National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

JANUARY 2010 *VOLUME 4 ISSUE 1*

Down to the Wire

During the Solid Rocket Booster (SRB) recovery for the Space Shuttle mission STS-116, an injury occurred on the retrieval ship MV Freedom Star. On December 12, 2006, the ship was towing a booster into port when the tow wire jumped from its tow chute and struck a nearby crewman. The crewman sustained impact injuries to his abdominal region and minor abrasions to his arms and hands. He was hospitalized for twenty-four days.

Background

Solid Rocket Boosters

Two Solid Rocket Boosters (SRBs) power the space shuttle's first two minutes of flight. The largest solid-fuel rockets thus far ever flown provide 80 percent of all thrust during space shuttle launch. After burning their fuel, the SRBs jettison away from the orbiter approximately 26.3 miles above the Earth's surface. Soaring upward for another 70 seconds, they then tumble into the Atlantic, where NASA recovers the spent SRBs and refurbishes them for later missions. Re-use of SRBs saves millions of tax dollars each year.

Recovery Process

Currently, a NASA Contractor owns and operates two SRB retrieval ships, *Liberty Star* and *Freedom Star*. Both vessels support ocean-based research and other assignments beyond SRB recovery. Before beginning a recovery operation, each crew reconfigures and tests onboard equipment for recovery operations for up to a week. The ships then head out to sea to find both spent SRBs and tow them to Port Canaveral for shipment to the vendor.

When found, a booster floats upright, entangled in its parachute (Figure 1). Divers disentangle the parachute, which is winched aboard the ship along with the nose cone. Divers swim alertly beneath the bobbing SRB to plug the exhaust nozzle and attach an air hose from the ship. Compressed air displaces seawater until the booster tips onto its side for easy towing. A heavy tow wire from the ship is attached and the air hose is used to counter water leaks.

What Happened?

Mission Delays

Freedom Star's crew faced setbacks that severely compressed their schedule for this mission. A ship's fuel tank leak caused the crew to work three unplanned days to repair the tank and configure the ship for SRB recovery. Heavy rain and strong winds hindered the process of readying the vessel. Despite these distractions, the crew got *Freedom Star* under way on the scheduled December 7 launch date for STS-116. Unfortunately, the launch was scrubbed for cloud conditions; *Freedom Star's* crew returned to port by next morning and departed again on December 9. That night, STS-116 launched successfully at 8:47 PM. Two SRB's floated down, but recovery would have to wait. Required to offload tracking radar operators who were embarked for the

Figure 1: A retrieval ship arrives at a half-submerged Solid Rocket Booster after a shuttle launch.

Freedom Star crewman sustains injuries during SRB recovery mission.

Proximate Causes:

- *Freedom Star* made right-hand turns that caused the SRB to trail to the starboard side of the ship.
- The tow chute pins were removed from the tow chute while towing the SRB.
- Crewman remained in the hazardous area at the stern.
- Tow wire jumped out of the tow chute.

Underlying Issues:

- Lack of Configuration Control
- Lack of Physical Controls
- Hazards Awareness
- Lack of Situational Awareness

shuttle launch, the crew had to return overnight to Port Canaveral when high winds and seas made helicopter transfer too risky. After a quick stop at the dock, *Freedom Star* rejoined *Liberty Star* at the SRB recovery area on December 10, the day before the tow wire mishap.

A First Injury

After reaching the left hand SRB and conducting the initial recovery tasks, the crew began to secure SRB components on the *Freedom Star* deck using the on-board crane. During this process, portions of the SRB's parachute became entangled with the heat shield covers. The crane operator maneuvered the crane slightly to help a crewman untangle the lines. This slight movement caused the frustum – the heavy, nose-cone portion of the SRB – to jerk unexpectedly upward and skip in the direction of a crewman. (Figure 2) He could not escape the path of the frustum, which ultimately came to rest on his left foot, causing an injury serious enough to require immediate medical evacuation by helicopter. To reduce medevac transit time, *Freedom Star* suspended SRB recovery and again sailed toward shore, causing even further delays.

Figure 2: Liberty Star at sea. Note the frustum sitting on the aft deck, still attached to the on-board crane.

