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HYDRASET MODELS A, B, C, & D AUXILIARY HOIST CONTROL FAILURE MODES AND EFFECTS ANALYSIS (FMEA) AND CRITICAL ITEMS LIST (CIL)

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ATTACHMENTS

A- NPR 8715.3 Section 3.6, "Hazard Assessment"

B-"HYDRA-SET Incident Investigation Report" dated May 3, 2004, Yury Flom, Materials Engineering Branch, NASA GSFC.

1.0 SUMMARY OF FINDINGS

1.1 System Criticality

The Hydra-set Models A, B, C & D Auxiliary Hoist Controls, are of similar design and differ only in physical size and lift capacity. The specific units covered by this FMEA are as follows:

SEREAL #	MODEL	CAPACITY
A1-354	A	2,000 lb
A1-383	A	2,000 lb
A2-420	B	5,000 lb
A5-525	C	10,000 lb
A5-551	C	10,000 lb
A5-852	C	10,000 lb
A10-314	D	20,000 lb

The above units are all assessed as critical. Failure of these units could result in personnel injury and or damage/loss of flight hardware. The specific similarities in design are summarized below:

- Each unit has a single retaining ring, which prevents the piston rod bushing from being ejected under system pressure. Failure of this ring would result in rapid pressure loss and uncontrolled lowering/dropping of the payload. The maximum distance of the payload lowering/dropping would be limited to the piston travel of the specific unit.
- Four head bolts are used to attach/connect upper and lower cylinder heads to the main body of the unit. Preload on these head bolts is critical since they maintain the upper and lower Hydra-set pressure boundary. If preload were lost on any two of four head bolts, hydraulic fluid leakage and uncontrolled lowering/dropping of the payload could result. The maximum distance of payload lowering/dropping would again be limited to piston travel unless tensile failure or thread tear-out of head bolts were to occur.

1.2 Mechanical Critical Items.

1.2.1 Retaining Ring

The retaining ring in these units is identified "critical" by the Failure Modes and Effects Analysis (FMEA). The HYDRA-SETS are hydraulically operated and failure of the retaining ring would result in loss of fluid pressure and Hydra-set lift capability. The payload would drop a maximum distance equivalent to the range of piston travel but no further. Restraint provided by the four head bolts would prevent further piston motion. Controlled payload lowering would be maintained from that point, using the crane, unless Hydra-set structural

failure was experienced or the payload was situated at height less than piston travel.

1.2.2 Head Bolts

The four head bolts are also identified "critical" by the FMEA. Loss of preload on these bolts could result in hydraulic pressure loss and uncontrolled lowering of the payload.

1.3 Electrical Critical Items

There are no electrical functions associated with this lifting device.

1.4 Critical Flex Hoses

There are no flex hoses identified to be critical Items.

1.5 Critical Orifices

There are no orifices identified to be a Critical Items.

1.6 Critical Filters

There are no filters identified to be a Critical Items.

1.7 Criticality Category 1R Items

The head bolts are identified as category 1R and are evaluated in 1R Worksheet, Section 5.2. No single credible cause was identified to result in the loss of the redundant items.

1.8 Critical Control/Monitor Functions

There are no control/monitor functions associated with this system.

1.9 Sneak Circuits Identified

There are no Sneak Circuits to be analyzed.

1.10 Areas of Concern and Recommendations

Several recommendations are presented to improve the level of protection and minimize or negate the uncertainties identified in the failure modes and effects analysis. In summary, the recommendations are as follows:

- Retaining Ring should be replaced with a new ring each time the unit is re-assembled.
- Proper seating of the retaining ring should be verified by way of depth gage or measurement on installation.

- Rotation of the load relative to the Hydra-set should be minimized. This can be accomplished by addition of caution note in the handling procedures.
- Inclusion of Category 1R Items in the Periodic Inspection Procedure.
- Hydra-set Operator Certification on annual basis.

1.11 Risk Assessment

Risk assessment was performed in accordance with NASA Safety Manual NPR 8715.3, Section 3.6 "Hazard Assessment". The Hydra-set Models A, B, C, and D are considered safe to operate. The overall risk assessment is as follows:

- Hazard Severity Class: II-Critical
- Probability Estimation: E-Improbable
- Risk Assessment: 5-Acceptable

Implementation of the recommendations would add control measures to improve equipment reliability and minimize failure risks. It is noted that, the Attachment described failure incident was experienced prior to:

- Mandatory requirement for replacement of retaining rings with a new ring on re-assembly.
- Dimensional inspection for proper seating of retaining rings on reassembly.
- Check of pre-load on four head bolts.

2.0 SYSTEM SUMMARY

2.1 Specifications

Refer to the respective "Operation and Maintenance Manuals" Section 2.2 below.

2.2 Documentation List

The following documents were used in the performance of this analysis:

1. NSTS 22206 Revision D, December 10, 1992, "Requirements for Preparation and Approval of Failure Modes and Effects Analysis (FMEA) and Critical Items List (CIL)."

2. NASA STD 8719.9," "NASA Safety Standard for Lifting Devices and Equipment", May 2002 or latest revision.

3. GMI 1710.6, "Certification and Re-certification of Lifting Devices and Equipment and Critical Lift Requirements", latest revision.

