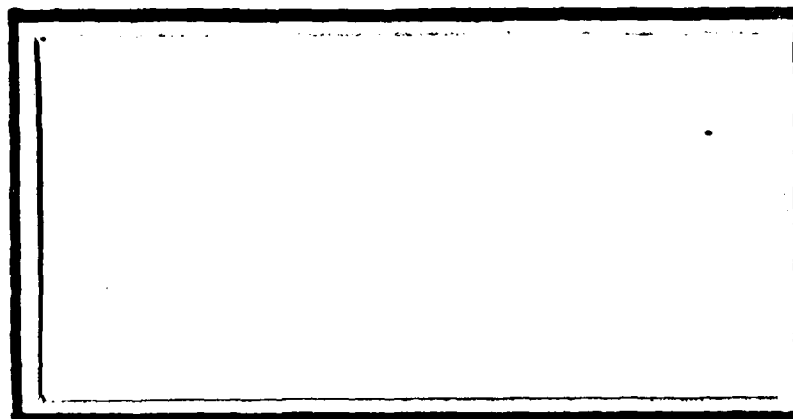


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AIRCRAFT SCHEDULED STRUCTURAL MAINTENANCE
PROGRAMS: CURRENT PHILOSOPHIES AND METHODS IN
THE UNITED STATES AND THEIR APPLICABILITY TO THE
ROYAL AUSTRALIAN AIR FORCE

THESIS

George W. Breen, BE
Flight Lieutenant, RAAF

AFIT/GLM/LSM/88S-5

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AIRCRAFT SCHEDULED STRUCTURAL MAINTENANCE PROGRAMS:
CURRENT PHILOSOPHIES AND METHODS IN THE UNITED STATES
AND THEIR APPLICABILITY TO THE ROYAL AUSTRALIAN AIR FORCE

THESIS

Presented to the Faculty of the
School of Systems and Logistics
of the Air Force Institute Of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Logistics Management

George W. Breen, BE
Flight Lieutenant, RAAF

September 1988

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Preface

The purpose of this study was to determine current structural maintenance philosophies and methodologies in use in the United States of America (USA) and to compare these to the current methods used by the Royal Australian Air Force (RAAF). The RAAF last reviewed its maintenance philosophy in the early 1970s and structural maintenance requirements have not been covered entirely separately before.

This thesis has been rewarding in that it has highlighted the difficulties involved in the management of technical equipment in the absence of perfect information. No maintenance program is ever perfect to begin with and is rarely optimal. Maintenance programs require both technical and managerial expertise to balance the various operational and resource constraints against the attendant safety risk inadequate maintenance poses. The integrated and dynamic nature of maintenance programs is readily seen, particularly in the commercial arena.

I wish to thank all those who gave me their time to discuss the various aspects of structural maintenance. In particular, I thank them for their willingness to admit that, so far, no one solution is considered perfect.

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Abstract

→ This thesis concentrates on determining the status of maintenance philosophy development and, in particular, on structural maintenance methodologies. An extensive treatment of the historical development of structural characteristics and design methodologies which effect structural maintenance requirements is given.

Additional support for current philosophies and methodologies is obtained from interviews with both commercial and military practitioners employed in managing structural maintenance programs. These results, together with the extensive literature review lead to the conclusion that operators in the United States of America all subscribe to the MSG/RCM doctrines and use the structural maintenance methodology detailed in the MSG-3 document.

A comparison between these methods and those used by the Royal Australian Air Force (RAAF) reveals that there is little philosophical difference between the two, however the methodologies vary considerably. The RAAF's procedures are based on MSG-3's predecessor document MSG-2 which did not have a dedicated structural maintenance methodology. (KR) ←

The report concludes that there is sufficient evidence to supporting the effectiveness of the MSG-3 structural methodology and, therefore, it should be adopted by the RAAF.

**AIRCRAFT SCHEDULED STRUCTURAL MAINTENANCE PROGRAMS:
CURRENT PHILOSOPHIES AND METHODS IN THE UNITED STATES
AND THEIR APPLICABILITY TO THE ROYAL AUSTRALIAN AIR FORCE.**

I. Introduction

Background

Aircraft structures have unique characteristics which make the determination of initial scheduled and through-life maintenance requirements difficult. In particular, aircraft structures are one of the few aircraft systems which are designed to last the complete lifetime of the aircraft. Structures deteriorate due to one, or a combination, of the following three mechanisms:

- a. Fatigue accumulation,
- b. Environmental corrosion, and
- c. Accidental damage (17:1393,21:22).

Maintenance managers aim to provide a safe airframe which performs at the required standard throughout its operational life at minimum overall cost. To achieve this goal, initial maintenance programs for new aircraft are currently developed using a decision logic approach. Commercial airlines use the MSG-3 approach as endorsed by the Federal Aviation Administration (FAA) and Air Transport

Association's (ATA) Maintenance Steering Group (MSG).

Military organizations use a version of the same process known as Reliability Centered Maintenance (RCM).

The MSG/RCM method provide an analytical approach to determining maintenance tasks for new aircraft, including structures. The main purpose of this process is to develop a maintenance program, for all aircraft systems including structural assemblies, which maintains inherent levels of safety and reliability. This method provides a default logic which is used when the applicability or effectiveness of a maintenance task is not known. Consequently, the initial program developed from these methods is not optimal, actual operating experience is required to validate and update an initial program. In addition, management techniques exist which can be used to smooth operational and environmental differences across a fleet of similar aircraft.

The Royal Australian Air Force (RAAF) use a procedure based on MSG-2 to determine the initial maintenance program for new aircraft. The procedures used are consistent with the RAAF's maintenance philosophy known as the RAAF Analytical Maintenance Policy (RAMP). The RAMP method for the determination of maintenance tasks for aircraft structural items is given in Reference 10 Section 5

Chapter 2. An analysis of the applicability of MSG-3 logic diagrams in 1983 concluded that there appeared to be little benefit in adopting the expanded logic diagrams of MSG-3 (29:1). Although this review did not specifically focus on structures, it did recommend that:

The clearer logic paths could be introduced into MEA but only after analysis by a dedicated team when sufficient data on the practical results of MSG-3 is available. (29:1)

After eight years of industry experience with MSG-3 in the United States of America (USA) a review of the applicability of current structural maintenance philosophies to the RAAF is desirable and timely.

Statement of the Problem

RAAF staff involved with the determination of scheduled maintenance programs are unsure of the currency of RAAF maintenance philosophy and, in particular, the currency of the structural methodology outlined in Reference 10.

Consequently, a review of structural maintenance philosophies and management techniques used by military and commercial aircraft operators in the USA would enable an objective look at the currency of RAMP philosophies and methodologies. Differences can then be reviewed with respect to an updating of the RAMP philosophy.

Research Questions

The following research questions will be addressed to obtain the most recent information on structural maintenance philosophies:

1. What philosophies and methods are used by commercial aircraft operators in the United States for managing scheduled maintenance for aircraft structures throughout their operational life?
2. What philosophies and methods are used by the United States Air Force (USAF) and the United States Navy (USN) for managing scheduled maintenance for aircraft structures throughout their operational life?
3. Are any of the methods identified above significantly different to the methods detailed in RAMP or used by the RAAF?
4. Of the differences identified, are any potentially significant enough to warrant inclusion in RAMP or RAAF maintenance policy?

Scope/Limitations

To adequately cover maintenance philosophy development the general development of maintenance philosophies must be determined first. Structural maintenance requirements were initially developed in conjunction with procedures for aircraft systems. The unique characteristics of aircraft structures (fatigue, corrosion etc) however, have

necessitated different procedures for determining scheduled maintenance requirements than for other aircraft systems. Thus, the broad development of aircraft maintenance philosophies and methodologies will be covered.

Scheduled maintenance normally consists of a maintenance task and a task interval. This thesis will only discuss tasks and periodicity in general terms, particularly when necessary to demonstrate a concept. It is not within the scope of this thesis to discuss actual task efficiencies, effectiveness or methods for determining task intervals.

This thesis is aimed at providing a management perspective on maintenance philosophies in an attempt to identify opportunities for better structural maintenance management. The technical issues involved will not be addressed in detail.

Assumptions

Throughout the research it will be assumed that the analysis of maintenance tasks starts with complete manufacturers data on structurally significant items, failure modes and effects, levels of redundancy and an items criticality. Furthermore, it is assumed that this information will normally be required and thus produced in due course.

Definitions

Accidental Damage. Physical deterioration of an item caused by contact or impact with an object or influence which is not a part of the aircraft, or by improper manufacturing or maintenance practices (21:33).

Age Exploration. A systematic evaluation of an item based on analysis of collected information from in-service experience. It assesses the item's resistance to a deterioration process with respect to increasing age (21:33).

Damage Tolerant. A qualification standard for aircraft structure. An item is judged to be damage tolerant if it can sustain damage and the remaining structure can withstand reasonable loads without structural failure or excessive structural deformation until the damage is detected (21:33).

Fleet Leader Concept. Inspections on specific aircraft selected from those which have the highest operating age/usage in order to identify the first evidence of deterioration in their condition caused by fatigue damage (21:34).

Item. Any level of hardware assembly (i.e. system, sub-system, module, accessory, component, unit, part, etc.) (21:36).

Other Structure. Structure which is judged not to be a Structural Significant Item. "Other Structure" is defined both externally and internally within zonal boundaries (21:37).

Overhaul. Overhaul (OH) is a preventive maintenance process performed on items 'off aircraft'. It involves systematic disassembly, replacement or restoration of worn parts and comprehensive testing to restore the item to a condition such that it meets both specified physical tolerances and standard and performance standards (11:A-2).

Preventative Maintenance. Preventative maintenance is defined as the maintenance actions that delay or prevent the occurrence of a known failure mode (11:A-2).

Reliability-Centered Maintenance (RCM). RCM is a disciplined logic or methodology used to identify preventative maintenance tasks to realize the inherent reliability of equipment at a minimum expenditure of resources (13:7).

Safe Life Structure. Structure which is not practical to design or qualify as damage tolerant. Its reliability is protected by discard limits which remove items from service before failures are expected (21:37).

Scheduled Maintenance Check. Any of the maintenance opportunities which are prepackaged and are accomplished on a regular basis (21:37).

Structural Assembly. One or more structural elements which together provide a basic structural function (21:37).

Structural Detail. The lowest functional level in an aircraft structure. A discrete region or area of a structural element; or a boundary intersection of two or more elements (21:37).

Structural Element. Two or more structural details which together form an identified manufacturer's assembly part (21:37).

Structural Function. The mode of action of aircraft structure. It includes acceptance and transfer of specified loads in items (details/elements/assemblies) and provide consistently adequate aircraft response and flight characteristics (21:38).

Structural Significant Item (SSI). A structural detail, structural element, or structural assembly which is judged significant because of the reduction in aircraft residual strength of loss of structural function which are consequences of its failure (21:38).

Threshold. The specific value of a usage parameter (flight cycles, flight hours, etc.) at which the first inspection of some particular level or method should be conducted (21:38).

II. Background and Literature Review

Introduction

The purpose of reviewing available literature on aircraft structural maintenance programs is to determine the following:

- a. The characteristics of structural maintenance.
- b. The evolution of structural maintenance methods.

Characteristics of Structural Maintenance

This section describes the characteristics of aircraft structures and how these effect structural maintenance programs.

Purpose. The purpose of an aircraft structure is to provide the following:

- a. aerodynamic lift,
- b. fixed and moveable flight control surfaces (excluding actuating mechanisms),
- c. volume for crew, passengers and payload (generally pressurised),
- d. internal volume for fuel,
- e. a means for transition between ground and air modes (undercarriage),
- f. mounting points for engines,
- g. mounting points for other ancillary items(25:229-230).

Aircraft structures are normally considered as three separate but integrated parts: the fuselage, wing, and tail-plane. Aircraft structural performance effects the primary mission of the aircraft. Each structural assembly and its elements must be able to support their share of the flight and ground loads throughout the operational flight envelope and for the whole economic life.

Characteristics. Aircraft structural characteristics depend on two things, the material used and the design methodology. Design methodology is discussed later in this section.

The wood and cloth structures of early aircraft had quite different deterioration modes compared to the materials commonly used today. These deterioration modes dictate certain detail design practices to the designer; whether an item requires a protective coating to avoid dissimilar metal corrosion or whether the item should be designed to be easily replaced due to poor fatigue characteristics. Ultimately, material properties dictate the performance limitations of the design but, more importantly, future maintenance requirements are dictated by these inherent characteristics. These characteristics provide the designer with various trade-offs during the design process which will ultimately affect the structural integrity of the aircraft as it ages.

Failure of a structural assembly usually results in flight safety consequences and therefore must be avoided. Additionally, aircraft structures are generally difficult and expensive to repair.

The structure is designed as an integral unit, and corrective maintenance on any structural item removes the entire airplane from service. Moreover, because the failure of any major assembly is critical, all parts of the structure are designed to survive to very high ages (25:108).

Consequently, the basic airframe is designed to last the service life of the aircraft without major repair. Safety and economics dictate that structural failures be avoided, however, this goal is rarely achieved due to the nature of performance and operational cost trade-off required with aircraft designs.

Most common aircraft structures are made from aluminium. Aluminium aircraft structures have three principle damage mechanisms which degrade their integrity. They are as follows:

- a. environmental deterioration, (corrosion and stress corrosion),
 - b. accidental damage, (such as from manufacturing flaws, ground handling equipment, and bird strikes), and
 - c. fatigue damage (caused by cyclic loading)
- (17:1393,25:238).

Figure 1 shows the relationship between damage phase and the principal parameters controlling source of damage.

