National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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The Unknown Known

On February 25th, 2008, the B-2 bomber aircraft "Spirit of Kansas" lifted off the runway at Andersen Air Force Base in Guam. Seventeen seconds later, the crew was unable to control the aircraft and its left wing struck the ground. Before take-off, the plane's computers had called for an internal Air Data System calibration. Because of Guam's humidity, there was moisture in the air data sensors during calibration. During taxi for takeoff, the moisture evaporated. Now, the miscalibrated Air Data System sent skewed data to the Flight Control System, which pitched the aircraft nose up 30^0 upon takeoff. Unable to regain control, the B-2's two-member crew ejected safely before the plane crashed and burst into flames. The $1,407,006,920 aircraft was totally destroyed.

Figure 1: The *Spirit of Kansas* crashes in Guam

BACKGROUND

The "Spirit of Kansas" was one of the original Northrop Grumman B-2 Spirit aircraft developed during the cold war. Commonly known as the "Stealth Bomber," the Northrop Grumman B-2 Spirit can penetrate dense anti-aircraft defenses to deliver up to 50,000 lbs of munitions. The B-2 Fleet is based out of Whiteman AFB, Missouri, but the Air Force has deployed aircraft to Andersen AFB in Guam since 2004.

FLIGHT CONTROL SYSTEM

The B-2 is a fly-by-wire aircraft which uses a Flight Control System (FCS) to respond to a pilot's commands. Essential flight data enters the system through 24 Port Transducer Units (PTUs). Using the PTU air pressure measurements, four flight computers independently calculate airspeed, angle of attack, sideslip, and altitude. Three of the four computers must agree before the FCS uses these calculations to move various flight control surfaces.

PITOT HEAT

During the B-2's 2006 deployment in Guam, the extremely humid environment required frequent Air Data System (ADS) calibrations. Line maintenance technicians telephoned B-2 manufacturer technical representatives to ask advice on this new environmental issue. Support engineers recommended using the aircraft's pitot heater to dry the PTU's before calibrating the ADS. Pitot heat is supplied to prevent icing of pitot-static sensors in flight; extensive ground use could overheat and damage the pitot-static system. Several maintenance technicians used pitot heaters successfully to dry moist PTU's and accurately calibrate the Air Data System, but this technique was not formalized in a technical order change or captured in a "Lessons Learned" report. Only some of the ground crews and pilots working with the B-2s during their 2007-2008 deployment were aware of the ADS's sensitivity to moisture and the pitot heat workaround.

February 25, 2008: B-2 Bomber "Spirit of Kansas" crashes after takeoff at Andersen Air Force Base in Guam.

Proximate Cause:

- Moisture in the Air Data System caused the miscalibration of several Port Transducer Units. This initiated a tightly coupled chain of events that culminated in the B-2's crash.

Underlying Issues:

- Critical information communicated ineffectively.
- Inadequate understanding of complex interactions between the Air Data and Flight Control Systems among both management and technician/ maintenance personnel.

What Happened?

On February 25, 2008, the “Spirit of Kansas” and another B-2 were preparing to return in formation to Whiteman AFB, MO after a four-month deployment at Andersen AFB in Guam. The mishap aircraft would follow the lead aircraft.

9:29AM: During the pre-flight check, the mishap flight crew received an “AIRDATA CAL” message, indicating that the Air Data System needed to be calibrated. The pilots and flight control specialist working on the aircraft were not aware of the pitot heat technique, so they calibrated the Air Data System without turning on the pitot heat to dry the PTUs. The calibration procedure created a significant bias in three of the twenty-four PTUs.

10:29AM: As the crew prepared for takeoff, they turned on the pitot heat (per the checklist), which dried the moist sensors. Skewed air data caused an altimeter error of 136 feet above actual airfield elevation, but the crew did not notice the error because there were no field elevation placards in view near the runway.

10:30:12AM: The B-2 began its takeoff roll, but approximately 19 seconds after the brakes were released, the Master Caution Light illuminated, along with a Flight Control System caution on the status display. The crew noted air data fault indications, but approximately six seconds later, the FCS rescinded the caution lights. The pilots continued the takeoff because all caution lights had cleared and their instruments indicated that airspeed was well above the B-2’s go-no-go airspeed of 100 Knots Indicated Air Speed (KIAS).

