A STUDY OF RELIABILITY CENTERED AIRCRAFT MAINTENANCE AND OPPORTUNITIES FOR APPLICATION BY THE UNITED STATES COAST GUARD

by

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ABSTRACT

This thesis is a study of the field of reliability-centered-maintenance (RCM), based on the proposition that RCM concepts and methodologies could be applied to improve the efficiency of the United States Coast Guard's aircraft maintenance program.

The thesis first examines the historical development of aircraft preventive maintenance programs and then explores basic reliability concepts. The central theme of RCM is that the design of any preventive maintenance program should be derived by structured decision processes and based primarily on quantifiable reliability characteristics.

The next phase of the thesis reviews the United States Coast Guard's aircraft maintenance program. An organizational model is proposed that would facilitate integration of RCM concepts into the existing program. In addition, a reliability study of one particular aircraft component is conducted as a demonstration of techniques, and as a typical problem area that should benefit from RCM concepts. In another technical example, a computer model is developed that could be used to track power plant reliability trends. Actual reliability data is used throughout.

The thesis concludes that there are significant opportunities for the application of RCM techniques to enhance the Coast Guard's aircraft maintenance program. These techniques should prove cost effective, assist with reliability goals, and enhance overall program effectiveness.

Thesis Supervisor: Professor Arnold I. Barnett
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ACKNOWLEDGEMENTS

This thesis is the culmination of a great educational experience. I dedicate it to my family, specifically my wife, Linda, and my children, Jill and Jim. We have been separated for the majority of this year and, at times, it has been arduous for us all. Despite the separation, they steadfastly provided their love, support, and encouragement in allowing me this opportunity. I express my heartfelt thanks.

I also would like to express my sincere appreciation to my thesis advisor, Arnold Barnett. His insightful comments and guidance were an invaluable aid to my learning experience.

I thank the United States Coast Guard for selecting me as a Sloan Fellow and giving me this unique opportunity. I hope that what I have learned during the preparation of this thesis, and in the program in general, might be of some benefit to the service.

Last, but not least, I would like to thank all of my classmates in the M.I.T. Sloan Fellows Class of 1989-1990 for their true friendship.

PREFACE

The preparation of this thesis has been an outstanding and invaluable learning experience. I initially became interested in aircraft preventive maintenance programs as a junior pilot in the Coast Guard, while stationed at Coast Guard Air Station Corpus Christi Texas in 1977. About that time, I began to wonder whether any mechanical device, aircraft in particular, could be "over-maintained". It was said, and I was of the opinion, that the Coast Guard "over-maintained" its aircraft.

For example, it seemed that we brought the old HU-16E "Albatross" seaplanes in for major maintenance every couple of months. We completely disassembled most of the systems, inspected, serviced, and generally "nurtured" the aircraft. After this period of "care", it often took a week or more to work out all the bugs that the maintenance had introduced. About the time that the aircraft again started flying reliably, with minimal in-flight discrepancies, it was time for another major inspection.

I wondered how the "experts" decided on the most efficient level of preventive maintenance. Of course, as a "nugget", I didn't dare question the wisdom of our procedures. I then decided to get directly involved in the program. I applied for, and was accepted into, the student engineering officer training program. I later became a full-fledged aircraft maintenance officer. Of course, I still had not reached the point where I had the necessary credibility to question our procedures. Even after 13 years in the aircraft maintenance field, I'm still not sure that I've reached that point. Nevertheless, in this thesis I will attempt to examine the logic and basis behind preventive maintenance. What are the best ways to maintain mechanical or electronic equipment? How does the Coast Guard maintain its aircraft? How <u>should</u> we should maintain our aircraft? Why? Are there improvements that can made?

In the preparation of this paper, I initially focused on two areas. First, I attempted to become reasonably knowledgeable of the basic concepts, and latest developments in the fields of reliability, preventive maintenance, and engineering related stochastic analysis.

In the second part of my study, I conducted an overall review of the United States Coast Guard's aircraft maintenance management system, in search of opportunities for improvements in quality and efficiency through the application of some of these previously learned techniques.

Finally, I will suggest some models for the application of reliability-centered-maintenance (RCM) techniques to the Coast Guard system.

Chapter 1 presents a short history of the development of preventive aircraft maintenance and outlines some of the basic concepts and considerations that should go into making decisions about the design of a preventive maintenance program. To provide background material, I have also tried to summarize what I have learned about the relationships between the major organizations that have been instrumental in developing today's aircraft maintenance standards.

Chapter 2 addresses reliability-centered-maintenance (RCM) concepts specifically. It explains the meaning of RCM and describes the basic building blocks of the field. Several basic actuarial analysis techniques are presented, along with a short synopsis of decision logic methods for deciding which tasks should be a part of the maintenance program. Further and more detailed information on these topics is available from a variety of sources, many of which are listed as references.

Chapter 3 is an overview of the US Coast Guard aircraft maintenance management system as it presently exists, and a view to the future. This overview will hopefully provide the reader with enough background to judge the wisdom and applicability of some of the later recommendations.

Chapter 4 addresses the application of specific RCM techniques to the Coast Guard system and includes a discussion of some important considerations in that application.

Chapter 5 develops that application in a more detailed manner and suggests an organizational model for implementation.

Chapter 6 is a sample analysis of a hydraulic pump used on the Coast Guard's HU-25 "Falcon" fanjet aircraft. This analysis includes a range of possible techniques and tools that might be useful. All of the statistical techniques are very basic and amenable to practical use. Real data was used in hopes that the findings might be put to practical use.

In Chapter 7, I will present an example of a reliability trend monitoring model that I feel could be useful to the Coast Guard program.

Based on what I have learned during my studies, and the research that I have done in the preparation of this thesis, Chapter 8 will be my overall impression of the efficiency of the Coast Guard aircraft maintenance program. In this chapter, I will also attempt to point out any areas that I believe may present opportunities for efficiency and reliability improvements.

Throughout my study, it was slightly surprising to learn that the design and modification of preventive maintenance programs is still far from being an exact science. It appears to me that this field of preventive maintenance stands to benefit greatly from the application of the more recently developed operations research and advanced information systems tools. Unfortunately, I did not have the time available to become familiar enough with some of these techniques to intelligently suggest areas for application.

The phase of the thesis in which I reviewed the Coast Guard maintenance program was particularly difficult. I attempted to take an objective look at the systems that are presently in place, or are planned for the near future. Having been a part of this "system" for approximately 13 years, I tried to view "traditional" methods only according to their effectiveness, both from economic and safety standpoints.

In summary, I have attempted to recommend additions and changes that might give the quickest and most effective returns from a cost benefit standpoint, without diluting the potential for long term improvements in reliability and safety.

CHAPTER ONE

AIRCRAFT MAINTENANCE MANAGEMENT
AND
RELIABILITY

EARLY DEVELOPMENT

To provide a general background from which to consider the development and application of a reliability centered maintenance (RCM) program, I think it useful to discuss the evolution of preventive aircraft maintenance.

The following information summarizes my personal experiences in the aircraft maintenance field, plus numerous interviews with aircraft maintenance managers and engineers, and an extensive literature search.

Historically, aircraft preventive maintenance programs were based on what the "experts" felt was necessary to provide the required level of safety and reliability. Their advice and decisions were based on good judgement and years of experience. They had survived to be successful in the maintenance field and had subsequently become respected. Experience was considered to be the best teacher and most of the development and evolution of preventive maintenance programs was done somewhat intuitively.

Although some analytical work was performed on the reliability of specific components, there seemed to be minimal reference to logical, scientific, or statistical considerations. "We've always done it that way," was an oft heard phrase.

Since early flight was considered quite risky, critical components were inspected or replaced quite frequently to ensure reliability. Components that were experiencing unacceptably high failure rates were inspected, overhauled, or replaced more frequently in an effort to improve their reliability, and thereby, safety.

When a new aircraft was initially brought into service, the design of the preventive maintenance program for the aircraft was made extensive enough to satisfy the Federal Aviation Administration (FAA) and generally developed on the assumption that this airframe, and its systems, would exhibit reliability characteristics closely approximating those of previous, similar systems. The manufacturer's recommendations were usually taken by the operators as the gospel. Often there was no in-service reliability or failure data available to justify chosen intervals or procedures.

Another consideration used to determine which tasks would comprise the preventive maintenance program was what could be done, instead of what should be done. The feeling seemed to be that, if a little bit of preventive maintenance was good, then a lot, must be better. In other words, within certain limits, an organization should do as much preventive maintenance as it could afford.

It was assumed that reliability, and therefore safety, was some function of the frequency of periodic inspections and overhauls. Little concern was given to the actual consequences, or lack thereof, of any particular failure.

Due to the many major technological developments that occurred in the 1950s and 1960s, the complexity of aircraft and aircraft systems increased dramatically. Modern design and manufacturing techniques also greatly improved inherent reliability.

Given the previously discussed procedures for developing aircraft preventive maintenance programs, the new aircraft systems were maintained similar to the old, often without regard to such factors as improved reliability, additional redundancy, or criticality. With increased system complexity, maintenance costs began to quickly accelerate.

As commercial aviation blossomed in the late 1950s, commercial operators and the FAA started collecting and analyzing actual reliability data. They slowly began to realize that the reliability of aircraft systems, and the frequency of inspection and overhaul intervals were not necessarily directly related.

In 1960, a task force, comprised of representatives from both the FAA and the airlines, was formed to investigate possible methods of insuring and improving aircraft reliability. Initial efforts concentrated on analyzing and improving the reliability of powerplants in particular. The results of this task force were published in an FAA document which stated that the development of this program was towards the control of reliability through an analysis of the factors that affect reliability and to provide a system of actions to improve low reliability levels when they exist.[1] The application of science to the problem of aircraft preventive maintenance program design had begun in earnest.

By 1965, studies within the airline industry began to show that overhauls of complex equipment had little or no quantifiable effect on reliability. With the design and development of the Boeing 747 as the first wide bodied, turbine powered aircraft, concern was developing over the high level of reliability necessary to insure the safety of the large number of passengers that this aircraft would be transporting.

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1. FAA/Industry Reliability Program, (Federal Aviation Administration), Nov. 7, 1961. p. 1.

In July of 1968, a "Maintenance Steering Group" (MSG), made up of representatives from the FAA, the airlines, and the aircraft manufacturers, produced a handbook that could be used for the development of an approved maintenance program for the Boeing 747.[2] This document, titled "Handbook MSG-1, Maintenance Evaluation and Program Development", included decision logic procedures for the development of an acceptable preventive maintenance program and, since it was aimed specifically at the Boeing 747, it contained many items specific to that aircraft.

In 1970, a similar group was formed to update this publication and provide a more general and universally applicable format. When this revision was published, it was renamed as the "Airline/Manufacturer Maintenance Program Planning Document" MSG-2.

By 1979, almost a decade after the publication of MSG-2, the industry decided that enough had changed in the RCM field to require another update of the document. A composite task force was again formed. This group was more diverse and consisted of representatives from the Air Transport Association (ATA), the FAA, the Civil Aviation Authority of the United Kingdom (CAA/UK), the US Navy, U.S. and foreign airlines, and various aircraft and engine

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[2] Joseph A. Pontecorvo, "MSG-3-A Method for Maintenance Program Planning", paper #841485, Society of Automotive Engineers Inc. (SAE), 1984, p. 1.

manufacturers from throughout the world.[3] Although the result of their work was based on the same fundamental concepts as the previous handbooks, the new manual, MSG-3, was designed to be somewhat more straight forward and user friendly. This updated version also recognized several new regulations that were in effect, particularly those dealing with the structural damage tolerance requirements published by the FAA in Federal Aviation Regulation (FAR) 25.571.

In 1987, after applying the MSG-3 analysis to several new aircraft, the lessons learned in the previous 8 years were again used to update the manual, this time in the form of "Revision 1 to MSG-3". This revision became effective on March 31, 1988 and, as of this writing, has become an international standard for the development of aircraft preventive maintenance programs.

A flavor of the concept behind this publication can be found in the beginning paragraph of the preface to the latest revision. It states, "Airline and manufacturer experience in developing scheduled maintenance programs for new aircraft has shown that more efficient programs can be developed through the use of logical decision processes."[4] These "logical decision processes" are actually decision

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[3] Ibid., p. 2.

[4] Airline/Manufacturer Maintenance Program Development Document (MSG-3), (Air Transport Association of America, 1988), p. v.

trees that can be used to select exactly which tasks should comprise the preventive maintenance program.

RISK MANAGEMENT

In the area of risk management, the Federal Aviation Administration (FAA) has set the goal of designing and maintaining aircraft such that loss of life will be "extremely improbable". They have further defined this risk as "extremely improbable", if loss of life occurs in only one in every one billion flights. To put this into perspective, at the present level of air carrier activity in the United States system, it is estimated that it would take 200 years to achieve one billion flights![5]

This overall level of reliability (10^{-9}) may seem to be unattainable. Thus far, it has not even been approached in the overall record of commercial aviation.

However, statistical analysis of the dual engine failure probabilities of twin engine aircraft, now certified for extended overwater operations, has shown that these goals are, at least in theory, attainable. These analyses have been based on the failure rates of the most modern high-bypass turbojet powerplants. Predicted reliability has recently allowed certification of twin engine transport-

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[5] F. Stanley Nolan and Howard F. Heap, Reliability-Centered Maintenance (Dolby Access Press, 1978), p. 340.

category aircraft to conduct extended overwater operations for up to 180 minutes. Previously, only aircraft with three or more engines were certified for this type operation.

The key to proving this high level of reliability is the assumption that redundant systems, such as dual engines, are statistically independent. Of course this is often not the case. For instance, Eastern Airlines Flight 855, a Lockheed L1011, lost power on all three engines over the Bahamas due to a maintenance procedural error committed prior to the flight on all of the engines by the same mechanic. Another non-independent possibility is fuel. Fuel systems are independent, but the fuel tank source is not. Dependent factors such as these make it highly unlikely that this desired level of reliability will ever be approached.

ECONOMIC CONSIDERATIONS

Before considering the actual design or modification of a program of preventive maintenance, we might first consider the reasons that a program exists in the first place.

The dedication of resources to preventive maintenance is an investment, similar in many ways to the variety of other investments that any typical organization must make to be successful. From an economic point of view, theoretically, all rational investments are made assuming that they will show some level of positive return, either in the long or short term. Therefore, techniques similar to those used in the financial management community might be applicable to these resource allocation decisions.

Also similar to typical financial investment decisions, preventive maintenance analysis often contains variables which can only be considered under conditions of uncertainty. As previously mentioned, many of the variables associated with flight safety, and the risks that exist in aerial flight, are not easily quantifiable. The monetary loss of an aircraft, passengers, and crew due to mechanical failure is quantifiable only if assumptions are made which might place an economic value on the human life involved. If these assumptions were made, the high value that would traditionally be put on human life would probably not be an active constraint on the allocation of resources to preventive maintenance. Therefore, other constraints would take effect and drive the decision.

Fortunately, the cost functions that bear upon the problem are becoming more readily quantifiable. With the evolution of modern data collection methods and management information systems, the costs of operational delays, cancelled flights, passenger approval ratings, load factors, overhauls, etc., are predictable with a relatively high degree of accuracy.

Even assuming questionable accuracies and conditions of uncertainty, the rational investment of resources should produce a positive return. That is, the economic cost of doing the maintenance should be less than the return derived from the results. For maintenance that does not affect safety of flight, these decision parameters are often quantifiable. For example, there are direct and indirect costs for the delay or cancellation of a flight. The direct variable costs such as loss of revenues and arranging alternate transportation for the passengers are easily quantifiable. However, the indirect costs, such as the long term ones reflecting passenger dissatisfaction, are blurred and modified by a number of other variables.

Neglecting for a moment aircraft safety, which is very difficult to quantify in either risk or economic terms, maintenance decisions that clearly do not affect safety should be based on a cost-benefit analysis. For variables that are unknown or uncertain, approximations can be made to design models which behave closely in line with the actual system. Sensitivity analysis will often show that only general orders of magnitude are needed to reach near optimum decision points. Some practical examples of these concepts will be demonstrated in Chapter 6.

PREVENTIVE MAINTENANCE GOALS

In the long run, preventive maintenance can only attempt to accomplish one thing. At the limit, it can only assure inherent design reliability. No amount of preventive maintenance can improve on a component's inherent reliability.

Figure 1-1 is an illustration of this concept. Without redesign, the widget can never be more reliable than some inherent level. This is due to the fact that there are virtually no items that improve their reliability or increase their resistance to failure over time. In the short run there are exceptions to this. Such is the case of items exhibiting "infant mortality" characteristics. An initial increase in reliability will occur over time, but eventually the curve will, at best, become level.

In other words, neglecting items demonstrating "infant mortality" characteristics, if an item was replaced or inspected so frequently that the interval approached 0, the inherent reliability would still be the best that was obtainable. In fact, as a general rule, very few maintenance tasks, such as overhaul or rework even recover the initial, "like new" reliability levels.

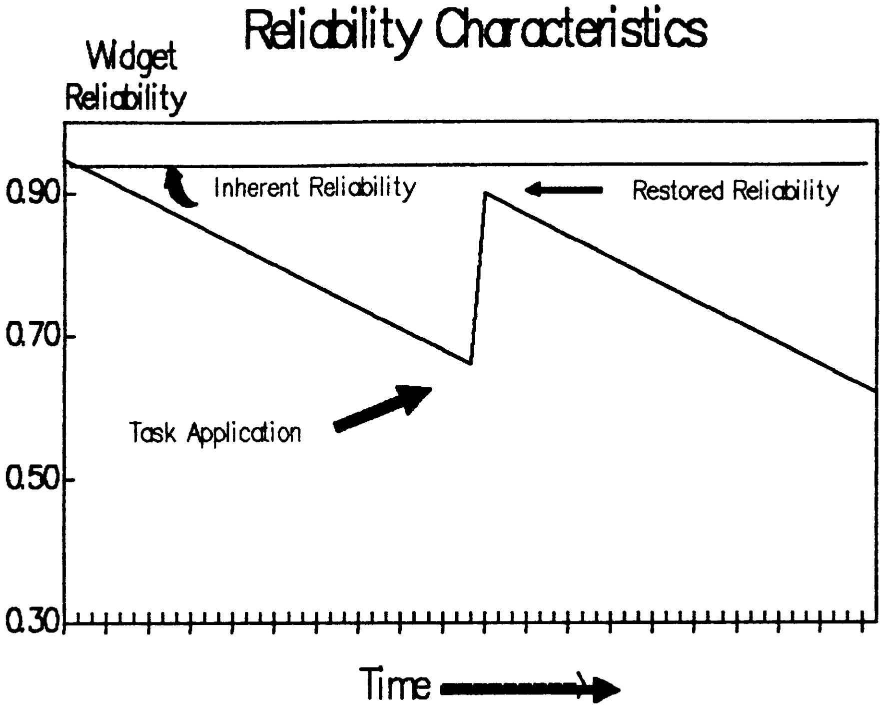

Figure 1-1

With that in mind, then the goal of a preventive maintenance program should be to accomplish <u>only</u> those tasks necessary to maintain some <u>desired</u> level of inherent performance and reliability, extend useful life, or maintain cosmetic appearance. The phrase, <u>desired</u> level of performance and reliability, is included to recognize the fact that potential inherent performance and reliability may, in some cases, be excess to requirements. Cosmetics are included because, in the airline industry, a nice looking aircraft will elicit indirect long run cost savings by maintaining passenger approval ratings and, therefore, load factors.