Damage Phase	PRINCIPLE PARAMETERS CONTROLLING GIVEN SOURCE OF DAMAGE AND DAMAGE PHASE		
	FATIGUE	ENVIRONMENTAL	ACCIDENTAL
Initiation	Quality Cyclic Stress Operating Environment Flight Cycles/ Hours	Corrosion -Operating Environment -Protective System Stress Corrosion -Material Sensitivity Level of Sustained Tensile Stress	Random Discrete Event from a cause not normally encountered during fleet ops.
Growth	Material Geometry Cyclic Stress Operating Environment Flight Cycles/ Hours	Extent of conditions that caused damage initiation May result in subsequent crack growth if not detected and repaired	May result in subsequent crack growth if not detected and repaired

Figure 1 Principle Damage Sources (17:Figure 3)

Of the three sources of damage highlighted above, environmental and accidental causes are viewed as random occurrences. Little can be done to eliminate or predict them. Fatigue damage on the other hand, accumulates with usage. Most fatigue damage is accrued during flight/ground transitions (or flight cycles) or accumulated in proportion to a particular flight (or mission) profile. Therefore, based on manufacturers testing, damage due to fatigue

accumulation can be predicted with reasonable accuracy. Additional accuracy can be achieved if fatigue is monitored on a flight by flight basis for individual aircraft.

Fatigue damage can be managed through good design practices, prototype testing, and thorough inspection through-out an airframes life. The fatigue mechanism is reasonably well understood, however, the exact accumulation of damage in an aircraft structure depends on "usage variables such as the type of mission flown, stores carried, operating gross weight, the number of landings, pilot techniques, etc (15:1)." Additionally, factors such as corrosion, accidental damage, manufacturing flaws, and maintenance practices can also affect the rate at which damage is accumulated (25:235).

Thus, it is the aim of the aircraft designer to produce a design which is robust in a variety of operational scenarios. Particular attention must be paid to keeping the anticipated stresses below the level necessary to ensure safe operation until the economic life of the aircraft is reached. The economic life of an aircraft is normally governed by the structural integrity of the airframe.

Usage Effects. In the commercial and military operating environments aircraft are used quite differently. The stress spectra that normal commercial aircraft are designed to is benign compared to that of the military.

Consequently, methods used to track airframe damage, in particular fatigue damage, are different.

Due to the rate at which fatigue damage can be attained in the military environment, individual aircraft can achieve damage at rates which are not linearly related to actual flight hours. Hence, methods which relate cumulative damage to flight hours, particularly for non-transport aircraft, can be very misleading.

Structural Design Philosophies. There are two structural design philosophies which have been used for current as well as past aircraft. These are "safe life" and "damage tolerant". Definitions of these terms are contained in Chapter 1, but the difference between the two can be summarised as follows:

- a. Safe life: The safe-life method first determines the maximum number of cycles a particular item can withstand (analytically, empirically or by full scale or coupon test) without failure and divides this number by a scatter factor (normally 3 or 4). Safe life assumes a defect free initial structure.
- b. Damage Tolerant: A design method which examines the residual strength of an assembly after failure of an element. It assesses the effect on operating safety of having undetected failures present in a structure. Defects are assumed to be present in the structure when

manufactured. This technique is also known as redundant or fail-safe design. Figure 2 summarises the differences in terminology.

Term	Description
Safe-Life	Replace at specific age regardless of condition, eg. undercarriage component.
Fail-Safe	The failure of an item is not safety or mission critical: the structure is damage tolerant.
Damage Tolerant	The ability of an item to perform adequately after a failure of a component. Primarily a result of redundant design techniques.
Durability	Primarily a function of the material. The ability of the material to perform adequately when flawed.

Figure 2: Structural Design Terms (17,21,25)

Safe-life design was used extensively up until the acceptance of fracture mechanics as a structural damage analysis and decision making tool. The USAF used the Safe life approach up until 1970. At that time damage tolerance requirements were written into MIL-SPEC-1530 (12).

An examination of the pre - 1969/70 approach to durability and safety reveals that in the design phase there was emphasis on initial static strength and a "safe-life" fatigue design approach was utilized with the assumption of an initial flaw free structure. Analyses leading to mean life estimates were conducted with a scatter factor introduced to account for such factors as environmental effects, material property variations and initial quality variations. There were no damage tolerance design requirements for protection of the aircraft structure from flaws either induced from in-service operation or existing in the as-delivered new structure (8:1).

The main reasons for changing the specifications from safe-life to damage tolerant are summarised below.

The fixed performance and functional requirements resulted in low weight allowances which in turn forced the selection of high strength fracture sensitive materials and use of high design stress levels. In an effort to prevent initial manufacturing flaws which would be catastrophic when combined with high stress levels, it was necessary to adopt high cost materials and manufacturing processes and quality control programs. Such efforts drive up program costs and experience has shown that even the most careful manufacturing and quality control program will not eliminate all initial manufacturing flaws (8:1).

A number of military operational airframes which were designed to safe-life criteria were reevaluated under these new requirements and found to be "damage tolerant". A damage tolerance structural analysis of an F-5E was conducted in 1976-78 and commented that:

... while the F-5E aircraft was not specifically designed to the damage tolerance requirements, features were incorporated which have contributed to the airframe's success in meeting and exceeding its durability requirements and its adaptability to later application of damage tolerance (22:18).

Therefore, although the design rules changed, a lot of existing aircraft met the new requirements. The biggest advantage in undertaking the damage tolerance analysis was that it enabled the effect of life extensions on structural integrity to be assessed.

Damage tolerance analysis is a logical extension of fatigue analysis and is a fundamental tool in establishing a cost effective structural maintenance program as well as protecting the safety of any operational aircraft (22:39).

Whilst this activity was going on in the military area, similar changes were made to the Federal Aviation Regulations (FAR) which affect design methodology.

Commercial jet transport structures have been designed and certified according to a fail-safe philosophy for over twenty years. Airframes thus have the ability to sustain maximum anticipated or fail-safe loads with significant structural damage; for example, wing structures were designed to carry the full design-limit load with a skin crack extending across two stringer bays. ... This was recognized in the recent revision of the Federal regulations for damage tolerance (FAR 25.571), with which both the Boeing models 757 and 767 comply (17:1393).

Figure 3, shows a comparison of the difference in analysis methods required by FAR 25.571.

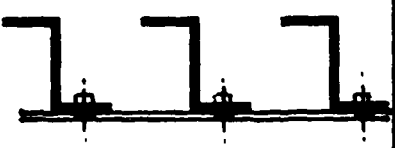
ANALYSIS	OLD FAR 25.571(PRE 1978)	NEW FAR 25.571(POST 1978)
RESIDUAL STRENGTH	Single element or obvious partial failure 	Multiple active cracks 
CRACK GROWTH	No analysis required	Extensive analysis required
INSPECTION PROGRAM	Based on Service History FAA Air carrier approval	Related to Structural damage characteristics and past service history Initial FAA Engineering and air carrier approval

Figure 3: Damage Tolerance Regulation Comparison (19:Figure 1)

This change in emphasis results in the acknowledgement that aircraft structures made from fatigue susceptible materials eventually crack, and this may or may not have an impact on operating safety/economics. The effect of design method on the safety and structural maintenance is shown in Figure 4.

Structural Maintenance Requirements

The goal of a structural maintenance program is to ensure the structural integrity of the airframe with the minimum use of resources throughout the airframes useful life. Initially, a maintenance program based on the inherent quality of the design needs to be implemented. The structural integrity of the airframe must be monitored throughout its life to ensure that functional failures due to fatigue, corrosion or accidental damage do not occur.

Maintenance programs suffer a dilemma. By the time enough information is available to accurately determine the maintenance program for a particular fleet of aircraft, either usage or accumulated age changes the failure rate or damage accrual mechanisms to the point where the program implemented is never optimal. The maintenance program based on actual historical data always lags the optimal program.

Maintenance is normally classified as scheduled or unscheduled. Items which exhibit the tendency to wear-

STRUCTURAL CATEGORY		SAFETY ANALYSIS REQUIREMENTS		STRUCTURAL MAINTENANCE CONSIDERATIONS		
		TECHNIQUE OF ASSURING SAFETY	TECHNOLOGY CONTROL METHOD	PRIMARY PURPOSE	REQUIREMENTS	PLANNING BASIS
STRUCTURALLY SIGNIFICANT ITEMS	DAMAGE-TOLERANT DESIGN	① SECONDARY STRUCTURE	DESIGN FOR LOSS OF COMPONENT OR SAFE SEPARATION	ECONOMICS	SCHEDULED MAINTENANCE TASKS FOR DETECTION AND REPAIR OR PREVENTION OF DAMAGE	PREVIOUS EXPERIENCE WHEN SIMILAR TO EXISTING STRUCTURE MANUFACTURER'S RECOMMENDATIONS WHEN NEW MATERIAL AND/OR CONCEPT
		② DAMAGE OBVIOUS OR MALFUNCTION EVIDENT	ADEQUATE RESIDUAL STRENGTH WITH EXTENSIVE DAMAGE - OBVIOUS DURING WALKAROUND OR INDICATED BY MALFUNCTION			
		③ DAMAGE DETECTION BY PLANNED INSPECTION	INSPECTION PROGRAM MATCHED TO STRUCTURAL CHARACTERISTICS	SAFETY	ADEQUATE INSPECTIONS FOR TIMELY DETECTION AND REPAIR OR PREVENTION OF DAMAGE	MANUFACTURER CONTROLLED RATING SYSTEMS • ACCIDENTAL DAMAGE ^a • ENVIRONMENTAL DETERIORATION ^a • FATIGUE DAMAGE ^b
	SAFE-LIFE DESIGN	④ SAFE LIFE	CONSERVATIVE FATIGUE LIFE	SAFETY	DETECTION AND REPAIR OR PREVENTION OF ACCIDENTAL DAMAGE AND CORROSION	MANUFACTURER CONTROLLED RATING SYSTEMS

^a Applicable throughout operational life.

^b Applicable after aircraft reaches threshold for detectable size fatigue damage.

Figure 4. Structural Analysis Requirements and Maintenance Considerations

(19:1395)

out, i.e they have an increasing conditional probability of failure with age, normally benefit from scheduled maintenance. Bear in mind, however, that aircraft operators are interested in two aspects of maintenance: maintenance programs must ensure safe operating capability, and/or there must be an economic benefit derived from performing maintenance. If neither of these criteria affect the component or assembly being considered then maintenance should not be performed (25:47).

Scheduled maintenance tasks for structures are usually one of two types: scheduled discard, or scheduled inspection. Discard tasks are applicable when a component has a known life (expressed in operating hours or flight cycles) and its failure has safety consequences. Inspections determine whether the item has failed (for hidden details), or the existence and/or extent of fatigue cracking, corrosion damage or accidental damage.

The optimum structural maintenance plan consists of those tasks necessary to convince the operator and regulator that the probability of either a safety of flight failure or an economically undesirable failure is low enough to allow continued operation to the next scheduled maintenance period.

Regulator versus Operator Requirements. In the civilian arena, certain aircraft design requirements are

specified and enforced by the Federal Aviation Administration (FAA). Aircraft not designed to the Federal Aviation Regulations (FAR) will not receive type certification and therefore can not be operated in the US.

Regulatory bodies usually specify the following design criteria:

- a. Load spectra.
- b. Safety margins.
- c. Design methodology.
- d. Detail design requirements (anti-collision light fixtures etc) (25:230-231).

In the military, parts of the same organisation have the role of regulators and others that of operator. Military aircraft are not normally required to conform to the standards set by the civilian aviation community. The military therefore specifies the whole aircraft requirement, from safety and design to operational performance. However, responsibilities are usually assigned to many different parts of the customer organisations.

Generally, in the civilian arena, the FAA details the required safety and load spectra aspects of design and maintenance. The operator is more concerned with operating economy. On the other hand, the military, as regulator and operator specifies both. This difference in regulator/operator relationship can produce differences in the way in

which specifications and maintenance requirements are generated (5:10).

Initial Programs.

During the late 50's, commercial airline operators were becoming concerned at the rising costs of aircraft maintenance. Existing maintenance philosophies required that all items, including the airframe, be withdrawn from operation at a specific interval to be overhauled. The purpose of the overhaul was to bring the equipment back to a "as new" condition. This type of philosophy was known as the "hard time" maintenance philosophy. With the rapidly increasing complexity of aircraft, more and more aircraft items required overhaul. Aircraft structural complexity caused an increase in the number and length of inspections required.

A "new look" for maintenance was required to allow the commercial operators to stay in business. An industry body, the Air Transport Association (ATA), in conjunction with the FAA and aircraft manufacturers, formed a group to study the problems relating to the maintenance program for the B747. This "Maintenance Steering Group" or MSG produced a document known as "Handbook: Maintenance Evaluation and Program Development (MSG-1)(19)" which gave a decision logic for determining maintenance requirements based on the inherent

reliability and design features of the B747. Figure 5, summarises the basic differences between the old and new maintenance philosophies. The specific approach used on the B747 was modified to provide a generic framework for the determination of scheduled maintenance tasks for entire aircraft. The original document evolved into what is known today as MSG-2 (21).

Nowlan and Heap (25:B4) give an excellent treatment of the evolution of commercial airline maintenance philosophy up until 1978. Nowlan and Heap (25) produced a maintenance philosophy in response to USA Department of Defense (DOD) directives to implement the MSG-2 process to all aircraft in the DOD. This document was adopted by the DOD and is known today as Reliability Centered Maintenance (RCM).

The initial MSG process treated structures as it did other aircraft systems. MSG-2 handled structures slightly differently by prescribing a method of rating structural damage mechanisms with respect to particular structurally significant items. In terms of fatigue, it provides a rating system which is based on a ratio of the fatigue life of the structure to the airframes designed economic life.

In 1980 MSG-2 was reviewed and updated. Subsequently, MSG-3 (21) was published. The majority of changes to MSG-2

TRADITIONAL	CURRENT	COMMENTS
Preventative maintenance can make an item more reliable.	Preventative maintenance can only achieve the inherent reliability.	An items maintainability can only be altered by modification.
To increase reliability, increase scheduled servicing.	The scheduled maintenance requirements for an item are inherent. Scheduled maintenance is ineffective for some items.	Scheduled maintenance includes both preventative and failure finding tasks. Some items do not have effective or efficient tasks for preventing or detecting failures or imminent failures.
To increase reliability, increase servicing frequency.	For some items, no amount of servicing is effective in ensuring the inherent reliability is achieved.	Analysis of failure modes results in a determination of maintenance applicability. Effectiveness in preventing premature failures can only be determined by operating experience.
Reliability decreases with age.	The reliability of an item is inherent and may increase, decrease or remain constant.	Extensive analysis of operating data by the commercial airlines has shown that less than 10% of items have a decreasing failure rate with age.
There is a definite interval at which to do maintenance.	Intervals are set based on past experience and revised based on operating experience.	Not all items which have an increasing failure rate have a point at which the rate of failure increases.
To increase safety, increase maintenance.	Only some failures affect operational safety.	The effects of failure determine whether failures effect safety. Only maintenance on safety critical items will ensure safety.
Safety and reliability are closely related.	Reliability only effects safety when the probability of failure between maintenance actions is high.	Safety is failure effect. Reliability is an inherent characteristic.