10:30:49AM: Pilot #1 rotated the bomber’s nose for takeoff at an indicated speed of 142 KIAS (actual speed was later estimated to be 132-134 knots) with a normal stick force, attempting to establish a standard pitch attitude and climb rate. As the nose gear lifted off the runway, the FCS calculated a negative angle of attack (severe nose-down attitude) based on skewed ADS data and pitched the aircraft nose up 30°. Pilot #1 tried to regain control of the aircraft, but the low energy condition (high angle of attack, high gross weight, high temperature, low airspeed) proved unrecoverable. The aircraft yawed and rolled to the left; as the left wing scraped the ground, both crewmembers ejected. Aircraft wreckage spread across 18,964 square meters on the infield between parallel runways. Composite-fed fires took eight hours to put out.

Proximate Cause

The US Air Force accident board concluded that moisture in the PTU’s caused significant bias to be programmed into the ADS during calibration. Based on this skewed data, the flight computers calculated an inaccurate airspeed and negative angle of attack, which contributed to the early rotation, 30^0 pitch-up, and subsequent stall and crash. Hindered by inadequate altitude and airspeed, as well as degraded flight controls response due to the biased data, the pilot was unable to recover the aircraft.

Figure 2: Emergency teams respond to the crash site

Underlying Issues

Indicator & Instrumentation Problems

The “Spirit of Kansas” followed the lead aircraft, which successfully lifted off the runway with a take-off roll distance of approximately 5,825 feet and a calibrated airspeed of 145-147 knots. Due to the errors in the Flight Control System (FCS), the mishap aircraft took-off 1,450 feet shorter and 13 knots slower than the lead aircraft. The *Kansas* had traveled only 4,375 feet when it took off at an indicated airspeed of 142 KIAS (12 knots faster than actual airspeed).

During the takeoff roll, the mishap crew received a yellow “Master Caution” light in the cockpit and briefly observed a row of fault indications in the Air Data Matrix section of the display, but the caution light and fault indicators vanished almost immediately. The crew reacted as trained and elected to continue takeoff because the yellow caution indication did not require an automatic abort and because they had already passed the go-no-go decision speed. They did not know their actual airspeed was 12 knots slower than indicated due to ADS miscalibration. Why did the caution lights vanish? The investigation’s analysis found that the angle of attack row in the Air Data Matrix had displayed two yellow X’s and two white X’s. This is known as a “2-on-2” condition; during a “2-on-2,” the FCS must reconcile data differences between two channels and two other channels, and reconcile both pairs with a previously acceptable value. As the “Spirit of Kansas” rolled down the runway, the FCS was trying to reconcile data differences introduced as a bias during the air data calibration. When two channels resolved to within the established parameters, the FCS logic exited the “2-on-2” condition and the FCS caution was rescinded.

Undocumented Workaround

When flight line technicians first noticed increased air data calibration requirements during the B-2's 2006 deployment in Guam, written procedures did not address the humid climate; as a result, maintenance technicians followed established practice and sought advice from manufacturer's support personnel. This ADS calibration issue typically occurred as a time-critical preflight discovery by the flight crew, rather than during a scheduled maintenance check. Such unscheduled maintenance was not documented in the same detail as scheduled work. Thus, the issue was never documented in a formal technical order change or a "Lessons Learned" report. Because the workaround calibration technique was not documented, some flight control technicians and all but one supervisor were unaware of the moisture issue and technique to overcome it.

Failure to Recognize Critical Information

The accident investigation board concluded that the pitot heat technique was not recognized as "critical information." Most interviewed lacked profound knowledge of the complex ADS/FCS interface. Had the crew or management understood the significance of the air data calibration, they might well have formally raised the issue for resolution. The board identified several factors that veiled the implications of the frequent "AIRDATA CAL" requirement message:

"The board had to consult aircraft design engineers who had not been associated with the B-2 program for over 10 years to find a level of understanding in the system that raised concerns over a need to calibrate PTUs on the aircraft."

-USAF Accident Investigation Board

Incomplete Understanding- The ADS calibration was viewed as an altimeter readout calibration only; the importance of PTU inputs to the Flight Control System was not understood. During the course of the investigation, the review board contacted manufacturer design engineers who had not been involved with the B-2 program for over 10 years, to obtain complete understanding of FCS interactions. Skewed PTU sensor data effectively bias Flight Control System decisions, but a discrete PTU problem was only discoverable in the ground maintenance mode of the FCS. Once the crew switched from maintenance mode to begin takeoff, their warnings and indicators would not specify a problem from the PTUs.

