AD-768 343

UNITED STATES ARMY HELICOPTER ROD END BEARING RELIABILITY AND MAINTAINABILITY INVESTIGATION

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Systems Associates, Incorporated

Prepared for:

Army Air Mobility Research and Development Laboratory

June 1973

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1a

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AD 768843

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Systems Associates, Inc. 444 West Ocean Boulevard Long Beach, California	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

U.S. ARMY HELICOPTER ROD END BEARING RELIABILITY AND MAINTAINABILITY INVESTIGATION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Sheldon Dockswell
James L. Huffman

6. REPORT DATE June 1973	7a. TOTAL NO. OF PAGES 118 / 123	7b. NO. OF REFS 82
8a. CONTRACT OR GRANT NO. DAAJ02-71-D-0003 b. PROJECT NO. Task 1F162205A11906 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAMRDL Technical Report 73-35 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) Systems Associates, Inc. Report 73-012	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Eustis Directorate U.S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia

13. ABSTRACT

This investigation was carried out to identify, isolate, and verify the causes of problems with rod end bearings (REB) used on U.S. Army helicopters and to trace the resulting effects on helicopter availability. Design requirements, quality assurance provisions, maintenance procedures and practices, test requirements, and procurement practices were analyzed to assess their impact upon the current problems.

Excessive play between ball and race was found to be the REB's chief failure mode. Design does not adequately contend with a vibratory environment which tends to cause widening of the race. Quality assurance was neither imposed upon the bearing vendors nor demonstrated by airframe manufacturers. A recommendation was made for a specification to be developed to govern existing or new designs, which include a stainless steel ball with a ceramic coating and a graphite race, a slotted spherical bearing, and an elastomeric spherical bearing. The recommended specification for helicopter REB's includes bond and material integrity, loading, vibration, dust, misalignment angle, qualification and conformity requirements.

Specific recommendations for improvements to the policies, practices, and procedures are made in the report; hardware improvements are also discussed.

DD FORM 1473 1 NOV 65

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Bond and material integrity						
Ceramic coating						
Conformity						
Dust						
Elastomeric spherical bearing						
Graphite race						
Excessive play between ball and race						
Loading						
Misalignment angle						
Qualification						
Slotted spherical bearing						
Specification development						
Stainless steel ball						
Vibration						

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DEPARTMENT OF THE ARMY
U. S. ARMY AIR MOBILITY RESEARCH & DEVELOPMENT LABORATORY
EUSTIS DIRECTORATE
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This report, on helicopter rod end bearings, was prepared by Systems Associates, Incorporated, under the terms of Contract DAAJ02-71-D-0003, Delivery Order 0002. It presents a discussion of the basic or underlying causes of reliability and maintainability (R&M) deficiencies that have been found to exist in rod end bearings used in Army helicopters in the current inventory. Included in the report are discussions of the impact of design requirements, test requirements and procedures, quality assurance requirements and procedures, maintenance practices and procedures, training of maintenance personnel, and lagging technology upon various failure modes that are prevalent in rod end bearings. Also discussed is the influence of past Army procurement policies and procedures upon the basic causes of R&M deficiencies.

Results of this effort and other similar efforts have been used by this Directorate as a basis for initiating R&D programs to evaluate and recommend changes to design requirements, test requirements and procedures, and quality assurance provisions for flight control, hydraulic, electrical, and fuel systems and components.

The project engineer for this effort was Mr. Richard I. Adams, Military Operations Technology Division.

Task 1F162205A11906
Contract DAAJ02-71-D-0003
USAAMRDL Technical Report 73-35
June 1973

U.S. ARMY HELICOPTER ROD END BEARING RELIABILITY AND MAINTAINABILITY INVESTIGATION

Final Report
Systems Associates, Inc. Report 73-012

By

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SUMMARY

This investigation was carried out to identify, isolate, and verify the cause of problems with rod end bearings (REB) used on U.S. Army helicopters and to trace the resulting effects on helicopter availability. Design requirements, quality assurance provisions, maintenance procedures and practices, test requirements, and procurement practices were analyzed to assess their impact upon the current REB problems.

Presently used swaged race designs are not fabricated in a manner which permits them to contend with the U.S. Army helicopter operational environment. These swaged races tend to move away from the spherical ball when used in the vibratory environment induced by helicopters. The result of the combination of this swaged design approach and the helicopter vibratory environment is excessive play between the ball and the race.

Quality assurance provisions were not formally imposed upon the bearing manufacturers by the various helicopter airframe manufacturers. Consequently, their procurement practices and the handling and processing of REB failure data also contribute to their inefficacy. Rod end bearings are replaced in the same manner as a nut or a bolt; therefore, their removal and replacement are not tracked in the U.S. Army Maintenance Management System (TAMMS) computer printouts. This situation with TAMMS exists in spite of the fact that these removals and replacements are recorded on Maintenance Request Forms (DA Form 2407). Computer printouts are kept only for those REB's that contribute to helicopter safety-related problems.

Design recommendations include the use of a stainless steel ball with a ceramic coating and a graphite race, a slotted spherical bearing, and an elastomeric spherical bearing. U.S. Army helicopters should have all military specification REB's installed as replacement parts as soon as nonmilitary specification inventory REB's are depleted. The specifications that control these bearings should include bond and material integrity, axial loading limits, radial loading limits, vibration, dust, misalignment angle quantification, and conformity requirements. Maintenance inspections must be performed more frequently for high-load bearings located near the rotors. All control linkage bearings and pitch change links should have acceptable tolerances included for dial indicator measurement. Sudden trends toward unswaging should be grounds for investigation and replacement of the REB.

Helicopter REB qualification should not be in the nature of endurance testing without maintenance. Normal maintenance and inspection of control linkages should be made periodically. This assures that failure of an REB will not create a cascade effect nor be masked in this if it does occur. Acceptance of helicopter REB's must be based upon contractual criteria that are detailed enough to require rejection if an airframe manufacturer fails to use parts from a qualified product list.

Failure to document and certify receiving inspection sampling and REB installation on each helicopter should also be cause for helicopter rejection. Data gathered during this study indicated that no quality control procedures, specifications, or recorded results were presently being used. It is strongly recommended that REB vendor and airframe manufacturer quality control, qualification certification, and conformity sampling results be contractually required on every helicopter procurement.

A cost model and related cost data are presented for current and proposed REB designs. This model shows that substantial maintenance-related cost savings can be realized by using recommended improved bearing designs.

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INTRODUCTION

This investigation was performed to establish the basis of problems currently being experienced by the U.S. Army on their current-inventory helicopter REB's. This report describes the various study activities that were performed with the primary intent of isolating the basic causes of existing failure modes. These activities covered data acquisition and analysis, failure modes and effects analysis, analysis of requirements, practices and procedures, recommendations for improvements in documentation and hardware, and cost savings that can be anticipated as a result of implementing the various design improvement recommendations.

Early in this investigation it became apparent that a great many similarities existed in the REB failure modes of various types of Army helicopters. Consequently, the UH-1H REB's were used as the baseline design upon which this investigation was performed. This adoption of a baseline design does not in any way bias any recommendation presented. Therefore, all the revisions and solutions presented can be considered applicable to all current-inventory U.S. Army helicopters.

The following listing contains sources of the data used in this investigation:

1. U.S. Army Agency for Aviation Safety (USAAAVS) reports
2. Reliability and Maintainability Management Improvement Techniques (RAMMIT) reports
3. U.S. Army Aeronautical Depot Maintenance Center (ARADMAC) reports
4. Navy Maintenance Material Management (3M) data
5. Failure Rate Data (FARADA) Handbook for Helicopter Equipments
6. Long Beach National Guard Rotary Wing Facility, Long Beach, California
7. New Cumberland Army Depot, New Cumberland, Pennsylvania
8. Forty-Ninth Aviation Battalion, Stockton, California
9. Federal Aviation Administration (FAA), Oklahoma City, Oklahoma
10. U.S. Army Aviation Test Board, Cairnes Army Air Field, Daleville, Alabama

Failure modes and effects analyses (FMEA) were performed on the lubricated and tetrafluoroethylene (TFE)-lined type REB. Failure modes, the associated probable failure causes, and failure effects on the REB, next assembly, and helicopter were developed in this analysis. Also, design/maintenance compensating provisions and recommendations were made in the FMEA relative to each failure mode.

Failure causes determined from the FMEA were used to assess the adequacy of design requirements, quality assurance, maintenance, and testing. Design requirements cover specification control documents and drawings, component selection criteria, military specifications and standards, design requirements to eliminate induced failures, and contract specifications. Quality assurance provisions include discussions on vendor manufacture quality control and shipping inspections, airframe manufacturer receiving inspections, initial installation procedures, functional test procedures, mandatory inspection points, and component sampling procedures. Maintenance procedures and practices investigated were categorized by maintenance manuals, periodic inspections, shelf-life considerations, failure criteria and detection, maintenance personnel skill level, qualifications and training, special tool requirements, and component accessibility. Test requirements and procedures were analyzed in terms of environmental tests and procedures, systems compatibility testing requirements and procedures, qualification test requirements and procedures, flight test plans and procedures, service test plans and procedures, and acceptance test procedures and results.

A cost model was developed to predict costs incurred by REB failures as a function of unit cost, installation time, labor costs, mean time between failures, and fleet size. Existing and proposed REB designs are compared using the model to determine costs. Revisions and solutions are presented for changes in documentation and hardware in each of the areas within the Requirements, Procedures, and Practices section.

FAILURE DATA COMPILATION AND ANALYSIS

Although a wide spectrum of data sources were contacted and visited during the course of the REB study, very little quantitative data were available for analysis. In nearly all cases, failures of REB's did not constitute sufficient justification for failure reports to be prepared. The cost of an individual REB does not put it in the category of those "condition" items for which historical feedback information is normally required. In terms of data quantity and generic applicability to the problem, the FAA Regional Malfunction or Deficiency (M or D) Trend List was the most productive source of information. However, most of the FAA failure data pertaining to aircraft do not include items in the Army inventory. The following paragraphs present the REB failure data which were obtained during the course of this study, and their sources.

RELIABILITY AND MAINTAINABILITY MANAGEMENT IMPROVEMENT TECHNIQUES (RAMMIT) ANALYSIS

The UH-1H, AH-1G, and CH-47 RAMMIT reports were used as potential sources for identifying and reducing failure data. The two types of RAMMIT reports investigated during this analysis are as follows:

1. Aircraft Component Time Since Installation, Overhaul or New (ACTION) reports
2. Major Item Special Studies (MISS)

Aircraft Component Time Since Installation, Overhaul or New Analysis

Three ACTION reports (UH-1H, AH-1G and CH-47) were analyzed during this investigation. The period covered by each ACTION report ranged from 1 January 1964 through 30 June 1971. The type of data in the ACTION report structure usually provides a rationale for removal in terms of Failure Mode (FM), Time Since Last Installation (TSLI), Time Since Last Overhaul (TSLO), and Time Since New (TSN) for each part number. Information for the ACTION reports is extracted from applicable portions of Component Removal and Repair/Overhaul Records (DA Form 2410).

DA Form 2410 is used to provide installation, removal, overhaul, operating time, and control information for reportable aircraft components and parts. The components/parts included under the 2410 reporting system are time-change items. Time-change items include both finite life and time between overhaul. These items are removed from service for overhaul or retired after specified periods of operation because of design limitations and/or safety. Certain condition-change items are reported upon because of their high cost or a need for intensive management. Selected-condition items are those which are removed from service when their condition becomes unserviceable and historical feedback information is required for effective management.

Major Item Special Study Analysis

The MISS reports analyzed during this study were considered to be representative of all MISS reports. The period covered in each report ranged from 1 January 1964 through 30 June 1970.

As with the ACTION reports discussed above, data for REB's are not extracted from the applicable DA Form 2410's or other similar maintenance forms. Consequently, no meaningful data pertaining to REB failure causes or frequency of failure were found in them.

RAMMIT Analysis Conclusions

Technical Bulletin TB JJ-1500-307-25, entitled "Aircraft Components Requiring Maintenance Management and Historical Data", does not designate REB's as time-change or condition-change items. This lack of a specific requirement for maintenance management information is considered the basic reason for the nonexistence of REB data in the two RAMMIT reports previously described. This situation of not processing REB data exists even though the RAMMIT failure code index makes provisions for "failed rod end bearings" with a 710 code number.

These RAMMIT failure data clustered around two distinct Mean Time Between Failures (MTBF): 330 hours and 2700 hours. Further analysis of this phenomenon showed that the 330-hour MTBF bearings were those that were used in high radial loading applications. The 2500-hour MTBF bearings were those that were used with low radical loading applications.

NAVY 3M DATA

Navy 3M data from the Maintenance Support office at Mechanicsburg, Pennsylvania, were also examined. The format used did not include material failure causes for subsystem components. Reports that track failure modes for specific end items are generated locally at certain user organizations. For instance, such data were being generated at the Marine Corps Air Facility, Santa Ana, California. However, the data did not contain suitable information for the present analysis. The 3M system reports on both mechanical and electrical/avionics failures with the emphasis placed upon avionics failures. The mechanical-type REB data required for this analysis were not present in the 3M data inspected during this investigation.

FAILURE RATE DATA PROGRAM

The Failure Rate Data (FARADA) Handbook for Helicopter Equipments published by the Naval Fleet Missile Systems Analysis and Evaluation Group contains only one entry relating to REB failure. This datum, involving the failure of a transmission push rod end bearing, does not provide a sufficient basis for a meaningful failure analysis.

MANUFACTURERS' FAILURE DATA

Bell Helicopter

There are indications that sufficient raw data pertaining to REB's exist at Bell Helicopter. However, these data have not been processed into a meaningful format due to Bell funding restrictions. Therefore, no data pertaining to REB's installed in Bell helicopters were available for this analysis.

Boeing-Vertol

Rod end bearings used for the CH-47 are procured, according to a Boeing specification, from outside vendors. Source inspections are vigorously pursued by the bearing vendors. One bearing out of every lot of one hundred is tested to destruction. Measurements are conducted upon the concentricity of the bearing to the race. On lined bearings, the uniformity of the lining is checked. Bond integrity tests are also performed on all bearing linings. All failure data obtained from these tests represent only quality control problems. These data cannot be used to postulate performance data because the bearings' predominant failure mode in operational use is excessive play due to cold flowing of the liner between the spherical ball and the outer race.

In-service failure data were available on only three types of REB's--all of them connecting links in the rotor control subsystem. For one of these items, only one failure had been documented; for the other two, 14 and 25 failures were documented. Operating times were not recorded. These few data points were considered insufficient to make any meaningful analysis and/or conclusions.

Sikorsky Aircraft

Only a small amount of failure data was available on REB's for the CH-54, A and B Models. The tabulated data supply only component time, failure rate, and maintenance man-hours, with no indication of failure mode. Verbal information indicated that the basis for most failure reports was excessive play in the bearing. Very often the data forms were not completed accurately and the failure cause was undefined. This made interpretation of these data difficult, and meaningful conclusions could not be drawn.

Hughes Tool Company

Although no recorded failure data were available at Hughes, some general information was obtained on failure modes. Most of the REB's for both the OH-6A and TH-55 are of the TFE-impregnated fiber design. In some areas, such as those close to the engine, metal bearing rod ends are used for heat-sink purposes. These are of two basic designs: the permanent dry film lubricated type and the zerk grease fitting type REB.

The TFE-impregnated fiber bearings are manufactured with various types of fiber. The use of these was necessitated by the variation in applied loads. The main problem associated with this type of bearing is that the excessive load forces can eventually be applied in several different ways. The predominant causes of load increases are as follows:

1. Upgrading of the airframe. This upgrading usually takes the form of a substitution of a larger horsepower engine. This higher output engine increases helicopter performance and the various loads applied to the airframe.

2. Use of the helicopter beyond its originally specified design flight environmental and use envelopes.

The REB designs are usually not changed to correspond to increase the applied loads caused by either 1 or 2.

Excessive loads cause elongation of the bearing housing and cold flowing of the TFE substance. This cold flow results in an increase of play to accelerate wear of the bearing and TFE surfaces. When hydraulic actuators are attached to the rod, the bearing can receive the equivalent of many times the actual flight hours because of actuator dither induced by rotor shaking forces being transmitted to it from the rotor through the flight controls. This is also applicable to straight mechanical systems, but to a much lesser degree.

The permanently lubricated REB also has inherent problems associated with it. The service life of the bearing is not adequate when the bearing is subjected to the environment and vibration found in current-inventory helicopters. Steps have been taken at Hughes to relubricate these bearings by applying high-pressure grease under the bearing surface. The results to date have not been sufficient to make concrete evaluations of this relubrication process of permanently lubricated REB's.

The REB that can be greased is adequate only if maintained in accordance with the preventive maintenance schedules. Lack of sufficient attention coupled with the tempo of combat operations, inaccessibility of the bearings that require frequent lubrication, and the ingestion of solid contaminants into the bearing causes REB failures. The result is lack of grease and/or contamination of the bearing and race surfaces, with excessive surface wear and premature failure. No data were recorded on the rates of failure for any of these bearing types, nor were the actual failure modes documented or quantified. Except for the general but undocumented observations previously mentioned, no quantitative data were available for any meaningful analysis.

FIELD DATA

U.S. Army Aeronautical Depot, Corpus Christi, Texas

The U.S. Army Aeronautical Depot, Corpus Christi, Texas was visited in an attempt to acquire REB data. However, REB use data were not available because all helicopters scheduled for overhaul at this facility were completely disassembled without checking any parts. The various part types are checked and/or rebuilt prior to reassembly or installation in the helicopter.

Seventy-Sixth Aviation Group, Long Beach, California

The REB's used on the UH-1C's at this facility are the spherical type which require periodic greasing. This type of bearing is constructed with a larger clearance between the ball and the race than the self-lubricating or TFE-lined bearings. The larger clearance is required to provide room for the grease. (See Figure 1.)

Detail (b) of Figure 1 graphically demonstrates that as bearing rotation occurs, the grease-coated portion of the ball is exposed to contaminants. This exposed grease-coated surface tends to retain dust particles and ingest them into the area between the ball and the race; thus contaminants are ingested when the ball rotates back to its original position. These dust particles build up and act as an abrasive, causing accelerated bearing wear. The bearings were being replaced after 100 hours, on the average.

New Cumberland Army Depot, New Cumberland, Pennsylvania

New Cumberland Army Depot overhauls CH-47 helicopters; however, no failure data are initiated or collected at this facility. During this visit only verbal information was conveyed, the essence of which indicates that the replacement rate on CH-47 flight-control REB's "approaches 100 percent," primarily because of excessive play in the various REB's.

Forty-Ninth Aviation Battalion, Stockton, California

This facility was contacted to discuss maintenance practices, procedures, and manuals for the CH-47 helicopters, the transition to which was made in 1971. This is a California National Guard unit, the majority of whose maintenance personnel are ex-regular Army with Vietnam experience.

The personnel interviewed indicated that they had attended the Fort Eustis CH-47 school. The curriculum there was, they felt, too short to train

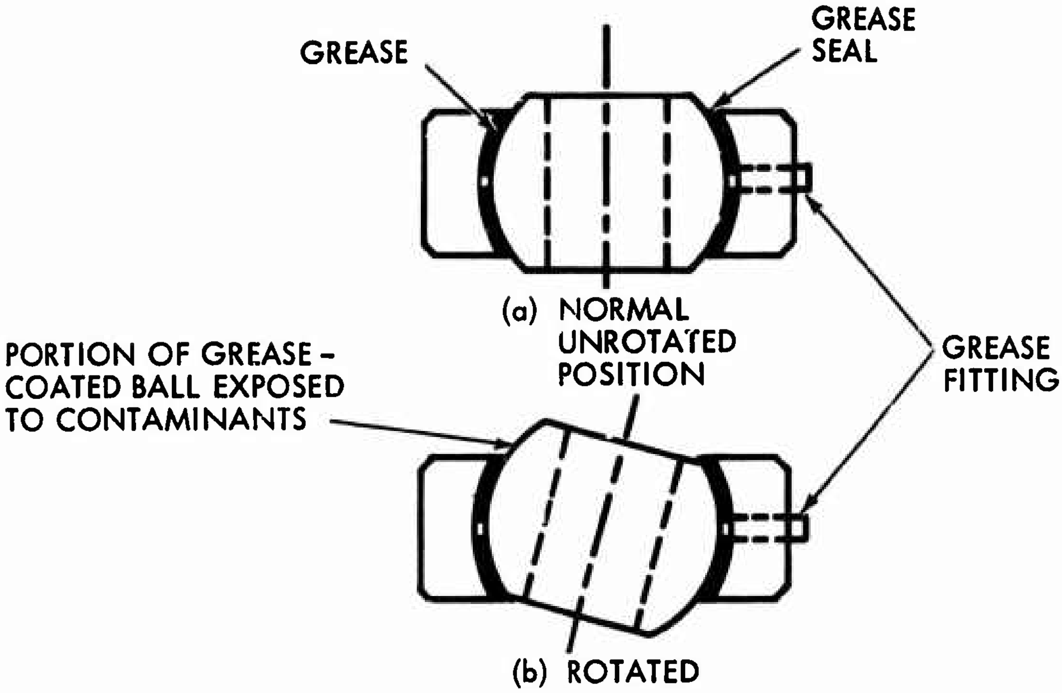


Figure 1. Periodically Greased Type Bearing.

even experienced maintenance personnel in all of the required trouble-shooting, removal, replacement, and repair and rigging procedures. Also, too much time of the already shortened course was devoted to TAMMS procedures, which, though necessary, should be taught as the subject of another short course for those who require it.