Figure 5: Comparison of Maintenance Concepts.

revolved around clarifying logic inconsistencies in the decision process as well as treating aircraft structures in a new way. Other significant differences in the MSG-2 to MSG-3 structural maintenance procedures are:

- a. The decision logic is task oriented.
- b. Effects of concurrent or multiple failure are considered.
- c. The responsibility for developing rating schemes/systems has been assigned to the review team,
- d. Safety and economic items are clearly separated (21:iii).

MSG-3 departed from a generic rating scheme to one which selects structural significant items and uses a manufacturer's supplied rating scheme. This transfers the onus of providing a rating scheme to the manufacturer.

The MSG method of determining initial programs is as follows:

- a. Determine the structurally significant items.
- b. Using manufacturer supplied information, determine failure modes and effects.
- c. Determine applicable and effective maintenance tasks (discard if safe-life or inspection if damage tolerant);
- d. Determine task interval.

The maintenance concepts embodied in RCM and MSG-3 are very similar. In the assessment of structures, and in

particular, maintenance/inspection intervals, RCM has a generic method of approaching structural deterioration rating systems. MSG-3 on the other hand, leaves the determination of the ratings scheme up to the team analyzing the maintenance requirements. The resulting maintenance program is more flexible with individual aircraft being given sufficient unique consideration.

The MSG approach leaves an audit trail of maintenance action decisions that can be used to review the maintenance program as operating experience is accumulated. In addition, for items which no experience data exists a series of default decisions are required which allow initial requirements to be determined. These usually result in additional structural inspections to help identify possible problems and effective maintenance tasks. Ultimately, an initial maintenance program which ensures structural integrity and collects the required data for continued confidence in the airframe will be achieved.

In the analysis of structural items, however, the determination of inspection intervals for damage-tolerant structure is based on an assessment of the effect of failures on residual strength, the relationship of fatigue-test results for individual items to the design goal for the overall structure, crack propagation characteristics, and the anticipated rate of corrosion. All these assessments involve some degree of prediction. The results are therefore treated very conservatively, not only because they are extrapolations from test data, but also because manufacturing variations, differences in operating environments, and different loading histories may lead

to wide variations in fatigue life from one airplane to another (25:273).

Therefore, the initial structural program details what is known about the structure tempered with operator experience and manufacturer's predictions. As generally insufficient information is available to fully define the maintenance requirements of a new aircraft, some method is required to either track usage or to ensure appropriate checks are made to determine the correct maintenance posture for an item.

Through Life Programs.

Structural maintenance programs recognise the random nature of structural failures caused by the three damage mechanisms and therefore, prescribe fault finding tasks (inspections) at intervals such that safety and economics are preserved. In particular, in a controlled environment, corrosion and fatigue damage can be accurately estimated, but in reality the factors which contribute to these mechanisms, namely weather and usage variability cannot be controlled. Estimates for corrosion damage are normally made by operators familiar with their own environment because analytical techniques can not accurately predict when damage will start or how quickly it will propagate. Likewise, fatigue damage can accumulate at different rates due to differences in routes, weather and flying techniques.

Initial fatigue estimates are made by the manufacturer based on design load spectra.

For a given aircraft operator, his environment/route structure/usage pattern will result in either more or less damaging use than the design spectra. To counter this there appears to be two current methods;

- a. safety by inspection, and,
- b. individual aircraft monitoring.

Within the RCM philosophy, a method called "age exploration" is described. Age exploration is defined in Chapter I. Age exploration is a safety by inspection scheme. As described in References 21 and 25, age exploration applies equally to both aircraft systems and structures. However, the concept of age exploration is slightly different with structures than with systems. Unlike systems, structures are generally designed to last for the entire life of the aircraft. Except for replaced safe-life structure (such as undercarriage), the age of each structural assembly within the aircraft is the same.

In the case of structure, therefore, the inspection program itself is the only vehicle for age exploration, and the inspection samples consist of individual airplanes, rather than samples of parts from different airplanes. The initial inspection interval for each structurally significant item is set at only a fraction of the age at which evidence of deterioration is expected to appear, not only to find and correct any conditions that may reduce the anticipated design life, but also to identify the age at which reduced failure resistance first becomes evident (25:108).

Commercial usage is such that major differences in exposure to structural damage mechanisms does not occur.

Consequently the age of most parts of a given structure is the same as the total age of the airplane. This makes it possible to concentrate age-exploration activities on the highest total-time airplanes (25:108).

This has lead to the development of the "fleet leader" concept where the highest time aircraft are inspected to determine the appropriate inspection interval for follow on aircraft.

As the structure ages in service the intervals for many individual items will be adjusted to ensure that deterioration is found as early as possible, and some items that are unacceptably short-lived may have to be modified to increase their fatigue lives. In general, however, the state of the art is now such that the designer can often establish quite meaningful predictions of fatigue life, and as these predictions have been borne out by experience, there has been a tendency to begin age exploration at increasingly higher ages with each new design (25:275).

As it became clear that the oldest member of the fleet were more likely to provide new information about fatigue damage, inspection emphasis shifted to what is often termed the fleet-leader concept, concentration of heavy structural inspections of the airplanes with the highest total time. This approach not only provides the same amount of information in the shortest calendar time, but identifies the age at which fatigue damage is likely to appear before the younger aircraft reach this age limit (25:275).

The fleet leader concept is particularly valid for commercial operations where aircraft usage is not severe (relative to military use) and major differences in damage exposure do not exist. In fact, if sufficient differences

exist in operational scenarios between operators of the same aircraft then the results of fleet leader aircraft sampling inspections must be treated cautiously.

If different airplanes in the fleet are to be assigned quite different types of missions or will be operating in different types of environments, it may be advisable to develop a separate set of inspection intervals for each kind of operation and implement these tailored programs from the outset. Any initial structure program, however, merely specifies the start of age exploration for each item to determine its actual fatigue characteristics (25:273-274).

A different approach is used in the military to ensure structural integrity. Due to possibly large variations in usage between aircraft of the same fleet, structural maintenance management aimed at a tailored program for individual aircraft becomes both necessary and viable.

The USAF's Aircraft Structural Integrity Program (ASIP) and Engine Structural Integrity Programs (ENSIP) are designed to specify, from the concept stage through to aircraft retirement, the structural maintenance management techniques which will be used. ASIP requirements are as follows:

- a. Establish, evaluate, and utilize the structural integrity (airframe strength, rigidity, damage tolerance, and durability) of the airplane.
- b. Acquire, evaluate, and utilize operational usage data to provide a continual assessment of the in-service integrity of individual airplanes.
- c. Provide a basis for determining logistics and force planning requirements (maintenance, inspections, rotation of airplanes, system phaseout, and future force structure).

d. Provide a basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft designs.(12:3)

These ASIP activities are normally performed by the contractor responsible for the structural design of the aircraft. The four aims stated above translate into the following sub-programs:

- a. Environmental Stress Spectra Program. This program periodically updates the stress spectra used for the design to determine if it is representative of actual usage. Differences found can be related back to particular critical points and new life/damage assessments made.
- b. Individual Aircraft Tracking (IAT). The individual aircraft tracking program allows the determination of cumulative fatigue damage for each aircraft.
- c. Force Structural Maintenance Plan (FSMP). The FSMP details the maintenance actions and modifications required to ensure structural integrity throughout an airframes life.

Together these programs and elements provide detailed information about the airframe, its previous usage and its projected useful life. Depending on the aircraft type and mission profiles there exist a number of techniques for achieving the goals of ASIP. These are well documented in References 4 and 7. The methods described fall into three categories:

- a. Manual flight profile recording and damage translation based on standardised mission profile/stress spectra.
- b. "G" loading exceedance data and its translation to critical point damage accumulation.
- c. Direct measurement of critical point stress/strain through use of strain or crack growth gauges.

Each of these categories are applicable to specific aircraft types and their respective mission profiles. Reference 4 provides guidance on each methods applicability. Each of these methods require considerable resources to implement, ranging from sophisticated aircraft mounted data acquisition systems to extensive data processing computers.

Effectiveness of RCM/MSG Approaches

The RCM/MSG approach has been implemented in both military and commercial operating environments. This begs the question of just how effective are these methodologies in achieving their aims.

... under traditional maintenance policies the initial program for the Douglas DC-8 included scheduled overhaul for 339 items, whereas the initial program for the DC-10, based on MSG-2, assigned only seven items to overhaul. One of the items no longer subject to an overhaul limit in the later program was the turbine engine. Elimination of this scheduled task not only led to major reductions in labor and materials costs, but also reduced the spares-engine inventory required to cover shop maintenance by more than 50 percent. Since engines for larger airplanes now cost upwards of \$1 million each, this is a respectable saving (25:5).

The above shows that the positive effect that the MSG approach had in the commercial area. However, in the military implementations, there has been less success in quantifying improvements brought about by RCM.

The first military implementation of RCM/MSG methodology in the USA was on a squadron of P3's operated by the USN. Initial estimates of saving through the improved maintenance methodology a 50 percent reduction in scheduled maintenance tasks, increased aircraft availability, reduced manpower, and a lengthening of maintenance intervals (15). This reported success caused a service wide adoption of the RCM/MSG process with the hope of greater savings across all armed services (2:17-19,27:27-34).

During budget testimony for financial year 1986 the US services were asked to estimate cost savings due to the implementation of RCM. None of the services were able to do so. Lack of appropriate data was quoted as one of the main reasons for not being able to quantify savings. The USAF stated that "the point of RCM is increased availability of weapons without a decrease in safety or reliability (28)."

Consequently, the effect of RCM/MSG on aircraft maintenance is not as easily measurable in the military environment as it is in the commercial.

Overview

So-far, the relationship between structural characteristics and maintenance programs has been developed. The historical development of structural maintenance program philosophies has been discussed and the different methods used by both military and commercial operators have been presented. In particular, the reasons for differences between commercial and military approaches has been presented. The overall effectiveness of RCM/MSG programs was also briefly discussed.

Current structural maintenance practices appear to follow the MSG-3 approach with the military monitoring fatigue on an individual aircraft basis. Chapter IV will discuss whether the literature and actual practice coincide and whether these methods and those used by the RAAF coincide.

III. Methodology

This chapter details the methodology used to answer the research questions detailed in Chapter I.

General Methodology

This research effort is exploratory in nature. The main purpose of the research is to identify current philosophies or methodologies which may be beneficial for the RAAF to pursue in updating its structural maintenance philosophy and methodology. Aircraft maintenance philosophies have tended to be evolutionary and have been derived from commercial operator reactions to regulatory pressures. Consequently, the primary sources of information for this thesis are public domain reports and other published information. Chapter II consists of a broad summary of the major developments in maintenance philosophy and structural methodologies since about 1965.

To determine current structural maintenance methods the most current documents of maintenance policy need to be referenced. These were already available through the literature review effort and where applicable were applied. Corroborating data was obtained through a series of telephone interviews with maintenance program managers at the organisations reviewed. In this way some added insight into the issues as well as discussion on some of the

subjective aspects of structural maintenance could be obtained.

The telephone interviews were casually structured so that the interviewee would not feel defensive about their organisations policies. The questions listed in Appendix A were answered during the course of the interview.

Specific Methodology

Research Question 1.

What philosophies and method are used by commercial aircraft operators in the United States for managing scheduled maintenance for aircraft structures?

The purpose of this question is to ascertain the current structural maintenance philosophy used by various commercial airline companies. Both regulatory bodies and the airlines will be approached. To answer this question the following organisations were contacted:

1. Federal Aviation Administration (FAA). The FAA is the regulating body for commercial airlines in the United States. Each airline must have a maintenance program for each aircraft type approved by the FAA's Maintenance Review Board (MRB). Therefore, the FAA's maintenance requirements are important because they specify the minimum levels of maintenance which airlines are to perform.
2. Air Transport Association of America (ATA). The ATA was responsible for convening the Maintenance Steering Group (MSG) which produced MSG-1 through MSG-3. Through the MSG

process new philosophies are developed and refined. ATA is most likely to know the types of maintenance policies being practiced throughout the USA by various commercial airlines.

3. Trans World, Piedmont and Eastern Airlines were contacted by telephone to determine current methods used by the commercial sector.

Research Question 2

What philosophies and methodologies are used by military aircraft operators in the United States for managing scheduled maintenance for aircraft structures?

The following military organizations will be researched to obtain the necessary data:

1. Headquarters Air Force Logistics Command (HQAFLC)- HQAFLC is the approving authority for all USAF maintenance programs.

2. Naval Air Systems Command (NAVAIR) - NAVAIR was the first military organization to implement a maintenance philosophy based on the commercial airlines' MSG approach and therefore have the most experience with its implementation in a military environment.

Personal contact was possible with HQAFLC personnel, particularly the ASIP program manager. The NAVY was researched through the many available current reports.

Research Question 3

Are any of the methods identified above significantly different to the method detailed in RAMP?

To answer this question required firstly, that the maintenance philosophies in use in the USA be examined against that used by the RAAF. To do this a published set of philosophical aims were compared to the RAAF's stated policy. Secondly, similarities and differences in the logic diagram methodologies were determined. The methodology currently used by military and commercial aircraft operators (MSG-3) was used as a baseline for this comparison.

Research Question 4

Of the differences identified, are any significant enough to warrant inclusion in RAMP?

