



AEROSPACE RECOMMENDED PRACTICE

ARP6412™

Issued

2023-05

Recommended Practice for Landing Gear Integrity Programs

RATIONALE

This SAE Aerospace Recommended Practice (ARP) is intended to provide landing gear manufacturers or landing gear system sustainment organizations guidance for implementing a landing gear integrity program.

TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	Purpose.....	3
2.	REFERENCES.....	3
2.1	Applicable Documents	3
2.1.1	SAE Publications.....	3
2.1.2	Other Publications.....	3
2.2	Acronyms	4
3.	LGIP MASTER PLAN.....	5
4.	LANDING GEAR DEVELOPMENT AND LGIP DATA INTEGRATION	5
4.1	Landing Gear Development Guidance.....	5
4.2	LGIP Data Management	5
4.2.1	Bill of Materials.....	5
5.	LANDING GEAR AGE AND USAGE ASSESSMENT	5
5.1	Component Selection.....	5
5.2	Deterministic Assessment.....	6
5.3	Probabilistic Assessment	6
6.	LANDING GEAR MODELING.....	6
7.	LANDING GEAR STRUCTURAL ANALYSIS.....	6
7.1	Standard Structural Analysis Requirements	6
7.2	Other Structural Analysis Components.....	7
7.3	Analysis Details.....	7
7.4	Loads.....	7
7.5	Validation	7
8.	FATIGUE SPECTRA DETERMINATION.....	7
8.1	Aircraft Original Equipment Manufacturer (OEM) Spectra.....	7
8.2	Analyze Fatigue Spectra for Legacy Aircraft	8
8.3	Establishment of an Updated Usage Spectrum and Re-Baselining	8
8.3.1	Flight Data Recorder.....	8

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2023 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

SAE WEB ADDRESS:

Full document details: SAE ARP6412

For more information on this standard, visit
<https://www.sae.org/standards/content/ARP6412/>

Documents

Document Sharing Hub

9.	SERVICE LIFE RISK ASSESSMENT FOR STRUCTURALLY CRITICAL COMPONENTS.....	8
9.1	Fleet Usage Analysis	9
9.2	Fatigue Life Analysis	9
9.2.1	Statistical and Fatigue Methodologies	9
9.3	Risk Assessment Analysis	9
9.3.1	Service Life Risk Assessment at Least Material Condition (LMC)	9
10.	ANALYTICAL CONDITION INSPECTION (ACI)	10
11.	LANDING GEAR RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM) ANALYSIS	10
11.1	RAM Analysis Data	10
11.1.1	Component Condition Analysis	10
11.1.2	Solution Development	10
12.	SERVICE LIFE RISK ASSESSMENT FOR FUNCTIONALLY CRITICAL COMPONENTS.....	11
12.1	Failure Modes, Effects, and Criticality Analysis (FMECA)	11
12.2	Risk Assessment.....	11
13.	LGIP RECOMMENDATIONS AND IMPLEMENTATION.....	11
14.	NOTES	11
14.1	Revision Indicator.....	11
APPENDIX A	RECOMMENDED METHODOLOGIES FOR CONDUCTING PROBABILISTIC PART AGE AND USAGE ASSESSMENT.....	12
APPENDIX B	RECOMMENDED METHODOLOGIES FOR MODELING	19
APPENDIX C	RECOMMENDED METHODOLOGIES FOR LANDING GEAR STRUCTURAL ANALYSIS	21
APPENDIX D	RECOMMENDED METHODOLOGIES FOR FATIGUE SPECTRUM DETERMINATION	23
APPENDIX E	RECOMMENDED METHODOLOGIES FOR LANDING GEAR SERVICE LIFE RISK ASSESSMENT	24
APPENDIX F	RECOMMENDED METHODOLOGIES FOR ANALYTICAL CONDITION INSPECTION PLANNING	30
APPENDIX G	RECOMMENDED METHODOLOGIES FOR LANDING GEAR RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) ANALYSIS.....	31
Figure 1	Graphical representation of service life.....	8
Table 1	Weighted distribution model variable descriptions.....	15
Table 2	Sample studies to examine effect of exponent n on final safe life results	17

INTRODUCTION

This document describes recommended practices for implementing a Landing Gear Integrity Program (LGIP). This program is especially applicable to landing gear systems that have not completely integrated serial part tracking.

