

# Lessons Learned From the Development, Operation, and Review of Mechanical Systems on the Space Shuttle, International Space Station, and Payloads

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## Abstract

The Mechanical Design and Analysis Branch at the Johnson Space Center (JSC) is responsible for the technical oversight of over 30 mechanical systems flying on the Space Shuttle Orbiter and the International Space Station (ISS). The branch also has the responsibility for reviewing all mechanical systems on all Space Shuttle and International Space Station payloads, as part of the payload safety review process, through the Mechanical Systems Working Group (MSWG). These responsibilities give the branch unique insight into a large number of mechanical systems, and problems encountered during their design, testing, and operation. This paper contains narrative descriptions of lessons learned from some of the major problems worked on by the branch during the last two years. The problems are grouped into common categories and lessons learned are stated.

## Introduction

The Mechanical Design and Analysis Branch at JSC is responsible for the technical oversight of over 30 mechanical systems flying on the Space Shuttle Orbiter and the ISS. The branch houses the MSWG, which has the responsibility to review all mechanical systems on all Space Shuttle Program (SSP) and ISS payloads to verify compliance with the fault tolerance requirements as part of the payload safety review process. These responsibilities give the branch unique insight into a large number of mechanical systems, and problems encountered during their design, development, testing, and operation.

This paper describes some of the recent problems worked by the branch, and lessons that can be learned from them to improve future mechanical systems. The paper contains narrative descriptions of some of these problems. The problems are grouped into common categories and lessons learned are stated. The categories used are derived from the Mechanical Systems Safety memorandum [1]. The letter has 11 key design implementation and verification provisions to be followed to help ensure that credible failure modes have been reliably and effectively controlled as a result of a thorough design, build, and test process for mechanical systems. For this report, some categories will be combined, some omitted, and others expanded upon, to arrive at the list of categories: binding, jamming, and seizing; fastener locking and preload; strength; positive indication of status; and testing. Following each example, lessons learned are stated.

## Binding/Jamming/Seizing

This provision addresses the prevention of mechanism binding, jamming, and seizing. Appropriate design features include dual rotating surfaces or other mechanical redundancies, robust strength margins such that self-generated internal particles are precluded, shrouding and debris shielding, proper selection of materials and lubrication design to prevent friction welding or galling, and others. Adequate dimensional tolerances on all moving parts are needed to ensure that functional performance will be maintained under all natural and induced environmental conditions. Tolerances associated with mechanical adjustment (or rigging) must also be taken into account. Mechanical system designs must ensure compatibility of lubricants used with interfacing materials, other lubricants used in the design, and the natural and induced environments. Designs must also ensure that appropriate quantities of lubricant are specified.

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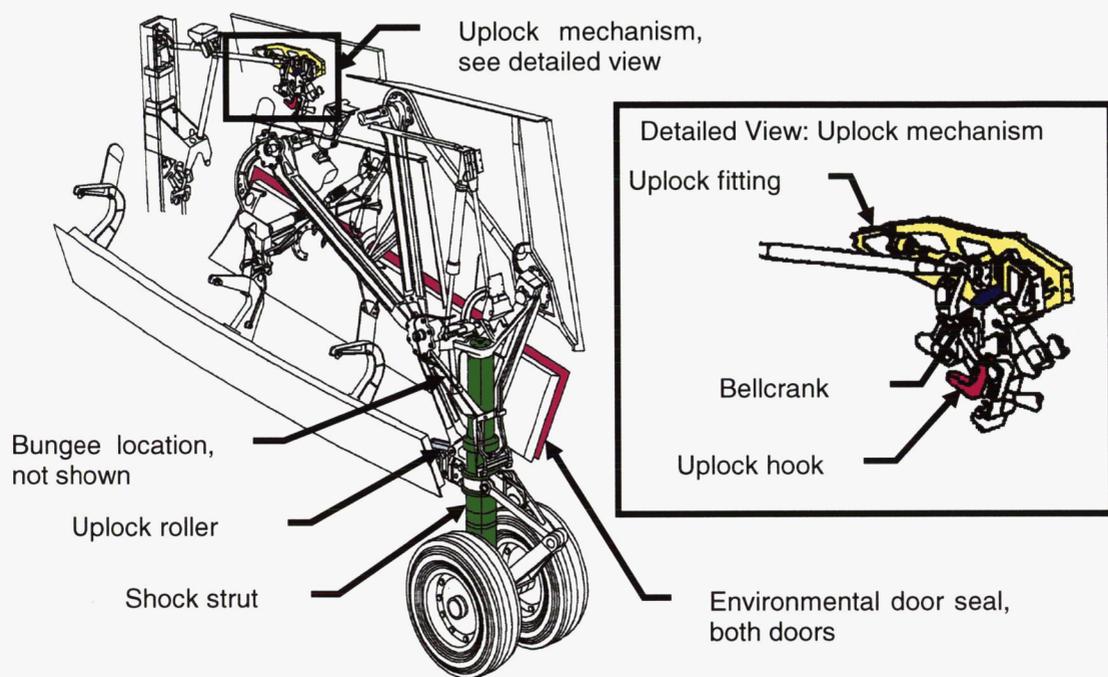
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### Nose Landing Gear Uplock Mechanism

The Space Shuttle Orbiter's nose landing gear, nose landing gear door, and nose landing gear uplock mechanism, shown in Figure 1, are interconnected, and must be rigged and operated together.

