



AEROSPACE INFORMATION REPORT

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A Guide to Extending Times Between Overhaul for Rotorcraft Power Train
Transmissions Using Monitoring Data

RATIONALE

This SAE Aerospace Information Report (AIR) provides insight and guidance into both proven and proposed practices for extending Times Between Overhaul (TBO) on Rotorcraft Drive Trains through the use of monitoring data. Manufacturers of commercial transport rotorcraft are currently required by Federal Aviation Administration (FAA) Advisory Circular (AC) 121-22C and other international equivalents to develop maintenance programs that are guided by the tenets of the Maintenance Steering Group (MSG)-3, Volume 2. The maintenance processes of MSG-3 were refined over many years by the international aviation industry with the objective of reducing costs while increasing reliability and enhancing safety. Time-in-Service (TIS) monitoring data and associated metrics enable maintenance processes to meet the objectives of MSG-3. Future Health and Usage Monitoring System (HUMS) equipment is anticipated to produce monitoring data that may also be used to establish extensions to inspection intervals of power train assemblies for rotorcraft fleet operators while also meeting the objectives of MSG-3.

FOREWORD

The objective of this AIR is to provide background information that will help industry in establishing extended power train TBO intervals for rotorcraft through the utilization of monitoring. This includes examples of manual and automated historical health and usage records developed from monitoring power trains and validated through physical evidence (e.g., transmission tear down analyses (TDAs)). This report contains examples that illustrate methods for extending TBOs based on the data obtained during operator usage.

Because of the complexity involved in accepted practices for establishing TBOs, the introduction section provides a detailed overview of how initial power train TBOs are typically established by the Original Equipment Manufacturer (OEM) and the variables evaluated prior to consideration of extending power train TBOs towards achieving the benefits of reduced costs, without sacrificing aircraft reliability and safety. Then the need for extending TBOs to reflect fleet experience and operator usage is discussed. Finally, examples of proven and proposed methods of extending TBOs supported by a team of industry, academic engineers, and operators are provided.

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1. SCOPE

Time in Service (TIS), or flight hours, logged in maintenance records against an installed rotorcraft transmission is normally used as the “official” time on wing metric for the transmission’s component wear out inspection interval requirement and, in some instances, retirement change on life limited parts. This AIR addresses traditional methods of transmission TBO extensions and introduces rotorcraft transmission monitoring usage metrics that could be used to modify TIS inspections by tracking torque to determine both loads on life limited parts and component wear.

This is a document of the SAE HM-1 Committee intended to be used as a technical information source and is not intended as a legal document or standard. This AIR does not provide detailed implementation steps, but does address general implementation, past experience, concerns and potential benefits.

1.1 Purpose

The purpose of this SAE Aerospace Information Report (AIR) is to provide information and guidance for use of monitoring data from transmissions in the rotorcraft power trains so as to enhance or replace the traditional TIS metric for inspection intervals and life limited component replacement. The scope of this document is limited to those inspections, analyses, and devices that can be considered appropriate for routine maintenance.

Some commercial helicopter operators such as those supporting the Oil and Gas Producers (OGP) community have helicopters equipped with HUMS and have trained HUMS data analysts. The addition of HUMS functionality has enhanced the flight safety of large transport helicopters supporting the OGP around the world (see Appendix A: [1], [2], [3], and [4]) and offer the opportunity to enable MSG-3 maintenance for rotorcraft. Operators recognize that more accurate monitored data than logbook Flight Time (FT also known as TIS) data offers them an opportunity to better manage aircraft inspections and life limited part replacement while potentially achieving both cost and safety benefits. As such, commercial helicopter operators desire to utilize the transmission monitoring data to improve operational efficiency and effectiveness.

All of the major rotorcraft OEMs in the UK, Europe and the USA are involved in the refinement and implementation of MSG-3, Volume 2 (for helicopters). The information provided herein provides a potential point of departure for the implementation of MSG-3 maintenance intervals for rotorcraft transmissions as the OEM engineering teams develop the details of MSG-3 Volume 2 (see Appendix A: [5], [6], and [7]).

