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AGE EXPLORATION IN NAVAL AVIATION

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Abstract

In this paper, an overview of the United States Navy's newly developed aviation age exploration process is given. As age exploration is a subset of the Reliability-Centered Maintenance (RCM) program, the underlying concepts of age exploration, RCM, and their relationship to each other, are explored. Age exploration is depicted as a multi-faceted analyzation, marrying diverse types of information with maintenance engineering logic and statistical formulation. Specific applications of the age exploration process in the Navy's aviation community are presented. It is shown how the knowledge gained from age exploration enables the designer of the RCM requirements to effect maximum uptime of the equipment at the lowest cost within the bounds of safety.

I. Introduction

Definition

The concept of age exploration is based on the fact that mechanical equipments have an inherent reliability. Age exploration collects and analyzes operating data to determine the exact effect operating age has on its condition. With this knowledge, maintenance tasks may then be designed to protect the equipment, enabling it to realize its inherent reliability.

Background

Age exploration is an outgrowth of the maintenance practices used by the commercial airline industry. Initially, maintenance for scheduled carriers was a craft learned through experience and rarely examined analytically. As new aircraft grew in complexity, maintenance costs grew proportionally. In the 1950's these costs reached a level that forced airline management to take a new look at the concept of preventive maintenance.

The old belief that there is a fundamental cause-and-effect relationship between scheduled maintenance and operating reliability was questioned. Studies of operating data had begun to contradict traditional maintenance practices. The traditional belief was that because mechanical parts wear out, they should be overhauled, and the more overhauls, the more reliable the equipment. It was also believed that this had a direct, beneficial effect on operating safety.

Actuarial studies on failure data showed that these time-honored hardtime policies were ineffective. This was because, for many items, the probability of failure did not increase with operating age. Also, from the safety aspect, it was found that some failures could not be prevented no matter what maintenance precautions were taken.

In 1960, a task force consisting of the airlines and the Federal Aviation Administration (FAA) was formed to study scheduled maintenance. The result was an FAA/Industry Reliability Program, which eventually led to the document, Handbook: Maintenance Evaluation and Program Development, and later, in 1970, to a second document, MSG-2: Airline/Manufacturer Maintenance Program Planning Document. The MSG-2 document was developed for the American and European Commercial Carriers. The objective of the MSG-2 (as it came to be known) was to develop a scheduled maintenance program at the lowest cost, while assuring the maximum safety and reliability of equipment. As an example of the benefits of this program, the initial program for the McDonnell Douglas DC-8 under traditional maintenance policies included scheduled overhaul for 339 items. In contrast, the DC-10, under the MSG-2 concept, was assigned only seven items to overhaul.

Reliability-Centered Maintenance

The Navy's maintenance program has evolved from the MSG-1 and MSG-2 concepts into the Reliability-Centered Maintenance (RCM) program.# The RCM program relies on two main precepts. These are that scheduled maintenance tasks are based on: 1) Hard Time (HT) removals, and 2) scheduled inspections. Hard time removals require the hardware to be replaced at fixed intervals, based on an analysis of failure-age data, and that it be either overhauled or discarded. A scheduled inspection is a fixed interval inspection and may be either an inspection to detect impending failures (on-condition) or to detect functional failures (failure finding) which have occurred. See figure 1, The RCM Decision Diagram.

Relationship of Age Exploration to RCM

The RCM program is based on specific tasks selected on the basis of the actual reliability characteristics of the equipment they are designed to protect. Any preventive maintenance program can be developed and implemented with incomplete reliability information. The RCM logic dictates that a default decision, which is a decision made in the absence of complete information, will then be made. Generally, there is a deficiency of data on the variation of failure resistance with age, variation of conditional probability of failure with age, and the operational values of failure symptoms (a physical indication of an impending failure). Therefore, an important element of RCM is age exploration, which is a procedure for the systematic gathering and analysis of this information, which is, in effect, a requirement as a result of the RCM default decision. See figure 2, Relationship of Age Exploration to RCM.

#Most of the following discussion is based on the text by F. Stanley Nowland, Howard F, Heap, Reliability-Centered Maintenance, Department of Defense Contract No. MDA 903-75-C-0349, March 1979.