Following replacement of the door environmental seal, rigging was performed to achieve proper seal compression. During nose landing gear cycling, the gear uplock indication did not illuminate because the mechanism did not reach the full uplock condition. Binding in the rotational fitting between the uplock fitting and the bellcrank prevented the uplock mechanism from going to the full over-center position for gear uplock. Measurements of the width of the bellcrank and the internal width of the fitting showed an interference fit between the two assemblies. Rework on the bushings per specification requirements removed the interference condition, allowing the bellcrank to move freely.

**Lesson Learned: Proper tolerancing and inspection are critical to preventing interferences in mechanical systems.**



**Figure 1. Nose Landing Gear Mechanisms**

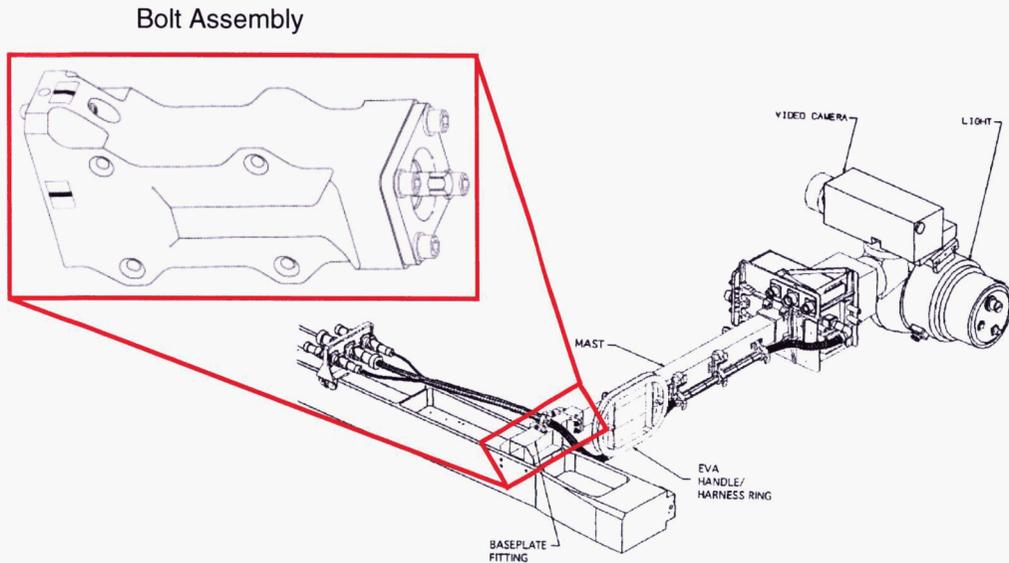
During subsequent nose landing gear retract operations, there was an early indication that the gear uplock mechanism was in the gear-up position. As the shock strut was entering the wheel well and bringing the doors closed, the gear stalled prior to being fully up and locked. After an immediate halt to operations the gear fell freely to the down position. It was observed that the uplock hook was in the gear-up position, thus preventing the uplock roller from engaging. Upon investigation, it was discovered that when hydraulic pressure was applied to retract the gear, the uplock actuator immediately drove the uplock hook closed to the gear-up position. Normally, the mechanism is in a gear-down over-center condition and cannot move prior to gear uplock roller engagement. When the gear uplock roller enters the hook, the roller pushes the mechanism out of its over-center position and allows the uplock hook to engage with the strut and bring the gear to the up-and-locked over-center position. A new source of binding in the mechanism had prevented the hook from being in the full down position. During the rework of the mechanism for the binding described above, inadvertent damage was imparted on the bungee spring. Tooling used to assist in the rework efforts described above is believed to have caused bent/raised metal on the bungee end cap. The resulting binding in the bungee prevented the mechanism from freely going to the full down over-center position. A replacement bungee was installed, and rotational pins and linkages in both the

gear uplock and in the door uplock mechanisms were inspected with no signs of damage observed. The mechanism now properly “snaps” into both the gear-up and gear-down over-center positions.

**Lesson Learned: Repair and rework of mechanical assemblies can cause collateral damage.**

#### Video Camera Support Assembly

The Video Camera Support Assembly (VCSA) is used to mount video cameras in any of 14 potential positions on the truss segments, nodes, laboratory module, or habitation module on the exterior of the ISS. As shown in Figure 2, the VCSA is mechanically attached to ISS primary structure with a threaded bolt that is installed by an astronaut during an extra-vehicular activity (EVA).



**Figure 2. Video Camera Support Assembly**

During testing, the VCSA bolt experienced extremely high running torques. The recorded running torque values were higher than the Pistol Grip Tool, which was to be used to drive the bolt during an EVA, was able to generate. Investigation revealed that no lubricant thickness was specified on the bolt drawing, and that the dry film lubricant thickness on the bolt was 10 times thicker than the requirement by the application specification, causing an interference with the female threads. In addition, the surface of the bolt was not bead-blasted prior to lubricant application, as required by the application specification. To resolve the issue, the dry film lubricant was removed and the bolts were returned to print by first bead-blasting the surface, and then reapplying the lubricant.