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1828B	A Guide to Engine Lubrication System Monitoring
AIR4174A	A Guide to Aircraft Power Train Monitoring
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
JA1012	A Guide to the Reliability-Centered Maintenance (RCM) Standard

2.1.2 ANSI Accredited Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ANSI/AFBMA Std 9-1990	Load Ratings and Fatigue Life for Ball Bearings
ANSI/AFBMA Std 11-1990	Load Ratings and Fatigue Life of Roller Bearings
ANSI/AGMA 1010-F14	Appearance of Gear Teeth - Terminology of Wear and Failure

2.1.3 ASM Publications

Available from ASM International, ASM International World Headquarters, 9639 Kingsman Road, Materials Park, OH, 44073, Tel: 440-338-5151, <http://www.asminternational.org/>.

ASM Handbook Volume 19	Fatigue and Fracture
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2.1.4 Airlines for America (A4A) Publications

Available from Airlines for America (A4A), 1301 Pennsylvania Avenue, NW, Suite 1100, Washington, DC 20004, Tel: 202-626-4000, www.airlines.org.

MSG-3 Volume 2	Operator/Manufacturer Scheduled Maintenance Volume 2 – Rotorcraft, Revision 2013.1
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2.1.5 CAA Publications

Available from Civil Aviation Authority, CAA House, 45-59 Kingsway, London, WC2B 6TE <http://publicapps.caa.co.uk/modalapplication.aspx?appid=11>.

CAA Paper 2011/01	Intelligent Management of Helicopter Vibration Health Monitoring Data (2011)
CAP 753	Helicopter Vibration Health Monitoring (VHM), Guidance Material for Operators Utilizing VHM in Rotor and Rotor Drive Systems of Helicopters (2012)

2.1.6 FAA and FAR Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 25.1309-1A	System Design and Analysis
AC 29-2C MG15	Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS)
AC 43.13-2B	Acceptable Methods, Techniques, and Practices – Aircraft Alterations
AC 121-22C	Maintenance Review Boards, Maintenance Type Boards, and OEM/TCH Recommended Maintenance Procedures
CFR 43.5	Approval for Return to Service After Maintenance, Preventative Maintenance, Rebuilding, or Alteration
CFR 29.571	Fatigue Tolerance Evaluation of Metallic Structure
CFR 29.1309	Equipment, Systems, and Installations

CFR 1.1 FAA, Department of Transportation – Definitions, Abbreviations and General Requirements

CFR 91.409 General Operating and Flight Rules - Inspections

CFR 145 Repair Stations

2.1.7 NASA Publications

NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, 757-864-9658, Fax: 757-864-6500, <http://ntrs.nasa.gov/>.

NASA TM-217896 Integrating Condition Indicators and Usage Parameters for Improved Spiral Bevel Gear Health Monitoring

NASA TM-105668 Full-Scale Transmission Testing to Evaluate Advanced Lubricants

NASA CR-198446 Feasibility Study of Rotorcraft Health Usage Monitoring System: Results of Operator's Evaluation

2.1.8 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-178C Software Considerations in Airborne Systems and Equipment Certification

RTCA DO-254A Design Assurance Guidance for Airborne Electronic Hardware

2.1.9 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

ADS-79E-HDBK Condition Based Maintenance Systems for US Army Aircraft Systems

ADA066579 Reliability Centered Maintenance

2.2 Related Publications

A list of publications is provided for informational purposes in Appendix A. These publications are not a required part of this SAE Technical Report.

2.3 Definitions

ALERT: A warning produced by the VHM system that requires further processing or an investigation to determine if a maintenance action is required. This CAP 753 definition relates to the Caution Threshold as addressed in this report.

ALGORITHM: A procedure or formula for solving a problem.

B10 LIFE: A measurement of the time by which 10% of a population of a product will have failed. The term originates from the manufacture of anti-friction bearings and is used to express the minimum lifetime of 90% of a given batch of bearings operating within speed and loading tolerances.

COMBINING TRANSMISSION: An intermediate transmission (or gear box) that is located between two or more engines and the main rotor transmission (or main gear box) (see Appendix B).

CONDITION BASED MAINTENANCE: A maintenance action taken by the operator that is based upon HUMS data analysis which is addressed in the OEM Maintenance Program.