4. Maintenance History File.

5. NASA Safety Manual NPR 8715.3, Section 3.6 "Hazard Assessment".

6. DEL PUB 81-1 HYDRA-SET MODEL A Auxiliary Hoist Control, "Operation and Maintenance Manual.

7. DEL PUB 81-2 HYDRA-SET MODEL B Auxiliary Hoist Control, "Operation and Maintenance Manual.

8. DEL PUB 81-3 HYDRA-SET MODEL C Auxiliary Hoist Control, "Operation and Maintenance Manual.

9. DEL PUB 81-4 HYDRA-SET MODEL D Auxiliary Hoist Control, "Operation and Maintenance Manual.

10. DEL PUB 85-6 HYDRA-SET MODEL D Auxiliary Hoist Control, "Operation and Maintenance Manual.

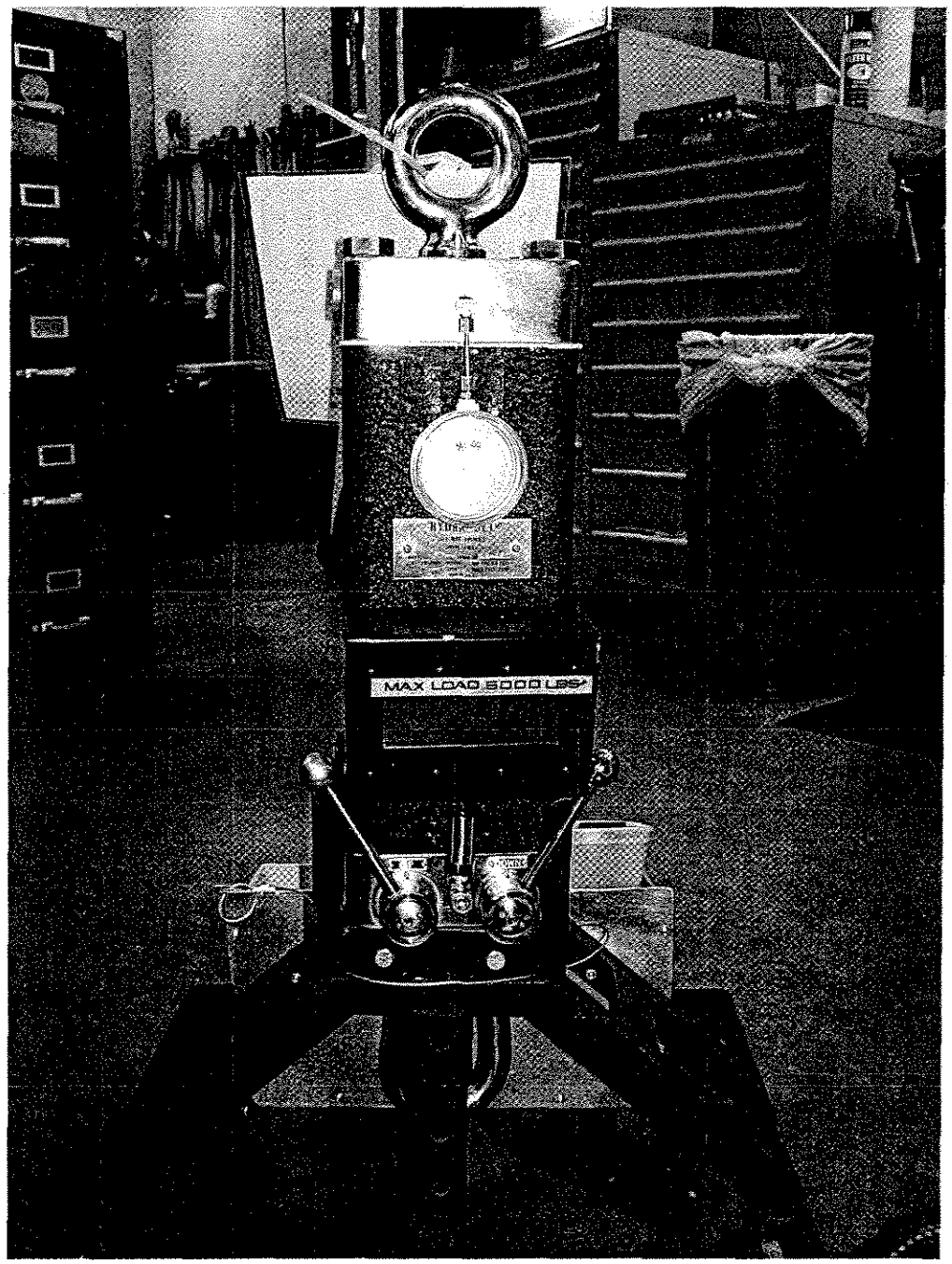

Figure-1 HYDRA-SET Model D Auxiliary Hoist Control

Note: Models A, B, C and D are same except for size And capacity.

3.0 DEFINITIONS AND GROUND RULES

3.1 Definitions

Definitions for the preparation and clarification of the Failure Modes and Effects Analysis are listed below.

Critical Item - A critical item is defined as any one of the following:

1. A Criticality Category 1, 1S or 2 Single Failure Point.

2. A redundant hardware item where the second failure results in loss of life or vehicle and the item is not capable of checkout during normal ground operations (i.e., a single fault tolerant item which fails Redundancy Screen A).

Critical (Reliability Impact) - If loss or improper performance of any one of the system's functions, without regard to redundancy, could result in loss of life or loss of flight hardware or damage to flight hardware, the total system is assessed as Critical. If loss or improper performance of all of the system's functions could not result if any of the aforementioned effects, the system will be considered Non-critical.

Criticality Category

Criticality	Potential Effect or Failure
1	Single failure, which could result in loss of life or flight hardware.
1R	Two redundant hardware items, which if both failed, could result in loss of life or vehicle (or loss of a safety or hazard monitoring system).
1S	Single failure in a safety or hazard monitoring system that could cause the system to fail to detect, combat, or operate when needed during the existence of a hazardous condition and could result in loss of life or flight hardware.
2	Single failure, which could result in loss (damage) of flight hardware.
3	All others.

Failure Modes and Effects Analysis (FMEA) - A bottoms up systematic, inductive, methodical analysis performed to identify and document all identifiable failure modes at a

prescribed level and to specify the resultant effect of the modes of failure. It is usually performed to identify critical single failure points in hardware. The FMEA is subsidiary to a Hazard Analysis.

Hazard Analysis - A hazard analysis shall, as a minimum, determine potential sources of danger, identify most probable failure modes, and recommend resolutions for those conditions found in the hardware-facility-environment-human relationship that could cause loss of life, personal injury, or loss of lifting device, facility, or load.

Redundancy Screens - Redundancy screens must be addressed for all Criticality Category 1R items. Determination of "Pass," "Fail," or "N/A" (not applicable) must be documented in the summary list of 1R items. The GSE redundancy screens are defined as follows:

(a) Screen A - The redundant item is capable of being checked and verified during normal ground operations.

(b) Screen B - Loss of the redundant item is readily detectable by the operator. (This screen is not applicable to standby redundancy.)

(c) Screen C - Loss of all redundant items cannot result from a single credible cause, such as contamination. It is assumed here that loss of the redundant item(s) is not detectable by scheduled test, inspections, and maintenance nor operator's daily check prior to first use daily.