**Lesson Learned: Dry film lubricant thickness is important and the appropriate surface preparation must not be overlooked.**

#### **Fasteners**

Fasteners remain one of the most problematic areas on mechanical systems. The problems can generally be grouped into two subcategories, the first related to secondary locking features (or lack thereof), and the second related to fastener installation torque and the resulting fastener preload.

### Secondary Locking Features

For decades, dating back to the development of aircraft engines, the response of fastened joints to vibration environments has been a critical issue. Failures of critical fastened joints led to the development of “secondary” locking features that served as a method to guarantee that fasteners would not rotate and back out under vibration environments. Preload was recognized as a “good” method to prevent bolt rotation, but it was neither highly reliable nor predictable. So, “positive” locking methods were developed for highly critical joints, such as lockwire, cotter pins, locking tab washers, and safety cable. These locking methods are very reliable, but are also very labor intensive and thus expensive. To decrease labor, prevailing torque locking features were developed that rely on friction to help decrease propensity for bolts to rotate. Prevailing torque locking features include lock nuts, deformed thread keenserts, helicoils, and various types of locking patches and pellets.

Liquid Locking Compounds (LLCs) including epoxy have also been used as secondary locking features, but these have proven to be unreliable. LLCs are very sensitive to application process and environmental factors and cannot be verified after installation without breaking the bond. At JSC, the Engineering Directorate has been critically evaluating use of LLCs and has implemented policies restricting its use.

Many of the problems with secondary locking features can be traced to a lack of well-defined requirements. Using explicit language such as this can help:

“Each bolt, screw, nut, pin, or other fastener used in a safety critical application shall incorporate two separate verifiable locking features. Preload may be used as one of the features combined with a conventional aerospace secondary locking feature that is positive locking and vibration rated [2].”

***Lesson Learned: Clear secondary locking feature requirements need to be specified in program and project requirements documents.***

Over the past two years a significant number of problems have been encountered on many different pieces of hardware relating to either the lack of a secondary locking feature or the improper use of such features.

### External Stowage Platform 2

The External Stowage Platform 2 (ESP-2) was a payload mounted in the payload bay of the Space Shuttle Orbiter on STS-114. ESP-2 had several space station Orbital Replacement Units (ORUs) attached to it. After docking, the ESP-2 was removed from the payload bay and mounted to the external airlock on the ISS.

Following a test failure caused by migration of an uncured LLC, NASA Materials and Processes (M&P) and Structures and Mechanisms personnel advised both the ISS and Shuttle programs to closely restrict the use of LLCs and to develop application procedures for its use. As a result of the policy, an investigation of all uses of LLCs on ISS began. It was determined that an LLC had been used in some locations to assemble the ESP-2. The NASA ISS M&P System Manager advised the ISS Program that the installation procedures for ESP-2 did not call out the use of primer on the titanium inserts as recommended and that the design should be corrected by using a standard, verifiable locking feature.

It was decided to attempt qualification of the hardware with the LLC as configured, while following a parallel path to fix the hardware if the test was not successful. A conservative vibration test used to generically qualify secondary locking features was adapted to the ESP-2 LLC configurations. The test was performed at lower-than-flight preloads to help isolate performance of the secondary locking feature from preload. Five samples each of five different configurations were tested. All samples were assembled using the same process as on the ESP-2 flight hardware. All 25 samples showed various degrees of rotation following testing and were therefore determined to be failures. Upon disassembly of several of the samples, it was observed under microscopic inspection that the LLC had cured, but had failed to adhere to the titanium properly. The bolts with LLC were removed and replaced with bolts that had a verifiable locking feature, a Mylar locking patch, to resolve the issue.

**Lesson Learned: Liquid locking compounds are very application process-sensitive and not verifiable, and therefore are not recommended for use as a secondary locking feature.**

An interesting observation during the testing was that there appeared to be a relationship between fastener preload and LLC adhesion, which may warrant further study. For details, refer to JSC-62850 [3].

#### Resupply Stowage Rack

The Resupply Stowage Rack (RSR) is used to carry pressurized cargo to the space station in the Multi-Purpose Logistics Module (MPLM). The RSR consists of various sizes of locker compartments. These compartments, which accommodate individual stowage trays or bags, are bolted into the rack structure. The compartments have structural doors with latches, shown in Figure 3.



**Figure 3. RSR Latch Mechanism**

Only one month prior to the scheduled launch of STS-114, an issue was discovered with the locker door mechanism on the racks installed into the MPLM. The locker doors were held closed by a 90-degree latch that was held in the closed position by a single thumb screw. The thumb screws thread into locking inserts, but all had zero running torque due to numerous installation cycles. In addition, the engineering drawings required the thumb screws to be torqued "hand-tight". Testing was quickly performed to determine that a maximum of approximately 0.34 N-m could be achieved, far less than a fastener of this size would be nominally torqued. The fasteners essentially had no secondary locking features, and very low preloads. One of the lockers contained a 36.3 kg component with a high-pressure tank, which created a safety concern if the fasteners backed out and allowed the component to fall out of the open locker door.