The Mishap Occurs

The following morning, *Freedom Star* resumed recovery of the booster. Divers inserted the air hose and removed the excess water from the SRB, causing it to fall into a horizontal position. The crew attached a steel tow wire and headed for Port Canaveral. After only a few hours of smooth sailing, the crew awakened the *Freedom Star* Captain and informed him of a problem: *Liberty Star's* tow wire had separated from the other SRB. Since *Liberty Star* was scheduled to arrive back at the port first, *Freedom Star* must now wait behind its sister ship while the connection was re-established.

After resuming their return to Port Canaveral, *Freedom Star's* Captain ordered the SRB in tow brought closer for better control. As a precaution, the crew inserted the air hose one last time into the booster to remove excess water. However, when the crew tried to retrieve the hose, it snagged beneath the SRB. Divers worked unsuccessfully to free it until recalled onboard due to rough seas.

As *Freedom Star* approached the channel, outbound shipping traffic required the ship to gain still closer control of the SRB to safely pass the other vessel. Concerned about the snagged hose, the Captain ordered the tow wire shortened further. But as the tow winch wound more tow wire on board, the tow shackle jammed in the tow chute. Excess stress caused the tow winch clutch to fail. The Captain immediately ordered right-hand turns north of the channel to avoid traffic until the crew repaired the tow winch.

After the repairs were completed an hour later, the Captain once again gave the order to shorten the tow. He also directed his crew to pull the tow chute pins so the shackle could pass through the tow chute. One of the crewmen immediately followed the order and, after pulling the pins, remained near the chute to observe the tow. (Figure 3) While conducting a final right-hand turn, the SRB drifted far enough right of the ship to pull the tow wire to the right, up and out of the chute which lacked its safety pins. The tow wire struck the nearby crane ladder, pinning it against the frustum already on deck. Standing near the tow chute, the crewman who had pulled the pins was injured when struck in the torso by either the wire or the ladder (the only equipment damaged in the mishap).

PROXIMATE CAUSE

After removing the pins from the tow chute, the crewman lingered nearby, unaware that he had placed himself in a potential path of the wire under load. As the ship made right turns, only the chute resisted the wire's pull toward his side of the deck. Without the pins to keep it in place, the tow wire leaped out of the tow chute and struck the crewman.

Figure 3: The 67-ton shackle could not pass through the tow chute with the pins in place, as depicted above.

Underlying Issues

Lack of Configuration Control

During previous recovery missions, the *Freedom Star* crew used a smaller 17-ton shackle to connect the tow wire to the SRB. This shackle easily passed through the tow chute with pins in place. However, the 17-ton shackle was difficult to assemble, needing a rubber mallet to bang it into place. Because of this, a new deck supervisor changed the configuration, choosing the 67-ton shackle instead, a decision that would prove critical on the day of the mishap. (Figure 4) The supervisor was able to do this without any review or approval because the *Freedom Star's* towing assembly had no formal configuration control. Other than a single diagram in the recovery operating procedure identifying the components, no drawings or assembly instructions existed. Crewmembers were both forced and freed to improvise, long traditional in deck-line-handling tasks.

Lack of Physical Controls

The Mishap Investigation Board (MIB) observed that when Crewman 2 received the command to remove the tow pins, he executed the task easily, and needed no tools to remove the pins. No labels warned of the pins' safety importance. No record of tow chute design engineering review or Safety and Risk Analysis was found. Either process could have identified the tow chute pins as a safety barrier. Properly labeled as safety barriers, these physical controls might have been kept in place when the tow wire was under side tension. In addition, *Freedom Star's* parent company did not identify towing as a hazardous operation. Towing involves significant energy in the towline with potential hazards to personnel and critical space flight hardware. Operations that were deemed hazardous such as insertion of the plug beneath the bobbing SRB required a standardized set of procedures, which included a safety assessment and pre-task briefing.

Hazard Awareness

While aware of general hazards associated with ropes and cables, why did crewmen not appear to recognize the potential hazard of removing the tow chute pins while the tow wire was under tension? First, there was a lack of proper employee hazard awareness training. Second, there was no safety briefing prior to this potentially hazardous action of pulling the tow chute pins while under tow and at sea. Third, the deck supervisor failed to evaluate the situation when the order to remove the pins was given and intervene. Finally, removing the pins to pass the shackle through the tow chute had become a routine operation. The crew had been using the larger shackle for a number of recovery missions, and had repeatedly removed the tow chute pins to allow it to pass. The crew could believe that past success foretold future success. But conditions had changed around them: increased wind, high seas, days and nights of compressed workload, approaching traffic, a previously injured shipmate gone, and Port Canaveral beckoning.

