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TO: John Mosich

FROM: Design Integration Dept.

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ABSTRACT/SUMMARY

The qualification test results for the RMS End Effector (EE) are compared to the specification to which the EE was designed and to the test plan for verifying conformance of the EE to the specification. Significant differences exist, but only the most important are discussed. The EE performance in the qualification test program has had several anomalies, including component failures and replacements, complete jamming, and revised test standards. The qualification test was not re-run after each failure, as is normally required, but continued as if the failure did not occur. When the EE jammed during rigidization, the test was shortened to that amount of equivalent usage. A structural loading test, the final test requirement, was accomplished after partial disassembly, cleaning and replacement of the dry lubricant with a wet lubricant on the ball screws. The EE functioned adequately, but failed to meet the criteria for interface separation at the preload condition. The EE qualification test record does not validate compliance to its performance requirements, but indicates, instead, that the EE has failed to operate successfully in its specified environment.

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INTRODUCTION/BACKGROUND

Canada developed the Remote Manipulator System (RMS) under an agreement between the National Research Council of Canada (NRCC) and NASA. Spar was the prime contractor to NRCC for the Design, Development, Testing and Engineering (DDT&E) of the first flight system, including the qualification models. The RMS comprises a fifty foot Manipulator Arm (MA) with six joints, six degrees of freedom and an End Effector (EE) for grappling and connecting to payloads. Aerospace representatives were invited and attended Spar's presentation of the End Item Data Package (EIDP) for the Flight EE, 7 - 9 July 1981. The EIDP was the first opportunity to receive and discuss detail information about the design and development of the EE, the background, the anomalies and changes that led to the current configuration, which is significantly different than the Engineering Model EE. The Qual EE was being tested simultaneously with the manufacturing of the Flight EE because of the tight delivery schedule. Since the qualification test was not completed, the Flight EE has been flown on the Orbiter based on a flight-by-flight acceptance by NASA.

NASA has scheduled 3 November 1982 for the Operational Readiness Review to formally accept the RMS including its EE. Review Item Dispositions (RID) have been submitted to NASA JSC for formal review and discussion of concerns relative to the design and performance of the RMS, including the EE. The Data Review Meeting at Spar began the RID review. A Joint Review Board sanctioned the RID actions. The Air Force requested additional information regarding the RID actions and the rationale for their disposition. During the discussions at JSC, concerning the EE anomalies and the irregularities of the EE qualification, NASA requested a memorandum to summarize the EE qualification test failures. This memorandum discusses the major inadequacies observed by the Design Integration Department during the EE qualification program.

QUALIFICATION TEST DISCUSSION

The Acceptance Test is established to insure functional performance, proper manufacturing, and correct configuration. The Qualification Test (QT) is the formal demonstration that the design, manufacturing, and assembly have resulted in the EE conforming to the specification requirements. If a malfunction occurs during the QT, repairs and replacements are made and the test should begin again. Spar followed these guidelines initially in the EE QT program, as indicated by the three beginnings for the EE QT-- 3 March, 17 August, and 17 November 1981-- when various malfunctions required EE repairs. (Refer to TABLE I. for the complete QT chronology and note that the 24 August failure was for complete jamming of the ball spline. New assembly alignment jigs and fixtures were part of the solution to prevent future ball spline jamming.). Since the last QT beginning, 17 November, Spar has deviated from these QT guidelines. Failures have occurred and repairs have been made, but the QT was continued rather than starting over. Failures and repairs that occur during a QT are not a demonstration that the EE will conform to specification requirements, but rather an indication that the EE will fail. Some wear can be expected from the QT, but breakage, jamming, deformation, or corrosion damage are serious malfunctions that indicate a design change is required and improvements should be made to the EE.

CHANGES MADE DURING THE QUALIFICATION TEST

After 10 mission-equivalent vibration tests (subsequently redefined as 15 missions in the Z-axis) and a humidity test, the Qual EE jammed during rigidization. A squeaking noise, which preceded the jam, signalled a loss of lubricant in the ball screws. Disassembly of the EE was required to free the mechanism. The inspection during the disassembly disclosed that after the 10 mission-equivalent test, five bearings had cracked severely, the snare drive spur gear teeth were severely worn, gear debris covered exposed gears and bearings, and significant corrosion contamination had occurred. Spar-T.256, page B-19 states:

> "It was decided to correct the most severe anomalies. The test was stopped and the guide bearings (were) replaced, corrosion was removed from the ball screws and snare cables and the (bearing) track indentations were blended out. The unit was reassembled and the QVT was continued."

Three major points can be surmised at the end of 10 missions of the QT:

(1) Several significant failures had occurred, but parts were replaced and the QT continued. Consequently, one set of hardware did not function throughout the QT.

(2) Since no internal inspection was conducted during the 10 mission test, it cannot be determined when each failure occurred.

(3) With the EE in such unsatisfactory condition at 10% of its expected life, can an RMS user have confidence that the RMS will last even 10 missions.