CONDITION INDICATOR (CI): A measure of detectable phenomena derived from sensors that show a change in physical properties related to deterioration (normal or abnormal) or a specific failure mode or fault.

CONTROLLED SERVICE INTRODUCTION: A period in-service time where capabilities and functions are evaluated when capabilities and functions could not be verified prior to entry into service (including support functions).

CREDIT: (1) To give approval to a HUMS application that adds to, replaces, or intervenes in industry accepted maintenance practices or flight operations. (FAA, AC 29-2C Chg 3, MG15); (2) Given the necessary validated accumulation of reliable and effective data, maintenance credits may be sought in the way of (a) relaxation of the extent or form of testing employed following the reconditioning and/or installation of replacement components. (b) Extension of component retirement life, for example from 5000 to 10000 hours may be achievable through changing the basis of retirement from elapsed time or flying hours to measured load exposure through usage monitoring. (NASA CR-198446); (3) Credit awarded to equipment maintenance practices (i.e., inspections, overhaul, on wing life limit) based on selected aspects of actual service usage history of specific monitored equipment versus design usage of general equipment population (ADS-79E-HDBK).

FAULT: Mechanical degradation has progressed to the point where legacy fault detection has produced an alert indicating a corrective action is required by the OEM maintenance program to ensure Continued Airworthiness.

FLIGHT TIME: Per the definitions, reference CFR 1.1, Title 14 General Definitions: Flight time means: Pilot time that commences when an aircraft moves under its own power for the purpose of flight and ends when the aircraft comes to rest after landing; time-in-service, with respect to maintenance time records, means the time from the moment an aircraft leaves the surface of the earth until it touches it at the next point of landing (aka airborne time).

GROUND STATION: A ground station is the means of access to VHM data, including alerts, for immediate post-flight fault diagnosis by the responsible maintenance staff. It should also be capable of accessing other historical and relevant health monitoring data from other aircraft in the fleet, for the purpose of comparison, to assist in the analysis of exceedances and fault diagnosis. A ground station may have the ability to link interactively to ground stations at other line stations, the operator's main base and third party engineering support over an internet or intranet connection or by a direct dial-up modem. While initial VHM systems used a specific computer as a ground station a "virtual" ground station using means of access to a central server may also be acceptable. However, it would need to be substantiated that integrity of data could be maintained to an appropriate standard. (Refer to CAA Paper 2011/01 and CAP 753.)

HEALTH INDICATORS: A health indicator (HI) algorithm uses multiple condition indicators (CI) to construct a composite health indicator; for the purposes of detecting mechanical defects in gears, bearings, and shafts.

HEALTH MONITORING: Procedures by which selected incipient failure or degradation can be determined.

HEALTH AND USAGE MONITORING: Procedures by which selected incipient failure or degradation (health monitoring) and/or selected aspects of service history (usage monitoring) can be determined.

HERTZIAN: A frequency created by a parametric oscillation and measured in cycles per second.

HUMS: Health and usage monitoring system; equipment by which selected incipient failure or degradation (health monitoring system) and/or selected aspects of service history (usage monitoring system) can be determined. The HUMS term does not name any specific method or technology; it typically consists as a variety of onboard sensors and data acquisition systems. The acquired data may be processed onboard the rotorcraft or on a ground station (or a combination of both) providing the means to measure defined criteria and generate instructions for the maintenance staff and/or flight crew for intervention.

INCIPIENT DEFECT: The initial stage of degradation that typically leads to a fault.

INPUT MODULE: A Transmission Module positioned between a single engine and the main rotor transmission.

L10 LIFE: The life that 90% of a sufficiently large group of apparently identical bearings can be expected to reach or exceed. The median or average life, sometimes called Mean Time Between Failure (MTBF), is about five times the calculated basic rating life

METRIC: A method of measuring something.

POWER USAGE: Power usage refers to the pilot's application of varying torque settings through the aircraft power train over a series of flight and turn-up operations to perform a mission. The record of accrued usage is typically recorded on the maintenance logs as a function of accrued TIS since new or since overhaul or both.

POWER USAGE HOURS: A power usage metric that is based upon an exponential equation that uses torque (real-time or a time history) to compute power usage factor.