RELIABILITY CENTERED MAINTENANCE

DECISION DIAGRAM

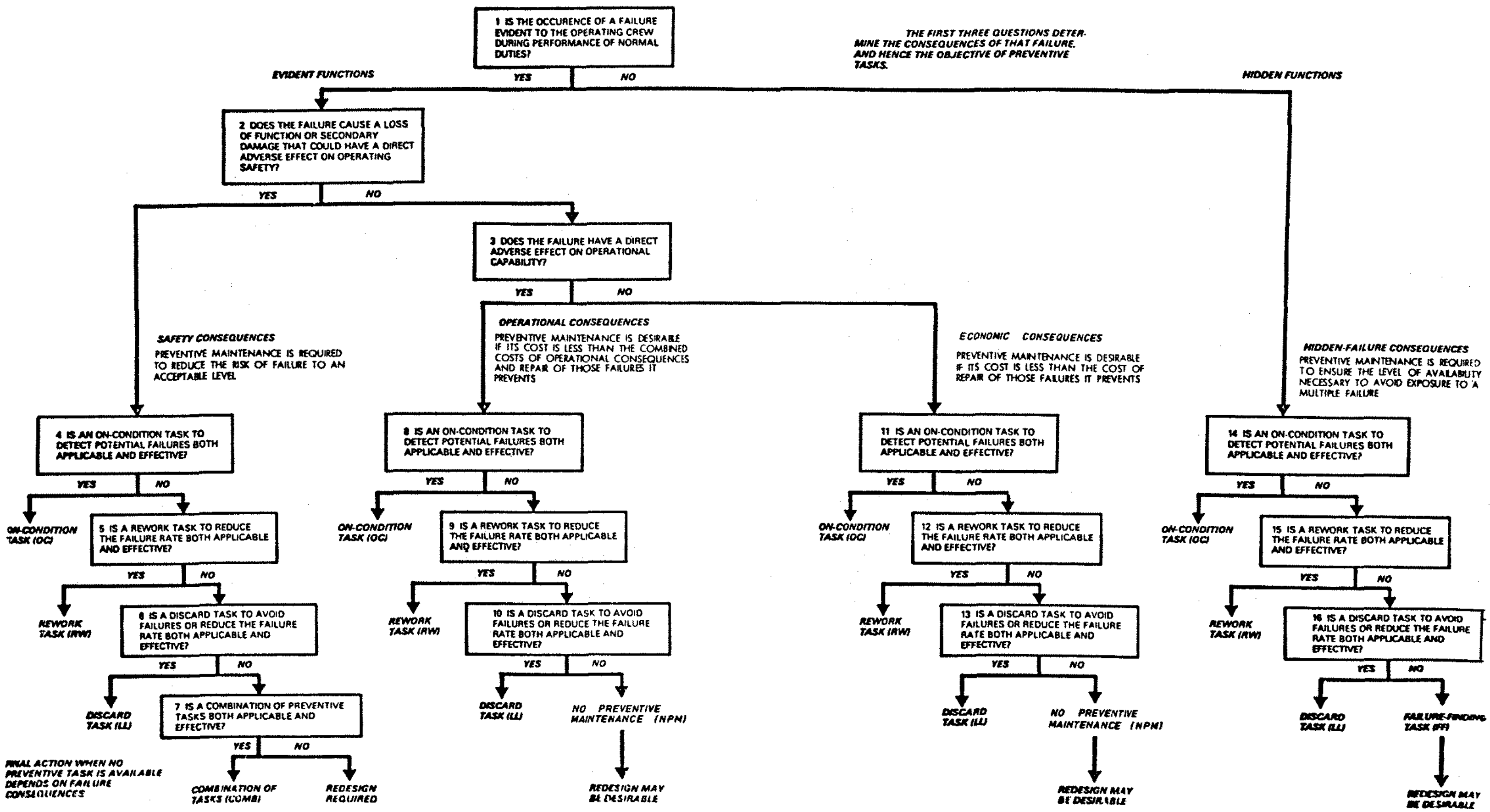

FIGURE 1

RELATIONSHIP OF AGE EXPLORATION TO RCM

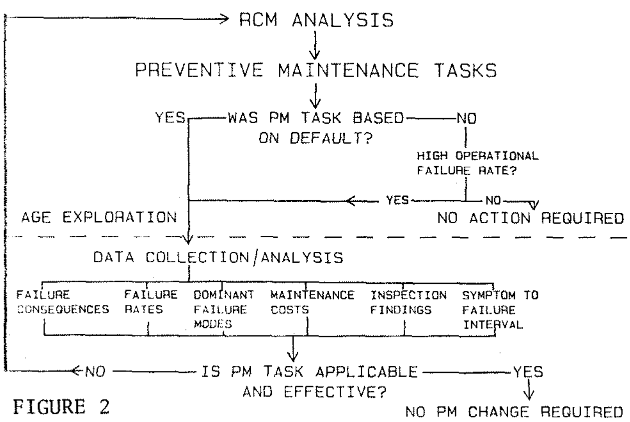

FIGURE 2

Age Exploration Process

Age exploration consists of two parts: 1) to detect decreases in reliability and 2) to validate or determine the criteria for applicability and effectiveness of the basic preventive maintenance tasks. Decreases in reliability can be detected through examination of in-service equipment to determine if the degradation is caused by increases in the rates of known failure modes or failure modes not anticipated. The determination or validation of applicability and effectiveness in general requires special data collection programs.

Age Exploration Routine

The age exploration process includes the monitoring of the equipments condition, performance, and failure rates. It also includes the evaluation of inspection findings and the determination of age-reliability relationships. The analysis of this data is used to respond to the actual operating characteristics of the equipment, through the adjustments in the task intervals. In addition, certain unnecessary and maintenance overintensive tasks may be eliminated; the desirability of additional tasks can be assessed, and the task interval may be expanded. See figure 3, Results of Age Exploration.

II. Application of Concepts

The initial age exploration requirements are generated from the RCM analysis. Other age exploration requirements may be generated for new equipment added to the existing system, failure modes not anticipated, or unforeseen failure rates of in-service equipment.

Data Collection

The maintenance data collection system is the heart of the age exploration process. It is necessary to track the history of the equipment from the time it enters service until it is retired, tabulating its age at failures. Analysis of this data provides the basis for recommended changes to the maintenance program.

