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A Rational Approach for an Aging Mechanical Systems Program

March 2009

Final Report

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16. Abstract

In 1998, the White Commission recommended expanding the Federal Aviation Administration Aging Aircraft Program to include mechanical and electrical systems. In 1999, an aging mechanical systems study was initiated. The Aging Transport Systems Rulemaking Advisory Committee found that mechanical systems were a low priority; however, the National Transportation Safety Board recommended that these systems be reviewed, including those for smaller transport airplanes. Since that time, a mechanical systems group conducted several studies of airplane flight control systems. During those studies, it was difficult to determine which mechanical components should be reviewed. A filter process was developed to determine the critical parts that are subject to aging. This report describes the flow chart filter process and suggests several methodologies for evaluating components identified with it. Using this process, parts were identified for several airplanes. The examination of several parts taken from high-time airplanes revealed defects that apparently were not found during normal maintenance. Some of these findings are provided in this report.

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LIST OF ACRONYMS

AANC	Airworthiness Assurance and Nondestructive Inspection Validation Center
AD	Airworthiness Directive
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
MRB	Maintenance Review Board
SE-DLP	Single-element, dual-load path

EXECUTIVE SUMMARY

With safety being paramount in the Federal Aviation Administration's regulated perspective, this report addresses the issue of aircraft mechanical systems and examines one method to be proactive in mechanical system safety.

This report documents methods to define an approach to determine critical components of mechanical systems that may impact aircraft safety. This approach entails following flow charts as a filtering mechanism to systematically eliminate noncritical systems until it determines which systems are critical for aircraft safety.

The methodology described in this report is developmental. However, using a specific mechanical system as a test case, the presented methodology was successful in functioning as a proactive safety enhancement technique. The researchers believe that this methodology could be applied to any airplane mechanical system, potentially increasing that systems safety, effectively increasing the overall safety of the airplane.

1. INTRODUCTION.

1.1 BACKGROUND.

In several sessions of the 9th Annual Conference on Aircraft Aging, logistical issues, such as schedules, costs, and obsolescence, were addressed. From a regulatory perspective, aging systems in commercial transport aircraft have a singular issue: safety. This is a departure from military and aircraft priorities where mission readiness and rapid deployment are paramount and must be addressed. In transport aviation, economics are a major concern for manufacturers and airlines. However, for regulators, the safety of the flying public is paramount and is the main issue addressed in the Federal Aviation Administration (FAA) Aging Aircraft Program. The FAA is not as concerned with reliability, economy, on-time departures, and parts availability. However, manufacturers and airlines have a vested interest in these areas and are probably better equipped to address such concerns. Manufacturers, operators, and the military are also very interested in safety. However, the benefits of proactively pursuing aging issues are not always apparent, and financial pressures may discourage expenditure in this area. After all, even in a simple mechanical system, there are thousands of parts and examining each one could be costly.

1.2 PURPOSE.

The purpose of this report is to describe an approach that allows a person or company to determine the parts or assemblies that could be critical to safety and that could be affected by aging. The determined subset of parts should be a much smaller number than the total number of parts in the entire system; therefore, it should be less resource-intensive to evaluate this smaller subset than to evaluate the entire system.

2. THE FAA SYSTEM.

Prior to describing the aging system approach, it is important to understand the following four key elements the FAA relies on to build safety into flight systems.

1. Design Integrity
2. Manufacturing Consistency
3. Operations and Qualifications
4. In-Service Safety Management

These elements form a figurative net that should catch safety issues before the systems are affected by aging.

2.1 DESIGN INTEGRITY.

The governing minimal design standards that a transport airplane must comply with to receive type certificates are contained in Title 14 Code of Federal Regulations (CFR) Part 25. A key

requirement to ensure system safety and reliability of mechanical systems is 14 CFR 25.1309. Briefly, the standard requires that:

- The systems shall be designed so any single failure will not result in a catastrophic failure.

- In a given system, combinations of failures that result in catastrophe will be extremely improbable (not expected to occur in the flight life of a particular airplane model).

- The system shall contain cautions and warnings that allow pilots to take appropriate actions after a failure and allow adequate reliability to limit latency of certain failures that may only be detected in maintenance.

- Interaction of failures with other systems will be addressed. Compliance with these requirements is usually shown by several analyses. Fault tree analysis is an example of an analysis used for compliance to 14 CFR 25.1309. The following assumptions are associated with fault tree analyses:

  - Fault trees are done correctly and failure modes are fully understood
  - The components are designed and manufactured correctly
  - The airplane is assembled and maintained correctly
  - The environment is fully understood
  - Undetected failures will remain undetected only for a limited period of time

2.2 MANUFACTURING CONSISTENCY.

The governing manufacturing standards are contained in 14 CFR Part 21 Subpart G. These standards require that a manufacturer have the ability and quality control to repeatedly build a part per the airplane type design.

2.3 OPERATIONS AND QUALIFICATIONS.

2.3.1 Maintenance Operations.

14 CFR 25.1529 is the governing maintenance standard that a transport airplane must comply with to receive a type certificate. This standard requires that an applicant prepare instructions for continued airworthiness. The specific maintenance tasks associated with mechanical systems are developed in a maintenance task analysis conducted by the FAA Maintenance Review Board (MRB). The Board consists of FAA engineers and inspectors and manufacturer and airline representatives. The analysis method usually follows the Air Transport Association's manufacturer-scheduled maintenance process. This process involves an analysis that ensures that all components that impact safety or that leaves the airplane one failure away from catastrophe are maintained with specific tasks conducted at specific intervals. The performance of these tasks makes the assumption that the airplane will be maintained correctly and in a timely fashion. The time between the task intervals may be increased if an operator can provide supporting evidence that the increase will not effect safety. This time increase is known as

escalation. The escalation of a lubrication task interval coupled with a missed lubrication caused excessive wear of the jackscrew/nut on Alaska Air Flight 261. Transport airplane operators generally take the manufacturer's maintenance program and the MRB report and customize them to establish their own maintenance program. The operator maintenance program is accepted by the FAA under the provisions of 14 CFR Part 121 Subpart L. Accompanying guidance is found in FAA Order 8300.10.

