Short Circuiting the Controller – Missteps in Maintenance and Inspection of Process and Wiring in STS-93

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Abstract. During the launch of the Chandra X-Ray Observatory in 1999, an in-flight anomaly occurred a few seconds after liftoff. A power fluctuation caused two Main Engine controllers to drop offline. Fortunately, due to redundancy, the Space Shuttle Columbia was able to successfully reach orbit and avoid an abort. After the successful deployment of Chandra and the safe return of the crew, investigation revealed that the controller failure was due to a wire short in the payload bay. It was suspected that the Kapton insulation on the wire rubbed off against a burred screw head, the result of overtightening of the screw during a maintenance event 4 to 5 years prior to the STS-93 mission. Vibrations led the abraded wire to short during flight. The Space Shuttle Program was grounded for 4 months while a program-wide inspection and wire chafing mitigation effort of all orbiter wiring ensued.

Keywords: Human Factors · Human-systems Integration · Systems Engineering · Human Factors engineering · Wiring · Safety · Maintenance · Training · Arcing · Maintainability and Supportability

1 Introduction

1.1 Mission Objectives

The primary objective of the Space Transportation System mission 93 (STS-93) was to deploy the 50,000-lbs., $1.5 billion Chandra X-Ray Observatory. Chandra, the world's most powerful X-Ray telescope, would allow scientists from around the world to study some of the most distant and dynamic objects in the universe. Stripped of nearly 7,000 pounds of its own gear to make room for the payload, the orbiter assigned to this mission was Space Shuttle Columbia (OV102). Prior to STS-93, Columbia had 25 flights and was NASA's oldest orbiter.

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On March 15, 1998, Eileen M. Collins, a Colonel in the U.S. Air Force (USAF), was selected to command this mission, making her the first woman ever to command a Space Shuttle mission. She led a crew of four astronauts: Jeffrey Ashby, a Captain in the U.S. Navy and pilot of the Shuttle, and mission specialists Catherine G. Coleman, USAF Lieutenant Colonel, Steven A. Hawley, Ph.D., and Michel Tognini, French Air Force Colonel.

Columbia was scheduled to launch on Tuesday, July 20, 1999, at 12:36 a.m. EDT from the Kennedy Space Center (KSC) in Cape Canaveral, FL.

1.2 July 20, 1999: Ready, Set... Cutoff?

At 12:36 a.m., Eileen and her crew sat aboard Shuttle Columbia on Launch Pad 39-B at KSC, ready for launch. Ralph Roe, the Shuttle Launch Director, had just given Eileen and her crew the go for launch and wished them good luck. Just shy of T-minus 45 seconds on the countdown, everything was looking good for launch. For the next half minute, the countdown continued smoothly. At T-minus 10 seconds, the Ground Launch Sequencer (GLS), the program that inputs commands to perform the final critical tasks to put the vehicle in launch configuration (monitoring as many as 1,000 different measurements), gave Columbia's computers the go to start the engines. The final countdown began – "T-minus 10... 9... 8... 7... CUTOFF!... We have uh... hydrogen in the aft."

Between the 10-second and 7-second mark, the hydrogen burn-off igniters started. The orbiter's hazardous gas detection system indicated a 640 PPM concentration of hydrogen in Columbia's aft engine compartment, which was more than double the allowable amount. Leaking anything is never good news but starting the engines with leaking hydrogen can be catastrophic.

Without a second to lose, Ozzie Fish, the primary hazardous gas system engineer, called out for an immediate stop. Barbara Kennedy, the primary GLS engineer, initiated a manual cutoff of the GLS less than a half-second before the Shuttle's three main engines would have started at the T-minus 6 seconds mark.

Eileen and her crew exited the shuttle and at 1:30 a.m., the engineers convened to study the problem. Following the preliminary system and data evaluation, the launch team determined the indication of the hydrogen leak to be a false positive. From this, there was good news and bad news. The bad news was this false alarm led to a 48-hour launch scrub turnaround. The good news was, (besides the obvious being that the crew and vehicle were safe) due to the quick reaction of Ozzie and Barbara, the launch sequence was stopped in the nick of time, saving the team from a week-long turnaround.