After identification of differences, their origin and possible application to the RAAF environment will be discussed. The discussion will be based on the concepts presented in Chapter II. This discussion will be a highly subjective, but consistent with the research conducted.

IV. Findings, Comparison and Discussion

Introduction

This chapter presents the data which was collected and compares the different structural maintenance management techniques used by American commercial and military operators and the RAAF. This chapter, therefore, answers research questions 3 and 4.

Findings

The discussion of scheduled structural maintenance philosophies can be divided into three areas: Initial Programs, Program Reviews, and Through-life Management techniques. The discussion of the findings will follow this same format.

Initial Programs. Figure 6 is a summary of the initial program methodologies used by the organisations approached. All operators have adopted the tenants of the MSG approach in one of its forms. In the USAF this approach is known as RCM, in the USN - AMP and in the RAAF, RAMP. The following is a brief overview of each operators program. All the commercial operators have been discussed at the same time due to the similarity in their responses during interviews.

Commercial. Due to the regulatory process for obtaining type certification for aircraft through the FAA in the US, all commercial operators use the same approach for

	Initial Program	Program Review
COMMERCIAL		
TWA Piedmont Eastern	MSG MSG MSG	MSG MSG MSG
MILITARY		
USAF USN	RCM (MSG-3) AMP (MSG-3)	RCM (MSG-3) AMP (MSG-2)
RAAF	RAMP (MSG-2)	RAMP (MSG-2)

Figure 6: Methods for Determining or Reviewing Maintenance Programs

determining scheduled maintenance requirements. Structural programs are put together by working groups consisting of manufacturer, operators and the FAA to determine an initial maintenance program for the aircraft type. The FAA's Maintenance Review Board then approves the initial program and each operator submits a program tailored to its unique operating environment or scenario. After the initial requirements are determined each operators program may be substantially different from all other operators of the same aircraft type. See Figure 7 for details.

USAF. The USAF currently subscribe to the RCM philosophy as given in MIL-STD-1873 which is based on MSG-3. The RCM analysis brings together the structural information generated by the ASIP/ENSIP programs and integrates it with the past experience of the maintenance program managers.

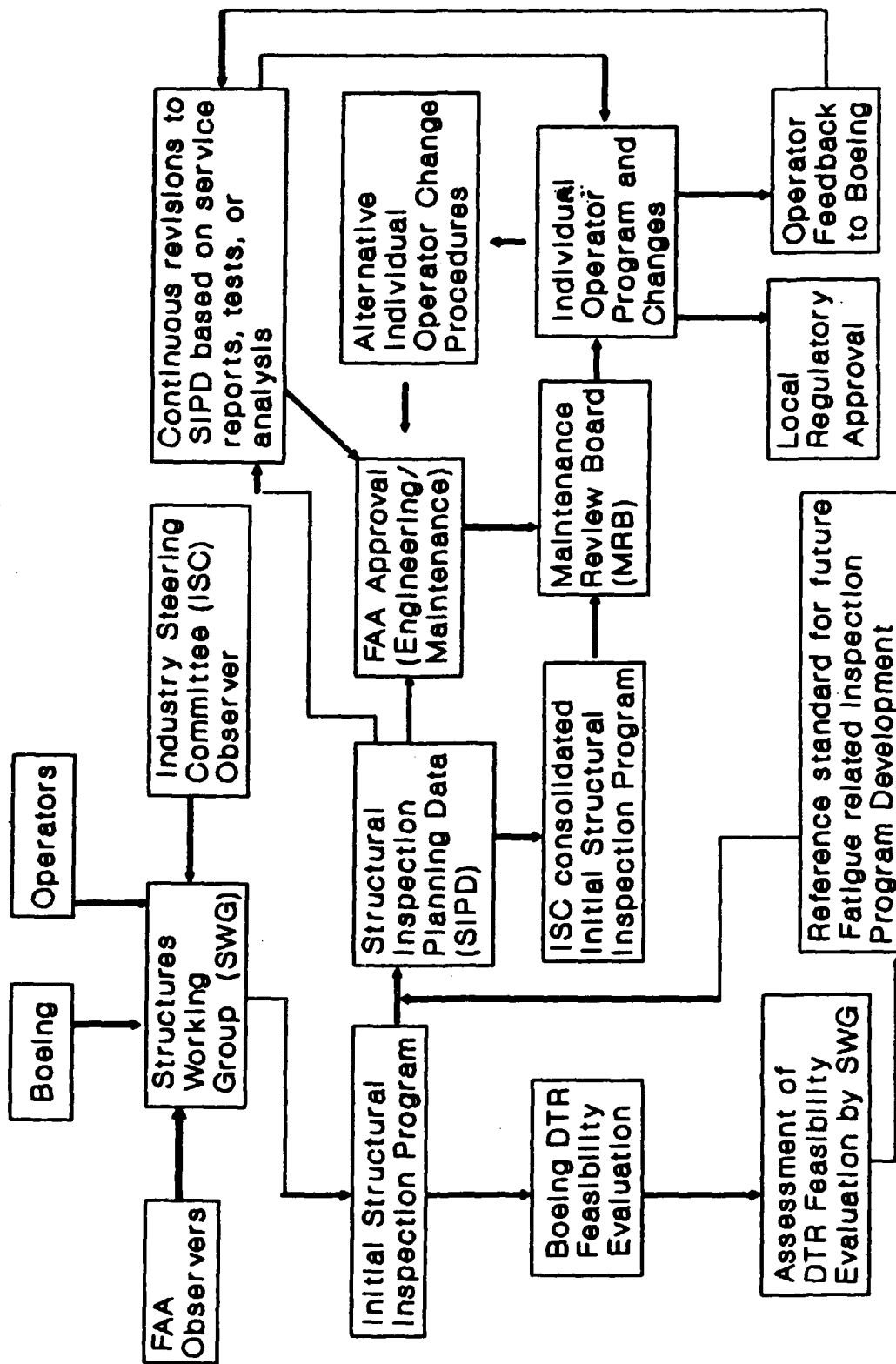


Figure 7: Development and Approval of Initial Inspection Program and Change Procedure

(17: Figure 16)

Initial maintenance programs based on RCM are normally generated by contractor. For large transport aircraft, the procedures contractors use tend to follow commercial practice except that USAF programs, such as ASIP/ENSIP, tend to be folded in. Consequently, USAF procedures do not differ greatly from those given in MSG-3 (13,32).

USN. The USN's structural procedures are based on MSG-3 and known within the Navy as the Analytical Maintenance Program (27:30-34). These procedures are thus very similar to those used by the commercial operators.

RAAF. The majority of aircraft purchased by the RAAF are done so "off the shelf". Consequently, the RAAF have little to no control over those design decisions which affect the long term maintainability of the airframe. Notwithstanding this however, the RAAF normally perform their own maintenance engineering analysis (MEA), using available manufacturer and operator data, to determine the initial maintenance program for the structure.

This analysis is conducted in accordance with the RAMP procedures specified in Reference 10. These procedures are based on MSG-2 (1).

Maintenance Program Reviews. Maintenance program reviews are conducted for many reasons, but primarily to validate and update initial programs. Mechanisms which trigger structural scheduled maintenance reviews include

structural modifications, premature failures, results of inspection programs, or even changes in operations. In addition, initial programs are normally reviewed at some predetermined calendar interval. The following are some details of each operators methods for conducting program reviews.

Commercial. Changes to scheduled maintenance programs in the commercial airline scenario has to be approved by the FAA. Therefore, a logical and rigorous procedure needs to be used. For this reason the Airlines keep records on those components which they believe there is benefit in reviewing scheduled maintenance actions. Primarily, this benefit is economic.

Consequently, commercial airlines make extensive use of the data packages already developed for the initial programs and then they add to this data with their own operational experiences. The same logic processes present in the initial programs are generally followed to support any recommended changes. The MSG-3 style of analysis is commonly utilised when applicable.

USAF. Although the USAF uses contractors to generate the initial structural maintenance programs for new aircraft, RCM (13) is used to evaluate new tasks and to re-evaluate maintenance programs efficiency. Inputs used to trigger a re-analysis come from the field, ASIP/ENSIP

programs or as a result of other non-routine investigations (25,31).

USN. The USN use the methods detailed in the AMP to review their maintenance programs. They use "a dedicated age exploration technique and actuarial analyses (31:847)" to justify any changes to programs.

RAAF. The procedures in Reference 10 include a logic diagram for determining the level of analysis required to justify changes to a maintenance program. This logic diagram is reproduced in Appendix G. After the level of analysis is determined the appropriate analysis is undertaken.

Through-Life Management. Through life management refers to those techniques used to ensure structural integrity through out the life of an airframe. The initial program is based on many assumptions regarding the operational environment and the way the aircraft will be used. Consequently a method is required which will satisfy both the regulators and the operators that the equipment is safe to use. In addition, the effects of mission changes and aircraft utilisation need to be estimated at some time.

The following is a brief discussion of the methods used by various operators.

Commercial. The Age-exploration program is the primary method of determining the through-life condition of

a fleet of aircraft. The assumption of average usage rates and high time aircraft being representative of the fleet is the under-pinning of the age exploration program.

Commercial operators sample the high time aircraft in their own fleet or, in conjunction with other operators of the same aircraft, in the whole fleet and use the results of these sampled inspection programs to justify interval changes within the existing maintenance program (3,6,9,23).

USAF. Military operators are not as comfortable with the notion of fleet-leader sampling as the commercial operators are. Hence, the USAF expend a great deal of resources tracking individual aircraft usage.

The USAF use many methods to track individual aircraft fatigue damage accumulation Reference 4 describes each in detail. In particular, different methods are employed depending on the type of aircraft and its mission profile. The following are the four main methods used

- a. manual logs,
- b. acceleration exceedance data,
- c. stress/strain transfer function,
- d. crack growth.

In addition to IAT, the USAF regularly performs Environmental Stress Spectra surveys of a fleet to ensure that the average spectrums that were applied during design

and are being applied in conjunction with the IAT programs are valid.

USN. The USN's methods appear to be somewhere between the methods used by the USAF and those used by commercial operators. They subscribe heavily to the age-exploration concept as well as recording usage parameters. The USN's most recent acquisition, the F/A-18, is being managed as follows:

The age exploration program will be based upon examining statistically determined samples of aircraft structure at designated cyclic thresholds (flight hours, catapults, arrestments, operating cycles, calendar age, etc.) to determine material condition (31:849).

Each F/A-18 has strain gauges bonded to the structure at seven locations. The in-flight strain is recorded on an in-flight recorder whenever specified exceedance criteria are met. Flight data such as airspeed, roll rate, altitude, and "G" load are concurrently recorded on the tape with the strain gauge information. These data will be definitive and extremely valuable to the sustained structural age exploration program (31:850).

Through the analysis of data, the significant or critical airframe elements requiring periodic inspection will be confirmed. Elements requiring redesign will be isolated, and recommendations to structural service life limits will be made (31:850).

The above demonstrates the age-exploration program being used by the USN on the F/A-18 as well as the use of individual aircraft data to backup the program. The aircraft data is not used to program specific maintenance tasks or to determine the timing of modification programs for individual aircraft.

RAAF. The RAAF also conducts individual aircraft tracking programs on aircraft in its fleet. The following methods are used:

- a. Simple hours based life.
- b. Safe life and fatigue meter data.
- c. Durability and Damage Tolerance Assessment (DADTA) incorporating safety-by-inspection and fail-safe philosophy based on crack growth modelling.
- d. Strain range recording using the Aircraft Fatigue Data Analysis System (AFDAS).
- e. Mission profile recording (16:2).

These methods are very similar to the methods outlined in Reference 4.

Comparison

The purpose of this section is to compare the structural maintenance philosophies and methods currently in use in the US against those used by the RAAF. Previously, as shown in Figure 6, it was shown that all US operators base their initial program and program review procedures on the philosophy and methods described in MSG-3. Consequently, the task of comparing the RAAF with US operators becomes one of comparing the RAAF Analytical Maintenance Plan to MSG-3.

The success of any comparison usually lies in the establishment of a base line from which to make comparisons. MSG-3 is a detailed methodology for determining aircraft maintenance requirements. It includes a methodology for determining structural maintenance requirements. However,

nowhere in any of the MSG documents is the maintenance philosophy or precepts described. Consequently, since Nowlan and Heap (25) are the only source of a clear description of the precepts of modern maintenance programs, the precepts presented in their report will be used as the philosophical baseline for comparison. These precepts are consistent with the methodologies expressed in the MSG series documents.

The MSG-3 document will be used as a methodology baseline as it represents the latest in the MSG evolutionary cycle.

Philosophy. The major precepts described by Nowlan and Heap are reproduced in Appendix B. The maintenance concepts upon which the RAAF base their maintenance programs on is contained in Reference 11. Each major RCM precept was examined to determine whether the same or an equivalent concept was contained in RAMP. The result of this analysis is contained in Appendix C and supports the contention that the major precepts of RCM can be found in RAMP.

MSG-3 Methodology. The structural maintenance methodology used by MSG-3 is presented in Appendix D. This was used as a basis for comparison of RAMP structural maintenance methodology.

Attached at Appendix F is the structural logic diagram used in MSG-3. Appendix G contains a logic diagram RAMP uses to determine the level of analysis required for

structural items whilst Appendix H contains the logic diagram used to determine maintenance requirements. A cursory look at these diagrams reveals substantial differences in content and logic flow.

The results of the comparison are presented in Appendix E and basically show little similarity between the procedures used in MSG-3 and RAMP.

Discussion

The RAMP flow-chart is loosely based on MSG-2 procedures (1). MSG-3 was not a significant departure from the basic method supported by MSG-2 as the philosophy review indicates. However, as noted in Chapter II there are some significant differences in structural maintenance methodology. In particular the following differences are significant with respect to aircraft structures:

- a. MSG-3 takes a consequence of failure approach.
- b. Task orientated program development, (MSG-2 was maintenance process oriented).
- c. Recognises damage tolerance rules of FAR 25.571.
- d. Definite applicability and effectiveness criteria has been developed to provide a more rigorous selection of tasks.
- e. Structures logic directly assess the possibility of structural deterioration process. "Considerations of fatigue, corrosion, accidental damage, age exploration and

others, are incorporated into the logic diagram and are routinely considered (21:iii)."

f. Multiple failures are considered in structural evaluation.

g. The responsibility for determining rating schemes for the structural damage process now rests with the program review team (21:ii-iii).