The FAA also has a higher-level maintenance task known as a Certification Maintenance Requirement. These are maintenance tasks derived directly from the fault tree analysis and are required at specific intervals for a specific airplane to be considered airworthy. This higher-visibility maintenance task is listed in the airplane's type data sheet.

2.3.2 Flight Operations.

Various requirements in 14 CFR Part 25 Subpart G and Part 121 specify certain operation requirements and limitations. These standards define limitations within which the airplane should be operated. In essence, these standards help ensure that the airplane is operated as it was intended to be.

2.4 IN-SERVICE SAFETY MANAGEMENT.

The FAA implements several processes to address safety issues identified in the fleet, for example, the Airworthiness Directive (AD) process defined in 14 CFR Part 39. In service, if an airplane or airplane model has, or is likely to have, a deficiency that could jeopardize continued safe flight and landing, the FAA will mandate repair via an AD. The FAA requires manufacturers and operators to report certain events that may have fleet safety implications (see 14 CFR 21.3, 121.563, 121.703, and 121.704). Additional processes that may be considered are the Aging Structures Program and the Aging Wiring Programs. These programs were developed to address deficiencies found in service that cross all airplane models.

3. AGING ISSUES.

If the elements described in section 2 are conducted as stated in this report, and all assumptions are met, then the industry would have airplanes that would age as designed. If done correctly, there would be no single catastrophic failures. Moreover, failures leaving the airplane one failure away from a catastrophe would be fully addressed through monitoring or through acceptable maintenance intervals that allow repair in a reasonable time period. Components would be correctly manufactured. Maintenance would be done properly and on schedule. The airplane would be operated within its limitations, and if there was a safety concern, it would be addressed through an airworthiness process. Regulatory elements, unfortunately, do not anticipate all the issues. For example, airplanes certified to older requirements may not have complete coverage; fault tree analysis does not account for human errors and some parts may not have adequate inspectability. Table 1 lists some examples.

Table 1. Well-Known Aging Aircraft Events and Violated Assumptions

Event	Aircraft	Status	Cause	Violated Assumption
TWA 800	B-747	Fatal/hull loss	Faulty wiring caused a spark that ignited fuel tank	Interactions not assessed
Aloha 243	B-737	Fatal/hull damage	Widespread fatigue cracking of lap splice	Environment and maintenance
America West 450	B-737	Hull loss	Failed check valve after a hydraulic leak and fire	Latent failure
Air India	B-727	Hull loss	Faulty wiring caused a spark that ignited the fuel tank	Latent failure
Not available	B-757	AD inspection	Worn stabilizer jackscrew (blocked grease port)	Design
Not available	B-747	AD inspection	Stress corrosion cracking of elevator control rods	Design

TWA = Trans World Airlines

The events in table 1 demonstrate that, sometimes, the human application of the standards does not fully address all issues that arise during the life of an airplane. The Trans World Airlines and Aloha accidents revealed specific weaknesses in certain components, such as wire insulation that became brittle with aging and structural lap splice fatigue that was not caught by any of the regulatory elements. Other components that are not as widely used have also caused accidents, such as the failed check valve on American West Flight 450. Determining which components impact airplane safety depends on the criticality of the application and requires knowledge of the failure modes and effects. The researchers may know that a part is critical, but they may not know if an aging issue exists with it. Factors, such as reliability, understanding of the parts' environment, and system architecture, may affect whether the part poses a threat as a function of age. One way to address aging mechanical systems problems would be to wait for specific component failures, and as each reveals itself, make fleet corrections. In light of the accidents cited, this reactive approach is not the best option. A proactive aging mechanical systems program should have the ability to reveal aging components that affect flight safety prior to an event.

3.1 PROPOSED APPROACH.

Considering the events listed in table 1 and the elements discussed above, the methodology defines an approach to determine critical components that could impact aircraft safety and could be subject to aging. The approach begins with the flow chart filter process shown in figures 1a and 1b. The flow chart assists the user in systematically eliminating (filtering) the vast number of noncritical systems, assemblies, and components, as well as critical components that are immune to the effects of aging from further assessment. The smaller remaining subset of components would require further evaluation or action. User instructions, notes, and definitions are in appendix A. In addition to the systematic and efficient advantages of the approach, it is

believed that by being general and straightforward, this method can be adopted by operators and manufacturers for any mechanical system (in reality, any system) with minimal resource allocation. One caveat of the approach is that the user must have aircraft and system safety assessment knowledge (e.g., hazard assessment, failure modes and effects analysis, as well as knowledge of the airplane's service history).