Take-two of the STS-93 launch was rescheduled to be in two days.

1.3 July 22, 1999: Don't Rain on My Parade

The external hydrogen burn-off ignitors at Launch Pad 39-B were replaced after the first launch scrub, and the countdown clock began again. Forty-eight hours following the prior launch attempt, weather officers identified a storm cell in the area that produced lightning strikes within 8.5 miles of the launch pad. According to the shuttle launch criteria, lightning-producing storms cannot be closer than 20 nautical miles from the launch site. At the T-minus 5-minute mark, the countdown clock was held, pending weather clearance. Roe even added 10 minutes to the launch window, but it seemed like the storm was there to stay.

After much-anticipated waiting, at 1:20 a.m., the launch was officially scrubbed, and attempt three was re-rescheduled in less than 24 hours.

1.4 July 23, 1999: Third Time's the Charm

"Eileen, the weather is cooperating tonight, and the launch is ready to go," Roe stated for the second time in three days, giving Eileen and her crew the go for launch. At around a quarter past midnight, the countdown clock began. At T-minus 9 minutes, the GLS auto sequence was initiated.

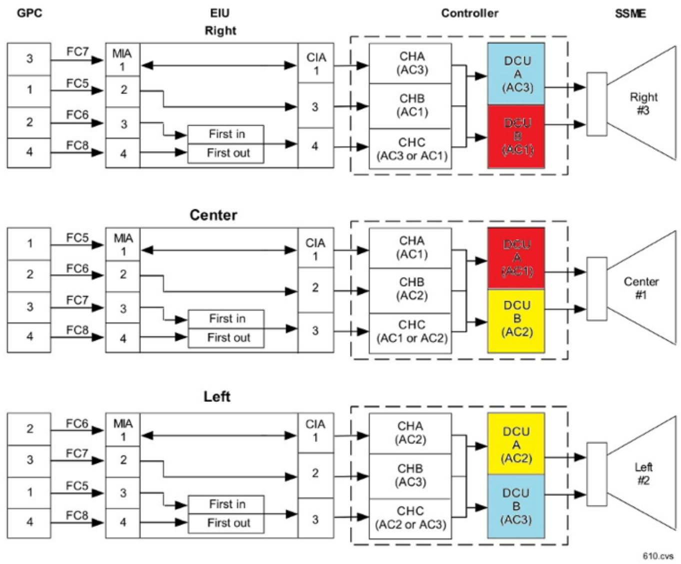
A smooth six minutes went by, and at around T-minus 3 minutes, the pressurization of liquid oxygen and liquid hydrogen tanks began. A couple minutes before launch, the Launch Control Center sent a final message to the crew of Columbia: "A few days delayed, but the same enthusiastic launch team wishing Columbia's crew success on your mission." Eileen responded, "Thanks for all the great work, and we'll see you in five days."

At T-minus 31 seconds, the GLS issued a go to Columbia's onboard computers to start their automatic sequence. At T-minus 10 seconds, the spark igniters near the main engine nozzles burned off residual gaseous hydrogen, and the final command from the ground computers was given to start the engine.

At T-minus 6.6 seconds, the three engines started and came to a full thrust: "5... 4... 3... We have a go for engine start... 0... We have booster ignition and liftoff of Columbia reaching new heights for women and x-ray astronomy!"

After the fairly uneventful countdown, Columbia was still not in the clear. Everyone remained on the edge of their seats as Columbia blasted off. For any launch to be successful, there are a list of things that need to go right, but for a failure, only one thing needs go wrong. All within the first few minutes of flight, problems arose that could have resulted in either a Return to Launch Site (RTLS) Abort or Loss of Vehicle and Crew (LOVC).

Problems During Ascent. About five seconds after launch, Mission Control at Johnson Space Center announced, "AC bus sensors off. We're evaluating the fuel cell." They detected a voltage drop on one of Columbia's electrical buses. As a result of this power fluctuation, a primary and back-up Main Engine controller, DCU-A (digital computer unit) on the center engine and DCU-B on the right engine (highlighted in red in Fig. 1), dropped offline. Thankfully, that still left at least one working controller, AC-2 and AC-3 highlighted in yellow and blue, respectively, for all three engines.



