National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Vicious Cycle

The year was 1967, and the United States and the Soviet Union had engaged in a race to the moon. While the world watched as two nations broke old records and set new milestones in Earth orbit, aerospace history was being made on a less publicized, suborbital, stage. High above Edwards Air Force Base, test pilots pushed known limits of materials, guidance, and human performance in the North American X-15. Called "the most successful research airplane in history," the X-15 probed the hypersonic flight environment to carry out otherwise impossible experiments. After 190 flights, the X-15 had flown up to Mach 6.7 (4,520 miles per hour) and set an altitude record for manned winged vehicles (354,199 feet) that would stand until the Shuttle launched years later. But on November 15, the program saw tragedy. That day, U.S. Air Force Major Mike Adams was piloting the number three aircraft when a drift in heading caused the X-15 to reenter the atmosphere perpendicular to its ballistic flight path. The aircraft departed controlled flight. At 62,000 feet, severe g forces tore the aircraft apart, and Major Adams perished in the accident.

BACKGROUND

X-15 Flight Test Program

North American Aviation constructed three X-15 research vehicles in the late 1950's for a flight test program that sought to investigate winged flight at the edge of space. The program, funded by the U.S. Air Force and developed through collaboration between the Air Force, Navy, and NASA, allowed researchers to study the effects of dynamic pressure, heating rate, and total temperature on aircraft stability and control. Later, the X-15 would also carry experiments related to the guidance system that would be used for Apollo navigation to the moon.

A typical flight began with the aircraft shackled under a wing of a specially modified B-52A (Figure 1). The X-15 rode the bomber to an altitude of approximately 45,000 feet before dropping away and allowing its rocket engine to propel it to an ascent of over 350,000 feet – more than 66 miles above the surface of the earth. Approximately 84 seconds later, the pilot would shut down the engine, and the remainder of the flight would continue unpowered. An X-15 flight usually lasted for 10 minutes from launch to touchdown on Rogers Dry Lakebed.

Figure 1: The North American X-15 rides beneath the starboard wing of a specially modified B-52A to launch altitude.

Peak altitudes for the X-15 often extended beyond the borders of the atmosphere, so X-15 pilots routinely experienced several minutes of microgravity. Conventional aircraft control surfaces (rudder, ailerons, horizontal stabilizers) are ineffective without air to push against, so designers equipped the X-15 with small rocket thrusters to give pilots control above the atmosphere. The left side of the cockpit housed a side stick that offered manual control of rockets in the nose and wingtips. The side stick allowed pilots to maintain correct attitude and to position the aircraft at the proper angle of attack for reentry. The third X-15 aircraft (X-15-3) integrated ballistic control with aerodynamic control inputs made from the right side stick using a new and unique reaction control system (RCS).

Stability Augmentation

Minneapolis-Honeywell developed an adaptive flight control system (AFCS) called the MH-96 for the X-15-3. An AFCS was designed to either amplify or resist pilot inputs to increase aircraft stability and control. The MH-96 constantly analyzed the aircraft's response to the current speed and altitude and compared it with a programmed

Pilot loses control of X-15; Aircraft Suffers In-Flight Breakup

Proximate Causes:

- Electrical disturbance deactivates automatic reaction control system
- Aircraft reenters at incorrect angle of attack
- Adaptive control system becomes saturated; prevents pilot from regaining control of aircraft

Underlying Issues:

- Qualification of Hardware
- Qualification of Flight Crew
- Human Factors Considerations

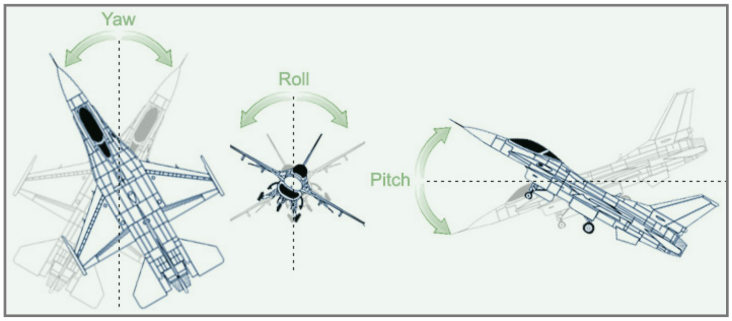

Figure 2: Diagram depicting yaw, roll, and pitch on an aircraft.

model. The system then issued guidance commands to the aircraft to match the model. To do this, the MH-96 adjusted a property of incoming electrical signals known as gain. Moving the control stick on the pitch, roll, or yaw axes sent corresponding electric signals to the MH-96. Amplifying or dampening the gain from those signals affected the pitch, roll, or yaw of the aircraft (Figure 2). As aircraft altitude increased, the MH-96 increased gain levels. As aircraft altitude decreased, the MH-96 would reduce gain levels. For example, aircraft angle of attack must be reduced after reentry. To accomplish this, the system sensed increasing dynamic pressures and these triggered a decrease in gain which adjusted the horizontal stabilizers and decreased the aircraft's pitch rate response to prevent the system (pilot included) from overstressing the aircraft as denser air was encountered.