The discussion of failure problems and trends of REB's for the engine control and flight control systems revealed that those that are TFE lined have not, for the most part, caused problems. As has been the case on other types of helicopters, the REB that can be greased has had a higher failure rate than the TFE-lined bearings. Problems with cold flow and separation have been noted in the past, but recently this has not been a problem. Supplier quality control procedures reduced this problem to tolerable limits, personnel contend.

Federal Aviation Administration

The FAA Aeronautical Center in Oklahoma City was contacted in an effort to obtain REB failure data. This center publishes a Regional M or D Trend List, Report No. RIS:FS8330-13, on all failures reported on civilian aircraft. The FAA maintains these M or D data by aircraft model and series type. Air Transport Association coding is used to describe all the aircraft subsystems. All FAA data relating to the civilian Bell 250 (UH-1) were obtained and analyzed. This data source identified worn bearings (excessive play) as the predominant failure mode. The flight times on excessively worn bearings ranged from 107 hours to 418 hours.

U.S. Army Agency for Aviation Safety, Fort Rucker, Alabama

At USAAAVS, various problems are being experienced with the large Uni-ball that is located at the base of the UH-1H actuator tube. The new races are being received with dry film lubricant, which wears out in a very short time and thus results in a high rejection rate. A possible solution to this problem is the use of a stainless steel ball coated with hard ceramic with a graphite outer race. As discussed in the Solutions section of this report, this solution is equally applicable to the REB.

Copies of USAAAVS computer runs, dating from October 1969 to March 1972, were reviewed for information pertinent to REB failures. Less than ten failures were documented.

U.S. Army Aviation Test Board, Cairnes Army Air Field, Daleville, Alabama

Personnel at this facility presented general information concerning basic bearing failure modes which was similar to that received at Fort Rucker. No quantified data were available for analysis. A large one-piece bearing (KACARB KST 6099) that replaces the Uni-ball that is used at the base of the UH-1 actuators was flight tested at this facility. The 6099 bearing was flown for 1961 hours, after which it failed. The present design lasts approximately 100 flight hours, with maximum times of 300 flight hours being experienced. This KACARB bearing appears to solve all of the Uni-ball problems previously discussed.

FAILURE MODES AND EFFECTS ANALYSIS

This Failure Modes and Effects Analysis (FMEA) was performed early in the program to identify the REB potential failure modes, causes, and effects. This analysis formed the foundation for the detailed analyses of the underlying causes for premature failures of the spherical REB's. Also, proposed remedies or solutions for future design and procurement specifications, maintenance practices and procedures, and inspections and checks were identified during this analysis.

Initially the elements and/or functions of the bearing that contribute to helicopter performance and safety were identified. These criteria were used to establish the prevalent failure modes upon which the remainder of this study was based.

METHOD OF ANALYSIS

These FMEA's provide potential failure mode and effect identifications for the two most prevalent REB types used in current-inventory U.S. Army helicopters. These types are the lubricatable and the self-lubricated TFE-lined rod end spherical bearings. An FMEA was performed for each pertinent element of these two types of bearings. Interviews with various Army and National Guard maintenance personnel in conjunction with this study indicate that permanently lubricated bearings are being replaced on a one-for-one basis by improved state-of-the-art bearings such as TFE-lined bearings. Therefore, the permanently lubricated bearings were not considered during this analysis.

The columnar headings of the FMEA data sheets are defined as follows:

1. Item/Function - Identifies a discrete bearing type and its function in any type of control system.

2. Failure Mode - Defines the potential failure modes based upon the function of the bearing type identified.

3. Probable Failure Cause - Identifies the probable causes of the failure modes. The reference of these causes is apt to change during different phases of operations, so consideration was given to the dynamics of the operation, rather than the likelihood of occurrence.

4. Failure Effect, Subassembly - Identifies the effect of the potential failure on the performance of the rod end spherical bearing assembly by itself without consideration of the other related components or functions of the subsystem.

5. Failure Effect, Next Assembly - Identifies the failure effect in combination with other components or functions to determine

if there is a compounding or mitigating result to the control subsystem.

6. Failure Effect, End Item - Identifies the failure effect in combination with other subsystems or functions to determine if there is a compounding or mitigating result to the helicopter and/or flight crew.

7. Design/Maintenance Compensating Provisions - Defines the manner in which the design compensates for the failure mode and/or reduces the probability of occurrence. The maintenance provisions available to reduce the probability of occurrence are based upon adherence to the preventive maintenance schedules presented in the applicable technical manual.

8. Remarks/Recommendations - Presents remarks pertinent to the usage and recommendations involving interface with other systems.

The following procedure is used on the FMEA forms in order to eliminate needless repetition of phrases in the "Design/Maintenance Compensating Provision" and "Remarks/Recommendations" columns:

1. Each "Probable Failure Cause" that associates with a distinct "Failure Mode" was assigned a number.

2. Then the "Design/Maintenance Compensating Provisions" and/or "Remarks/Recommendations" are presented as they minimize or eliminate each particular numbered Probable Failure Cause (or group of causes) that contributes to the specific Failure Mode being addressed.

FAILURE ANALYSIS

Each failure mode was analyzed to determine the cause and mechanism that results in the failure. In the case of a spherical REB, for example, it may be lack of lubrication or improper loading that causes the bearing to jam. The FMEA was also used to establish the relevant failures for use in the life-cycle cost model. Figure 2 presents an example of a lubricatable rod end spherical bearing. Detail A displays the swaged type of spherical bearing, while Detail B displays the insert type of spherical bearing. The FMEA for the lubricatable bearing is shown in Figure 3. The lubrication schedule for the UH-1D/H helicopter REB is shown in Figure 4. Figure 5 presents an example of self-lubricating (TFE-lined) REB, while Figure 6 presents its FMEA.

The FMEA for the lubricatable bearing is presented herein for informational purposes and to demonstrate that this design approach was adequately addressed during this analysis. Lubricatable bearings that may currently be in service are being replaced by TFE-lined bearings as they

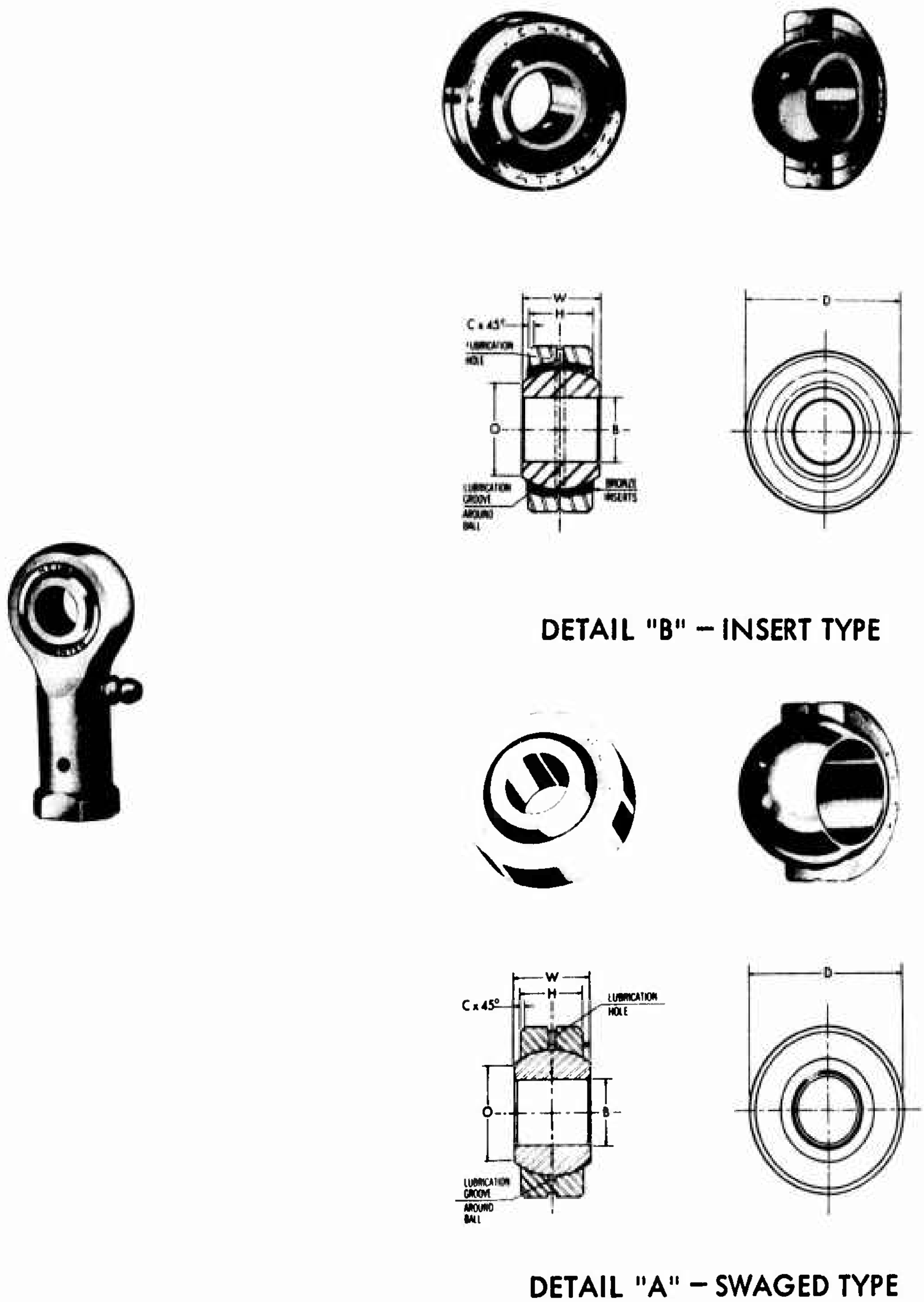


Figure 2. Example of Lubricatable Rod End Bearing.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
ROD END BEARING (LUBRICATABLE) Transfers forces from one control link to another and allows relative rotation between the links. Details of the two types of lubricatable bearings are presented in Figure 2.	Outer race and/or ball cracks.	1) Lack of lubrication. 2) Improper lubricant used during maintenance. 3) Operational loads exceed the rated load of the bearings. 4) Bearing housing/race improperly swaged to the ball during manufacture. 5) Bearing seal insert (see Detail "B" of Figure 2) improperly swaged to bearing housing. 6) Excessive grease pressure applied to bearing, blowing out or damaging insert seal.	Cracking of ball and/or race can cause • Further damage to the ball and/or race. • Excessive tolerance (play) build-up between ball and race. • Excessive friction between ball and race. • Welding of ball to race by heat buildup.	Control rod linkage may • Vibrate excessively, causing further damage to other control system components. • Become very stiff, causing further damage to other control system components. • Become disengaged, causing loss of transfer of control forces.	Helicopter controls such as flight or engine controls may • Be oversensitive to pilot's inputs. • Be too stiff to transfer pilot's inputs. • Be disengaged by an open link.		1) The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking of visible control rod linkage for damage and security. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking of all control rod linkages for damage, security, excessive wear, and play of the bearings. TM 55-1520-210-20 provides that lubricatable rod end bearings must be lubricated every 100 hours or 1000 hours as provided by the lubrication chart. 2) TM 55-1520-210-20 provides that Mil-G-25537, Grease for Aircraft/Helicopter Oscillating Bearing, should be used to lubricate the rod end bearings as provided in Figure 4.	1) The daily and intermediate preventive maintenance checks should require (for adequate lubrication) a visual inspection of lubricatable rod end bearings that are open to the environment. The lubrication frequency for some rod end bearings such as those located at the hydraulic servocylinder (reference 6 of Figure 4) should be lubricated at the 100-hour frequency under normal operating conditions. The lubrication frequency for all rod end bearings should be increased to allow for sand and dust conditions encountered in such operational environments as Southeast Asia.

Figure 3. Lubricatable Rod End Bearing FMEA.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							3) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when selecting the rod end bearings. 5) TM 55-1520-210-20 provides that all lubrication is to be accomplished by use of a hand type grease gun. The following are applicable to probable failure causes Nos. 4 and 5 only: Military specifications and normal commercial flight safety practices require that rod end bearings be 100% magnetic or dye penetrant inspected. Qualification testing is to be performed per MIL-STD-105.	The daily, intermediate, and periodic inspection checklists should provide for verification of adequate lubrication of all lubricatable rod end bearings. 3) One of the prime contributors to overstress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings. The following are applicable to all probable failure causes: Consideration should be given to replacing lubricatable rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report.

Figure 3 - Continued.

ITEM, FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing. Wholesale replacement of lubricatable rod end bearings with bearings that will not meet the requirements of the control system should not be accomplished for the sole purpose of eliminating the lubrication requirement.
	Ball and/or race scored or pitted.	1) Lack of lubrication. 2) Improper lubricant used during maintenance. 3) Operational loads exceed the rated load of the bearing. 4) Bearing housing/race improperly swaged to the ball during manufacture. 5) Bearing seal insert (see Detail "B" of Figure 2) improperly swaged to bearing housing.	Scoring and/or pitting of the ball or race may cause • Further damage to the ball and/or race. • Excessive tolerance (play) build-up between ball and race. • Excessive friction between ball and race.	Control rod linkage may • Vibrate excessively, causing further damage to other control system components. • Become very stiff, causing further damage to other control system components. • Become disengaged, causing loss of transfer of control forces.	Helicopter controls such as flight or engine controls may • Be oversensitive to pilot's inputs. • Be too stiff to transfer pilot's inputs. • Be disengaged by an open link.		1) The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking for damage and security on visible control rod linkage. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear, and play of the bearings on all control rod linkages.	1) The daily and intermediate preventive maintenance checks should require (for adequate lubrication) a visual inspection of lubricatable rod end bearings that are open to the environment.

Figure 3 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
		6) Excessive grease pressure applied to bearing, thus blowing out or damaging insert seal. 7) Lubricants contaminated with sand, dust, or abrasive matter. 8) Lubricants contaminated with moisture.					2) TM 55-1520-210-20 provides that MIL-G-25337, Grease for Aircraft, Helicopter Oscillating Bearing, should be used to lubricate the rod end bearings as provided in Figure 4. 3) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating, radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when rod end bearings are selected. 6) TM 55-1520-210-20 provides that all lubrication is to be accomplished by use of a hand type grease gun.	The lubrication frequency for some rod end bearings such as those located at the hydraulic servo-cylinder (reference 6 of Figure 4) should, under normal conditions, be lubricated at the 100-hour frequency. The lubrication frequency for all rod end bearings should be increased to allow for sand, dust and high moisture conditions encountered in such operational environments as Southeast Asia. 3) One of the prime contributors to over-stress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings.

Figure 3 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							A) The following is applicable to probable failure causes Nos. 4 and 5 only: Military specifications and normal commercial flight safety practices require that rod end bearings be 100% magnetic or dye penetrant inspected. Qualification testing is to be performed per MIL-STD-105. B) The following is applicable to probable failure causes Nos. 1, 7 and 8 only: TM 55-1520-210-20 provides that lubricatable rod end bearings must be lubricated every 100 hours or every 1000 hours as provided by the lubrication chart. See Figure 4.	A) The following are applicable to all probable failure causes: Consideration should be given to replacing lubricatable rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.

Figure 3 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								Wholesale replacement of lubricatable rod end bearings with bearings that will not meet the requirements of the control system should not be performed for the sole purpose of eliminating the lubrication requirement. B) The following is applicable to probable failure causes Nos. 1, 2, 7 and 8 only: The daily, intermediate and periodic inspection checklists should provide for checking for adequate lubrication of all lubricatable rod end bearings.

Figure 3 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
	Ball separates from race.	1) Operational loads in axial plane exceed load rating of bearing. 2) Bearing housing/race improperly swaged to the ball during manufacture. 3) Bearing seal insert (see Detail "B" of Figure 2) improperly swaged to bearing housing. 4) Excessive grease pressure applied to bearing, blowing out or damaging insert seal.	Race may be permanently deformed.	Control rod linkage may become disengaged, causing loss of transfer of control forces.	Helicopter controls such as flight or engine controls may be disengaged by the open link.		1) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when the rod end bearings are selected. 4) TM 55-1520-210-20 provides that all lubrication is to be accomplished by use of a hand type grease gun. A) The following are applicable to probable failure causes Nos. 2 and 3 only: Military specifications and normal commercial flight safety practices require that rod end bearings be 100% magnetic or dye penetrant inspected. Qualification testing is to be performed per MIL-STD-105.	1) One of the prime contributors to overstress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings. The following are applicable to all probable failure causes: Consideration should be given to replacing lubricatable rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.

Figure 3 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							B) The following are applicable to all probable failure causes: The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking of visible control rod linkage for damage and security. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear and play of the bearings on all control rod linkages.	Wholesale replacement of lubricatable rod end bearings with bearings that will not meet the requirements of the control system should not be performed for the sole purpose of eliminating the lubrication requirement.

Figure 3 - Continued.

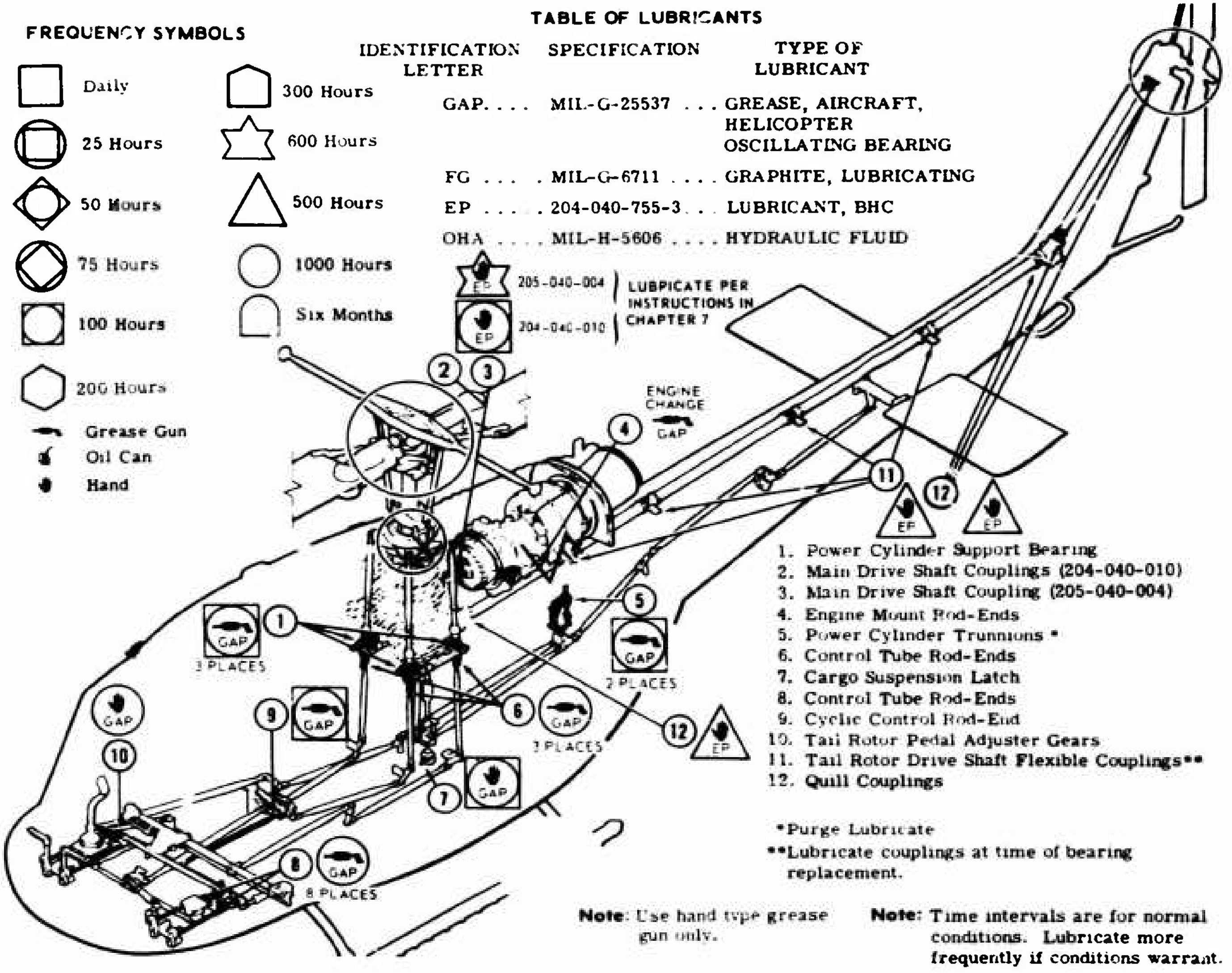
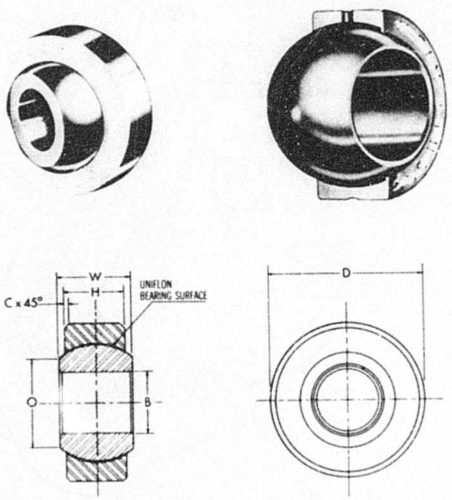


Figure 4. Example of UH-1D/H Lubrication Requirements.