Time to Effect - The time for the failure effect to occur in this analysis is specified as follows:

ST	Short Term - Months
LT	Long Term - Years

3.2 Ground Rules

This analysis is developed in accordance with NSTS 22206, Revision D, "Requirements for Preparation and Approval of Failure Modes and Effects Analysis (FMEA) and Critical Items List (CIL)."

The following ground rules and assumptions are established for this analysis:

a. Critical lift crane operators are certified annually to operate cranes and Hydra-sets.

b. This analysis assumes worst-case scenario when analyzing Ground Support Equipment (GSE).

c. Passive components are not analyzed in this FMEA, but should be considered in a Hazard Analysis, not part of this effort.

d. Failures of redundant items which meet the criteria described in 3.1.(a), (b) and (c) above are classified as Criticality Category 1R. Requirements for periodic test, inspection or functional validation of these items are invoked through the appropriate operation and maintenance requirements documentation. Single failure within the system controls which could cause loss of a 1R item is not be identified as 1R but is listed as a cause of the failure of the 1R items which it controls. Such system controls are included in the periodic test, inspection or functional validation requirement invoked on the 1R item.

e. Redundancy screens are addressed for all Criticality Category 1R items. Determination of "Pass," "Fail," or "N/A" (not applicable) are documented in the summary list of 1R items.

f. Failures due to human error in system setup (e.g., manual valves erroneously in the wrong position) are not considered in this FMEA.

g. This analysis assumes that all components, lubricants, and hydraulic fluids and fluid levels are as recommended by the original equipment manufacturer.

h. Fluids

1. Internal leakage is included in the assessment of the "fail open" failure mode.

2. External leakage is considered where leaks are detrimental to system operation or personnel safety.

3. All components located in the system downstream of the final filter are assessed for a possible source of contamination (e.g., transducers, temperature probes, component soft goods).

4. Filters, orifices and flex hoses are analyzed in the FMEA as part of the respective system.

i. The following classification of failure modes, as a minimum, is included in the CIL:

1. All Functional Criticality Category 1 and 2 items.

2. All Functional Criticality 1R items where (1) first failure could result in loss of life and/or flight hardware or (2) next failure of any redundant item could cause loss of operator/lifting device.

3. All Functional Criticality Category 1R items that fail one or more redundancy screens.

j. This FMEA only analyzes the failure modes and effects of the HYDRA-SET system and components. Other safety issues involving operating personnel qualifications, inherent hazards of a specific critical lift, and provisions for facility protection and emergency recovery during lift operations, etc., to be addressed in the specific Critical Lift Procedure. The Procedure is usually initiated and funded by the Project, if warranted, and developed by integration support personnel.

4.0 CRITICALITY ASSESSMENT

4.1 Criticality Assessment Worksheets

This system input and output functions are assessed on the following Criticality Assessment Summary sheet.

The Criticality Assessment Worksheets are performed to determine whether the GSE is Critical or Non-critical in terms of reliability impact. If loss or improper performance of any one of the system's functions, without regard to redundancy, could result in loss of life or loss of flight hardware or damage to flight hardware, the total system is assessed as Critical. If loss or improper performance of all of the system's functions could not result in any of the aforementioned effects, the system is considered Non-critical.

SYSTEM CRITICALITY ASSESSMENT SUMMARY WORKSHEET				
System HYDRA-SET Models A, B, C, D	Drawing See Figure 1, page 4	Location Building 7,10,15 and 29	Prepared by E. Hemminger 10/6/04	
INPUT/OUTPUT	FUNCTION	TIME PERIOD	EFFECT OF LOSS/FAILURE	CRIT. CAT.
Hydraulic Lift System	Provides ability to raise/lower loads up to but not exceeding HYDRA-SET capacity.	Pick up, transport, and deposit of the load.	Failure of the overall lift system could cause the load to drop a maximum distance equal to piston stroke. Could cause personnel injury and or damage/loss of flight payload.	Crit.

5.0 FAILURE MODES AND EFFECTS ANALYSIS AND CIL

5.1 Mechanical FMEA Worksheets

The mechanical components of the HYDRA-SET Modela A, B, C,D are identified from documents referenced in the Documentation List and are analyzed on the following worksheets.

FAILURE MODE AND EFFECTS ANALYSIS (FMEA) WORKSHEET

SYSTEM: HYDRA-SET Model A, B, C & D Auxiliary Hoist Control
SUBSYSTEM: Lift
REFERENCE: HYDRA-SET Model D Auxiliary Hoist Control Operation & Maintenance Manual DEL PUB 81-4, August 1988

PREPARED BY: E. Hemminger
DATE: October, 2004

NO.	PART NAME	FAILURE CAUSE	FAILURE EFFECT ON SYSTEM PERFORMANCE	FAILURE EFFECT ON CRITICAL HARDWARE AND/OR PERSONNEL SAFETY	TIME TO EFFECT	CRIT CAT
1	Hoist inner & outer Cylinders	Surface scratches on fluid surfaces causing by-pass leakage.	Piston rod unloading due to by-pass leakage.	Loss of lift control due to unintentional piston motion.	LT	2
2	Head Upper & Lower Housing Flanges	Distortion, excessive deflection due to pressure and or pre-load application	Piston rod unloading due to by-pass leakage.	Loss of lift control due to unintentional piston motion.	LT	2
3	Cylinder Seal Rings multiple	Surface debris	Hydraulic oil leakage and resultant piston rod unloading.	Loss of lift control due to unintentional piston motion.	LT	2R
4	Plunger Rod Assembly	Excessive wear and scratches on rod surface resulting in seal leakage.	Intermittent piston hang-up and unloading due to leakage.	Loss of lift control due to unintentional piston motion.	LT	2
5	Plunger Rod Bushing	Excessive wear and scratches on bushing inner surface resulting in seal leakage.	Intermittent piston hang-up and unloading due to leakage.	Loss of lift control due to unintentional piston motion.	LT	2
6	Retaining Ring	Broken or distorted, out of specification.	Loss of hydraulic fluid/pressure.	Sudden movement/loss of load.	ST	1
7	Piston head Tie Bolts multiple	Loss of pre-load on minimum two of four bolts	Hydraulic oil leakage and unloading.	Uncontrolled movement/loss of load. Requires multiple failures.	LT	1R
8	Rod Wiper Assembly	Wear and abrasive damage	Intermittent loss of fluid and resultant unloading.	Uncontrolled movement/dropping the load.	LT	3
9	Pump & Down Valve Ass'y	Wear and abrasive damage	Unable to lift or lower load.	Unable to lift or lower load.	LT	3