As there are literally hundreds of thousands of parts in a modern military aircraft, careful judgment must be exercised in developing the data requirements. The Navy uses data from a variety of sources, and ranks the data according to the severity, or consequences of failure. Generally, the data priorities are as follows:

1. Safety reports: failures directly influencing safety.
2. Quality Deficiency Reports/Engineering Investigations: failures that directly affect operational capability.
3. Dedicated age exploration study: the causes of failures, the verification of the preventive

RESULTS OF AGE EXPLORATION

REFINEMENTS OF INITIAL MAINTENANCE PROGRAM			MAJOR REVISIONS TO INITIAL MAINTENANCE PROGRAM		
INSPECTION TASKS			RESULTS OF TECHNOLOGICAL CHANGE		
PROPOSED ON-CONDITION TASKS	PROPOSED AGE LIMIT TASKS	ITEMS ASSIGNED TO NO PREVENTIVE MAINTENANCE	UNANTICIPATED FAILURE MODES OR CONSEQUENCES	NEW OR REDESIGNED ITEM	CHANGES IN INSPECTION TECHNOLOGY
CONFIRM THAT REDUCTION IN FAILURE RESISTANCE IS VISIBLE.	DETERMINE AGE RELIABILITY RELATIONSHIP TO CONFIRM THAT CONDITIONAL PROBABILITY OF FAILURE INCREASES WITH AGE.	MONITOR AND EVALUATE OPERATIONAL DATA TO SEE WHETHER SOME APPLICABLE AND EFFECTIVE TASK CAN BE DEVELOPED.	DEVELOP ON-CONDITION TASKS TO PREVENT CRITICAL FAILURE AND TO PREVENT OR REDUCE FREQUENCY OF EXPENSIVE FAILURES AT LOW AGES.	CONDUCT RCM ANALYSIS OF ITEM WHEN IT FIRST ENTERS SERVICE.	EVALUATE APPLICABILITY AND EFFECTIVENESS OF NEW ON-CONDITION TECHNIQUES.
DETERMINE RATE OF REDUCTION IN FAILURE RESISTANCE.	IF FAILURES ARE AGE RELATED, DETERMINE WHETHER A COST EFFECTIVE AGE LIMIT EXISTS.		DEVELOP DESIGN CHANGES NECESSARY FOR PERMANENT CORRECTION OF PROBLEMS.	REFINE MAINTENANCE REQUIREMENTS THROUGH AGE EXPLORATION.	
CONFIRM OR MODIFY POTENTIAL FAILURE CONDITION.	IF A COST EFFECTIVE INTERVAL CAN BE FOUND, ADD TASK TO PROGRAM.		DEVELOP FAILURE FINDINGS TASKS FOR HIDDEN FUNCTIONS NOT IDENTIFIED IN INITIAL PROGRAM.		
ADJUST INSPECTION INTERVAL AND AGE FOR FIRST INSPECTION, IF APPLICABLE.			DEVELOP ON-CONDITION OR OTHER TASKS TO CONTROL CRITICAL OR AT HIGH AGES, WHERE PRODUCT IMPROVEMENT MAY NOT BE ECONOMICALLY JUSTIFIED		