MAINTENANCE TASKS

The interaction between the maintenance program and the hardware, is the actual application of the maintenance task. The task is the vehicle for execution and, therefore, is a key to success.

Two important descriptors that will be used extensively in determining maintenance tasks and their selection, are applicability and effectiveness. It is extremely important when applying RCM concepts to an aircraft maintenance program that these words be clearly understood.

A maintenance task is said to be applicable if, given the failure characteristics of the item to which it is applied, the task is capable of improving on the reliability that the item would exhibit without the application of the task. In other words, it does no good to do maintenance if the task is incapable of: (1) Detecting an actual or potential failure, (2) Detecting reduced resistance to failure, or (3) Improving the present resistance to failure.

Additionally, a task is said to effective if it has the ability to reduce the failure rate of an item to some required or acceptable level. In other words, assuming it will be applicable, will it be good enough to provide acceptable end results? If there is not a task which is both applicable and effective, then item redesign may be necessary.

In actual practice, maintenance tasks are also segmented into two distinct divisions: scheduled and unscheduled. Scheduled tasks refer to those that are planned, in an effort to reach the preventive maintenance goals stated above. Unscheduled tasks are those initiated by some type of failure. Unscheduled tasks may also assist in reaching reliability goals, particularly in the case of redundant systems.

First, let us examine unscheduled tasks in more detail. As the name implies, the timing of unscheduled tasks is not subject to the direct control of management and, therefore, to any improvement in program design efficiency by reliability centered maintenance methods. Also tasks of this type are always applicable and, hopefully, effective. If not, equipment redesign is required. Of course, the actual procedure and scheduling of the repair itself is subject to management control and, therefore, efficiency gains can be derived on that basis. Those decisions are usually best made at the time of occurrence when the maximum amount of data is available for review. Some prior planning and considerations can be made, and manuals such as a minimum equipment list (MEL), or a configuration deviation list (CDL) can assist in quickly arriving at safe, consistent decisions. The goal of a good reliability program is to minimize the frequency of unscheduled maintenance tasks. A good maintenance management information system will also credit the scheduled maintenance requirements with completion, if the unscheduled task fulfills those requirements.

This thesis will focus on the design of the preventive, or as they are more commonly called, scheduled maintenance tasks.

TASK TYPES

Nolan and Heap described four basic scheduled maintenance task types.[6]

1) Scheduled inspection of an item at regular intervals to find any potential failures.

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[6] Reliability-Centered Maintenance, p. 50.

2) Scheduled rework of an item at or before some specified age limit.

3) Scheduled discard of an item (or one of its parts) at or before some specified life limit.

4) Scheduled inspection of a hidden-function item to find any functional failures.

This is a useful structure but seems to include, under one definition, tasks which encompass several different type procedures.

A more specific segmentation under the scheduled maintenance task classification might include the following:

Service
Lubrication[7]
Inspection
Rework
Overhaul
Scrap (discard)

This segmentation does not completely align with standard air carrier industry usage, but more closely matches the

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[7] Service and lubrication are normally grouped under a single, combined classification due to their similarities.

present U.S. Coast Guard aircraft maintenance management system.

Although not without exception, the above task descriptions are generally listed in the order of increasing cost or complexity. The specific definitions of these scheduled tasks are generally self-evident, but several deserve further discussion.

The difference between a rework and an overhaul task is often blurred. A rework task generally requires the removal of a specific component from the airframe, and the repair or replacement of the parts of that component that are unserviceable or are approaching unserviceability. Another more descriptive term that is often applied to rework is inspect-and-repair-as-necessary (IRAN). In contrast, an overhaul generally requires a more extensive inspection and the return of all parts of the component to a "like-new" or "near-new" condition.

The category of inspection can be further segmented into, operational checks (fault finding), functional checks (quantitative check comparing performance against established limits), visual inspections, and non-destructive inspections. Although most preventive maintenance inspections are non-destructive, the term non-destructive inspection or NDI, in industry vernacular, has come to describe methods such as radiographic, eddy current, ultrasonic, dye penetrant, and magnaflux.[8] Figure 1-2 depicts the relationship between the different task categories.

With that background, the next chapter will review the characteristics of reliability and present a short synopsis on some of the concepts and tools available within the field of reliability centered maintenance.

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[8] Another term, commonly used in the industry, is non-destructive testing (NDT).

CHAPTER TWO

RELIABILITY

A DEFINITION OF RELIABILITY

The dictionary defines reliability as the extent to which an experiment, test, or measuring procedure yields the same results on repeated trials.[1] However, in the field of engineering, a more specific definition is necessary. There have been several technical definitions of reliability proposed, but the most common, and the one found in a variety of maintenance and engineering literature, is: The mathematical probability that an item will survive a given operating period, under specified operating conditions, without failure.[2]

To expand upon this definition slightly, I would construe survival without failure to mean that the item continues to function (or maintains the ability to function, if not in actual operation) at a level that meets some specified level

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1. Webster's New Collegiate Dictionary, (Springfield:Merriam Company, 1974). p. 976.

2. Nolan and Heap, p. 40.

of performance. This survival need only occur within a certain, bounded set of reasonable environmental conditions.

RELIABILITY CENTERED MAINTENANCE

The term, reliability centered maintenance is a broad one that has come to describe a system that attempts to base maintenance decisions on their proven or predicted ability to maintain or improve equipment reliability. Ideally, managers of reliability centered maintenance programs apply operations management style analysis, using objective logic and statistical techniques, to arrive at optimum program designs from a standpoint of reliability and efficiency. This chapter will provide a brief overview of some of the more important techniques that are in use today.

DESIGNER-MAINTAINER RELATIONSHIP

The relationship between the designer and the maintainer is a very important one. Their dependence on one another is crucial to a successful and safe product. As previously pointed out, preventive maintenance cannot provide reliability beyond that which is inherently designed into an item. Additionally, components will seldom, if ever, approach their inherent reliability levels if not properly maintained. The designer should consider the preventive maintenance requirements in the initial design. Quality is today's manufacturing buzz word and reliability is often the most important aspect of that quality. A high level of reliability is emerging as an increasingly necessary property of a marketable, quality product. Additionally, designers are taking into account the maintainability factor in their initial design. This is particularly true of modern aircraft systems. Improvements such as accessible inspection ports, tell-tales, and potential failure indicators are becoming much more common. This trend bodes well for both maintainers and designers alike.

MAINTENANCE INTERVALS

Maintenance intervals are the quantitative measure of operational experience or environmental exposure that is normally allowed to occur between the accomplishment of preventive maintenance tasks. The most common units used to describe these intervals are flights, flight hours, operating hours, cycles, landings, or any of the standard calendar measures. In special cases, such as exposure to harsh operating environments, spectrum hours may be used to take into account possible accelerated aging characteristics. Also generally included as maintenance intervals are special inspection or event-oriented intervals. These intervals are defined by the occurrence of a special event, such as a hard landing, an overspeed, flight through heavy weather, etc.

HARD-TIME ITEMS

Hard-Time items are generally known throughout the industry as those components requiring replacement with new items at a specific interval. Usually these intervals are based on hours or cycles of usage. These type of items are typically those that are non-redundant, critical in nature, and virtually no positive failure rate is acceptable. Items such as turbine disks are frequently assigned hard times based on data obtained from laboratory testing done to predict failure. After some sample data is obtained, the reliability function is estimated, and suitably high safety factors are then applied in an attempt to establish, with a high degree of confidence, that an extremely improbable chance of failure exists in actual usage. After removal, hard time components are typically scrapped or discarded.

ACTUARIAL ANALYSIS TECHNIQUES

When applying actuarial analysis techniques to reliability centered maintenance programs, we are dealing in the field of inferential statistics. This is a very important concept to keep in mind throughout any RCM analysis. That is, we are using statistical methods to estimate the characteristics of some population based on sampling results.

The maintenance organization does not have data to describe the in-service equipment, therefore, we must predict its behavior based on previous experience. This has some very interesting and important implications. The sampling techniques, although they typically consist of reported failures, can introduce significant biases into the analyses. Failures of a particular component can be induced by associated components that are operating out of established limits, or they may even be caused by a specific maintenance action or inspection. Therefore, it is very important to separate correlation from causation.

Actuarial analysis can describe and predict the behavior of a population based on a reasonable sample, but it can only assist in establishing causation. For example, the failure rate of a particular pump may begin to show a high correlation with age, when, in fact, a change in operating procedures has precipitated the increase. Experience, in-depth technical knowledge, and good judgement are still required to execute an effective program and solve reliability problems.

Before we begin to discuss several useful actuarial analysis techniques, we should first recognize some limiting factors. In the endeavor of designing an aircraft maintenance program, the ultimate goal is to establish an efficient system which provides no failure data to analyze. When analyzing critical items such as wing attach points, we hope there will never be any failure data available. In fact, one should expect that if a critical component does fail, the fleet will most likely be grounded if a specific cause is not determined, or if a solution to the problem is not immediately available. This means that the initial design of critical components is the key to aircraft safety. Also, since all items will eventually fail, the allowable service life must be short enough to make the failure of these components extremely improbable.

One of the most important pieces of information we might derive for any component is its reliability function. This can be expressed mathematically and is typically approximated by one of several methods. As a means of predicting when the probability of failure rises to a certain level for a particular item, the reliability function allows the analyst to design inspection or replacement intervals to avoid high failure probabilities with some desired level of confidence.

In analyzing critical items, a factor that often limits the usefulness of statistical analysis is a very small data base from which to glean failure data. In this situation, prototype and laboratory testing to failure, do provide some data on which to establish initial maintenance requirements such as safe life limits. But, if field failures begin to occur, the equipment is quickly removed from service and redesign is accomplished.

DESCRIPTIVE STATISTICS

Simple descriptive statistics are the most common and most easily derived set of measures available to the analyst; however, their usefulness is quite limited. Measures of central tendency, such as mean, median, and mode, can be useful in describing such parameters as Mean Time Between Failure (MTBF) and Mean Time Between Removal (MTBR). Measures of dispersion such as standard deviation (sigma) can also be informative in describing, for instance, the levels of confidence in certain measures.

However, extreme caution must be exercised in the use of these sort of descriptive statistics. In these types of analyses, a Gaussian or normal distribution is most often assumed and this is not always the case in reliability. Also, depending on the size of the sample, unusual and infrequently occurring values, often called outliers, can significantly skew the analyst's results.

Additionally, using these measures alone, does not take into account hard-time intervals that can disguise or misrepresent the actual characteristics of a particular component. For instance, a component, whose frequency of failure is normally distributed, might exhibit a lower MTBF if a life limit were established which did not allow components to operate beyond a certain age, and therefore, removed components that would have otherwise remained in service and contributed operating time to raise the MTBF.

These statistics are still useful as a means of failure trend analysis and their simplicity makes them very amenable to computer generation on a real time basis. Thresholds, based on descriptive statistics, can be established that will automatically alert the analyst to changing reliability trends.

SURVIVAL CURVES

A basic tool for the analysis of age-reliability characteristics is the survival curve. A survival curve is a graphic representation of the mathematical probability that a component will survive to some given age level. The probability is generally expressed as a number between one and zero and plotted on the ordinate. Percentages are also sometimes used. The age can be expressed in any applicable unit (eg. hours, cycles, landings, etc.) and is generally plotted along the abscissa. The unit selected to represent age is normally that which has the highest correlation with survival, but may be represented by different units on different curves for the same component. The curves are typically derived from data gleaned from fleet experience. If, for instance, during data analysis, it was discovered that by the time the first component reached an age of 1000 hours, one half of the population had failed, then the probability of survival at that point on the curve would be 0.5 or 50%. The mathematical expression that might be formulated to describe the resultant curve is often referred to as the reliability function. Figure 2-1 is the survival curve for the Pratt and Whitney JT8D-7 turbine engine of the Boeing 737, based on 1974 data.[3]

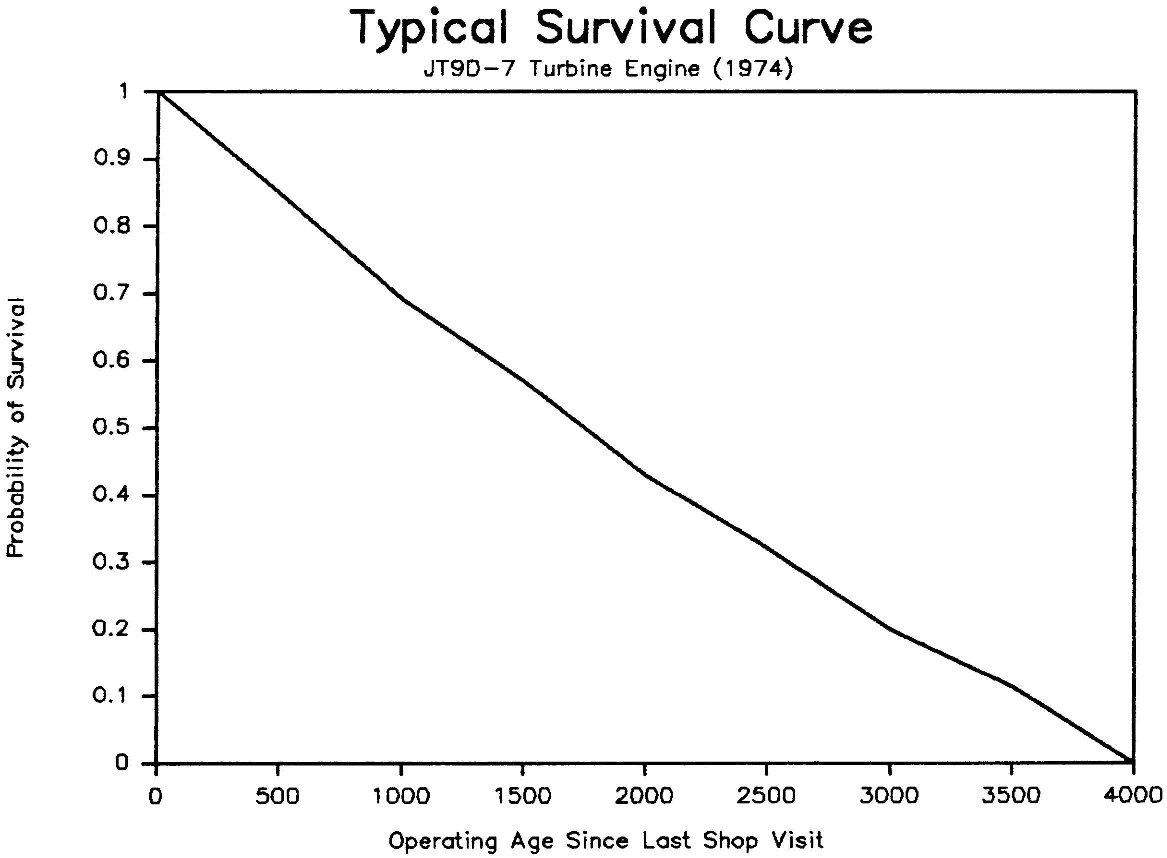

Figure 2-1

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[3] Source of figure 2-1 data is United Airlines Reliability Department.

CONDITIONAL PROBABILITY CURVES

A more useful tool, in describing the reliability versus age characteristics of a component, is the conditional probability or probability density curve.

The main difference between this curve and a survival curve is that, unlike the survival curve, this curve depicts the conditional probability of failure for a component entering a given age interval. This means that the item must first survive to begin the interval to be counted in the data. Therefore, this curve measures a more continuous probability of failure. This requirement of previous interval survival results in the use of the term "conditional." The ordinate value is the probability that an item entering a specific interval will fail during that particular interval.

This type of curve is frequently referred to as a wear-out curve. An item is said to exhibit wear-out characteristics if it shows an increasing conditional probability of failure with age. Figures 2-2 through 2-7 depict the six shapes which are most commonly encountered in actual practice. It should be noted, that the curves exhibiting an increased conditional probability of failure with age, comprise only a total of about eleven percent (11%) of typical aircraft items.[4] One of the many uses of this curve is the prediction of the effect of various life limits on failure rates.