DETAIL A

Figure 5. Example of Self-Lubricating Rod End Bearing.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
SELF-LUBRICATING ROD END BEARING Transfers loads from one load link to another and allows relative rotation between the links. Figure 3 presents an example self-lubricating rod end bearing.	TFE liner peels out or cold flows.	1) Improper bonding of TFE to race assembly. 2) Operational loads exceed the rated load of the bearing. 3) Bearing housing race improperly swaged to the ball during manufacture.	TFE liner peeling may cause • Further damage to the ball and/or race. • Excessive tolerance (play) build-up between ball and race. • Excessive friction between ball and race. • Welding of ball to race by heat buildup.	Control rod linkage may • Vibrate excessively, causing further damage to other control system components. • Become very stiff, causing further damage to other control system components. • Become disengaged, causing loss of transfer of forces.	Helicopter controls such as flight or engine controls may be • Oversensitive to pilot's inputs. • Too stiff to transfer pilot's inputs. • Disengaged by an open link.		2) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when the rod end bearings are selected. A) The following are applicable to probable failure causes Nos. 1 and 3 only: Paragraph 4.6.8 of MIL-B-81820A, "Bearings, Plain, Self-Lubricating, Self-Aligning, Low Speed", provides for testing linear condition and bond integrity as part of the MIL-Spec bearing quality provisions.	2) One of the prime contributors to overstress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings. A) The following are applicable to probable failure causes Nos. 1 and 3 only: MIL-B-81819 for high-speed applications should incorporate the provisions of paragraph 4.5.8 of MIL-B-81820A. B) The following are applicable to all probable failure causes: The daily, intermediate and periodic inspection checklists should provide an operational check for excessive friction on all control systems.

Figure 6. Self-Lubricating Rod End Bearing FMEA.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							B) The following are applicable to all probable failure causes: The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking of visible control rod linkage for damage and security. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear and play of the bearings on all control rod linkages.	Consideration should be given to replacing rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.
	Outer race and/or ball cracks.	1) Improper bonding of TFE to race assembly. 2) Contamination ingested by TFE liner. 3) Operational loads exceed the rated load of the bearing. 4) Bearing housing/race improperly swaged to the ball during manufacture.	Cracking of ball and/or race can cause • Further damage to the ball and/or race. • Excessive tolerance (play) build-up between ball and race.	Control rod linkage may • Vibrate excessively, causing further damage to other control system components. • Become very stiff, causing further damage to other control system components. • Become disengaged, causing loss of transfer of control forces.	Helicopter controls such as flight or engine controls may be • Oversensitive to pilot's inputs. • Too stiff to transfer pilot's inputs. • Disengaged by an open link.		3) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when selecting the rod end bearings.	3) One of the prime contributors to overstress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings.

Figure 6 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
			• Excessive friction between ball and race. • Welding of ball to race by heat buildup. • Ball to disconnect from race.				A) The following are applicable to probable failure causes Nos. 1 and 4 only: Paragraph 4.6.8 of MIL-B-81802A, "Bearings, Plain, Self-Lubricating, Self-Aligning, Low Speed", provides for testing liner condition and bond integrity as part of the MIL-Spec bearing quality provisions. B) The following are applicable to all probable failure causes: The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking of visible control rod linkage for damage and security. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear and play of the bearings on all control rod linkages.	A) The following are applicable to probable failure causes Nos. 1 and 4 only: MIL-B-81819 for high-speed applications should incorporate the provisions of paragraph 4.5.8 of MIL-B-81820A. B) The following are applicable to all probable failure causes: The daily, intermediate, and periodic inspection checklists should provide an operational check for excessive friction on all control systems. Consideration should be given to replacing rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race.

Figure 6 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.
	Ball and/or race scored or pitted.	1) Improper bonding of TFE to race assembly. 2) Contamination ingested by TFE liner. 3) Operational loads exceed the rated load of the bearing. 4) Bearing housing/race improperly swaged to the ball during manufacture.	Scoring or pitting of ball and/or race may cause • Further damage to the ball and/or race. • Excessive tolerance (play) build-up between ball and race. • Welding of ball to race by heat build-up. • Ball to disconnect from race.	Control rod linkage may • Vibrate excessively, causing further damage to other control system components. • Become very stiff, causing further damage to other control system components. • Become disengaged, causing loss of transfer of forces.	Helicopter controls such as flight or engine controls may be • Oversensitive to pilot's inputs. • Too stiff to transfer pilot's inputs. • Disengaged by an open link.		3) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when selecting the rod end bearings.	3) One of the prime contributors to overstress is change in operational commitments or airframe growth without due regard for increased stress on the original design rod end bearings. A) The following are applicable to probable failure causes Nos. 1 and 4 only: MIL-B-81819 for high-speed applications should incorporate the provisions of paragraph 4.5.8 of MIL-B-81820A.

Figure 6 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							A) The following are applicable to probable failure causes Nos. 1 and 4 only: Paragraph 4.6.8 of MIL-B-81820A, "Bearings, Plain, Self-Lubricating, Self-Aligning, Low Speed", provides for testing liner conditions and bond integrity as part of the MIL-Spec bearing quality provisions. B) The following are applicable to all probable failure causes: The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD/PMI, require checking of visible control rod linkage for damage and security. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear and play of the bearings on all control rod linkages.	B) The following are applicable to all probable failure causes: The daily, intermediate and periodic inspection checklists should provide an operational check for excessive friction on all control systems. Consideration should be given to replacing rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.

Figure 6 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS/ RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
	Excessive tolerance (play) between ball and race.	1) TFE liner has flowed. 2) Improper bonding of TFE to race assembly. 3) TFE liner worn due to ingestion of contamination. 4) Operational loads exceed the rated load of the bearing. 5) Bearing housing/race improperly swaged to the ball during manufacture.	TFE liner peeling may cause • Further damage to the ball and/or race. • Increased tolerance (play) build-up between ball and race. • Insufficient friction between ball and race. • Ball to disconnect from race.	Control linkage may • Vibrate excessively, causing further damage to other control system components. • Become disengaged, causing loss of transfer of forces.	Helicopter controls such as flight or engine controls may be • Oversensitive to pilot's inputs. • Disengaged by an open link.		4) Military specifications and commercial practices for the design of rod end bearings provide for their axial and radial static and oscillating radial load testing and for their subsequent rating. Control system design practices also consider the above parameters when selecting the rod end bearings. A) The following are applicable to probable failure causes Nos. 1, 2, 4, and 5 only: Paragraph 4.6.8 of MIL-B-81820A, "Bearings, Plain, Self-Lubricating, Self-Aligning, Low Speed", provides for testing liner conditions and bon[d] integrity as part of the MIL-Spec bearing quality provisions.	4) One of the prime contributors to overstress is change in operational commitment or airframe growth without due regard for increased stress on the original design rod end bearings. A) The following are applicable to probable failure causes Nos. 1, 2, 4, and 5 only: MIL-B-81819 for high-speed applications should incorporate the provisions of paragraph 4.5.8 of MIL-B-81820A. B) The following are applicable to all probable failure causes: The daily, intermediate and periodic inspection checklists should provide an operational check for excessive friction on all control systems.

Figure 6 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							B) The following are applicable to all probable failure causes: The daily and intermediate preventive maintenance checks, TM 55-1520-210-20 PMD PMI, require checking for damage and security on visible control rod linkage. The periodic preventive maintenance checks, TM 55-1520-210-20 PMP, require checking for damage, security, excessive wear and play of the bearings.	The presently used bearings have initial gaps of approximately 0.003 inch between the ball and the race. These should be replaced with bearings with very small initial gaps, not to exceed 0.0001 inch. Consideration should be given to replacing rod end bearings with either • Slotted type bearings with the race lapped to fit the ball, or • Carbon inserted race. Details of these recommendations are provided in the Solutions section of this report. The feasibility of replacing each rod end bearing must be considered with respect to the availability of a suitable replacement bearing.

Figure 6 - Continued.

wear out or fail. Field interviews conducted during this study indicate that U.S. Army personnel feel that TFE-lined bearings completely satisfy the "Form-Fit-and-Function" requirements necessary for a one-for-one substitution. The TFE-lined bearing's load rating compatibility with the load-carrying requirements of the control system appears to have been overlooked prior to this substitution process. The main criterion for selection and use of the TFE-lined design is its low servicing requirement when compared to the lubricatable bearing design. This servicing advantage is offset by the acceleration in wear being experienced by these TFE-lined bearings when they are used in the higher-loading control system applications (i.e., flight control linkage REB's used in the proximity of the rotor hub).

The bearings presently in service aboard current-inventory U.S. Army helicopters are predominantly of the TFE-lined self-lubricating type. All recommendations presented in the FMEA's are directed toward solutions of the problems associated with the use of the TFE-lined bearings.

As a general rule, the REB's are located in areas not readily accessible for servicing; therefore, those that required periodic greasing did not receive it. This shortened the operational life of the lubricatable bearing, which were replaced with TFE-lined, or other self-lubricating type, bearings aboard most current-inventory U.S. Army helicopters.

The FMEA indicates that the predominant failure mode is excessive play between the ball and the outer race, caused by the fabrication approach used in the construction of these bearings. The bearings are fabricated with the use of the spherical ball as a mandrel. The outer race, which consists of softer material than the ball, is swaged (squeezed) around the ball. It tends to spring radially away from the ball after the radially inward swaging process is completed. This springback usually results in a radial clearance of from 0.002 inch to 0.003 inch between the ball and the race. Whenever swaged bearings are exposed to extended vibratory environments, such as those induced by a helicopter, they wear rapidly. This wear is revealed by the radial movement between the ball and the race. This outward radial movement is referred to as "play" and is caused by the hard ball hammering against the softer outer race. Interviews with various maintenance personnel indicate that the REB's used in the more severe vibratory environment in the vicinity of the rotor blades require replacement much more frequently than those installed in the less severe vibratory environment induced by the control links.

REQUIREMENTS, PROCEDURES, AND PRACTICES

This section presents the results of the analyses of requirements, procedures, and practices presently being used by REB vendors, airframe manufacturers, and the U.S. Army on current-inventory helicopters. Pertinent documents were reviewed, with primary attention given to those areas that, by their deficiencies, result in hardware performance problems of REB's aboard U.S. Army helicopters. The helicopter design requirements as delineated in MIL-H-8501A were used as a baseline to establish the standard requirements.

Each requirement, procedure, and practice was then reviewed as to its ability to satisfy the basic performance criteria. Whenever control documentation anomalies were found, they were documented along with their foreseeable impact upon the performance of the REB's.

DESIGN REQUIREMENTS

The areas of design requirements investigated during this REB investigation are as follows:

1. Specification control documents and drawings
2. Component selection criteria
3. Military specifications and standards
4. Design requirements to eliminate induced failures
5. Contract specifications
6. Degree of compliance with the stated criteria

Specification Control Documents and Drawings

Helicopter manufacturer source control drawings were investigated and found to adequately identify potential suppliers of REB's. This reference to an REB manufacturer's part number constituted the entire design specification part of the contract between the vendor and the various helicopter manufacturers. The vendor part numbers and airframe manufacturer part numbers were generally listed on the face of the drawing. The materials were sufficiently identified along with dimensions and tolerances. However, there were no tolerances specified for radial or axial play. This lack of definition of initial play could result in delivery and eventual use of bearings that are unsuited for use aboard helicopters.

Review of REB manufacturers' drawings revealed that inconsistencies exist in the requirements for inspection. For example, the requirements for fracture testing per MIL-I-6866 or MIL-I-6868, or interchangeability per MIL-I-8500, were not imposed upon all REB designs. Not one of the more than 20 existing inventory helicopter REB's investigated had military specifications (MS) imposed upon the bearing design. None of the four bearing specifications (MIL-B-8948(ASG), MIL-B-81820A, the MS14103 version of MIL-B-8948, or the proposed MIL-B-81819) were referenced in any of the source control drawings reviewed. There were separate military specifications for threads, heat treating, and in some cases greasing. The specifications were not universally applied, and when applied they did not cover the entire REB. There were no requirements for any environmental testing. It is therefore concluded that the parts for which drawings have been supplied may not be up to military standard requirements for REB's.

This lack of control is considered to be a significant factor contributing to the high replacement rates being experienced by REB's. The federal stock number assignment does not imply that these bearings are eligible for the U.S. Government Qualified Parts Lists (QPL). Parts entered on these QPL's have passed part-certification qualification testing. This evaluation did not uncover any documented evidence that the majority of bearings presently in use aboard helicopters have passed part-certification testing. Environmental qualification testing has been notably absent from REB selection criteria. Axial, static, dynamic, and ultimate load standards are not imposed by source control drawings.

Component Selection Criteria

Component selection criteria are those design characteristics that must be verified. Consideration must be given to location, corrosive environment, fatigue, misalignment required by control system design, and specific load-carrying performance characteristics required.

Review of existing bearing specifications such as MIL-B-8942(ASG) and MIL-B-8948(ASG) and a proposed bearing specification, MIL-B-81819, revealed that material selection, dimensions and bearing tolerances are the only criteria specifically addressed. These documents do not require bearing performance in the vibratory environment induced aboard helicopters.

Inverviews conducted with various design personnel indicate that REB selection is based upon static load-carrying capability and corrosion resistance. Consideration is not given to the bearing's ability to perform in the vibratory environment.

Military Specifications and Standards

The results of the analysis of military specifications and standards that govern the design of REB's and the spherical bearings that are installed in the REB assemblies are discussed in the following paragraphs.

Military specifications applicable to spherical rod end bearings, such as MIL-B-8948(ASG), which governs TFE-lined REB's, do not contain sufficient design requirements to assure bearing performance aboard helicopters. REB's governed by MS21230, MS21242, and MS21243 are used aboard helicopters. These MS bearing design requirements are dictated by MIL-B-8948(ASG). The design qualification requirements established in paragraph 3.1 of MIL-B-8948(ASG) invoke MS21230 and MIL-B-8942 in addition to those shown in MIL-B-8948. Both MIL-B-8942 and MIL-B-8948 state that the design shall conform to MS21230, MS21231, MS21232 and MS21233 while MIL-B-8948 states that the design shall conform to MS21242 and MS21243. These MS's establish only the dimensional configuration, surface finish material, and hardness of the ball and race. Both MIL specs establish a maximum wear of 0.006 inch as a failure of the oscillating radial load portion of the design qualification tests. The maximum number of cycles that must be sustained by a bearing subjected to a load equivalent to one-third of its limit load is 1,000,000, a requirement that does not represent sufficient time for a bearing installed aboard a helicopter. For example, MIL-H-8501A, which applies to cockpit controls, establishes a vibratory frequency of 32 cycles per second (cps). If this 32 cps were used for an estimate of expected life, then 1,000,000 cycles would represent 31,250 seconds or 8.68 hours of helicopter operation. The 32 cps experienced in the cockpit is probably lower than the frequencies present at other parts of the helicopter. Therefore, it can be stated that the 1,000,000-cycle design requirement established for REB qualification is insufficient to guarantee any meaningful useful bearing life aboard U.S. Army helicopters.

Design verification is divided into quality inspection and quality conformance tests. Lot rejection criteria are not established for failure to pass these tests.

The predominant cause of removal and/or replacement of REB's has been established as excessive wear between the ball and the outer race. Generally 0.012 inch maximum wear is permitted before these bearings are replaced. The preceding discussion indicates that the bearing designs presently used were verified by qualification test to last 8.68 hours. Interviews with maintenance personnel at various maintenance depots indicate that the bearings experience replacement rates ranging from 95 percent to 100 percent. The unrealistically low oscillating load qualification requirement is probably the major cause of the helicopter bearing replacement rate being experienced by the U.S. Army.

Military Standards

Military Standard MS21230 forms the basic standard for self-aligning spherical bearings. Standards MS21232 and MS21243 deal with the rod end versions of the MS21230 spherical bearings. Tolerances and dimensions are adequately specified except for ball-to-race tolerance and thickness of liner. These are crucial because TFE is subjected to deformation upon vibration so that small clearances are required to minimize ball kinetic energy and the potential amount of deformation in the vibratory environment.

Vibration and other environment test methods are established in MIL-STD-810B for determining the resistance of equipment to the effects of natural and induced environments peculiar to military operations. The test methods provided in MIL-STD-810B inconjunction with U.S. Army helicopter operating environmental parameters would be sufficient to verify the design integrity of REB's. However, the existing REB design requirements do not include these environmental considerations. In addition, applicable portions of MIL-STD-810B are not imposed upon REB designs.

Design Requirements To Eliminate Induced Failures

The most probable causes of REB failure are presented in the Failure Modes and Effects Analysis section of this report. These causes are:

1. Excessive radial loads (including vibratory loads)

2. Improper bonding of liner to race

3. Ingestion of solid contaminants

Excessive loads are a cause of failure which could be corrected by choosing bearings that are capable of withstanding the oscillating loads experienced. Ultimate static loads and axial proof loads are not selected with enough of a safety factor to ensure that the bearings will withstand the helicopter environment. A detailed critique of existing design requirements in the area of oscillating loads is presented in the Military Specifications and Standards portion of this report.

Existing source control drawings specify the precise type of adhesive that should be used to bond the liner to the outer bearing race. MIL-B-81820A was the only bearing specification which established a bond integrity test as part of the lot acceptance process. The absence of this liner bond integrity test requirement from the REB controlling documentation is probably the major cause of problems that are being experienced with the bearing race linings.

The ingestion of solid particles between the ball and the race contributes to the acceleration of bearing wear. This ingestion of solid particles tends to be a vicious cycle: the initial gap between the ball and the race permits solid contaminants to enter the raceway and to abrade the raceway, accelerating wear and thus resulting in a larger gap. Recovery is not the predominant cause of bearing wear responsible for the high replacement rate being experienced. The presence of these particles within the bearing contributes to the wear of the linings. Abrasive wear alone would not cause the rejection rates presently being experienced. This lining wear in combination with the radially outward deformation of the race results in raceway-to-ball gaps and the necessity of replacing the bearing.

Contract Specifications

The source control drawings discussed in the Specification Control Documents and Drawings section of this report form the complete set of contract specifications used to procure REB's. These specifications establish a comprehensive set of design qualification requirements. Detailed instructions are provided for manufacturers who want to have their bearing designs qualified and entered on the applicable QPL. These specifications presently establish an effective procedure for REB design qualification.

Review of helicopter manufacturer specification control drawings shows that the existing REB military specifications are not imposed upon bearing vendors. Therefore, the only controls that exist are the physical dimensional tolerances and material integrity. These are maintained by the bearing vendor and not by the helicopter manufacturer.

A second area of difficulty exists with the specific parameters which are used as the basis for design qualification. These specifications present a contradiction between a satisfactory qualification procedure and unsatisfactory detailed qualification performance parameters that must be satisfied when the procedure is applied. This paradoxical situation results in the satisfactory qualification of parts to meet performance requirements that are too lenient for helicopter applications.

Degree of Compliance With the Specified Criteria

This analysis indicates that no formal procedure exists to enforce compliance with specification control documents, drawings, military specifications, realistic design requirements, or contract specifications. Component selection criteria were not established, nor were military specifications imposed upon the bearing vendors or the helicopter airframe manufacturers.

Many of the problems with current-inventory helicopters were the result of the U.S. Army requirement for a large quantity of helicopters in a short period of time for use in Southeast Asia. As a consequence, design concepts for commercial helicopter applications were used for military versions of similar helicopters. Because of this urgent need for helicopters, availability of similar commercial design concepts, and competition for funds, numerous exceptions to military specifications were granted. While this procedure was an acceptable standard under the above conditions, steps must be taken in the future to ensure that all operational requirements are incorporated into the design of military equipment.

The benefits to be derived from incorporating all Army operational requirements into the basic design are as follows:

1. Decreased failure rates

2. Decreased maintenance man-hours

3. Increased availability

4. Decreased logistics requirements

5. Lower life-cycle cost for the helicopter system

QUALITY ASSURANCE

This analysis was performed to evaluate the possible cause-and-effect relationship between existing Quality Assurance (QA) provisions and the inherent (design) induced failure of REB's. The areas investigated are as follows:

1. Vendor Quality Control (QC) and shipping inspection

2. Airframe manufacturer receiving inspection

3. Initial installation procedures

4. Functional test procedures

5. Mandatory inspection points

6. Component sampling procedures

7. Degree of compliance with the specified requirements

Vendor Quality Control and Shipping Inspection

Vendors of REB's require a comprehensive QC program to assure that failures caused by manufacturing defects and/or improper handling are minimized. Such a program can prevent the delivery of poorly constructed, mislabeled, and defective parts.

Discussions held with various REB manufacturers revealed that QC programs do exist at their respective facilities; however, they concentrate only upon material integrity and dimensional conformance to drawings.