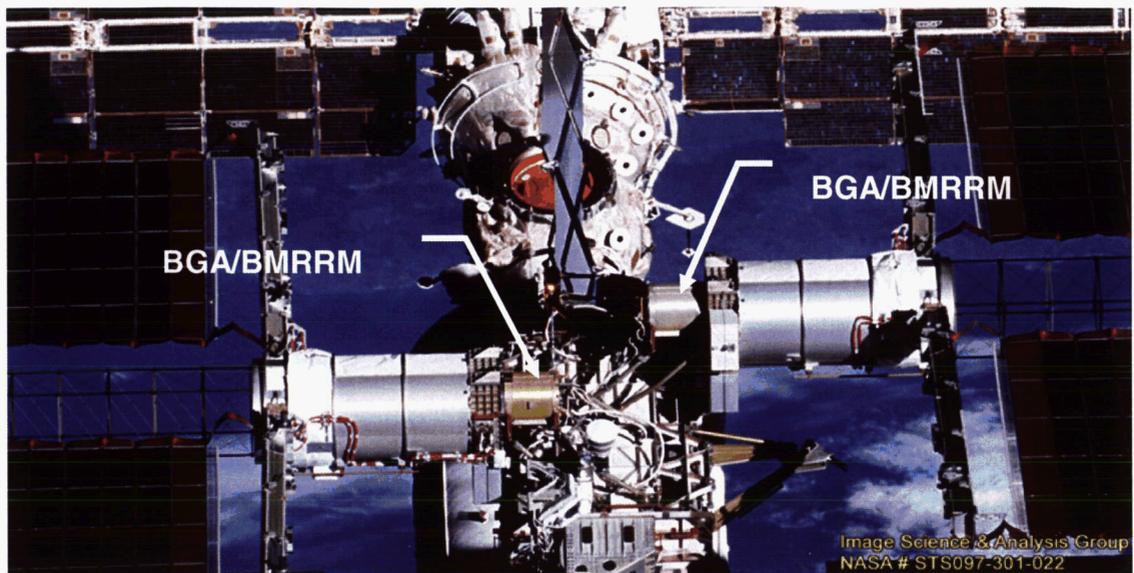
Any fix to the lockers required opening the Payload Canister and the MPLM hatch, which had already been closed out for flight. Because of this, a decision was made to temporarily fix all of the lockers (about 40) with Permacel Tape. The tape worked because it did not have to prevent the loss of preload, only locker latch rotation. While not very elegant, this was an acceptable fix for STS-114. Prior to any future flights, a secondary locking feature is being added to this system. The proposed concept consists of a slider, which fits over the existing handle and prevents the thumb nut from backing out, and can be slid away to permit operation.

**Lesson Learned: Measure running torque during each fastener installation cycle and keep a record for verification. Replace locking features that do not exhibit running torques within design specifications.**

**Lesson Learned: Fasteners and locking inserts are not the proper locking feature solution for latch designs requiring many cycles.**

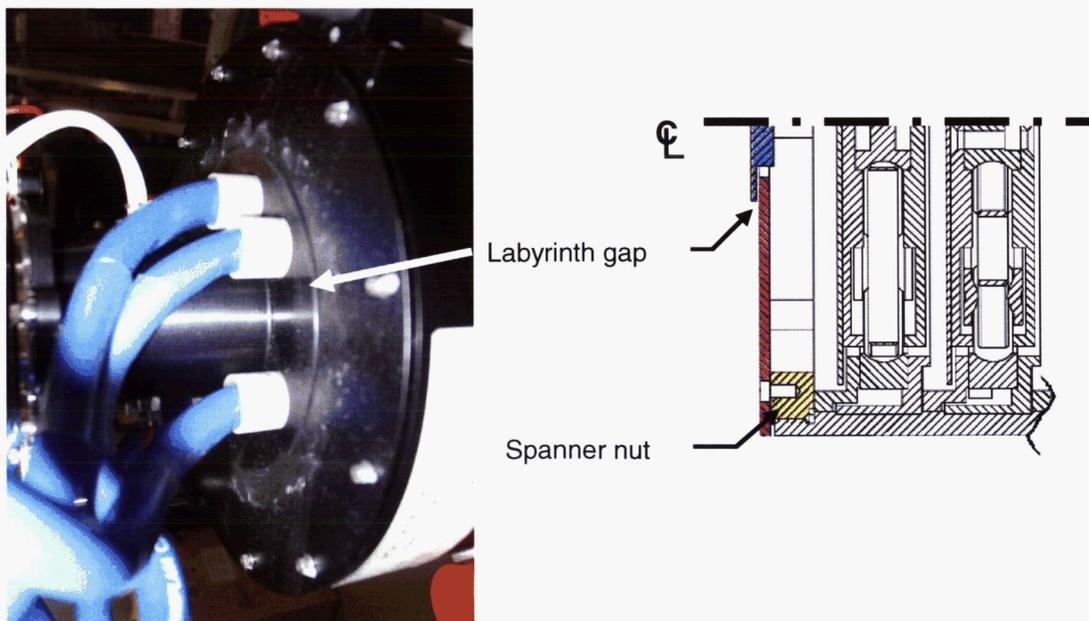
### Bearing Motor Roll Ring Module Spanner Nut

The Bearing Motor Roll Ring Module (BMRRM) is part of the space station Beta Gimbal Assembly (BGA), which provides mounting and gimbaling for the space station solar arrays. The BGA and BMRRM are shown in Figure 4.