Main Engine Command Flow

Fig. 1. A diagram from the Shuttle Crew Operations Manual showing how the Main Engines were wired for redundancy. NASA image

If there had been any other AC bus issues, it would have caused one entire engine to shut down. Ultimately, the redundant set of DCUs in each engine controller saved Columbia and her crew from a very risky contingency abort.

As the ascent continued, the engines cut off 0.15 seconds too early due to low liquid oxygen level, which caused an orbiter underspeed of 16 ft/s. The low-level liquid oxygen cutoff should not have happened since an adequate reserve is always loaded. However, this early cutoff did not necessitate an abort to orbit (ATO), but the attained orbit was seven miles short of that originally projected.

For the remainder of the ascension, the center and right main engines functioned smoothly and the orbiter underspeed was still within the acceptable margin allowing Columbia to successfully climb to orbit. Although a few miles short of the initially projected orbit, the orbiter eventually attained the proper altitude. After successful confirmation of the engine shutdown and orbital insertion, Flight Director, John Shannon commented, “Yikes. We don’t need another one of those.”

Mission success - Chandra was deployed!

2 Underlying Issues

2.1 Wiring

What caused the voltage drop that resulted in the loss of the electrical buses? The post-flight inspection revealed soot on a screwhead and a hole in a stretch of 22-gauge Kapton insulated wiring (Fig. 2). The single strand of AC current carrying 14-gauge polyimide wire was located nearly half-way down the payload bay. The Shuttle Independent Assessment Team (SIAT), formed in September 1999 to do an assessment of the Shuttle Program after this mission, reported that the wire had rubbed and chaffed against a burred screwhead. This burr was later determined to be the result of over tightening by a technician during a maintenance refurbishment. Then, during another ground processing event possibly years after, somebody inadvertently stepped on the wiring harness causing some of the Kapton insulation to rub off against the burred screwhead. SIAT suspected the wire damage was pre-existing and was caused 4 or 5 years prior to the flight.

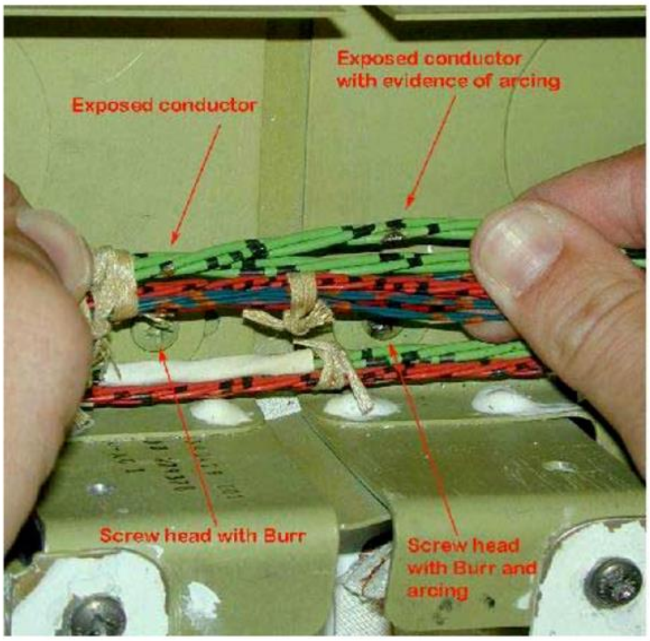


Fig. 2. Carbonized insulation due to arc damage. NASA image

Fast-forward to the launch – the power was turned on with the vehicle sitting on the launchpad, so systems confirmed there was electrical flow through those wires. What really set off the arcing of the wire was the vibrations of the vehicle during launch. A common saying amongst NASA engineers is “Test like you fly, fly like you test”. Unfortunately, in this situation, there was no way to test by recreating the vibration by a launch. See Table 1 for summary of events leading to the loss of AC buses.

Table 1. Series of events leading to the wire short during STS-93.