POWER USAGE BIN: The product of the Usage Factor assigned to a torque bin multiplied by the time spent in the Bin.

ROTOR TURN TIME: The time the rotor starts to the time it stops after the final landing, and for the time between start and rotor stop for ground turn-up. See rotor-in-motion time.

ROTOR-IN-MOTION TIME: All of the time that the rotor is turning. Typically, this applies to the time on the ground before takeoff, during intermediate stops, and after the last landing. Time spent conducting maintenance with the rotor engaged is also included as is the time spent preparing for a flight that is aborted.

SAFE LIFE: The capability of a structure to continue performing its intended function without repair, and without initiating damage within a designated retirement interval. Stiffness, structural stability, dynamic behavior, load transfer, and functional performance characteristics remain within the design criteria. Residual strength maintains ultimate load capability with a specified probability.

THROUGHPUT POWER: The power that passes through a given transmission of a power train.

TIME-IN-SERVICE: See flight time.

TORQUE BIN: The magnitude of the torque selected to develop a torque spectrum or power usage spectrum. A torque bin that is greater or equal to 3% torque and less than 6% torque defines a 3% torque bin. In a real-time analysis or an analysis of a 10 Hz torque time history, the torque bin is defined by the torque reading every 0.1 second. The time interval (0.1 seconds) is multiplied by the torque recorded during the given tenth of a second.

TRANSMISSION ENDURANCE TIME: The time that a transmission can be operated at a specific power setting without a defect requiring corrective maintenance.

USAGE MONITORING: Procedures by which selected aspects of service history can be determined.

VHM DATA: Vibration Health Monitoring data (CI or HI) available from a HUMS.

VHM SYSTEM: A VHM system typically comprises vibration sensors and associated wiring, data acquisition and processing hardware, the means of downloading data from the rotorcraft, the ground-based system and all associated instructions for operation of the system.

2.4 Terminology

A&P	Airframe and Powerplant
A4A	Airlines for America (formerly ATA)
AFBMA	Anti Friction Bearing Manufacturer's Association
AC	Advisory Circular
AIR	Aerospace Information Report
AS	Airspeed
ATA	Air Transport Association of America Incorporated
CAA	Civil Aviation Authority of the UK
CFR	Code of Federal Regulation
CBM	Condition Based Maintenance

CI	Condition Indicator
CSI	Controlled Service Introduction
DAL	Design Assurance Level
DOM	Director of Maintenance
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FDR	Flight Data Recorder
FH	Flight Hour
FHA	Functional Hazard Assessment
FMECA	Failure Mode and Effects Criticality Analysis
FSDO	(FAA) Flight Standards District Office
FT	Flight Time (also known as TIS)
GW	Gross Weight
HI	Health indicator
HUMS	Health and Usage Monitoring System
ICA	Instructions for Continued Airworthiness
IGB	Intermediate Gearbox
Kt(s)	Knot(s)
MGB	Main Rotor Gearbox (main rotor transmission)
MSG-3	Maintenance Steering Group - 3
MDT	Mean Down Time
MPD	Maintenance Planning Document
MRB	Maintenance Review Board
MRBR	Maintenance Review Board Reports
MTBF	Mean Time Between Failure
MTBR	Mean Time Between Removal
MTBUR	Mean Time Between Unscheduled Removal
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration

NDI	Non-Destructive Inspection
NHP	Notional High Power
NRP	Normal Rated Power
O&G	Oil and Gas
OEM	Original Equipment Manufacturer
OGP	Oil and Gas Producers
PUF	Power Usage Factor
PUH	Power Usage Hours
RCM	Reliability Centered Maintenance
RII	Required Inspection Items
RPM	Revolutions Per Minute
RTCA	Radio Technical Commission for Aeronautics
RTT	Rotor Turn Time
SAR	Sea Air Rescue
SUMS	Structural Usage Monitoring System
SN or S-N	Stress versus Number of Cycles
STC	Supplemental Type Certificate
TBO	Time Between Overhaul
TC	Type Certificate
TCH	Type Certificate Holder
TDA	Tear Down Analysis
TRGB	Tail Rotor Gearbox
TIS	Time in Service (also known as FT)
UK	United Kingdom
USC	University of South Carolina
VHM	Vibration Health Monitoring
VNE	Speed, Never Exceed