**Figure 4. BGA and BMRRM**

The BGA BMRRM assembly was experiencing anomalous behavior after acceptance vibration testing: it would rotate smoothly in one direction, but would rotate slightly then seize when rotated the opposite direction. A layer of debris was also noted on the exterior of the assembly, as shown in Figure 5. Disassembly and inspection revealed that a large spanner nut, which was used to capture and preload the internal components of the roll ring and housed inside the BMRRM, had loosened and rotated out. As the nut rotated out, it closed up the clearance in a labyrinth gap as shown in Figure 5, resulting in metal to metal contact between the rotating and fixed parts of the housing components and generating the debris.



**Figure 5. BMRRM Debris and Labyrinth Gap and Spanner Nut**

Pre-delivery photographs and post-installation photographs taken with a borescope were evaluated to determine if multiple units had experienced a similar loosening problem. No other units were found with this problem.

A review of the drawings and build processes revealed that the nut design used a light preload and a small amount of LLC on its threads as its primary and secondary locking features. Due to a general concern for the locking design and the inability to define the exact cause of the failure, a mechanical lock was devised to fix the problem. The lock will be installed on all seven serviceable units. The three on-orbit units cannot be serviced.

While the vendor had what appeared to be a properly documented and controlled application process, the LLC had failed, allowing the nut to loosen. When the situation was discussed with the LLC manufacturer, they noted that the application fell outside of the recommended usage for their product because of the large size of the spanner nut and low preload and therefore would not guarantee its function.

***Lesson Learned: Liquid locking compounds cannot be depended upon when used in applications outside of manufacturer's guidelines.***

Pre-test, post-test, and post-installation photos were used as a non-destructive method to identify any other instances of nut movement. Since the units are not visible after being fully assembled into their next higher assembly, a borescope was used to obtain the photographs needed to clear the units.

***Lesson Learned: Maintain photo documentation of mechanical systems during assembly and subsequent testing and usage with similar viewing angles to allow for comparisons.***

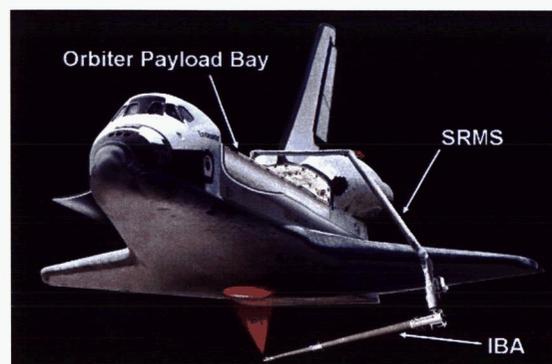
***Lesson Learned: Provide access for inspection of mechanical systems.***

#### Torque/Preload

A significant number of issues have been worked during the past two years relating to fastener installation torque and the resulting fastener preload. Many of these issues were the result of the improper installation torque being applied to the fasteners. Others were the result of an improper torquing sequence applied to a fastener pattern. A recurring theme has been a lack of understanding of the torque-tension relationship.

#### Inspection Boom Assembly and Shuttle Remote Manipulating System

The Inspection Boom Assembly (IBA) supports components of the Orbiter Boom Sensor System, including sensors and video cameras used by the crew for situational awareness and inspection of the Orbiter. The IBA and Shuttle Remote Manipulator System (SRMS) are mounted in the payload bay of the Orbiter. During flight the IBA is removed from the payload bay and operated as an extension of the SRMS, as shown in Figure 6.



**Figure 6. IBA on SRMS**

An installation drawing review of the IBA handrails revealed that unusually high torque values had been specified for some of the IBA fasteners, for which the vendor was not able to supply any supporting test data. An analysis assessment showed that several fastener groups within the IBA could potentially be

torqued above the yield strength of the fasteners. Similarly, a stress assessment for the SRMS bolts revealed that several SRMS fasteners could potentially be torqued above their yield strength as well.