LGIP develops and executes objectives for landing gear systems, including antiskid and brake control systems. This requires that design service life and service history for all landing gear parts are known and monitored. Some of the elements covered are mandatory and others are elective or dependent upon customer requirements or desires.

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides guidance on the definition, development, and establishing a LGIP.

1.1 Purpose

The purpose of this ARP is to document the best practices for establishing a LGIP.

The approach recommended in this ARP is not intended for application to large civil aircraft and is not intended as a primary means of compliance to 14 CFR 25.571 (and related regulations such as CS25.571, etc.) This recommended practice is intended for applications where life limited components have been placed into service and no tracking of their usage has been conducted. The use of this ARP will serve to reduce (but not eliminate) the risk to the aircraft and fleet from a landing gear fracture. The primary means of landing gear structural component life management for civil aircraft designed to 14 CFR 25 is by tracking, for each serialized component, the calendar time usage, the number of flights seen, and (for some aircraft) the number of flight hours. When a component reaches its published limit, it is removed from service and destroyed. This ARP may, upon review by cognizant engineers and regulators, have applicability for civil aircraft where life tracking of components has been determined to be applied after initial certification and management of a previously untracked fleet is required.

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.

ARP1598 Landing Gear System Development Plan

AS8860 Landing Gear Structural Requirements as Listed in the MIL-886X Series of Specifications

2.1.2 Other Publications

NIST/SEMATECH e-Handbook of Statistical Methods, <http://www.itl.nist.gov/div898/handbook/>, October 30, 2013.

ASTM E606, Standard Test Method for Strain-Controlled Fatigue Testing

MIL-STD-1530, Department of Defense Standard Practice: Aircraft Structural Integrity Program (ASIP)

MIL-STD-1798, Department of Defense Standard Practice: Mechanical Equipment and Subsystems Integrity Program (MECSIP)

Kaisarlis, G.J., Diplaris, S.C., Sfantsikopoulos, M.M. (2008). Geometrical position tolerance assignment in reverse engineering. *International Journal of Computer Integrated Manufacturing*, 21(01), 89-96.

2.2 Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ACI	Analytical Condition Inspection
ARP	Aerospace Recommended Practice
ASIP	Aircraft Integrity Program
BCA	Business Case Analysis
BOM	Bill of Materials
CDF	Cumulative Distribution Function
CG	Center of Gravity
CSI	Critical Safety Item
DOT	Department of Transportation
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FEA	Finite Element Analysis
FEM	Finite Element Model
FMECA	Failure Modes, Effects and Criticality Analysis
GD&T	Geometric Dimensioning and Tolerancing
HRI	Hazard Risk Index
ID	Identification
LGIP	Landing Gear Integrity Program
LMC	Least Material Condition
MLG	Main Landing Gear
MMPDS	Metallic Materials Properties Development and Standardization
NIST	National Institute of Standards and Technology
NLG	Nose Landing Gear

OEM	Original Equipment Manufacturer
P/N	Part Numbers
PDF	Probability Density Function
PLM	Product Lifecycle Management
RAM	Reliability, Availability, Maintainability
ROI	Return on Investment
S/N	Serial Number
SCC	Stress Corrosion Cracking

3. LGIP MASTER PLAN

LGIP practices, methodologies, and configuration management techniques are established in an aircraft system specific LGIP master plan. To develop the LGIP master plan, the landing gear system manufacturer or maintainer shall review best practices and lessons learned from other landing gear programs to prepare their LGIP master plan. The LGIP master plan shall provide a clear path for executing the LGIP program, manage LGIP data, and determine the methodology for inspection and operational loads gathering. The LGIP Master Plan shall be submitted to the cognizant engineering authority for review and approval prior to implementation.