2.5 Symbols

α	The exponent of the PUF formula can be adjusted to fit a certain gearbox by increasing or decreasing the value of α . The baseline value of α is 1.
β	The term β represents the initial value of y when $x = 0$ for the equation $y = f(x) = \beta \cdot b^{ax} = \beta \cdot b^{(\frac{x}{\tau})}$
b	The term b represents a base (or growth factor)
τ	The term τ is a time constant describing the time required for y to increase by a factor of b when x is a time variable
Δt	An increment of time
$^{\circ}\text{C}$	Temperature in degrees Celcius
$^{\circ}\text{F}$	Temperature in degrees Fahrenheit
N_r	Rotor speed (RPM)
Q	Percent Torque (as applied to transmissions of a power train)
$Q(t)$	Torque as a function of time

3. INTRODUCTION

3.1 Background

Common rotorcraft power train, transmission critical components are made up of gears, bearings, shafts, clutches, and housings. For transmissions, these components are typically inspected periodically at overhaul. At the time of a scheduled transmission overhaul, various components are inspected and any components exhibiting a condition that could result in performance degradation (or, in few instances, approaching life limits) are replaced. After the scheduled overhaul, the transmission is considered to possess the same capabilities and performance characteristics that it possessed when new. The following provides a description of transmission critical component design so as to provide a basis from which to depart when considering an extension to a TBO or going to an on-condition status with no TBO.

3.1.1 Gears, Shafts, Clutches, and Housing Design

Structural design of rotorcraft transmission gears, shafts, clutches, and housings is typically accomplished using a “safe life” probabilistic based approach. Although FAA Code of Federal Regulation (CFR) 29.571 may make the safe life approach less typical in the future, current basis for transmission design using the safe life approach is still the norm. The safe life of a component is that usage of the component consisting of loads within a time period (assumed in design and validated during test) when there is a low probability that the component strength will degrade due to structural fatigue cracks. Structural fatigue cracking occurs during cyclical loading and unloading of a component that is above the specific material's endurance limit. The endurance limit is the highest value of the stress amplitudes in a symmetrical cycle of mechanical load variation (or the maximum stress of an asymmetrical cycle) to which a material can be subjected for an unlimited number of cycles without failure.

Designing with a safe life approach theoretically requires no inspections for structural fatigue in a transmission gear tooth, shaft, clutch, and housing during the design life as analyzed with anticipated usage loads. Safe life analysis is performed during transmission design since:

- Transmissions are difficult to access;
- Transmissions may not be opened and inspected by first line maintainers due to complexity rendering them susceptible to disassembly/assembly error without: experts present with overhaul experience, proper tooling, inspection devices, and acceptance checkout facilities;
- Once structural fatigue cracks form, cracks can propagate rapidly to catastrophic conditions due to the rapid number of cycles occurring at high loads.

Therefore, rotorcraft transmission gears, shafts, clutches, and housings are typically designed for infinite structural fatigue life (10^7 load cycles for ferrous materials and 10^9 for non-ferrous components) while assuming a conservative load usage spectrum accounting for varying types of usage. Designing safe transmissions using an approach that requires little field removal and intervention with the safe life methods has traditionally been deemed appropriate by industry from a cost and maintenance burden perspective.

A problem with the safe life approach is there is no easy method for extending the life of the component without proving the structural integrity through the use of extended full-scale testing, which may also potentially result in structural modifications. The safe life evaluation determines maximum allowable material flaws (e.g., porosity) with which the component is still capable of performing its function while retaining its design strength without repair and without initiating structural damage within a designated service/replacement interval (refer to CFR 29.571).

Note, however, surface flaws may be generated from flight operations, meteorological environments, and component maintenance. For example, vibratory (Hertzian) loading, fretting, corrosion pitting, rotor shaft bending, and contaminated lubricant can all contribute to surface wear. The potential for surface wear increases as throughput power is increased from some low value to a maximum value when the parent aircraft is operating at normal rated power. The relationship between loads and surface wear due to metal to metal contact with components in motion is discussed in ANSI/AGMA 1010-F14, ASM Handbook Volume 19, NASA TM-217896, and Appendix A: [8], [9], and [10]. Wear is also a function of design, manufacturing and installation issues which may exacerbate the degree of wear encountered by a given component.