FAILURE MODE AND EFFECTS ANALYSIS (FMEA) WORKSHEET

SYSTEM: HYDRA-SET Model A, B, C & D Auxiliary Hoist Control
SUBSYSTEM: Lift
REFERENCE: HYDRA-SET Model D Auxiliary Hoist Control Operation & Maintenance Manual DEL PUB 81-4, August 1988

PREPARED BY: E. Hemminger
DATE: October, 2004

NO.	PART NAME	FAILURE CAUSE	FAILURE EFFECT ON SYSTEM PERFORMANCE	FAILURE EFFECT ON CRITICAL HARDWARE AND/OR PERSONNEL SAFETY	TIME TO EFFECT	CRIT CAT
10	Lower Eye Roll Pin	Twisted, over-compressed	If roll pin backs out, Lifting Eye could become unthreaded resulting in, loss of load	Requires multiple failures.	LT	2R
11	Return Force Gauge	Physical damage, hydraulic leakage	Loss of pumping force indication.	Unintentional movement of payload.	LT	2
12	Load Gauge	Physical damage, load sensing failure	Loss of Load sensing.	Could Exceed allowable load.	LT	2

CRITICALITY CATEGORY 1R WORKSHEETS

SYSTEM: HYDRA-SET Model A,B C & D Auxiliary Hoist Control DATE: October, 2004
SUBSYSTEM: Lift PREPARED BY: E. Hemminger
REFERENCE: NSTS 22206, Revision D

NO.	PART NAME	FAILURE CAUSE(S)	FAILURE EFFECT	REDUNDANCY SCREENS		TEST AND INSPECTION REQUIREMENT(S)
				PASS	FAIL	
1	Piston Head Tie Bolts	Loss of Preload.	Head bolt joint separation resulting in hydraulic fluid leakage and uncontrolled piston movement/could result in dropping the load.	A B C		• Operator inspection prior to first use daily. • Frequent inspection monthly. • Periodic inspection annually.

6.0 RATIONALE FOR ACCEPTABILITY

The retaining ring and piston head tie bolts were the only mechanical critical items identified by the FMEA. The retaining ring was originally specified as 1 due to a previous failure as discussed in Attachment to this FMEA. However, as justified below, the ring was downgraded from critical to 2 based on the following:

- Retaining Rings will no longer be re-used. This was allowed by previous maintenance procedures.
- New rings will be used on reassembly and proper seating of rings will be verified by dimensional inspection and or use of a depth gage.
- Frequent and periodic maintenance inspections, including operational load testing, will continue to be performed to mitigate failure during flight hardware use.

For the head tie bolts, it is noted that Criticality 1R items <u>are acceptable</u> in that it is capable of checkout during normal ground operations. Documentation of the following data elements: Design, Test and Inspection, Failure History and Operational Use are provided to categorize the analysis for risk assessment.

6.1 Design

HYDRASET design has been verified in accordance with applicable ASME/ANSI/ASTM Codes. This insures sufficient design margins are used for all pressure and load bearing parts and requires that proof testing be performed to verify load capacity and workmanship. This design process minimizes the probability of occurrence of the critical failure modes and their causes.

6.2 Test and Inspection

Operator inspection prior to use in addition to Frequent and Periodic Inspection and maintenance per "Test & Inspection, Cleaning and Overhaul Procedure for Manual HYDRA-SET Positioning Devices", Man-Tech Document #40-06-186-3

6.3 Failure History

One Failure has been experienced during performance of frequent monthly inspection. On 4 March, 2004 a 5000 lb capacity Model B HYDRA-SET suddenly failed at the conclusion of its 3000 lb load test. Details of this incident and corrective action are included in Attachment to this FMEA.

6.4 Operational Use

Failures due to human error are not considered in the performance of a failure modes and effects analysis. This factor is minimized by way of certification training as recommended in section 1.10.

7.0 AREAS OF CONCERN AND RECOMMENDATIONS

The following recommendations are provided to further improve operational safety and reliability of this equipment for flight project support.

7.1 It is recommended that:

7.1.1 Critical HYDRA-SET inspections be performed by certified personnel only;

7.1.2 All Critical and Criticality Category 1R items identified in this analysis be included in the Frequent (monthly) and Periodic (annual) inspections.

7.1.3 Frequent and Periodic inspections be performed according to approved RECERT inspection procedures only.

7.2 All critical item identified as a result of this analysis will be checked during frequent monthly inspections and prior to normal use.

All redundant hardware items identified are capable of checkout during normal operations. The time for failure to occur for these components was determined to be "Short Term," i.e., months. Implementation of the aforementioned scheduled test and inspections are recommended to mitigate these failure modes.

Operators trained in the safe operation of the equipment can minimize the risk of human error. The risk of human error is further reduced by the center requirement which mandates crane operators attend annual refresher training on use of cranes and Hydra-sets.

8.0 RISK ASSESSMENT

Risk assessment was performed in accordance with NASA Safety Manual NPR 8715.3, Section 3.6 "Hazard Assesment". The HYDRA-SET Models A, B, C and D are considered safe to operate. The overall risk assessment is as follows:

- Hazard Severity Class: II-Critical
- Probability Estimation: E-Improbable
- Risk Assessment: RAC#5-Acceptable

Rationale for acceptability is discussed in Section 6.

ATTACHMENT-A

NPR 8715.3 Section 3.6 "Hazard Assessment"

The hazard assessment process is a principal factor in the understanding and management of technical risk. Hazards are identified and resultant risks are assessed by considering probability of occurrence and severity of consequence. Risk may be assessed qualitatively or quantitatively. System safety is an integral part of the overall program risk management decision process. A sample format to document the risk process is provided in Appendix E.

