

**A Historical Analysis of Crane Mishaps
at Kennedy Space Center**

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Cranes and hoists are widely used in many areas. Crane accidents and handling mishaps are responsible for injuries, costly equipment damage, and program delays. Most crane accidents are caused by preventable factors. Understanding these factors is critical when designing cranes and preparing lift plans. Analysis of previous accidents provides insight into current recommendations for crane safety.

I. Introduction

Cranes and hoists are used throughout Kennedy Space Center to lift everything from machine components to critical flight hardware. Unless they are trained crane operators, most NASA employees and contractors do not need to undergo specialized crane training and may not understand the safety issues surrounding the use of cranes and hoists. A single accident with a crane or hoist can injure or kill people, cause severe equipment damage, and delay or terminate a program.

Handling mishaps can also have a significant impact on the program. Simple mistakes like bouncing or jarring a load, or moving the crane down when it should go up, can damage fragile flight hardware and cause major delays in processing. Hazardous commodities (high pressure gas, hypergolic propellants, and solid rocket motors) can cause life safety concerns for the workers performing the lifting operations.

Most crane accidents are preventable with the correct training and understanding of potential hazards. Designing the crane with human factors taken into account can prevent many accidents. Engineers are also responsible for preparing lift plans where understanding the safety issues can prevent or mitigate potential accidents.

II. Crane Accident Statistics

The Bureau of Labor Statistics tracks occupational fatalities across all industries. The most recent industry-wide study of crane-related occupational fatalities was released in 2008¹.

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Fatalities	97	93	80	90	72	80	62	87	85	72

Table 1. Crane-related fatal occupational injuries, 1997-2006¹.

Table 1 shows a small decline from the high fatality totals in the late 1990s but the fatality rate remains consistent through the early 2000s. Since no other industry-wide studies have been performed since 2008, it is assumed that these fatality rates have remained consistent.

Figure 1 analyzes the causes of crane-related fatalities in 2006. Falling objects, including load drops, caused nearly half of the fatalities. One-third of the falling objects were parts of the crane or the crane itself (crane collapse).

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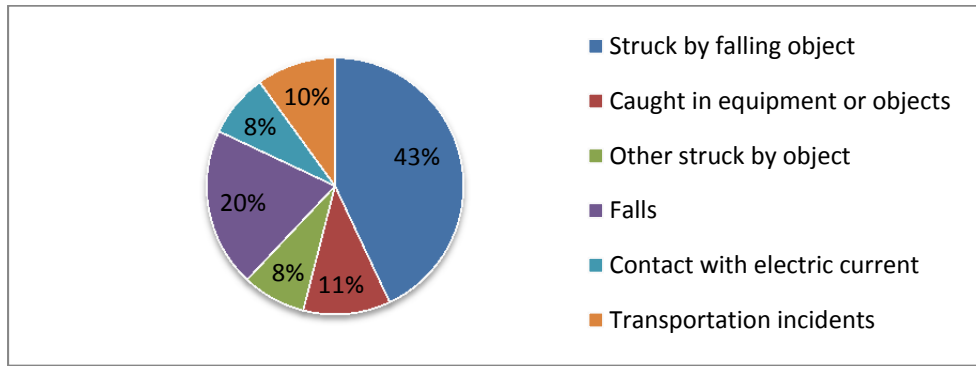


Figure 1. Causes of crane-related occupational fatalities, 2006¹.