A safe life approach normally requires teardown inspections (e.g., overhauls) to remove components prior to surface and incidental flaw damage from reaching a critical size. Inspections at designated service/replacement intervals then ensure the capability of critical structural components to continue performing their intended function without initiating damage within the next designated interval. Safe Life methodology substantiates the safe life within the specified probability and confidence intervals via analysis and tests when subjected to operational and oscillatory loads within the specified design usage. This same methodology must be revisited when introducing changes to the manufacture, operation, or maintenance intervals of power train components.

Key points in safe life substantiation of power train gears/shafts/clutches/housings relative to establishing a power train TBO are:

- There is an assumed usage constraint by the power train OEM intended to capture how the OEM's targeted market will operate the rotorcraft while not incurring structural fatigue cycles;
- There is an assumed allowable surface flaw size constraint the OEM intends the power train components will sustain over a period of time in the operating environment and will be captured during overhaul inspections before becoming hazardous. These surface flaws must have a specified probability of being detected with a verified confidence level before component failure becomes hazardous; and
- The OEM must define an appropriate scatter factor in the distribution of component failures that is dependent on variability in materials, component geometry, and manufacturing processes.

3.1.2 Bearing Design

There exist various performance parameters to be evaluated in selecting each bearing design for its respective power train application. The following are some example parameters that are typically used in selecting bearings in the design of a transmission:

- Dynamic Radial Load
- Applied Radial Load
- Applied Axial Load
- Radial Load Factor
- Axial Load Factor
- Size of bearing based on shaft size
- Loading Conditions (radial and thrust)
- Shaft Speed (RPM)
- Operating Temperature
- Reliability (L10 life required)
- Material Life Factor
- Lubrication Life Factor

For rotorcraft transmissions, bearing life is normally the primary parameter that requires a unique methodology in calculating the contact fatigue life. As previously discussed, transmission component fatigue life calculations use a probabilistic approach. For bearings, life predictions are based on statistical evaluation of a large number of bearings operating under similar conditions. Transmission bearing life is performed employing “B10” or “L10” life analyses that calculate the probability of encountering rolling element and raceway surface anomalies as a result of contact fatigue. The B10/L10 life approaches are an Anti-Friction Bearing Manufacturers Association (refer to AFBMA Std 9 and 11) expression for indicating 10% of the bearings under specified conditions will fail at any point prior to reaching the design life, synonymous with a bearing life associated with a 90% reliability against fatigue.

Specifying a B10/L10 life does not guarantee that a bearing will have a 90% reliability when installed in the real world. The calculation for B10/L10 life assumes proper lubrication is provided, no shock or unacceptable vibration exists, bearing alignment is within tolerance, no debris enters the bearings, and ambient temperatures are within a specified operating range. In the real world, none of these conditions are realistic and the installed life of the bearing will depend on the application and maintenance. To get as close as possible to the specified life, the installer and end user must follow the recommendations in the OEM's installation and maintenance instructions.

Bearings are especially vulnerable to Hertzian contact fatigue failure. Hertzian contact fatigue generally results in spalling, which may be detected (through chip detection or vibration monitoring) and is usually associated with significant operational capability remaining from the onset of the spalled surface. Similarly, Hertzian contact fatigue may occur on the surface of transmission gears, shafts, and clutches. As a result, accepted design and operational practice is to employ chip detectors in rotorcraft transmissions to provide sufficient indication of impending gear, bearing, and shaft failures due to contact fatigue, to allow for timely emergency alerts and rotorcraft landing.