3.6.1 Risk Assessment Code (RAC). The RAC is a numerical expression of comparative risk determined by an evaluation of both the potential severity of a condition and the probability of its occurrence. RAC`s are assigned a number from 1 to 7 in a risk matrix (see figure 3.2.). The RAC number will serve as a means to prioritize corrective actions, e.g., RAC 1 is unacceptable and mitigation actions must be taken immediately or operations terminated, RAC 2`s must be addressed before RAC 3`s, etc. (Requirement 25246). Differences between higher number RAC`s (beyond 4) probably cannot be discerned due to low risk levels. The cognizant safety and program officials may approve variations to the matrix.

3.6.1.1 Severity is an assessment of the worst potential consequence, defined by degree of injury or property damage, which could occur. The severity classifications are defined as follows:

Class I - Catastrophic - A condition that may cause death or permanently disabling injury, facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission.

Class II - Critical - A condition that may cause severe injury or occupational illness, or major property damage to facilities, systems, equipment, or flight hardware.

Class III - Moderate - A condition that may cause minor injury or occupational illness, or minor property damage to facilities, systems, equipment, or flight hardware.

Class IV - Negligible - A condition that could cause the need for minor first aid treatment though would not adversely affect personal safety or health. A condition that subjects facilities, equipment, or flight hardware to more than normal wear and tear.

3.6.1.2 Probability is the likelihood that an identified hazard will result in a mishap, based on an assessment of such factors as location, exposure in terms of cycles or hours of operation, and affected population. The following is an example of Probability Estimation:

A - Likely to occur immediately. ($X > 10^{-1}$)

B - Probably will occur in time. ($10^{-1} \geq X > 10^{-2}$)

C - May occur in time. ($10^{-2} \geq X > 10^{-3}$)

D - Unlikely to occur. ($10^{-3} \geq X > 10^{-6}$)

E - Improbable to occur. ($10^{-6} \geq X$)

(derived from Mil Std 882-System Safety Program Requirements)

	Probability Estimate				
Severity Class	A	B	C	D	E
I	1	1	2	3	4
II	1	2	3	4	5
III	2	3	4	5	6
IV	3	4	5	6	7

Figure 3.2 Risk Assessment Code Matrix

ATTACHMENT-B

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

Reply to Attn of: 541

December 9, 2004

TO: 540/Recertification Program Manager/Stanley Chan

FROM: 541/Materials Engineering Branch/Yury Flom

SUBJECT: Hydra-Set Incident Investigation Report

INTRODUCTION

On March 4, 2004 a 5000 lbs capacity hydraulic load positioner Hydra-Set® Model "B" S/N A2-420 was undergoing its regular monthly maintenance at GSFC. At the conclusion of the 3000 lb load test, the unit suddenly failed while still under load, allowing the piston to drop to its lowest point and releas*ing* the entire quantity of hydraulic fluid. Even though no damage to hardware or personnel injury *was* experienced during this incident, the behavior of this Hydra-Set was noted as abnormal and the current investigation was initiated.

In response to the incident, an independent investigation team, consisting of Dr. Yury Flom (chair), Mr. Ed Hemminger and Mr. Jerome Kosco and was formed. The purpose of the investigation was to determine the root cause of the Hydra-Set malfunction and, more importantly, to assess the impact of this incident on the remaining inventory of hydraulic positioners at Goddard.

This report will present the technical details of the investigation, identify most probable contributing factors *to* the Hydra-Set malfunction and offer recommendations to insure against similar incidents in the future.

In case the reader finds some minor discrepancies between this report and any previously written or verbal data pertaining to this incident investigation, the information contained in this report takes precedence over all other technical communications released prior to this publication

CONCLUSIONS

Factors contributing to Hydra-Set malfunction are identified as follows:

1. The root cause of the incident is related to the repeated use of the same, perhaps even the original retaining ring installed in the unit when it was purchased in 1988.
2. In the course of its service life, repeated compressions of the same retaining ring during maintenance assembly and disassembly operations, most likely deformed the ring beyond the manufacturer's dimensional specifications. This was verified by dimensional inspection of the failed ring.
3. As verified by testing, a deformed, out of specification ring, when properly seated, did not result in failure under load. However, the same ring when partially seated, did fail under load. It is noted that the ring had to be severely out of specification particularly with regard to out of plane twist or displacement.
4. The Investigation Team could not conclusively determine whether a properly installed out of specification ring would experience rotation and partial unseating during normal maintenance operations. But as previously noted, an incomplete or partially seated out of specification ring could be displaced under load from its retaining groove. Once outside the groove, the retaining ring could no longer support the axial thrust load, which then leads to the Hydra-Set failure.
5. The investigation found no evidence of any latent manufacturing defects that might have contributed to the incident or gradually degraded the performance of the Hydra-Set.
6. Exercising the Hydra-Set within its working load range may not be sufficient to verify the correct seating of the retaining ring. It is possible that even a partially seated retaining ring can support certain axial thrust loads.

RECOMMENDATIONS

1. Retaining rings should be replaced with a new ring on removal from the unit.
2. It would be beneficial for Hydra-Set and the retaining ring manufacturer's to specify that retaining rings not be re-used. This is particularly important when these units are being used for handling of critical hardware.
3. Full seating of the retaining rings should be verified at each installation. This step should be mandated in the Hydra-Set maintenance and re-assembly procedures. The verification of correct seating could be accomplished by dimensional check or by any other means such as "seating gage", as described later on this report.
4. Rotation of the load relative to the Hydra-Set should be avoided to the maximum extent possible to prevent the possibility of the ring being unseated from its groove.

INVESTIGATION SYNOPSIS

The failed Hydra-Set was disassembled and the components critical to the investigation such as the retaining ring, bushing, piston rod and the lower head were delivered to MEB for the evaluation, see Figs 1,2. All components were found to be physically intact and, except for the excessively deformed and out of specification retaining ring and some minor scratches on the inner groove edge of the lower head, the examination revealed no other material or dimensional discrepancies.