4. LANDING GEAR DEVELOPMENT AND LGIP DATA INTEGRATION

4.1 Landing Gear Development Guidance

Landing gear design and development shall be guided by ARP1598 and the LGIP master plan developed for the specific aircraft system.

4.2 LGIP Data Management

Define the purpose, process, and methodology by which LGIP data shall be acquired, organized, and managed. Data includes engineering drawings, models, analysis, technical manuals, test reports, maintenance actions, and failure reports. Use of a product lifecycle management software tool is recommended to integrate and manage the large amounts of data that will be compiled.

4.2.1 Bill of Materials

Organize and provision Bills of Materials (BOM) for each aircraft landing gear configuration. The parts listing for each landing gear assembly should incorporate Serial Number (S/N) effectivity of parts should be included where applicable within the assembly to maintain the integrity of the configuration control for the landing gear assembly throughout its service life.

5. LANDING GEAR AGE AND USAGE ASSESSMENT

This section provides a methodology for selecting components for assessment of component age and usage. Age is defined as time (usually in years) of a component and captures the time period of part procurement to current status. Usage is defined as the accumulation of cycles, hours, landings, etc. The resultant age/usage data are then compared to the minimum service life criteria to determine remaining useful life, for probabilistic assessments, this process is described in Section 9.

5.1 Component Selection

Select components for analysis that are critical to gear function and/or are in the direct load path between the aircraft and the ground. When considering each of these items, it is important to capture all applicable configurations. All revisions, dash number changes, replacement Part Numbers (P/Ns), and next higher assembly purchases shall be considered when reviewing the purchase history of each item.

5.2 Deterministic Assessment

A deterministic assessment is the recommended approach for obtaining component age and usage information. This is done by examining the individual part's serial number, or other identifying information, from a tracking system to identify age and usage data. This method assumes that an accurate part tracking methodology is utilized, and age/usage information is readily available.

5.3 Probabilistic Assessment

When available part tracking information is insufficient to perform deterministic assessments of a component, then an estimate of the current age/usage of a component can be developed using a statistical model based upon probable part age and/or corresponding aircraft usage distributions. See Appendix A for recommended methods for conducting probabilistic age assessments.

6. LANDING GEAR MODELING

Develop and verify three-dimensional (3D) solid models for all landing gear assemblies and associated components (including wheels, brakes, valves, etc.). The solid model geometries generated shall be of sufficiently high fidelity to facilitate the creation of detailed Finite Element Models (FEMs) to accurately assess the stress state throughout each component. To ensure the accuracy of each solid model being developed, verification drawings shall be developed with dimensions pulled from the solid model for direct correlation with the legacy source drawings, such as an Original Equipment Manufacturer (OEM) controlled engineering data repository. See Appendix B for recommended modeling methodologies.

7. LANDING GEAR STRUCTURAL ANALYSIS

This section is intended to provide an airframe manufacturer or landing gear system supplier minimum engineering requirements for landing gear system structural analysis. The results of these analyses can be used as compliance data to support airworthiness certification. In addition, the results can also be used in conjunction with the analyses performed to comply with the recommended practices contained in ARP1598, 4.2. ARP1598 establishes the need for accurate, concise, and complete documentation (i.e., analysis reports, modeling descriptions, load cases, etc.) that serves as the formal definition of the strength of the complete landing gear structure. All load carrying structures whose failure or modification may result in damage to the aircraft or injury to personnel shall be substantiated by analysis. Included in this analysis shall be all structures, fasteners, welds, or bonds in the primary load path.

Some sections of ARP1598 may not be applicable to all air vehicle development or modifications; thus, it is the responsibility of the acquisition authority to identify the applicability of the detailed structural analysis section to comply with the specific program/project objectives.