3.1.3 Transmission Design Reliability Validation

OEM validation and substantiation of the combined rotorcraft transmission component reliabilities is achieved through a series of analyses and tests. With exception of transmission drive shafts, gear teeth, and clutches, industry practices are that none of the bench and system level rotorcraft transmission tests perform a complete run out of any component to failure at their calculated fatigue life since the quantity and duration of testing would not be economically feasible. Testing, analyses, and experience have proven current standards are sufficient to achieve reliable transmission performance with safety mitigation devices (e.g., chip detection, pressure, temperature, and filter monitoring). Although not exhaustive or tailored towards any particular OEM, transmission reliability analysis and testing typically includes the following types of testing and analyses as applicable to validate and ensure design reliability:

- Finite element stress analyses
- Housing deflection analyses to assess peak stress levels
- Fatigue life analyses with application of mean minus three sigma material properties
- Critical speed analyses
- Thermal analyses
- Bearing B10/L10 lifing analyses
- Gear tooth bending lifing analyses for infinite life determination
- Torsional stability analysis
- Service life calculations (MTBF/MTTR/MTBR/MDT/MTBUR)
- Lubrication system flow and attitude testing
- Filter bypass, impending bypass, and proof pressure testing
- Transmission loss of lubricant testing
- Debris detection/monitoring testing
- Heat exchanger inlet/outlet flow and pressure testing
- Transmission endurance testing
- Gear tooth bending testing to 10^7 cycles for infinite life determination
- Gear pattern testing
- Gear load distribution survey
- Drive shaft testing
- Clutch cycling, overrunning, stroking fatigue testing
- Vibration and resonance testing
- Pressure/temperature sensor proof testing
- Transmission temperature survey

- Subcomponent environmental testing
- Shaft critical speed testing
- Overstress testing
- Overspeed testing
- Torsional stability flight testing
- Reliability testing
- Tear down analysis with dimensional and non-destructive inspection (NDI) evaluations

After testing, the requirements during physical tear down for a new design are that the transmission components shall not exhibit any signs of wear or failure as described in various commercial standards. The presence of wear or failure would invalidate the assumptions performed under safe life methodology wherein the existence of no anomalies is assumed.

Torque load is normally the primary, but not the only, driver of transmission wear and structural fatigue (e.g., contact, bending). Excessive torque loading of the power train components by an operator is capable of introducing structural fatigue cycles, accelerated contact fatigue anomalies, and accelerated wear in the transmission components. To inhibit occurrences of a rotorcraft operator from placing too much load on the power train components, OEMs place hardware (mechanical stops) and instructional (operations manuals) load constraints for power train usage. These constraints are implemented to avoid the onset of undetectable, subsurface structural fatigue anomalies as well as detectable, surface anomalies from excessive and accelerated loading not anticipated by the OEM designers. Other contributors to transmission wear and fatigue are shaft bending loads, environmental conditions, and lubricant condition.

3.1.4 Transmission TBO Establishment

The specific speeds, loads, temperatures, and lubrication requirements are unique to each transmission design. As a result, the susceptibility to fatigue for each component is unique to the transmission application. Therefore, transmission teardown analyses (TDAs) with dimensional and NDI inspections are required to be performed at an OEM designated TBO interval or when an applicable field exhibited condition (i.e., on-condition) is discovered. Upon removal, overhaul is performed to remove and replace components with unanticipated contact fatigue surface anomalies and ensure component wear is within acceptable limits for continued use up to the next overhaul or sensor alert. In some instances, if a life limited structural component (versus an infinite life component) was designed into the transmission then OEMs assign a TBO that is less than the life of the lowest life component so the life limited structural component may be retired and replaced. Other objectives in establishing a TBO include minimizing total overhaul costs during the transmission service life and attainment of high aircraft availability by maintenance scheduling.

Integral to any discussion of TBO is a graphic illustration of the bathtub curve. As shown in Figure 1, the bathtub curve depicts one of the assumptions implied in the utilization of a TBO: at some future time in the life of a component the undesirable occurrence of an increasing rate of failure will take place.