Airframe Manufacturer Receiving Inspection

Interviews with airframe manufacturer personnel revealed that receiving inspection of REB's was considered as an unnecessary function.

The REB's are received and installed on helicopters without any formal QA inspections. Helicopter systems containing REB's are functionally checked out when they are completely assembled. This same procedure is used at the U. S. Army helicopter overhaul facilities. These airframe manufacturer QA personnel indicated that receiving inspection would be initiated only if the functional checkout data indicated that a problem exists. They could not define a quantitative set of rules that would establish the existence of a problem.

Initial Installation Procedures

Discussions held with airframe manufacturers failed to produce documentation as to installation practices and procedures. However, each manufacturer states that there are such procedures in use. The adequacy or inadequacy of their procedures could not be ascertained by this analysis, since these data were not formally supplied or established during the investigation. The enforcement of definitive installation procedures would eliminate installation-induced failures such as connecting rods disconnecting or bending during normal flight.

Functional Test Procedures

The airframe manufacturers did not release any manufacturing functional test procedures for this analysis. Their reluctance was based upon the lack of an existing requirement for their participation in this investigation.

Informal information obtained during interviews indicates that a formal QA inspection is performed during flight tests. These flight test inspections are performed to verify the integrity of various systems, the test requirements of which are discussed later in this report in the Test Requirements and Procedures section.

Mandatory Inspection Points

Rod end bearings for control systems have certain inspection criteria that should be clearly enumerated on QA inspection sheets. Investigations at vendors, airframe manufacturers, and U.S. Army facilities failed to verify the existence of these inspection sheets. The airframe manufacturers indicated that such procedures exist, but they were not available for this analysis.

Component Sampling Procedures

To be effective, a QA program must include provisions for component sampling. Specifications such as MIL-B-8948(ASG) and MIL-B-81820A both reference MIL-STD-105 with respect to sampling procedures. The method of checking design conformity through lot sampling is crucial to a valid QA program.

No evidence was found to reveal that specific acceptance quality levels from MIL-STD-105 were being imposed upon bearing vendors. Criteria or requalification procedures for rejected lots were not found to exist at bearing vendors or airframe manufacturers.

MIL-STD-105 establishes various Acceptable Quality Levels (AQL). This standard is referenced but it is not imposed. Formal assurance does not exist to verify the quality of bearings being installed on U.S. Army helicopters.

Degree of Compliance With the Specified Requirements

Helicopter manufacturers have not imposed upon bearing vendors contractual requirements for lot sampling to verify quality. Military Specifications MIL-B-8942 and MIL-B-8948 do specify sampling plans from MIL-STD-105. Neither specification establishes the maximum radial clearance between the ball and the race to be used for rejection criteria. The following characteristics are used to establish quality conformance:

1. Dimensions
2. Identification of Product
3. Workmanship
4. Preparation for Delivery
5. No-Load Breakaway Torque
6. Hardness
7. Magnetic Particle or Penetrant Inspection

It may be that only the highest quality commercial parts are being used, but this does not mean that these components meet or exceed the quality required by the military specification. To demonstrate that commercial and military standard parts do reflect the quality required by the applicable military specification, such tests as component sampling and functional tests must be performed. There was some evidence of sampling for the purpose of QA by one airframe manufacturer. No data were available to indicate the level of quality or the degree of conformity to the military specification requirements.

Neither installation procedures, mandatory test procedures, nor functional test procedures were furnished by the airframe manufacturer. They claim to have such procedures and that they are used, but because of proprietary rights they could not divulge them. Mandatory testing points for use by U. S. Army maintenance verification personnel are indirectly set forth in TM38-750 but not by the applicable TM (i. e., TM55-1520-210-20), so Army facilities could not be expected to comply.

MAINTENANCE PROCEDURES AND PRACTICES

The analysis in this section identifies the problem areas with the following:

1. Technical maintenance manuals
2. Periodic preventive maintenance inspection procedures

3. Component shelf life considerations

4. Failure criteria and detection methodology

5. Maintenance skills and training

6. Special equipment and tool requirements

7. Component accessibility

The degree of compliance with technical references used when performing maintenance on U.S. Army helicopter control system REB's is also presented.

Maintenance Manuals

The various Levels of Repair (LOR) maintenance manuals which govern the maintenance, inspection, replacement, and checkout of flight control system REB's were reviewed and analyzed to determine the following:

1. Are applicable documents adequately considered for technical reference?

2. Is assignment of LOR responsive to hardware operational requirements?

3. Is the applicable subsystem to be repaired adequately described?

4. Are all adjustment procedures including tolerances provided?

5. Are material/manpower requirements including special tools and test equipment set forth?

6. Are skill levels required to perform assigned maintenance tasks presented?

Technical References

The general tone of a technical manual as well as the frequency of reference to other manuals can encourage or discourage its use as a tool in maintenance procedures. The direct support technical manuals make repeated references to other documents. These references never identify the appropriate information. These factors tend to discourage the mechanics from using the manuals. The resulting practice of depending upon experience, rather than going by the book, contributes to poor installation and maintenance inspection procedures, premature removals, and early REB failures.

Level of Repair

REB's are treated as low-value discard items. When required, these items are removed and replaced without being repaired. Therefore, the various LOR's are not designated for REB's.

Subsystem Description

Rod end bearings are not treated as an individual system or subsystem in any of the technical maintenance manuals. These bearings are referred to as they exist within a system such as flight control, engine control, etc. Problems arise because the REB designs presently being used require individual identification as a maintenance item. This lack of maintenance requirement identification contributes to the REB problem in a minor way.

Materials/Manpower Requirements

The materials requirements pertaining to REB maintenance consist of replacement part numbers. Manpower requirements necessary to install them into a system and properly adjust that system are not specified either in the organizational, direct support, or general support maintenance manuals.

Lack of specific maintenance requirements such as torque values, allowable wear limits, clearances, and maximum times between inspections are factors that contribute to premature bearing failures.

Skill Level Requirements

Skill level requirements to perform the specific maintenance tasks are not identified in the Army TM. Skill level should be identified in terms of Military Occupational Speciality (MOS) in combination with pay grade and experience. Lack of skill level requirements, especially in the area of preventive maintenance, contributes to early REB failures in the following modes:

- Improperly rigged control systems can result in induced bending of links and frozen bearings.
- Rattling of links can cause accelerated wear of the bearings.

Periodic Preventive Maintenance Inspection Procedures

The various types of preventive maintenance inspection procedures used to determine the readiness condition of the helicopter were examined for

1. Frequency and interval criteria of inspections
2. Clarity and thoroughness of procedures
3. Material and manpower requirements

The daily, intermediate, and periodic inspections are intended to be performed at the organizational level to identify and correct deficiencies before malfunctions occur. Specifically, these inspection procedures were investigated relative to preventive maintenance performed upon REB's.

Inspection Intervals

Organizational level inspection intervals for systems containing REB's are established by using aircraft flight hour intervals. While this may not directly affect bearing performance, scheduling periodic inspections is difficult to predict because it cannot be readily determined which aircraft will reach the next inspection flight-hour interval. Critical inspections are degraded and maintenance management is under duress when an unusually large number of helicopters require an inspection interval at any one time. The establishment of a calendar time basis for these periodic inspections would facilitate both maintenance and flight assignments. The flying units would have precise information about the time period any specific helicopter would be unavailable for use. Maintenance personnel would know the numbers of helicopters and the type of maintenance load to expect during any time interval.

1. Preventive Inspection Procedures (Daily)

   All sequence numbers in the UH-1D/H Preventive Maintenance Daily (PMD) were reviewed for preventive maintenance procedures regarding REB's. As previously stated, they are not identified as end items for scheduled or unscheduled maintenance, and therefore the skill and experience level of the helicopter crew are relied upon for effective inspection of REB's in control linkages. They are not identified as an item requiring daily inspection. Absence of daily inspections could contribute to accelerated bearing wear resulting from dirt or fluid contamination and/or poor REB linkage adjustment detection.

2. Preventive Inspection Procedures (Intermediate)

   The 100-hour Preventive Maintenance Periodic (PMP) inspection interval on the UH-1H requires the REB's between the collective sleeve drive plate and mast to be checked for excessive play. Rod end bearings on the elevator control linkage are also checked for excessive play and wear on the UH-1H. Lack of specifics regarding wear tolerances, material condition, and preventive maintenance actions can result in premature failure or possibly unnecessary removal. Other helicopter model 100-hour PMP instructions make a general reference to REB's with the statement "Check rod end condition."

A review of these procedures reveals that the U.S. Army does not adequately define many specific details and inspections that are considered mandatory for effective maintenance. The preventive maintenance inspection checklists do not provide tolerances or adequate references for determination of these tolerances. They should provide these tolerances or adequate references to other applicable U.S. Army documents such as the helicopter TM. In addition, only general references are made to REB's and not to a specific check that must be accomplished. Important areas may not be inspected because of these generalities.

Technical References

The daily, 250-hour, and 100-hour preventive maintenance checklist inspection procedures referred to other technical sources for the various helicopter subsystems or components that contain REB's.

The U.S. Army helicopter preventive maintenance checklists are intended for use by maintenance personnel. These checklists do not define specific maximum wear tolerances for REB's. The allowable wear tolerances are provided in the organizational maintenance manuals. Applicable organizational maintenance manuals were reviewed for troubleshooting procedures applicable to flight control systems. They define the probable failure cause and they indicate that corrective action is needed. No reference was made to the specific manual that outlines the repair or replacement procedure that should be used to correct the problem. This situation leaves an "open loop" with respect to verifiable and consistent repair of the REB.

Component Shelf Life Considerations

The predominant failure modes associated with REB use are as follows:

1. Excessive gap between the ball and the race
2. Contamination or corrosion of ball or race

The metallic bearing parts such as the ball and race are not subject to deterioration over time if the bearing is properly packaged. All liner materials presently used in bearings will not deteriorate even if left unpackaged. All bearing specifications reviewed specify packaging per MIL-B-197. Shelf life should not be a factor in bearing performance if the bearings have been packaged in accordance with MIL-B-197 and the package has not been damaged.

Failure Criteria and Detection

Rod end bearing failure is usually diagnosed as a result of excessive vibration in the system or too much or too little force required to operate the control systems. These are symptoms of excessive radial or axial wear of bearings, bearing contamination or cracking, and/or bent links.

An example of REB failure detection criteria is presented in Table I. Figure 7 presents a representative example of REB applications for the UH-1D/H helicopter discussed in Table I. The values in this table were extracted from the UH-1D/H organizational TM (e.g., TM55-1520-210-20). Typically REB wear is measured with a dial indicator for both axial and radial directions. Excessive bearing wear can also be detected by low forces required to move the control stick or high-frequency vibrations, while corroded or bound bearings are characterized by high stick or pedal forces.

Maintenance Personnel Skill Levels, Qualifications and Training

1. Flight control system maintenance school lesson plans were reviewed, and interviews were conducted with field maintenance personnel in order to assess the possibility of maintenance-

TABLE I. EXAMPLE UH-1D/H REB APPLICATIONS
Control tubes (3) between bell crank and servo valve at servo valve end (P/N 47-140-252-3)
- 0.012 inch radial and axial maximum allowable wear limit
- Torque nut 100-150 inch-pounds
Pitch change links (2) in main rotor group at lower end (P/N 204-011-175)
- 10.5 inch center to center ± 0.030 inch
- Torque nut 200-250 inch-pounds
- 0.010 inch radial and axial maximum wear limit
Damper link rod end (2) in main rotor group at lower end (P/N 47-140-252-5)
- 0.012 inch axial and radial wear tolerances
Tail rotor pitch change linkage (P/N 204-011-762-1, -7, -11)
- 0.020 inch axial or radial play
- Torque blade assembly end 60-110 inch-pounds
- Torque crosshead end 50-70 inch-pounds

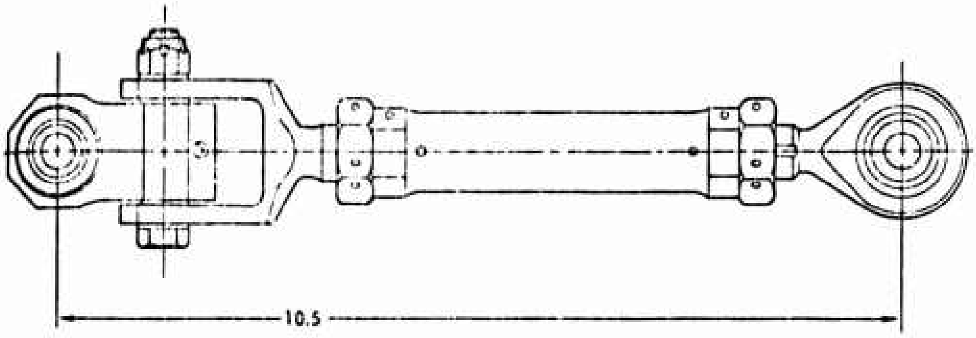


Figure 7. Pitch Change Link Assembly.

induced REB problems. The courses reviewed were conducted at the U.S. Army Transportation School, Fort Eustis, Virginia.

2. The lesson plans appear to be followed and attempts are made to keep them updated. An interview with an instructor at the school indicated that the course should be lengthened. He stated that tolerance buildups in flight control systems were common "gripes" by pilot and crew chiefs. He also stated that the replacement rate of Flight Control System (FCS) REB's was a big problem. Even when the total displacement of an FCS was measured and it was within tolerance, bearings were still replaced because the system did not respond well and excessive noise due to vibrations was evident.

3. The direct/general support (68 series) courses do not instruct personnel in the use of maintenance verification. This maintenance verification involves the checking of maintenance actions by another person after they have been performed. The instructors interviewed felt that the need for such maintenance verification is evidenced by the high incident rate of REB failures being experienced after initial REB replacements. Accelerated bearing wear is usually experienced when installation and rigging errors are not observed and corrected.

The following comments are applicable to Publication No. 253-110-14, "AH-1G Flight Control Systems":

1. No reference is made to maintenance-related quality assurance, i.e., maintenance verification.

2. Emphasis is placed upon "knowing-the-systems." The explanations presented do not go into sufficient detail because they depend upon the previous experience of maintenance personnel. These explanations do not list the most likely failure modes, failure causes, or mistakes encountered with REB's. Because of the prodigious quantities of information in the manuals, maintenance personnel must rely heavily upon memory; this is considered a major factor in the variability of the quality of repair.

3. The lesson plans do not sufficiently emphasize the reasons for good maintenance practices as they relate to exposed surface preventive maintenance, i.e., the necessity for cleanliness of moving parts on a day-to-day basis.

Other instructors at the school indicated that on-the-job-training (OJT) was relied upon in lieu of formal training. Formal school training is not offered after the initial course. Maintenance personnel trainees can eventually qualify for crew chief without any additional schooling. The lack of formal training and the lack of periodic verification of existing maintenance skills can be major factors in REB maintenance-induced failures.

Special Equipment and Tool Requirements

Organizational maintenance manual TM55-1520-210-20P-2 contains a list of airframe tools, ground support, and flyaway items for the helicopter that is to be maintained. The tool requirements are not always prescribed as a part of maintenance procedures. The listing is adequate and pertinent to each model helicopter. Field interviews indicate that tool availability would not contribute to REB failures. While tool availability is not considered a problem, misuse of tools, as related to skill level, could contribute to REB failures.

The special tools and their specific applications for REB maintenance are as follows:

- Dial indicator - Measure bearing radial and axial wear
- Micrometer - Measure ball diameter
- Protractor - Detect angular freedom of rotor blade grips when installing linkage
- Spring force measurer (fish scale) - Measure required force to deflect control stick
- Torque wrenches - To apply appropriate torque to bolts during rigging operation

Component Accessibility

Fuselage panels requiring removal for access to various REB's are not described or shown on the applicable maintenance checklists or organizational maintenance manuals presently in use.

The maintenance checklists previously mentioned are provided to maintenance personnel by the Department of the Army. They are formatted on plastic-coated 7 x 9-1/2-inch cards, and are intended for use while performing maintenance checks on all Army helicopters. Different sets of cards exist for daily, intermediate (25 hours), and periodic (100 hours) checks.

Omission of panel identity is not viewed as the cause of REB failures per se, but it does indicate the incompleteness of the technical publications.

The time required to remove and replace access panels cannot in itself be considered as a cause of maintenance-related failures. However, the time element is important since maintenance personnel avoid performing certain tasks because they do not want to take the time to remove and replace access panels. The types of maintenance actions often not performed include inspection, cleaning, adjustments, and lubrication at assigned intervals. Because these types of periodically required maintenance activities are not performed, they are considered contributors to REB failures.

Degree of Compliance With the Specified Requirements

All of the technical maintenance manuals ranging in level from daily preventive inspection to the depot overhaul were reviewed. Field interviews regarding their use were also conducted. The conclusion reached is that the manuals are not referred to and are not complied with. There is also an overall lack of written procedures regarding REB problems.

Periodic inspection is not addressed in the scheduled maintenance cards in terms of failure tolerances. Noncompliance is mainly due to lack of failure criteria in the daily, 25-hour, and 100-hour inspection interval checklists. These preventive maintenance checklists are not self sustaining or self explanatory and do not effectively tie in with the technical maintenance manuals and are, therefore, not effective.

There is no reference to MIL-B-197D in the REB military specifications with respect to packaging and storage. MIL-B-197D type protection is probably not required as long as direct exposure to force, vibration, or contamination is avoided. Some sort of realistic protection should be provided in lieu of MIL-D-197D.

Despite the use of definitive failure criteria, sufficient documentation was not available to determine compliance with the detection of REB failures. The existing organizational maintenance manuals did not show which failure detection methods were used to determine the original existence of the problem. The effects of the failure, the use and specific applications to which REB's are put, and useful bearing life aboard a helicopter were sometimes given. Helicopter failure data relating to REB wear and increases in ball-to-race breakaway torque were obtained by extrapolating flight control malfunction data and/or reported instances of excessive vibration.

Various special tools such as protractors and dial indicators are provided to measure the wear dimensions (excessive play) between the race and the ball. The effective use of these measuring devices requires disassembly and removal of the REB's from the helicopter. Once the bearings are removed, it is just as easy to replace them as it is to perform the measurement. Therefore, the bearings are not checked when they are installed aboard the helicopter because the inspection checklists do not specifically require this action and the tools provided for this inspection require their removal from the aircraft. The tools to be used at the various levels of maintenance are listed in the special parts and tools manuals. This was not identified as a problem area contributing to failures. Improper use of tools as related to skill levels is, however, a contributing factor to REB failures.

Formal training of maintenance personnel is too short and not sophisticated enough to be effective. Refresher courses and/or periodic assessment of maintenance personnel skills is nonexistent. The existing heavy reliance upon OJT, combined with the nonexistent verification of maintenance personnel skills, results in misrigging which contributes to accelerated bearing wear.

Access to REB's is adequate; however, this access is not presently shown in inspection and maintenance procedures. As stated above, the time required to remove and replace the access panels tends to discourage the performance of the periodically required REB inspections and checks.

The lack of access identification does not directly affect performance, but it causes the required check not to be performed. Thus erratic or nonexistent performance of required maintenance checks is a contributor to accelerated wear of REB's.

TEST REQUIREMENTS AND PROCEDURES

Testing of REB's for use in U.S. Army helicopters was analyzed to evaluate the inherent design and present procedures with respect to the projected mission scenarios. The specific testing requirements and procedures investigated during this analysis were as follows:

1. Environmental test and procedures

2. System compatibility testing requirements and procedures

3. Qualification test requirements and procedures

4. Flight test plan and procedures

5. Service test plan and procedures

6. Acceptance test procedures and results

7. Degree of compliance with the specified test procedures and requirements

Testing in itself will not minimize or eliminate existing design failure modes or failure causes. These tests serve only to identify and verify the existence of a specific failure mode when the design is required to perform in a particular set of environmental situations. The identified and verified failure modes can be eliminated only by changes within the design itself or by elimination of the specific cause of the particular failure mode.

Environmental Test Procedures

Environmental testing procedures are essential to adequately predict the performance characteristics of REB's in their intended environment. Procedures for environmental testing are covered by MIL-STD-810, but the document requirements are not imposed upon the supplier of REB's used aboard Army helicopters.

The use of environmental testing in REB design approaches would result in the identification of any design weaknesses prior to the production phase in the life cycle. This timely design weakness identification would result in design changes and/or compensatory maintenance provisions. These changes would reduce helicopter downtime caused by unscheduled maintenance of systems containing REB's.

System Compatibility Testing Requirements and Procedures

System compatibility testing is an essential process because it establishes the performance adequacy of the REB's when installed within a helicopter system such as the flight controls. The conduct of these tests is governed by the procurement and design specifications for the end-item helicopter as well as the component specifications.

Present systems tests include checking high and low pitch of the blade grip with a protractor and adjusting the length of the link properly. Lock nuts are tested to assure lack of rod end housing movement relative to the rod. Center-to-center lengths between REB's of the same link are tested. The tubes which have REB's are checked for cracks. The location and direction of fastening nuts, bolts, and lock washers with respect to the bearing are specifically stated. A dial indicator and procedure for its use are specified for checking on axial and radial play on some REB's; tolerances are listed for each bearing. All of these test items are sufficient to identify system compatibility problems that exist. Verification that these tests has been performed could not be found. This lack of formally documented verification is a major factor contributing to the inconsistency and variability in REB performance aboard helicopters.