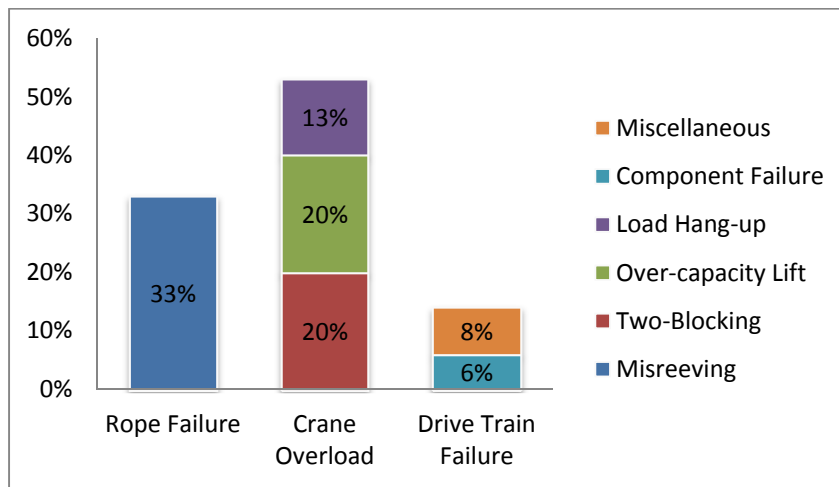


Figure 2. Typical causes of load drops².

A study by crane manufacturer Ederer, Incorporated², concluded that there are five major reasons for load drops. As shown in Fig. 2, most load drops are caused by conditions that overload the crane. This study was limited to cranes in enhanced safety fields; specifically they chose data from the nuclear power industry, chemical processing areas, and aerospace applications where cranes are maintained to stringent safety levels and operators are properly trained. The following analysis will show that nearly all of these conditions can be prevented with proper attention before and during the lifting operations.

III. Analyzing the Typical Causes of Load Drops

A. Mis-spooling and Misreeving

Most cranes and hoists use wire rope to lift the load. The rope can leave the grooves on the drum (mis-spooling) or jump out of the sheaves in the reeving (misreeving). In both cases, the rope crosses over the grooves or sheave edges and can pile up over other sections of rope, become fouled in other parts of the reeving, or fall off the end of the drum. This causes severe rope damage or failure due to cutting or excessive pressure on the rope.

Figure 3 shows properly spooled and reeved rope on the 175-ton overhead crane in the Vehicle Assembly Building (VAB). At the left end of the spool, an empty groove can be seen. This groove is designed to a specific depth based on the diameter of the wire rope being used. If the rope were to cross the edge of this groove under load, it would likely be sliced, causing rope failure. Similarly, if the rope inside one of the hook blocks left the path of the sheaves, it could also lead to rope failure or damage to the sheaves.



Figure 3. Properly spooled and reeved wire rope on the Vehicle Assembly Building 175-ton overhead crane. *Left: Spool on drum. Right: Primary and auxiliary hook blocks with reeving.* Credit: author.

1. Delta 186 INSAT-1D Mishap – Cape Canaveral, FL³

In 1989, the Indian government contracted to launch the INSAT-1D communications satellite on a Delta IV rocket at Cape Canaveral. During storage operations of a lid on an upper platform, the hook block of the 3-ton hoist was displaced approximately 14 degrees from the center of the hoist while the block was lifted without a load attached. This caused the wire rope to mis-spool around the drum, randomly overwrapping the wire rope (Fig. 4). Individual wires and then strands broke due to local interferences between the overlapping cables and the crane housing. The falling wire sections were caught by the debris shield above the hook and were not seen by technicians. During the next lowering operation, the broken section of the rope came off the spool causing the hook and debris shield assembly to fall and impact the top of the satellite. This caused \$10 million of damage to the spacecraft and delayed the launch by a year.

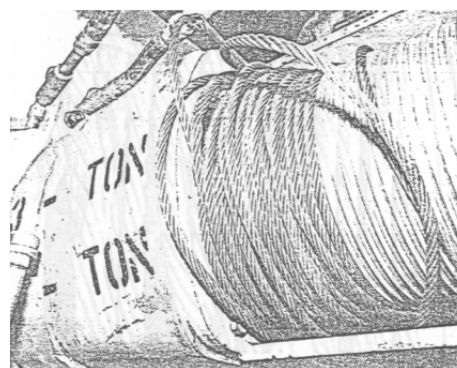


Figure 4. Mis-spooled, spiraled and overwrapped wire rope on 3-ton hoist.³

The primary cause of the accident was the side loading of the hoist while lifting the hook block. The manufacturer recommended a maximum fleet angle of 4 degrees, significantly smaller than the measured 14 degree offset. A contributing cause was improper training: operators had only been warned about side pulls with loads attached, not without. Additionally, lighting around the cable drum was inadequate to view the spooling operations from the hoist control pendant and the debris shield hid the initial indicators of rope failure.