The MH-96 was also designed to blend the RCS with the aerodynamic controls. The RCS sensed the amount of gain in the system. A 90% gain threshold activated the RCS. The RCS would disarm when it sensed gain thresholds below 60% to conserve rocket control fuel. This meant that as the aircraft escaped the densest layers of the atmosphere, the ballistic thrusters engaged automatically, allowing the aircraft to remain controllable as the stabilizers became less effective.

Attitude Indicator

The X-15 attitude indicator occupied the center of the cockpit's control panel. The instrument was a freely rotating sphere commonly referred to as the "8-ball," and its faceplate displayed a fixed reference aircraft symbol. The sphere itself was bisected into white and black areas representing sky and earth, respectively. The typical X-15 ballistic flight profile prevented pilots from seeing Earth's horizon until re-entry; moreover, the degree of precision flying required by the mission demanded constant reference to flight instruments until landing.

Figure 3 displays the pilot's attitude indicator; aircraft pitch, roll, and yaw were adjusted primarily in reference to the vertical and horizontal needles and cross-checked using other instruments. Input to the vertical needle was pilot-selectable. For initial (boost) phase and much of re-entry, the vertical needle indicated sideslip (the amount of yaw either to the left or right of center). As the aircraft reached higher altitudes and conducted certain scheduled experiments, pilots could activate a switch to change the vertical needle's input to display a preset specific roll angle needed for a specific experiment (this was referred to as PAI – precision attitude indicator). This was a major design departure for a performance instrument considered critical to maintaining controlled flight; it was done because the X-15 instrument panel had limited area available.

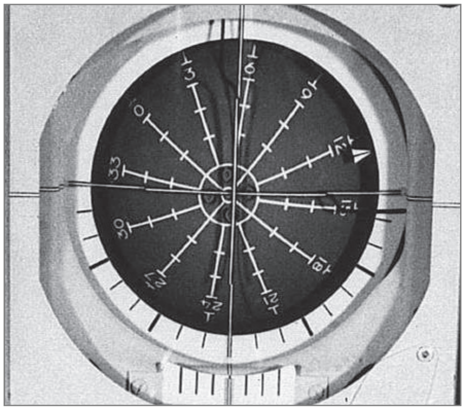

Figure 3: The attitude indicator occupied the center of the cockpit console. The vertical and horizontal crosspointers could indicate either pitch and roll amounts or angle of attack and sideslip. This feature played a significant role in the X-15's crash.

Mission Objectives

The X-15's 191st flight had a planned altitude of 250,000 feet. The flight's ten minute duration was packed with a full experiment schedule which included solar spectrum measurements, ultraviolet exhaust plume measurements, boost guidance, and micrometeorite collection. The X-15 would also carry a traversing probe in the pod of its right wingtip. The traversing probe was a measuring tool used for a specific experiment (called a bow-shock standoff measurement), and it was driven by a 115-volt, 400-cycle electric motor. This probe had been used on X-15-1 in 1963, but neither the probe nor the motor had ever undergone thorough qualification tests for their ability to withstand low pressures, high temperatures, or other environmental factors. No requirements for such testing existed.

WHAT HAPPENED?

Just before 10:00 am on November 15, 1967, Major Mike Adams waited inside the cockpit of the X-15-3 as the B-52A carried it to launch altitude. At 10:30 am, at a 45,000 ft altitude, Major Adams dropped from the B-52 and accelerated into a steep climb. Seconds later, an electrical arc shot from the traversing probe into the aircraft electrical system, causing a disturbance that persisted for 60 seconds. The disturbance drove MH-96 system gains below 50%, disarming the RCS.

Major Adams shut down the engine as planned at 140,000 feet. At 10:31:33, he activated the PAI and began a wing-rocking maneuver necessary for the exhaust plume measurement. However, Major Adams exceeded the bank angles specified in the flight plan, possibly due to the degraded flight system performance triggered by the electric arc. Major Adams could have used the left side stick to engage manual control over the rocket thrusters at this time, but he did not. During the rocking maneuver, system gains finally rose above 90%, activating ballistic control for the first time, but just seconds later, at 10:32:25, a second arc and electric disturbance coursed through the aircraft. The disturbance drove MH-96 system gains to their minimum levels, deactivating the automatic RCS again. During the maneuver, the aircraft had begun a slow but steady yaw to the right.