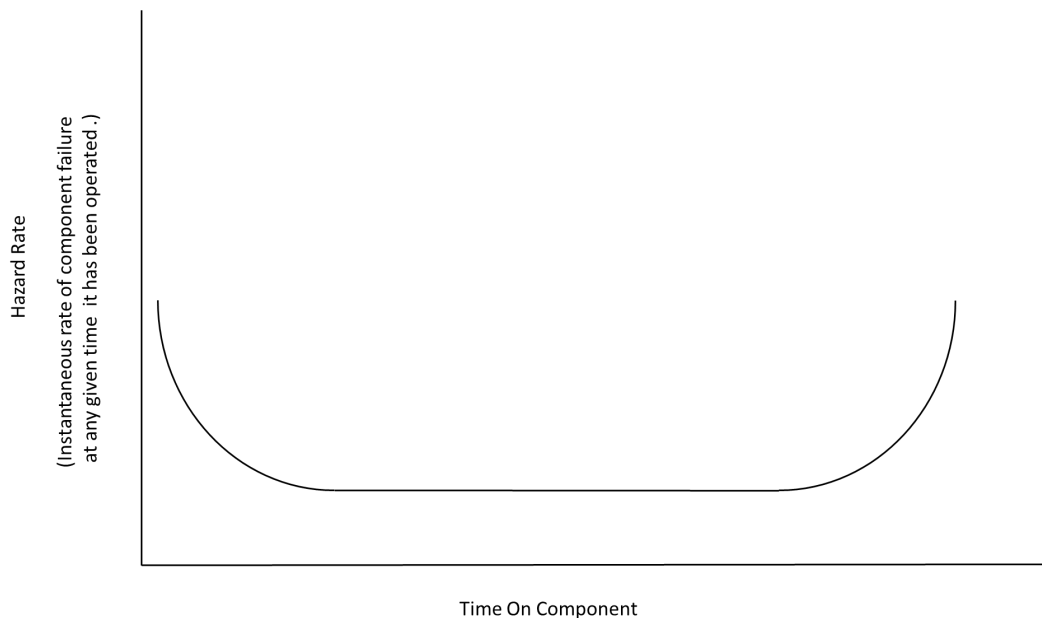


Figure 1 - Hazard rate bathtub curve

The general term for the increasing rate of failure as depicted in the bathtub curve is the hazard function. Hazard function describes how the failure rate of a given unit or module changes as its operating time increases. The important point to remember is that hazard function is a conditional expression: if the component reaches a certain operating time it will have an indicated failure rate. The figure is therefore very appropriate to the issue of TBO placement. The alternatives at any given point in time are either to impose a TBO and cause the removal of the component from service, or allow it to continue to operate and be exposed to its future failure rate.

Practical application of the bathtub curve indicates there are actually three curves to consider, representing three stages, which might be expected to occur in the life time of a part (Figure 2). The first is called a break-in or *infant mortality* stage, during which the equipment is characterized by a relatively high failure rate. The second is called the *operating* stage, during which equipment experiences a constant failure rate characterized by a stable failure rate. The third stage is called the *wear-out* phase, which is the time when the aged equipment experiences a high failure rate that increases rapidly due to worn parts.

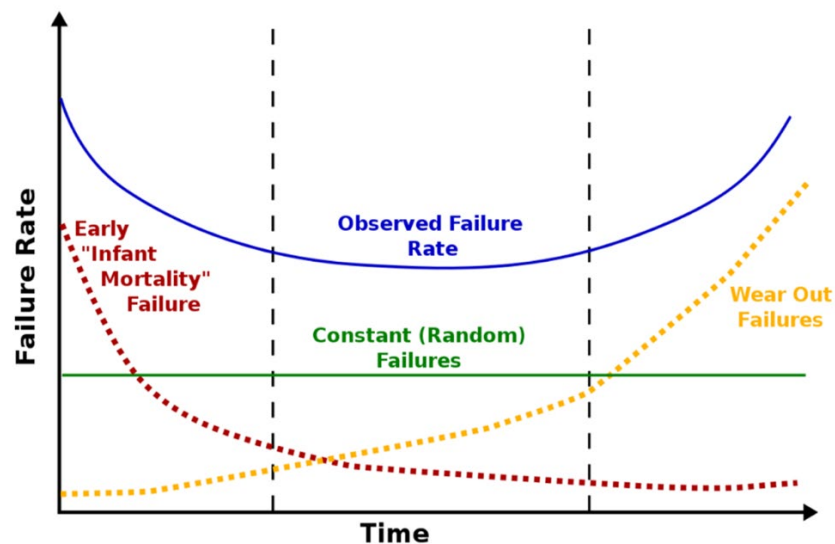


Figure 2 - Failure rate bathtub curve stages