National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Hit the Bricks

"Flawless" was one description of the May 31, 2008 launch of the Space Shuttle Discovery on mission STS-124. So when the NASA Safing team at Kennedy Space Center set out to inspect Launch Pad 39A following that launch, they were surprised to find the area littered with debris. Powerful exhaust from Discovery's liftoff breached the flame trench wall at the base of the pad. Hot gases had penetrated the trench lining system, blasting 3,540 refractory bricks into and beyond the trench. Direct damage cost was estimated at $2.5 million.

BACKGROUND

Structure

The U.S. Army Corps of Engineers completed Launch Complex 39 on Merritt Island, Florida in 1965. A group of launch support facilities sprawling over several square miles, LC-39 was built to launch the massive Saturn-5 on Apollo missions. Its two virtually identical Launch Pads A and B became center stage as the world watched the Space Race.

By 1973, LC-39 Pad A had supported 12 Apollo launches. Apollo came to a close, and NASA began modifying both pads for the new Space Shuttle Program (SSP). Moveable service structures for Apollo gave way to permanent structures to access the Shuttle orbiter. These structures would be protected from acoustic vibration damage during liftoff by the same sound suppression system Apollo used: an elevated, 300,000 gallon water tank would release its entire capacity during the launch. The water would muffle the roar of the main engine and the solid rocket boosters (SRBs), generating massive amounts of steam in the process (Figure 1). An A-shaped flame deflector channels the exhaust into a flame trench at the base of the launch pad (Figure 2). When the launch pad was modified for the transition to SSP, the flame deflector was coated with a spray-on, heat resistant concrete compound known as Fondu Fyre. Additional flame deflectors, also coated with Fondu Fyre, were added to the launch pad to provide supplementary protection from the SRBs' exhaust plume.

Flame Trench

The flame trench rests on 3-foot-thick concrete walls and an 11-foot-deep concrete floor. Lined with refractory bricks to protect the concrete, the intact system was designed to withstand temperatures up to 3,000 degrees Fahrenheit, positive and negative pressures of 2 to 10 pounds per square inch, and flame velocities nearing Mach 4. Wall bricks such as those that were blasted loose are larger than standard red masonry bricks at 6 by 3 by 13.5 inches; they weigh 19 pounds each. Built using an interlocking tongue and groove design, the big bricks were glued with epoxy and anchored to concrete-embedded steel rails. The integrity of the trench is inspected before and after each space shuttle launch for any foreign object debris or for any visual damage.

Figure 1: Space Shuttle Discovery launches from Pad 39A at Kennedy Space Center

Launch of STS-124 damages launch pad: Repairs estimated at $2.5 million

Proximate Causes:

- Ops team did not detect deteriorating condition of flame trench wall.
- LC-39 Pad A cleared for launch
- Dynamic loads from Space Shuttle launch tore bricks away from corroded anchor systems.

Underlying Issues:

- Poor program transition processes
- Aging infrastructure

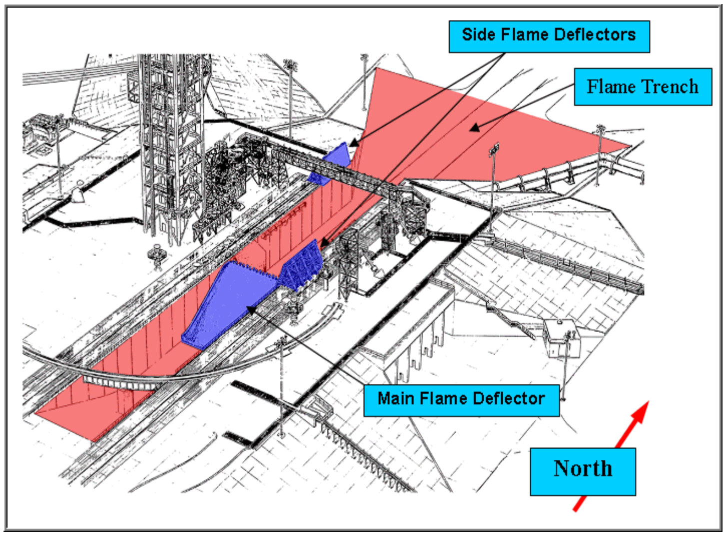

Figure 2: The flame trench is 450 feet long, 58 feet wide and 42 feet deep. The mouth of the trench extends to a width of 300 feet at the north end.