2. Lessons Learned

Several lessons can be learned from this accident to prevent future mis-spooling incidents. The most important is that hooks should be centered under the hoist while lifting the hook block, regardless of whether a load is attached. Providing adequate lighting of the cable drum allows operators to watch the spooling operation. This includes considering potential lighting problems when redesigning platforms and supports. Hoists can also be equipped with enhanced safety features including hoist spooling bars, rope guides, or photocells to alert when a mis-spool occurs. These features are not required by current safety standards but greatly enhance the overall safety of the hoist.

Misreeving did not occur in this accident but it can be avoided by keeping tension on the wires in the hook block. Allowing the load to bounce or the ropes to go slack can cause the rope to leave the groove in the sheaves.

B. Two-Blocking

Two-blocking occurs when the load block is lifted beyond the maximum safe hook height of the crane. Specifically, a component of the load block comes in contact with the upper block or trolley structure. When this happens, the crane control will automatically adjust the motor torque of the hoist in an effort to maintain the commanded speed of the hoist. The energy from machinery inertia is also not dissipated and the output torque of the hoist greatly increases. The rope can be cut immediately by the edge of the trolley, the grooves on the drum or sheaves, or simply pulled in half. After a two-blocking incident, damage from excessive motor torque may be hidden in areas such as couplings and gear reducers.

1. Orbiter Payload Bay Access Platform Mishap⁴

In 1985, during final closeout procedures for the orbiter Discovery, one of the Orbiter Processing Facility (OPF) Payload Bay Access Platforms failed. It fell from a stowed position, impacted chains supporting other work platforms, and pierced the protective blanket and payload bay door (Fig. 5). The falling platform struck a technician on a work platform below, bruising his shoulder and breaking his leg. This accident caused \$200,000 damage to the orbiter and platform and delayed the launch for three weeks.

Technicians had been trained to use the upper limit switch as a lift stopping point, which violated both OSHA and the NASA Lifting Standard safety rules. The upper limit switch on this particular platform was broken, which caused the telescoping structure to impact the supporting structure (two-blocking). This problem had been noted and the platform had been tagged out of service four days prior to the accident. Technicians mistook the tags for older tags and used the platform in the days leading up to the accident. Since the upper limit switch was broken, the technicians used the sound of the hoist to tell them when to stop. This two-blocked the hoist every time it was stowed. A linkage in the hoist eventually broke and failed when the platform was moved.

The design of the telescoping tube system made it impossible to inspect the linkages in the hoist without disassembling the telescoping tube. After the accident, the remaining payload bay access platforms were disassembled for inspection and all of them showed signs of having been repeatedly two-blocked. As a result, the hoists and telescoping tubes were redesigned for easier inspection and safer operation.

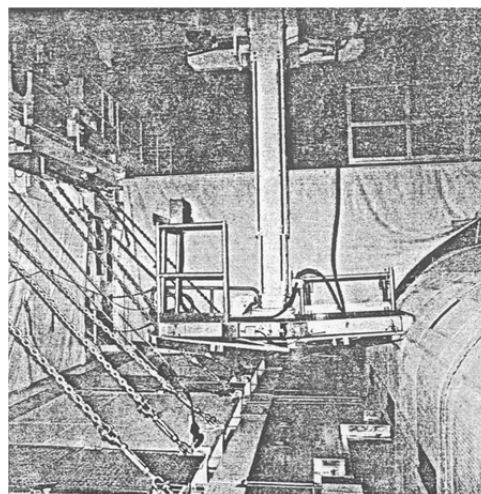


Figure 5. Payload Bay Access Platform after accident.⁴ Orbiter is on the right.