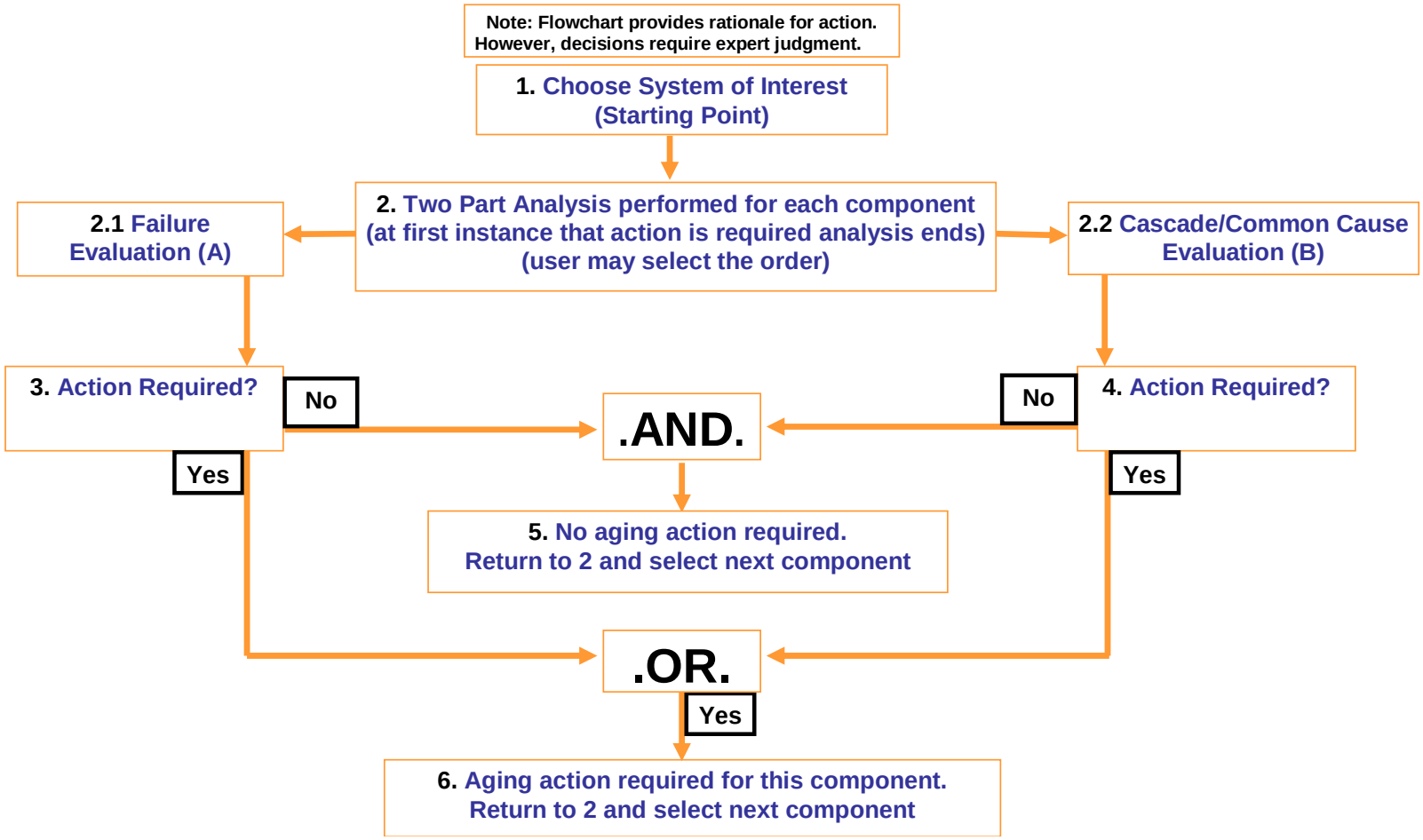

Figure 1a. Aging Mechanical Systems Methodology (Flow Chart Filter Process)