Ball screw jamming occurred again when the QT was continued and disassembly to free the mechanism was again required. This occurred between 54 and 80 mission-equivalent cycles at the reduced vibration test level in the Z-axis only. At this time, the dry lubricant on the ball screws was replaced with a wet lubricant so that an additional rigidization could occur to complete the final QT structural load test. The QT was terminated at this time, after 80 missions. The original goal of 100 missions could not be obtained, even with refurbishment and new hardware.

DRY LUBRICANT FAILURES

The dry lubricant, Lubeco 905, has been the contributor to several major failures of the EE during the QT. Dry lubricant is not recommended by the manufacturer of the ball screws or the ball spline. Spar has recognized the same problem on ball bearings, and in the EE has replaced Lubeco 905 with

Braycote 3L-38RP, a wet lubricant, on the high speed motor bearings and the highly loaded, low speed, snare drive bearings. (Braycote was not approved for space applications at the beginning of the EE design, when Spar wanted to use a wet lubricant.)

TABLE II summarizes the major failures in the EE during the QT. The jamming of the ball screws, both times, is directly related to the break down of Lubeco 905. Further, Lubeco 905, has contributed to the extreme corrosion damage and related contamination during a relatively mild humidity test. (Ten days at room temperature in 95% humidity using distilled water.) Spar's Materials Group, page B-20, Spar-T.256, states:

> "The report concluded that the severe humidity environment adversely affected the dry lubricant causing break-down. The active chemical compounds formed by the break-down were sulphurous/sulphuric acid and molybdic acid these compounds attacked the metal causing the corrosion noted. Additionally, the corrosion indicates a reduction of lubricant which would explain the erratic rigidizing performance noted."

The dry lubricant significantly increases the corrosion damage in the EE. Changes should be made to the EE to reduce or eliminate corrosion damage from such a mild test environment. Corrosion damage continues with time, and it is reported that the clevis pins in the cable end fittings of the Qual EE cannot readily be removed because of the corrosion bonding. This effect was undoubtably a contributor to some of the last QT failures for the snare cables not returning to their grooves. RID 04.06.04 reduced the importance of the cables not returning to their grooves, but the loss of lubricant in the cable fitting will eventually cause the cable to stick out in the EE, which is not acceptable, even by the RID action.

VIBRATION TEST PSD MODIFICATION

The proper vibration tests Power Spectral Density (PSD) criteria for the acceptance test and the QT is difficult to establish, requires careful consideration during the hardware design, and often leads to controversy. There is an accepted approach to this problem, however, based upon using a mathematical "model" to establish a simulated replica of the actual hardware, and for comparing its response to a specific hardware test. Validation of the math model requires close correlation of the output response frequencies and response curves produced from the math model, to corresponding curves produced from the test hardware, when each are excited by the same input criteria. For the RMS and EE, this process was followed by using test data from Rockwell International for establishing the vibration input and using a math model Spar generated for establishing the RMS response. From this sequence of calculations, a PSD of 0.8 g^2/Hz was established for the EE design criteria and test requirement. Testing the EE at this condition for 10 mission-equivalent, or 10% of its life, and a humidity test, caused complete jamming, gear wear, broken bearings, corrosion damage, and a "loosened" mechanism. The EE, as designed, was unable to withstand this environment. Subsequently, Rockwell performed a vibration, test using the engineering model manipulator arm mounted on the Manipulator Positioning Mechanism (MPM), and forwarded the information to Spar. When Spar used this new information to refine the PSD criteria for the EE QT, they did not adjust their math model of the manipulator arm to match the Rockwell test results. The elimination of this mandatory step, invalidates all subsequent calculations and modifications to the PSD test criteria. Proper validation was not done as confirmed by Spar-T.256, Issue B, page B-51, which states:

> "Correlation with the test data was not good. It corresponds to about 3% damping. High frequency (> 120Hz) cannot be compared due to limitations of the finite element model; no low frequency (<40Hz) data was provided by RI. Thus the comparable range is small, even within this range the natural frequencies do not match the RI data. The 'average' peak Q's in each axis were 6.07 in test data and 5.67 from the finite element model for damping of 3%. However, individual values range considerably."

Note: The finite element model is the "math" model, and the underlining is by the author.

Additional iterative modification to the finite element math model must be done to match the MPM test results. Poor correlation between corresponding data, and natural frequencies which do not match, does not provide a proper basis for refined calculations. Individual peak "Q's" must be matched and averaging "Q" values should not be done. The PSD of $0.8g^2/Hz$, originally established, is probably too high, but the new value of $0.02g^2/Hz$ seems too low. The ground handling criteria for the RMS uses a PSD of $0.067g^2/Hz$. Certainly the Orbiter vibration environment during launch is more severe than the ground handling environment.

To establish the proper test criteria for the EE, the math model that Spar developed must be validated by close correlation of shape and frequency, to the MPM test results from Rockwell. A damping factor thus obtained can be used to calculate the revised PSD criteria for the EE QT.