Reference 29 contains a discussion on whether the RAAF Maintenance Engineering Analysis (MEA) should amend its flow/logic diagrams to MSG-3 format. The conclusions reached at that time were as follows:

a. Both MSG-3 and MEA result in task orientated maintenance programmes derived from similar analysis logic.

b. MSG-3 is designed specifically for new transport aircraft.

c. MSG-3 is expensive in terms of man-power and data requirements, especially for structural analysis; this task could only be undertaken by the airframe manufacturer.

d. The clearer logic paths could be introduced into RAAF MEA, but only after analysis by a dedicated team when sufficient data on the practical results of MSG-3 is available.

e. MSG-3 is expected to have a minimal impact on the scheduled maintenance of specifically designed military aircraft. (29:1).

Careful examination of the MSG-3 document and Reference 10 supports the contention that both result in effective/efficient tasks. Maintenance programs are by necessity task orientated. To specify a maintenance process as part of a maintenance program is not practical. The MSG-3 logic diagram recognises this and evaluates maintenance actions from a task viewpoint rather than the process viewpoint. This subtle difference between the MSG-2 and 3 approaches, does not impact the final maintenance program. It is quite likely that a maintenance evaluation team would arrive at a similar maintenance program under both schemes, however the clearer logic paths of MSG-3 would help maintenance program developers as well as providing the consistent basis for further reviews.

Figure 7 showed the major steps required to determine an initial structural maintenance program. The operator (RAAF) is primarily responsible for determining task efficiency and has an input into task selection and effectiveness. Consequently, with respect to initial program development, a decision diagram which will aid in the selection of tasks which are both effective and efficient would be useful. This requires that the decision process/methodology considers all likely deterioration processes and potentially effective tasks.

To determine the effect of structural deterioration processes on aircraft structures, a rating scheme is normally used. The rating scheme is devised by the review team which normally comprises manufacturer and operator representatives and considers the three deterioration modes experienced by structures. Figure 8 describes the key considerations for accidental damage rating (ADR) and environmental damage rating (EDR) of aircraft structures. Ratings for structures is considered the domain of the manufacturer. In the past the RAAF have had access to the rating schemes devised by other operator/manufacturer review teams. This is not expected to change in the future, particularly for aircraft made in the USA.

Consequently, the use of a logic diagram similar to that in MSG-3 would be consistent with RAAF requirements.

Additional Issues. During the course of this research two issues surfaced which were not part of the research requirement but never-the-less warrant a brief mention. The two issues were:

- a. The integration of fatigue data and RCM/MSG methodologies.
- b. Further improvements to the MSG process.

Rating Category	Application		Primary Responsibility		Key Consideration
	EDR	ADR	OPERATOR	MAKER	
Visibility	#	#	#		Visibility for inspection after access.
Sensitivity to damage size or growth	#	#		#	Relative sensitivity within zone considered. External : Multiple element damage. Internal : Single element damage.
Environmental Protection	#		#	#	Comparison with previous protection system recent service history.
Exposure to adverse environment	#		#		Corrosion experience in same zone.
				#	Material susceptibility to stress corrosion and potential for preload.
Likelihood of accidental damage		#	#		Operator experience in same zone.
Strength after accidental damage.		#		#	Likely size of damage relative to critical damage size.

Figure 8: Key Considerations and Responsibilities
for EDR and ADR Evaluation (17: Figure 12)

Integration of Fatigue Information. Discussions with members of the USAF involved with RCM (32) and ASIP (24) revealed a cultural gap in the integration of the information from both programs into an overall structural

maintenance program. From the reading of the ASIP and Force Management literature (4,7,8,14) it is easy to get the impression that the USAF are only concerned with fatigue damage and individual aircraft tracking programs. The intention of RCM is to incorporate the inspection requirements of the ASIP/ENSIP programs with the entire scheduled maintenance requirements for the aircraft. In particular, the specific inspection requirements need to be folded into the overall inspection requirements to ensure the most efficient packaging of scheduled tasks.

Discussions with ASIP staff (24) revealed two objections to the RCM approach. These were as follows:

- a. The use of rating schemes for environmental and accidental damage to change fatigue inspection intervals.
- b. The possibility of damage being introduced by requiring too frequent inspections of areas which require the disassembly of other areas of structure.

The use of rating schemes has been widespread in commercial applications since the MSG/RCM methodology recognised that structures required a unique way of handling its requirements. These rating schemes acknowledge the randomness of some damage mechanism which would not normally be considered. In addition they allow the operator to fold his experience into the program through changes to inspection frequencies on known problem areas. Since

corrosion, in particular, can have an adverse effect on the fatigue characteristics of the structural details, sufficient inspections must be catered for. Corrosion inspections are normally done via the zonal inspection system, RCM/MSG is the best method available for ensuring that fatigue critical areas are adequately inspected.

The actual maintenance program is determined by structural specialists who are aware of the ramifications of inspections which require dismantling of other structure to achieve the inspection. Good education programs would help alleviate any fears of poor maintenance practice being put into a program.

The key to structural maintenance efficiency is having the fatigue program fully integrated with the structural and other maintenance requirements.

To a limited extent this same cultural gap is present in the commercial arena (6).

MSG-4? At the time of this research effort a revision to MSG-3 is before the FAA for approval. With respect to structures it was determined that the major change would be that the structural methodology would reflect the practice of rating SSI's for environmental and accidental damage prior to folding in the fatigue requirements (6).

Reference 5 identified a number of other areas of the MSC-3 process which could be improved from a manufacturers perspective. The 13 recommended changes include rewording the logic questions to reflect maintenance goals, simplifying the logic diagrams and improving the Maintenance Significant Item (MSI) selection process.

V. Conclusions and Recommendations

Conclusions

The RAAF's maintenance philosophy, detailed in Reference 11, is consistent with current maintenance philosophies being used in the United States of America (USA) by both commercial and military operators. The methodology for determining scheduled structural maintenance requirements is not current with methods being used in the USA.

Previously, RAAF assessments of the MSG-3 maintenance methodology concluded that a wait and see attitude should be taken. There is now sufficient evidence the success of the MSG-3 approach, by both commercial and military operators to support the adoption of its methodology. Consequently, the structural methodology outlined in MSG-3 (21) and repeated in Appendixes D and F should be adopted by the RAAF for all new aircraft of American origin.

Recommendations

The following actions are recommended:

- a. RAMP (10) be amended to include the structural maintenance methodology outlined in Appendix D.
- b. RAMP be amended to include the structural maintenance logic diagram outlined in Appendix F.

Recommendations for Further Study

The following areas of further study are recommended:

- a. Apply the MSG-3 methodology to a RAAF aircraft structure which has already been assessed under a MSG-2 approach.
- b. Review current methods used to determine initial inspection intervals for aircraft structures. Determine the statistical validity of sampling schemes and full scale tests.
- c. Examine whether the MSG-4 (the soon to be released MSG-3 revision) would be worth adopting by the RAAF.
- d. A cost benefit analysis of Individual Aircraft Tracking programs be undertaken to determine if they are worthwhile.
- e. An investigation of ways of measuring maintenance performance in a not for profit organisation.
- f. An analysis of the statistical significance of the results of fatigue tests done on only one airframe. In particular, determine the validity of maintenance programs based on these test results.

Appendix A

Telephone Interview Framework

1. Were any of these subjected to MSG maintenance program evaluation techniques.

Discuss those that were, or why they weren't.

2. Do you use the MSG process to determine maintenance program changes.

Discuss.

3. Do you partake in age-exploration of structural items.

4. Do you track fatigue information on an individual aircraft basis.

Discuss any methods used to track usage parameters.
Discuss what is done with the information.

5. Do you record environmental stress spectra to validate the design spectra applied.

6. Do you use any method of usage averaging. i.e do all aircraft operate on exactly the same routes, are they rotated or dedicated to particular routes.

7. Do you have any incentive to remove tasks from the maintenance program.

8. On what basis are aircraft selected for structural maintenance; age (flight cycles or hours) or accumulated damage?

Appendix B

RCM - A MAINTENANCE PHILOSOPHY

An operator's maintenance program has four objectives:

1. To ensure realization of the inherent safety and reliability levels of the equipment.
2. To restore safety and reliability to their inherent levels when deterioration has occurred.
3. To obtain the information necessary for design improvement of those items whose inherent reliability proves inadequate.
4. To accomplish these goals at a minimum total cost, including maintenance costs and the costs of residual failures.

Reliability-centered maintenance is based on the following precepts:

1. A failure is an unsatisfactory condition. There are two types of failures: functional failures, usually reported by operating crews, and potential failures, usually discovered by maintenance crews.
2. The consequences of a functional failure determine the priority of maintenance effort. These consequences fall into three categories:

- a. Safety consequences, involving possible loss of the equipment and its occupants.
 - b. Operational consequences, which involve an indirect economic loss as well as the direct cost of repair.
 - c. Non-operational consequences, which involve exposure to a possible multiple failure as a result of the undetected failure of a hidden function.
3. Scheduled maintenance is required for any item whose loss of function or mode of failure could have safety consequences. If preventive tasks cannot reduce the risk of such failures to an acceptable level, the item must be redesigned to alter its failure consequences.
4. Scheduled maintenance is required for any item whose functional failure will not be evident to the operating crew, and therefore reported for corrective action.
5. In all other cases the consequences of failure are economic, and maintenance tasks directed at preventing such failures must be justified on economic grounds.
6. All failure consequences, including economic consequences, are established by the design characteristics of the equipment and can be altered only by basic changes in the design:
- a. Safety consequences can in nearly all cases be reduced to economic consequences by the use of redundancy.

b. Hidden functions can usually be made evident by instrumentation or other design features.

c. The feasibility and cost effectiveness of scheduled maintenance depend on the inspectability of the item, and the cost of corrective maintenance depends on its failure modes and inherent reliability.

7. The inherent reliability of the equipment is the level of reliability achieved with an effective maintenance program. This level is established by the design of each item and the manufacturing processes that produced it. Scheduled maintenance can ensure that the inherent reliability of each item is achieved, but no form of maintenance can yield a level of reliability beyond that inherent in the design.

A reliability-centered maintenance program includes only those tasks which satisfy the criteria for both applicability and effectiveness. The applicability of a task is determined by the characteristics of the item, and its effectiveness is defined in terms of the consequences the task is designed to prevent.

8. There are four basic types of tasks that mechanics can perform, each of which is applicable under a unique set of conditions. The first three tasks are directed at preventing functional failures of the items to which they

are assigned and the fourth is directed at preventing a multiple failure involving that item:

- a. On-condition inspections of an item to find and correct any potential failures.
 - b. Rework (overhaul) of an item at or before some specified age limit.
 - c. Discard of an item (or one of its parts) at or before some specified life limit.
 - d. Failure-finding inspections of a hidden-function item to find and correct functional failures that have already occurred but were not evident to the operating crew.
9. A simple item, one that is subject to only one or a very few failure modes, frequently shows a decrease in reliability with increasing operating age. An age limit may be useful in reducing the overall failure rate of such items, and safe-life limits imposed on a single part play a crucial role in controlling critical failures.
10. A complex item, one whose functional failure may result from many different failure modes, shows little or no decrease in overall reliability with increasing age unless there is a dominant failure mode. Age limits imposed on complex components and systems (including the equipment itself) therefore have little or no effect on their overall failure rates.

The RCM decision diagram provides a logical tool for determining which scheduled tasks are either necessary or desirable to protect the safety and operation capability of the equipment.

11. The resulting set of RCM tasks is based on the following considerations:

- a. The consequences of each type of functional failure.
- b. The visibility of a functional failure to the operating crew (evidence that a failure has occurred).
- c. The visibility of reduced resistance to failure (evidence that a failure is imminent).
- d. The age-reliability characteristics of each item
- e. The economic tradeoff between the cost of scheduled maintenance and the benefits to be derived from it.

12. A multiple failure, resulting from a sequence of independent failures, may have consequences that would not be caused by any one of the individual failures alone. These consequences are taken into account in the definition of the failure consequences for the first failure.

13. A default strategy governs decision making in the absence of full information or agreement. This strategy provides for conservative initial decisions, to be revised on the basis of information derived from operating experience.

A scheduled-maintenance program must be dynamic. Any prior-to-service program is based on limited information, and the operating organization must be prepared to collect and respond to real data throughout the operating life of the equipment.

14. Management of the ongoing maintenance program requires an organized information system for surveillance and analysis of the performance of each item under actual operating conditions. This information is needed for two purposes:

- a. To determine the refinements and modifications to be made in the initial maintenance program (including the adjustment of task intervals)
- b. To determine the needs for product improvement.

15. The information derived from operation experience has the following hierarchy of importance:

- a. Failures that could affect operating safety.
- b. Failures that have operational consequences.
- c. The failure modes of units removed as a result of failures.
- d. The general condition of unfailed parts in units that have failed.
- e. The general condition of serviceable units inspected as samples.

16. At the time an initial program is developed information is available to determine the tasks necessary to protect safety and operating capability. However the information required to determine optimum task intervals and the applicability of age limits can be obtained only from age exploration after the equipment enters service.

17. With any new equipment there is always the possibility of unanticipated failure modes. The first occurrence of any serious unanticipated failure immediately sets in motion the following product-improvement cycle:

a. An on-condition tasks is developed to prevent recurrences while the item is being redesigned.

b. The operating fleet is modified to incorporated the redesigned part.

c. After the modification has proved successful, the special task is eliminated from the maintenance program.

18. Product improvement, based on identification of the actual reliability characteristics of each item through age exploration, is part of the normal development cycle of all complex equipment.