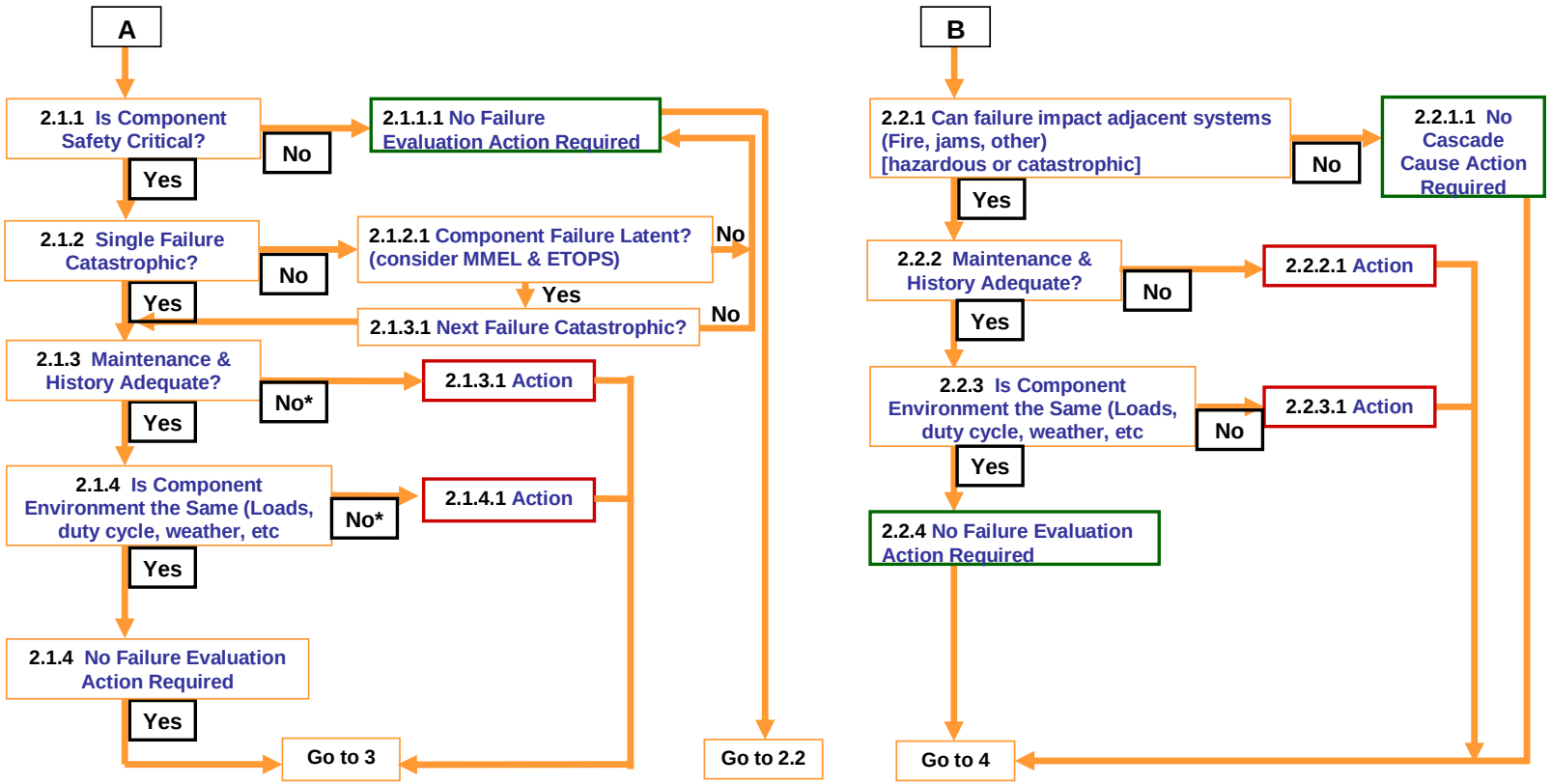

Figure 1b. Aging Mechanical Systems Methodology (Flow Chart Filter) Failure Evaluation (A) and Cascade/Common Cause Evaluation (B)

3.2 APPROACH ASSUMPTIONS.

The proposed approach assumes the following:

- The analysis will be performed by a person with adequate system, installation, and historical knowledge to be able to correctly assess each system, assembly, and component.

- Single and dual failures adequately cover aging system phenomena.

- Dual failures are of concern only where there is significant latency.

3.3 NEGATIVE PRESSURE RELIEF VALVE SYSTEM EXAMPLE.

The flow chart filter process was applied to a negative pressure relief valve system. These valves allow cabin pressure to follow atmospheric pressure during emergency descent conditions ensuring that the external pressure does not damage the aircraft fuselage. The flow chart first directs the user to perform the failure evaluation (A), as shown in figure 2a. The flow chart filter prompts the user to determine whether the component is critical. In this case, the failure of the negative pressure relief valve system is critical. However, since there are typically three or more pressure relief valves, a single failure is not catastrophic. The system eventually will pass the failure evaluation. However, the system is subject to common failure mode evaluation (B), as shown in figure 2b. In the field, a check is performed to ensure that the valves are not obstructed. But in this case, the negative pressure relief valves are never functionally checked. Since a nonfunctional valve would not be identified, the flow chart prompts the user for an action. An example of this action might be to test some high-time negative pressure relief valves.

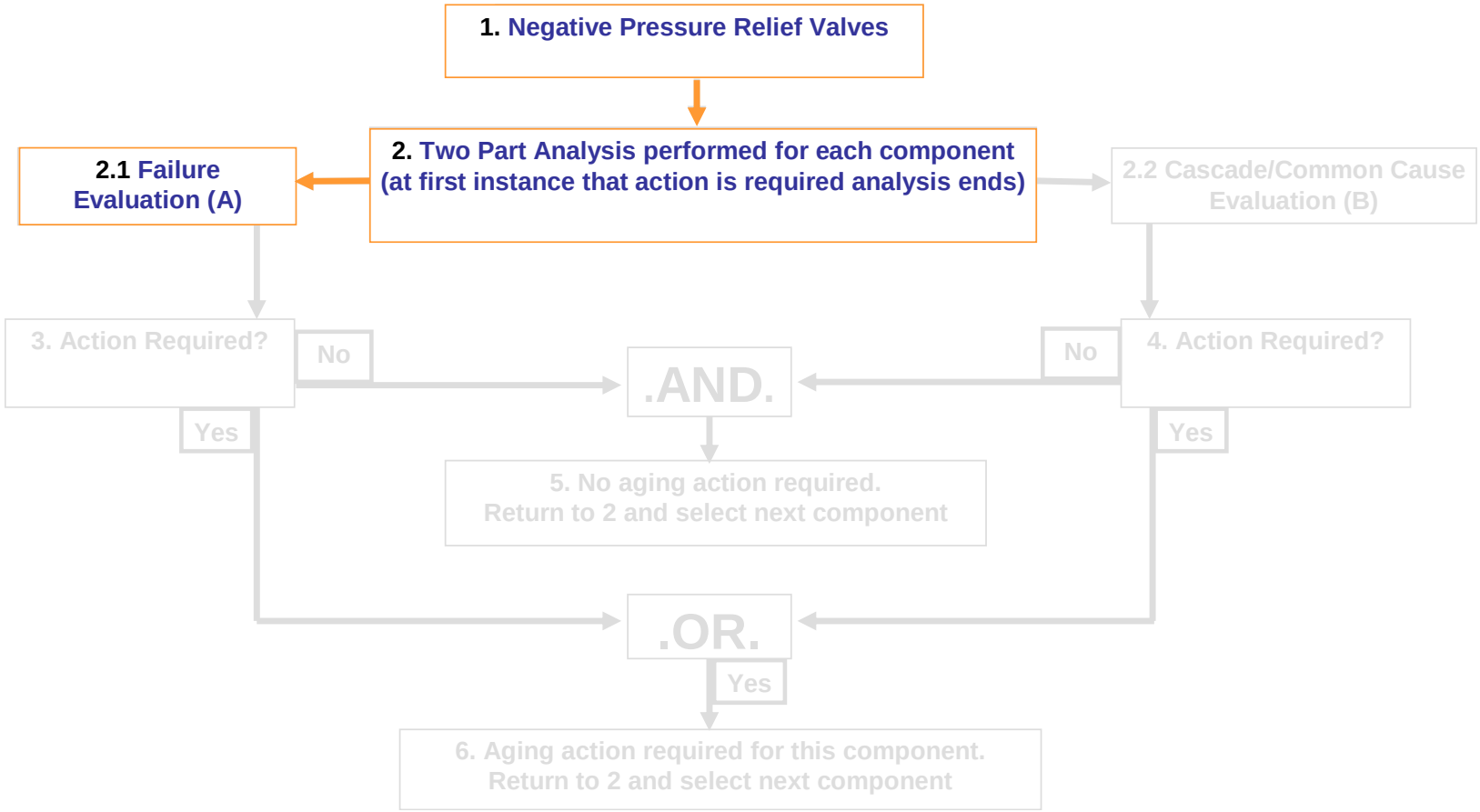

Figure 2a. Aging Mechanical Systems Methodology Hypothetical Example (Negative Pressure Relief Valve System)