EE FAILURE DISCUSSION

TABLE II summarizes the major EE failures which occurred during the QT. TABLE III presents a list of parts replaced, and TABLE IV, the failures which occurred during the QT since the last restart, beginning, 17 November 1981. Even after reducing the vibration PSD criteria with an invalid math model and testing in the Z-axis only, significant failures occurred. The EE mechanism bound during rigidization, the snare cables did not return to their grooves, and the rigidization signal flag failed. These malfunctions accumulated between 54 and 80 missions. TABLE V, page A-39, Spar-T.256, which is included to summarize the EE condition at this time, shows the statement "No corrective action is required". This statement does not seem appropriate after the series of severe malfunctions which had accumulated. TABLE VI, page B-41, Spar-T.256, further confirms the continual degradation which occurred. Clearly the dry lubricant breakdown is a contributing cause for many of the malfunctions. Spar's Materials Group documents the dry lubricant failure on pages B-20, and page B-21, Spar-T.256, documents that repetitious and continual degradation of the dry lubricant on the ball screws occurs. The dry lubricant, Lubeco 905, is not satisfactory for application on the ball screws, ball spline, and cable end fittings. The EE was disassembled, cleaned, and the dry lubricant removed from the ball screws; wet lubrication was added to the ball screws to allow rigidization. Rigidization of the EE was required to perform the cross axis test, which was required to verify the structural integrity. During the cross axis test, the EE failed to meet the test criteria for separation at the preload condition. (Page C-4, Spar-T.256) This is a poor record of performance that is compounded by the fact that the failures, replacements, disassembly etc. were part of a continuing QT, where even the sequence of the test phase, during which the failures occurred, was not rerun.

The most critical gear tooth contact in the EE-- the snare pinion to quadrant gear-- was worn significantly during the first ten mission-equivalent test. The gear teeth contours were changed in shape from the wear, and the gear particle debris covered adjacent components. The degraded condition of the EE was found by observation during the disassembly which was required to free the first ball screw jam. The first jam occurred on 12 January 1982, at Spar, after the 10 mission-equivalent tests and the humidity test. Since the gear wear debris was not directly related to the ball screw jam, (gear wear debris can easily jam the ball screws, however in this specific test, gravity caused the debris to fall on the gears mounted on the base plate), and the capture mechanism continued to function, the gear wear was not considered a failure. However, such significant wear, so early in the mission life, is of concern and the cause should be determined so changes can be incorporated to prevent excessive wear and subsequent failures.

The failures and malfunctions which have occurred during the QT are normally found during a programs development testing. A development test model of the EE was not made; the EE program skipped from a engineering model, through a major design concept change, directly to the Qual model EE. Development problems are normal, should be expected, and should be resolved as they occur. In this case, these failures were disclosed during the QT. In effect, the Qual EE was the development model, however design changes to reduce the failures have not been implemented, nor has re-testing been performed to verify that the design changes will prevent the failures.

TEST CRITERIA DISCUSSION

Design margins for the Acceptance Test and QT are extremely important to establish credibility for the EE and validity for the QT. An environmental design margin is an increase in the environmental range used to establish the EE design and to be verified by the QT. The environment design margin is intended: (a.) To accommodate differences among qualification and flight units due to variations in parts, materials, processes, manufacturing, testing, and degradation during useage; (b.) To incorporate the allowable test condition tolerances; (c.) To recognize that the QT is a series of singular tests applied sequentially, where the operational environment occurs simultaneously. Wear, breakage and failures are an indication that the environmental design margin has been violated and the expected life in the operational environment will be less than the life achieved in test. Design changes to the EE are required for it to meet the specification. These changes should be accomplished and the QT performed on the modified EE to validate successful hardware operation in the specified environment.

CONCLUSION

The EE Qualification Test has not demonstrated conformance to the specification requirements, but has shown instead that the EE has a significant probability for random failures, may jam in operation, is susceptible to humidity, has limited life components and is a high risk to abort payload operations on an Orbiter flight. For proper qualification, a modified EE must be tested to validate successful hardware operation in the specified environment. The QT test criteria must be correctly refined, with slight margins above the expected operating environment, to establish the test conditions for the EE QT. Page B-1, Spar-T.256 states:

> "Because of the complexity and the number of modifications and re-tests to which the end effector was subjected, a 'clean' QT program was not obtained. However, the consensus reached by NRCC and JSC projects offices was that the end effector was qualified with the acceptance of certain inspections and preventative maintenance actions."

Significant deviations from a normal qualification procedure have occurred during the EE program. Many anomalies and several complete failures occurred. Reducing the operational requirements of the qualification test to the level achieved prior to failure does not provide confidence that a second EE will perform the same way. The record indicates that another EE will also fail. Design changes can improve the EE and several should be implemented. Verification of the End Effector qualification is still required.

REFERENCES

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