Appendix C

Results of Comparison Between
Maintenance Philosophies

RCM Objective	RAMP (AAP 7001.038-1) Paragraph reference	Comments
1	106,115	Supported
2	104	Supported
3	Supported through data collection.	
4	115,116	Supported
RCM Precept		
1	445	Supported
2		
a.	427-431	Supported
b.	432-434	Supported
c.	435	Supported
d.	441-444	Supported
3	430	Supported
4	444	Supported
5	435	Supported
6	130	Supported
a.	439	Supported
b.	These two items represent modifications which would become evident later or be fixed during production	
c.		
7	129-130	Supported
8	227	Supported
a.	219	Supported
b.	230-233	Supported
c.	240	Supported
d.	241-245	Supported
9	408-409,421	Supported
10	409-410	Supported

- 11 Supported
a. It is difficult to track down a specific
b. reference to support these concept which
c. are the foundation of this philosophy.
- 12 436-437 Supported
- 13 Default strategies are not directly used.
Common sense and sound judgement on the
part of the assessor is expected.
- 14 729 Supported
a. 731-732 Supported
b. This aspect is not directly covered by
maintenance analysis but is a by-product
of the modification process.
- 15
a. The concept of a hierarchy of failure
b. data is not particularly relevant.
c. Safety of flight failures are always
d. given priority. The rest are handled
e. in order of operating/economic precedence.
- 16 726(a) Supported
- 17
a. The chain of events followed after
b. the discovery of a new failure mode
c. is not a philosophical issue.
- 18 Supported through modification program.

Appendix D

MSG-3 Structural Methodology

The method for conducting structural item analysis as given in MSG-3 is as follows:

1. Identify items as Structurally Significant Items (SSI) or Other Structure.
2. Classify SSI's as damage tolerant or safe-life structure.
3. For each damage tolerant SSI, rate separately its susceptibility to each of the three deterioration processes:
 - a. Fatigue.
 - b. Environmental deterioration.
 - c. Accidental Damage.
4. Select for each damage tolerant SSI the following inspection features:
 - a. Level and method of inspection.
 - b. Inspection threshold.
 - c. Frequency of inspection (repeat interval).
 - d. Fleet leader/age exploration program, if applicable.
5. For each safe-life SSI, rate separately its susceptibility to the two deterioration processes:
 - a. Environmental.
 - b. Accidental Damage.

6. Select for each safe-life SSI the following inspection features:

- a. Level and method of inspection.
- b. Threshold of initial inspection (if appropriate).
- c. Frequency of inspection (repeat interval).

7. Overlay the inspection requirements for each SSI according to the deterioration processes for which it was rated. Consolidate tasks and document the results.

8. For Other Structure, establish appropriate maintenance tasks based on:

- a. Past experience, and/or,
- b. Manufacturer's recommendation for new materials and/or concepts.

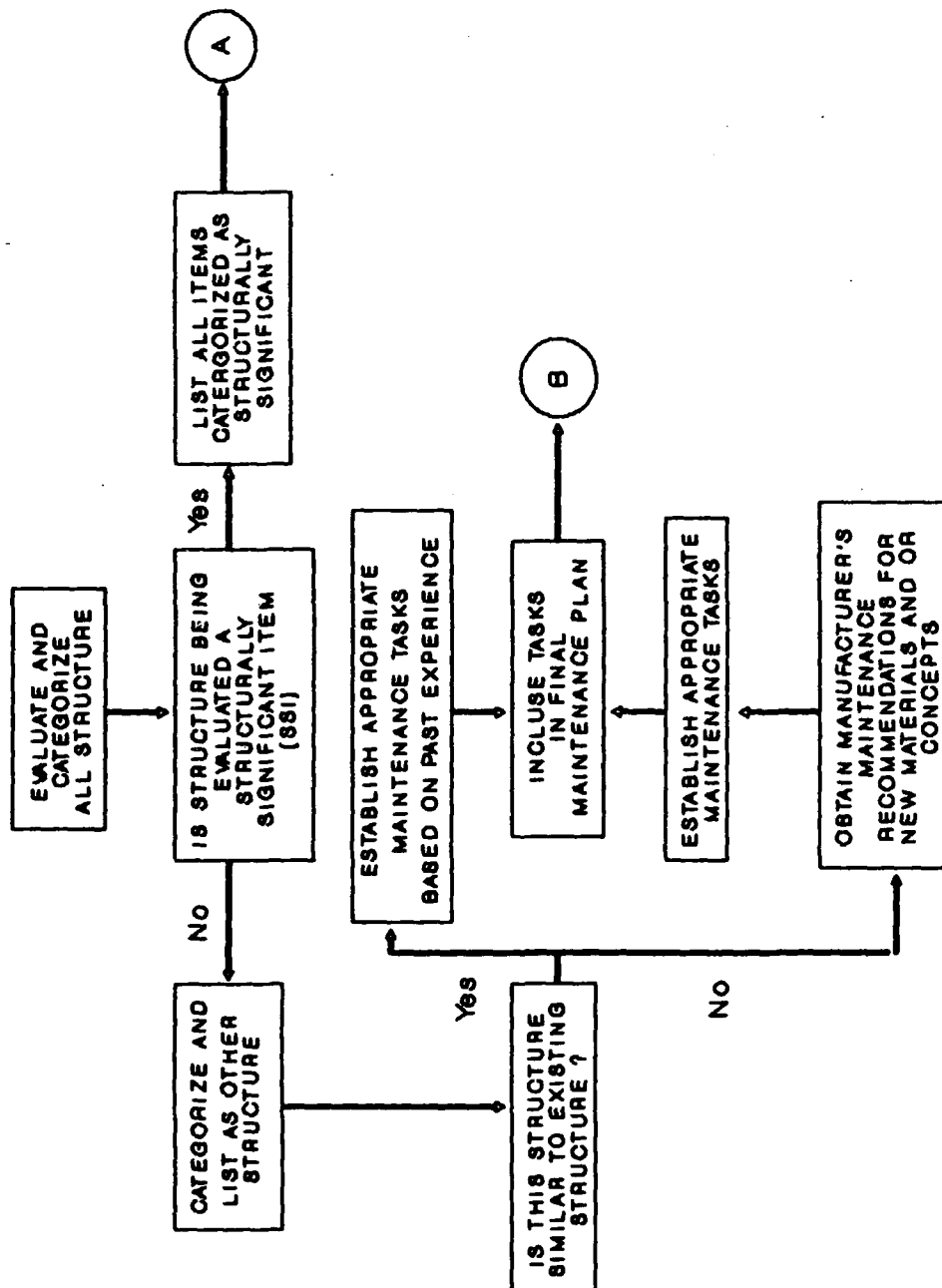
Appendix E

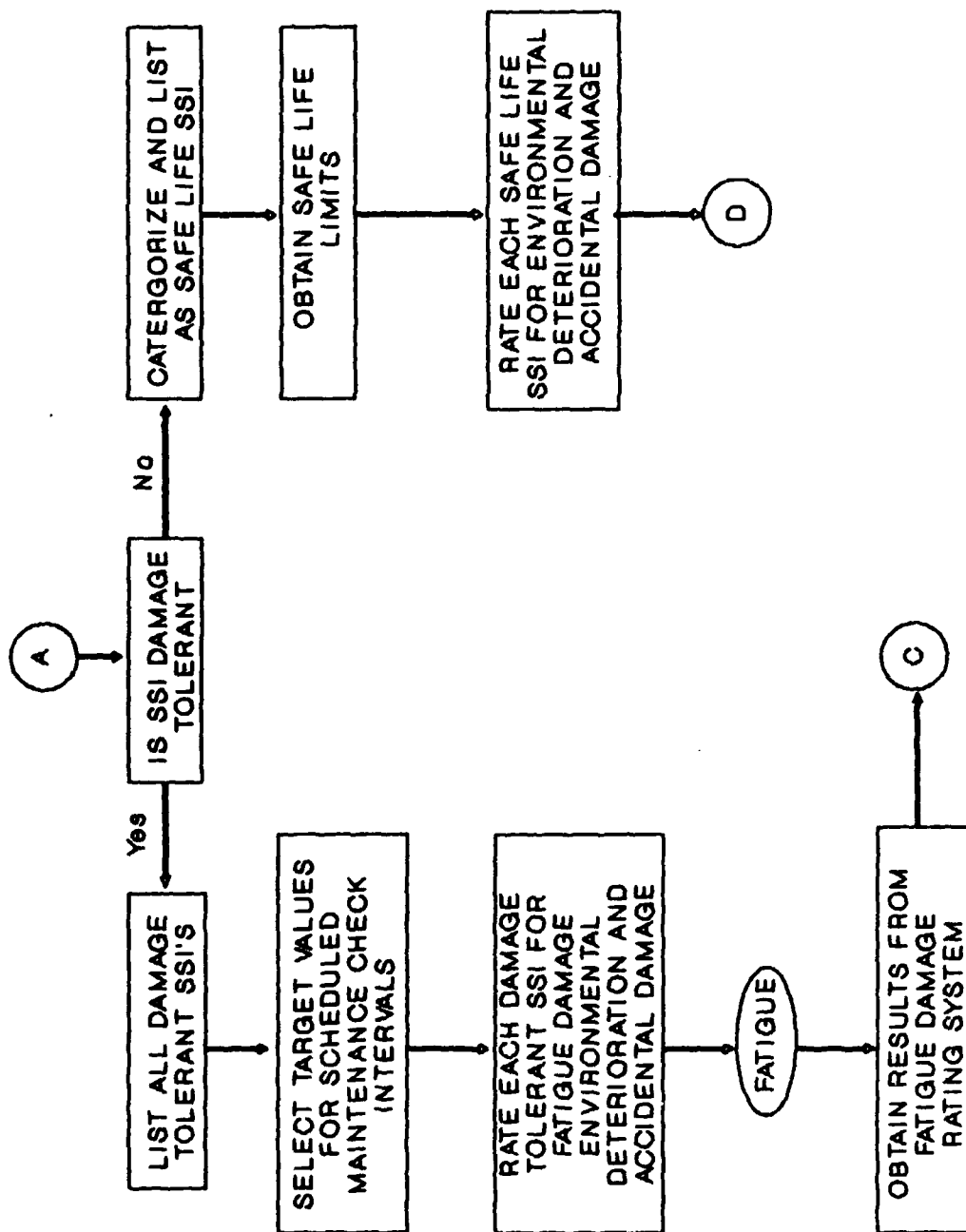
Results of Comparison Between Structural Maintenance Methodologies

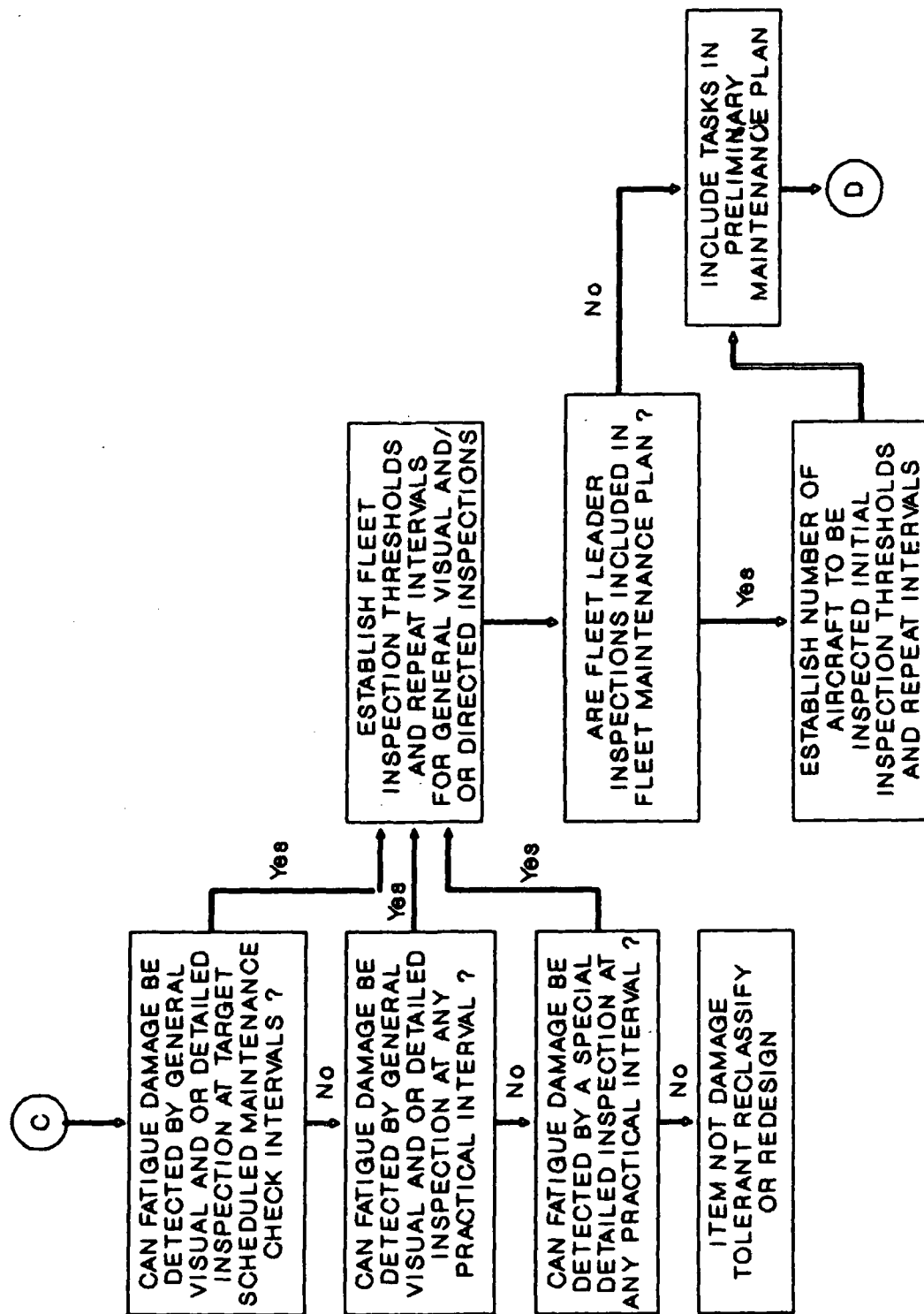
MSG-3 Method	RAMP	Comments
1	No	Classified as Primary
2	No	or secondary.
3	No	Rating schemes not used.
4	No	Inspection thresholds normally given. Fleet Leader/Age Exploration not formally done.
5	No	Rating schemes not used.
6	No	Rating schemes not used.
7	Yes	All tasks arising from analysis are consolidated into one program.
8	Yes	All structure subject to zonal requirements.