Qualification Test Requirements and Procedures

The military specification which governs REB qualification testing is MIL-B-8948(ASG). This specification or its proposed successor MIL-B-81819 is applied to bearings installed on current-inventory helicopters by airframe manufacturers. Neither the vendors nor the Army present documentation which describes qualification testing of REB's used on Army helicopters. Qualification tests, when completed, are one-time tests unless components are modified or operational requirements are changed.

The qualification testing of the REB must be imposed prior to full-scale production. This testing period is the time to determine if the REB is of appropriate inherent design for its intended operational environment. For this purpose, the test objective is to simulate conditions more severe than actual Army operational conditions of high vibration loads, cyclic rates, and other environmental conditions encountered such as dust, dirt, fluid contaminates, salt spray, and heat.

Flight Test Plans and Procedures

This analysis considered flight testing as those activities performed by the airframe manufacturers and those performed by the Army. The airframe manufacturers use flight testing for design and/or production validation prior to helicopter delivery. Army flight test activities are performed to qualify or accept new helicopters and to validate maintenance activities.

Individual airframe design validation or predelivery flight test procedures were not available for analysis during this investigation. Therefore, statements pertaining to their adequacy in detecting REB problems cannot be made.

Army engineering flight tests are structured to expose new helicopter designs to prolonged operational conditions. These tests are normally conducted in a manner which would expose indications of design weakness and failure modes. Tests of this nature are performed at helicopter maximum gross weight for extended time periods.

The Army maintenance verification flight tests check the flight control system for lack of response, binding, and creeping in both cyclic and collective pitch. Vibration is monitored at low frequencies, which may indicate excessive play at main rotor pitch change REB, or high frequency, which may indicate damage to a tail rotor pitch chain link REB in many flight modes. The flight test procedures for linkage performance are capable of detecting many existing control system failures or impending failures. An excerpt from UH-1D/H organizational maintenance manual TM55-1520-210-20 is shown in Table II. This table demonstrates the high degree of adequacy inherent in these flight test procedures, which provide for formal documentation of each parameter listed therein.

Service Test Plans and Procedures

Service tests are usually performed as part of, or in conjunction with, system qualification testing, usually at U.S. Army installations, and with the use of existing flight and maintenance personnel. These tests determine the operational serviceability of the system when the maintenance/service is performed by U.S. Army personnel. Any maintenance problems that would exist with a new design are identified. The manufacturers then make appropriate changes and the item is retested. When successfully completed, these tests provide the Army with maintenance data that are used as inputs for manual preparation, training, level-of-support decisions, and maintenance workload planning. The Army then has reasonable assurance that the new design will possess the required availability when it is introduced into the inventory.

Information was not found to verify that formal maintainability demonstration was performed per MIL-STD-471 or any other set of requirements.

Acceptance Test Procedures and Results

Formal acceptance test documentation that verified the performance of helicopters which were used as a baseline for this study was nonexistent. Interviews with various Army procurement personnel indicate that these helicopters were purchased as operational "off-the-shelf" hardware. This procurement policy resulted in acceptance of helicopters without formally verified performance characteristics. Consequently, the original REB's installed in these helicopters were of commercial quality and not of military standard quality. Various retrofit programs are resulting in the use of military standard parts in place of commercial parts.

Indications exist that new helicopter design procurements do include formal acceptance testing. It is therefore safe to assume that the use of non-military standard REB's will be eliminated in the next-generation Army helicopters.

Degree of Compliance With the Test Procedures and Requirements

This study revealed that formal testing, test plans, or test requirements were not used by REB vendors, nor by helicopter manufacturers, during initial design procurements.

Many of the current problems with current-inventory REB's used on helicopters were the result of the Army requirement for a large quantity of helicopters for use in Southeast Asia. As a consequence, design concepts used for commercial helicopter applications were used for military versions of similar helicopters. Because of this urgent need for helicopters,

TABLE II. TEST PROCEDURES

Before Starting Engine	
Pedals	Freedom of movement through range of travel, neutral.
Starting Engine and Runup	
RPM 6000	Force trim OFF, check controls for any tendency to creep or motor, freedom.
	Note
	Keeping the fingers around the cyclic grip, but not touching it, lightly tap the cyclic in various directions with the fingertips. Movement should stop when pressure is stopped. Each pedal should be checked by tapping lightly with the foot with no pressure on the opposite pedal. The controls should not motor or creep when no pressure is applied. With force trim OFF, the controls should operate smoothly (no creeping, binding or chattering) with no feedback or excessive friction, within about 1 inch of controls center.
Force Trim ON	Check cyclic gradient forces nearly the same in all directions, no play. Recheck in all directions within 1 inch of cyclic center.
	Note
	With force trim ON, it should take approximately equal force to move the cyclic in all directions while making movements of approximately 1 inch. Force required to move the pedals should be about the same for either pedal. Using the cyclic release button, position the cyclic and pedals in

TABLE II - Continued	
	various positions, within about 1 inch of neutral. The controls should hold the selected positions and the spring force should be the same in all directions.
Collective Pitch Lever	Adjustable friction completely free. Check built-in friction is 8 pounds minimum, 12 pounds maximum.
	Note
	Move the collective up to about mid-travel and then back down. The force required to move the collective should be 8-12 pounds and be about the same in each direction. It is recommended that a fish scale be used to make this check with greater accuracy. However, the correct effort to lift the collective is about the same as that required to lift a loaded M-1 rifle. Friction may be noticeably less on abnormally damp days. Friction adjusted on damp days may be too heavy on dry days.
Collective Pitch Lever	Minimum check--adjustable friction will adequately increase friction, set friction OFF.
Hover Checks	
Cyclic	Move various directions. Note tip path plane for proper movement.
Tail Rotor Pedals	Depress each slightly; feel that aircraft tries to turn in proper direction.
Collective Pitch	Increase smoothly, noting that the CG feels normal until at 3-5-foot hover.

TABLE II - Continued	
Control Position	Stabilized hover. Cyclic should be nearly centered, pedal position normal. Note vibrations; any excessive control displacement should be sufficient warning to require rigging check. Consider wind influences.
Control Response	Check with small inputs; note any lack of response or binding. Lack of proper response or binding is cause to terminate flight and determine cause.
Turns	Make hovering turns in both directions to check tail rotor response and rigging.
Sideward Flight	Fly in both directions to check cyclic response and rigging.
Flight	Do backward and forward flight into a 15-knot wind to check cyclic response and rigging.
Takeoff and Climb	
Normal Takeoff	Climb at 60-70 knots. Note control positions normal.
Autorotation	Note vibrations. Note that sufficient right pedal remains.
Hydraulic Control switch OFF	Caution light ON. Check that helicopter is easily controllable; no excessive forces to right front quandrant; cyclic and pedal forces. Collective should go down and up in pressure without excessive force. There should be no excessive feedback in the controls.

TABLE II - Continued	
Engine Topping Out	
Concurrent Vibration Test	Check control positions and forces. Note that sufficient left pedal remains. Note vibration level.
Control Rigging Check	
Airspeed Test	Needle and ball centered. Note that cyclic control is nearly centered, force trim holds controls in position. Right pedal should be slightly forward. Investigate rotor vibrations. Aircraft should fly smoothly through entire speed range.
Airspeed to Hover	Accomplish a zero-airspeed 1500-foot altitude hover. Note any 1-per-revolution vibration.
Stabilized Airspeed	70 knots. Note vibration level. Descend with low pressure and note increased vibrations.
Level Off and Accelerate	Increase airspeed from 70 knots to VNE unless vibrations become severe. Note any 1-per-revolution vibrations and airspeed at which they became evident.
After Landing Check	
Controls	Collective pitch full down, cyclic centered, pedals neutral.

the availability of existing commercial designs, and competition for available funds, numerous exceptions to military specifications were granted.

Definitive steps have been taken to formally verify designs by testing which will affect future helicopter procurements. Therefore, nonconformance to formal testing requirements for design performance verification is a problem that is limited to current-inventory helicopters.

REVISIONS AND SOLUTIONS

The revisions and solutions to the problems identified and verified during this investigation are presented in this section. The proposed remedial actions are divided into the following two categories:

1. Revisions for identified documentation problems
2. Solutions for identified hardware anomalies

REVISIONS

The revisions to the various documents that are used to control or verify the adequacy of REB's operating in the U.S. Army helicopter environment are presented in this section. These revisions are intended to reduce or eliminate the causes of many of the failure modes specifically addressed in the previous sections of this report. All identifiable costs associated with particular revisions are presented within the cost section of this document.

Design Requirements

Specification Control Documentation

Specification control documents such as drawings should include the specific requirements which the REB must satisfy. These will ensure that the Army's requirements are adequately improved during design and subsequent manufacture. The following requirements must be considered as a minimum:

1. Incorporation of applicable documents

a.	ABC-STD-50	Surface Texture (Formerly MIL-STD-10, Surface Roughness)
b.	FED-STD-1	Standard for Laboratory Atmospheric Conditions for Testing
c.	MIL-STD-100A	Engineering Drawing Practices
d.	MIL-STD-480	Configuration Control
e.	MIL-STD-810B	Environmental Test Methods
f.	MIL-STD-105	Sampling Procedures and Tables for Inspection by Attributes, 29 April 1963, Amended 20 March 1969

g.	MIL-I-6868	Magnetic Particle Inspection Process
h.	MIL-E-5272	General Specification for Environmental Testing, Aeronautical and Associated Equipment
i.	MIL-B-197D	Bearings, Anti-Friction, Associated Parts and Subassemblies, Packaging of, 31 December 1964
j.	MIL-I-6866B(ASG)	Inspection, Penetrant, Method of, 26 February 1964, Amended 30 January 1969
k.	MIL-I-8500B	Interchangeability and Replaceability of Component Parts for Aircraft and Missiles
l.	MIL-H-8501A	General Requirements Helicopter Flying and Ground Handling Qualities, 7 September 1961, Amended 3 April 1962
m.	MIL-F-9490C (USAF)	Flight Control Systems - Design, Installation and Test of, Piloted Aircraft, General Specification for, 13 March 1964
n.	USAS-114.5, Y14.5 1966	Dimensions and Tolerances for Engineering (Formerly MIL-STD-8)

2. U.S. Army operational environments (no specific reference to these requirements could be found in REB specifications)

   a. Vibration

   b. Shock

   c. Axial force

   d. Radial force

   e. Stroke length

   f. REB exposure to environmental factors

      Temperature
      Sand, dust
      Moisture

3. Tolerance requirements

   a. Axial

   b. Radial

4. Reliability and maintainability quantitative and qualitative requirements

   a. Mean Time Between Failures (MTBF)

   b. Mean Time to Repair (MTTR)

   c. Maintenance Man-Hours Per Flight Hour (MMH/FH)

   d. Availability

   e. Level of Repair

   f. Vibratory Loads

In addition, the typical operating requirements necessary for helicopter operations should be coordinated with and imposed upon REB suppliers by airframe manufacturers. Such an operational profile would determine the reliable performance of the flight control and other systems which contain REB's. This present lack of specific requirements during the design phase results in the premature removals for such failure modes as excessive wear tolerances. Most failures are induced by wear that involves violations of the environmental constraints of the original bearing design.

Component Selection Criteria

Criteria for selecting REB components must consider the following as a minimum:

1. Design life and cost constraints

   a. MTBF

   b. MTTR

   c. Availability

   d. MMH/FH

2. Design loads imposed by the system

   a. Input forces

   b. Output forces

   c. Vibratory levels and frequencies

3. Subsystem parameters

   a. Radial forces

   b. Axial forces

   c. Liner peel strength and bond integrity

   d. Misalignment angles

4. Operational environment

   a. Vibration

      Nominal
      Gunfire

   b. Helicopter purpose

      Gun ship
      Troops
      Cargo
      Medical/evacuation

   c. Temperature profile

      System ambient

   d. Sand, dust

   e. Moisture

Component selection criteria such as those shown in the preceding listing should be used to establish the bases for effective QA programs. The testing of REB's pursuant to these criteria provides the basis for a realistic Qualified Products List (QPL), whereas the present use of nonrepresentative criteria for helicopter REB increases the likelihood that they will not perform their intended function for acceptable periods of time.

Military Specifications and Standards

General specifications for the procurement of REB's and their components should include the provisions of MIL-STD-490, Military Standard Specification Practices. The requirements that should be imposed are as follows:

1. Item description

2. Characteristics

    a. Performance

    b. Physical characteristics

        Weight
        Dimensions
        Transport and storage requirements
        Durability factors
        Health and safety criteria
        Vulnerability

    c. Reliability

    d. Maintainability

    e. Environmental conditions

    f. Transportability

    g. Design and construction

        Materials and processes
        Electromagnetic interference
        Identification and marking
        Workmanship
        Interchangeability

    h. Safety

    i. Human performance

The U.S. Army helicopter operational requirements should be included in the REB specifications. Realistic operational environmental requirements should be incorporated into flight control system and REB specifications in order to minimize the possibility of anomalies occurring aboard Army helicopters. These improved specifications would reduce the number of premature failures that are being experienced with the presently used REB designs.

Examples of the inadequacies of current and proposed military specifications to cope with the actual operational requirements of the Army are MIL-B-8948(ASG) and MIL-B-81819 (proposed). MIL-B-8948, paragraph 4.6.3, entitled "Fatigue Load", specifically defines the method of applying the fatigue load to a bearing and the applicable MS for the determination of the size of the applied fatigue load. No accept/reject criteria are presented for this bearing fatigue test. The following criteria must be included in order to make the fatigue load test responsive to Army needs:

1. Radial and axial wear tolerances that must not be exceeded

2. Cyclic rate and fatigue load that must be sustained for each standard size bearing

3. Minimum test time without fracture of the ball and/or the race

MIL-B-81819 (proposed) is being developed at Naval Air Development Center (NADC), Warminster, Pennsylvania, by the Airframe Control Bearing Group, Code MAEN. While the scope of this NADC-proposed specification is broader than existing specifications because it covers a spherical bearing with a ceramic ball and carbon insert outer race, it is still inadequate for Army helicopter operational environmental needs. This proposed specification does not provide for the following:

1. Sampling of workmanship

2. Sampling of radial or axial play

3. Material or liner integrity tests

4. Contamination testing with an alternating load instead of a constant applied load

5. Vibration testing at the natural frequencies of the control linkage and at the dominant frequencies experienced by the airframe

Contract Specifications

Contract procurement specifications should be prepared for each type of REB intended for helicopter use. These specifications may be prepared by either the U.S. Army or its contractor.

These specifications should include the following as a minimum:

1. Specific design requirements

    a. Operating profile

    b. Miscellaneous control subsystem parameters

    c. Flight control subsystem parameters

2. Environmental requirement

    a. Vibration

    b. Temperature

    c. Sand, dust

    d. Moisture

3. Life-cycle cost constraints

    a. MTBF

    b. MTTR

    c. Availability

    d. MMH/FH

    e. Cyclic rate

    f. Fatigue limit loads

    g. LOR

When realistic contract specification requirements are imposed on the contractor, the likelihood of failure modes occurring is minimized.

Design Requirements To Eliminate Induced Failures

An FMEA should be accomplished for each preliminary design to reveal the failure modes, causes, effects, and design compensating provisions.

In determining the failure modes, attention should be given to the following performance parameters:

1. Vibration, shock
2. Axial and radial dynamic loading profile
3. Cyclic rate
4. Linkage force
5. REB exposure to environmental factors
   a. Temperature profile
   b. Sand, dust
   c. Moisture
6. Mission of helicopter
7. Component materials
8. State of the art

Quality Assurance

A comprehensive QA program plan for each helicopter and its essential components, such as REB's, must be established and imposed upon the contractor and his vendors. To be effective as a management tool, the QA program must consider the following areas as minimum.

Vendor Quality Control

Each vendor must establish a comprehensive QA program at his respective facility. This program should include, as a minimum the following:

1. Materials (ball, race, plating, liner)
2. Process procedures (heat treatment, finish, bonding, threading)
3. Load testing
   a. Dynamic (for compatibility with various fluids commonly used aboard helicopters, temperature extremes, vibration, and dust)
   b. Axial proof

c. Ultimate static

d. Fatigue

4. Process equipment used for

   a. Tolerances (inside diameters, outside diameters, axial and radial play, no-load rotational torque, misalignment)

   b. Inspections (dye penetrant, magnaflux, hardness)

   c. Environmental simulation tests (temperature chamber, fluids, vibration platform, dust)

5. Component sizing/tolerances (micrometer, dial indicator, electronic pickup device)

6. Liner integrity

   a. Uniformity (edges set back, no porosity, no excessively wide void between races, invariant liner thickness)

   b. Bonding (no tearing, tight adherence to edges and over 90 percent of contact area)

   c. Purity (no embedded contaminants)

7. Reference to applicable documents

   a. Military specifications (REB's, spherical bearings, fluid compatibility, drawings, fracture inspection, threading, wrenching)

   b. Military standards (spherical bearings, sampling, marking, finish)

   c. Contract specifications (qualification and conformity certification, warranty, military standards and specifications required for whole REB's)

   d. Vendor QA procedure (in accordance with a military specification and kept on file by Government and airframe manufacturer)

The following REB product characteristics require 100-percent QA inspection and should include the following as a minimum:

1. Material integrity (faults, cracks)
2. Surface finish (workmanship)
   a. Waviness
   b. RMS finish
   c. Scratched surface
   d. Threading
3. No-load rotational torque

The QA procedure should include provisions to inspect packing and shipping methods, procedures, and materials. The packing and shipping should be accomplished in accordance with the applicable military specifications. An example for QA testing and packaging is MIL-B-8948(ASG) for TFE-lined bearings; for packing, MIL-B-197D should be used. This further prevents defects in the REB.

Airframe Manufacturer Receiving Inspection

Receiving inspections at the manufacturer's facility should include as a minimum the following:

1. A visual inspection to determine if any obvious damage was experienced during shipping.
2. Operational checks of each REB production lot. These should be accomplished in accordance with the sampling techniques established by MIL-STD-105D and MIL-C-5503C.

The adequacy of source inspections by vendor QA personnel and the packaging and shipping techniques have a direct effect on the frequency of operational checks required by MIL-STD-105D. That is, as the rate of rejection increases, the more frequently the lot sampling checks must be performed.

As a minimum requirement, REB's should be visually inspected to determine if any obvious damage has occurred. It is recommended that the receiving inspection include a lot sample check of the ball-to-race tolerance and no-load rotational torque. The airframe manufacturer should sample dimensions, identification, workmanship, packing, conformity, liner bonding hardness, and material integrity. Hence, defective REB's will be rejected early enough to be cost effective.

The most prevalent failure mode that could be reduced or eliminated is binding, caused in transit and resulting in the REB's being bent and the ball jammed. This type of damage usually results from improper packaging, as noted. An operational inspection review should be required prior to installation in the helicopter, and it should also be performed whenever the package is damaged.

Initial Installation Procedures

When manufacturers install REB's in essential or safety-of-flight systems, QA personnel should inspect and verify the adequacy of the installation process. This observation procedure need not be a 100-percent inspection of each bearing, but the sampling method of observing some REB installations should be employed. The 100-percent inspection method should be used on the first few helicopters when personnel new to the job are used. This assures that defective bearings which would accelerate the bearing wear process are not installed. After an installation is complete and prior to operational "power on" checks, QA personnel must complete a 100-percent inspection process.

1. An installation check should be performed and include the following as a minimum:

   a. Verification that installation procedures are in the possession of mechanics

   b. Verification that installation procedures are followed by mechanics

   c. Verification that no physical defects were observed

   d. Verification that applied torque values are within tolerances

   e. Verification that safety wire or other positive locking provision requirements are accomplished in accordance with applicable military specifications

2. The preoperational QA inspection should be performed and include, as a minimum, verification of the following:

   a. Each REB linkage properly installed

      (1) Torque wrenches properly certified for accuracy

      (2) No physical defects such as oddly formed race, frayed liners, or bent rods exist

      (3) Safety wiring performed in accordance with the applicable specifications

b. The linkage movement not obstructed by excessive bearing friction, or interference with other items

c. All mechanical interfaces completed

d. Total play in the linkage within specified limits

Verification of the formal installation procedures should be furnished for each helicopter delivered to the Army.

The failure mode that would be minimized or eliminated would be that of connecting rods becoming disconnected or jammed in place during flight. The occurrence of such a failure would likely result in a loss of flight controls and subsequent crash damage to the helicopter. The initial installation inspections would minimize failure modes induced by installation errors. The same procedures should be used to verify REB replacement by U. S. Army maintenance personnel.

Functional Test Procedures

The airframe manufacturers should perform functional tests of REB's with QA personnel observing. During these tests, the QA personnel should as a minimum verify the following:

1. Allowable no-load rotational torques are not exceeded.

2. Allowable tolerances between ball and race are maintained.

3. Control mechanism responds to inputs in all modes without friction, creeping, or excess force required.

4. Functional flight tests are performed which show that no operational restrictions are encountered which are the result of REB linkage problems.