Lonely Command

Freedom Star's Captain was an experienced seaman who had led numerous recovery missions. Ordering the pins to be pulled, he did not recognize that this action would place personnel and hardware at risk. Based on a number of factors, the MIB believed that the Captain lost situational awareness: first, the Captain's workload immediately preceding the incident was high. He was directing coastal navigation, traffic avoidance, a medevac, winch repairs and towing reconfiguration involving snagged equipment. All this followed days and nights laboring to have his ship on station and ready despite delays and distractions.

Figure 4: The 67-ton shackle (L) is significantly larger than the 17-ton shackle (R- Shown attached to tow line).

The Captain may have also been under post-recovery schedule pressure. Although *Freedom Star* did not face a mandatory return time, the crew was trying to meet a published expected arrival time that had already been postponed due to other events during the recovery. Finally, fatigue may have also been a contributing factor to the Captain's loss of situational awareness. When the ship's crew was engaged in recovery operations, the Captain was always on duty, resulting in a 16-hour work period. During the three nights prior to the mishap, it appears that the Captain had only 6 hours or less to sleep. A study by The Federal Motor Carrier Safety Administration determined that individuals who fail to have an adequate period of sleep (7-8 hours in 24 hours) will suffer sleep deprivation, leading to reduced performance. Moreover, the deprivation accumulates with successive sleep-deprived days, as the Captain had experienced.

Aftermath

After medical evaluation and treatment at a local hospital, the crewman involved in the tow wire mishap was released to go home. However, the following day he began feeling nauseous and continued to have abdominal pain. Doctors later diagnosed internal injuries that kept him hospitalized for 24 days.

NASA conducted a review of SRB recovery operations and implemented immediate measures to ensure that all crewmembers would comply with applicable policies.

For Future NASA Missions

Safety and hazard analysis begins at the top of an organization. No organization can sustain safe operations without a top-down commitment to the controls demanded by the operating environment. At the same time, employees at risk should be trained to recognize hazards, and should be regularly encouraged to report them. Across the globe, NASA employees operate in an extremely wide variety of environments and use an even larger assortment of equipment. Whether they find themselves in a spacecraft, on a ship, or in a research laboratory, all employees can evaluate their surroundings and ask, 'Where is the energy? How much energy can be released? Will the controls in place work?'

Along these same lines, employees should not feel the need to bypass safety controls for the sake of meeting imposed or perceived deadlines. Repeated and consistent acceptance of fewer controls can reset one's 'margin of safety' expectations, giving a false sense of safety. Stored energy cares not if we overlook assessing its potential due to past success or lack of planning; it seeks release constantly.

In this example, the tow chute pins were not labeled as a safety device. However, in the aftermath of this incident, we can see how important they were to the safety of the crew. This highlights the importance of having a thorough process to identify unmitigated hazards, while detecting and correcting existing but flawed controls. This process should be revisited whenever the system or the environment changes significantly. Planning for off-nominal scenarios helps this effort.

Finally, failure to manage change within high-energy systems may lead to unforeseen consequences. Research indicates that as personnel take on multiple monitoring, operational and decision-making tasks, their ability to maintain situational awareness and make clear, concise, error-free decisions is degraded. Cumulative fatigue will degrade human performance regardless of the best training, experience and intentions.

Figure 5: Freedom Star's sister ship, Liberty Star, towing a Solid Rocket Booster near Port Canaveral.

Questions for Discussion

- Does your organization identify hazards in terms of energy transfer? Do existing controls match potential energy in the system? How do you know the controls will work?
- Do you conduct regular training to teach employees how to identify hazards?
- Are system changes or modifications documented, reviewed, and approved by a clear authority?
- How do you establish personal limits to recognize and mitigate excessive task load or loss of situational awareness?

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Developed by: ARES Corporation
Thanks to Gerald Schumann for his insightful peer review.

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