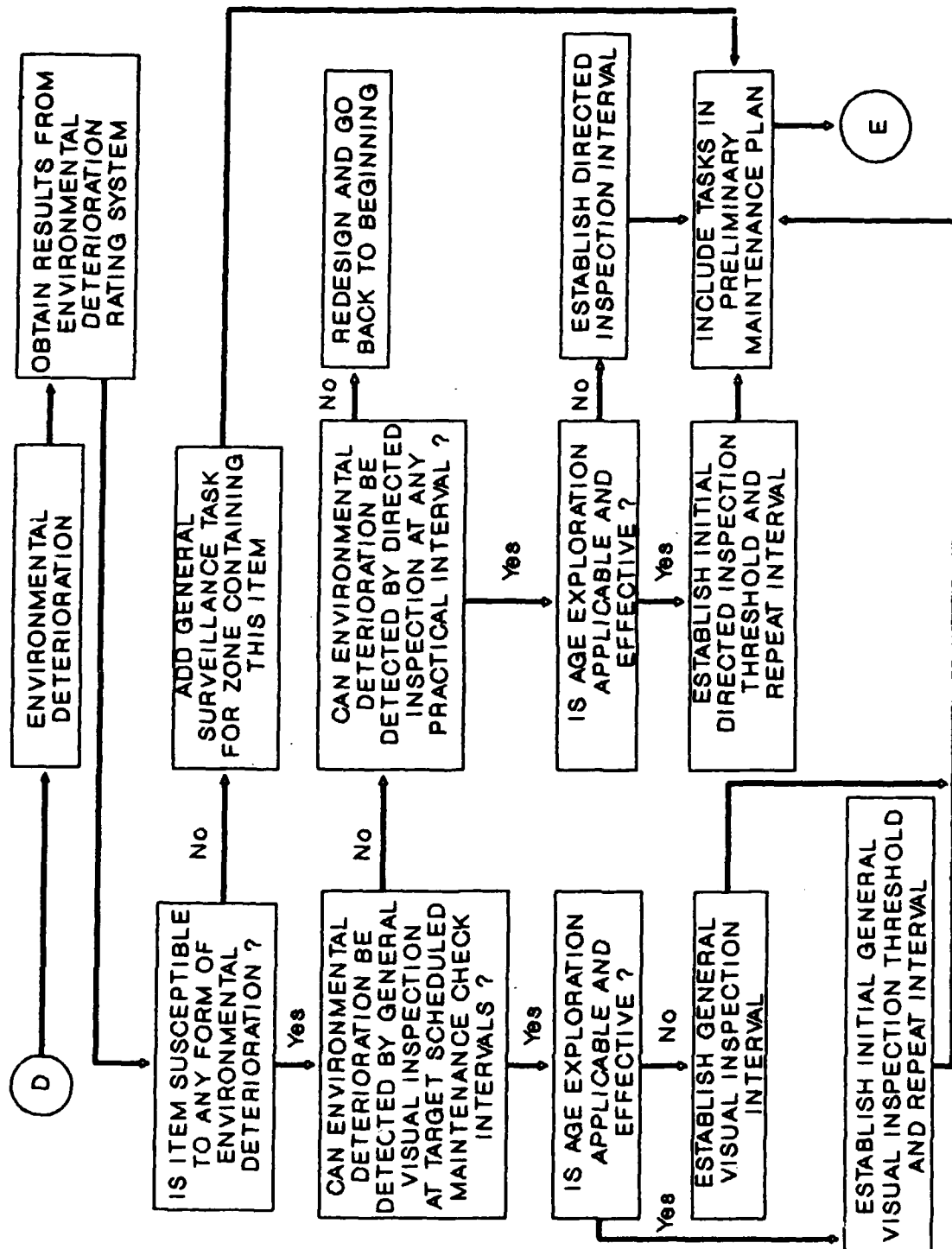
Note. Refer to numbering in Appendix D.

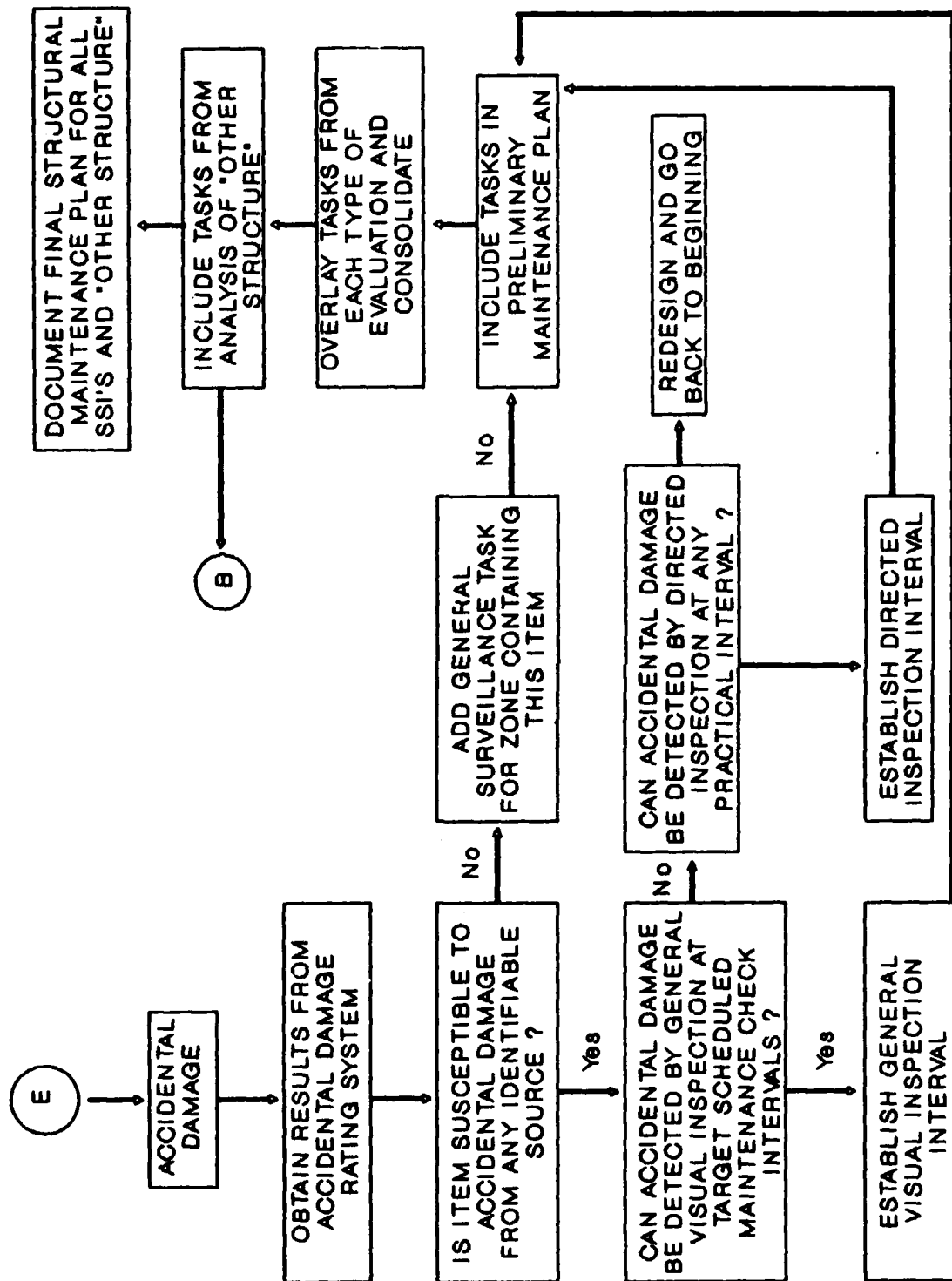
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MSG-3 Structural Logic Diagram