FIGURE 3

maintenance task, and the interval between symptom and functional failure.

4. Maintenance and Material Management System (3M): failure rates of units removed as a result of functional failures.

5. Depot Maintenance Data Collection System: the condition of parts that receive depot processing.

Sampling

The age exploration tasks generated from the RCM analysis must be practically formulated into a sampling program which is workable in the Navy's operating environment. Some requirements for age exploration, mostly safety related, must be accomplished outside of the operating environment in a test laboratory. Sampling tasks to collect age exploration data in the operating environment may be scheduled during periods of other scheduled inspections to ease the burden of special requirements. Sampling tasks for specific data collection purposes are required only for a period long enough to obtain the required information. Data collected during flight test programs and from "lead the fleet" aircraft are important to the age exploration program.

Analysis

Age reliability data can be analyzed using various methods. The Navy analyzes data using a dedicated age exploration technique and actuarial analyses.

Dedicated Age Exploration Study

A dedicated age exploration study is used when operational data is required that the normal information systems are not capable of supplying. The objectives of this type of study are manyfold; any may be applied to the specific problem at hand. The objectives are as follows: 1) to determine the desirability of implementing an on-condition task; 2) to determine the effectivity of, or to validate, an on-condition task; 3) to determine the scheduled maintenance interval; and 4) to adjust intervals on hard-time items.

The item to be studied is identified by part number, component, or system. The maintenance level is specified (organizational, intermediate or depot) from which the data is most easily obtained. The frequency of inspection is designated (sample size), as are the reporting requirements and detailed instructions. These requirements are then sent as an Age Exploration Directive to the appropriate organization for implementation.

The results of the test or inspection must be quantifiable or measureable. Some examples of quantifiable results:

Crack - length, depth
Corrosion - surface area affected, depth, type
time - seconds
force - pounds, psia, ft-lbs
wear - amount of wear indicators showing wear from a nominal or known value
dye penetrant results
x-ray results
eddy current readings
movement of play - measured movement from a fixed point

A table of likely results and their ranges should be included in the directive. This will help in reducing spurious data due to human or mechanical measurement error. See figure 4: An Example of a Dedicated Age Exploration Study.

AN EXAMPLE OF
DEDICATED AGE EXPLORATION STUDY

FLAP EXTENSION AND RETRACTION TASK

a. prepare aircraft for safe ground handling.

b. The following is a ONE TIME TASK:

Remove access pannels 3233.2, 3233-3, 4233-2,4233-3 and verify that installed actuator part numbers and serial numbers match those numbers listed in this directive (para 5.b). Reinstall the access panels. Report findings in accordance with para 10.bb. of this directive.

DO NOT REPEAT the above task during the duration of this age exploration directive.

c. Connect external electrical power.

d. Connect external hydraulic power to PC No. 2 hydraulic system.

e. Place flap handle in the DN position. Using a stopwatch, begin timing from the moment the first surface moves until the last surface stops. Note this time.

f. Place flap handle in the UP position. Using a stopwatch, begin timing from the moment the first surface moves until the last surface stops. Note this time.

g. Repeat above tasks e and f two (2) more times. Note the extension and retraction time for each cycle.