These procedures should be of sufficient depth and detail to ensure that the REB's will perform their intended purpose. These functional ground and flight test procedures should demonstrate adherence to the performance requirements set forth in the imposed contract and military specifications. Documented assurance that comprehensive functional test procedures have been used to verify helicopter performance should be provided with each helicopter delivered to the Army. This assures the Army that each helicopter has met or exceeded minimum operational requirements prior to delivery. This also reduces the likelihood of an in-flight failure caused by REB problems.

Mandatory Inspection Points

Rod end bearings for flight control systems have certain inspection criteria that should be clearly enumerated on QA inspection sheets.

These QA mandatory Inspection Point Checklists must be accomplished at airframe manufacturer, REB vendor, component supplier, and Army maintenance facilities by QA or maintenance verification personnel.

The mandatory Inspection Point Checklist for REB's installed in the helicopter should include the following as a minimum:

1. Mechanical links

    a. Links

        Securely fastened
        Not binding

    b. Safety wiring in accordance with accepted practices

2. Spherical bearings

    a. Gap between ball and race within specified limits

    b. Ball not cracked or corroded

    c. Breakaway torque within specified limits

    d. Race not deformed or damaged

Component Sampling Procedures

Certification of conformity tests should be mandatory. Explicit steps for permissible retesting of failed lots should be established. Sampling rates should be assigned to various quality conformance tests such as those set forth in MIL-B-8948(ASG) and MIL-B-81819. Tests which require a 100-percent check, such as no-load rotational torque, workmanship, and fracture checking according to MIL-I-6866 or MIL-I-6868, should be defined. These should be required of at least the bearing manufacturer. Then the manufacturer should have all the testing equipment available to him in order to qualify under the military specifications. There should also be sampling of such things as ball-to-race tolerance, no-load rotational torque, and misalignment angle maximum and minimum limits.

Rod end bearings and their constituent components such as balls, races, liners, and bonding materials are very amenable to lot sampling techniques. The frequency of these inspections should be governed by MIL-STD-105D.

Lot or batch testing/inspection for REB components should be performed and should include the following:

1. Material ingredients
2. Process procedures
3. Surface finish
4. Dimensional sizing
5. Process equipment
    a. Tolerances
    b. Inspections
    c. Calibrations
6. Component sizing/tolerances
7. Elastomer products - bonding integrity
8. Reference to applicable documents
    a. Military specifications
    b. Military standards
    c. Contract specifications
    d. Vendor QA procedures

Maintenance Procedures and Practices

Maintenance Manuals

These recommended revisions in technical and preventive maintenance manuals, if adopted, will eventually affect all aircraft in the Army inventory. For purposes of this report, manuals for the UH-1D/H are referred to as representative baselines for candidate improvements.

Reviewed were the following manuals which govern UH-1D/H helicopter maintenance:

1. TM55-1520-210-20PMD, Preventive Daily
2. TM55-1520-210-20PMI, Preventive Intermediate
3. TM55-1520-210-20PMP, Preventive Periodic

4. TM55-1520-210-20, Organizational Manual

5. TM55-1520-210-20P-1, 2, and 3, Organizational Maintenance Repair Parts and Special Tools List

The technical organizational and direct/general support maintenance manuals are essentially complete with respect to maintenance procedures. The following recommendations are made in order to make them more comprehensive and to improve the quality verification of aircraft maintenance:

1. Functional descriptions of each system should begin each chapter. This would assist in understanding the operation of the system and the required troubleshooting procedures. An example of functional description of the collective pitch control linkage can best be shown by a comparison between an Army TM and its equivalent Navy manual. (This linkage was used because it contains REB's.)

   Example from Army manual

   TM 55-1520-210-20

   9-8. Collective Pitch Control Linkage.

   Linkage between collective pitch control jackshaft and collective sleeve lever on swashplate support consists of push-pull tubes, bellcranks, and hydraulic power cylinder assembly.

   Example from Navy manual

   NAVAIR 01-110HCA-2-1

   6-30. DESCRIPTION. The collector lever and idler link assemblies are parts of the collective pitch control system. The lever connects to the idler link and to top of the collective control cylinder and the pins insert into bearings of the sleeve assembly.

2. Materials and manpower requirements should be provided for each maintenance procedure. An example of a Navy intermediate maintenance manual which includes materials and manpower requirements is:

NAVAIR 01-110HCA-2-1 | **SECTION VI Paragraph 6-30 to 6-31**

Spares and Repair Part Data

Repair of the lever and idler link assemblies is limited to replacement of bearings, seals and bushing.

Tools and Equipment Required

No special tools required.

Materials Required

Solvent	**P-D-680**
Corrosion Preventive Compound	**MIL-C-11796 Class 3**

Manpower Required

One man required.

Quality Assurance Required

Inspection is required when step is underlined.

These manpower and tools requirements do not exist in the corresponding Army manual.

3. Maintenance verification provisions need to be incorporated in the maintenance procedures at all levels of maintenance in order to certify the following:

   a. Proper material condition

   b. Correct component assembly or installation

   c. Proper system functioning following overhaul or repair

Incorporation of maintenance verification into all manuals will have a major impact on reducing accelerated REB wear resulting from improper maintenance.

Periodic Inspections

This investigation has uncovered certain weaknesses in the daily, intermediate, and periodic Army preventive maintenance cards. Samples of NAVAIR publications are included as representative of the recommended course of action to be followed.

1. Daily Preventive Maintenance

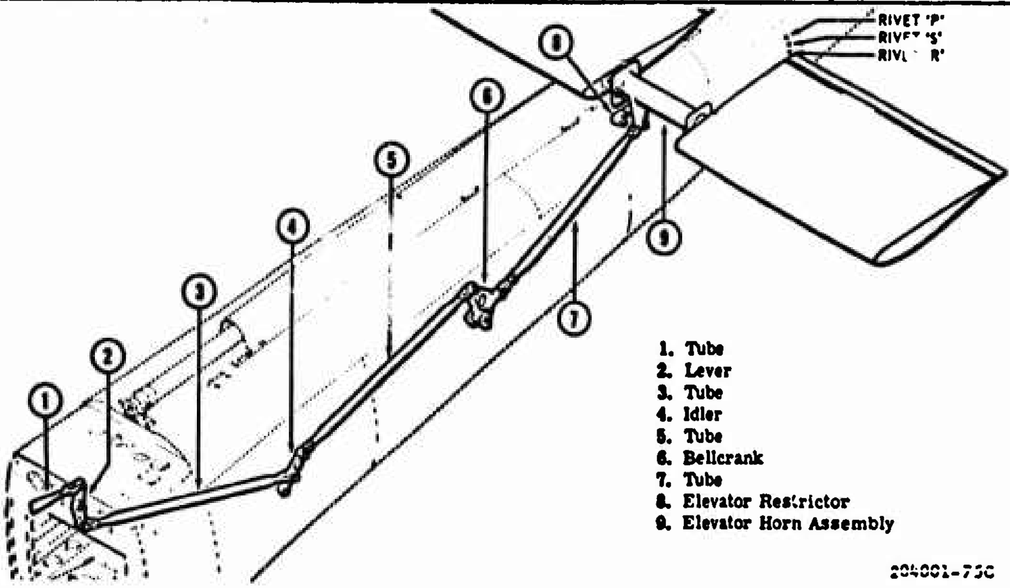
Figures 8 and 9 present examples of Army and Navy maintenance cards. The Army card is general in its wording but does define the tasks in enough detail to avoid maintenance-induced REB problems. On the Navy card the quantitative parameters necessary to perform effective maintenance are shown along with appropriate diagrams. Manpower, time to perform, test equipment, and material condition are presented on the Navy cards whenever such information is required. Warning and caution notes are also included when necessary. The Army should adopt a card system similar to that of the Navy. These cards should specify details of all actions that are performed during the daily preventive maintenance inspection process.

PERIODIC INSPECTION CHECKLIST TM 55-1520-210-PMP

Seq. No.	Freq.	Item and Procedure
		CRITICAL INSPECTION ITEM
3.4		CONTROL LINKAGE AND HYDRAULIC CYLINDERS IN FUSELAGE BELOW PYLON FOR SECURITY, DAMAGE, AND EVIDENCE OF LEAKS FROM CYLINDERS AND CONNECTING LINES. CHECK CYCLIC AND COLLECTIVE CYLINDERS FOR PROPER CLEARANCE BETWEEN SERVO VALVE AND INPUT LEVER ADJUSTING SCREW. CHECK CYCLIC AND COLLECTIVE CYLINDERS FOR SECURITY OF THE RETAINER AND TO ASSURE THAT THE TAB WASHER TANGS ARE BENT AND MAKING CONTACT WITH FLATS ON THE RETAINER. CAREFULLY INSPECT (BY A FEEL TEST) THE RETAINER (P/N 100621 OR P/N 100621-1) FOR LOOSENESS.

Figure 8. Example of U.S. Army Checklist.

CARD 30.1	PUBLICATION NUMBER NAVAIR 01-110HCA-6-4	ELEVATOR CONTROLS	CHANGED



TASK MIN.	WORK AREA	CARD 30.2	PUBLICATION NUMBER NAVAIR 01-110HCA-6-4	CHANGED	ELEC PWR N/A HYD PWR ON

TASK MIN.	WORK AREA			
		NOTE:		With cyclic stick in full aft position the elevator should align with rivet S, plus or minus 0.25 inch.
			c.	Turn hydraulic power OFF and direct assistant to disconnect hydraulic power cart.
25.0	6	2.		Elevator Control System.
			a.	Tubes for nicks, dents, corrosion, distortion and for security.
		NOTE:		The maximum allowable tolerance of bearings in the elevator system is 0.005 radial and 0.030 axial.
			b.	Lever for nicks, cracks, corrosion, security and excessive play in its three bearings.
			c.	Idler and bellcrank for nicks, cracks, corrosion, security and excessive play in its three bearings.
			d.	Elevator horn assembly for nicks, cracks, corrosion and security.
			e.	Elevator bearing supports for security and support brackets for cracks, corrosion, loose and/or missing rivets.
		ABC	f.	Elevator for axial and radial movement at inboard edge; 0.010 maximum.
		540S	g.	Elevator for axial and radial movement at inboard edge; axial 0.005 to 0.030, radial 0.010.

Figure 9. Example of U.S. Navy Maintenance Requirements Card for Same Helicopter.

2. <u>Intermediate and Periodic Preventive Maintenance</u>

These levels of scheduled maintenance are approximately equal to the Navy organizational calendar maintenance check. The main difference is in the interval. The Army uses flight hours, and the Navy uses calendar intervals. Figure 10, NAVAIR 01-110HCA-6-4, is another example of a scheduled maintenance inspection action involving an REB in the flight control system. It should be noted that each subsequent item inspected describes what actions are taken. Manpower, skill level, materials, and special tools are delineated. Maintenance verification is specified as an integral part of the process. Special notes are provided, as are warnings and cautions when required.

The following three areas regarding scheduled maintenance at the organizational level should be incorporated into the Army maintenance documentation:

a. Present detailed steps which must be taken for inspection.

CARD 35	TIME 00:30	RTG. NO. AMS 2	CALENDAR	CABIN AREA FLIGHT CONTROLS	ELEC PWR N/A HYD PWR N/A
TASK MIN.	WORK AREA	MOS. 6114 NO. 2	PUBLICATION NUMBER NAVAIR 01-110HCA-6-4	CARD SET DATE 15 February 1970	CHANGED

SPECIAL TOOLS/EQUIPMENT

Indicator, Dial 22A

TASK MIN.	WORK AREA	
30.0	2	1. Flight Controls.

NOTE: The bearings in the flight control system have a maximum allowable tolerance of 0.005 radial and 0.030 axial.

a. Collective control tubes, throttle jackshaft and bellcranks for corrosion, distortion and excessive play in bearings.

b. Forward and aft control tubes and bellcranks for corrosion, distortion and excessive play in bearings.

c. Lateral control tubes and bellcranks for corrosion, distortion and excessive play in bearings.

d. Tail rotor control tubes and bellcranks for corrosion, distortion and excessive play in bearings.

Figure 10. Flight Control Inspection Card.

b. Adopt an interval of scheduled maintenance which favors planned inspection.

c. Integrate maintenance verification into the inspection procedure as a requirement in writing. Thus, maintenance verification sign-off certifies that procedures, as specified, have been followed correctly.

Imposition of maintenance verification in writing would offset any tendencies to neglect performing required preventive maintenance.

Failure Criteria and Detection

The criteria to establish what is a defective piece of equipment and how to detect failures in FEB's should include the following:

1. State of the art
2. Allowable manufacturing tolerances
3. Bearing clearance criteria by inherent design
4. Load capacity
5. Allowable friction
6. Operational characteristics of the system in which the REB is installed

Establishment of such failure criteria and detection at the organizational level would reduce the presently significant level of REB removals which are due to accelerated wear. Examples of REB's that have failed at the organizational level are as follows:

1. Stiff controls
2. Excessive vibration
3. Peeling liner
4. Pitted or scored balls

The radial and axial play of each REB should be measured by a dial indicator every 25 operating hours for bearings mounted on or near the rotors and every 100 hours for bearings in the control linkage. Tolerances should be recorded and dated. If there has been a recent trend toward larger tolerances for a given REB, it should be replaced and the whole control linkage assembly should be examined because once the wear process accelerates, the tolerance will widen rapidly. The bearing may be out of tolerance by the next maintenance check.

Looseness in other control rod links (tubes) or other types of bearings may be causing the linkage to vibrate excessively, thus unswaging the REB in a control link. Tolerances must be included in the 25- and 100-hour preventive maintenance cards. Note that the linkage does not have to be disassembled to apply the dial indicator. There are various pedal deflections associated with allowable radial play. Excessive axial play indicates a worn or loose REB or loose threads. Data from the appropriate TM should be included on the preventive maintenance cards for each test mode of the control sticks and pedals.

Similar criteria could be used at other levels of Army maintenance, provided the REB is checked under conditions similar to those experienced in the helicopter.

Maintenance Personnel Skill Level, Qualifications, and Training

The following revisions are recommended:

1. Lengthen initial formal training. The "AH-1G Helicopter Repair Course" is currently 11 weeks, 3.5 days in duration. The personnel receive only 40 hours of instruction in the flight control and hydraulic systems. This should be expanded to 120 hours to include a minimum of 40 hours of actual rigging of the flight control system and maintenance practices concerning troubleshooting, removal and replacement of REB's.

2. Include pointers on good maintenance practices in the lesson plan. An example would be to keep REB surfaces free from contaminants such as oil, grease, sand, and dirt.

3. Institute follow-up formal training to augment OJT.

4. Identify skill levels required for performing maintenance.

Overall upgrading of training and skill level requirements provides a major impact on improved REB operational service life.

Special Tool Requirements

No recommendations for revisions are included for the tool requirements list or tool availability.

Component Accessibility

It is recommended that access panels be identified with respect to both scheduled and unscheduled maintenance. Access should be identified in the preventive maintenance and technical manuals. In corresponding Navy technical publications, access panels for the

UH-1E are readily identified and numbered 1 through 91; they are referred to in maintenance procedures in terms of removal and installation.

Test Requirements and Procedures

A comprehensive Test Program Plan must be established and these test requirements imposed upon contractors and their vendors for each helicopter design and its major components. To be effective as a management tool, the test program must consider the following areas as a minimum:

1. Environment
2. System compatibility
3. Qualification
4. Flight
5. Service
6. Acceptance

Each of these areas is discussed as to the specific recommendation to eliminate or minimize the current problems being experienced.

Environmental Testing

Environmental testing of aeronautical equipment is controlled by MIL-STD-810B. The operational characteristics required of the REB's, as delineated by the applicable contract specification, should be tested using the test methods of MIL-STD-810B for each category. During these tests, the REB's should be operated in accordance with the requirements set forth in the applicable contract specification. Some of these environmental tests are required by MIL-C-5503C; however, they do not adequately reflect the Arm operational environment. Realistic operating environmental parameters must be established in order to effectively test the systems containing REB's pursuant to the methods established by MIL-STD-810B.

The environmental characteristics recommended by MIL-STD-810B, Table I, and that should be considered as a minimum are as follows:

1. Temperature and Pressure

    a. High Temperature - The high-temperature test is conducted to determine the resistance of equipment to elevated temperatures that may be encountered during service life either in storage (without protective packaging) or under service conditions. In equipment, high-temperature conditions may cause the permanent set of packings and gaskets. Binding of parts may also result in items of complex construction due to differential expansion of dissimilar metals. Rubber, plastic, and plywood may tend to discolor, crack, bulge, check or craze. Closure and sealing strips may partially melt and adhere to contacting parts.

b. Low Temperature - The low-temperature test is conducted to determine the effects of low temperature on equipment during storage (without protective packaging) or service use. Differential contraction of metal parts, loss of resiliency of packings and gaskets, and congealing of lubricants are a few of the difficulties associated with low temperatures.

c. Temperature Shock - The temperature-shock test is conducted to determine the effects of sudden changes in temperature. Cracking or rupture of materials due to sudden dimensional changes caused by expansion or contraction are the principal difficulties to be anticipated. These could occur in service due to rapid altitude changes during shipments and airdrops.

d. Altitude - The altitude test is conducted to determine the effects of reduced pressure on equipment. Damaging effects of low pressure include leakage of gases or fluids from gasket-sealed enclosures and rupture of pressurized containers. Under low-pressure conditions, the physical and chemical properties of low-density materials change. Damage due to low pressure may be augmented or accelerated by the contraction, embrittlement, and fluid congealing induced by low temperature. Erratic operation or malfunction of equipment may result from arcing or corona. Greatly decreased efficiency of convection and conduction in heat-transfer mechanisms under low-pressure conditions is encountered. This test method is used for the purpose of determining the ability of equipment to operate satisfactorily during the following exposure to both reduced pressure and temperature conditions encountered during flight.

2. Corrosion and Erosion

a. Rain - The rain test is conducted to determine the effectiveness of protective covers or cases to shield equipment. This test is applicable to equipment which may be exposed to rain under service conditions. Where a requirement exists for determining the effects of rain erosion on radomes, nose cones, etc., a rocket sled test facility or other such facility should be considered. Since any test procedure developed would be contingent on requirements peculiar to the test item and the facility employed, a standardized test procedure for rain erosion is not included in this test method.

b. Humidity - The humidity test is applicable to all equipment and is conducted to determine the resistance of equipment to the effects of exposure to a warm, highly humid atmosphere such as is encountered in tropical areas. This is an accelerated environmental test, accomplished by the continuous exposure of the equipment to high relative humidity at an elevated temperature. These conditions impose a vapor pressure on the equipment under test and constitute the major force behind the moisture migration and penetration. Corrosion is one of the principal effects of humidity. Hygroscopic materials are sensitive to moisture and may deteriorate rapidly under humid conditions. Absorption of moisture by many materials results in swelling, which destroys their functional utility and causes loss of physical strength and changes in other important mechanical properties. Insulating materials which absorb moisture may suffer degradation of their electrical and thermal properties.

c. Fungus - The fungus test is used to determine the resistance of equipment to fungi and to determine if the equipment is adversely affected under conditions that are favorable to fungi development, namely, high humidity, warm atmosphere, and presence of inorganic salts.

d. Salt Spray - The salt fog test is conducted to determine the resistance of equipment to the effects of a salt atmosphere. Damage to be expected from exposure to salt fog is primarily corrosion of metals, although in some instances salt deposits may result in clogging or binding of moving parts. In order to accelerate this test and thereby reduce testing time, the specified concentration of moisture and salt is greater than is found in service. The test is applicable to any equipment exposed in service to salt fog conditions.

e. Dust - The dust test is used during the development, test, and evaluation of equipment to ascertain its ability to resist the effects of a dry dust (fine sand) laden atmosphere. This test simulates the effect of sharp-edged dust (fine sand) particles, up to 150 microns in size, which may penetrate into cracks, crevices, bearings, and joints and cause a variety of damage such as fouling moving parts, making relays inoperative, forming electrically conductive bridges with resulting "shorts", and acting as a nucleus for the collection of water vapor. Hence, this is a source of possible corrosion and malfunction of equipment. This test is applicable to all mechanical, electrical, electronic, electrochemical, and electromechanical devices for which exposure to the effects of a dry dust (fine sand) laden atmosphere is anticipated.

3. Mechanical

a. Vibration - The vibration test is conducted to determine if the equipment is constructed to withstand expected dynamic vibrational stresses and if performance degradations or malfunctions will be produced by the simulated service vibration environment.

b. Acceleration - The acceleration test is intended to determine structural soundness and satisfactory performance of equipment in an environment of steady-state acceleration other than gravity.

c. Shock - The shock test is conducted to determine that structural integrity and performance of equipment are satisfactory with respect to the mechanical shock environment expected in handling, transportation, and service use.

Environmental testing requirements of REB's are set forth in the proposed MIL-B-81819.

System Compatibility Tests

Specific details of system interface requirements such as those with the REB's should be delineated in the helicopter and systems detail specifications. In order to ensure that the REB's are compatible with systems such as the flight control system, the following requirements should be included as a minimum:

1. Linkage kinematics are mechanically adaptable to control system, and the REB cannot lock in place.
2. Operational forces do not exceed REB design loads.
3. The control system is functional throughout the operational envelope.