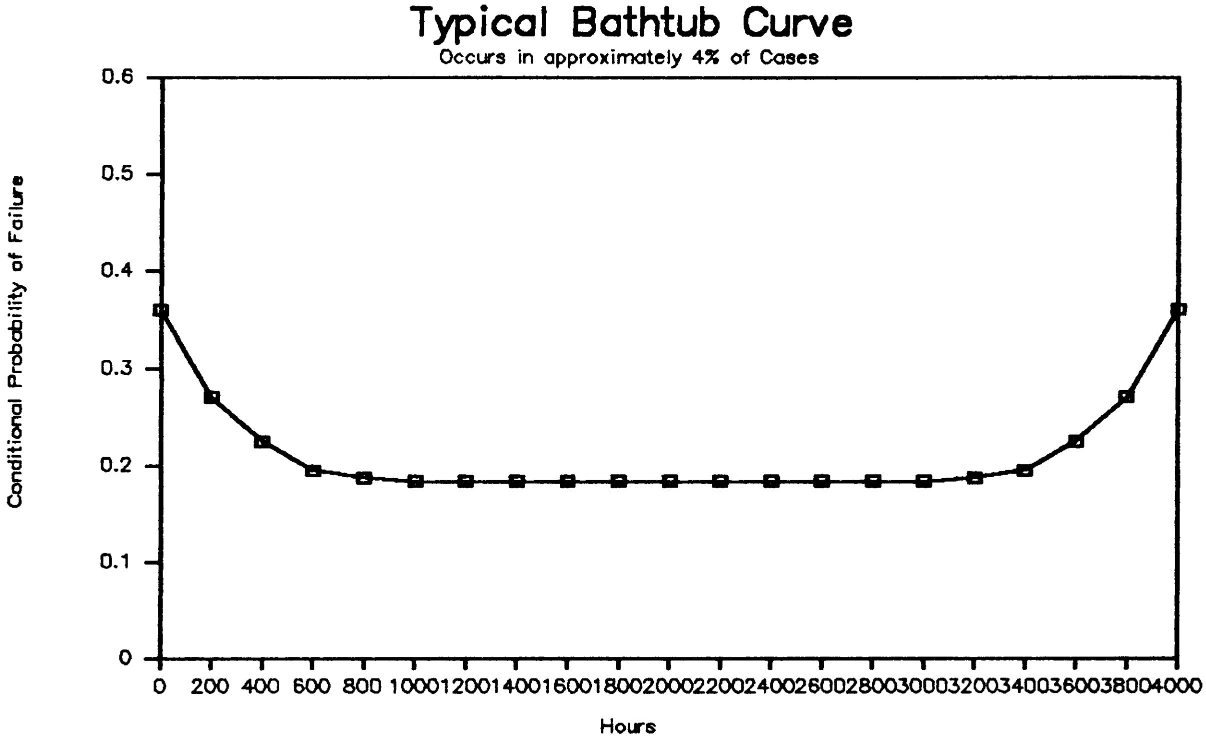

Figure 2-2

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[4] Nolan and Heap, p. 46.

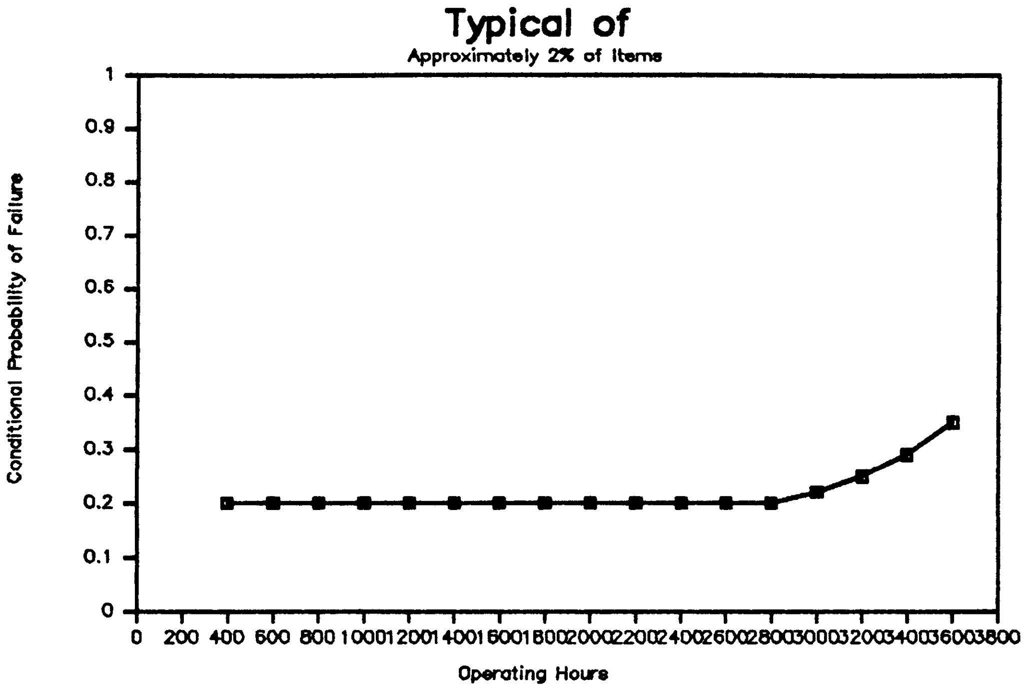

Figure 2-3

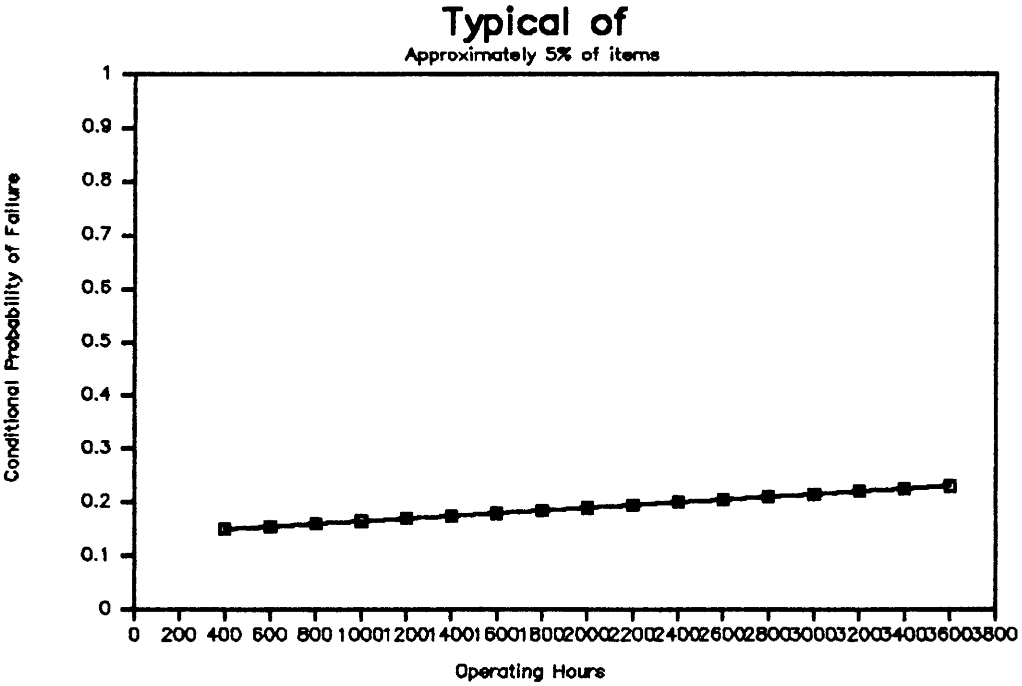

Figure 2-4

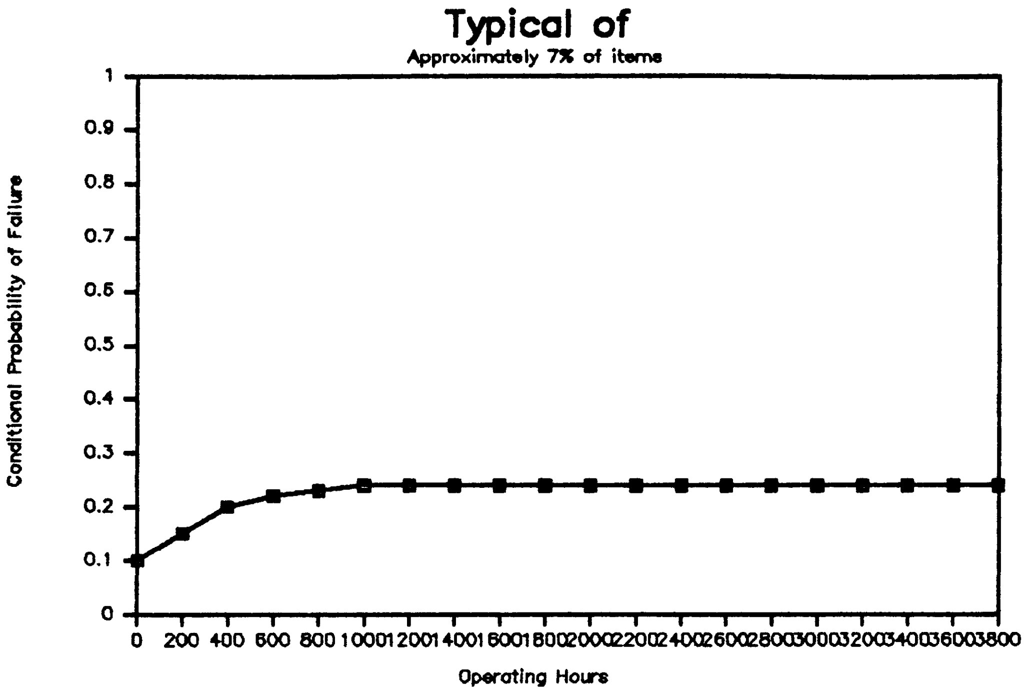

Figure 2-5

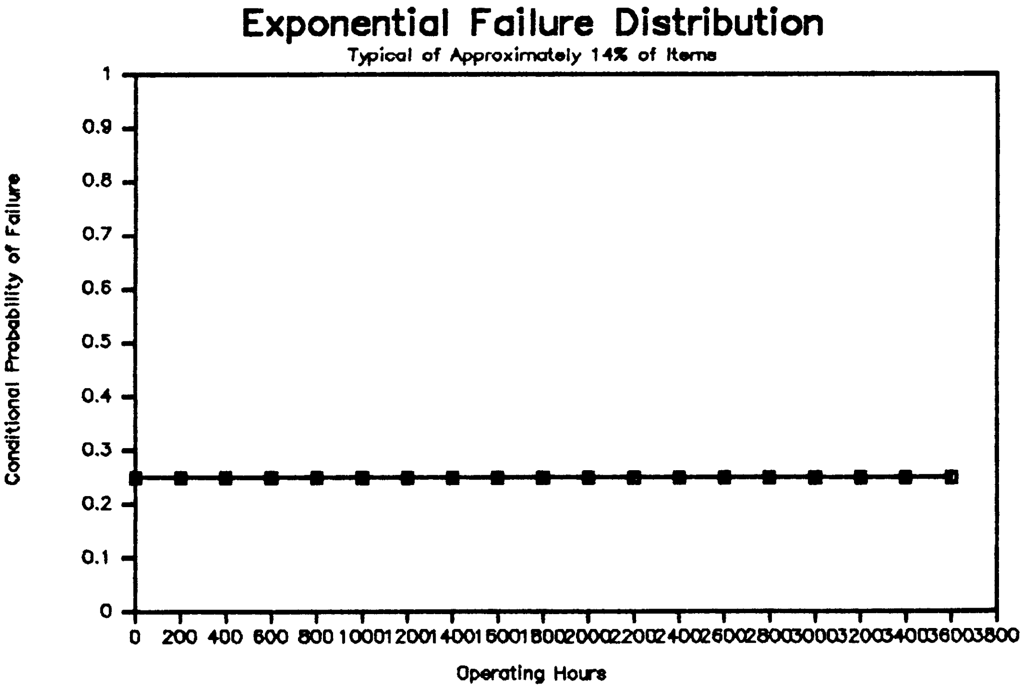

Figure 2-6

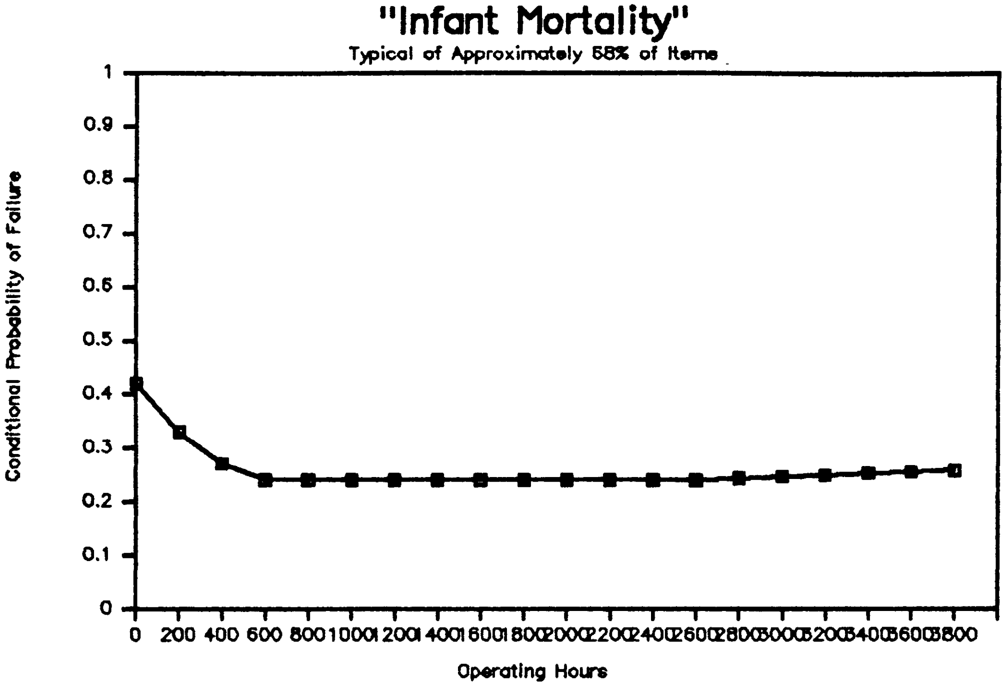

Figure 2-7

NORMAL (GAUSSIAN) DISTRIBUTION

The normal survival distribution (bell curve) is frequently encountered in reliability applications. It is typically characteristic of simple components which generally exhibit only one failure mode.[5] It can be used in its basic form if the mean of the data is positive and the standard deviation is small in relation to the mean. If this is not the case, then a normalized truncation of the distribution function should be accomplished. Normalized

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[5] Ibid., p. 415.

truncation will not be covered in this thesis, but standard formulas for truncation are available.[6]

EXPONENTIAL DISTRIBUTION

The exponential distribution is typically characteristic of the conditional probability of survival curves describing complex types of mechanical equipment and most electronic components. The exponential reliability equation is:

$$R(t) = e^{(-zt)} \quad \text{where} \quad t >= 0 \quad \text{and } z > 0.$$

t = time $\qquad$ z = descriptive constant

The first derivative of this function describes the survival density function and is represented by the function:

$$p(t) = -\frac{dR}{dt} = ze^{(-zt)}$$

The hazard rate, or conditional probability of failure, is represented by:

$$n(t) = z$$

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[6] H. L. Resnikoff, Mathematical Aspects of Reliability, (R&D Consultants Company) n.d., p. 41.

The fact that the hazard rate is a constant with this distribution is quite useful. It can be used to separate the increasing hazard rate items from the decreasing hazard rate items and, therefore, is a decision point for many maintenance policy decisions. During analysis it is be useful to use semi-logrithmic graph paper which, if the data approximates the exponential function, results in a linear plot.

Of course, some items exhibit both increasing and decreasing hazard rates over time. (See Figure 2-2 as an example.) In these cases, the areas exhibiting similar characteristics should be handled as separate segments.

WEIBULL DISTRIBUTION

The Weibull distribution was introduced in 1951 by the Swedish statistician Walloddi Weibull in order to describe the tensile strength of steel.[7] In the field of aircraft component reliability it has been found to closely approximate the survival curves of items which exhibit some degree of "infant mortality". That is, relatively high probabilities of failure in the early life stages, followed by a relatively monotonic conditional probability of failure thereafter. The low time data resemble the normal

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[7] *Ibid*., p. 44.

distribution but quickly approach linearity with either increasing of decreasing trends. The survival distribution or reliability function is expressed as:

$$R(t) = \exp(-zt^{s}), \qquad z > 0 \qquad s > 0$$

The probability density function is expressed by:

$$p(t) = -\frac{dR}{dt} = zst^{s-1}\exp(-zt^{s})$$

The hazard rate or conditional probability of failure is expressed by:

$$n(t) = zst^{s-1}$$

The Weibull distribution is frequently used in more the rigorous analyses, particularly for determining whether, based on a relatively small sample of data, a component exhibits a required level of reliability. The Weibull function is not unlike the normal distribution, but in addition to a dispersion parameter, it also contains a shaping parameter.

The actual analysis of data is normally done by plotting the data on Weibull probability paper. The ordinate of this graph paper is a double natural log scale of the percent failed, while the abscissa is a single natural log scale of the time to failure. If the plotted data fall into near linearity, then a Weibull function is indicated and subsequent predictions can be made.

DATA COLLECTION

The challenge in designing a system for reliability data collection seems to be the conflict of goals within most maintenance management information systems. Most systems are designed to provided information primarily for the following reasons:

1) To insure that the required maintenance was done and properly documented.

2) To act as a tickler (reminder) system to alert maintenance personnel to upcoming requirements.

3) To allow efficient scheduling by maximizing maintenance opportunities during non-flying availability and to package tasks into efficient groupings.

4) To allow the detection of increasing failure rate trends.

The design of a system to meet these needs may not provide the correct information necessary to conduct efficient RCM analysis. Ideally, a reliability test program is established from which data will be available from a set of components that begin operation at time zero ($t=0$) and records the time (t_f) at which failure occurs. The entire population continues in the test program until the program is terminated or all units have failed. Unfortunately, seldom is it feasible to conduct such tests.

However, given data such as time at removal, along with reason for removal, approximations can be made to plot reasonable survival (reliability) curves and derive reliability functions.

To monitor overall reliability trends, data such as in-flight engine shutdowns per thousand hours, mechanical delays or cancellations per hundred departures, or pilot reports per hundred landings may be useful. This type data is often the "bottom line" for commercial carriers. If undesirable trends develop, further research and analysis of secondary data may indicate areas for improvement.

It is tempting to design a system which will collect a nearly complete set of aircraft and system performance data. However, the task of the collection process itself can easily become a significant drain on resources. For simple tasks, the mechanic may spend more time documenting the maintenance than actually performing the task. Ideally, a system should only collect that data which will be useful and can be justified from a cost-benefit standpoint. In my experience with aircraft maintenance, very few systems collect too little data.

MSG-3 TECHNIQUES

As discussed in Chapter 1, the Airline/Manufacturer Maintenance Program Development Document, MSG-3 (Revision 1) forms the basis for the latest techniques for designing an aircraft preventive maintenance program. The manual is divided into two sections.

The first is general in nature and deals mainly with objectives and specific administrative requirements for the preparation of the Maintenance Review Board's report recommendations.