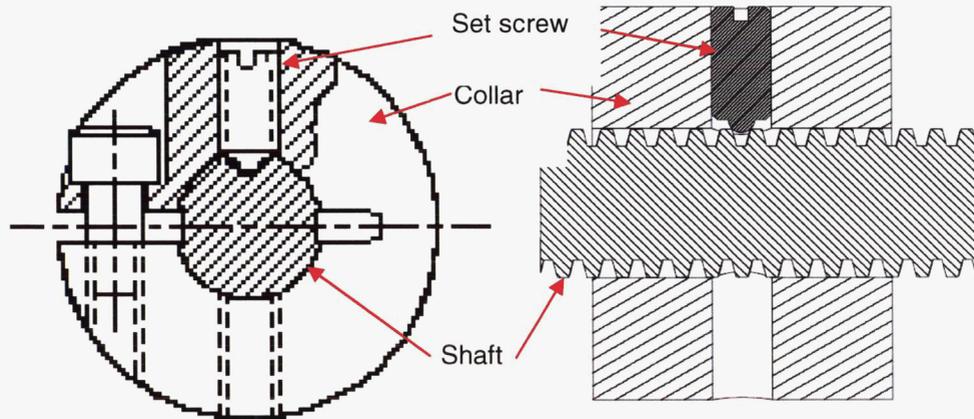
A series of tests was conducted at JSC to evaluate the suitability of this condition. Torque-tension tests were performed on four different fastener groups, two from the IBA and two from the SRMS, to directly measure the relationship between torque and preload. The tests were able to show that the IBA and SRMS were acceptable to fly in their current condition. For more details refer to JSC 63083 [4].

**Lesson Learned: Ensure torque tables are substantiated by relevant test data, accounting for the materials, lubricants, and installation process. Lubricants or sealants can significantly alter torque-tension relationships.**

#### Flight Releasable Attachment Mechanism

The Flight Releasable Attachment Mechanism (FRAM) provides a generic structural and electrical interface between spare ISS hardware components, called ORUs and either the Shuttle or ISS. The FRAM consists of an active half, which is mounted on the ORUs, and a passive half, which is connected to Shuttle payload bay carriers and on-orbit stowage locations. This provides interchangeability between storage locations.

After acceptance vibration testing of the FRAM, a post-test functional test and inspection revealed that a locking collar was loose and minor damage to an ACME thread was noted. The locking collar is shown in Figure 7.



**Figure 7. FRAM Locking Collar**

It was discovered that improper torquing of the locking collar clamping fasteners resulted in a loose collar and that the ACME thread on the shaft was damaged during the testing. The fasteners had been torqued to their full level individually and were not alternated or checked a second time around to ensure that the tightening of one fastener had not reduced preload in another. Unfortunately in this case, the clamping force of the collar was very sensitive to the order and manner of torquing the fasteners. To correct the problem, the fasteners were incrementally torqued to their full torque, while alternating between the two fasteners.

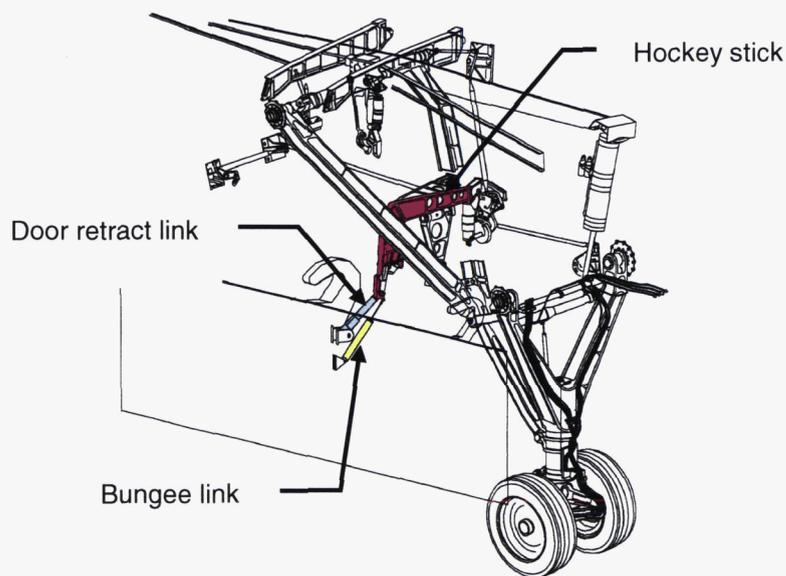
**Lesson Learned: Use proper torque sequence in multi-fastener patterns.**

## Strength

Mechanical system components and linkages need to be designed with sufficient strength to tolerate an actuation force/torque stall condition at any point of travel and maintain a positive margin of safety with an ultimate factor of safety applied. Mechanical systems that incorporate end of travel mechanical stops need positive strength margins for worst case dynamic loading conditions, considering variables in inertia properties, actuation force/torque, drive train resistance, and other environmental conditions. Exposed mechanical system components, protective shrouds and covers, and mounting structure need to accommodate inadvertent impact loads from manipulator systems, payload operations, and crew activity.