At 10:33, the aircraft approached the top of its climb, and Major Adams noticed the aircraft's lack of responsiveness due to the RCS's intermittent activity and ultimately due to its deactivation. He then used the left side stick to activate manual RCS control. The attitude indicator (set to PAI) showed that the aircraft required a roll to the right, but mishap investigators believe Major Adams instead interpreted the PAI vertical needle as sideslip rather than roll angle. He then made a yaw input to the right, which further increased the X-15's heading deviation.

Now the aircraft had reached the peak of its climb and had begun to descend but its pilot was likely unaware that it was skewed at right angles to its flight path. At 240,000 feet, Major Adams radioed to ground control that the aircraft "seems squirrely." Ground control did not have access to the aircraft's heading information, leaving them unaware of Major Adams' severe situation. Flight monitors told the pilot he was "a little bit high," but in "real good shape." Soon, rapidly increasing dynamic pressure threw the X-15 into a Mach 5 spin. Major Adams called to ground, "I'm in a spin," as he held both ballistic and aerodynamic controls against the direction of rotation in an attempt to break out of it. No procedure had been developed for this situation. Ground control lacked the telemetry to understand history's first hypersonic spin and could not advise anything but to keep the angle of attack high to safely perform the reentry.

After the aircraft had completed three revolutions, Major Adams' effort to hold anti-spin control inputs and the X-15's flight control system stopped the rotation, resulting in a 45 degree inverted dive. Major Adams still had 130,000 feet of altitude to recover from the dive, but the MH-96 began forcing the horizontal stabilizers into rapid, cyclic oscillation to their limit of travel. In response, the X-15 pitched violently (plus and minus 15 g's) and yawed almost as violently (plus and minus 8 g's). No procedure existed for this condition either; post-mishap simulations found the only way to break the cycle would have been to shut down the MH-96's gain changer. But the severe buffeting Major Adams encountered during the spin and dive likely resulted in him being incapacitated during the approximately 15 seconds that the airframe withstood such massive g forces. Major Adams was unable to eject before the X-15-3 broke apart (Figure 4).

PROXIMATE CAUSE

NASA and the USAF convened an accident board that concluded that Major Adams had inadvertently initiated, then increased right drift off his required aircraft heading because of distraction, misinterpretation of the attitude indicator, and possible vertigo. If the RCS had been operative, it would have resisted Major Adams' heading change, but the electric disturbance caused the MH-96 to disarm the automatic controls. The yaw became so severe that the aircraft reentered at right angles to the flight path, and increasing dynamic pressure pushed the X-15 into a hypersonic spin. By the time Major Adams recovered from the spin, pitch gains in the MH-96 had reached a maximum. The gains, in conjunction with system oscillations, sent commands to the horizontal stabilizers that exceeded their rate limits. These commands saturated the system, causing the external stabilizers to cycle up-and-down at 26 degrees per second. Since the stabilizers were already being driven at their rate limits, no capability to respond to pilot maneuvers or system augmentation remained. This prevented Major Adams from pulling out of the dive and righting the aircraft. At 62,000 feet, forces from this limit-cycle oscillation broke the aircraft into many pieces and Major Adams, unconscious, died in the crash.

UNDERLYING ISSUES

Qualification of Hardware

Investigation teams later recovered and reconstructed the traversing probe. After testing a similar system in an altitude chamber, they discovered that at pressures equal to those at 80,000 to 90,000 foot altitudes, current would arc through a distance of ½ inch. As pressure decreased (and altitude increased), arcing intensified and the gap distances the arc could jump increased. Additionally, exposed terminals and wires exhibited a corona discharge. Corona discharge is a term for the breakdown of air between electric cables resulting in ozone discharge. Either the arcing or the corona discharge could have been the source of the disturbance that entered the aircraft electrical system.

Figure 4: Responders survey the wreckage of the X-15-3 near Johannesburg, California.

Because the apparatus had been used on a previous X-15-1 flight, controllers assumed that the traversing probe and associated motor conformed to the engineering practices of the day, when in fact it had never been tested. Furthermore, the airplane on which the apparatus had last flown lacked the sensitive electric systems with which X-15-3 was equipped. If a corona discharge had occurred on X-15-1 for example, it would have gone unnoticed.