2. Cracked Gear Case Spider in 40-Ton Bridge Crane⁵

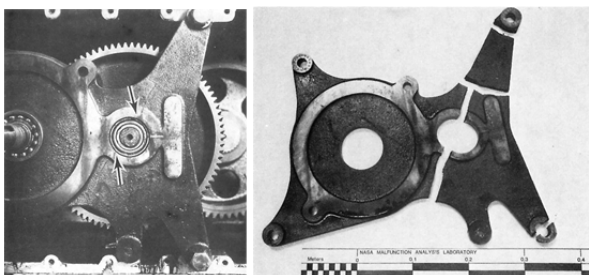


Figure 6. Cracked Gear Case Spider.⁵ Left: Spider inside crane. Right: Spider removed for inspection.

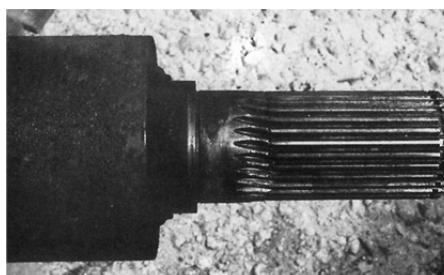


Figure 7. Deformed drum shaft spline.⁵

While most two-blocking incidents cause an immediate accident, damage from two-blocking can also be hidden. Changes in the crane behavior and noise levels prompted a special gearbox inspection of the 40-ton crane in Hangar AF. A crack was discovered in a gear case spider (Fig. 6) and the spline on the end of the drum shaft was deformed (Fig. 7). It was determined that the damage was caused by overload, most likely due to a two-blocking incident that had occurred three years prior. At the time of the inspection, Space Shuttle Solid Rocket Motor segments were being handled using this crane.

3. Lessons Learned

Two-blocking can cause severe accidents and significant damage to a crane or hoist. The most important lesson learned from these accidents is not to rely on the upper limit switch as a stop. Both OSHA and the NASA Lifting Standard require operators not to rely on the upper limit switch. The use of two upper limit switches is currently required on critical lift cranes by the NASA Lifting Standard. The use is also encouraged but not required on non-critical lift cranes and electric hoists.

Proper design dictates the first upper limit operates within crane's control circuit. When the switch is tripped, upward motion is stopped but the load can still be lowered with the normal operating controls. The second switch, higher than the first, operates within the crane's power circuit. When it is triggered, all crane power is removed, operations are stopped, and the system must be reset by an engineer or qualified technician before operations can continue. Adequate load drift margins between the limit switch activation and trolley structure need to be considered to avoid accidentally tripping both switches or contacting the crane before the load can be stopped.

After two-blocking has occurred, the entire hoist mechanism should be inspected for hidden damage. Proper lock-out/tag-out procedures should be followed to prevent further incidents until repairs can be made.

C. Over-capacity Lift

Cranes are rated based on the total load that they can safely handle. A "design factor" (sometimes called a "safety factor") is included in these calculations for additional margins of safety. It is a mistake to think this design factor allows for lifting loads above the rated capacity. It is only included to ensure that the crane can safely handle the load for which it is rated.

The Whiting Crane manual specifically refers to the use of "design factor" versus "factor of safety." The term "factor of safety" is misleading. It implies a level of protection that is not actually present and should not be used. The term "design factor" is broader because it includes consideration of the material properties, life expectancy, and stress levels. The design factor allows for variations in material properties, manufacturing tolerances, and operating conditions. It also helps to account for incorrect design assumptions. It does not imply that a crane can be loaded beyond the rated load. This is a hazardous operation that violates OSHA standards.⁶

Certain components, like the braking system, are not rated for lifting overloads, which is why lifting an excessive load can severely damage a crane or hoist. The brakes can fail, the structural members may incur excessive deflection, and the mechanical components can become misaligned, damaging gearing or couplings.

Mobile cranes are especially susceptible to the effects of over-capacity lifts. Safe lifting conditions on a mobile crane are calculated based on the load weight and the radius of the load from the crane's lower boom attachment point. These are kept in a load chart that is specific to each crane. The load chart values only provide a 10-15% operating margin, so a miscalculation or misunderstanding of the load weight or radius can cause the crane to tip.