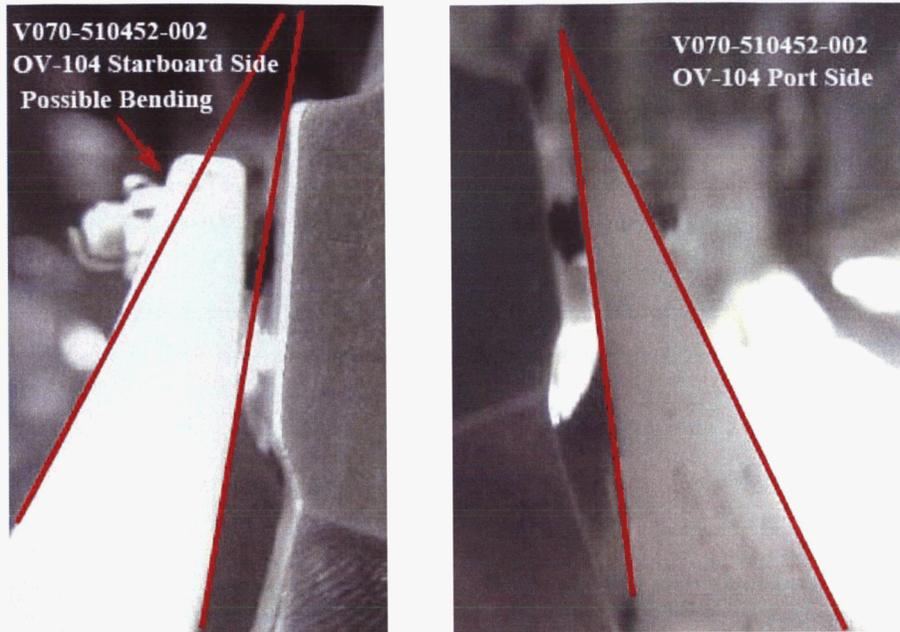
### Main Landing Gear Door Retract Mechanism

The Space Shuttle Orbiter main landing gear (MLG) door retract mechanism is shown in Figure 8. The door retract mechanism is a four bar over-center linkage, with the orbiter structure forming the fixed link. A spring-loaded bungee is also part of the mechanism and helps to hold the mechanism over-center when the door is open.



**Figure 8. MLG Door Retract Mechanism**

The door retract link on the starboard main door retract mechanism of Atlantis (OV-104) was found to be bent and cracked during a routine inspection. Figure 9 shows the damaged link in comparison with its counterpart on the port side.



**Figure 9. Comparison of Starboard and Port 452 Links**

Extensive failure analysis including metallography of the failed part, historical data retrieval, dimensional verification, loads analysis, and borescope inspection of Discovery, were conducted to understand the scope of the problem. It was concluded that the damaged part had adequate design properties, and that this part was damaged during replacement of the O-ring seals in the piston axle assembly of this main landing gear strut. This ground operation involved using a hoist to support the lower part of the main gear from overhead by attaching ground support equipment to the hockey stick. The over-center link was overloaded during this procedure, causing the damage. The vehicle flew two flights in this condition.

Discovery was inspected to ensure that it did not have a similar problem, and the damaged over-center link on Atlantis was replaced with a good link borrowed from Endeavour. Ground servicing procedures will be changed to prevent this problem in the future.

***Lesson Learned: Ensure that strength analyses are performed for planned ground operations of mechanisms, and prior to any unplanned ground operations.***

#### **Positive Indication of Status**

All movable mechanical systems should provide positive indication that the mechanism has achieved its desired position (i.e., ready-to-latch, latched, open, closed, etc.) and end of travel stops should be provided for all movable mechanical systems.

#### Limit Switches

Limit switches are often used to provide positive indication of status for mechanisms. Limit switches are small electronic devices not capable of sustaining high mechanical loads, and are typically protected by an actuating lever mechanism. Limit switches require ground rigging to set the actuation lever in the proper location. Due to their size, there is usually a small adjustment window in which the switch will indicate the proper status.

One example of an SSP mechanism that incorporates limit switches is the payload bay door drive mechanism. This system has switches that sense the position of its rotary actuators, and also indicate the location of the door. The rotary actuator limit switches are internal to the actuators, and are therefore protected from extreme thermal gradients between the hardware that is being sensed. The limit switches

that indicate the position of the door are incorporated into the bulkhead switch module, which is installed on the payload bay bulkheads, and are exposed to space.

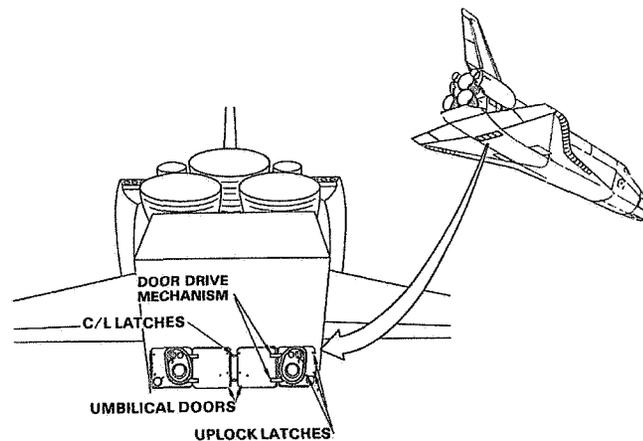
There have been numerous failures during missions with the bulkhead limit switch module and other limit switch applications. The switches do not accurately change status as the mechanism is operated, and take a few seconds to hours to flip to the proper indication. These failures do not always repeat themselves on the ground. The phenomenon is not currently understood, and despite tearing down the limit switch assembly, rebuilding, reinstalling, and ground rigging, the failures tend to repeat on orbit, and are attributed to thermal effects.