TRAILING EDGE FLAP SYSTEM TIME TABLE

EXTENSION TIME (SEC.)	RETRACTION TIME (SEC.)	
0-7.2	0-10.4	out of tolerance adjust/repair
7.3-10.3	10.5-13.5	within operating specification
10.4+	13.6+	out of tolerance adjust/repair

h. Disconnect external hydraulic power.

i. Disconnect external electric power

aa. AGE: Report age in terms of flight hours from aircraft log book.

FIGURE 4: An Example of a Dedicated Age Exploration Study. The purpose is to determine the flap actuator symptom and failure indications.

Actuarial Analysis

Actuarial Analysis is another way of evaluating age exploration data. Actuarial Analysis is used to determine whether an age limit would be applicable. It is primarily appropriate for those equipments that have failure rates which if taken singly, have no overwhelming consequences, but whose cumulative effect can be an important cost consideration.

The most useful measure of the age-reliability relationship is the probability that an item entering a given age interval will fail during that interval. This measure is usually called the conditional probability of failure (CPF), or hazard rate. If the conditional probability of failure increases with age, the item shows wearout characteristics. Wearout characteristics are an indication that perhaps an age limit would be effective in reducing the overall failure rate.

The applicability criteria for both scheduled rework tasks and economic-life tasks include two conditions which require the use of conditional-probability and survival curves derived from operating data:

(1) There must be an identifiable age at which the items shows a rapid increase in the conditional probability of failure.
(2) A large proportion of the units must survive to that age.

The Navy's Analytical Maintenance Program Analysis Support computer system has a model that calculates and plots the hazard rate on given items. See figure 5, Real Hazard Plot of the H-46 Power Plant Assembly. Notice the pronounced wearout at about 225 hours. This indicates that the probability of failure begins to increase rapidly at this age. This assembly is a good candidate for a rework task at about 200 hours. It is this kind of information which is useful in confirming a hard-time limit. It also indicates what age the limit would be beneficial.

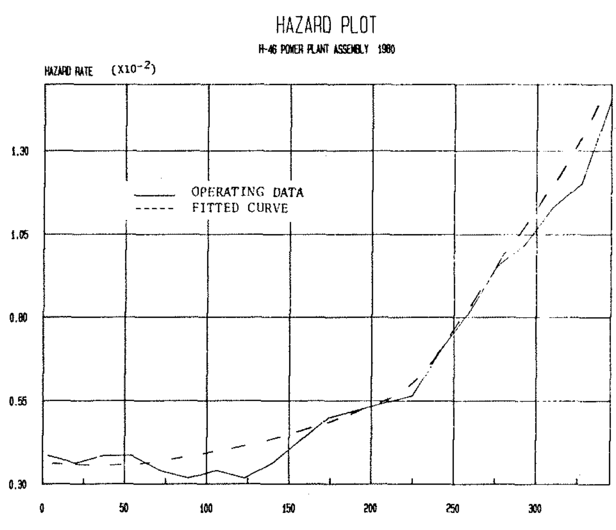

FIGURE 5

Application of Age Exploration Analysis

The initial requirements for age exploration are generated as a result of default decisions made during the completion of the RCM analysis. The age exploration sampling inspections are generated to collect age-reliability data. The data are analyzed to either refine or validate the original RCM logic decisions. Other age exploration requirements may be generated for new equipment added to the existing system, and for failure modes not anticipated, or for unforeseen failure rates. In each of these cases, the RCM logic should be followed and the proper age exploration requirements generated.

The analysis process consist of two elements: (1) the verification and refinement of RCM logic decisions, and (2) revisions to the preventive maintenance requirements and product improvement. The age exploration analysis will provide the following kinds of information:

a. The types of failures the equipment is actually exposed to, as well as their frequencies.
b. The consequences of each failure, ranging from direct safety to serious operational consequences, high repair costs, long out of service times for repair, and a deferred need to correct inexpensive functional failures.
c. Confirmation that functional failures classified as evident to the operating crew are in fact evident during normal performance of duties.
d. Identification of the circumstances of failure to determine whether the failure occurred during normal operation or was due to some external factor, such as bird strike.
e. Confirmation that on-condition inspections are really measuring the reduction in resistance to a particular failure mode.
f. The actual rates of reduction in failure resistance to determine optimum inspection intervals.
g. The mechanism involved in certain failure modes to identify new forms of on-condition inspection and parts that require design improvement.
h. Identification of tasks assigned as default actions in the initial program which do not prove applicable and effective.
i. Identification of maintenance packages that are generating few trouble reports.
j. Identification of items that are not generating trouble reports.
k. The ages at which failures occur, so that the applicability of scheduled rework and discard tasks can be determined by actuarial analysis.