In order to better understand the interaction between the Hydra-Set components when the retaining ring is not fully seated, a series of static compression tests were performed on the re-assembled components with the following results:

1. It was found that even a partially seated retaining ring would support high axial thrust loads of 3000 lb and greater. This was verified for various rings as described in Table 2 of this report. Therefore, partial insertion of the retaining ring is considered a sufficient condition for failure.
2. A severely distorted ring with out of plane twist, when fully inserted, was also found to support high axial thrust loading. However, this same ring when partially inserted, was found to fail under very low axial loading.
3. A test was also performed to see if an out of specification, over-compressed, but fully seated retaining ring might experience rotation during regular monthly exercise of the unit. No evidence of such rotation was observed.
4. However, some scratch marks on the groove bottom face were observed and may be indicative of relative rotation between the ring and the groove.
5. No direct evidence was found to indicate incorrect installation of the retaining ring in the failed unit. Consequently, the Investigation Team concluded that, relative rotation when combined with a partial seating of a severely deformed retaining ring could have caused the incident.

DISCUSSION

A detailed account of the Hydra-Set maintenance history and the investigation effort is given below.

SERVICE AND MAINTENANCE OF HYDRA-SET

The Hydra-Set under investigation is a manually operated 5000 lbs load capacity hydraulic actuator capable of positioning loads in very small vertical increments, see Fig.3 It was placed in service at GSFC in 1988. Since then, a certified crew, trained to operate and maintain these units by the manufacturer, has used them numerous times for positioning of critical hardware. In addition, all required inspection, cleaning, overhaul and re-certification of this unit has been performed at Goddard with exception of one time when the unit was sent to the manufacturer in 1997.

A typical maintenance schedule performed on all Hydra-Sets at Goddard, including the unit under investigation, is given below in Table 1.

Table 1 Maintenance Schedule.

PROCEDURE	FREQUENCY	PURPOSE	BRIEF DESCRIPTION
Frequent Inspection and Maintenance	Monthly	Maintain Hydra-Sets in good operating condition and detect any malfunctions	Visual examination for leaks, structural anomalies and operational tests to within 60% of load capacity, check for reasonable accuracy in vertical positioning and operation of fail-safe valve.
Periodic Inspection and Maintenance	Annual	Recertification of unit as liftworthy for critical operations	Consists of a static load test at 125% of rated capacity, operational tests and visual examination for leaks and structural anomalies, test of fail-save valve, calibration.
Scheduled overhaul	Every 24 months	Replacement of the seals and load proof test	Units are completely disassembled. All seals are replaced and components are inspected for damage. Unit is reassembled with new seals and other parts as needed. Static test to 200% of its load capacity.

The last time the failed unit was reassembled was in January 2004. Since then, the unit successfully completed two Frequent Inspection and Maintenance cycles for January and February. The unit failed on the third Frequent Inspection and Maintenance cycle for March, almost completing the 3000 lb load test when the retaining ring let go.

Important points:

- The Hydra-Set Operation and Maintenance Manual supplied by the manufacturer did not call for the replacement of the old retaining ring with the brand new one when the unit is reassembled.
- The overhaul kit sold by the manufacturer did not include a new retaining ring.

MATERIALS

Retaining Ring:

The retaining ring was internal series N5000 W 162 manufactured from the carbon spring steel (SAE 1060-1090) by the Waldes-Truarc company. The ring had zinc plate finish, was physically intact and showed no cracks. On both sides of the ring, the zinc plated surface had characteristic circumferential lines, as shown in Fig.4. Most likely these lines were the "foot prints" left on the zinc surface by the abutting edge of the inner groove. The fact that both sides of the ring have these imprints indicates a multiple use of this ring in the subject Hydra-Set. Hardness readings taken on the ring resulted in the average Rockwell "C" values of 45. Considering that in order to preserve the evidence the zinc plating was not removed from the ring prior to hardness measurements, these values were within the manufacturer's specifications.

Dimensional inspection of the ring performed in accordance with the manufacturer's recommended inspection procedure resulted in the average ring free diameter of 1.737 in. This falls below the ring diameter range of 1.804 in +0.035/- 0.025 specified by the ring and Hydra-Set manufacturers. In addition, the ring was not flat but deformed slightly out of plane, see. Fig.5. The ring thickness was found to be 0.064 in., which agreed well with the manufacturer's specification of 0.062 +/- 0.003

Other then the "foot print" lines, the surface of the ring is relatively featureless except for one corner of one lug showing some evidence of scraping, as shown in Fig.6

Important observations:

- Free ring diameter is smaller than minimum diameter specified by the manufacturer
- Print marks are on both sides of the ring
- The ring is out of plane
- One corner of one lug is scraped
- No scratch pattern is found on the ring surface around the edges

Lower Head:

The lower head was visually inspected for possible damage or defects around and inside the inner groove. The groove edge that supports the axial thrust load was found to be sharp and free from any unusual marks. In one location, however the edge was deformed as shown in Fig. 7. In the same location one can see two vertical marks on the inside surface of the lower head bore. These marks extend all the way from the groove edge to the outside edge of the bore. In several locations, the groove bottom had some circumferential scratch marks, as shown in Fig.8

Also, groove dimensions were carefully measured on Mitutoyo Coordinate Measuring Machine BH 305. The groove bottom diameter was found to be 1.710 in. measured at 12 different points around the groove circumference, which indicated almost perfect circular uniformity. The bore diameter was found to be 1.620 in. Consequently, the groove depth was found to (1.710 – 1.620)/2 = 0.045 in. The groove width measured to 0.068 in.

Hardness readings taken on the lower head body resulted in an average Rockwell "B" value of 79 which is slightly below Brinell hardness of 149 given for a free cutting low carbon steel plate used for the lower head fabrication.

Important observations:

- Groove dimensions and uniformity were found to be well within the manufacturer's specifications
- Radius of the compression edge of the groove was sharp around most of the circumference
- In one location the edge was flared.
- Two vertical scratch marks located in the vicinity of the edge deformation.

Bushing:

Brass bushing was visually examined for possible defect and dimensional discrepancies, see Fig. 9. Examination revealed no unusual scratch marks around the bushing outer edge. The edge radius was about 0.016 in which is roughly four times smaller than the maximum corner radius of 0.064 in allowed by the ring manufacturer's specifications.

Important observations:

- Examination revealed no surface or dimensional anomalies of the brass bushing.

Piston Rod:

Examination of the piston rod revealed no abnormal features. The recess machined on the inner face of the piston assures, that the piston does not make physical contact with the brass bushing, see Fig.10.