When Space Shuttle Columbia first blasted off in April of 1981 on its first mission (STS-1), post-launch inspection teams discovered a small number of dislocated refractory bricks in the flame trench. Managers issued an Engineering Order that called for the application of Fondu Fyre to the affected area. This process became the standard method for repairing erosion damage and loose or missing bricks. Launches in November of 1981 and in January of 1992 released bricks from the flame trench. Following each launch, Fondu Fyre repairs filled the resultant gaps.

What Happened?

Discovery Launch

Space Shuttle Discovery was scheduled to launch from pad 39A on May 31, 2008 on mission STS-124 to deliver “Kibo,” the centerpiece of the Japanese Experiment Module, to the International Space Station. Ten days prior to the launch, prep teams found no debris in the flame trench and photographed its condition. The day before the launch, final checks of the flame trench verified no debris or debris sources were present. On the day of the launch, the departure sequence began with the activation of water flow from the sound suppression system. Initiation of the flame deflectors and main shuttle engines followed. Soon after, controllers ignited the SRBs, and liftoff commenced.

Forces from SRB ignition caused a section of the flame trench wall that had previously been repaired with Fondu Fyre to tear away, creating a fracture in the brick lining. Hot gas seeped through this fracture and built up between the concrete wall and the covering of refractory bricks. The bricks, secured only with aging epoxy and corroded anchors, gave way to the pressure of the hot gas and burst away from the concrete at the control joint (Figure 3). Since the bricks were installed with a tongue and groove mechanism, their interlocking design propagated a cascading effect that blasted the bricks varying distances, some exceeding 1,800 feet. The flying bricks, shown by radar to travel up to 680 miles per hour, damaged the west flame trench wall and a nearby perimeter fence. A total of approximately 3,540 refractory bricks in a 20 foot by 75 foot area ripped loose in the mishap. Repairs were estimated to cost $2.5 million.

Proximate Cause

NASA investigators received full Shuttle program cooperation to access evidence. Completing a complex, challenging assignment in 30 days after the mishap, the investigation report described severe carbonation of the epoxy and extensive corrosion in the steel anchors. Because inspection teams lacked procedures and criteria that would have helped them detect this deterioration, the condition went unnoticed. Space Shuttle Discovery was then cleared for launch. During liftoff, the bricks were unable to withstand the pressure of the hot gas, which blew them away from the wall.

Underlying Issues

Inadequate Transition Process

As a passive system, the flame trench was exempt from the development of a Failure Modes and Effects Analysis (FMEA) during the transition from Apollo to the Space Shuttle Program. The torrent of water from the sound suppression system and salt spray from the nearby Atlantic Ocean had been known chemical stressors during Apollo. But now, the Shuttle’s twin solid rocket boosters emitted hydrochloric acid as an exhaust byproduct, bathing flame trench walls in corrosive acid. Without FMEA, the unique conditions and potential failures brought about by the SSP were never considered and the hazards of the environment were left unmitigated. Launch Pad 39A supported 70 launches for the Space Shuttle Program before the mishap. In those years of service, there had never been a significant flame trench failure. Past success may have bred such confidence in trench integrity that no documentation for material erosion was found, nor were procedures for preventive maintenance or repairs developed. Therefore, post-launch inspection teams had no standard physical inspection criteria, and their procedures were limited to visual inspections. Due to the lack of comprehensive inspection methods and equipment, the anchors and epoxy could not be assessed.