Areas of Applicability

Each of the three divisions, systems, powerplants and structures, has different failure patterns, and therefore requires different maintenance tasks. Age exploration activities in each of the three divisions tend to focus on different sources of reliability information.

Age Exploration of Systems Items

The systems division consists of a large number of readily replaceable complex items. The reliability of systems items usually tends to be low. Usually an initial systems program includes few preventive maintenance tasks other than servicing and failure finding inspections, and rarely are there defined age exploration requirements, as in the powerplant and structure programs. The cost of corrective maintenance is fairly low for most systems items, and when operating data indicates that additional preventive tasks are justified, it is generally because of an unexpectedly high failure rate that involves operational consequences. In some cases the failure rate may be high enough to warrant the replacement of certain components with more reliable ones. The principal age exploration tool in the systems division is actuarial analysis of failure data. Ordinarily the conditional probability of failure for a complex item is not expected to vary much with operating age. However, a newly designed system will sometimes show a dominant failure mode that is both age related and expensive enough to make an age limit task desirable.

Systems Example. The P-3 engine driven compressor that drives the air conditioning units for the aircraft, has been experiencing a high failure rate. An age exploration plan was designed to test the effectiveness of the on-condition inspection. The original inspection was designed to detect a particular failure mode at the 1200 hour phase inspection. This 1200 hour interval inspection is suspected of not detecting the failures. The age exploration plan is to shorten the current inspection time to 600 hours, and collect time to failure data from two groups of P-3 aircraft. One group will be inspected at 600 hours, and the other group will have the inspection eliminated. The data will be collected and statistically correlated for variation. The outcome is expected to be one of three alternatives: 1) the 600 hour inspection is able to detect the impending failure; 2) no inspection is able to detect the impending failure; or 3) the 1200 hour inspection is the optimal interval.

Age Exploration of Powerplant Items

Age exploration is an integral part of any initial powerplant program. A completely new type of engine, often incorporating new technology, is sometimes unreliable when it first enters service. During the first few years of operation premature removal rates are commonly high. The high removal rate makes it possible for the engine repair shop to obtain information not only on the parts involved in the failure, but on the condition of other parts of the engine as well. Most new aircraft engines experience unanticipated failures, some of which are serious. The first occurrence of any serious engine failure immediately sets in motion a developmental cycle. The cause of the failure is identified, and an on-condition task is devised to control functonal failures until the problem can be resolved at the design level. Modified parts are then incorporated in the operating fleet, and when continued inspections have shown that the modification is successful, the special task requirements are terminated.

Powerplant Example. One hundred forty-eight significant parts of the TF-30 engine, which powers the F-14, are sampled in the depot on an opportunity basis. Data was collected from both normal operating engines, and from lead-the-fleet, or Accelerated Simulated Mission Endurance Test (ASMET) engines. Slot wear data for the 8th stator, for example, were analyzed. See figure 6, TF-30 Slot Wear vs Time. There was no problem with slot wear up to 2400 hours. The 900 and 1200 hour inspection could therefore be eliminated. Results from the analysis of some other parts were that the inspection limits were extended for the afterburner flame holder and inner duct, the 2nd and 3rd turbine valves, and the high compressor spacers.

Not only were there improvements to the scheduled maintenance process, but new problems were identified as well. A growth and twist were discovered on the 3rd turbine blade, and the compressor intermediate case was found to be cracking. These discoveries prompted the revision of the depot processing requirements.