Extra effort should be made to locate limit switches so they are not subjected to extreme thermal environments. In the event that the switches must be installed in these environments, redundancy should be built into the limit switch system and extensive testing should be done to understand the interaction between the various components of the system under the applied thermal gradients.

***Lesson Learned: Ensure that thermal effects have been considered in the design and analysis of limit switches, and have been reproduced during environmental testing.***

#### External Tank Door Mechanisms

Following the External Tank (ET) jettison, the ET doors are used to close out the aft areas where the Space Shuttle Orbiter was attached to the ET. The doors, shown in Figure 10, are open for launch and ascent and then must be closed while on-orbit and remained closed for entry.



**Figure 10. ET Doors**

A centerline latch mechanism holds the doors open. Once the latches have been released, the ET door drive mechanism is used to drive the doors into a nearly closed, ready-to-latch position. The uplock mechanism then operates to pull the doors into a closed position.

For the ET door drive and uplock mechanisms, mechanical limit switches are incorporated into the actuators. This provides an indication that the actuator has rotated the proper amount, but does not directly indicate the status of the doors. If, for example, debris became wedged between the door and the frame, the actuator might be able to turn the correct number of degrees but the door opening might actually not be fully sealed. Given the external tank foam-shedding problem, this was a concern during the STS-114 return to flight mission. A better way to determine the true door status is being developed.

***Lesson Learned: Provide true indication of status for all safety critical mechanisms.***

## Testing

Proper testing of mechanical systems is extremely important, and cannot be over-emphasized. A comprehensive test program, including run-in tests, functional and environmental acceptance tests, qualification tests, and design life verification tests, is recommended to ensure that mechanical systems operate properly on-orbit. In addition, development testing, done early with prototype hardware, is extremely valuable and has proven to be cost effective by catching problems early when there is time to fix them.

One aspect of testing that is often overlooked, which will be discussed below, is the interaction of hardware inspections and functional verifications.

### Payload Bay Door Mechanisms

Each Space Shuttle Orbiter Payload Bay Door (PLBD) is comprised of multiple sections that are permitted to float along dry film lubricated shear pins. There are multiple requirements to inspect these expansion joint shear pins after a predetermined number of flights. At the same time, there are multiple door functional verifications for the operation of the PLBD mechanical systems (drive mechanism, bulkhead latch mechanism, and centerline latch mechanism). The shear pins are critical to the proper operation of the doors. In the event that the pins are replaced following a door functional, the door functional test must be repeated with the newly installed pins in place. Over the life of a vehicle, unanticipated actuations like these can add many cycles to mechanisms that were not necessarily accounted for during the original design phase.

In an integrated vehicle of various systems, there will be some overlap between hardware inspections and functional verifications. Numerous examples of this interrelation of maintenance requirements and functional verifications exist within the space shuttle program, including the interaction between tile replacement work and the cycling of the landing gear doors, star tracker doors, air data probe doors, vent doors, external tank door, etc.

***Lesson Learned: Design life of mechanisms should consider maintenance cycles of interfacing systems.***

***Lesson Learned: Processing work should be planned such that the fewest number of functional tests are performed, and cycles on mechanical systems should be tracked.***

## Summary

Several lessons learned have been presented in this report. A complete summary of the lessons are presented in Table 1. These lessons may prove to be of benefit for anyone who designs, develops, evaluates, or operates mechanical systems, regardless of the program.

**Table 1: Summary of Lessons Learned**

Category	Lesson
Binding, Jamming, and Seizing	Proper tolerancing and inspection are critical to preventing interferences in mechanical systems.
	Repair and rework of mechanical assemblies can cause collateral damage.
	Dry film lubricant thickness is important and the appropriate surface preparation must not be overlooked.
Fasteners: Secondary Locking Features	Clear secondary locking feature requirements need to be specified in program and project requirements documents.
	Liquid locking compounds are very application process-sensitive and not verifiable, and therefore are not recommended for use as a secondary locking feature.

Category	Lesson
	Measure running torque during each fastener installation cycle and keep a record for verification. Replace locking features that do not exhibit running torques within design specifications.
	Fasteners and locking inserts are not the proper locking feature solution for latch designs requiring many cycles.
	Liquid locking compounds cannot be depended upon when used in applications outside of manufacturer's guidelines.
	Maintain photo documentation of mechanical systems during assembly and subsequent testing and usage with similar viewing angles to allow for comparisons.
	Provide access for inspection of mechanical systems.
Fasteners: Torque/Preload	Ensure torque tables are substantiated by relevant test data, accounting for the materials, lubricants, and installation process. Lubricants or sealants can significantly alter torque-tension relationships.
	Use proper torque sequence in multi-fastener patterns.
Strength	Ensure that strength analyses are performed for planned ground operations of mechanisms, and prior to any unplanned ground operations.
Positive Indication of Status	Provide true indication of status for all safety critical mechanisms.
	Ensure that thermal effects have been considered in the design and analysis of limit switches, and have been reproduced during environmental testing.
Testing	Design life of mechanisms should consider maintenance cycles of interfacing systems.

#### **Acknowledgements**

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