STATIC COMPRESSION TEST

To better understand the behavior under load, of the retaining ring and other components inside the Hydra-Set, it was decided to perform a series of static compression tests. This testing did not replicate the exact hydraulic interaction between the components but did simulate the load carrying capacity of a partially and fully seated retaining ring under static load.

The investigation team felt that this testing would be beneficial in determining the ability of retaining rings in various states with regard to specification and groove insertion, to support static axial thrust loads. This, in turn, might lead to some clues as to what were the possible mechanisms of the Hydra-Set failure. The test schematic is shown in Fig.11. Table 2 below contains a summary of all static tests performed.

Table 2. Axial Compression Tests

Test No.	Configuration	Loads Applied	Results
1*	Retaining ring is partially seated. Both lugs are in the groove. No lubrication	470 lbs for 5 min. Unload and check the ring position. Reload and repeat two more cycles***	Ring did not come out. Remained partially seated.
2*	Retaining ring is partially seated. Only one lug is in the groove. No lubrication	Three 470 lbs/5 min cycles	Ring did not come out. Remained partially seated.
3*	Retaining ring is partially seated. Only one lug is in the groove. Lubricated**** with hydraulic fluid.	Applied one 470 lbs/5 min cycle Increased load to 1003 lbs.	Ring did not come out. Remained partially seated.
4**	Deformed retaining ring is partially seated. Only one lug is in the groove. Lubricated	Maximum load observed during ramping up portion of the first cycle was 25 lbs	Ring came out of the groove

5**	Deformed retaining ring is fully seated. Lubricated	After first cycle load was increased to 1000 lbs	Ring did not come out. Remained fully seated
6**	Deformed retaining ring partially seated. Both lugs are out, but the opposite side of the ring is in the groove. Lubricated.	After first cycle load was increased and reached 786 lbs.	Ring came out of the groove at 786 lbs
7	Deformed retaining ring is partially seated. Both lugs are in the groove. Lubricated.	After first cycle load was increased to 1000 lbs.	Ring did not come out. Remained partially seated.

Test notes:

* Tests 1 through 3 were performed with the used retaining ring removed from the fully operational 10,000 lbs capacity Hydra-Set (Model "C") which is almost identical in design to the failed Hydra-Set.

** Tests 4 through 7 were performed using the brand new ring that was deliberately over-compressed in a vice. It was also slightly bent out of flat. See Table 3 for ring dimensions.

*** One full cycle consisted of the load ramp to 470 lbs, 5 min dwell and ramp-down segments. It was estimated that 470 lbs was the force acting on the ring when the Hydra-Set is loaded to 3000 lbs

**** Lubrication with hydraulic fluid was used to simulate possible presence of the fluid in the inner groove of the Hydra-Set in service. The hydraulic fluid residue could have been left in the groove during unit re-assembly or possibly due to a small leakage around the seal

FREQUENT EXERCISE TEST

In addition to static compression testing, the Investigation Team also witnessed performance of a typical frequent inspection and maintenance test, performed on a Model "C" Hydra-Set. The purpose of this test was to determine if any rotation of the retaining ring or any other components in contact with the ring occurs during this monthly exercise. The position of the fully installed ring was marked relative to the lower head and the piston rod bushing. The unit was exercised by way of up and down motion with a 3000 lb test weight and rotation of the test weight to induce ring rotation in the groove. The ring position was inspected for any rotation and no relative rotation between the components was detected.

ANALYSIS

The average free diameter of the ring from the failed Hydra-Set was compared with the Hydra-Set manufacturer's specification as well as Waldes-Truarc company catalogue. In addition, the diameters of the over-compressed and the brand new, never used rings were measured as shown in Table 3.

Table 3. Average Free Diameters of the W-162 Retaining Rings

Rings Inspected	Ring from Failed Unit	Used Ring from Model "C"	New Ring Compressed Once	Over-Compressed Ring	New Ring, Never Compressed	Del Mar Avionics Drawing No. A5-5227, sheet 1	Waldes-Truarc catalogue
Average Free Diameter, inches	1.737	1.756	1.760	1.712	1.802	1.804 +0.035 -0.025	1.804 +0.035 -0.025

As indicated in Table 3, the Hydra-Set manufacturer's specification is identical to the ring manufacturer's catalogue value. From first glance it appears that the +/- tolerance given for the ring diameter is quite large. If we compare average free diameters in Table 3 above, to the specified catalogue minimum value of 1.779 inches (1.804 – 0.025), it becomes clear that the lower bound value of 1.779 exceeds the average free diameter of all rings used in the comparison with exception of a new never compressed ring. Even the diameter reduction due to the plastic deformation experienced by a new ring during its very first compression, results in an out of specification ring.

The Table 3 values for various rings, also confirms the ring manufacturer "Waldes – Truarc" assertion, that during the first compression cycle, the ring undergoes plastic deformation which reduces its diameter to some fairly stable value. According to the manufacturer, additional compressions should not significantly reduce this new diameter unless the ring is over-compressed during installation. The Model "C" ring in Table 3, was most likely compressed several times but changed very little from the once compressed value of 1.760 in. Whereas, the failed unit ring diameter of 1.737 was significantly less than the once compressed value of 1.760, indicating some degree of over-compression during one or more of its many installation cycles.

An additional factor with regard to ring usage is contained in the Ring Inspection section of the Waldes-Truarc catalogue. It states, that as long the ring average free diameter remains equal to or greater than the maximum groove diameter (interference fit), the ring is considered fully operative. Conversely, play between the ring and the groove after installation indicates that the ring has been over-compressed which may lead to application failure. The failed unit ring was verified to have an interference fit of approximately .030 in and yet could be rotated in its groove with very little resistance whereas a new ring installed in the same groove could not be rotated.

Comparing the lower head groove diameter of 1.710 with the Table 3 values, indicates that all rings remain operative per the manufacturer's definition, since their diameters exceed 1.710 in. This was proven by static test #5, Table 2, which was performed on a fully seated over-compressed ring. Test results confirmed that even this most out of specification ring was capable of supporting an axial thrust load of 1000 lbs when properly installed. This load exceeds the 470 lb. load experienced by the failed Hydra-Set. (A 470 lb. axial thrust force is acting on the ring when the Hydra-Set is loaded to 3,000 lbs).