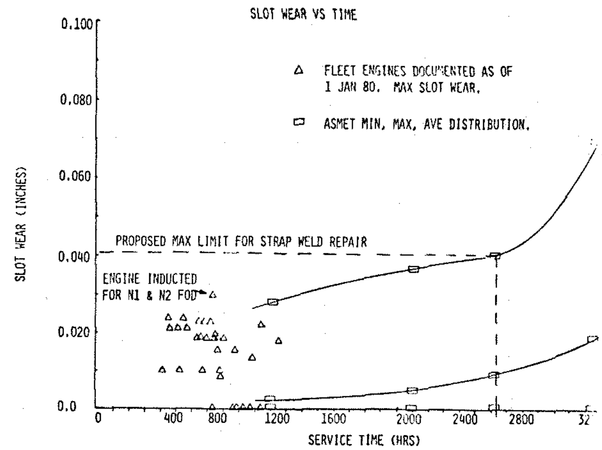

FIGURE 6

Age Exploration of Structures

Whereas systems and powerplant items are designed to be interchangeable, there is no simple way of replacing most structural elements. Repairs and even detailed inspection of internal parts of the structure involve taking the aircraft or equipment out of service, sometimes for an extended period. For this reason structural items are designed to last much longer than systems or powerplant components. Nevertheless, initial intervals in the structural inspection plan are only a fraction of this design life goal, both because of the consequences of a structural failure and because of the factors that can affect the design fatigue life in individual aircraft. These include variations in the manufacturing process, overloads encountered by individual aircraft, loading spectra that differ from the standards employed by the designer, environmental conditions causing corrosion, and accidental damage from foreign objects. In the structure division, the inspection program itself is the vehicle for age exploration. Thus, the initial intervals are intended not only to find and correct any deterioration that may have occurred, but also to identify the age at which deterioration first becomes evident for each structural item. The inspection findings and work performed are monitored by engineers, who record all the relevant findings on those aircraft designated as inspection samples. With this information there is a good basis for revising the age at which inspections of structurally significant items should begin in later delivery aircraft.

Structure Example. The F/A-18 is one of the newest aircraft being procured for the Navy. Its age exploration program is being established along with its maintenance program. 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. Additionally, actuarial information will be maintained on flight systems, engines and support equipment.

The statistical nature of the data collected and processed under this plan requires precise and complete standards of data collection data. Confidence limits will be established accurately only when the quality of the data is very high.

The plan will employ methods to determine the reliability characteristics of structurally significant items. This will include the establishing of cyclic thresholds, monitoring the physical condition and performance of each item, analyzing failure data, evaluating inspection findings to adjust task intervals and determining age-reliability relationships.

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

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 guage information. These data will be definitive and extremely valuable to the sustained structural age exploration program.

The F/A-18 makes extensive use of graphite/epoxy laminated structural elements with bonded joints, or advanced composite structure. The use of these materials must be considered as a technology with which the Navy has limited long-term experience. The large amount of advanced composite structure of the F/A-18 requires a means to determine the location and extent of existing interlaminar damage even though surface indications may be nonexistent. Recent advances in laser holography, acoustic emission and ultrasonic through transmission ("C" scan) are useful for this purpose and are being evaluated for use.

III. Summation: The On-Going Age Exploration Process

As has been presented, the initial age exploration requirements are based on default logic. As the program ages, the age exploration process allows the preventive maintenance requirements to change as the operating environment or the equipment changes. Therefore, the maintenance program becomes a dynamic system of changing preventive tasks, and adjusting intervals. Sustaining the RCM analysis then becomes the primary task of age exploration, through recommending revisions to the inspection intervals for certain tasks, and recommending product improvements through design modifications.

The Navy has not completed the RCM analyses on all of its aircraft. Preliminary estimates for the P-3 and F-14 scheduled maintenance however, indicate a savings of 48,373 man-hours per year for the P-3, and 32,574 man-hours per year for the F-14, using the RCM process. These savings are based on conservative maintenance requirements. With the application of age exploration, some requirements are expected to be loosened, and in certain cases, eliminated. Additional man-hour savings of 5% are considered attainable. The cumulative savings attributed to all fleet aircraft types are therefore extremely beneficial to the Navy.

To support a dynamic maintenance program, the Navy is continuously evaluating new analytical techniques and diagnostic systems that avoid wasteful equipment removals and inspections. As one Navy maintenance officer said, "We have to take a hard look at our inspection program, and we have to ask ourselves, 'are we over-inspecting?'" Age exploration is the tool that supports this concept.