Test requirements must be established to ensure that the REB's are functional throughout the operational envelope of the helicopter flight control system. The flight control system specification requirements should be used as the baseline functional requirements. The system should be functionally tested to establish the compatibility of the REB's with other flight control subsystem components, such as bell cranks, levers, pedals, hydraulic subsystems, and swashplates. These tests will ensure the Army and designers that the flight control system will function without excessive play in the linkage and without excessive load or vibration on the bearing prior to flight tests.

Qualification Test Requirements and Procedures

Component qualification tests should be in accordance with a military specification such as MIL-B-8948(ASG) or the proposed MIL-B-81819, both of which should include vibration, liner bonding, and ball-to-race tolerance tests. Qualification tests must be accomplished by the REB manufacturer, with certification of test results placed on record with the Government.

System qualification tests should include a series of flight tests with adequate maintenance procedures. These tests should be performed with Army and contractor personnel in attendance. This process would allow sufficient time for the development of REB wear due to inherent design and environmental conditions. Fatigue testing the helicopter without proper adjustments or inspections would give worse-case operational life, but the formulation of fault isolation of the REB failures would be difficult or impossible. Other failures in the control linkage that could promote an REB failure, such as the cascade effect resulting from an improperly maintained flight control system, could be identified.

Flight Test Plans and Procedures

Flight testing of control systems such as the flight control system and its components, i.e., REB, connecting rods, turnbuckles, and bell cranks, is required by MIL-F-9490C for Air Force aircraft and by MIL-F-18372(Aer) for Navy aircraft. It is recognized that Army military specifications can be used by the other branches of service; no specific requirement is addressed for Army fixed- or rotary-wing aircraft.

Flight test plans for Army helicopters, whether developmental, preproduction or production test flights by airframe manufacturer personnel for a new or modified helicopter, should include sufficient parameters to demonstrate that the helicopter will perform to the projected operational requirements.

Maintenance test flight provisions by Army personnel are governed by TB AVN 23-16. These provisions are general in nature, and the detailed test flight criteria for each helicopter design are governed by the applicable Army technical manual for that helicopter. Maintenance inspection personnel should attend Army test flights to ensure proper adherence to flight test procedures and detection of all symptomatic REB failures, especially those due to excessive wear.

Service Testing

Service testing of helicopters and other such essential equipment being supplied to the Army should be performed in general accordance with MIL-STD-471, Maintainability Demonstration Testing. Six test methods are specified in MIL-STD-471; the specific test method selected in maintainability demonstration must consider the following:

1. Risk - The probability that the task can be accomplished in a given time.

2. Cost - Allowable cost to conduct the demonstration.

3. Time - The time frame in which the test must be completed.

The method of selection should be based upon these criteria and should include the particular hardware and procuring activity requirements.

The Army personnel assigned should possess the applicable Military Occupational Speciality (MOS) (67xxx) for the flight control rigging tasks. In addition, these personnel and those with a crew chief MOS (67N20 for the UH-1 helicopter) should be able to maintain the flight control system containing REB's. The service test plan provision should enumerate the types of failures that are expected during the normal service of the helicopter within the projected operational parameters. Additional preventive maintenance checklist tasks should be included in the service test plans. The assigned personnel, with a MOS of 67N20 for the UH-1 helicopter, should be able to successfully demonstrate that each maintenance task can be accomplished by using the provided maintenance manuals, procedures, special tools, and spares provisioning.

Acceptance Testing

Acceptance testing requirements should be delineated in the test plan that each airframe manufacturer is required to submit to the procuring agency. This test plan should govern the scope and quantitative requirements of the acceptance test. In the case of the helicopter, the acceptance test must include provisions for both ground and flight test. For procurement of such equipment as REB's, these tests should include both operational test in simulated operational environments and a system compatibility test after installation in the designated helicopter.

SOLUTIONS

This section presents proposed solutions to alleviate the shortened life cycle and high replacement rate being experienced with REB's installed aboard helicopters by the Army. These solutions are segregated into immediate and long-range solutions. The immediate solutions involve the use of existing hardware in one-for-one replacements. This existing hardware has sufficient performance data to indicate that reductions in the present replacement rate can be obtained. The long-range solution represents a state-of-the-art change. These long-range solutions require further testing to demonstrate that actual performance improvements can be attained.

Immediate Solutions

Ceramic-Coated Stainless Steel Ball With Carbon Insert Outer Race

Use of the ceramic-coated ball/carbon insert outer race bearing shown in Figure 11 resulted in operational replacement rate decreases ranging from 100 percent to 800 percent when installed aboard U.S. Navy UH-2 Seasprite helicopters. These bearings have demonstrated this improvement under extended sea duty (i.e., when exposed to salt spray and moisture under vibratory loading). The carbon insert outer race limits the use of this type bearing to low-radial-loading applications.

Slotted Spherical Bearings

Figure 12 shows a slotted spherical bearing assembly sequence. The slotted bearing race allows the ball to be inserted into an accurately machined and lapped race of Stellite 6 material. This approach provides a hard race with a ball which is slightly softer and which has very small gaps. The slotted small gap design has not been used on helicopters, but satisfactory results have been obtained on jet engine thrust reversers.

The slot does weaken the race; however, this situation is adequately compensated for by the use of harder and stronger materials. Further compensation for this weakness can be attained by placing the closed end of the race in a manner which opposes the direction of maximum axial load.

Full lubrication is possible with this design approach. However, in many cases the hardness of materials presently being used eliminates the need for lubrication.

The ease of bearing disassembly makes inspection and maintenance a simple matter. If dry-film lubricants are used, reapplication can be easily made to either or both ball and race surfaces.

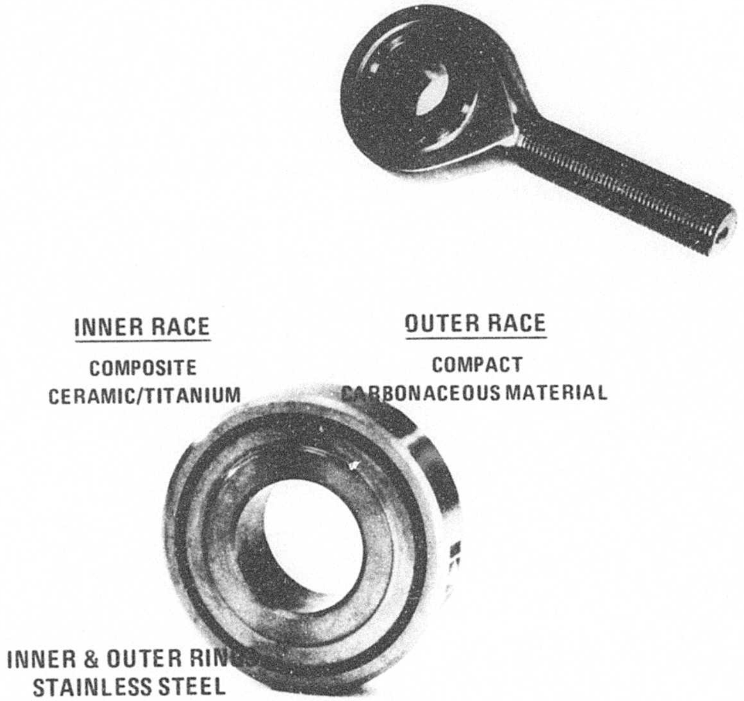


Figure 11. Typical Ceramic-Coated Ball/Carbon Insert Outer Race Rod End Bearing.

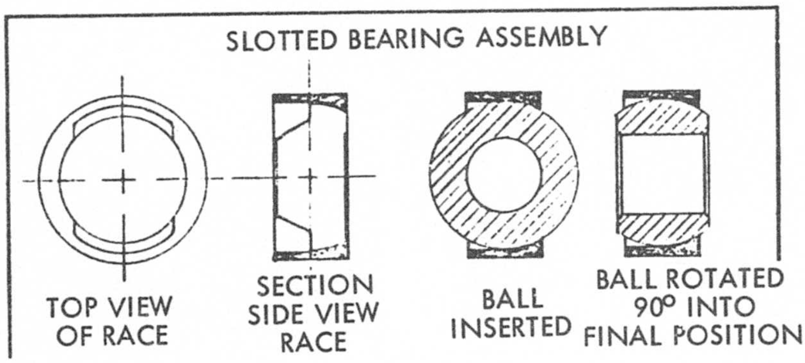


Figure 12. Typical Slotted Bearing Assembly.

Complete rerigging of a control system would not normally be required because the ball is the only item usually replaced.

Boots or Protective Coverings

Boots or protective coverings should be used over REB's when they are installed in an area that exposes them to various fluids and dirt particles. Figure 13 shows an example of a boot that improved the useful operational life of a bearing assembly on the UH-1 helicopter. A similar concept could be developed to protect REB's from the adverse environmental conditions.

All boots or protective covers that are installed aboard helicopters must be tested for compatibility with the fluids and dirt particles to which they will be exposed.

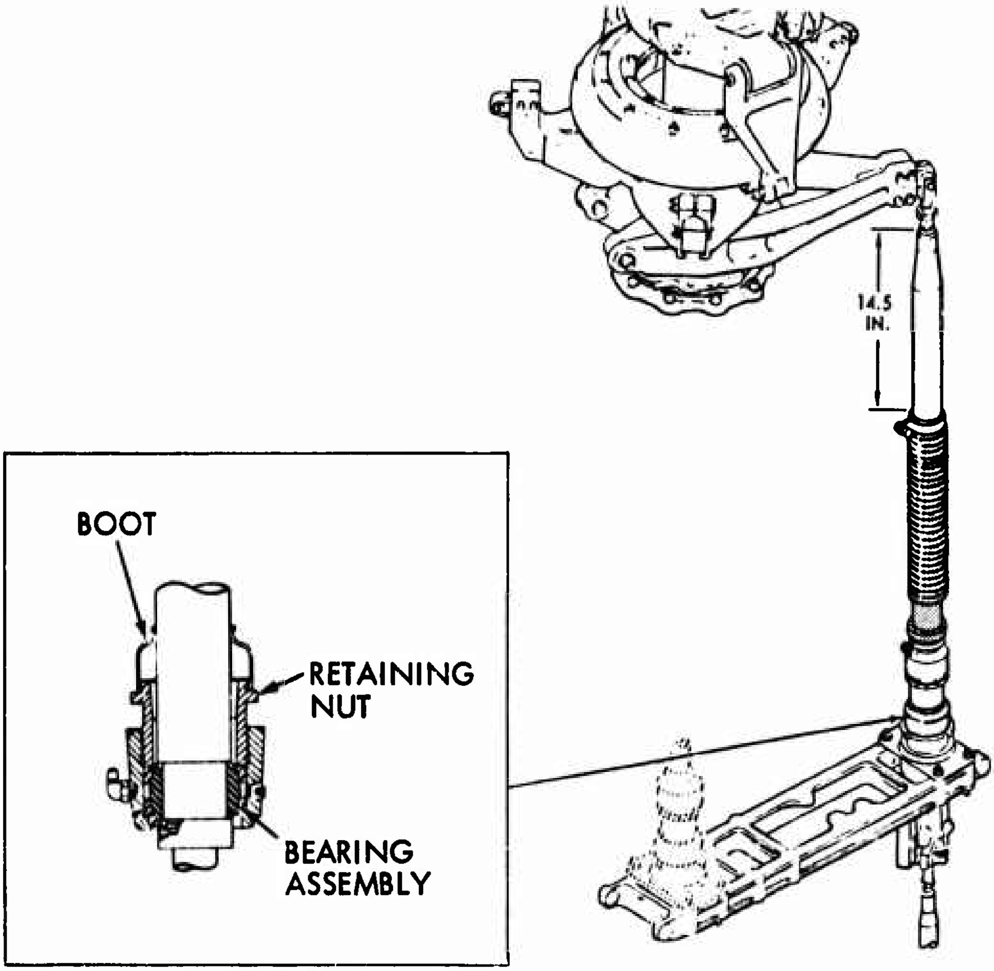


Figure 13. Example of Boot Protection for Bearing.

Long-Range Solution

During the course of the study, an elastomeric bearing was encountered which holds a potential for control linkage application in place of REB's. The elastomeric bearing needs no periodic lubrication. It has no movement between adjacent edges to cause wear. It is recommended that the elastomeric bearing be studied to determine if such a bearing can be developed to meet temperature, load, and size requirements for both the high- and low-load helicopter applications. Elastomeric bearings flying on the CH-53 have resulted in substantial reduction in cost and maintenance. Elastomeric bearings are currently manufactured for other applications. An example of an elastomeric bearing flight-tested aboard an AH-1 is shown in Figure 14.

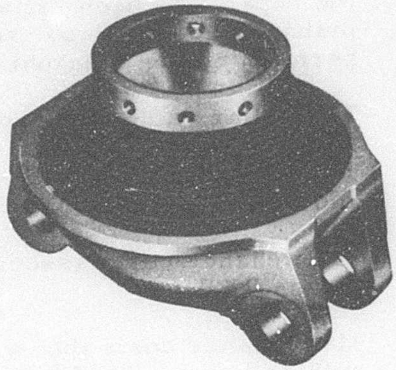


Figure 14. Example of Elastomeric Conical Bearing.

COST COMPARISONS AND SAVINGS

TOTAL COST SAVINGS

This section presents an estimation of the potential dollar savings that could be realized by the Army if improved REB designs were installed aboard their fleet of UH-1H helicopters. The definitions listed below are provided to facilitate comprehension of the remainder of this section.

Repair Cost	The time required to remove and replace the malfunctioned part multiplied by the labor rate of the personnel performing the repair action
Checkout Cost	The time required to check out and verify that the repair has been satisfactorily performed multiplied by the labor rate of the personnel performing the checkout action
Part Cost	The dollar value of a replacement part
Maintenance Cost (Total Cost)	The sum of the repair cost, the checkout cost, and the part cost
Current Costs	Maintenance costs associated with the current design REB
Expected Costs	Maintenance costs that would be associated with an improved REB design
Savings	The current cost minus the expected cost

All maintenance costs and savings shown in this section are presented at various confidence levels and/or risk levels. Confidence level as used in this section is in complete conformance with the defintion presented in Chapter 20 of U.S. Army Technical Manual TM38-715-1, entitled "Provisioning Techniques." This manual defines confidence level as ". . . a statistical determination of the probability of the repair parts' being available if one is demanded." The risk level presents the probability that parts will not be available when demanded. Risk levels are obtained by subtracting confidence levels from unity. Potential cost savings represent the dollar value of the maintenance costs that would not have to be expended on a new design. These savings result from a reduction in the number of maintenance actions required and the number of parts required to support a fleet of 1833 UH-1H helicopters for one year.

Specifically excluded from this analysis are logistics system costs, training costs, maintenance facilities costs, maintenance tooling costs, and savings that would be realized from increased helicopter availability.

The determination of these costs and potential savings in these areas of cost is beyond the scope of this investigation.

This cost analysis is based on the model shown in the appendix of this report. The cost model required specific information inputs, namely, repair cost, failure rates, flight time, and number of units per helicopter. These input data sources are discussed below.

Failure Rates

The failure rate data used in this study were obtained primarily from RAMMIT reports. Additional data were obtained from the FARADA handbooks, private industry reports, and information furnished by the FAA. One problem encountered in this data collection effort was the lack of reference to specific breakdown caused by bearing failure. The bearings are considered to be a part of the system within which they operate. Army reports cover the entire system, thus eliminating detailed reports on the parts within it (such as REB's). The bearing failure data used herein were extracted from these system data and were used in conjunction with the reported failure modes.

The RAMMIT failure data revealed that the failures of REB's installed aboard Army helicopters clustered around 330 hours MTBF and 2500 hours MTBF. The failure rates were therefore computed separately for the 330-hour MTBF and for the 2500-hour MTBF. These figures represent heavy usage or high radial loading for the 330-hour MTBF, and light usage or low radial loading for the 2500-hour MTBF. The rationale used was as follows: all costs were segregated into those associated with light usage and those associated with heavy usage. The results of these computations of annual maintenance costs are shown in Table III. The total costs shown in Table III are for a fleet of 1833 helicopters.

The columnar headings for Table III are defined as follows:

1. Confidence Level - Probability that sufficient parts will be available when a repair is required.

2. Number of Spares Required - Quantity of spares required for each confidence level for an expected number of failures (U) to occur in a given period when both bearings are replaced during each repair action.

3. Total Annual Cost - The total annual unscheduled maintenance and spares cost for each confidence level.

Repair Costs

The repair costs, as stated in the Army MISS reports, are based on a repair rate of $16.50 an hour. Repair time was set at 30 minutes after

TABLE III. ANNUAL MAINTENANCE COSTS ASSOCIATED WITH VARIOUS LIFE ROD END BEARINGS WITH TWO REPLACED PER REPAIR FOR 1833 HELICOPTERS

Confidence Level	Number Spares Required	Total Annual Maintenance Cost
1. MTBF = 330 Hours (Present Design) U = 930		
0.95	2,030	$ 11,907,168
0.90	1,990	11,672,544
0.85	1,958	11,484,845
0.80	1,948	11,426,189
2. MTBF = 2,500 Hours (Present Design) U = 125		
0.95	288	$ 1,689,293
0.90	278	1,630,634
0.85	272	1,595,443
0.80	266	1,560,250
3. MTBF = 1,650 Hours (Improved Design) U = 190		
0.95	426	$ 6,090,692
0.90	418	5,976,313
0.85	408	5,833,339
0.80	404	5,776,150

TABLE III - Continued		
Confidence Level	Number Spares Required	Total Annual Maintenance Cost
4. MTBF = 3, 300 Hours (Improved Design) U = 94		
0. 95	220	$ 3, 145, 428
0. 90	214	3, 059, 644
0. 85	208	2, 973, 859
0. 80	204	2, 916, 670
5. MTBF = 12, 500 Hours (Improved Design) U = 25		
0. 95	66	$ 943, 628
0. 90	62	886, 439
0. 85	60	857, 844
0. 80	58	829, 249
6. MTBF = 25, 000 Hours (Improved Design) U = 12		
0. 95	36	$ 514, 706
0. 90	34	486, 112
0. 85	32	457, 517
0. 80	30	428, 922

consulting a local Army aviation facility. It was reported that bearing replacement could take from 15 to 45 minutes depending on location. It was determined that some bearings are exposed while others are deep within the helicopter. Fortunately, the bearings with the lowest MTBF are those generally located in easy access areas (i.e., around the rotor). These areas are subjected to the highest degree of stress and vibratory loads, which cause the units to wear approximately nine times faster than those in low-loading locations. The last variable required for computing the total repair cost is the cost of the part itself. The average cost for the bearings currently in use is about $12.00. The cost of an improved bearing is assumed to be about $35.00. The combination of these figures yields a total repair cost per replaced REB of $32.00 for the current design and $78.00 on the improved version. The average was obtained by averaging the costs of 55 different bearing sizes presently in use by the Army. The improved bearing costs were provided by the manufacturers of the improved bearings. The total repair costs consist of the cost of two bearings plus $8.00 labor cost.

Flight Time

The flight time used in the calculations was based on groups of 10 helicopters, each flying an average of 73.8 hours a month. The monthly flight time was obtained from a MISS report on UH-1H helicopters.

Number of Units

With the use of technical manuals one may determine the actual number of REB's used on a helicopter. Also, by reviewing technical manuals it was ascertained that there are approximately 35 REB's on each UH-1 fuel and flight control system. These two systems were selected because they are most critical to flight operations.

For this study the REB is considered to be one unit consisting of two bearings premanently attached by a connecting rod; consequently if one bearing fails, the whole unit is replaced. In reality, most of the REB's used have one fixed connection and one removable bearing (required for aligning purposes). Because of this arrangement, some bearing failures can be repaired by replacing only the defective bearing, while others require removal of the whole unit. Generally, to expedite maintenance, the entire life durations were calculated by using the cost model previously described, the results of which are presented in Table III.

The REB test data analyzed indicate that the operational MTBF for REB's depends a great deal upon the environment in which the bearing is operated. Flight control linkages function in light-use and low-vibratory-load environments. Heavy-use bearings are those used in the main and tail rotor areas. Therefore, the potential cost savings are presented for a light use and heavy use. The light-use bearing can be expected to demonstrate a 2500-hour MTBF; the heavy-use bearing, a 330-hour MTBF. These two MTBF values were used to determine the potential cost savings associated with bearings in each usage environment.

After determining the annual costs at each duration level, a comparison chart was drawn to show the potential savings. The Bearing Cost Comparison, Table IV, defines the savings that can be realized at several confidence levels, and compares minimum and maximum improvement levels of savings. The current costs for the 330-hour and 2500-hour MTBF bearings shown in Table IV were derived from Table III. Projected annual cost and savings of the improved bearing were calculated by increasing the MTBF by factors of 10 for maximum improvement and 5 for minimum improvement. These factors were based on estimates of usage data on improved design bearings that replaced the present swaged design.

Interpretation of Results

Figures 15 and 16 illustrate that significant cost savings in maintenance can be realized by improving present REB design. Detailed projected savings are also shown in Table IV.

Costs Related to Specific Failure Modes

Excessive play between the ball and the race, caused by (1) the initial gap that exists between them and (2) the vibratory environment, is the primary REB failure mode. By eliminating this excessive play failure mode, an estimated cost savings of 95 percent can be realized.