1. Overturned Mobile Crane at Jay Jay Railroad Draw Bridge⁷

In 2010, a lattice boom mobile crane on a barge at the Jay Jay Railroad Bridge was setting pilings with a hydraulic driver. Several pilings had already been successfully placed on the south end of the barge. While placing a piling on the north-west end of the barge, the crane boom was lowered to avoid lifting the load over personnel and equipment. This increased the radius of the load very close to the maximum safe load radius. The load was swung clockwise toward the intended position. When it was perpendicular to the crane's crawler tracks, the crane began to tip. The operator was ordered to raise the boom to reduce the radius; however, he chose to lower the load using the hoist control instead in an attempt to safely lower the load onto a nearby barge. The load radius increased as the crane tipped further and the weight moved away from the crane. The barge also listed as the center of gravity of the crane moved, further exacerbating the tipping and the crane fell over (Fig. 8). The load fell into shallow water and the boom hit the pilings on the nearby barge. The operator sustained a minor laceration and the crane incurred \$100,000 damage.

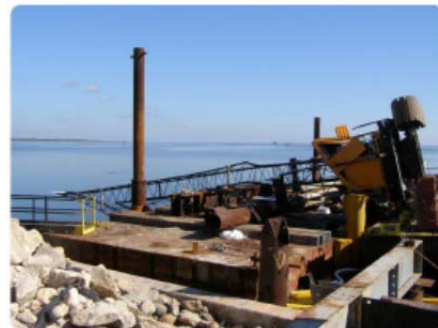


Figure 8. Overturned mobile crane on barge at Jay Jay Railroad Draw Bridge.⁷

The primary cause of the crane overturning was exceeding the lift capacity of the crane. The crane operator was told at the site safety meeting the previous day that the load (including the hydraulic driver) was 9 tons. The weight of the hydraulic driver was miscalculated by the lift planner and the actual load was 10.5 tons. Due to this, the safe load radius of the crane was less than expected. NASA gave the contractor approval to conduct operations in accordance with the lift plans, but did not review them to the level required to realize the mistake in the load weight.

2. Lessons Learned

Over-capacity lifts are usually caused by human error. In the case of the overturned mobile crane, the correctness of the actual load weight was not verified by the contractor or NASA before lifting. In other cases, crane

manufacturer load charts are not followed correctly. A key lesson is that lift planners should produce clear lift drawings that take into account multiple factors: safe lift restrictions based on load charts, reduced sling capacity due to angular displacement, and the location of the center of gravity of the load that is being lifted. A full understanding of the static and dynamic forces that occur during the lift is critical to keep the load safe.

D. Load Hang-up

A specific form of overloading is caused by the entanglement or snagging of the load during lifting. After the load has begun moving, the hoist, trolley, or bridge is prevented from moving which causes high torque loads in the hoist motor. Similar to two-blocking, this torque can be produced in a fraction of a second, damaging components in the gearbox, couplings, or the wire rope.

Load hang-ups can occur for a variety of reasons. Impacting or snagging the load on overhanging platforms is a common cause. Lifting a load while it is still attached to something else (the floor, a heavier object) is also a problem.

1. Improper Closing of Orbiter Payload Bay Door⁸

In the Orbiter Processing Facility, the opening and closing of the payload bay door is assisted by a Zero-G System. This system applies an exact counterweight to offset the weight of the door so the door could be opened and closed using orbiter power. A strongback is attached to the payload bay door which connected to a C-hook. The strongback provides structural stiffness to allow the doors to be opened and closed while the C-hook provides the interface to the Zero-G system. A cable passes through the C-hook and crane bridge and connects to a weight basket inside the weight cage affixed to the facility platform structure (Fig. 9).