Section two of the manual is more detailed in nature and contains specific methods and procedures to be used in the actual selection of the maintenance tasks. The definition used to determine maintenance significant items (MSI) is included in this section and forms the keystone to the entire decision process.

IDENTIFICATION OF SIGNIFICANT ITEMS

The initial step of the analysis, the identification of maintenance significant items (MSIs), is typically done by the manufacturer. According to MSG-3 (1), MSIs are defined as items whose failure:

1) Could affect safety

2) Could go unnoticed by the flight crew during normal operation

3) Could have a significant operational impact

4) Could have a significant economic impact

Some concern has been expressed about the approach that MSG-3 (1) proposes for selection of the appropriate level from which MSIs should be selected. The basic levels to be considered are system, sub-system, or component. MSG-3 advocates a "top-down" approach to identifying MSIs. Mr. Scott J. Bradbury of the Boeing Commercial Airplane Company advocates identifying MSIs at "<u>the highest manageable</u>" level, in contrast with what might be taken to mean, component level.[8] His technical paper is an excellent treatise on MSG-3 (1), and suggests several areas for improvement in the document.

Assuming that the MSIs have previously been identified, the entire process is based on a failure mode and effects criticality approach which begins with the consideration of whether the failure is evident to the operating crew during normal duties. Exactly what "normal duties" are comprised of has been the subject of great debate. Common sense and

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8. Scott J. Bradbury, "MSG-3 as Viewed by the Manufacturer (Was it Effective?)", paper #841485, Society of Automotive Engineers Inc. (SAE), 1984, p. 7.

extensive experience allows the working groups to make that decision.

IDENTIFICATION OF HIDDEN FUNCTION ITEMS

Hidden function items are those whose failure may go unnoticed by the operating crew during normal operations. This includes items which could fail in flight or on the ground, and not be noticed by either flight or ground crew during their normal duties. These type items are frequently back up or redundant systems, or emergency systems which are not tested until they are actually needed.

A number of discussions have occurred concerning how long the failure must go undetected to be considered "hidden". No firm rule seems to have been established and the decision has been left up to the judgement of the working group, depending on the particular characteristics of that item.

FAILURE ANALYSIS

The safety consequences of all failure modes are then considered. It is important that all modes of failure which are not extremely improbable , be identified and analyzed. This task is probably the most important, yet the most difficult facing the analysts. It is actually a combination of tasks and consists of identifying the function, failure mode, possible causes of failure, and criticality of failure for each particular MSI. It is very important that all possible failure modes be considered. For instance, a redundant fuel pump could fail to provide the required positive pressure with no effect on safety or operational capabilities of the aircraft. But, if it should fail to act as a fuel boundary, that is, to develop a serious leak, then that failure mode could be critical.

Throughout, the decision logic is clearly delineated and results in either task selection, mandatory redesign, or optional redesign. A high degree of systems knowledge, both technically and operationally, is necessary to come to the proper decisions. This broad knowledge requirement points to the use of working groups containing experts from a variety of disciplines.

Considering the number of MSIs on a large, modern transport category aircraft, one can quickly see that the task of developing an initial reliability based preventive maintenance program could be a monumental task.

In applying an MSG-3 (1) analysis, one must realize that regardless of the seeming rigidity of the procedures, the structure should only be considered a framework for the application of experience and good judgement. After all, the document was developed "by committee" and therefore represents a compromise of various interests and interpretations.[9]

This decision tree system should be useful in the analysis and modification of existing maintenance programs which were not developed under MSG-3. These analyses could be performed on specific items that are either exhibiting poor reliability, or are frequently inspected with no discrepancy findings.

Chapter 5 will provide additional detail, and suggest a specific area for application of MSG-3 techniques to the Coast Guard aircraft maintenance program.

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[9] *Ibid*., p. 2.

CHAPTER THREE

THE UNITED STATES COAST GUARD
AIRCRAFT MAINTENANCE MANAGEMENT SYSTEM

GENERAL DESCRIPTION

The United States Coast Guard (USCG) aircraft maintenance management system is a composite of United States Air Force (USAF) and Navy (USN) systems, commercial procedures, and USCG developed procedures.[1]

The Coast Guard operates a total of 223 aircraft, including a wide variety of both fixed and rotary wing types. Appendix 1 is a listing of the type aircraft that are presently in service.[2] In addition to those listed, the first of 32 Sikorsky HH-60J "Sea-Hawk" derivative helicopters was scheduled for delivery to the Coast Guard in March of 1990. The original maintenance program for this new aircraft will be designed using techniques similar to the MSG-3 format.

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1. Aeronautical Engineering Maintenance Management Manual, (Washington, DC: Commandant (G-EAE), United States Coast Guard, 1989), p. 1-1.

2. USCG Fact File 1989-1990, Commandant, U. S. Coast Guard, Washington, DC., n.p.

Maintenance on all of the Coast Guard's aircraft is accomplished, in large part, by Coast Guard personnel resources. The bases for these aircraft are scattered throughout the continental United States, Puerto Rico, Alaska, and Hawaii. This geographic diversity further adds to the complexity of the maintenance management task. Additionally, the salt water environment that the aircraft are exposed to on a daily basis, exacerbates the requirement for an effective and comprehensive maintenance program.

Organizationally, the maintenance management program is a hybrid system consisting of centralized support functions with almost complete decentralization of the actual day to day maintenance management. The management control system is in the military tradition, and is designed as a strict chain-of-command type, with authority and responsibility flowing from top to bottom.

In practice, a matrix type control system actually exists to some degree. The headquarter's aeronautical engineering division acts as a standards enforcement group and ensures field level compliance with applicable regulations.

"CORPORATE" LEVEL

At what might be referred to in business as the corporate level, the central office is located in Washington DC. This office is titled "Commandant (G-EAE)", and is considered the central management element of the system.

Figure 3-1 depicts the present organizational structure of this office. The head of this Aeronautical Engineering Division is an officer in the rank of Captain (O-6), who is ultimately responsible for the overall aeronautical engineering effort in the Coast Guard. The Captain is responsible for all maintenance activities, design, modification, disposal, procurement, and certification of all Coast Guard aircraft and associated support equipment.

This division consists of a wide variety of personnel who possess skills ranging from engineering to financial management. They provide support and oversight for all field and depot level maintenance activities. Certification and approval of all maintenance activity is either explicitly or implicitly done by this office. They are the authority that ultimately approves the design or modification of all preventive maintenance programs. The oversight of actual aircraft <u>operations</u> is accomplished through a different office in Coast Guard headquarters.

It should be noted at this point that Coast Guard regulations do not require the aircraft to be certified by, or meet the specifications of the FAA. Regardless, the aircraft and aircraft maintenance programs generally meet or exceed those requirements.

CENTRALIZED SUPPORT ACTIVITIES

Another major player in the Coast Guard's aircraft maintenance program is the Aircraft Repair and Supply Center (AR&SC) in Elizabeth City, North Carolina. This center, staffed by both civilian and military employees, accomplishes most of the major, depot level maintenance of the aircraft. It also supplies a majority of the required parts to field units, and overhauls or reworks a limited number of components.

The AR&SC also contains a technical engineering service which provides technical assistance to the Commandant's office and the field units. This technical element works under the direction of Commandant (G-EAE) and acts as a pool of engineering expertise for analysis and troubleshooting.

PRIME UNITS

Prime units are specially designated field units, usually air stations, that act as centralized monitoring points to assist Commandant (G-EAE) with monitoring the effectiveness of the maintenance program for a specific aircraft type. Their objective is to ensure a centralized point for technical responsiveness to field level maintenance management.[3] Theoretically, they are specially staffed with the most experienced technicians and managers for a particular aircraft system. They provide technical advice, monitor failure rates, and review procedural changes. Unfortunately, the effectiveness of these units varies widely throughout the organization. In some cases, due primarily to staffing problems, these capabilities exist in name only.

AIRCRAFT PROGRAM OFFICES

When a new aircraft is introduced into the Coast Guard system, an Aircraft Program Office (APO) is formed and monitors that introduction. These offices are typically co-located with the aircraft production facility. The engineering staff at the APO's act as the primary liaison between the manufacturer and the overall maintenance organization. This office is the key player in the development of an initial maintenance program for a new aircraft type. They must take the manufacturer's recommendations and mold them into a complete maintenance program for use by the Coast Guard. In this role, the APO often shapes the long term reliability and cost functions of a new aircraft.

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[3] Aeronautical Engineering Maintenance Management Manual, p. 2-8.

FIELD LEVEL MAINTENANCE ACTIVITIES

At the field level, the aircraft bases are referred to as air stations. As required by Coast Guard regulations, each air station has a command and control structure similar to the one depicted in Figure 3-2.

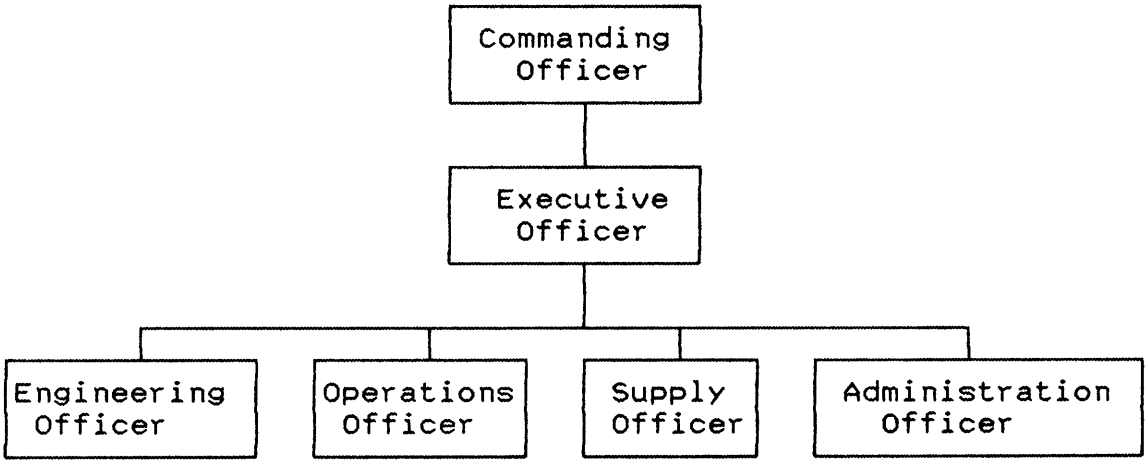

Figure 3-2

The Engineering Officer (EO) is the field level manager who is responsible for the execution of that unit's maintenance program. As depicted, the EO normally reports directly to the Executive Officer (XO). Depending on the size of the unit, an air station might have from two to five additional maintenance officers working directly for the EO.

Figure 3-3 is a typical organizational diagram for a field level aircraft maintenance group.

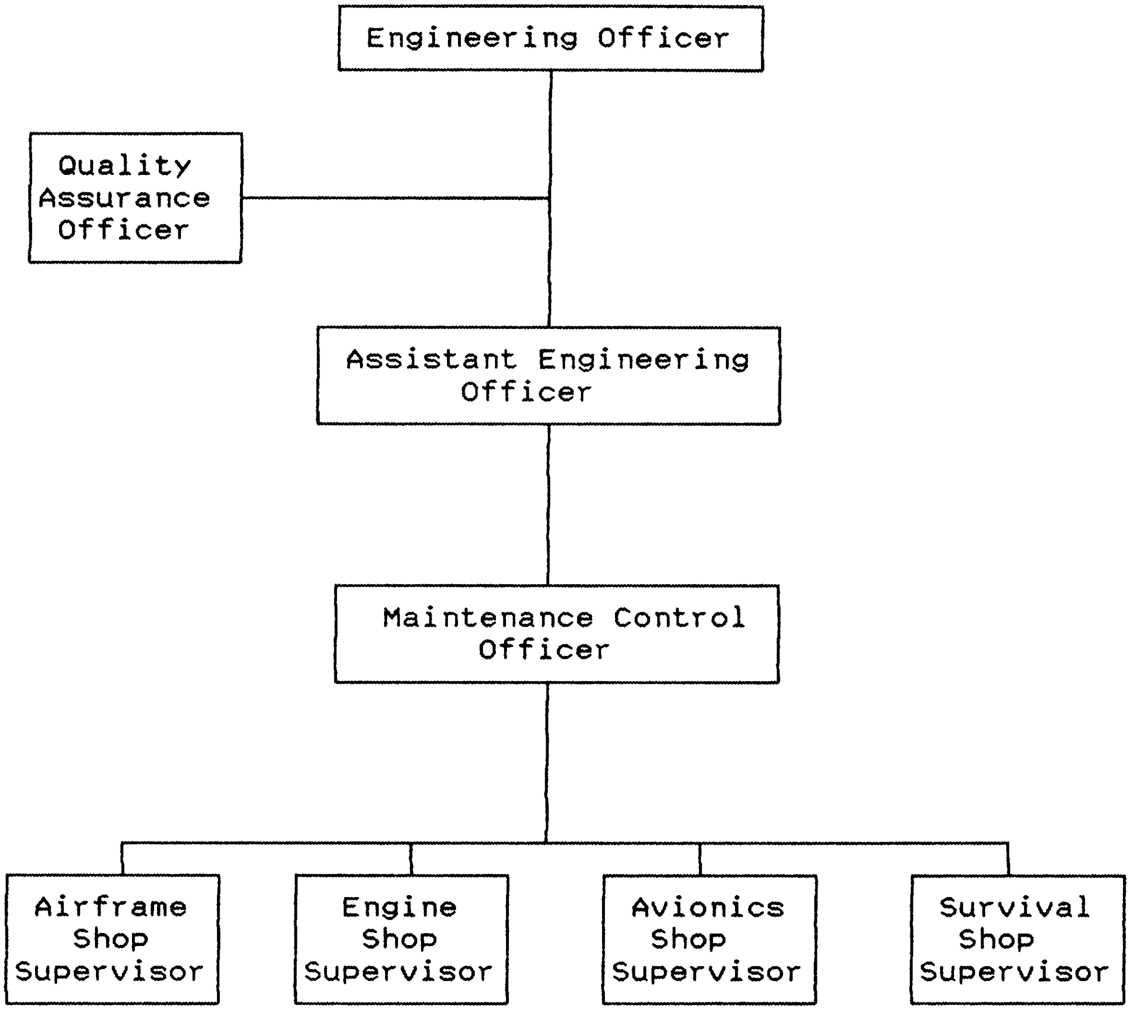

Figure 3-3

The actual maintenance, or "wrench turning", is accomplished by enlisted technicians who are highly trained through both formal classroom education and on-the-job training. An interesting and unique feature of the maintenance technicians and mechanics in the Coast Guard is that, unlike most other organizations, they also serve as aircrew on all missions and operate the aircraft that they maintain.

As these technicians gain seniority and experience, they are provided with additional technical and management training and are eventually moved into management responsibilities. It would not be uncommon for the "line" maintenance managers to have over twenty years of aviation maintenance experience.

The Quality Assurance department generally works directly for the Engineering Officer so that they may maintain independence from the "production" process. This allows a more objective analysis of the maintenance processes.

MAINTENANCE MANAGEMENT MANUAL

The primary document which prescribes the rules, regulations, required practices, and procedures to be followed in the maintenance of Coast Guard aircraft and associated support equipment is the Coast Guard's Aeronautical Engineering Maintenance Management Manual (COMDTINST M13020.1 series).[4] This manual is published by Commandant (G-EAE) and serves as the aircraft maintenance bible. It does not contain the specific program

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[4] Ibid., p.1-1.

requirements for each aircraft, but gives general guidelines for carrying out approved programs.

At present, it does not address reliability centered maintenance, either as a concept or a program. It does provide encouragement for units to suggest changes to the maintenance program via "normal channels".[5] Additionally, the manual provides a vehicle for suggestions for revision/changes to the Maintenance Procedure Cards (MPC's) via an Air Force form AFTO 22.[6]

ACMS SYSTEM

The Aircraft Computerized Maintenance System (ACMS) is now the primary tool for controlling the actual scheduled aircraft maintenance in the Coast Guard. This system has evolved, much like civilian aircraft maintenance systems, from a periodic maintenance concept to a more progressive concept. That is, each task is tracked separately and less packaging is done that would keep the aircraft out of service for an extended period.

In the USCG, prior to 1975, aircraft preventive maintenance was done on the basis of periodic inspections, replacements, or overhauls. The aircraft was removed from

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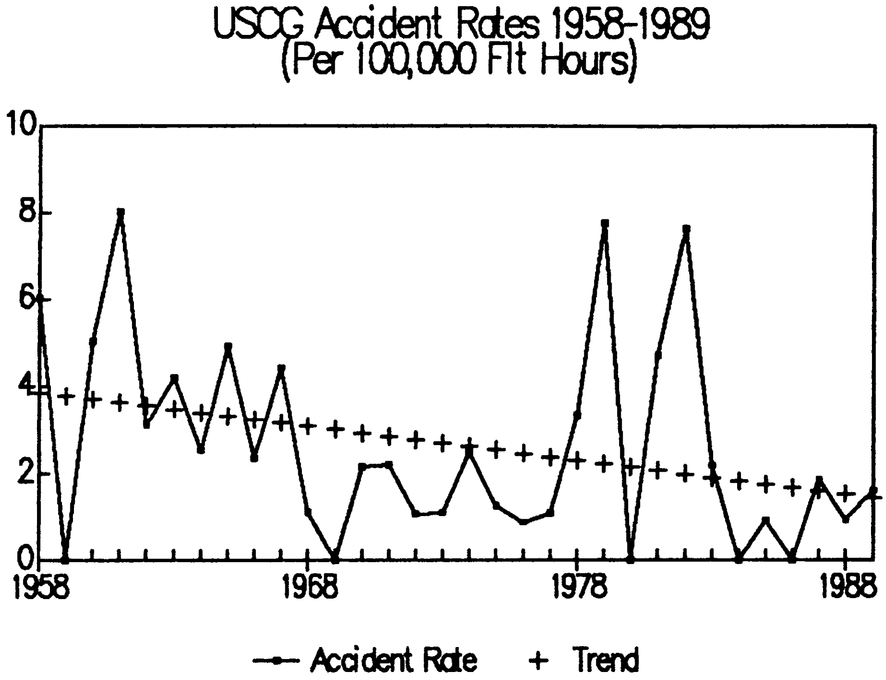
[5] Ibid., p. 8-7.