Investigators also discovered that the capacitor used in the device had only a 200 Volt rating, while the manufacturer recommended a 1000-V rating. Tests later showed that using a capacitor with the proper rating would not have prevented the corona discharge, but these findings highlight the lack of hardware qualification and testing procedures related to the flight.

Qualification of Flight Crew

The Official Accident Investigation Report postulates that Major Adams likely suffered from a prolonged episode of vertigo following the boost portion of the climb. Major Adams' apparent lack of awareness of the gross heading deviation despite properly functioning instruments and external visual cues corroborates this suspicion. Three other instruments could have served as cross-checks to verify aircraft heading, but Major Adams is believed to have fixated on a single display (the attitude PAI indicator). According to the report, "pilots are trained that the only way to overcome vertigo is to fly basic instruments and disregard attitudes suspected by their physical senses." Even then, cross-checking heading is necessary to maintain controlled flight.

On April 24, 1963, Major Adams took a vertigo test whose findings were recorded as follows: "Mike's response completely abnormal, eye motion was severe for 20 seconds, he became nauseated." The flight surgeon found that Major Adams had an unusual susceptibility to vertigo, but this was never placed in his medical records because there were no established standards for rating a person's degree of susceptibility to vertigo. Astronauts were required to undergo tests for "labyrinth sensitivity," but despite the fact that X-15 pilots also experienced conditions of microgravity, they were not subjected to the same tests. Major Adams was qualified for any special assignment despite this medical aspect. The board recommended labyrinth sensitivity testing for any X-15 pilot candidate.

Complicated Instrumentation

Although the attitude indicator was functioning properly, its ability to display two different settings added a degree of complexity that heavily impacted the pilot's ability to cope in a critical situation. Even without the complications the electrical disturbance introduced, the demands of the mission caused a high-workload and high-stress environment. The setting toggle could have been confusing even under nominal circumstances especially because it required rapid cross-checking of instruments. The mishap board recommended using the attitude indicator "only in the conventional manner."

Flight Control System Design

Many X-15-3 flights had experienced anomalies strong enough to affect operation of the MH-96, but they had always gone undetected by the pilots because the system was designed and built to recover from transients within a matter of seconds. Attempts to find the sources of the anomalies were unsuccessful, making the failure modes very difficult to diagnose, especially in a time-critical environment. However, since they did not seem to affect any of the flights on which they occurred, the flight control system design was thought to be satisfactory.

Throughout the duration of the flight, a lack of heading information crippled ground control's ability to monitor the situation and transmit useful guidance. If flight monitors had access to this crucial piece of telemetry, they would have been able to identify the drift before the aircraft started spinning. Furthermore, when Major Adams inadvertently increased the error, mission control could have tracked the deviation and relayed corrections to the pilot. The mishap board recommended that heading telemetry be provided to ground controllers and this was done.

AFTERMATH

Important lessons from X-15 digital flight control testing were incorporated in the Apollo Lunar Excursion Module (LEM) flight control system that assisted astronauts with six successful lunar landings. The Space Shuttle embodies many of the innovations pioneered and proven during the X-15 research program. The X-15 only flew eight more missions following Major Adams' death, and the program's funding ended in 1968. The Air Force posthumously awarded Major Adams with Astronaut Wings for his final flight, which he had attained an altitude of 266,000 feet - 0.38 miles beyond the official border of space.

FOR FUTURE NASA MISSIONS

The pilots who flew the X-15 faced an unprecedented challenge: control a hypersonic aircraft at higher altitudes and speeds than ever before, and conduct experiments simultaneously. After 190 missions, pilots had mastered the demanding task loads while handling numerous anomalies. The X-15-3 with its digital, adaptive flight control system introduced new complexity of operations on top of new cockpit instrumentation whose source data demanded constant cross-checks.

The X-15 program can still provide valuable lessons today, as commercial and government designers again conceive winged vehicles to carry humans at high rates of speed beyond Earth's atmosphere and back. Qualification of hardware, software, crew and passengers for this transitional environment must be as uncompromising as that cold, airless environment itself. Hypersonic departure from controlled flight, recovery procedures, and escape capability thus far has had only one actual data point. The outcome, which one could consider 'old knowledge' in the history of spaceflight, still cannot be considered 'deep knowledge' of the sort that is gained from continued study to one particular failure scenario using modern research and test tools.

Questions for Discussion

- To what extent can your systems tolerate disturbances that arise from situational anomalies?
- How often do you re-evaluate systems, processes, and assumptions for risks or flaws that may have been previously unconsidered?
- What measures have you taken to reduce workload and when your teams encounter high-stress environments?

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