Costs Related to Various Policies, Practices, and Procedures

The present design requirements permit the existence of an initial gap between the ball and the race, and contribute heavily to the unswaging in the helicopter vibratory environment. The estimated 95 percent potential cost savings would result from improvements in design and environmental and qualification testing. The remaining 5 percent of the potential cost savings can be realized if better maintenance and training are implemented.

TABLE IV. BEARING COST COMPARISON

Confidence Level	Current Cost, Present Design: MTBF, 330 Hours	Current Cost, Present Design: MTBF, 2500 Hours	Projected Cost Using Improved Bearing: Heavy Usage		Projected Cost Using Improved Bearing: Light Usage		Projected Annual Savings: Heavy Usage		Projected Annual Savings: Light Usage	
	Heavy Usage	Light Usage	Minimum Improvement	Maximum Improvement	Minimum Improvement	Maximum Improvement	Minimum Improvement	Maximum Improvement	Minimum Improvement	Maximum Improvement
0.95	$11,907,168	$1,689,293	$6,090,692	$3,145,428	$943,628	$514,706	$5,816,476	$8,761,740	$745,665	$1,174,593
0.90	11,672,544	1,630,634	5,976,313	3,059,644	886,439	486,112	5,696,231	8,612,900	744,195	1,144,522
0.85	11,484,845	1,595,443	5,833,339	2,973,859	857,844	457,517	5,651,506	8,510,986	737,599	1,137,926
0.80	11,426,189	1,560,250	5,776,150	2,916,670	829,249	428,922	5,650,039	8,509,519	731,001	1,131,328

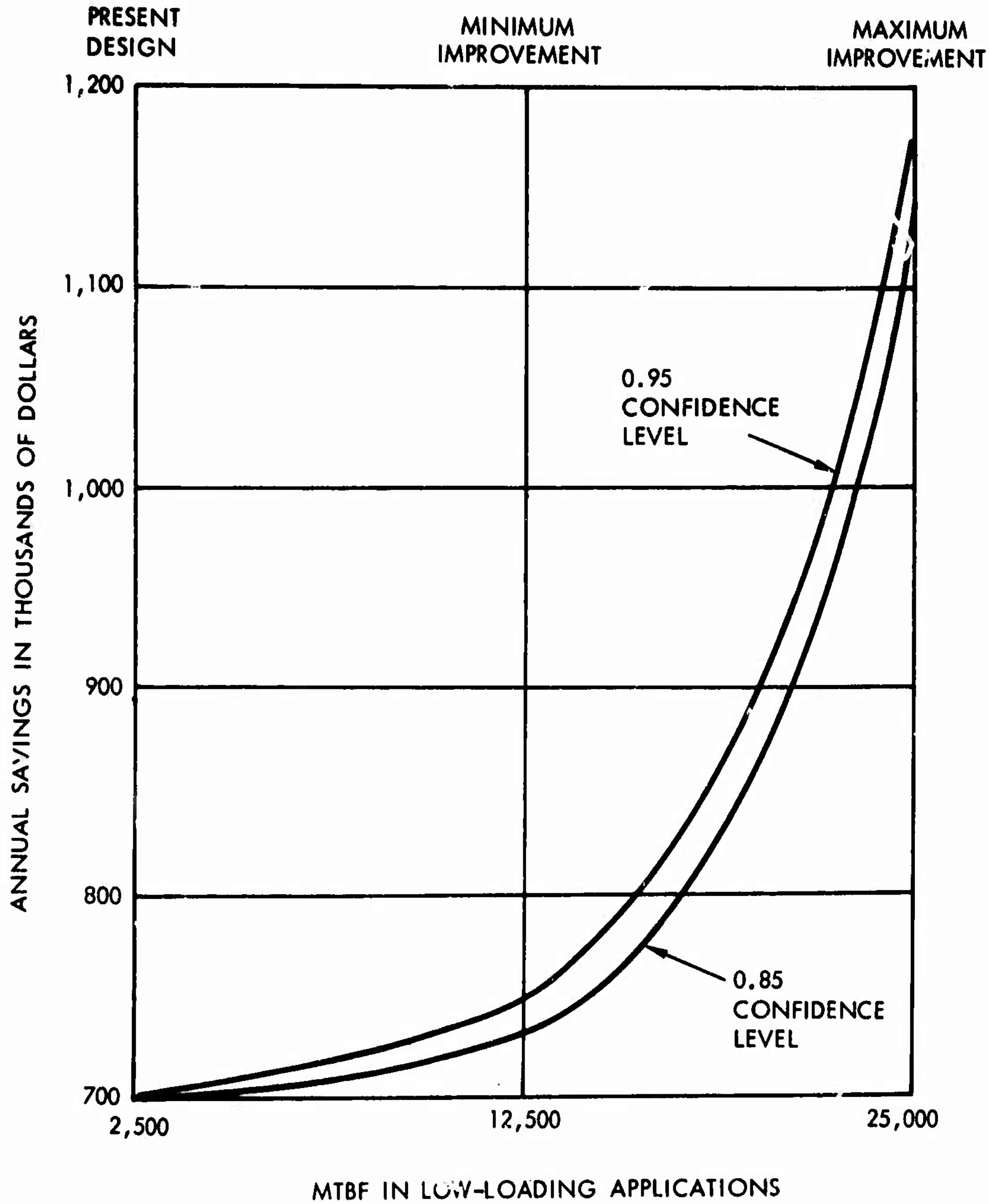


Figure 15. Annual Rod End Bearing Maintenance Savings at Various MTBF's, Low-Loading Applications.

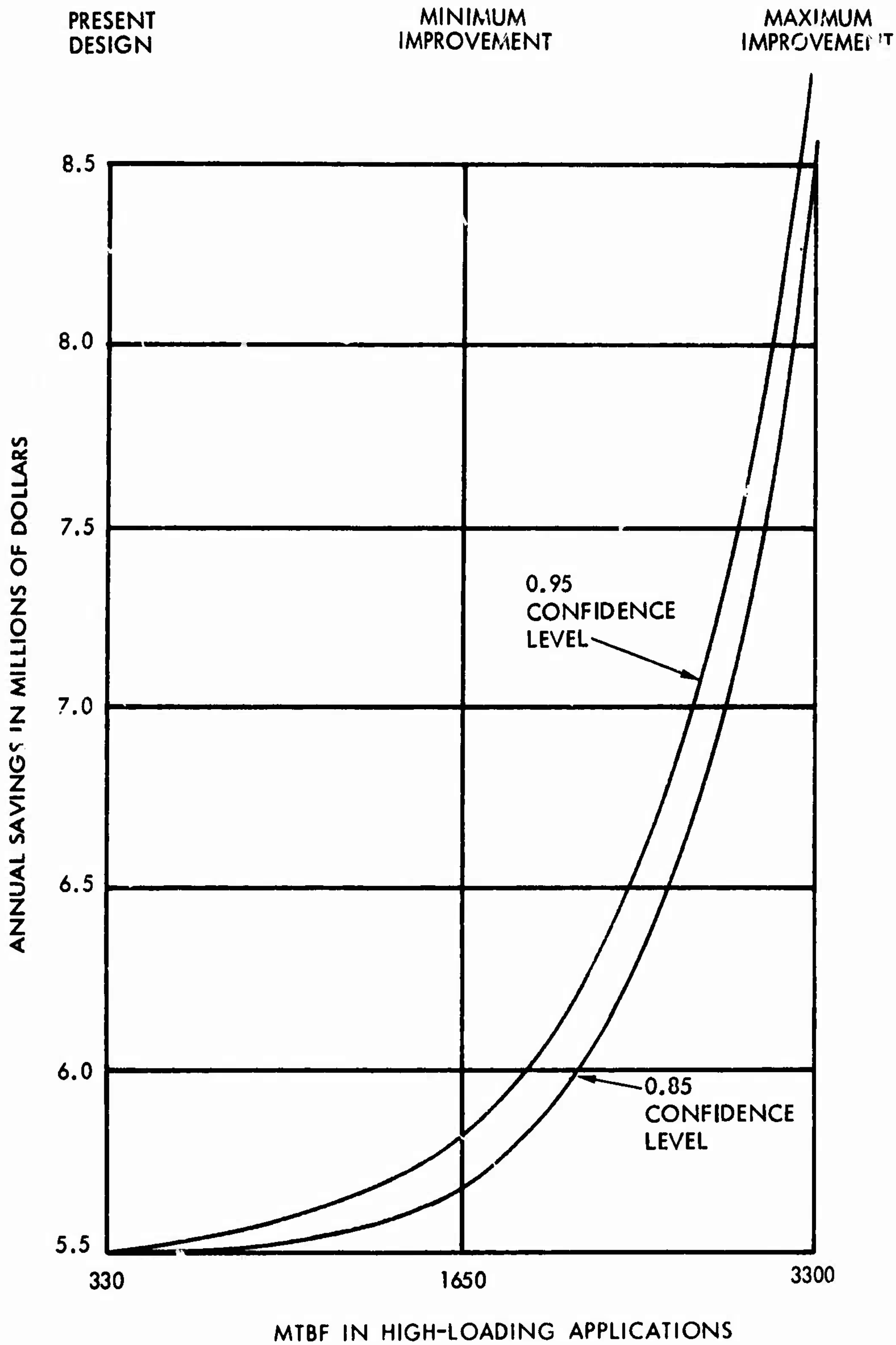


Figure 16. Annual Rod End Bearing Maintenance Savings at Various MTBF's, High-Loading Applications.

RECOMMENDATIONS

The recommended solutions and revisions to remedy inherent failure modes of the REB's are presented in summary form in this section and are discussed in detail in the Revisions and Solutions section. Specific recommendations are as follows:

1. Incorporate Army environmental and operational requirements into all applicable design requirements, test requirements and specifications, and quality assurance provisions.

2. Apply realistic maintainability, reliability, safety, human factors, and quality assurance parameters to each procurement of Army hardware.

3. Revise and upgrade maintenance requirements and procedures.

4. Use a stainless steel ball coated with hard ceramic with a graphite outer race enclosed in a stainless steel housing in low radial loading--highly corrosive applications.

5. Use slotted spherical bearings which are machined but not swaged with a hard race of Stellite 6, including a ball nearly as hard, to attain a closer tolerance between ball and race. This bearing should be used in high radial loading applications.

6. Use a boot or covering around the rod end so that there is less direct exposure of the bearing to moisture and dust. This should be used in those applications that specifically require protective coverings.

7. Provide contracts to the various airframe manufacturers so that their in-house REB data can be analyzed. Such analyses should provide the Army with a better data base for assessing REB performance aboard helicopters.

ABBREVIATIONS AND ACRONYMS

AIMD	Aircraft Intermediate Maintenance Department (USN)
AQL	Acceptable Quality Level
ARADMAC	U.S. Army Aeronautical Depot Maintenance Center, Corpus Christi, Texas
AVSCOM	U.S. Army Aviation Systems Command, St. Louis, Missouri
BFE	Buyer Furnished Equipment
DS	Direct Support
FAA	Federal Aviation Administration
FARADA	Failure Rate Data (FARADA) Program
FMSAEG	Fleet Missile Systems Analysis and Evaluation Group
GS	General Support
LOR	Level of Repair
MIL SPEC	Military Specification (sometimes only MIL)
MIL-STD or MS	Military Standard
MISS	Major Item Special Study
MMH/FH	Maintenance Man-Hours per Flight Hour
M or D	Malfunction or Defect
MOS	Military Occupational Speciality
67 MOS	Helicopter Crew Chief MOS
68 MOS	Helicopter Hydraulic Technician MOS
MTBF	Mean-Time-Between-Failures
MTTR	Mean-Time-to-Repair
NAVAIR	Naval Air Systems Command

OJT	On-the-Job Training
OPNAV	Office of the Chief of Naval Operations
QA	Quality Assurance
QC	Quality Control
RAMMIT	Reliability and Maintainability Management Improvement Techniques
REB	Rod End Bearing
SOW	Statement of Work
TAMMS	The Army Maintenance Management System
TB	Technical Bulletin
TBO	Time Between Overhauls
TFE	Tetrafluoroethylene
TM	Technical Manual

GLOSSARY

Accessibility	A measure of the relative ease of admission to the various areas of an item.
Availability	A measure of the degree to which an item is in the operable and committable state at the start of the mission when it is called for at an unknown (random) point in time.
Calendar Maintenance	Scheduled preventive maintenance performed at intervals measured in terms of days.
Capability	A measure of the ability of an item to achieve mission objectives, given the conditions during the mission.
Demonstrated	That which has been proved by the use of concrete evidence gathered under specified conditions.
Dither	Constant beat of rotor force causing flight control components to respond to this rhythmic force.
Failure	The inability of an item to perform within previously specified limits.
Failure Analysis	The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failures.
Failure Cause	The probable cause of the failure mode.
Failure Mode	The potential mode of failure associated with equipment function.
Failure Rate	The number of failures of an item per unit measure of life (cycles, time, miles, events, etc., as applicable for the item).

Human Engineering	The area of human factors which applies scientific knowledge to the design of items to achieve effective man-machine integration and utilization.
Human Factors	A body of scientific facts about human characteristics. The term covers all biomedical and psychosocial considerations; it includes, but is not limited to, principles and applications in the areas of human engineering, personnel selection, training, life support, job performance aids, and human performance evaluation.
Inherent	Achievable under ideal conditions, generally derived by analysis, and potentially present in the design.
Intermediate Maintenance (USN)	Equivalent in depth to DS/GS levels and performed at calendar intervals.
Life Cycle	The total existence of an item starting with the initiation of the basic concept and continuing through design, development, production, operational use, and eventual disposal.
Life-Cycle Cost	The total cost that is attributed to the item throughout its life cycle.
Maintainability	A characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources.
Maintenance	All actions necessary for retaining an item in or restoring it to a specified condition.
Maintenance Man-Hours per Flight Hour	The number of maintenance hours expended per flight hour to keep the helicopter flying.

Maintenance, Preventive	The actions performed in an attempt to retain an item in a specified condition by providing systematic inspection, detection and prevention of incipient failure.
Maintenance, Unscheduled	The actions performed, as a result of failure, to restore an item to a specified condition.
Maintenance Verification	Quality assurance/control inspections subsequent to maintenance actions at U.S. Army facilities.
Mean Time Between Failures (MTBF)	For a particular interval, the total functioning life of a population of an item divided by the total number of failures within the population during the measurement interval. The definition holds for time, cycles, miles, events, or other measure of life units.
Mean Time to Repair (MTTR)	The total corrective maintenance time divided by the total number of corrective maintenance actions during a given period of time.
Operational Readiness	The capability of a helicopter or component to perform its intended function when called upon to do so.
Quality Assurance	Quality control inspections subsequent to manufacture or maintenance at vendor or manufacturer facilities.
Reliability	The probability that an item will perform its intended function for a specified interval under stated conditions.
Safety	The conservation of human life and its effectiveness, and the prevention of damage to items, consistent with mission requirements.
Storage Life (Shelf Life)	The length of time an item can be stored under specified conditions and still meet specified requirements.

Wearout	**The process of attrition which results in an increase of the failure rate with increasing age (cycles, time, miles, events, etc., as applicable for the item).**

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MIL-STD-471	Maintainability Demonstration
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SPECIFICATIONS

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204-011-119	Bearing, Rod End, Upper Pitch Link
204-011-763	Bearing, Rod End, Pitch Control Tail Rotor
204-061-717	Bearing, Rod End, Male Shank, 0.190 Bore
204-076-428	Bearing, Rod End, Assembly of
206-001-052	Bearing, Plain, Rod End, Non-Lubricated, 0.250 Bore
206-001-054	Bearing, Plain, Rod End, 0.190 Bore

209-001-052	Bearing, Plain, Rod End, Non-Lubricated, 0.500 Bore
209-010-443	Bearing, Rod End, Upper Pitch Link
540-011-128	Bearing, Pitch Link, Upper Assembly of

Sikorsky Aircraft Drawings

6410-30403	Rod End Assembly Rotary Rudder (3 pp)
64107-11005	Rod End Assembly Adjustable Control Rod Rotary Wing Head (5 pp)
64107-11006	Rod End Assembly Adjustable Control Rod Rotary Wing Head (4 pp)
65113-07100	Link Assembly Rotary Rudder (4 pp)
65106-11104	Rod End Assembly Damper, Rotary Wing Head (4 pp)

Hughes Tool Company Drawings

369A1011	Rod End, Pitch Control, Main Rotor
369A7371	Bearing Assembly, Female, Collective Bungee
369A7372	Bearing Assembly, Male, Bungee, Collective (2 pp)
369A7951	Bearing, Standard Vendor (2 pp)

Baber-Colman Company Drawing

CYRB251	Bearing, Rod End

Conair Inc. Drawing

9291	Bearing, Rod End

Globe Industries Division of TRW Drawing

15D1299	Bearing, Rod End

The Fafnir Bearing Company Drawing

REM8ATC12-8	Code Ident 21335 (A Rod End Bearing)

APPENDIX
COST MODEL

This cost model has been created to assist the Army in its decision to implement new equipment or procedures. It can be used to estimate costs for continuing operations and for new systems.

The objective is to estimate the number of spares required to keep equipment operating over a certain period of time. In order to do this, there must be some way to forecast the number of chance failures that will occur within that period. Past performance has already indicated that point at which normal equipment "wearouts" will occur, and steps have been taken to replace parts before this expected wearout time. This is the effective preventive maintenance situation. Therefore, it is only the chance failures, the unexpected ones, that cause repair costs that are out of the normally expected projections. It is not possible to predict exactly when chance failures will occur, but over a long period of time their frequency is approximately constant. This constant rate was formulated by Poisson, and a table was constructed that lists the expected number of failures (U) and the probability of when those failures will occur.

The Poisson tables are set up to indicate three different probabilities: P(x), that exactly x number of failures will occur; C(x), that x or fewer failures will occur; and D(x), that x or more failures will occur in a given time. Since the task considered here is predicting the number of spares required for a certain length of time, it is the C(x) probabilities that prove most helpful. If the probability is very high that x or fewer failures will occur in a given time, then the probability of more than x failures is very low. By storing enough spares for x number of failures, there is little possibility of running out of spares during the time period considered.

In addition to projecting the number of failures, it is necessary to convert these numbers into dollar values. This is accomplished by determining the time required to repair (T_r) and check out (T_{co}) a malfunction and by multiplying that time by the military labor rate (R_r) for such work. In using this model, it is assumed that the labor rate is the same for checkout and maintenance personnel.

$$\text{Repair Cost} = C_r = T_r R_r$$

$$\text{Checkout Cost} = C_{co} = T_{co} R_r$$

Next, the total unscheduled maintenance cost (C_t) for each repair action is determined by adding the part cost (C_p) to the repair and checkout costs. This part cost includes logistics and administrative costs.

$$C_t = C_p + C_r + C_{co}$$

or

$$C_t = C_p + R_r(T_r + T_{co})$$

At this point it becomes necessary to further examine the predictive portion of the cost model. The model is based on the well-known exponential formula for reliability $R(x) = e^{-\lambda t}$. In the formula, e is the natural log base 2.71828, λ is the chance failure rate, and t is the operating time for which we are seeking the reliability of a population of equipments. This formula was expanded by Poisson into one that gives the probability (P) that a certain number of failures (X) will occur in the same period of time (t). The formula reads

$$P_{(X)} = \frac{(\lambda t)^X e^{-\lambda t}}{X!} = P_{nx} \text{ of the cost model}$$

This formula has been proved valid, and the tables of the Poisson distribution have been used extensively by reliability engineers and probability statisticians.

When the expected number of failures (U or λt) is known, the tables can be used directly to find the probability of those failures occurring. If the tables indicate that the probability of that number of failures (x) occurring is very high, then it can be assumed with some confidence that (x) number of spares will be sufficient to keep the population operative. The tables are set up to indicate the extra number of spares that should be stored if a higher degree of confidence is required.

As an example, assume that an item of equipment is to be exposed to operation for a period of 200 hours with a failure rate of 0.1 and a corresponding MTBF of 10 hours, then 20 failures would be expected.

$$U = \lambda t = 0.1 \times 200 = 20$$

The probability that exactly 20 failures will occur is stated as P(x) = 0.08883532. Thus, exactly 20 failures are expected to occur less than once in 10 samples. The probability that 20 or fewer failures will be observed is stated as C(2) = 0.55909258. The probability that 20 or more failures will be observed is stated as D(20) = 0.52974374. If spares are to be provided to assure 90-percent confidence that the 200 hours of operation can be completed, 26 spares would be required, i.e., C(26) = 0.92211322.

In order to use this formula, certain data are required. It is necessary to search the maintenance data to determine the actual failure rate (λ) for the certain item under consideration. These data will also indicate the number of items (n) on each piece of equipment. Aviation records indicate the average number of flight hours per piece of equipment in a group. In this particular case, the total operating time (T) for a group of helicopters must be determined. This time is further expanded to indicate the operating time of all study items that are operative on each helicopter in the group. This total operating time per item is multiplied by the number of items in the group to produce the time (t) used in the formula.

The cost model combines the probability of failure (P_{nx}) with the cost of unscheduled maintenance (C_t) associated with that number of repairs (Z) to indicate the expected cost for unscheduled maintenance.

$$Ce = ZC_t P_{nx}$$

or

$$Ce = ZC_t \sum_{i=1}^{x} \frac{(\lambda t)^i}{i!} e^{-\;t}$$

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