A Low-Profile Problem- Supervisors were generally not aware of the increased air data calibration requirement during deployment. The increased requirements only surfaced during brief deployments in Guam, and never registered as a concern at the B-2's home base at Whiteman AFB in Missouri. Maintenance supervisors were focused on issues that grounded jets, and air data calibrations had never been recorded as preventing a take-off.[1]

Aftermath

The "Spirit of Kansas" was a total write-off, with an estimated \$1.4 billion in property damage. While the pilot sustained only minor injuries, the co-pilot suffered compression fractures in his spine (he was expected to make a complete recovery). The investigation determined that both pilots acted appropriately during the mishap and followed procedure correctly.

Following the accident, the 509th Bomb Wing Commander ordered a "safety pause" in order to allow the unit to review procedures. During the "safety pause," the B-2 fleet was not officially grounded, but all flight operations were temporarily suspended. The B-2 fleet returned to flight on April 15th, 2008. As a result of the USAF findings, pitot heat was added to the PTU calibration procedure.

Applicability to NASA

Configuration Management

This incident illustrates the crucial need to **document changes and workarounds developed in the field**. The pitot heat technique would have pre-empted this accident if it had been widely-known and incorporated into the standard calibration process. Every procedure—no matter how simple or mundane—must be treated as if mission success and the safety of the crew depends on properly performing every detail of the procedure. This requires an **open line of communication** between team members and between various teams. Always ensure the issue is captured when a workaround seems necessary to a process; share the information with cognizant supervisors and personnel with need to know, using a closed loop reporting system such as PRACA (Problem Reporting and Corrective Action), or IRIS (Incident Reporting Information System).

At NASA, we also need to continue to **focus on capturing and transferring knowledge from personnel** who work on complex systems and sophisticated hardware. The "Spirit of Kansas" accident investigation board had to talk to people who had not worked on the B-2 for ten years to find someone who completely understood how the aircraft functioned. As NASA transfers hardware from one generation of engineers to the next, we need to ensure designers pass on their know-

[1] There was a B-2 takeoff abort due to abnormal cockpit indications earlier in the deployment, but no record of the issue causing the abort was found.

ledge to their successors and leave detailed documentation for future personnel.

Systems Engineering

This incident illustrates the importance of **developing a comprehensive understanding of the systems and hardware we work with**. The accident board's report implies that, had personnel fully understood the significance of the air data system calibration, the pitot heat technique would have been written into the formal calibration procedure. Although we frequently work with only a small part of NASA's complex projects, understanding the "big picture" can help us make better decisions. On a similar note, even **complex sustainable systems should not require profound knowledge in the field**. From a design standpoint, the relationships between all the elements in a system should be transparent.

Another lesson to draw from this incident is a reminder that **equipment tests and calibrations should simulate field use as closely as possible**. Here, the process called for equipment calibration without pitot heat even though pitot heaters would be used during flight. This was probably intentional—pitot heaters were known to overheat if left running on the ground—but as we design calibration and testing procedures, the discrepancy between moisture in the PTUs on the ground and the dry PTUs in flight is a reminder that we need to duplicate field use conditions in testing and calibration whenever possible.

Finally, the lack of field elevation placards on the runway points to the need for **external points of reference**. The *Spirit of Kansas* pilots had no way of knowing their altimeter was inaccurate because there were no visual indicators on the runway. Further, the time-proven practice of calculating required takeoff distance and externally crosschecking actual distance against runway 'distance remaining' placards was not used. When an operational margin of safety is subject to external conditions, we need to verify system control effects using external points of reference.

Questions for Discussion

- How do you determine when "tricks of the trade" are significant? How can you improve your processes for capturing and sharing those techniques?
- Do you work with systems or hardware that you do not understand? How much do you need to know to do your job well? How can your department/program increase general understanding for all personnel?
- How can your department/program improve knowledge transfer and minimize the inevitable loss of wisdom that comes when an employee retires or leaves the program/project?
- While many B-2 technicians were familiar with the pitot heat technique, only a few supervisors had heard of the workaround. What can be done to encourage communication both between peers and throughout the management hierarchy?

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