In 1990, an incident occurred in which the weight basket was left pinned to the weight cage. During the previous shift, preparations had been made to close the right payload bay door. The Zero-G fixtures had been installed on the right side of the orbiter and the inhibit switches on the crane bridge had been activated to prevent movement. Since the procedure was due to be completed by the following shift, the weight baskets were left pinned to the weight cages. On the next shift, a technician was assigned to perform work on a different area of the orbiter. This work was not part of the master schedule. During the walkdown, the technician only checked the left side of the Zero-G system, which was not hooked up to the bridge. The technician then turned off the inhibit switches and moved the crane bridge approximately 6 feet to the aft of the orbiter. This pulled on the Zero-G system and caused the weight

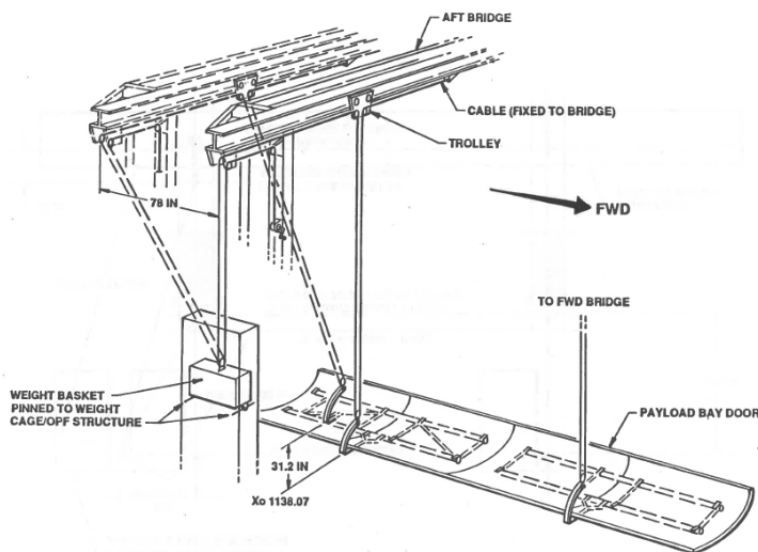


Figure 9. Diagram of Zero-G system attached to crane bridge showing deflection due to moving crane bridge.⁸

basket to jump off the track, breaking a pulley, fraying a cable, and deflecting the C-hook. The aft portion of the payload bay door was displaced upward 31 to 33 inches. The door was undamaged but required \$75,000 of analysis. The damaged fixtures required \$45,000 to replace and repair.

2. Solid Rocket Motor Handling Ring Mishap⁹

When Solid Rocket Motor (SRM) segments are shipped, the factory installs a lifting ring for transport. This ring consists of two parts, a solid handling ring over a segmented ring. The segmented ring is attached to the clevis that is later used to assemble the segments together. During processing at KSC, a lifting beam is attached to the solid handling ring and the 132 bolts connecting the segmented ring to the solid handling ring are loosened. The 129 shipping pins securing the ring to the SRM case are removed and the entire handling ring is lifted off with a crane.

In November 1985, technicians were in the process of removing the pins from the lifting ring. There were 31 pins left to remove when the lead technician asked the crane operator to pick up the approximate weight of the lifting fixture (11,000 pounds) to aid in pin removal. The crane operator watched the load cell indicator while moving the hoist very slowly upward. About 85 seconds later, they heard a loud bang and the lifting ring jumped upward. The emergency stop on the crane was activated. The SRM clevis was damaged in multiple places with elongated pin holes and a piece of metal gouged out of the clevis. Two segmented ring segments were damaged: one with an elongated hole and the other with a broken corner.

The primary cause of the accident was removal of the ring being performed without following the approved procedure. The procedure prohibited crane movement until all shipping pins were removed. Apparently, the request to lift 11,000 pounds was an attempt to take the weight of the forward handling ring off the segment. This, along with not loosening the handling ring bolts, had become common practice to aid in pin removal. The 11,000 pounds was not calculated. It had been derived over several processing operations as the indicator on the load cell that best facilitated the pin removal.

The load cell system experienced intermittent failures during post-accident testing. Use of the load cell was not called for during segment handling procedures but had been used a number of times against procedure. The load cell was not calibrated and had a history of inconsistent readings with loads under 20,000 pounds. When the crane was returned to service, the load cell system was turned off and a formal agreement was signed to discontinue use.

The final contributing factor to the accident was the slow response and inattention of the operators. It took 85 seconds from the beginning of the lift until the ring segment failed. The lead technician and quality control representative were not watching the lift; they were working to stamp previously completed steps. The second technician and the crane controller were the only observers. The second technician was busy instructing other technicians and pulling pins (no pins should have been removed during lifting operations). The crane controller was not on the work platform because the emergency stop pendant was in an awkward location. No one noticed the handling ring rise. The lift was conducted solely based on the load cell digital readout.