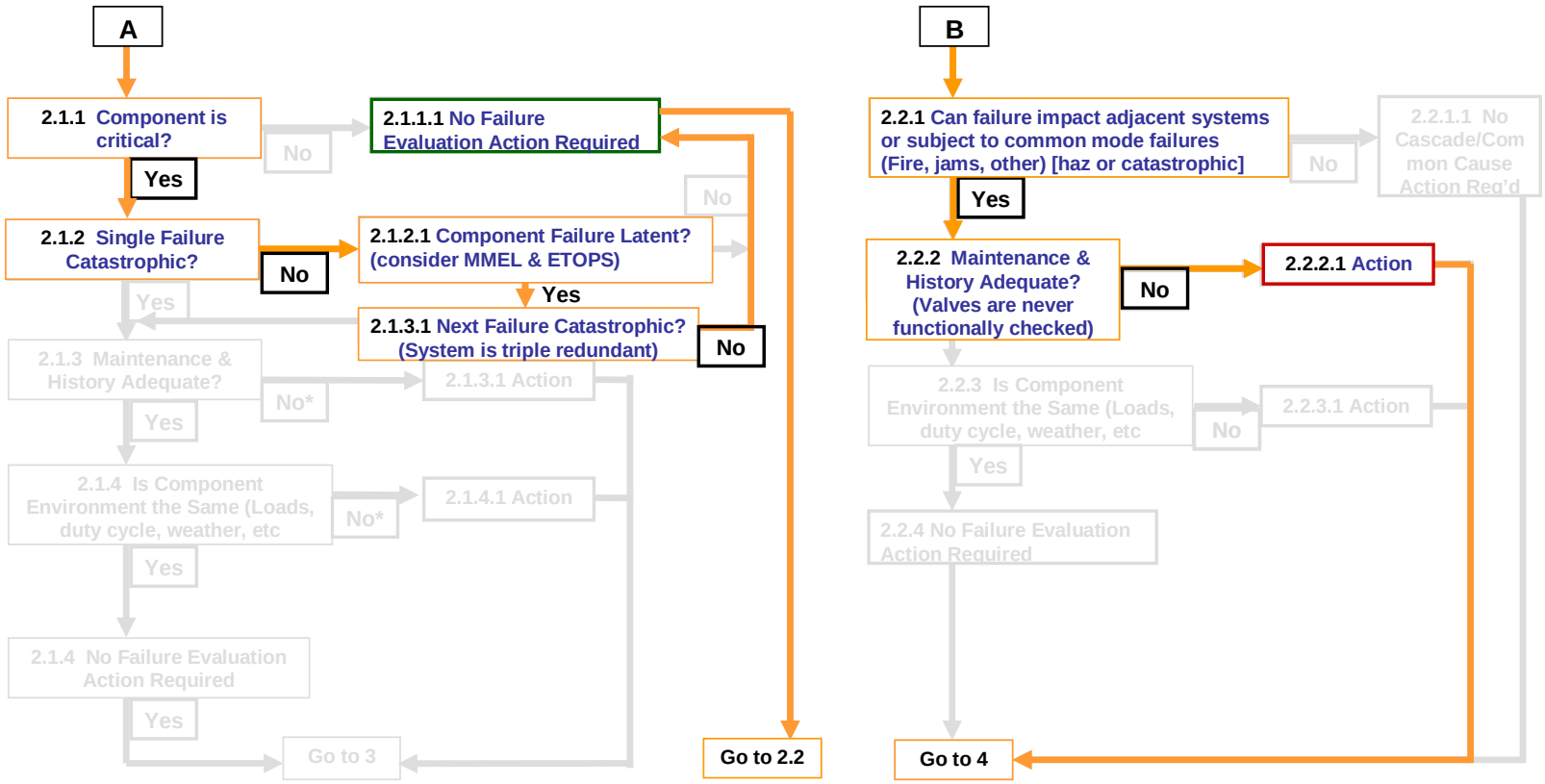

Figure 2b. Aging Mechanical Systems Methodology Hypothetical Example Extended (Negative Pressure Relief Valve System)

3.4 HOW TO PROCEED IF THE FLOW CHART RECOMMENDS AN ACTION.

Once the subsets of critical components, assemblies, and systems have been identified using the flow chart filter process, the next step is to investigate the health of these critical components in the field. Sampling, statistical analysis, and information-gathering methods are briefly described here as a means to determine if airworthiness action is needed. See reference 1 for further information regarding each respective method. Examples of airworthiness actions included revising maintenance programs that increase inspection interval frequency, replacing components after a specific number of flight hours (hard time), and creating new or revised testing techniques that can reveal component weaknesses. If a finding is significant enough, airworthiness action could be warranted.

3.4.1 Sampling.

This method involves inspecting or testing a random sample of recently retired or high-time components to infer the condition of field components and to detect any aging trends [2 and 3] (see section 3.5).

3.4.2 Statistical Analysis.

Several statistical analysis methods can be applied—such as risk analysis—using in-service repair records to detect aging and the optimal time for maintenance actions [3 and 4]. Markov Latent effects analysis was used to identify cultural and organizational precursors, and operational factors that contribute to accidents [5].

3.4.3 Information Gathering.

This method requires gathering numerous pieces of information such as Safety Assessment Data, Manufacturer Design Data, Operational Data (Maintenance data and flight), Database Searches, and Interviews with engineering, maintenance, and repair shop personnel [6]. Once collected, the data is analyzed to determine if critical components require additional action.