[6] Ibid.

service at specified intervals, often for extended periods, while all of the necessary work was accomplished. All required tasks were manually tracked and were grouped as packages, called "check packages". These packages were designed to include all tasks that would come due prior to the next "check". The "check package" often included several hundred tasks that were required to be accomplished during that particular maintenance period. All of the required tasks were completed prior to releasing the aircraft for flight and, once completed, only very minor scheduled maintenance was necessary prior to the next "check". This system was simple to manage, but lacked flexibility and had the disadvantage of removing the aircraft from service for an extended period of time.

The effectiveness of the periodic maintenance system, from a reliability and safety standpoint, is difficult to compare with the present system. As indicated by Figure 3-4, the overall accident rate in Coast Guard aviation seems to be experiencing a downward trend, however, there are several variables that might be correlated to that trend.

Mission profiles have been continually changing to employ advanced technology. Two modern aircraft types have been added to the fleet, phasing out some aircraft that were often manufactured prior to the birth of their pilots! Flight training has also experienced significant advances. Visual flight simulators have been constructed and are utilized for annual proficiency training by all pilots. Maintenance training has also been improved by the addition of many advanced courses.



Source: USCG Headquarters

Figure 3-4

About 1976, the Coast Guard implemented a progressive maintenance program in which each required task was tracked separately. The idea was to progressively maintain the aircraft, task by task, and negate the requirement to take the airframe out of service for an extended period. The maintenance could be accomplished on an incremental basis, when the aircraft was not scheduled to fly. Most tasks would be accomplished late at night, after the normal flying day, and would therefore, increase aircraft availability when the demand was normally the greatest.

Today's ACMS is a third generation of the initial progressive system. The tasks are tracked separately and great flexibility is provided to the maintenance managers. The system is a real time one, with each air station having an on-line computer terminal tied into a mainframe computer which contains the data base for all Coast Guard aircraft.

The system was initially designed as a tool for tracking and scheduling tasks. It now serves to document task completion and acts as an electronic aircraft history or logbook. A minimal paper trail is still required, but only between the technician who actually does the task, and the terminal operator who enters the data. The system has yet to evolve to the point where the technician inputs the data from his shop.

DATA COLLECTION

The actual data is collected from the written reports of the technicians whom accomplish the tasks. A standard ACMS card format is used by the technician who records primarily that data necessary to track and schedule the tasks. Additional data, such as results of the inspection, reason for removal (in the case of components), and remarks are also input. A sample of an ACMS maintenance procedure card (MPC) is included as Appendix 2.

DATA COMPILATION

The data that is collected is stored in tabular format in a relational data base architecture. A variety of standard management reports are available, in real time, to any maintenance manager. Additionally, there is a built-in query system that allows an individual manager to search and select particular data from any one table. This allows for customized reports, as long as all of the desired data resides within the same table. Fortunately, software is available on the mainframe to also make queries between tables. This capability is not available to the field units.

A shortcoming of the system, as far as reliability analysis is concerned, is that _failure_ data is not specifically recorded. When an item fails on the aircraft it _should_ enter the data base as a component removal, that is, if it is serial number tracked, and, is not repaired in place. When the technician removes a component, he or she must choose a removal code to indicate why the component was removed. The standard codes are: Time, Trouble, Cannibalization, and Other. It is assumed that the

"Trouble" code reflects failure, but the "Other" code is for unknown reasons unless the mechanic includes more specifics in the optional remarks section. It is not always clear whether a component actually failed. This lack of failure data collection is due to the initial design of the system, which was as a task scheduling and tracking mechanism.

Good approximations can be made from removal data, since removals are coded as to reason, however, if the technician's remarks are not complete, then actual failure modes may be unknown.

Another factor that minimizes the availability of useful data has been a concerted effort to simplify the system and reduce the number of components that require serial number tracking. As a general rule, if a component is not time sensitive, that is, it is not required to be overhauled, reworked, or scrapped at a certain age, then it is not tracked by serial number. In this respect, the present configuration of ACMS presents challenges to a reliability analyst.

AIRCRAFT DISCREPANCY REPORTS

In addition to the ACMS records, a paperwork system is used to record aircraft discrepancies and corrective actions. This system consists of forms, designated as CG-4377's, which are commonly called "pink sheets".

The aircrew initiates the discrepancy block of this form when failures or other problems are detected. The technician "signs it off" when the discrepant condition is corrected, indicating what action was taken to correct the discrepancy. If the discrepancy was one involving safety of flight, a quality assurance inspector must also sign the form indicating that the repair was accomplished using the proper procedures and was inspected for quality. If the repair is one that is included under the ACMS, then the technician must remember to also provide the data to that system by completing an ACMS maintenance procedure card. The completed forms (CG-4377) are retained in a book for aircrew review prior to accepting the aircraft for the next flight. A minimum of three flight's results are required to be available for review at any given time.[7] After removal from the "pink sheet" book, the forms are physically filed according to date and specific aircraft number. This data is not input to any collection system, but is retained for a minimum of one year and then discarded.

AMMIS

A new system that is presently in the early stages of development for use in the Coast Guard is the Aircraft Maintenance Management Information System or AMMIS. The

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[7] Ibid., p. 4-8.

vision of this system is that it will consolidate the present ACMS data base with existing data bases for the supply of aircraft parts, publications, maintenance procedures, aircraft utilization, aircrew training and flight requirements, and mission employment. An attempt will be made to integrate a majority of the present features of existing information resource management systems into one comprehensive system. At this point in development, the hardware design is conceptually a single main frame or a cluster of supermini computers located at the Aircraft Repair and Supply Center.[8]

The software design will be the big challenge. The functional requirement will be to create an efficient, user-friendly management information system which consolidates essentially seven different data bases across approximately 88 terminals at 35 sites throughout the continental United States, Hawaii, Alaska, and Puerto Rico.[9]

Chapter 4 will discuss opportunities and possible problems with the development of this system as it relates to the development of a reliability centered maintenance program.

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8. "Coast Guard ADP Justification for AMMIS", Coast Guard ADP Plan, 1987, p. 4.

9. Ibid., p. 1.

CHAPTER FOUR

RCM CONCEPT INTEGRATION
INTO
USCG AIRCRAFT MAINTENANCE MANAGEMENT

There are many underlying aspects and important considerations in the implementation of any new program. This chapter will deal primarily with those aspects which I believe are most important for the successful integration of an RCM program into the Coast Guard's aircraft maintenance management system.

Only general recommendations and considerations will be addressed here, however, several of these factors are felt to be essential to program success. Chapter 5 will go into more detail concerning specific designs and will suggest possible organizational models for an RCM program.

ENVIRONMENTAL ASPECT

The flight environment in which virtually all Coast Guard aircraft operate, is one of the harshest, if not the harshest environment in aviation. Constant exposure to a salt water atmosphere, actual water immersion for some of the amphibious helicopters, and a high percentage of heavy weather operations, creates demands on the reliability of equipment unknown to most operators. Items normally considered to be not failure critical, quickly become so, during the high percentage of night, off-shore,(no visual reference) operations.

CREDIBILITY

With that in mind, one of the most important considerations in the application of any sort of RCM program to Coast Guard aircraft maintenance management is credibility. Given the high risks inherent in such flight operations, minimization of controllable risks, such as those effected by preventive maintenance programs, becomes an extremely important and highly visible goal.

As depicted by Figure 4-1, the overall accident rate for Coast Guard aviation has historically been slightly lower than the charter air carrier rate. However, the Coast Guard rate remains much higher than the scheduled air carrier operators, whose rates have averaged below 0.5 accidents per 100,000 flight hours over the past 10 years.[1]

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[1] "FAA Air Transportation Statistics, 1987", (Washington DC: US Government Printing Office, 1988), Table 9.7. p. 185.

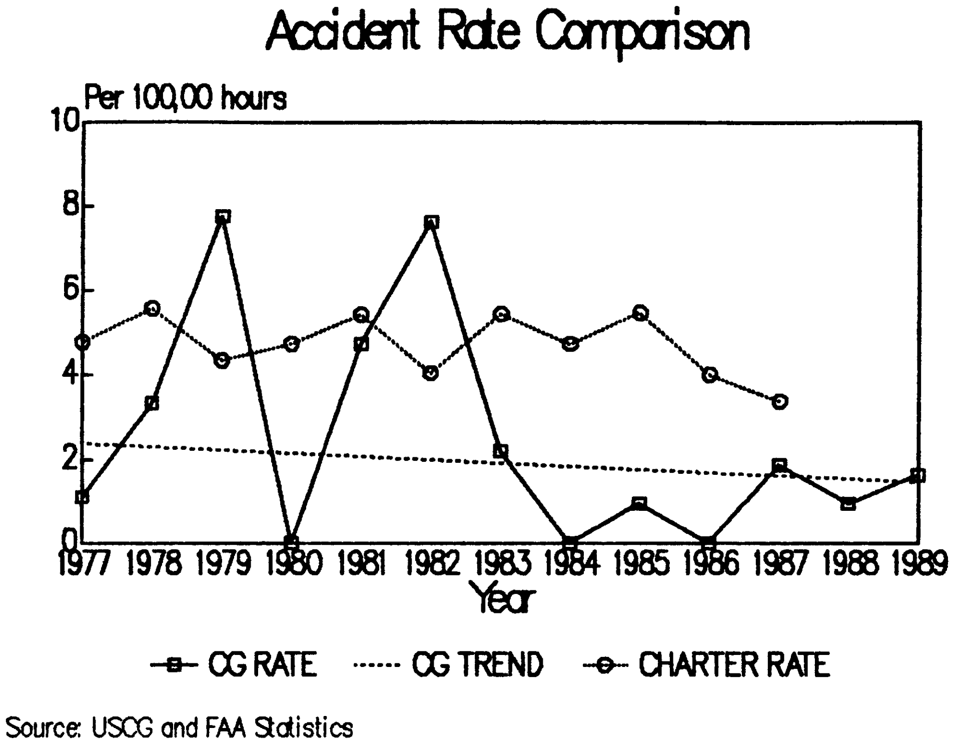

Figure 4-1

Although the specific statistics for the Coast Guard were not available, in my experience, only a small percentage of this rate could be attributed to mechanical failure. Comparable statistics <u>are</u> available from the civilian sector. They indicate that only 17.8% of the accidents between 1972 and 1983 were attributable to either <u>mechanical failure</u> or <u>maintenance error</u>. That percentage is down from 21% between 1959 and 1983. This compares with 68.8% attributable to the <u>cockpit crew</u>, up from 66.9%![2]

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[2] Nagel, David C., <u>Human Factors in Aviation</u>, (San Diego: Academic Press Inc., 1988), p. 265.

Despite this apparent lack of statistical culpability for poor safety records, maintenance program credibility is essential, particularly from an internal acceptance perspective.

Any RCM program must be viewed by the rank and file as a sincere attempt to increase reliability. In an interview with Mr. Vince Perez, a reliability analyst with Air Midwest Inc., indicated that even in the commercial air carrier arena, an analyst's credibility with the maintenance personnel was the key to a successful program. He alluded to "drinking beer with the maintenance guys" to establish this trust.

This is especially true in the Coast Guard. As previously mentioned in Chapter 3, the technicians also fly and operate the aircraft on which they do maintenance work. This puts them personally at risk if reliability and safety is compromised. Any indication, or even the perception, that the program is designed to rationalize an attempt to decrease maintenance requirements and/or resources would not be acceptable. The resultant program would, at best, be doomed to mediocrity, and, at worst, fail completely. Therefore, credibility is the cornerstone of a successful program.

There are, however, several other important elements that should also be kept in the forefront during program design.

CONSISTENCY

The reliability program needs to be consistent. Treatment of one aircraft type or system must closely parallel that of another. They would not necessarily have to match exactly, but concepts and applications must appear uniform. Extensive cross qualification exists within the ranks of the aircrewmen and this alone dictates a high degree of standardization between aircraft types. This will be particularly important, not only to maintain credibility, but to ensure equal quality across reliability programs.

There would seem to be two primary means of controlling consistency or, as it is frequently referred to in the Coast Guard, standardization. First, the program could be centralized and operated by a select few personnel. This does not necessarily require that the program be physically co-located for all of the different aircraft types, but co-location should be a serious consideration. Despite modern communication systems, co-located offices still generally result in improved communications between the personnel involved in program administration.

Another method to maintain standardization would be the publication and enforcement of strict regulations and procedures, coupled with monitoring by a central controlling unit. This bureaucratic method is less desirable since the inherent loss of flexibility will surely result in a longer evolutionary cycle and additional manpower will be required for monitoring. If the program is centralized, consistency should not pose much of a problem.

STRUCTURED FORMAT

A structured, yet flexible format of specified procedures should be developed. This may initially consist only of a general job description for the program manager and/or analyst. But, as the program evolves, the format should gradually become more rigid. It is important that, initially, plenty of discretion be provided to the manager and analysts. This will allow for quicker program optimization.

The format of the program will depend, in large part, on the actual physical structure of the program organization. Factors such as field input and feedback, manufacturers recommendations, and data availability should be primary considerations. Written guidelines should eventually be promulgated to ensure clear communication of the methods, goals, and procedures to be followed.

Initially, the structure should be general enough to allow the necessary flexibility, yet specific enough to maintain some degree of control. Lack of at least some initial structure will result in more of an experiment, and less of a program. The resultant effort will lack credibility and, therefore, effectiveness.

TRAINING

It appears at the present time, that the Coast Guard does not have any aircraft maintenance managers who are well trained in reliability centered maintenance procedures and associated actuarial analysis methods. Several managers have attended short reliability seminars which review the basic concepts and procedures, but without subsequent opportunities to apply this training, the newly learned skills will quickly be lost.

To have an effective program, a general understanding of RCM program concepts and methods will be required of all engineers and managers. It will also be necessary to employ a few select personnel who are expert in the application of these techniques.

The student engineering program presents significant opportunities for the general education of all new maintenance officers. The RCM program manager should include as a requirement that each class of student engineers be familiarized with the concepts of RCM as applied by Coast Guard.

Another area that should be a prime consideration for personnel training is the Aircraft Program Office (APO).

The managers and engineers in this office recommend the initial design of the maintenance program for a new aircraft, yet they typically have little or no training to undertake this important task. Even a brief course to familiarize them with the general concepts of RCM would assist them in designing a more efficient maintenance program.

The training or experience that will be required of the actual analysts and program administrators is much more extensive. As for this expertise, it could be purchased or developed from within. Ideally, the reliability program manager or head analyst would be intimately familiar with Coast Guard aircraft, engines, and systems. This goal would tend to favor development from within. If that is not possible, then extensive experience with similar aircraft or systems should be sought.

Most reliability analysts were engineers first. When the commercial air carrier maintenance community develops an initial preventive maintenance program, the personnel who comprise the working groups, and recommend the actual tasks and associated intervals, are highly experienced aircraft engineers who are familiar with the aircraft and its systems. Regardless of their source, personnel who are not fully trained or highly motivated to learn, will not have the requisite degree of credibility.

It is particularly important that the analysts be thoroughly familiar with statistical sampling techniques, actuarial analysis, logical decision processes, and automated data processing equipment.

MAINTENANCE MANAGEMENT REVIEW PROGRAM

The Coast Guard's present maintenance management review (MMR) process may contain significant opportunities and possibly create a framework for RCM program implementation.

The original concept behind the MMR was to allow the various echelons within the aircraft maintenance management community to come together and discuss problems and develop solutions. The format was typically a one week conference at a major field unit, usually the prime unit. All of the major players from the maintenance management community for that one particular aircraft type were in attendance, and the chairman of the meeting was usually the headquarters program manager for that aircraft.

Proposed agenda were submitted by any concerned managers and prior to the conference were reviewed by the prime unit.[3] The objective of the conference is to discuss and examine all technical aspects of the aircraft's maintenance program, swap ideas, and seek solutions to problems.

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[3] Aeronautical Engineering Maintenance Management Manual, (COMDTINST 13020.1B), p. 2-9.

Unfortunately, like many group problem solving sessions, the effectiveness of these meetings was, in large part determined by the leadership abilities of the chairman.

Given the short time allowed to discuss the inevitable myriad of problems, another factor that hindered their productivity was the lack of equal access to information bearing on the problems. The field level managers knew how they were affected, while the headquarters level managers knew the reasons, but often had no timely solutions available to them.

Instead of seeking innovative solutions to problems, the result was often a general complaint session with the field managers asking for support from above that was not available. Some of the meetings were extremely productive, but some tendered minimal results.

Due to a variety of factors such as increased logistical problems, lack of manpower, acceptance of two new aircraft into the fleet, and a general dissatisfaction with the results, the MMR process for mature aircraft has been relatively unused during the past five years.

ORGANIZATIONAL RESPONSIBILITIES

Any attempt to integrate an RCM program into an existing organization must clearly delineate specific program responsibilities. Therefore, a review of the capabilities and limitations of the various candidates that are presently in existence, and obvious key players would be helpful in making any recommendation.

Ultimately, Commandant (G-EAE) must assume overall responsibility for RCM program management. It is they who control the maintenance effort and will approve any modifications. However, the personnel resources depicted within the organizational structure of Figure 3-1, contain very little reserve and all of the officers assigned would seem to have more responsibilities than they can effectively carry out.

AR & SC Engineering Division is another element that could conceivably be a key player or administer a program, but they are also task saturated. Most of the reliability type analysis that is presently being accomplished is done by this division, but they do not have a reliability section, *per se*.

Prime units are also resource elements worthy of consideration, even though across different aircraft programs there has been inconsistent use of their capabilities. They are assigned a myriad of other responsibilities, but most maintenance program modifications that occur under the present system are administered by the prime unit representatives. At present, they lack the personnel and skills necessary to fully carry out an effective reliability program.

The organizational elements that really stand to benefit the most from a reliability program are the field maintenance units. Unfortunately, they too are lacking of any reserve capacity to establish individual systems. Establishment of reliability programs at each unit would be ineffective and inefficient.

At present, the central computer facility for the ACMS data base is located at a civilian contractor, the Technical and Management Services Corporation (TAMSCO), located in Beltsville, Maryland. One Coast Guard maintenance officer is assigned, on site, as the contracting officer's technical representative. This officer works under the direction of the Information Resource Management Branch at headquarters. (See Figure 3-1)

This organizational element, although very limited in scope, does contains opportunities for RCM program development.