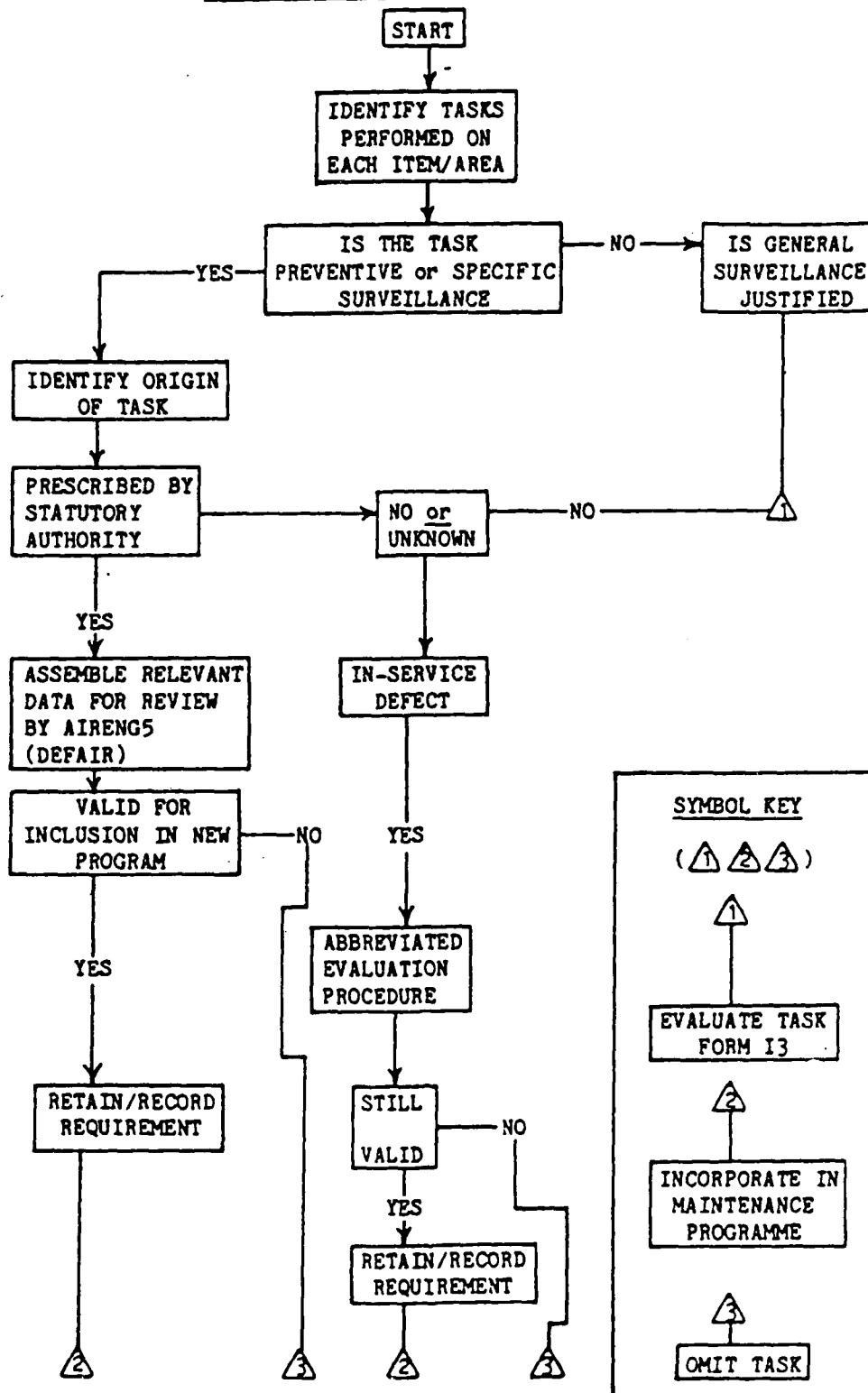




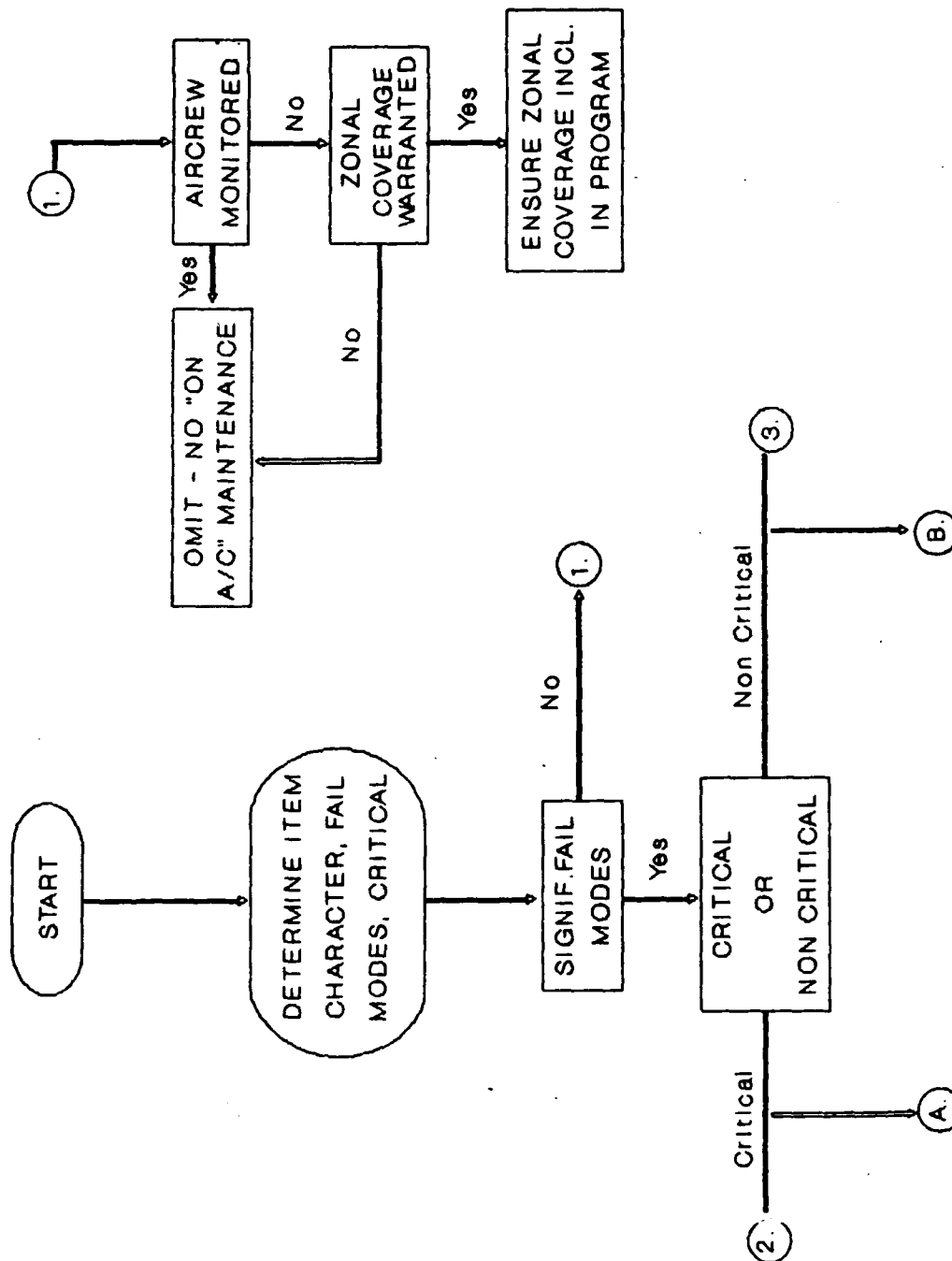


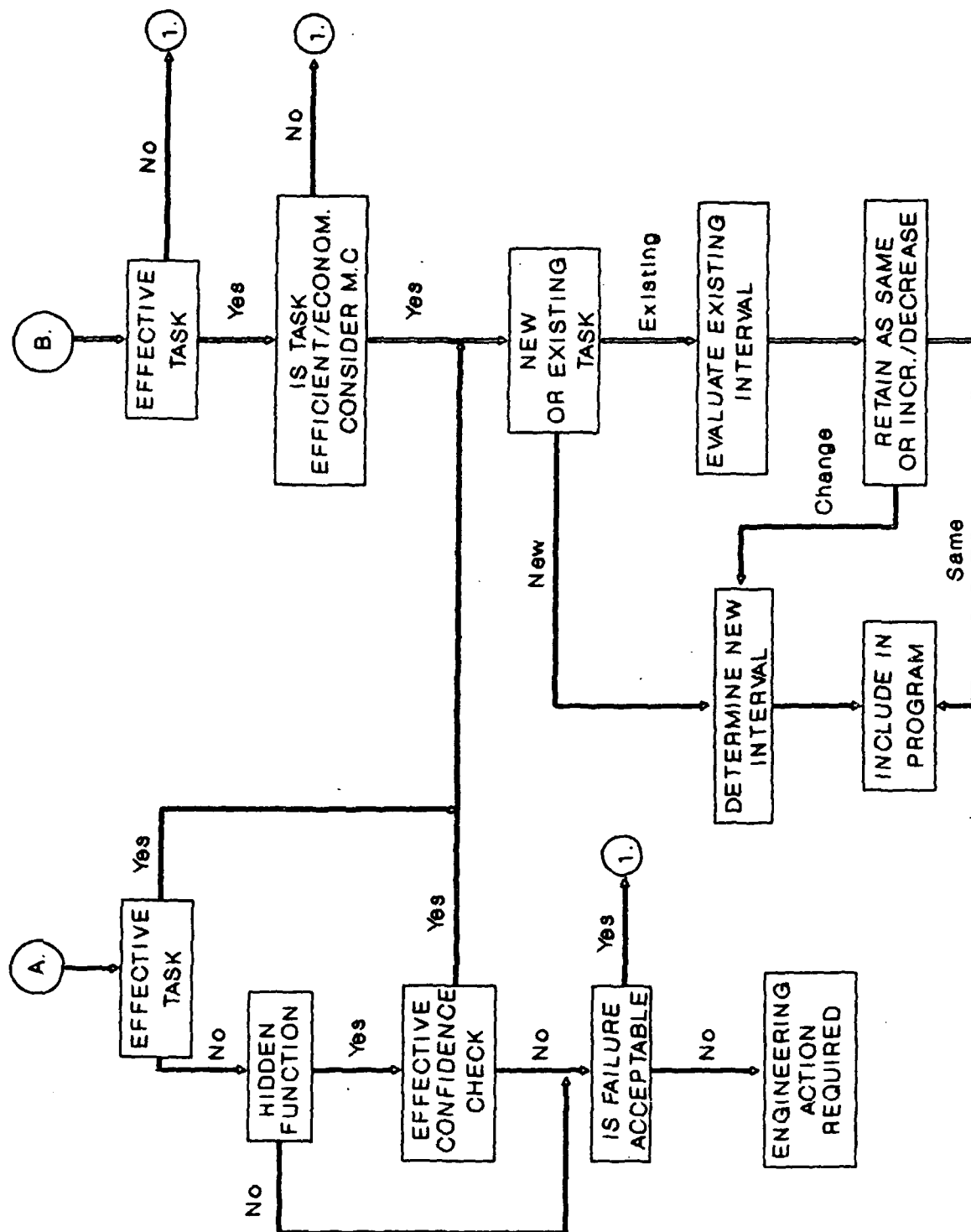


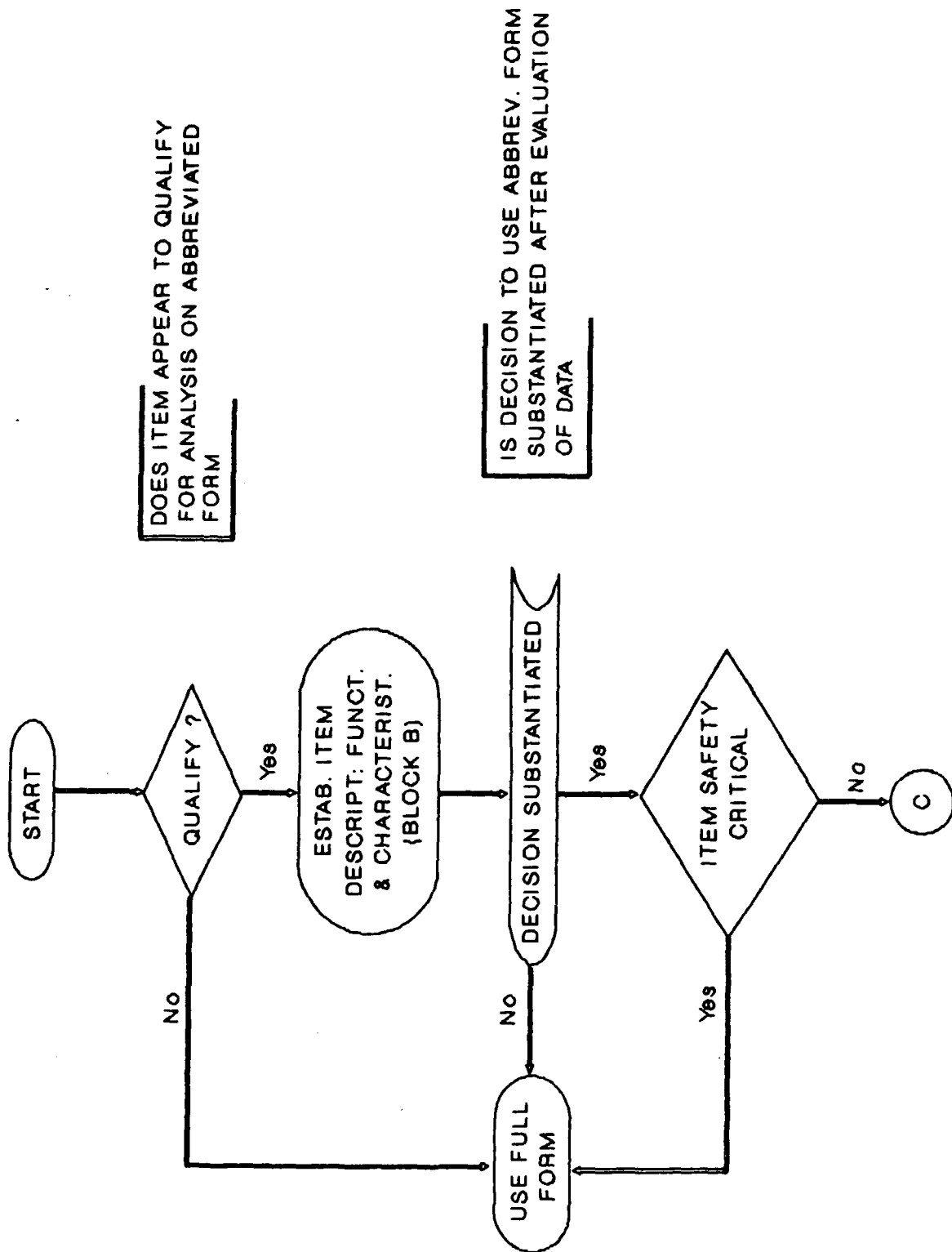
Appendix G
Level of Analysis Diagram

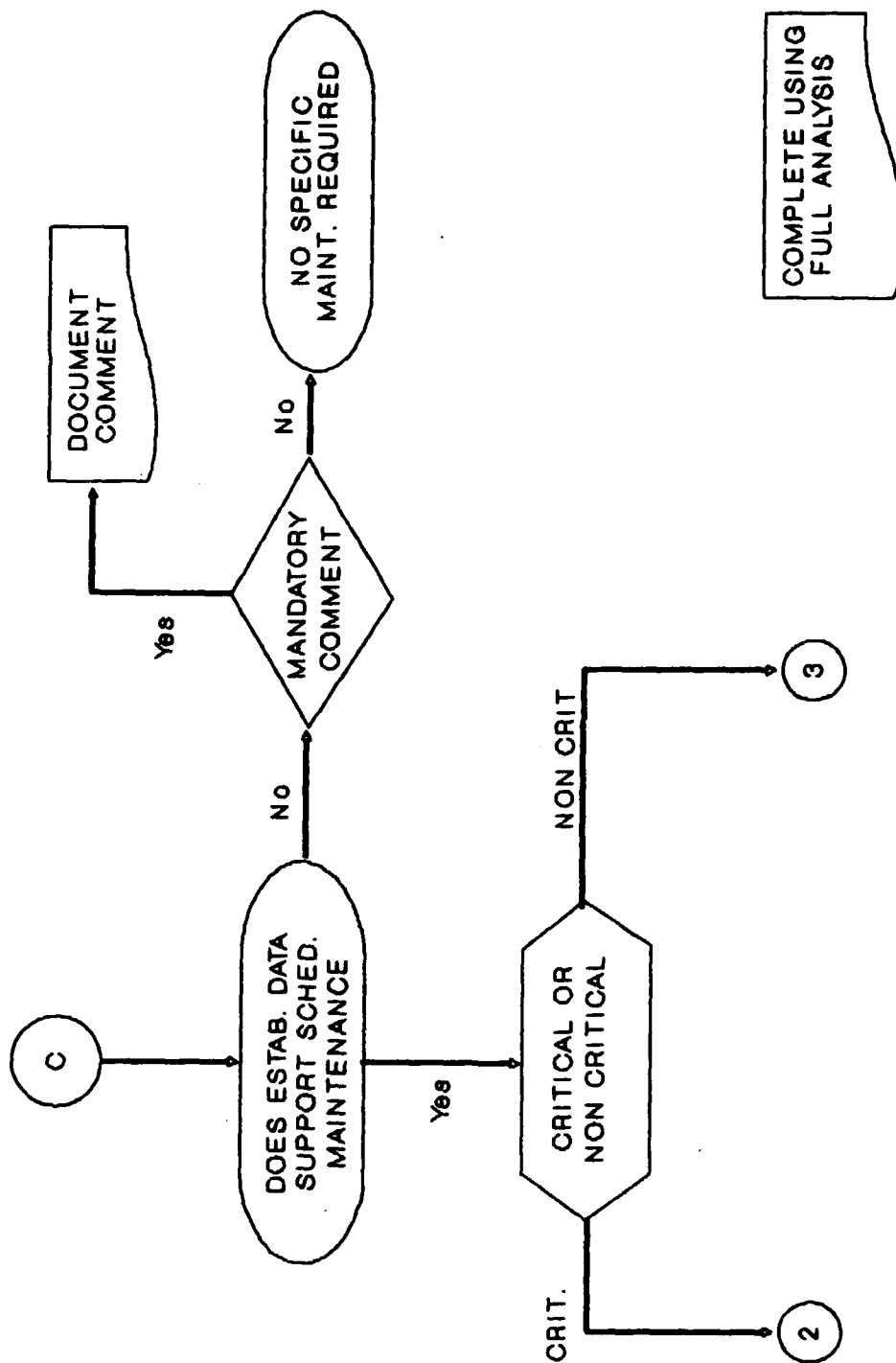


Appendix H
RAAF Decision Logic









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This thesis concentrates on determining the status of maintenance philosophy development and, in particular, on structural maintenance methodologies. An extensive treatment of the historical development of structural characteristics and design methodologies which effect structural maintenance requirements is presented.

Additional support for current philosophies and methodologies is obtained from interviews with both commercial and military practitioners employed in managing structural maintenance programs. These results, together with the extensive literature review lead to the conclusion that operators in the United States of America all subscribe to the MSG/RCM doctrines and use the structural maintenance methodology detailed in the MSG-3 document.

A comparison between these methods and those used by the Royal Australian Air Force (RAAF) reveals that there is little philosophical difference between the two, however the methodologies vary considerably. The RAAF's procedures are based on MSG-3's predecessor document MSG-2 which did not have a dedicated structural maintenance methodology.

The report concludes that there is sufficient evidence to supporting the effectiveness of the MSG-3 structural methodology and, therefore, it should be adopted by the RAAF.

END

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