Unrecognized Warnings

Prompted by the Columbia tragedy in 2003, outside consultants inspected the infrastructure of the entire launch complex. Several deteriorated Pad 39A flame trench wall areas were found. In 2005, an inspection conducted to study launch pad fitness for transition to the Constellation Program (CxP) revealed erosion in several areas of the flame trench. In addition to past incidents of dislodged bricks, these were

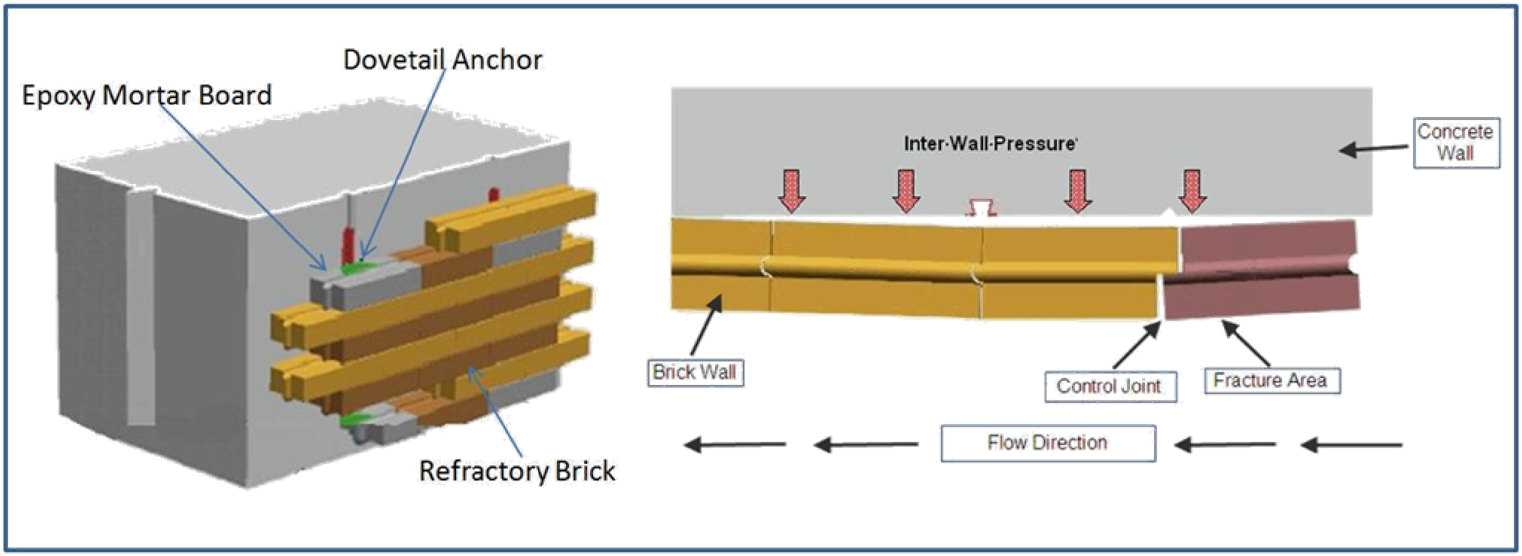

Figure 3: Cutaway depicting construction design of brick lining. The refractory bricks yielded to the pressure of the gas between the concrete wall and brick lining because carbonation of the epoxy reduced its adhesion and because repeated exposure to salt, water, and hydrochloric acid corroded the dovetail anchors.

signals of a deteriorating infrastructure, and examiners recommended a more thorough investigation including assessments of the state of the epoxy mixture, tongue and groove mechanism, and dovetail interlocking system. Operators, however, remained confident in the flame trench's integrity, and because the infrastructure receives lower priority than the mission, a 2006 petition to repair eroded refractory brick was denied because of limited funding. A 2007 Hazard Report pertaining to the vehicle's structural integrity during launch was updated to include dislodged Fondu Fyre and refractory brick as acceptable debris sources.