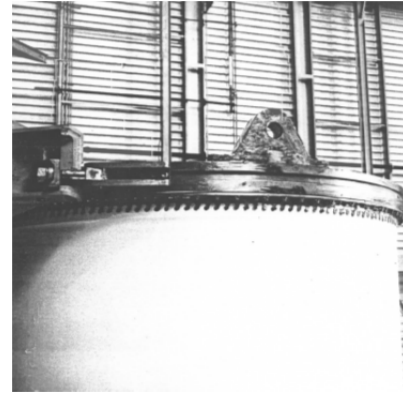


Figure 10. Handling ring installed on SRM segment.⁹

3. Lessons Learned

In the Payload Bay Door accident, the operating manual required a thorough walkdown and inspection of the bridge before moving. Performing complete walkdowns of the lifting area can significantly minimize load hang-ups. The lift area should be clear of hazards in all directions. The load should be free from constraints (bolts, pins, etc.) and observers should be used to alert the crane operator of other potential hazards. A good practice is to start lifting operations at slow speeds in case the load is accidentally constrained.

As learned from the SRM Handling Ring mishap, crane operators should not rely on single indicators such as load cell readouts – multiple indicators including hook position indicators, hoist ammeter, and outside observers should be checked during lifting. The emergency stop operator should be close enough to the lift to be aware of potential problems and stop the lift if necessary.

Approved lifting procedures should be included in the pre-task briefing and followed during the lift. Unapproved deviations can cause significant risk to workers and damage to flight hardware. A move coordinator should be in charge of critical lifts and aware of restrictions and the accepted lift procedures. The move coordinator should monitor the entire lifting operation.

E. Component Failure

Failure of crane and hoist components includes gearboxes, couplings, brakes, and assembled parts. Nearly all component failures are caused by human factors including improper design, not building parts as designed, improper assembly or alignment of components, improper inspection and testing, or overloading of components.

Material failure can also cause components to fail. This is very rare and can be caused by engineers choosing the wrong material for a component or a problem in the production of the chosen material.

1. *Payload Canister Mishap*¹⁰

The Shuttle Payload Canister was damaged due to a crane component failure in 1989 (Fig. 11). The canister and test weight were used to load test lifting fixtures in the Payload Changeout Room at Pad A that had been recently modified. After validation, the test weight and canister were moved to the Vehicle Assembly Building (VAB) for removal of the test weight from the canister. Due to other operations in the VAB, a mobile crane had to be used to remove the test weight.

While removing the test weight, the crane was very close to its maximum safe lift radius due to miscalculations in the radius by the operators. After initially being lifted approximately 6 inches, the weight suddenly dropped back onto supports on the edge of the canister. No thorough analysis was conducted on the incident. The task leader was assured by other personnel that everything was okay and the lift continued. After the load was raised above the canister again, the operator swung the test load to the left toward the waiting trailer. The boom then spontaneously lowered rapidly. This boom run caused the weight to swing away from the crane, exceeding the safe lift radius and causing the crane to tip. The weight crashed into the payload canister, causing an estimated \$287,000 damage that took two months to repair.

The investigation board determined that the primary cause of the accident was problems with the boom hoist brake. The brake release was not assembled properly: the spring retainer was missing and had been replaced with a thin flat washer. The washer failed and both the washer and the spacer were pushed inside of the spring (Fig. 12). This affected the ability of the brake release mechanism to actuate. Additionally, the boom hoist brake was misadjusted to the point where the boom hoist brake would not release when actuated. The boom hoist motor drove through the brake when raising and lowering the boom, causing wearing and heating of the brake. This caused reduced brake torque to the point where the brake finally slipped.



