process issues noted above.

AFTERMATH

The Apollo 204 Review Board was established on January 28th and consisted of 10 people, 7 of whom were NASA employees. The analysis ultimately involved 1500 experts in 21 panels investigating different aspects of the accident. The final report of the Board, released April 5th, was 3000 pages long.

NASA aggressively responded to implement the Board's suggestions, switching to "Block II" (upgraded) spacecraft already in development, which included many of the recommendations of the Board, such as better hatch design which would open outwards and be operable in less than 10 seconds. Better fire resistant materials were developed for spacesuits, concerns about a pure oxygen environment for ground tests were addressed, higher quality wiring with abrasion protection and fireproof coatings was used, new emergency procedures and equipment were added, and almost all flammable materials inside the spacecraft were removed. In all, about 1500 changes were made, resulting in a more secure and safer vehicle. In addition, NASA implemented management changes moving astronauts into more management positions and creating an independent flight program office at Headquarters. Additionally, space flight centers were tasked to review all aspects of design, manufacturing, test, and flight from a safety standpoint.

LESSONS LEARNED FOR NASA

The Apollo 1 case study is particularly import for NASA to consider in development of designs for the Orion spacecraft and Ares family of booster rockets. The design tradeoff process must actively engage with the design system safety hazard analysis process to ensure that any mitigation measure or safeguard for a known hazard in the accepted design is indeed implemented and verified with rigor. The Apollo 1 case demonstrates how previous success (over 1000 hours of flight) with a recognized, but not properly mitigated hazardous condition, can lull managers, designers and operators into complacency, believing that a fire is highly unlikely or that the danger was overstated. Program and project managers, team members, and assurance professionals need to ask every day: have we just been lucky or do we have real margins and real hazard mitigation measures in place?

"In memory of Those who made the ultimate sacrifice so others could reach for the stars"

- Apollo 1 Memorial Plaque

The case further underscores the need to understand material properties (e.g. flammability) across the full range of operating environments, in this case a 100% oxygen atmosphere. Understanding consequence, in a risk management context can be an abstract proposition. Many people involved in the Apollo program had no real appreciation for the dangers associated with the 100% oxygen operational environment. More hands-on engagement with hardware and test environments, fire and explosion training, and/or hazard demonstrations will assist designers of space systems to better understand risks.

Another important theme is systems engineering and integrated hazard analysis (one sub-system hazard triggering other sub-system events). Had the wiring designers considered the consequence of a short circuit arc in a 100% oxygen atmosphere with flammable material present, certainly a more robust physical abrasion protection system would have been implemented.

A final topic to consider, and one of the most vexing challenges for the engineering profession, is the responsibility to ensure that the solution to one problem does not become the source of the next. Avoiding this outcome is a principal role of the systems engineering discipline. Consider the inward opening door that mitigated the likelihood of losing the door and swamping the capsule as occurred on the Mercury MR-4 mission. This improved hatch proved an egress liability in the case of the Apollo 1 fire. The second example embedded in this case study is the evolution of wiring in aerospace systems. Recognizing the cold-flow vulnerability of Teflon, Dupont developed an extremely abrasion resistant wire in the late 1960s known as Kapton polyimide (perhaps in-part a response to Apollo-1 fire). While possessing may admirable qualities in terms of durability, Kapton insulated wire proved, over time, to be vulnerable to cracking on tight radius turns and had a hidden and insidious failure mode known as arc-tracking (a current limiting short circuit) which can lead to a catastrophic event known as flash-over. Kapton related failures occurred in both military and civil aerospace applications, most notably TWA Flight 800.

Questions for Discussion

- To what extent is systems engineering emphasized and executed within your program? Who are the leaders in your work group who promote and elevate the systems perspective?
- In engineering tradeoff deliberations, are all risks and/or hazards treated in a balanced fashion? Do certain risk issues have a "louder voice" at the table?
- How do you avoid complacency when you have repeatedly been successful at inherently hazardous or difficult tasks?
- Do you review hazards and critical items in your project or program periodically to ensure that they are still appropriate, correct, and that any controls and other mitigations are properly implemented?

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Multiple references under "Apollo 1, Apollo 204, Mercury, Gemini" available at NASA web sites within the following domain http://www.hq.nasa.gov/office/pao/History.

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