AFTERMATH

To repair the flame trench, workers stripped refractory bricks from a 25 by 100 foot section of the east wall and a 25 by 80 foot section of the west wall (Figure 4). The exposed area was then covered with steel mesh, and Fondu Fyre was applied over the lattice. Repairs were completed in time for Atlantis' STS-125 mission (Hubble Space Telescope maintenance).

Launch Pad 39B was suspected to contain similar weaknesses in its refractory brick, but no major repairs were planned; its use was limited to the launch of a backup shuttle for Atlantis in case a rescue flight was necessary. Pad 39B would then be decommissioned for transition to the Constellation Program.

The Mishap Investigation Team (MIT) recommended the SSP define more accurately how far any liberated flame trench components could fly, and determine if such debris could pose damage risks to the shuttle or surrounding structures. In a move to prevent similar occurrences, MIT also recommended the Launch Vehicle Processing Directorate and Engineering Directorate to develop comprehensive criteria for inspecting the flame trenches of Launch Pads A and B and to develop maintenance procedures for both sites. In addition, MIT recommended NASA and Contractor Ground Systems Engineering to develop an analysis for the trends of refractory brick loss at both launch pads. CxP was asked to define load requirements for the Ares launch vehicles and perform a risk analysis for failure modes within the flame trench. This analysis is still in progress.

FOR FUTURE NASA MISSIONS

The failure in the flame trench was a result of several factors, but the sweeping transition from Apollo to SSP played a most significant role. Flame trench upkeep was driven by assumptions based on an apparently reliable history. However, the hydrochloric acid corrosion was unconsidered and therefore unmitigated. Program and Center management failed to recognize the signs of a deteriorating infrastructure and initiate comprehensive inspection, maintenance and repair processes. The need for such processes is prevalent not only in high-visibility structures such as KSC's launch pads, but also in research laboratories and facilities in Centers across the country. In 2009, a Committee on the Assessment of NASA Laboratory Capabilities, appointed by the National Research Council, toured several Centers in order to determine the adequacy of NASA facility equipment and maintenance. They learned that approximately 80 percent of NASA facilities are more than 40 years old, but because of inadequate funding, facility repair jobs are not implemented despite the fact that the consequence and probability of failure in those facilities are both ranked very high. This lack of funding forces Centers to allow some equipment and facilities to "run to failure," but when large, high-powered equipment is not maintained, risks of catastrophic and costly mishaps are intensely amplified. Facility support offices at all Centers face a backlog of deferred maintenance versus known failure modes that threaten numerous assets needed for research and operations. Even though this mishap did not so much spring from deferred maintenance as from a maintenance need that was never properly identified, it highlights the fact that vigilance over systems and infrastructures is crucial to identifying even subtle hazards before they become mishaps.

Change is inevitable within any organization. NASA faces a new era and an uncertain future. The coming decade raises many questions concerning potential teaming with commercial launch vehicle builders, and emerging technologies, methods, and standards. Many NASA facilities, purpose-built to serve one program, survive today to serve new Center or Program needs beyond the facility's intended service life. Whenever high-energy transfers impact such a facility, cumulative kinetic effects over time conspire with other environmental attacks and new user processes to weaken even the most carefully conceived structure. Degraded integrity is inevitable; the facility itself becomes a system operated to failure unless increased vigilance is applied over decades to discover incipient failure conditions that patiently wear away structural margins that seem massive.

Figure 4: Workers strip loose bricks from the flame trench wall for the Fondu Fyre application.

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Questions for Discussion

- Does any part of your facility structure or high-energy systems lack inspection or planned maintenance procedures?
- How do you capture risk scenarios where failure potential is measured in decades?
- What function was your facility designed to support compared to what it supports now?
- What environmental stressors did not affect your facility until after it was built?

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