Figure 11. Dropped test weight in Payload Canister.¹⁰



Figure 12. Washer and spacer pushed inside spring.¹⁰

2. *Failure of Winch #6, Solid Rocket Service Platform, Mobile Launcher Platform*¹¹

During proofloading of the service platform lifting system, the platform was loaded with sand bags so that 12,500 pounds was placed on each of the four winches (Winches #5, 6, 7 and 8). The platform was initially lifted to check for clearance issues. It was then lifted further into the Solid Rocket Booster (SRB) exhaust cavity. It was during the second lift sequence that the cable on Winch #6 began a second wrap on the drum. During this overwrapping period, the cable failed. The other cables followed and the service platform overturned and fell to the ground.

Visual examination of the winch system indicated that the drum flange came off of Winches #5 and 6. On both of these winches, the wire rope wrapped itself around the drum shaft (Fig. 13). The wire ropes then failed due to rapid tensile overload (shock load) caused by the load dropping and catching suddenly. This



Figure 13. Separated end plate on Winch #6.¹¹ Note cable wrapped on shaft.

happened when the drum flange came off and the rope jumped off the drum onto the drum shaft. Detailed examination by the Malfunction Analysis Branch determined that the weld on the drum and end plates displayed a “gross lack-of-penetration” and “numerous areas of lack of fusion.” The end plate weld on Winch #7 also exhibited cracking, but did not fully separate. Winch #8 suffered severe cracking in the housing of the drum gear box and motor.

The manufacturer contended that the end plates were never designed to support the side load created by overwrapping the cable on the drum. They stated that the drum was designed to support the original cable length of 36 feet without overwrapping.

All of the winches in this accident were replaced at the contractor’s expense. Other similar winches on the Mobile Launcher Platform were modified at NASA’s expense to support potential overwrapping. The wire ropes were also shortened to the original 36 feet specified.

3. *Lessons Learned*

Component failure, while rare, can be minimized by including proper design factors within the design and including quality steps in the fabrication of selected components. This ensures that components can withstand unexpected load shifts. Lifts that are close to the recommended safe load limits can easily exceed them if a component failure happens.

The manufacturer guidelines should be followed with all lifting equipment. This includes the recommended length of rope in the system as well as the intended use of the components.

Stringent quality control programs should be followed during fabrication. Non-destructive testing, as well as visual inspection, can be performed on major components. Equipment should be rigorously tested before using to detect flaws in design and fabrication. In-service inspection and testing should be performed throughout the life of the equipment, including periodic load testing of critical crane systems.

F. Designing for Component Failure

Standard commercial systems have limited redundancy. This means that catastrophic failure of one component in the load path (motor brakes, gearboxes, couplers) will allow the load to fall.

Another type of design is called Single-Failure Proof design. In this format, the design of the lifting system allows any single component to fail without catastrophic results. It is assumed that every component has the potential to fail. Some components, such as the crane structure, do not have a credible likelihood of failure so they are assumed not to fail. Focus is placed on components with a significant likelihood of failure such as gearboxes, motor brakes, and couplings¹².

In Single-Failure Proof design, redundancy is added at critical points in the crane design. Additional hoist brakes are added to the hoist drum to prevent the load from falling due to holding brake failure. Redundant load paths can be added to the hoist machinery and wire rope reeving so that a failure in one load path, such as a component or rope failure, does not lead to catastrophic failure and unacceptable movement of the load.

Single-Failure Proof cranes can cost significantly more to construct and maintain due to required redundancies in the components and the complexity of the control systems. These types of cranes are often used at KSC to lift valuable spacecraft and explosive components in the Vehicle Assembly Building and other areas where this added protection is needed.

IV. Conclusion

Cranes are widely used across many areas of KSC. Failure of these cranes often leads to injury, high damage costs, and significant delays in program objectives.

Following a basic set of principles and procedures during design, fabrication, testing, regular use, and maintenance can significantly minimize many of these failures. As the accident analysis shows, load drops are often caused or influenced by human factors. Therefore, proper training and understanding of crane safety throughout the workforce is critical. It is important that the engineers designing the cranes, lift planners preparing the lift plans, operators performing the lifts, and training officers conducting the operator training all understand the problems that can happen with cranes and how to ensure the safety of the workforce and equipment being lifted.

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