7.1 Standard Structural Analysis Requirements

Landing gear structural analysis reports shall address the following load, strength, and life requirements:

- a. Static 1G loads for stress corrosion cracking analysis
- b. Limit strength
- c. Ultimate strength
- d. Fatigue life

7.2 Other Structural Analysis Components

Landing gear structural analyses may require the following analysis types or others not listed depending on program/project objectives:

- a. Damage tolerance analysis
- b. Dynamic loads analysis
- c. Kinematics analysis
- d. Statistical analysis
- e. Tolerance stack/wear allowance analysis

7.3 Analysis Details

Each part shall be analyzed based on the design intent and load environment of the landing gear structure when integrated into the air vehicle. The structural analyses shall address all failure modes and worst case combined loads. Appendix C provides recommendations for structural analysis categories, joint analysis, computed analysis, and safety.

7.4 Loads

Analysts shall ensure ultimate and limit loads are correctly identified and used consistently throughout the structural analysis process. The loads used in these analyses shall include the additional rigging or other preloads to be applied to components or structures according to aircraft system operating or maintenance manuals. Component weights and Center of Gravity (CG) shall be determined and included on the component drawings as applicable. Depending on the complexity of the structure being analyzed, the analyst may perform a detailed loads analysis to support a detailed structural analysis using the FEM.

7.5 Validation

Structural analyses used for airworthiness justification requires analysis validation. Validation is the correlation of analysis results to real world testing. This is accomplished by on-aircraft or physical testing. The type/extent of validation shall be determined by the needs of the specific program/project. Validation testing shall be documented in the following reports:

- a. Validation test plan report
- b. Validation test results report

8. FATIGUE SPECTRA DETERMINATION

The LGIP Master Plan shall identify the fatigue spectra for conducting landing gear analysis. The spectra shall be periodically reviewed and validated.

8.1 Aircraft Original Equipment Manufacturer (OEM) Spectra

For new aircraft systems, OEMs shall coordinate technical planning with landing gear systems designers during the requirements and design phases. OEMs shall coordinate updates to the fatigue spectrum with the technical representative for applicable landing gear systems. Landing gear sustainment activities shall determine if available spectra from the OEM are sufficient for landing gear analysis for current load cases.

8.2 Analyze Fatigue Spectra for Legacy Aircraft

Aircraft in service beyond their designed service life are prone to an increase in failures of landing gear components. Increased age and severity of usage contribute to the susceptibility for fatigue and environmentally assisted failures such as Stress Corrosion Cracking (SCC). To address this increase in susceptibility of failure, landing gear sustainment activities shall periodically assess the validity of the fatigue spectra used for analysis. When appropriate, additional loads spectra shall be obtained. Appendix D contains recommended methods for fatigue spectrum determination.

8.3 Establishment of an Updated Usage Spectrum and Re-Baselining

Compile the loads spectrum and usage spectrum into a fatigue spectrum (or spectra if fleet operating conditions have changed enough over time to warrant multiple spectra). Use inputs from additional sources such as the aircraft OEM spectrum, and MIL-A-886X (AS8860) with approval from the Landing Gear Systems Engineering Authority, particularly to represent the low occurrence/high load events that likely cannot be built into the loads survey test plan due to the high risk nature of including such events during on-aircraft testing.

8.3.1 Flight Data Recorder

Use loads survey data to establish a correlation between the test instrumentation data and the Flight Data Recorder (FDR) or equivalent. Utilize that correlation and a statistically representative segment of the fleet FDR data to determine an appropriate usage spectra. The fidelity (signal to noise ratio and signal bandwidth), axes of motion, and condition of selectable landing gear features that are included in the recorded data must be considered in determining what correlations may be feasible using FDR information.

9. SERVICE LIFE RISK ASSESSMENT FOR STRUCTURALLY CRITICAL COMPONENTS

Service life for structurally critical components is the total fatigue life of a component as determined by the developed fatigue spectra. A service life risk assessment then establishes the risk of fatigue failure of a given component by comparing the current usage distribution (accumulated fatigue damage) with the component's failure probably distribution (Figure 1). Structurally critical components are defined as those designed in accordance with a safe life methodology. Safe life is a design concept in which damage does not initiate in the structure and the structure maintains its design ultimate load capability up to the safe life limit¹, at which point the structure must be replaced.