3.5 SAMPLING CASE STUDY.

Using the flow chart filter process outlined in figures 1a and 1b, the FAA determined that single-element, dual-load path (SE-DLP) flight control components used on many airplane models should be investigated. These components were considered because (1) they are typically critical relative to safety, (2) they are typically not fully inspectable, and (3) they may be in use for the life of some airplanes. Boeing 737 and 747, and Airbus A300 aircraft models were selected for further study using sampling. These models were chosen because they were older models and not because of any known or suspected issues. At the present time, a number of SE-DLP components from six B-737, six B-747, and three A300 aircraft have been sampled. This work was performed with the cooperation of the aircraft manufacturers and orchestrated by the FAA Airworthiness Assurance and Nondestructive Inspection Validation Center (AANC), operated by Sandia National Laboratories in Albuquerque, New Mexico.

The AANC inspections searched for any signs of erosion, corrosion, excessive wear or fretting, cracks, impact damage, or other signs of mechanical degradation. Some components were also inspected against original equipment manual specifications. Data collected (for example, length of crack, depth of impact damage, etc.) included supporting photo documentation and quantified information detailing.

In-service inspection of SE-DLP components consists of a general zonal visual inspection of the installed components on the aircraft and typically occurs during an aircraft C-check inspection interval. To simulate a C-check inspection, the AANC performed on-aircraft visual inspections (when feasible) of the selected SE-DLP components and noted any findings. The components were then removed from the aircraft; visual inspections before and after cleaning and after disassembly were performed. Any additional findings also were noted. When necessary, the visual inspections were supplemented with a nondestructive inspection, such as fluorescent penetrant, eddy current, radiography, and ultrasound. In cases where components were never intended to be disassembled, or where visual access was limited, the components were destructively sectioned.

The more notable findings are shown in this report; however, for results of all Boeing SE-DLP components tested, see reference 7. Reference 1 summarizes the results of the A300 SE-DLP component sampling.

Through sampling, the researchers identified components containing a hygroscopic, resin-based bond adhesive (BAC5010 Type 38). Hygroscopic adhesive was prone to absorbing moisture, which caused corrosion that is visually hidden. In certain cases where the corrosion was significant, stress corrosion cracking was observed. Figure 3 shows cracks found on a B-747 inboard elevator rod assembly. The component was sectioned to reveal the hidden load paths (inner- and outer-rod interface), and corrosion was found on both load paths, as shown in figure 4.

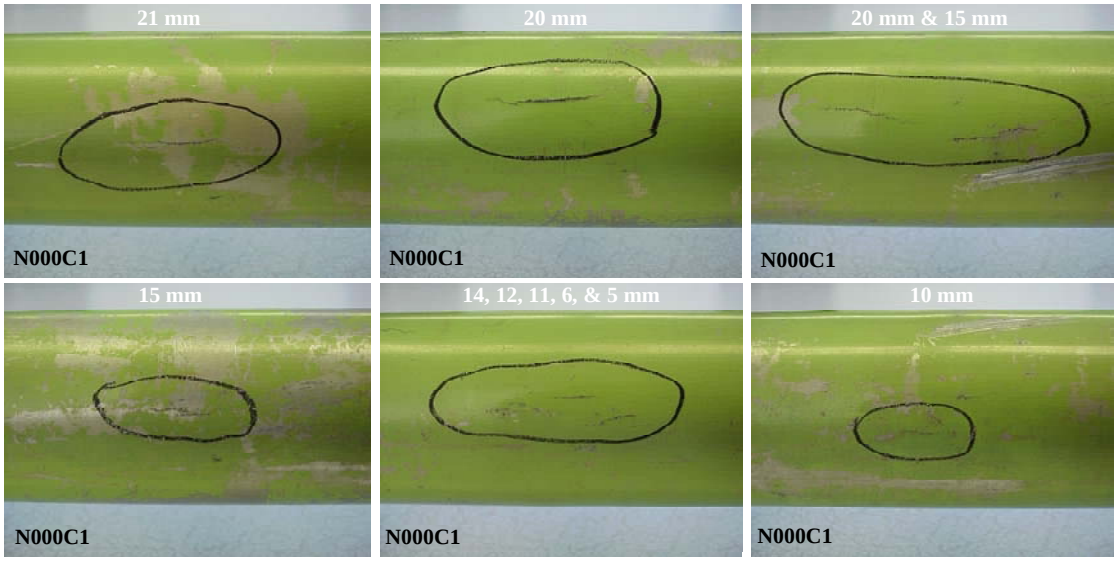

Figure 3. Visual Inspection of B-747 Elevator Rod Assembly Reveals Fatigue Cracks