It is important to recognize that the rings may be fully operative when subjected only to static loading conditions. However, for dynamic (sudden, impact or cyclic) thrust loads or relative rotation conditions, the performance and rated capacity of the rings may be diminished when the ring assembly is outside its dimensional specifications.

Let's consider dimensional characteristics of the lower head inner groove, the retaining ring and the brass bushing that came from the failed Hydra-Set. The ring free diameter 1.737 in (see Table 3) is outside the allowable range. The groove dimensions are well within the manufacture's specifications. The bushing abutting edge has no chamfer and its corner radius is well below maximum allowable (0.016 in << 0.064 in). Thus, neither the bushing nor lower head have any dimensional discrepancies that would downgrade the performance of the retaining ring. As far as the ring is concerned, it is very difficult to tell whether it had the diameter of 1.737 inches prior to the last re-assembly cycle or as a direct result of the ring deformation when it was forced out of the groove during this incident. In any case, since its diameter exceeds the groove diameter, this ring meets the criterion of fully operative one, providing that it is subjected to static loading only.

Failure due to a static or dynamic overload can be ruled out as a possible cause of the incident, since the failure mode under such conditions would be a fracture of the retaining ring or the abutting edge of the inner groove. Therefore, we should consider other conditions that may lead to Hydra-Set failure. One of these conditions is a relative rotation.

When the piston rod bushing rotates relative to and exerts thrust load on the ring, frictional forces will act on the ring body. This can cause the ring to "walk out" or otherwise unseat from its groove.

The ring manufacturer provides a formula to calculate maximum thrust load under rotation of:

$$P_{rr} \leq \frac{s\,t\,E^2}{\mu\,18\,S}$$

Where: $\boldsymbol{P_{rr}}$ = allowable thrust load exerted on the ring by the bushing, **s** is maximum working stress of ring, **t** is the ring thickness, **E** is largest section of ring; $\boldsymbol{\mu}$ is coefficient of friction between ring and the groove and **S** is bushing diameter. From the Waldes-Truarc catalogue, **s** = 250,000 psi; **t** = 0.064 in; **E** = 0.164 in; for $\boldsymbol{\mu}$ we can use 0.2 as given in the sample calculations in the catalogue and **S** = 1.5 in;

If we substitute the values in the formula, the allowable thrust $\boldsymbol{P_{rr}}$ can not exceed 80 lbs! This is rather low load considering the fact that the ring is subjected to about 780 lbs thrust when the Hydra-Set is under its maximum working load of 5000 lbs.

Since rotation of the piston rod can be transferred to the bushing only through the sealing O-rings, and the crane hook is equipped with the thrust bearing, it is not clear how any rotation of the load lifted by Hydra-Set can be transferred to its retained parts.

In fact, the Investigation Team did not observe any relative rotation as a result of the routine Hydra-Set maintenance test, which was performed for this very purpose.

Nevertheless, the calculation above does demonstrate that the retaining ring is very sensitive to any rotational movements of the retained parts, particular when Hydra-Set is under heavy load. The circumferential scratch marks observed in the bottom of the failed unit ring groove may be indicative of a relative rotation between the ring and the lower head, refer Fig. .... On the other hand these scratch marks could also have been caused by rotation of the ring during installation and/or attempts to rotate the ring within the groove to check for proper seating of the ring in its groove. The hardness difference between the ring and the groove material is so large that the ring can scratch the groove easily when it is manually rotated while fully seated.

Another condition that can cause the ring to slip out of the groove when the Hydra-Set is under load is incomplete or partial installation of the ring. It is possible to assemble the Hydra-Set with a partially installed retaining ring. The unit does not have any design feature that would prevent incorrect or partial seating of the retaining ring. It has been demonstrated by static test # 1,2,3 and 7 in Table 2, that a partially seated retaining ring can support static thrust loads as high as 1000 lbs.

It can be concluded, therefore, that depending on the Hydra-Set service conditions, a partially installed retaining ring may not fail or "walk out" of the groove on the initial loading cycle, but can continue to operate "normally" until loading conditions change (static to dynamic) or it slowly creeps out of the groove when subjected to sustained loads over a long period of time. The amount of axial static thrust load required to unseat a partially seated ring depends on how "badly" it is out of specification and in particular how much it is twisted out of plane. This was demonstrated by static tests # 4 and 6 in Table 2, which indicate that it might take as little as 25 lbs or as much as 786 lb. to force a partially seated ring out of the groove, depending on how much the ring is out of specification.

Since the components of the ring assembly were found to be intact with no evidence of physical damage, the Investigation Team believes that the ring became almost fully unseated prior to leaving the inner groove completely. It appears that only a corner of one lug was still keeping the ring in place when it finally was forced out of the groove during the last Hydra-Set exercise. Close examination of the abutting groove edge revealed a small flared portion of the edge and the two vertical scratch marks on the surface of the bore, as shown in Fig. 8 These features are consistent with the surface markings that would have been left by the retaining ring "walking out" of the groove with one of its lugs still partially located inside the groove. Most likely this was the lug that has some evidence of scraping action on the plated surface of one of its corners, as shown in Fig. 6.

Based on the results of this investigation we conclude either relative rotation and/or improper installation could result in the unseating of the ring. It is difficult to say with confidence what exactly caused the retaining ring to "walk out" of the groove. It was beyond the scope of the current investigation to perform a comprehensive study of the effects of rotation of the Hydra-Set under load, on the tendency to unseat the retaining

ring. Such a study would require a significant amount of time and effort to account for many possible combinations of loading conditions, static and dynamic etc. Instead, the Investigation Team felt it was more constructive to focus on prevention aspects and to make constructive recommendations to insure against future similar incidents.

The most important recommendation based on this investigation is the replacement of the retaining rings with new ones each and every time the Hydra-Sets are serviced and re-assembled. The new retaining ring should be included in the manufacturer's overhaul kit. In addition, ring replacement should be reflected in both, the Hydra-Set and the retaining ring manufacturer's literature and maintenance manuals. Furthermore, it would be very helpful to have some means of verification that the retaining ring is being fully seated every time the ring is replaced. A simple gage can be machined for this purpose as shown in Fig. ... . It is also important to avoid any relative rotation within the ring assembly when the Hydra-Set is under the load.

A great deal of information on properties of the retaining rings used in this investigation was taken from the Waldes Truarc ring catalogue, available on their web site.

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