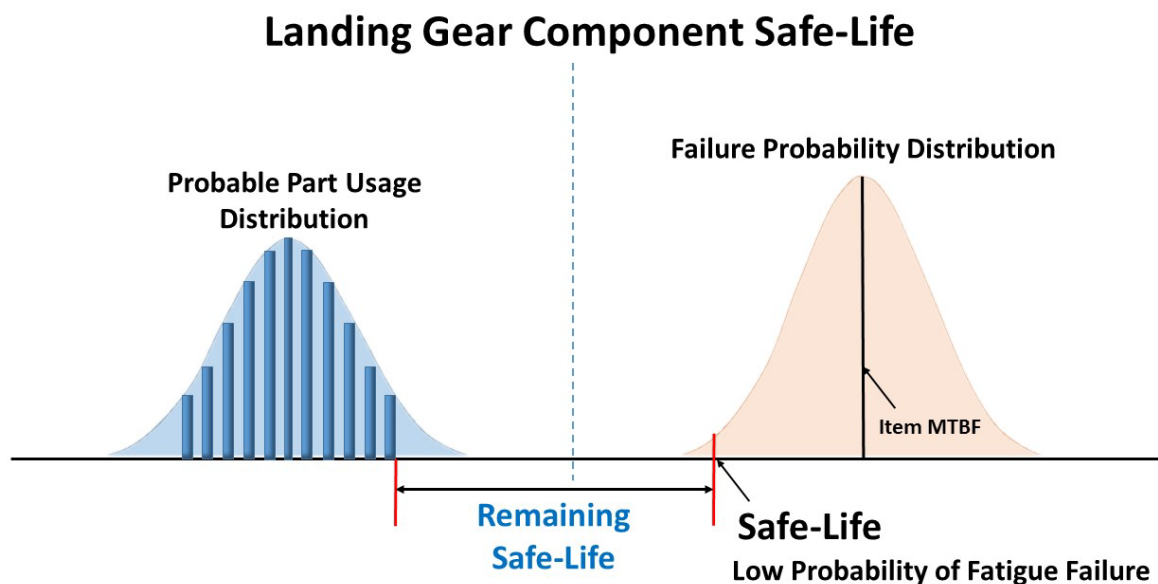


Figure 1 - Graphical representation of service life

¹ MIL-STD-1530 Department of Defense Standard Practice: Aircraft Structural Integrity Program (ASIP)

9.1 Fleet Usage Analysis

Fleet usage analysis relates the part age distribution to aircraft usage statistics. The result is expressed as a statistical distribution of the probable number of landings for the part being examined. The resulting distribution can then be compared with the Service life limit for each component. Service/safe life design criterion is four lifetimes of the respective aircraft for damage-intolerant components (parts where a defect smaller than the minimum detectable defect is impactful upon life).

9.2 Fatigue Life Analysis

Many structural landing gear components have a limited fatigue life. Factors affecting fatigue life include applied loads over several landing cycles, under various load spectra; premature failure due to SCC; and the effect of overhaul practices on individual components. Use fatigue analysis models to combine aircraft ground load and usage spectrum with the results of finite element stress/strain computations to perform an analysis of accumulated damage to each surface node location on the FEM. Likely fatigue failure locations are identified as nodes which exceed 100% damage with the fewest lifecycle counts. The lowest cycle count found over the entire surface of the part becomes the expected fatigue life of the part.

9.2.1 Statistical and Fatigue Methodologies

The statistical distribution of fatigue life requires various assumptions. Determine and record probability and statistical assumptions used to calculate the probability of crack initiation in non-damage tolerant structures, including an explanation of the reasons for the assumptions. Assumptions include the type of distribution used (such as the Birnbaum-Saunders Distribution) and design life assumptions. See Appendix E for service life risk assessment methodologies.