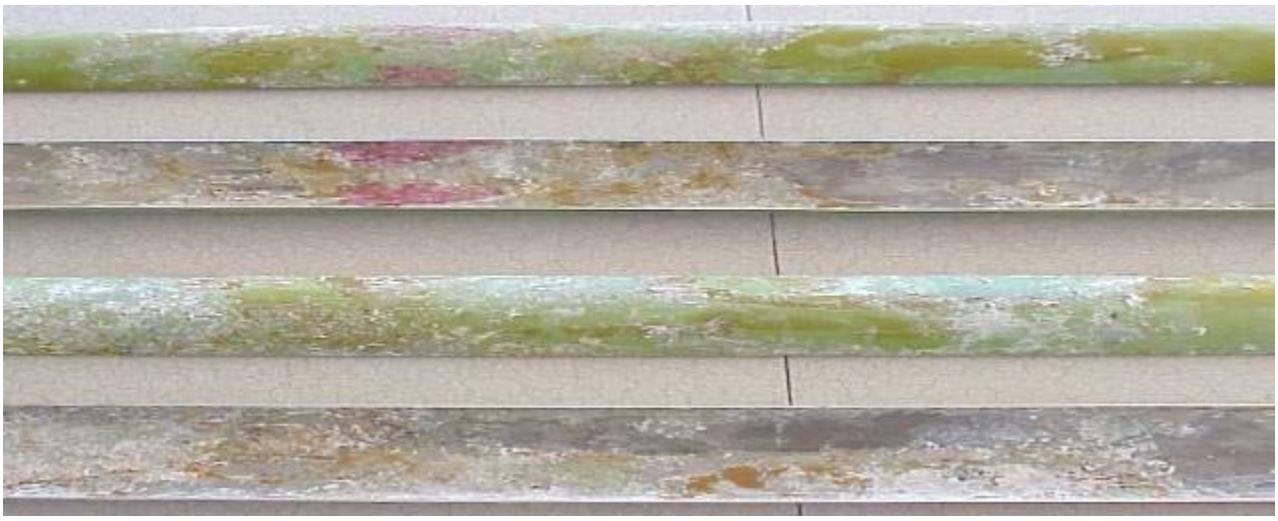

Figure 4. Sectioning of B-747 Elevator Rod Assembly Revealed Corrosion

Corrosion and cracks were found in other parts that used the epoxy-based adhesive. Table 2 summarizes our findings.

Table 2. B-747 Hygroscopic Adhesive Findings

Part Name	Part Number	Model	Discrepant/ Total Sampled	Finding
Elevator rod assembly	65B81011-504/-513	B-747	2/12 Corrosion and 1/12 cracks	Hygroscopic adhesive
Elevator rod assembly	65B81011-413/-414	B-747	2/12 Corrosion	Hygroscopic adhesive
Input rod assembly	93677	B-747	1/6 Cracks	Hygroscopic adhesive

The AANC learned that Boeing replaced the adhesive with a sealant-based bond adhesive for all new components. Components containing the sealant-based bond adhesive were also sampled and destructively sectioned, and no corrosion was observed. In addition, the FAA issued AD 90-25-10 that required repeated external visual inspection and internal borescope inspection. However, the corrosion was located in the outer portion of the inner rod and the inner portion of the outer rod, and since it is visually hidden, the AD inspections could not detect the corrosion.

Table 3 summarizes the crevice corrosion findings for B-737 elevator rod assemblies.

Table 3. B-737 Crevice Corrosion Findings

Part Name	Part Number	Model	Discrepant/ Total Sampled	Finding
Elevator rod Assembly	69-44427-3	B-737	2/6 crevice corrosion	Damage to cad layer

Two of the six components sampled contained crevice corrosion in areas where damage to the cadmium protective layer was observed. The areas included the internal wrenching bolt and mating rod surface. Figure 5 shows the crevice corrosion found on one of the internal wrenching bolts. Despite these findings, Boeing does not consider the corrosion to be an airworthiness issue.

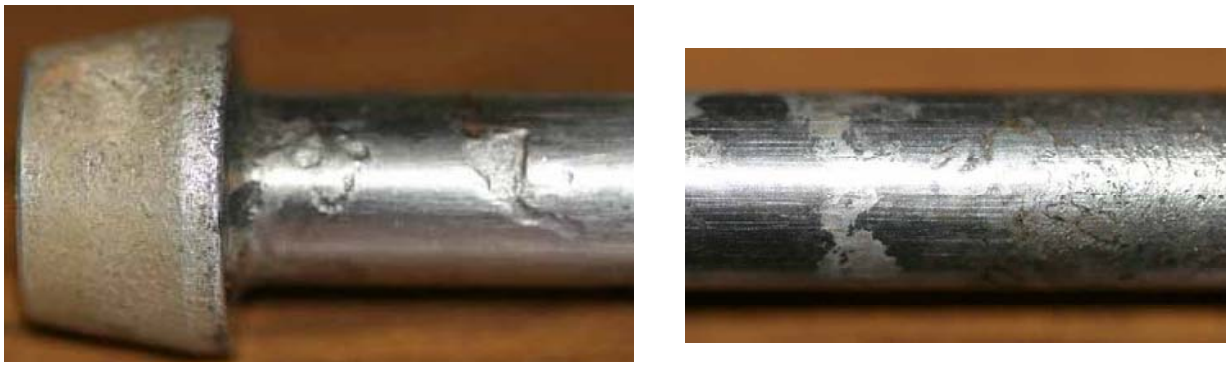

Figure 5. Disassembly of Elevator Rod Assembly Reveals Crevice Corrosion on Inner Bolt

A similar finding, which was also not considered an airworthiness issue, was corrosion detected on the outer tube of the A300 rudder actuator drive shaft assembly. Table 4 summarizes the findings.

Table 4. A300 Corrosion Findings

Part Name	Part Number	Model	Discrepant/Total Sampled
Rudder actuator drive shaft assembly	A2727085000000	A300	2/2 corrosion on outer shaft

An Airbus investigation concluded that damage of the protective nickel layer was not a manufacturing defect, and the cause was mechanical damage from in-service use. The drive shaft material loss of 0.1 mm is within the normal dimensional tolerance. Note that corrosion on the outer shaft should be visible during an in situ zonal inspection, as shown in figure 6.