When?	Maintenance Event A	Maintenance Event B	Launch Day – Vibrations	Launch Day – Wire Short	Launch Day – Voltage Drop
What happened?	Overtightening of screwhead by a tech resulting in a burr	Technician stepped on the wire harness causing the wire to chafe against burred screwhead	Vibrations during the launch sequence was enough to allow contact between the exposed conductor and exposed metal area on burred screwhead	Wire arced to the burred screwhead and shorted	Voltage drop caused the failure of the AC 1 inn 2 of the 3 Space Shuttle Main Engines

2.2 LOX Post Pin

In the Space Shuttle Main Engines (SSME), hot hydrogen gas is mixed with cold liquid oxygen (LOX) in just the right way to protect the engine through the start transient, main stage, and the shutdown transient. The way this is done is the LOX is first introduced through stainless steel tubes called LOX posts (Fig. 3). The robustness of the tubes is generated from the cooling by the LOX inside and the heating by the hot hydrogen outside.

Huge forces work on the LOX posts, especially during start up when the vibration forces are high. If one were to break off there could be possible LOVC. Therefore, to eliminate the potential of a LOX post failure, inspections of posts are performed using ultrasound. It was common practice to deactivate a post if it showed signs of wear or fatigue. To deactivate a post, a gold pin was hammered into the LOX post supply orifice (Fig. 4) and a vacuum leak check was performed. The tapered gold LOX pin, measuring about 1” long and 0.1 inches in diameter, was responsible for shutting off the LOX flow through the post, reducing high-cycle fatigue loading. In the history of the program, 212 LOX posts were pinned in this way including STS-93. There had been 19 prior instances of pin loss during ground testing with no impact damage.

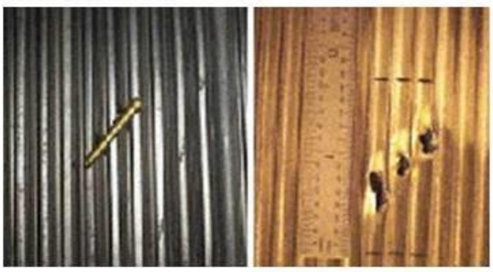


Fig. 3. Ejected LOX pin and 3 ruptured tubes. NASA image

After Columbia landed, post-flight inspection of the affected right engine indicated that LOX post 32 in row 13 had shot out and ruptured the narrow part of the converging nozzle and into the nozzle extension. Three nozzle coolant tubes out of five were breached (Fig. 3), causing a hydrogen leak into the hot steam of gas coming out of the engine. Consequently, triggering the premature engine shut-off. The LOX pin shot past the three tubes and also dinged the Main Combustion Chamber but there was no penetration of the coolant channels there.

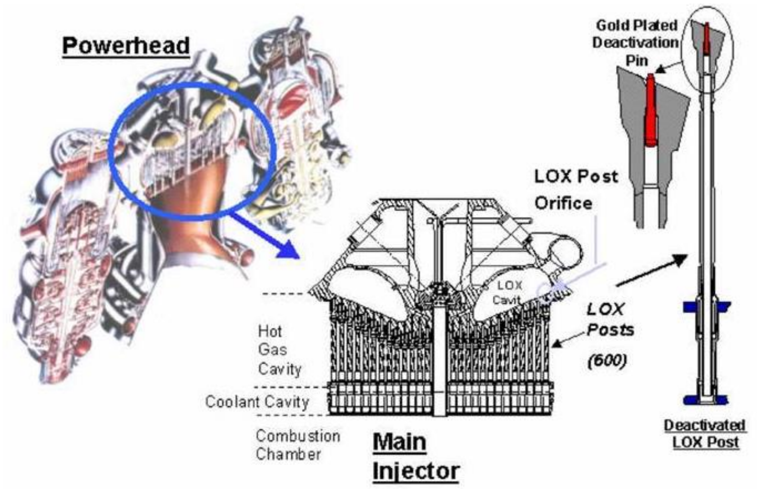


Fig. 4. Powerhead, Main Injector and Liquid Oxygen Post details. NASA image

To all observers – human and digital – it appeared that the right amount of hydrogen was going into the engine because the leak was downstream of the hydrogen flow meter. Analysis showed that if the shuttle had lost five or 6 tubes, there would be a localized hot spot on the nozzle that could potentially burn through and end in a loss of the whole engine.