PERSONNEL RESOURCES

In today's budgetary climate, it will be very difficult to create new and additional personnel resources to carry out such a program. Opportunities do exist within the framework of a special program, administered by the Commandant, that allows the addition of personnel resources for new program implementation. If it can be clearly proven that overall manpower requirements will be reduced by the program, then supplemental resources may be available of such a program.

If good records are maintained, this proof should not be difficult to obtain. Historically, the application of RCM techniques to preventive maintenance programs has shown significant savings both in manpower and materials. Programs that have had no modifications subsequent to initial development have yielded labor and material cost reductions on the order of 30-40%.[4]

Therefore, this avenue of support for the program should be explored in detail as data becomes available to demonstrate the expected manpower savings.

DATA AVAILABILITY

The ACMS collects vast amounts of data. Software subsystems allow transformation of some of the data into meaningful reliability information. One very important consideration should be kept in mind however. The ACMS database was not designed to support a reliability program! It was designed to schedule and document preventive maintenance.

Therefore, some data that is used in a typical RCM program is not easily retrievable. Several useful pieces of data

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4. A. M. Smith, et al., "Enhancing Plant Preventive Maintenance Via RCM", Proceedings from the Annual Reliability and Maintainability Symposium, 1986, 120-123.

are not even collected and therefore, totally unavailable within the system.

During an interview, the Maintenance and Engineering Branch Chief stated that one thing we don't need is a requirement to collect any additional data. In the short run this is an understandable limitation. In the long run, the implementation of the consolidated AMMIS will necessarily result in expanded data collection. This will present significant opportunities to expand the ACMS data base and include data that will further support an effective reliability program.

SUMMARY

In summary, several of the factors just mentioned, especially credibility, consistency, and training, will bear heavily on the success of any attempt to establish an effective RCM program. During the initial phases of program implementation, these aspects should be kept continuously at the forefront of consideration. The program manager would do well to periodically review program direction, particularly as it relates to the three previously mentioned key factors.

CHAPTER FIVE

RCM PROGRAM IMPLEMENTATION MODEL

Conceivably, many different organizational designs could be applied to implementing an RCM program for the Coast Guard. I have interviewed, and discussed possible options with managers and engineers from a wide variety of related disciplines, including the air carrier industry, academia, the other armed services, and the Coast Guard aviation community itself.

The design outlined in this chapter is only one of several feasible choices. This particular design was chosen as a compromise based on all known limitations.

This chapter will outline some specific details for a program that could be established to apply RCM techniques to the Coast Guard's aircraft maintenance management system. General recommendations, and areas that deserve special attention are also included for many segments.

This model bears likeness to systems that are presently in operation in the civilian air carrier industry. An effort has been made to properly modify its design to meet the differences and peculiarities in the Coast Guard maintenance management system. I attempted to carefully consider all of the alternatives, including the option of, "no program".

ALTERNATIVES

Five conceptual designs were considered:

(1) Continue on present course, do not implement RCM techniques.

(2) Random application of RCM techniques through progressive training of our maintenance managers (no formal implementation).

(3) "Clean slate" RCM program design with the addition of internal resources.

(4) Contracting an outside source to establish and administer a program.

(5) RCM integration into the present maintenance program using existing resources.

The alternative of not applying RCM techniques was ruled out because, as the next chapter should demonstrate, there may exist significant opportunities for efficiency gains within that framework. Based on my discussions with a variety of air carrier maintenance managers, RCM techniques can assist greatly in monitoring and guiding the dynamics of a maturing maintenance program. In that industry, the application of RCM techniques resulted in changes whereby ineffective maintenance tasks were often deleted, and tasks that could positively impact reliability were added. Effective application of RCM techniques allowed the air carriers to institute maintenance program changes which were automatically accepted by the FAA, and yielded significant long term benefits. Based primarily on their success, I believe that the establishment of a Coast Guard RCM program provides a significant opportunity for efficiency enhancements.

The random training approach might be successful over a long period of time, but program implementation would be dependent on finding an individual to push the program. Seldom do new programs that initially require additional work, implement themselves.

The clean slate method was ruled out due to lack of additional personnel resources required. In the present budget climate, if the necessary resources were requested, the probability of obtaining approval for those resources would be low.

The best selection would seem to be a formal integration into the present management system. The integration approach is a compromise, based on a realistic assessment of the perceived probabilities of success for the other alternatives.

LIMITATIONS

The proposed plan is designed to:

(1) Minimize any requirements for additional resources.

(2) Minimize additional workloads placed on existing resources.

(3) Minimize the need to increase the number of forms, or complexity of administrative paperwork.

In the proposed design, I have also attempted to use what little manpower resource slack might be available to gain a foothold on RCM application. This was done under the assumption that the program will prove itself worthy of expansion, based on its production of reliability and efficiency enhancements. Some level of increase in personnel resources will be necessary, but the justification and cost savings should quickly be apparent. To assist program acceptance and credibility, and to facilitate program survival or growth, opportunities for early success should be sought.

Given those constraints, a comprehensive description of one possible implementation model follows. First, the primary organizational elements are described, followed by a basic procedural system proposal.

THE MAINTENANCE REVIEW BOARD

A central element that should be included in any RCM program is an internal maintenance review board. The term internal is used in the commercial operator environment, and indicates that this is not the maintenance review board that establishes the initial maintenance program and contains representatives from the manufacturer, airline and FAA. The "internal" qualifier can be deleted in the Coast Guard's context.

This concept, similar to the Coast Guard's MMR, consists of a board that is formed to provide the airline operators with an FAA accepted system by which they can modify their maintenance program to take advantage of operating experience.

The maintenance review board is a group normally comprised of higher level management, which is responsible for reviewing, and approving or disapproving modifications to the preventive maintenance program.

Assuming that a structured reliability program is in place, the members of this review board need not be reliability or engineering specialists. In fact, an uninitiated and unbiased outlook might be preferred, so that the normally unasked questions might come forth.

In the commercial world, the function and structure of this process is spelled out by FAA Advisory Circular 120-

17A. This document contains general concepts and procedural requirements for a commercial operator establishing an RCM program. It is currently under revision, with AC 120-17B expected to be approved and published by the fall of 1990.

Although these FAA requirements are not binding on the Coast Guard, the principles espoused by the publication are sound and should be continually reviewed by program managers.

This advisory circular addresses the specific procedures that are required, but even in the commercial arena, formal boards are not always required or necessary. Very large and sophisticated operators with a strong engineering function may assign appropriate responsibilities to different organizational elements with one specific element assigned an oversight role.

For instance, at Northwest Airlines, the engineering department consists of 40-50 engineers and there is a relatively loose reliability program structure.[1] Yet, an internal maintenance review board comprised of upper management makes the final approval or disapproval.[2] Similar frameworks have been used extensively in commercial aviation and have proven their worth many times over.

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[1] Per discussion, March 14, 1990 with Mr. Dave Nakata, Director of Central Production Planning, Northwest Airlines, Inc.

[2] Ibid.

The key to success is systematic review by competent engineers or analysts. The idea is that systematic modification may approach, at the limit, optimization of task and interval selection.

BOARD CONSTITUENCY

The Coast Guard's Maintenance Review Board would best be comprised of the Chief, Aeronautical Engineering Division (G-EAE), the Chief, Maintenance and Engineering Branch (G-EAE-3), the specific aircraft program manager, and any other representatives required to provide the expertise necessary to make an approval or disapproval decision. The purpose of the review board is not to complete a separate analysis, but to take the analysis that has been given, and to judge if the revision is justified. In the early stages, as the RCM program takes effect, the board should meet to monitor the direction and progress of the program and provide course corrections as necessary.

MEETING FREQUENCY

Initially, the board should meet at least monthly to review the general progress of RCM development. These meetings can be informal, but should be attended by the RCM program manager. As the program matures, the meeting frequency will be dictated by the number of program revisions that require board decisions. For simple and obvious decisions, the approval process can consist solely of the completion of a maintenance program revision form, such as that depicted in Appendix 2. Questionable, unclear, or large groups of analyses may dictate the convening of a formal maintenance review board for that aircraft type. Additionally, a formal board should be convened at least annually to review program progress and direction. This meeting could be held in conjunction with the present maintenance management review process.

RELIABILITY ANALYSIS SECTION

The reliability analysis section could start as a subsection of the present aircraft maintenance analysis group at the ACMS contractor, Technical and Management Services Corporation (TAMSCO). Ideally, staffing should consist of one analyst for each aircraft type. The analyst should be thoroughly familiar with the aircraft and its systems, RCM concepts, including the MSG processes, and reliability statistics. Extensive knowledge of sampling procedures and the ACMS data base structure and access will be necessary. The contracting officer's technical representative (COTR) can be the oversight authority for the program.

The main objective of this section should be to provide systematic review; in addition, it may perform analyses that are requested by other elements within the maintenance organization. The COTR should monitor workloads and provide guidance in establishing priorities of work. There is some danger that the analysts will become a pool talent, used only to analyze specific problems, and will be unable to provide the desired systematic review. This tendency should be monitored closely by the program manager in order to maintain program integrity and maximize the efficiency gains that should be available.

INITIATION OF MAINTENANCE PROGRAM REVISIONS

Any person or organizational element in the maintenance organization should be allowed to initiate a maintenance program revision recommendation.

A form similar to Appendix 3 could be used throughout the organization for this purpose. Ideally, this form, or one of similar format, could be included in standard ACMS software. The originator would input to the form on the computer terminal, using as much justification documentation as necessary. Routing should be electronic. Actual paper work is not necessary, and should be avoided, if possible, throughout the ACMS. If required, hard copy could be output and filed after approval or disapproval. The software should be designed so that only the originator can modify the original proposal. Each level of review can input comments or additional supporting documentation only to the appropriate section of the form. The electronic routing capability will minimize response time, while the comment limitation will maintain system integrity.

The flexibility of allowing anyone one to input recommendations will maximize the potential of an RCM program, and follow the example of most large commercial operators. The drawback of providing this flexibility is that some man-hours will be wasted reviewing recommendations that are obviously not supportable. However, the gains associated with the additional input should easily offset the losses.

It is expected that the reliability analysis group will initiate the vast majority of the recommendations, since it will be their primary job to provide systematic review. Therefore, the analysis and justification will normally be completed by that section. However, when the form is initiated by another element, regardless of the relative routing order depicted on the form, the first step in review process should be the reliability analysis section. If the originator did not, for any reason, provide sufficient analysis or justification, the reliability section should provide the necessary analysis followed by a disposition recommendation. If the recommendation is clearly not supportable, the form should be returned to the originator indicating that fact. This will minimize unnecessary review.

DOCUMENTATION REQUIREMENTS

A form, similar to Appendix 3, should be adequate to provide all necessary documentation for program revision once it has been completed. Specific requirements concerning format, type, or amount of justification should not be developed. This is due to the wide variety of analytical methods or justifications that should be acceptable. The controlling factor will be whether the justification is sufficient to garner approval from the maintenance review board.

INITIAL PROGRAM DIRECTION

As previously discussed, to prove program worth, initial efforts should be aimed at early, significant gains in efficiency or manpower savings. To accomplish this, the most fertile areas should be initially selected for primary efforts. Aircraft that have been in operation for an extended period have generally approached task optimization through informal age exploration techniques. Therefore, the aircraft that are relatively new to the Coast Guard program should be the focus of initial efforts. More specifically, the HH-65A "Dauphin" helicopter and the HU-25 "Falcon" fanjet should be fertile areas.

The maintenance program for the HH-65 aircraft was developed along lines similar to the MSG-2 process and that development data is available through Aircraft Program Office (APO) sources.[3] Since many USCG peculiar items were added to the program, and since the program is still in a relative stage of infancy, RCM application should quickly yield significant efficiency improvements.

The HU-25 aircraft maintenance program was developed with reference to Dassault Corporation and Federal Express fleet experiences, with Coast Guard specific items added. Significant modification to the maintenance program has already occurred, but based on a quick review of the overall maintenance program requirements in accordance with MSG-3 techniques, some opportunities for efficiency gains may still exist.

Most of the other aircraft in the Coast Guard fleet are mature, and their maintenance programs have, over time, been fine tuned to optimize efficiency. This is not to say that gains are not available within these programs, there should simply be less room for improvement.

The new HH-60J Jayhawk helicopter now entering the fleet is being developed with procedures similar to MSG techniques and is partially supported by the US Navy. Some Navy fleet

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3. Per interview with Commander Paul Garrity, USCG.

reliability analysis information will be available as a starting point, but the Coast Guard experience will most likely differ significantly. As with any new aircraft, age exploration and reliability analysis based on the Coast Guard specific operating environment should also yield high productivity. This aircraft, as it matures, will be an excellent candidate for reliability trending work.

In summary, the problem is where to start. The previous discussion should provide some issues that warrant prime consideration.

SPECIFIC TECHNICAL PROCEDURES

To provide specific technical guidance in the development of an RCM program, the following goal descriptions for the analysis section should provide some direction.

(1) A systematic review of maintenance program requirements should be established, addressing applicability and effectiveness of specific, existing tasks.

MSG-3 (1) format can be used as a tool for accomplishing this, and for justifying revisions if indicated by the analysis.

In the present system, there is a report, called the Inspection and Services Summary, that might assist in locating opportunities for using the MSG-3 techniques. This report lists all of the required inspections and services on a particular aircraft type. It details the total number of inspections during a given time interval, the number of discrepancies found, and the number of no-defect inspections performed.

This data is interesting, but alone is inadequate to make decisions as to applicability or effectiveness of maintenance tasks. For example, the maintenance procedure itself could be generating the discrepancies noted.

It could serve two useful purposes however. First, it should highlight systems and components exhibiting low reliability characteristics, particularly those that are not highly visible or are not tracked by other methods. Secondly, it will indicate the number of inspections that were performed needlessly, that is, no discrepancies discovered. When combined with the techniques available through MSG-3, sound maintenance program modifications can be implemented, which are based on reliability data and structured decision processes. At present, review of maintenance programs is done on a sporadic basis, and no systematic or structured process for program modification exists. The ultimate goal should be the systematic review of the maintenance program, with an eye toward improvements in efficiency and reliability.

(2) A trend model for tracking power plant unscheduled removal rates could be developed and maintained. An example of such a model is provided in Chapter 7 using the ATF3 engine. Tracking of mean-time-between-removal (MTBR), mean-time-between-overhaul (MTBO), and conditional probability of failure (as a function of time-since-overhaul (TSO)) for all repairable serial number tracked components might also be desirable.

(3) The in-flight engine shutdown rate should also be monitored as a trending model. The necessary input data is available from message based incident reports. Manual collection will initially be required. An automatic alerting capability is desired.

(4) An attempt should be made to conduct conditional probability analysis for all serial number tracked components, for which such analysis would be meaningful. These analyses would be particularly useful for items experiencing reliability problems, or those presently designated for scheduled overhauls or restorations. The results of the analyses can be used to analyze the effectiveness of time-between-overhaul (TBO) policies.

(5) Establish a removal rate trend model for all serial number tracked components with automatic alert capabilities.

based on some method of smoothing. A simple and widely used method, easily accomplished on the personal computer, is linear regression. Chapter 7 provides the power plant tracking model which, with minimal modification, could be used for component removal tracking.

REPORTING REQUIREMENTS

Initially, a written report should be developed to indicate the specific areas being monitored or analyzed, and exactly what type of analyses are being accomplished. Opportunities for efficiency gains, reliability problem areas, undesired trends, and changes in program scope should be highlighted and brought to the attention of top management. As the program matures, adjustments to the type and frequency of required analyses, and therefore reports, will most likely be required. Managers may find some of the reports to be useless, while others that would be extremely valuable are not provided. This is to be expected and the requirements for specific reports should not be chiseled in stone. However, there needs to be very specific requirements, officially published, monitored for completion, and documented in writing.

The exact frequency of the reliability analyses should also be specified. Initially, a monthly recapitulation or compilation of these reports should be provided to top management. (Commandant G-EAE) Once computerized, very little manual data analysis should be required. In fact, some of this data is now available, upon request, from the present ACMS software programs.

SUMMARY

This chapter has provided a general guideline for initial efforts into reliability centered maintenance. It is difficult to predict many of the problems that might arise with any implementation. Since people are the most important resource to any organization, careful personnel selection and placement is the key and is crucial to the development of an effective program. Based on my research, I believe that even minimal RCM effort would be worthwhile, and the program could easily pay its own way.

Using some of the previously discussed techniques, Chapters 6 and 7 will present several practical examples that are typical of a continuing RCM program.

CHAPTER SIX

COMPONENT RELIABILITY ANALYSIS

The basis for an effective reliability centered maintenance program is the analysis of the reliability data that is characteristic of the equipment in service. This chapter will provide an example of several analysis techniques that could be used to study the reliability characteristics of an aircraft component or system. Normally, an extensive analysis such as this would only be accomplished to investigate poor reliability, or to justify revisions to a maintenance program.

In choosing a component to be used as the example, I looked for one that seemed to exhibit poor reliability characteristics, was typically overhauled or restored on a scheduled basis, and one whose failure data was available through the ACMS data base.

The constant-speed-drive (CSD) hydraulic pump, which is used on the HU-25 Falcon Fanjet was specifically chosen for analysis. First, it is a repairable item and has a relatively short maximum time-between-overhaul (TBO). Secondly, since it is serial number tracked, there was adequate failure data available through the ACMS data base. Additionally, it is a relatively complex mechanism that might be expected to exhibit an exponential failure distribution characterized by a constant hazard rate.

This presentation is by no means an exhaustive list of techniques, but depending on the specific characteristics of the component, some of these may prove useful.

DATA COLLECTION

All of the raw data used in this chapter was obtained through the query capabilities of the Aircraft Computerized Maintenance System (ACMS). This capability is available to all Coast Guard aviation field units. However, at the field level, only one table may be queried at a time. Due to data base design, this limitation makes it difficult for field units to obtain the proper data necessary to accurately describe component reliability.

The analysts at the Technical and Management Services Corporation (TAMSCO), who maintain the data base, have additional software which allows query across multiple tables. Therefore, the single table limitation should not be a problem for actual program implementation.