9.3 Risk Assessment Analysis

The risk assessment for landing gear systems shall be determined using probability of fatigue failure of structural assemblies and their associated components based on appropriate aircraft system spectra. Assess the landing gear system's ability to perform without mishap or degradation due to past, current, and anticipated future operational requirements and document the results of these analyses. Analysis shall include:

- a. Accomplish FEM based strain life fatigue analysis for structural parts, based on the applicable fatigue spectrum(s).
- b. Analyze and estimate the current service life condition of landing gear based on the probabilistic age assessment and FEM fatigue life analysis using the applicable fatigue spectrum.
- c. Establish new service life baseline for components.
- d. Identify parts that are at risk of fatigue failure (either currently, or within the next 10 years) in component service life reports and perform risk assessment.
- e. Structural analysis to include evaluation at limit and ultimate loads, and SCC at 1G loading.
- f. Data from ACI and RAM tasks (see Sections 10 and 11) must be considered in the development of the service life risk assessment when found to be influential, e.g., oversized repair conditions, chronic corrosion issues, etc.

Use material fatigue properties accepted by the landing gear engineering authority or industry associations (e.g., ANSI, AISI, ASTM, etc.). If material data is not available, it shall be developed and provided per ASTM E606.

9.3.1 Service Life Risk Assessment at Least Material Condition (LMC)

To assist sustainment of repairable landing gear components, establish risk by determining probability for fatigue failure of structural Critical Safety Items (CSI) at Least Material Condition (LMC) based on operational spectra. Account for the probability of components operating at LMC based on actual material conditions obtained from Reliability, Availability, Maintainability (RAM) analysis (see Section 11).

10. ANALYTICAL CONDITION INSPECTION (ACI)

When the condition of landing gear components for an aircraft fleet is in question, an ACI can be conducted. Use ACI to identify (1) the remaining useful life of component(s) based on documented repair limits and drawing dimensions and (2) existing or developing failure modes, such as wear, recurring seal leakage, corrosion, cracking, component deformation, impact damage, thermal effects, grease, or hydraulic oil degradation. Document the results of the ACI so the data generated through the ACI can be used to refine mandatory aircraft inspection programs at both field and depot levels. See Appendix F for recommendations of ACI planning.

11. LANDING GEAR RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM) ANALYSIS

RAM provides an in depth look at historical aspects of the landing gear and investigates problematic components that show reliability and maintainability issues as well as quantifying the impact on aircraft availability and cost. Based on an in-depth historical evaluation of the landing gear system, the RAM analysis identifies deficiencies, validates current preventive maintenance requirements, identifies cost drivers, identifies potential design changes and validates/updates component repair processes. Viewing RAM concerns from a “systems” perspective permits identification of individual components that contribute to an entire system's deficiencies.

A clearer understanding of landing gear condition allows the engineer to focus on specific problems and issues, because the problems are specifically highlighted and prioritized. The LGIP, specifically the RAM analysis portion, facilitates a plan going forward to decrease repair time, decrease condemnations, decrease high costs, and most important to increase time between maintenance cycles. An overarching goal of LGIP is to assure system safety and to increase the time between overhauls. See Appendix G for RAM analysis methods.

11.1 RAM Analysis Data

Conduct a systematic review of service history and failure data from maintenance and supply systems. Ensure the time period of data collection covers at least one full cycle of all levels of inspection (field, minor, major, overhaul) for each aircraft in service.

11.1.1 Component Condition Analysis

Conduct component condition analysis to drill down into the part number level of assemblies. Conduct analysis to compile and consolidate key metrics used to establish a ranking comparison of problems. Direct investigation to identify any root causes and perform supporting analyses that define the corrective actions necessary to improve the in-service performance of the top maintenance drivers.

11.1.1.1 In-Service Site Assessments

Conduct on-site surveys of maintenance, supply, and operations personnel, at operational locations and intermediate and overhaul repair facilities regarding apparent deficiencies and potential improvements to landing gear system components. Visits shall be structured by an initial RAM analysis to reveal known and potential unknown issues. These surveys are used to identify problems that may not be apparent from the data analysis. Additionally, the field assessments can identify and document existing or developing failure modes, such as wear, recurring seal leakage, corrosion, cracking, impact damage from handling or use, thermal effects, and grease or hydraulic oil degradation.

11.1.2 Solution Development

Solution development shall follow the RAM data analysis and any follow-on analysis necessary because of the field and depot visits. See Appendix G for solution development activities.