3 Conclusion

Due to the in-flight wiring anomaly, the shuttle program was grounded for 4 months and led to a program-wide inspection of the wiring of all orbiters including Columbia. The NASA Space Shuttle program (SSP) determined that the root cause of this anomaly was workmanship. Corrective actions taken by the program included detailed inspection of all mid-body wiring and selected inspection of additional wiring, repair of wiring damage, redefining and standardization of wire inspection criteria to allow for less damage, and additional protection was added to selected critical wiring. The return of the Shuttle to flight status was based on repair of wire damage, wiring failure mitigation by overall Orbiter design, and maximum feasible separation of redundant systems. Other recommendations included quantifying and evaluating the current wire visual inspection processes, certifying technician/inspector by specially trained instructors, and minimizing the long-term use of polyimide wiring.

The ejection of the LOX post pin incident brought on a maintenance practice change that required damaged oxidizer posts to be removed and replaced as opposed to being intentionally plugged. During the engine block changes, Main Injector manufacturing processes were improved to preclude liquid oxygen post damage. There are no pinned posts in the fleet anymore. All STS flights starting with STS-103 used either Block II or Block II-A Space Shuttle Main Engines. None of these engines had deactivation pins in any of the liquid oxygen injector posts and it was not planned to fly any more pinned posts since 1999.

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Appendix: SIAT Assessment

The SIAT was chartered by NASA to provide an independent review of the Space Shuttle sub-systems and maintenance practices. During the period from October through December 1999, the team led by Dr. Henry McDonald and comprised of NASA, contractor, and DOD experts reviewed NASA practices, Space Shuttle anomalies, as well as civilian and military aerospace experience.

Wiring In-Flight Anomaly

Corrective Actions:

Maintenance Requirements. Each Shuttle vehicle contains over 200 miles of wiring throughout the vehicle. As with modern aircraft, Shuttle wiring is a critical system since multiple failures can lead to loss of a vehicle. The primary wiring used in the Shuttle is a nickel-plated copper conductor with 6 mil thick polyimide/FEP insulation (similar to MIL-W-81381, trade name "Kapton", a wire construction extensively used in aviation from the early 1970's to mid-1990's). While this insulation has performed well in many applications, there are known issues related to arc track propagation (carbonization of polyimide and rapid collateral damage to adjacent wiring), mechanical degradation when exposed to certain environments (ultra-violet radiation, high pH materials (>10), sustained long term exposure at elevated temperatures to moisture while under mechanical stress), and insulation cracking when the insulation is nicked and placed under tensile stresses. Polyimide wire insulation performs best in straight runs with minimal bending and flexing. Examination of the Shuttle mid-body would seem to be the ideal application for this type of wiring. The extensive wiring damage found on each vehicle appears to be related to the high and continuous exposure to personnel performing maintenance procedures on various Shuttle systems.

Inspectors have been encouraged not to conduct intrusive inspections to minimize induced wire damage. The most intense inspection has been conducted in the mid-body bays. An examination of the Problem Resolution and Corrective Action system data prior to recent inspections shows the mid-body area to be the fourth highest area with wire damage. The data as of November 18, 1999 shows that since the recent inspections in late August 1999, there have been 485 problem reports written related to wiring in the mid-body area.

Design Issues. According to an early 1990's NASA study, the redundancy in 318 criticality-1 (CRIT 1), which is a single failure that could result in loss of life or vehicle, circuits were compromised by placing the redundant circuits in the same wire bundle or clamp. There were 129 CRIT 1/1 areas identified that violate system separation requirements. NASA Standard 8080 requires that critical circuits be physically separated. As an example, six separate areas exist that, if compromised electrically, would result in the loss of all main engine controllers. A review of the data indicates only violations that could be eliminated required a waiver. At the time of this report, a review of criticality-2 (CRIT 2), which is a failure that could result in loss of mission, systems with respect to comprising redundancy was pending.

It is apparent the current wire tray design contributed to STS-93 wiring failures. The use of a wire tray allows wiring to touch metal surfaces, which has resulted in the wiring contacting screw heads and other sharp surfaces. A past and possibility current maintenance practice has changed tray design assumptions. The reuse of tray screws and an occurrence of burred screw heads have created an unexpected chaffing source. There was also considerable configuration variability between vehicles. In some cases, additional chafe protection was added, or screw heads were covered with a protective coating. The wire bundles were permitted to move in clamps and the trays. Typically, critical circuits must be kept physically separated from all surfaces and other wiring.