The data presented in this chapter was gathered by TAMSCO, and represents the latest that is available. Some inherent errors may still exist however. For instance, the time-to-failure data was manually derived from the significant component history records (SCHR) for all of the pumps in the fleet. The SCHR indicates the chronological history of each pump beginning with induction into the ACMS. Removals, installations, and overhauls are recorded, along with a section for remarks by the mechanic taking the maintenance action. In some cases, overhauls were accomplished at ages prior to the maximum TBO, without a remarks section entry indicating failure. In these cases, I assumed failure and included the data. Pumps that survived to maximum TBO were not included in the failure data, since they were assumed not to be actual failures.

These assumptions should be reasonable, but are not perfect. For instance, when a pump fails internally and the shaft does not immediately shear, the entire hydraulic system may be contaminated with metal particles. The opposite side pump might then be contaminated and be sent to overhaul, regardless of its actual status. The mechanic may also, in being conservative, mistakenly declare a good pump as failed.

It should be obvious that the analyst needs to exercise extreme care in selecting the sample methodology to minimize any errors or biases. The mechanic can also assist with data collection by always including remarks to indicate failure specifics, such as cause or mode. <u>Perfect</u> data are nearly impossible to obtain, and are generally not necessary for accurate and useful analysis. Critical review of collection methodology by another analyst, or an associate, is a good method to audit data accuracy. However, the analyst should always keep in mind that it is very easy to unintentionally collect data which will introduce significant errors into the analysis.

RELIABILITY ANALYSIS CONSIDERATIONS

This analysis will demonstrate several techniques that might be used to investigate the reliability characteristics of a component such as the HU-25 "Falcon" constant speed drive (CSD) hydraulic pump.

Before any analysis is attempted, the analyst should fully understand the system, its components, its operation, and any existing maintenance requirements such as inspections or life limits. Extensive system descriptions are available in the maintenance and flight manuals and all of the scheduled maintenance requirements are available through the ACMS data base. Such things as life limits and changes in maintenance procedures during the period under study, could significantly skew the data and generate inaccurate conclusions based on the analysis. For example, a significant mission profile change for a particular aircraft type, might result in changes in reliability data. For these reasons, the analyst must be more than a "number cruncher". To be effective, he or she must understand, or at least be familiar with, the details of the Coast Guard aviation operation.

A cursory system description is in order. The CSD pumps are mounted on the accessory gear box of each engine and provide the hydraulic pressure necessary to spin a constant speed motor which, in turn, drives an alternating current (AC) generator to provide power to other aircraft systems.

The most critical failure mode experienced thus far, has been the massive loss of hydraulic fluid. The risk of fire with a leak or internal pump failure is felt to be extremely improbable due to installation configuration. The pump is designed with a shaft that will shear in the event of internal failure. The failure of one pump causes the loss of main AC bus power and the loss of relatively non-critical items such as radar, autopilot, auto-throttles, navigation computer, and back-up transponder. For a variety of reasons, this entire system has proven to be quite unreliable, and has, therefore, been chosen for this analysis.

ANALYSIS METHODS

The raw data, displayed at the end of this chapter in Table 6-1, were obtained from the significant component history report (SCHR) records of the ACMS data base. This data was manually input to a personal computer which was used to arrange, sort, and analyze the data in several different ways.

There are many good personal computer software packages available which provide statistical and spreadsheet analysis and are easy to use. Some of the calculations required 10-15 seconds on an 80286 CPU operating at a clock speed of 10 Mhz. This delay becomes troublesome when manually adjusting the spreadsheet to accomplish some of the more extensive analyses. For that reason, a 10 Mhz clock speed should be considered the minimum for these type calculations.

BASIC STATISTICAL PARAMETERS

A good starting point in the analysis of a specific component is to derive a set of descriptive statistics for the failure distribution. Most statistical software packages designed for the personal computer can quickly provide the standard descriptive statistics, such as mean, median, mode, and standard deviation.

In this case, the mean of the time-between-overhauls is 726 hours and the standard deviation is 542 hours. This mean is generally referred to as mean-time-between-failure (MTBF), or the mean-time-to-failure (MTTF). In the case of repairable items, which exhibit a constant failure rate (exponential distribution), the term used is MTBF. For non-repairable items such as a light bulb, only one failure can occur, and the term used is mean-time-to-failure (MTTF). Since the CSD pump is a complex component, we might expect it to exhibit an exponential failure distribution, and since it is repairable, we will use the term MTBF.

With that assumption, the average failure rate, usually depicted by Lambda, is given by:

$$\textbf{Lambda} = \frac{1}{\textbf{MTBF}}$$

When computed in this manner, Lambda is the per hour failure rate. For the CSD pump data, the per hour failure rate is 0.001376. Normally, this rate is expressed per 1000 hours and in this case would be 1.376 failures per 1000 hours.

FAILURE FREQUENCY ANALYSIS

Another exercise, that might assist in analyzing failure characteristics, would be to plot the frequency of failures in some specified age ranges. This plot, called a failure frequency histogram, is depicted by Figure 6-1.

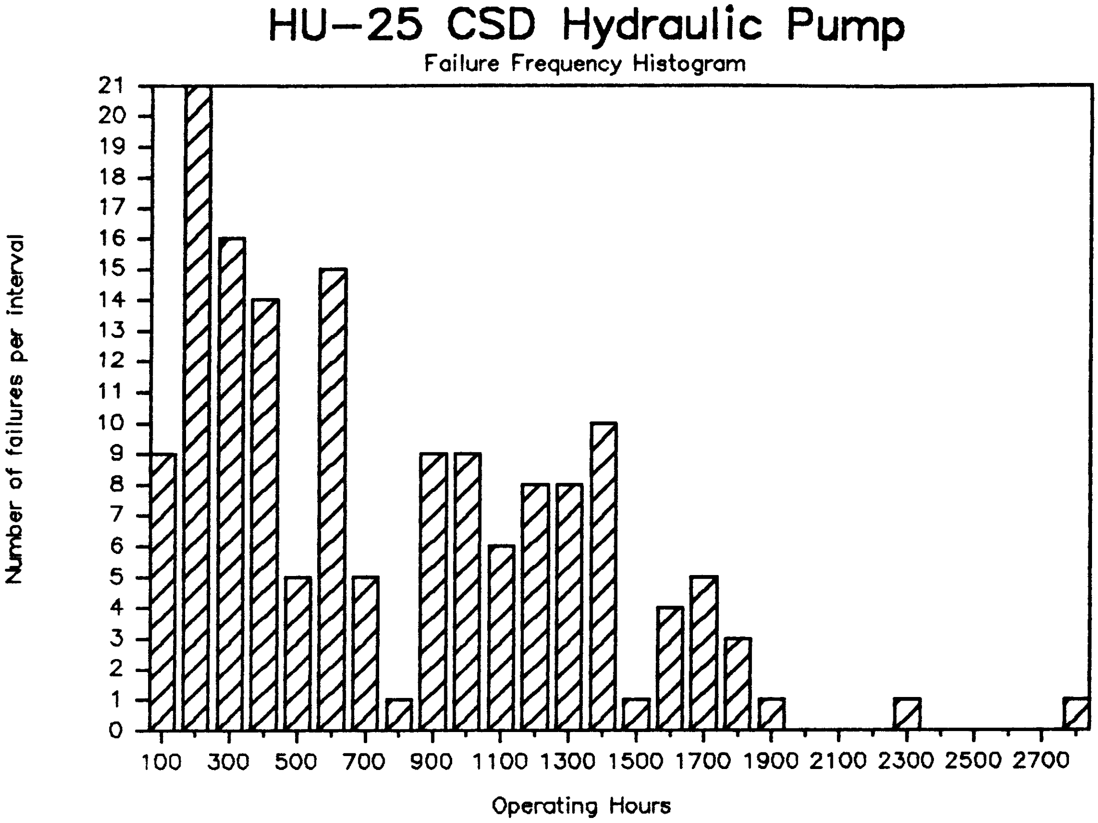

Figure 6-1

This bar graph depicts the number of failures experienced in each 100 hour interval.

It is not clear that this plot approximates any one of the previously mentioned types of failure distribution. It might appear to be a normal distribution, truncated at time zero, or some other type. The wide variety of distributions typically found in actual practice, show that the mean-time-between-failure (MTBF) is not a particularly useful statistic in determining age reliability relationships. For instance, the mean may be significantly skewed from the mode, which is the age exhibiting the highest number of failures. However, a symmetric histogram that indicates a high number of failures, tightly clustered about a specific age, would point to the existence of a predominate failure mode, characterized by the MTBF.

In the present case, further analysis will be necessary to fully investigate the reliability characteristics.

RELIABILITY FUNCTION

The next step in an analysis might be derivation of observed reliability statistics. This is best derived by first computing the reliability function, or probability of survival described by the sample data.

Probability of survival, P(s), is based on the number of pumps in the sample population that survive to a given age. The specific values of P(f) and P(s) for each failure point are computed in Table 6-1. They were calculated for each specific age using the following formula:

$$P(s) = \frac{N_s}{N_t}$$

Where:

N_s = Number of pumps surviving to the given age.

N_t = Total number in the population

The probability of failure, P(f), is either:

$$P(f) = 1 - P(s)$$

or;

$$P(f) = \frac{N_f}{N_t}$$

Where: N_f = Number of the population failing.

A resultant plot of the survival curve is provided in Figure 6-2.

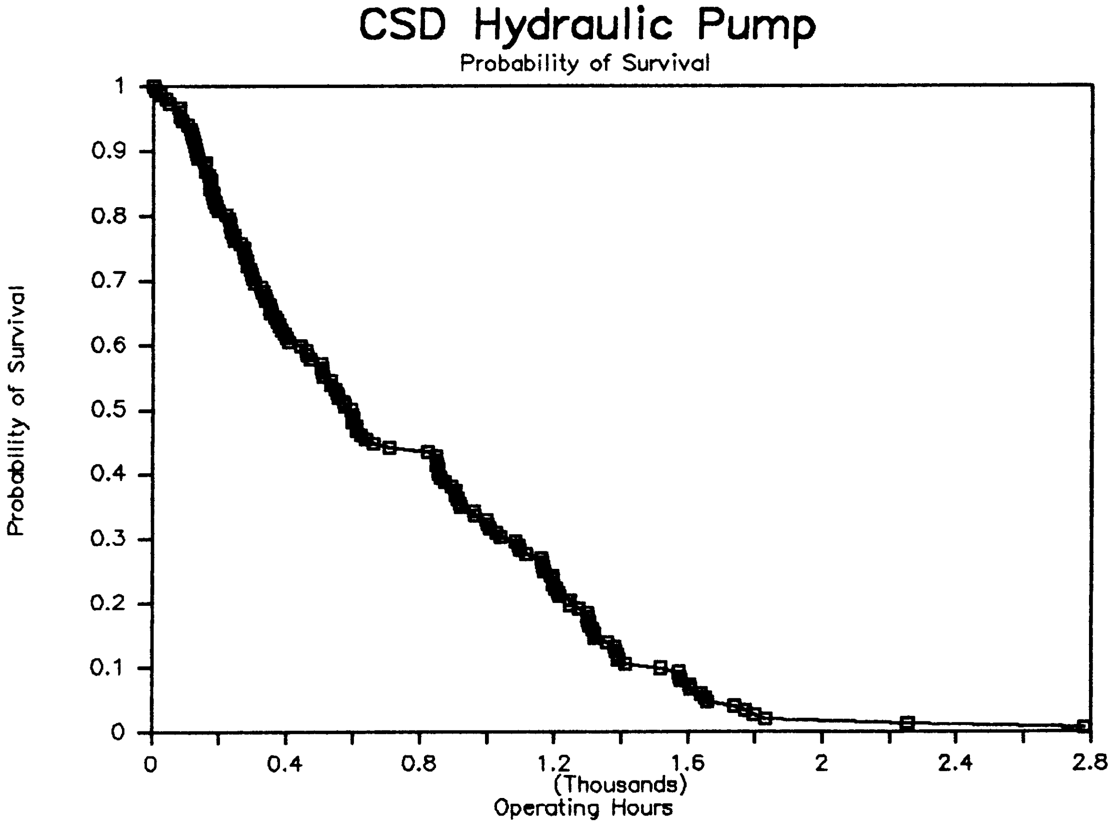

Figure 6-2

CONDITIONAL PROBABILITY OF FAILURE

What we would really like to know is: Given a component on the aircraft at a certain age, what is the probability that the component will survive a given interval beyond that age? As discussed in Chapter 2, this function is the conditional probability of failure.

The conditional probability of failure for the CSD pump has been derived for 100 hour intervals and is also included in Table 6-1. To provide consistent intervals, linear interpolations were accomplished to derive the necessary probabilities at even 100 hour intervals. Based on the apparent linearity of the previous survival curve, this linear interpolation should not significantly affect the analysis.

The conditional probability of failure, $P_c(f)$, is based on both the probability of survival to a given interval, and the probability of failure during the defined interval, in this case 100 hours. It is described by the following:

$$P_c(f) = \frac{P(s)_b - P(s)_e}{P(s)_b}$$

Where: $P(s)_e$ = Probability of surviving to the end of the interval.

$P(s)_b$ = Probability of surviving to the beginning of the interval.

The resultant plot of $P_c(f)$ versus age is provided as Figure 6-3. The straight line, which was fit to the curve using linear regression, is displayed in an attempt to demonstrate the upward trend.

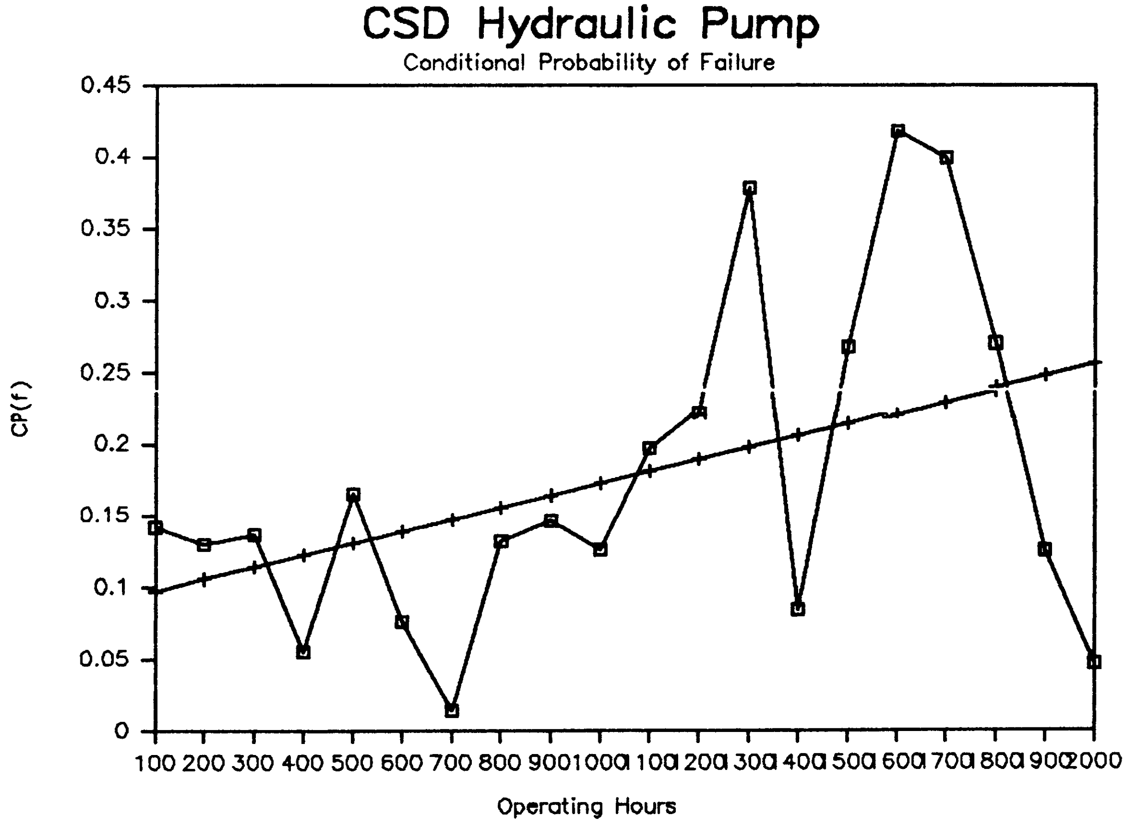

Figure 6-3

It does appear that the conditional probability of failure increases with age, but we need to analyze this further to determine how confident we can be that there _is_ an upward trend.

In analyzing the data, we must remember that the limiting TBO for this pump is either 1200 or 1800 hours.[1] Therefore, there will be little or no data for pumps that have survived beyond that general age range. There were only two pumps that remained in service beyond the maximum TBO (plus the allowable 10% extension). These may have been authorized age exploration extensions, but were most likely missed maintenance requirements.

CUMULATIVE EXPERIENCE

Another method to graphically depict the conditional probability of failure from a data set is the cumulative failure experience plot. Figure 6-4 is the plot resulting from the given data.

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[1] As per the ACMS maintenance requirements list. Two versions of the pump are presently in service, a modified pump is allowed to go to 1800 hours TBO, while the unmodified pump is allowed only 1200 hours TBO.