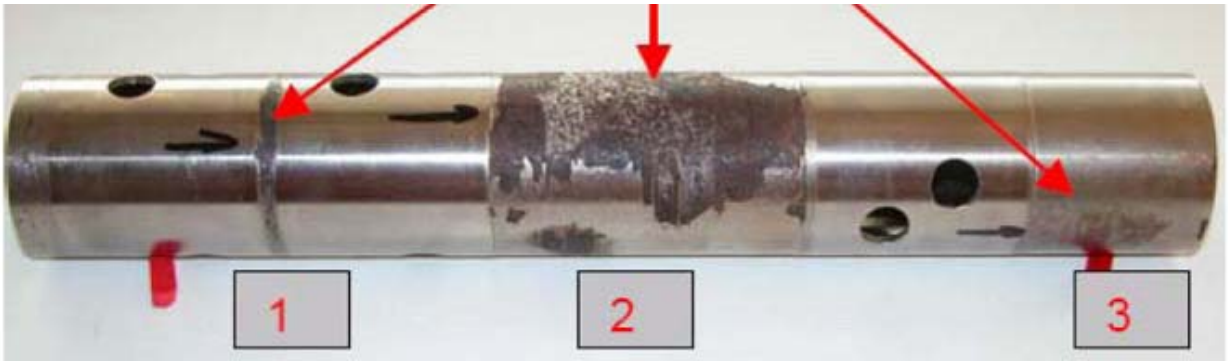

Figure 6. Corrosion Detected on an Outer Shaft

4. SUMMARY.

The FAA's primary concern is safety. This study developed an aging mechanical system methodology to identify safety-critical parts that may not be adequately maintained. A manufacturer, airline, or third party can apply the methodology by selecting a component, assembly, or system, and following the flow chart filter process. The methodology can be applied to any mechanical system. The filters eliminate components, assemblies, or systems that may not pose aging concerns and leave a smaller remaining subset of components that require further examination (action). Therefore, the flow chart filter process reduces the number of components requiring further examination, allowing efficient use of resources. One caveat is that the successful implementation of the methodology requires expertise and judgment of the user. Three examination methods were provided for further investigation of the smaller remaining subset of components highlighted by the flow chart filter process, including sampling, statistical, and information gathering. These investigative methods will better enable the user to determine if the components in question require an airworthiness action. The presented methodology was tested on specific systems and revealed stress corrosion cracks in flight-critical SE-DLP flight control components. Evaluation regarding the criticality and additional action of these components is being considered. While the methodology is purely developmental and currently has no regulatory authority, it can be adopted by aircraft manufacturers and operators to further enhance safety.

5. FUTURE WORK.

On-going work may refine and improve the methodology outlined in this report. Additional components have been identified for further investigation, including control torque tubes, hydraulic fluid fuses, check valves, pressure limiting, and pressure relief valves.

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APPENDIX A—FLOW CHART FILTER NOTES, DEFINITIONS, AND INSTRUCTIONS

A.1 NOTES.

- The methodology and approach described in this report is intentionally broad enough that it is applicable to all airplane systems and not just mechanical.

- This methodology and approach make the assumption that triple redundancy precludes aging failures (i.e., only single and dual failures are considered).

A.2 DEFINITIONS.

- Safety Critical—Failure may result in catastrophe or possibly a hazardous condition or leave the airplane vulnerable to the next single failure.

- Component—Any assembly, component, or part being considered. They should include hybrid multisystem components like bonding straps, autopilot components, and hydraulic conditioning components such as pressure limiters. Components in assemblies may also need to be considered. For example, a pressure-limiting valve in an autopilot actuator might fail latent; a subsequent autopilot hardover could be catastrophic. Therefore, the autopilot actuator internal component needs to be assessed individually. Components can also include general use items such as cables, wires, check valves, or structures.

- Service History—The service history described in this report was found in the Service Difficulty Reports, Airworthiness Directives, and other similar reports.

- Action Required—Indicates that some sort of systematic approach should be followed to evaluate the aging characteristics of the component. Three examination methods are presented for further investigation of the smaller, remaining subset of components highlighted (action required) by the flow chart filter process, including sampling, statistical, and information gathering. These investigative methods will better enable the user to determine if the components in question require an airworthiness action.

A.3 BLOCK-BY-BLOCK INSTRUCTIONS.

1. Choose a system. Any system can be a candidate for aging evaluation even if it is not as critical as a failure that could conceivably impact another critical system.

2. Select a chosen system component for analysis. Two analyses must be performed:

2.1 Failure Evaluation

2.1.1 Is the component safety critical (all failure modes must be considered)? If yes, go to

2.1.2 else

2.1.1.1 Direct failure is not safety critical. Go to **2.1.1.1** for cascade failure evaluation.

2.1.2 Is the chosen component failure considered catastrophic? If yes, go to **2.1.3** else

2.1.2.1 Is the component failure latent? (Will it be detected by the pilot?) Note MMEL and ETOPs should be considered. If no, go to **2.1.1.1** else.

2.1.2.2 Can any subsequent failure combined with this component failure be catastrophic? If no, go to **2.1.1.1** else

2.1.3 Are the service history and maintenance intervals considered adequate to assure component reliability and/or in-service degradation? (Have there been reports or is there a special inspection of test to determine degradation?). If there is any question, then this question should be answered 'NO.'. If yes, go to **2.1.4** else.

2.1.3.1 Action is required. This component should be evaluated to ensure that it will not pose aging system risk.

2.1.4 Is the component's environment unchanged, (e.g., is component subjected to the same loads, temperatures, and exposure to substances such as water, salt, deicing fluid fuel, oil)? If yes, go to **2.1.5** else.

2.1.4.1 Action is required. This component should be evaluated to ensure that it will not pose aging system risk.

2.1.5 Direct failure is not safety critical. Cascade analysis not required for this component.

2.2 Cascade/Common Mode/Cause Analysis

2.2.1 Can the component failure result impact surrounding systems? (Could the failure cause fire, smoke, leakage, vapors, jams, etc?) If no, go to **2.2.1.1** No further analysis required.

2.2.2 Are the service history and maintenance intervals considered adequate to assure component reliability and/or in-service degradation? (Have there been reports or is there a special inspection of tests to determine degradation?) If there is any question, then this question should be answered 'NO.' If yes, go to **2.2.4** else.

2.2.2.1 Action is required. This component should be evaluated to ensure that it will not pose aging system risk.

2.2.3 Is the component's environment unchanged (e.g., is component subjected to the same loads, temperatures, and exposure to substances such as water, salt, deicing fluid fuel, oil)? If yes, go to **2.2.4** else.

2.2.3.1 Action is required. This component should be evaluated to ensure that it will not pose aging system risk.

2.2.4 Go to block 4