Arc Tracking. Damage to wiring or insulation and aging of insulation are a concern to the Shuttle fleet. Several incidents have been recorded over the life of the program.

As the Shuttle fleet continues to age, additional problems are to be expected. Given the life expectancy of the Orbiters, it is essential to plan for maintenance related to aging, not solely for upgrades. As early as 1991, NASA documents reported that arc-tracking was a significant risk on the Shuttle, as identified in the following statement from the 1st. NASA Workshop on Wiring for Space Applications, held at Lewis [Glenn] Research Center in July 1991: "Arc propagation poses a significant and credible threat to mission safety and success in aerospace vehicles [Shuttle]. This workshop was attended by members of the Space Shuttle community including Johnson Space Center and was co-sponsored by NASA Headquarters, Code Q.

Arc tracking susceptibility has not been eliminated, as this is an inherent property of polyimide insulation. Laboratory tests have shown that current circuit breaker technology does not sense arc track events. Intermittent arcing is seen as a varying load by thermal circuit breakers and current spikes can exceed over 1000% of a circuit breaker's rating without tripping the device. Arc track events have occurred with one- and three-amp circuit breakers; many of the Orbiter circuits are protected by three-amp breakers. Circuit breakers can also fail and not trip during an electrical short.

Human Factors

<u>Findings:</u>

1. Communication difficulties exist between all parties particularly in accepting feedback from the workforce, Aerospace Safety Advisory Panel, and independent assessment groups. This factor erodes trust and loyalty within the workforce which are essential for safe work practices.
2. Failure to incorporate Human Factors as a critical part of the decision process has increased potential single point and multiple point failures.
3. Recent numerous changes and transitions adversely affect work practices, resulting in loss of technical and process-related corporate knowledge (see Issue 7).
4. Process improvements made during the transition period to Shuttle Flight Operations Contract have also brought workforce concerns.

5. Work stresses, including expanded work assignments and diminished team support, have reduced the capabilities of the downsized workforce. Innovative cross training approaches may be key to regaining competencies and taking advantage of the skill and experiences of an aging workforce.
6. The SIAT is concerned that in spite of the Aerospace Safety Advisory Panel recommendations and findings, supported by the SIAT, recurring human factors issues remain unresolved.
7. Employee surveys, although limited in current scope, show significant levels of Physical Strain (internalized chronic stress). Internalized chronic stress has been implicated in workers suffering from stress related disease (e.g., gastrointestinal, cardiac, migraines).

Recommendations:

1. Communications between the rank-and-file work force, supervisors, engineers and management should be improved.
2. Human error management and development of safety metrics, e.g., Kennedy Space Center Shuttle Processing Human Factors team, should be supported aggressively and implemented program wide.
3. Selected areas of staffing need to be increased (e.g., the Aerospace Safety Advisory Panel advised 15 critical functional areas are currently staffed one deep).
4. The SIAT recommends that the SSP implement the Aerospace Safety Advisory Panel recommendations. Particular attention should be paid to recurring items.
5. NASA should expand on the Human Factors research initially accomplished by the SIAT and the Air Force Safety Center. This work should be accomplished through a cooperative effort including both NASA and AFSC. The data should be controlled to protect the privacy of those taking the questionnaires and participating in interviews. Since major failures are infrequent occurrences, NASA needs to include escapes and diving catches (see Appendix 3 of the full report) in their human factors assessments.
6. Work teams should be supported through improved employee awareness of stresses and their effect on health and work. Workload and “overtime” pressures should be mitigated by more realistic planning and scheduling; a serious effort to preserve “quality of life” conditions should be made.
7. Teamwork and team support should be enhanced to mitigate some of the negative effects of downsizing and transition to Shuttle Flight Operations Contract. Most immediately needed is the provision of relief from deficits in core competencies, with appropriate attention to the need for experience along with skill certification. Further development of the use of cross-training and other innovative approaches to providing on-the-job training in a timely way should be investigated.