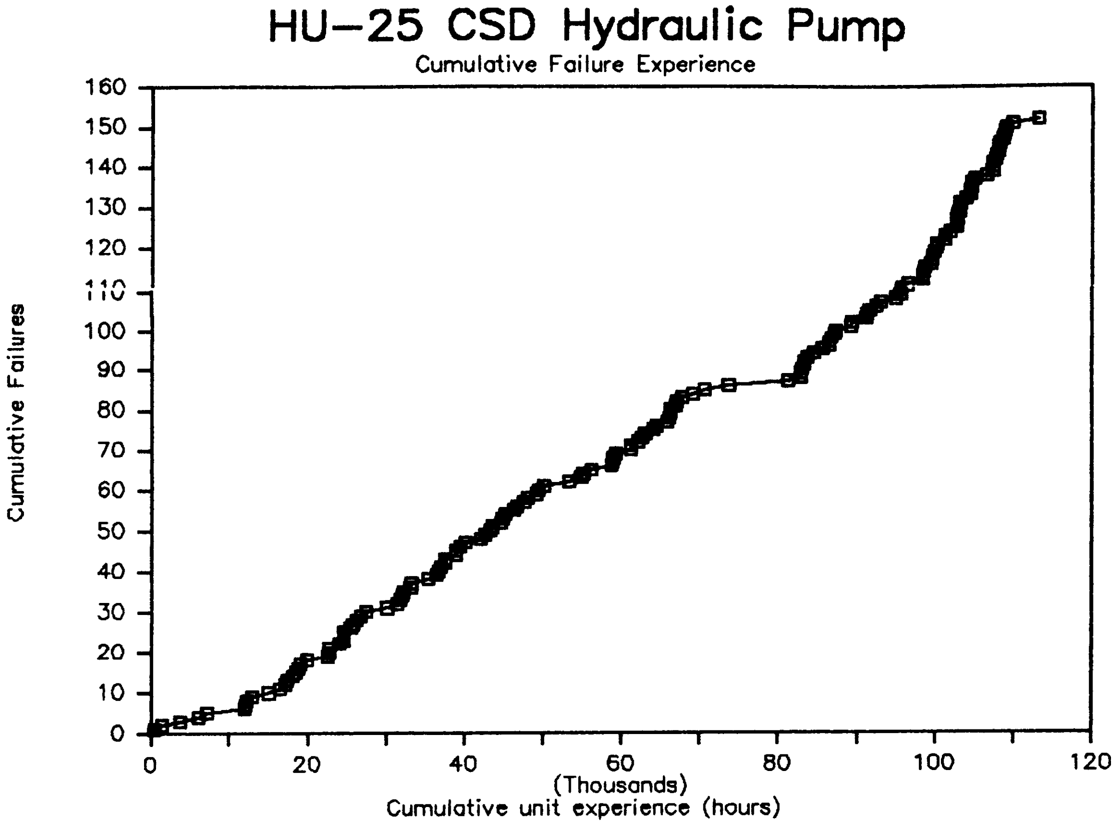

Figure 6-4

This curve is derived by computing the cumulative operating experience up to each failure age. The cumulative number of failures are then plotted versus cumulative experience.

This computation is easily done on the personal computer and the data for this plot is provided in Table 6-2 at the end of this chapter. This plot yields a larger number of data points and therefore, a distribution which appears more continuous than the discrete points defining the conditional probability curve of Figure 6-3.

The slope of this curve, at any point, is the conditional probability of failure at that point of _cumulative experience_. However, one must remember that the _slope_ is the conditional probability, not the point value. Note that in this case, the slope, and therefore the conditional probability of failure, is relatively constant, since the graph is nearly linear. Although cumulative experience is not synonymous with age, the data is sorted by increasing age, and therefore, the higher levels of cumulative experience should represent higher ages. To be meaningful, the data _must_ be sorted by increasing age.

This perception of a constant slope somewhat contradicts the feeling from Figure 6-3, that conditional probability of failure increases with age.

STATISTICAL SIGNIFICANCE

To determine which of these graphs provides the more accurate depiction, there are several statistical measures that might be useful.

To estimate our level of confidence in the upward trend appearing in our plot of conditional probability (Figure 6-3), several methods will be demonstrated.

First, a linear regression was performed to provide an equation describing the "best fit" line. The resultant equation was found to be:

$$P_c(f) = (0.000083576 \times \text{Hours}) + 0.08913$$

A Pearson correlation coefficient, (R), was then derived, in an attempt to describe the significance of the correlation between conditional probability of failure and age. Since the actual plot exhibits large variations, the coefficient of determination (R^2) was computed to be only 0.18026. This means that, based on the sample data set, about 18% of the variance in conditional probability can be explained by the variance in age, and vice versa. This is not a particularly significant correlation.

What we really would like to know is whether there is any upward trend. If conditional probability of failure does not increase with age, then a life limit or maximum TBO will not be effective in maintaining reliability.

Another method of investigating this would be to derive a t-statistic for the null hypothesis of a zero (0) correlation coefficient (no correlation). The t-statistic was found to be 1.83. After entering a standard table containing the distribution of "t" for given probability levels, the level of significance was found to be slightly better than 10%.[2] This was based on a two-tailed test, since I assumed that the slope may be negative or positive. A one-tailed test would yield a higher level of

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2. Zikmund, William G., Business Research Methods, (New York: The Dryden Press, 1988), Table 7, p. 698.

significance, but since the coefficient is so close to zero, I chose the more rigorous two-tailed test.

There are also tables available that allow entering directly with the Pearson correlation coefficient and of course, yield the same result. The 10% figure indicates that there is about a 10% chance of obtaining such a coefficient even if age and conditional probability are completely unrelated. Again, this is somewhat inconclusive.

To further examine this trend, we might derive Spearman's rank correlation coefficient (Rho). This coefficient measures the correspondence between two <u>rankings</u>. To derive this coefficient, the conditional probabilities are first rank ordered according to data predictions. Then they are rank ordered in ascending order of magnitude. These two rankings are then compared. Spearman's Rho is defined as:

$$\mathrm{Rho} = 1 - \frac{6S_r}{n^3 - n}$$

Where: S_r = the sums of the squared differences between the actual and ascending value ranks.

n = number of pairs of data points.

Table 6-3 provides the basis for this calculation. As indicated in the table, Rho is computed to be 0.287218. Based on reference to a standard statistical table, given that n = 20, there is greater than a 10 % chance of getting such a P-value even if the failure rates are completely uncorrelated with age.[3] If this is the case, an age limit would not decrease the overall failure rate.

OVERHAUL EFFECTIVENESS

Another reliability factor worthy of consideration is the effectiveness of overhaul. In other words, does an overhaul restore the component to a like-new status, characterized by the same reliability as a new part?

While manually entering the raw data into the personal computer, it appeared to me that overhauled pumps exhibited significantly shorter lives than new pumps. To research this perception, I developed Table 6-4. As indicated at the end of the table, an overhauled pump has, on average, a life that is 487 hours shorter than a new one. Of the total number of overhauls (57), 75.4% experienced a reduced subsequent life from that prior to the overhaul. Additionally, the MTBF of a new pump was 1010 hours, while the MTBF of an overhauled pump was only 349 hours.

One factor that could affect the accuracy of these statistics, is that we are dealing with <u>censored</u> data. In other words, the data does not include pumps that remained in operation at the end of the sampling period. These

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[3] Beyer, William H., <u>Handbook of Tables for Probability and Statistics, 2nd Edition</u>, (Boca Raton: CRC Press Inc., 1988), p. 447.

operating pumps might add to the MTBF of the overhauled group and minimize the MTBF difference.

A more accurate method of making an analysis to determine the difference in the MTBFs would be to include the operating pumps in the data base, thereby producing uncensored data. In this case, the uncensored data was difficult to obtain, given field level ACMS query limitations. Since this limitation does not exist at the mainframe, it should not be a problem for the analyst. When dealing with relatively short sampling periods or small sample sizes, the censoring of data can have significant effects and should be avoided if at all possible.

In this particular example, based on the length of the sampling period, and the total number of pumps sampled versus those remaining in operation, the difference between censored and uncensored data should not be significant.

Assuming the censored data to be accurate, then, to test the significance of the difference between the MTBFs, a "Z" statistic of 9.512634 was derived. Entering a standard table resulted in the conclusion that there was virtually no probability that these means were equal or that this variation was by chance alone. This finding is statistically significant and should activate a critical review of the quality of overhaul or overhaul specifications. A new pump, on average, appears to survive nearly three times as long as one that has been overhauled.

OVERALL EVALUATION

In summary, we cannot demonstrate with any reasonable level of confidence, that the conditional probability of failure for the CSD pump increases with age. That does not mean, of course, that there is no increase. Regardless, the existence of a required overhaul at 1200 or 1800 hours could well be inefficient. The failure rate remains high, yet the established life limit (maximum TBO) should not assist in lowering that rate. In fact, if the overhaul effectiveness is as bad as it seems, then an overhaul requirement may be hindering reliability.

The CSD conditional probability failure data exhibits significant variability and a curve or continuous function cannot be closely fit. Normally, a smooth curve might be fit to the data to allow the prediction of point values. Had the distribution approximated normal, exponential, or Weibull distributions, an equation describing the curve could have been derived. Point values could have then been predicted based on inputs to the equation.

Since we do not have a significant amount of data on pumps that remain in service beyond 2000 hours, a reasonable recommendation would be to select a sample of pumps and allow them to continue past 2000 hours. We could then follow these pumps closely to investigate the age-reliability characteristics beyond 2000 hours.

Another recommendation would be to extend all operating pumps to 3000 hours maximum TBO and then closely monitor failure rates. If, in fact, the failure distribution is exponential, then overall failure rates should remain stable.

ECONOMIC ANALYSIS OF TBO LIMITS

Since it appears that the procedure of overhauling pumps at a certain age limit does not assist with reliability goals, an economic analysis is in order. Assuming the previous statement is true, it follows that life limit generated overhauls provide no reduction of direct maintenance or operational costs. They will, in fact, add maintenance costs by requiring early removal of pumps that would otherwise continue in operation. Over the period covered by the data, only 15 pumps required overhaul due to reaching the maximum TBO. This is 10% of the 152 records, and corresponds very closely with the probability of survival to 1500 hours of 9.98%.

The only economic benefit of a limiting TBO might be a reduction in overhaul costs. If there was a failure mode at the higher ages which caused an increased overhaul cost or complete replacement, then a limiting TBO might be economically justified. The TBO limit would also have to reduce the incidence of this undesirable failure mode to be effective.

. Based on the limited significant component history record (SCHR) comments, it appears that even catastrophic pump failure was not age related. There were not enough mechanic remarks available to determine whether this was a correct observation. This lack of data supports the need for thorough mechanic comments.

The overhaul facility may be able to provide data on overhaul costs versus time since preceding overhaul (TSO). If available, this data could be used to analyze the economic efficiency of life limits versus operation to failure.

In this particular case, the assumed exponential failure distribution, and corresponding constant failure rate, will result in a total number of failures based only on hours of operation, irrespective of TBO limits. Any pumps removed for the TBO-required overhauls will be in addition to the overhauls generated by operating failures. Recently installed pumps will experience conditional probabilities of failure identical to the older pumps they replaced.

If failure rate increased with age, then as the TBO limit is decreased, the number of overhauls generated by failures should decrease and the number of failures generated by the TBO limitation should increase. To analyze this type of situation, the cost per hour should be derived for several different TBO limits, and the lowest cost per hour chosen.

Each lower TBO choice should generate a lower MTBF, by not allowing some number of pumps to continue past the limit. A TBO limit, in effect, truncates the higher end of the failure distribution, and therefore, reduces the mean.

In analyzing actual data, several hypothetical TBO limits might be set. The MTBF, corresponding to each TBO, could then be derived based on the sample data.

The total <u>average</u> overhaul cost per hour is given by:

$$\text{Cost/Hour} = \frac{[P(s)_{tbo} * C_{(tbo)}] + [P(f)_{tbo} * C_{(Fail)}]}{[P(s)_{tbo} * \text{TBO}] + [P(f)_{tbo} * \text{MTBF}]}$$

Where:

$P(s)_{tbo}$ = Probability of survival to TBO

$P(f)_{tbo}$ = Probability of Failure prior to TBO

$C_{(tbo)}$ = Cost of a TBO Generated Overhaul

$C_{(Fail)}$ = Cost of a failure generated overhaul

When the probability of survival to the limiting TBO is as small as in this case (10%), the TBO policy can have little effect of overall long term average costs. Too few pumps will reach the TBO limit. The above calculation neglects the maintenance cost of removing and replacing a pump that reached TBO limit. When a significant number of pumps begin to reach the TBO limit, then those costs must be added to the computation to maintain accuracy.

Of course the ideal situation from an efficiency standpoint is to operate the components to failure. This is justifiable only if reliability is not compromised, the difference between failure and overhaul costs are insignificant, and there are no safety related failure modes. This policy allows use of the entire failure distribution to maximize MTBF, thereby minimizing costs. When operating to failure, without a TBO limit, the average hourly overhaul cost is simply:

$$\text{Cost/Hour} = \frac{\text{Ovhl Cost}}{\text{MTBF}}$$

ECONOMIC ANALYSIS OF OVERHAUL FEASIBILITY

The MTBF statistics for overhauled and new pumps, derived during the overhaul effectiveness analysis, also provides data for another type of economic feasibility analysis. Given those statistics, we can examine the economic efficiency of overhauling pumps, versus purchasing new ones.

We will assume that the supply of new pumps is sufficient to provide all that would be required without causing excess demand and associated higher prices. Prior to making management decisions based on such an analysis, the accuracy of this assumption should be verified.

We found in the previous overhaul effectiveness analysis that an overhauled pump lasts only one-third as long as a new pump. (MTBF_{new}=1010 hours, MTBF_{ovhl}=349 hours) The cost per hour for each will be given by:

$$\text{Cost per Hour}_{(new)} = \frac{\text{Cost of New}}{\mathrm{MTBF}_{(new)}}$$

$$\text{Cost per Hour}_{(ovhl)} = \frac{\text{Cost of Ovhl}}{\mathrm{MTBF}_{(ovhl)}}$$

In this case, an overhaul would have to average approximately one third (1/3) of the cost of a new pump to produce an hourly cost equal to that of a new pump. This type analysis should be done on all repairable items, particularly those with overhaul costs which are high relative to new costs.

RECOMMENDATIONS

Based on the above analysis, and my maintenance experience, I would recommend that the Coast Guard consider extending the CSD pump TBO limit to 3000 hours.

The previous analysis seems to indicate that any increase in the probability of failure with age is minimal at best. Therefore, this extension of the TBO limit should have no significant affect on reliability. The lack of inherent reliability, particularly that of an overhauled pump, is the key factor. The economic gain by slightly reducing the number of overhauls should more than offset any other affects. It is possible that this extension might even increase MTBF slightly.

We still need to closely monitor the failure rate of the extended pumps to ensure that there is not an unexpected failure mode or any significant change in conditional probability of failure beyond 2000 hours. Once data is available to predict failure rates beyond 2000 hours, an analysis should be conducted to explore further extensions to the TBO limit.

Another factor to consider before adopting <u>any</u> new policy is the <u>perception</u> of those involved in the maintenance program. Based on the CSD pump's known <u>lack</u> of reliability, this extension may appear very unsound to those not familiar with reliability concepts. This <u>perception</u> of impropriety is worthy of consideration. As previously discussed, credibility is very <u>important</u>. If adopted, the justification behind the TBO extension should be clearly communicated to the mechanics. Without an explanation, the extension might be viewed as simply an unsound effort by management to ease an existent parts shortage.

In the meantime, in conjunction with the manufacturer, a redesign effort should be commenced to improve the inherent reliability of the pump to an acceptable level. At the very least, a significant portion of the units should be expected to survive to the limiting TBO.

Additionally, a critical analysis of overhaul procedures should be carried out. Depending on the cost of an overhaul versus the cost of a new pump, the maintenance program may save money and significantly increase reliability by electing to use only new pumps on the aircraft.

SUMMARY

The techniques and concepts presented above should provide several ideas to assist with component reliability and economic analyses. The analyst must continually be aware, that even given high degrees of statistical significance, correlation can never guarantee causation. The accuracy of the final conclusions will still be primarily based on experience and common sense.

Raw Data		Calculated Data				
Serial Number	Time to Failure	P(f)	P(s)	100hr Intervals	Linear Interpolated P(s)	Conditional Probability of Failure
016M896	3	0.0000	1.0000			
144M3461	9	0.0066	0.9934			
005M668	25	0.0132	0.9868			
105M2456	41	0.0197	0.9803			
017	48	0.0263	0.9737			
082M1570	80	0.0329	0.9671			
046M1181	81	0.0395	0.9605			
144M3461	82	0.0461	0.9539			
067M1470	87	0.0526	0.9474	100	0.941666	0.142249
003M690	102	0.0592	0.9408			
118M2575	112	0.0658	0.9342			
003M690	117	0.0724	0.9276			
065M1662	119	0.0789	0.9211			
035M1133	124	0.0855	0.9145			
074	127	0.0921	0.9079			
135M3451	129	0.0987	0.9013			
075	131	0.1053	0.8947			
057M1302	137	0.1118	0.8882			
110M2482	156	0.1184	0.8816			
110M2482	158	0.1250	0.8750			
063M1354	158	0.1316	0.8684			
088M1755	168	0.1382	0.8618			
042	172	0.1447	0.8553			
014M923	172	0.1513	0.8487			
031M884	172	0.1579	0.8421			
023M777	179	0.1645	0.8355			
064M1659	181	0.1711	0.8289			
111M2563	185	0.1776	0.8224			
012M694	189	0.1842	0.8158			
107	195	0.1908	0.8092	200	0.807715	0.129828

Table 6-1

060M1355	217	0.1974	0.8026			
137M3453	227	0.2039	0.7961			
028M882	231	0.2105	0.7895			
084M1759	233	0.2171	0.7829			
080M1567	234	0.2237	0.7763			
082M1570	242	0.2303	0.7697			
110M2482	243	0.2368	0.7632			
084M1759	262	0.2434	0.7566			
075	271	0.2500	0.7500			
024	274	0.2566	0.7434			
047	276	0.2632	0.7368			
093M2382	281	0.2697	0.7303			
019M898	281	0.2763	0.7237			
M3457	293	0.2829	0.7171			
052M1235	294	0.2895	0.7105			
124	299	0.2961	0.7039	300	0.702850	0.137240
021M001	305	0.3026	0.6974			
005M668	323	0.3092	0.6908			
068M1661	328	0.3158	0.6842			
024	335	0.3224	0.6776			
113M2567	338	0.3289	0.6711			
020	349	0.3355	0.6645			
104	351	0.3421	0.6579			
017	354	0.3487	0.6513			
028M882	366	0.3553	0.6447			
015	370	0.3618	0.6382			
043	379	0.3684	0.6316			
052M1235	384	0.3750	0.6250			
121M2578	395	0.3816	0.6184			
008M692	399	0.3882	0.6118			
063M1354	406	0.3947	0.6053	400	0.606390	0.055056
126	441	0.4013	0.5987			
060M1355	458	0.4079	0.5921			
040M1075	461	0.4145	0.5855			
039M1073	472	0.4211	0.5789	500	0.573005	0.165296

Table 6-1 (continued)

080M1567	503	0.4276	0.5724			
038M1076	504	0.4342	0.5658			
052M1235	505	0.4408	0.5592			
086M1761	509	0.4474	0.5526			
067M1470	532	0.4539	0.5461			
013M922	532	0.4605	0.5395			
095M2379	544	0.4671	0.5329			
134M3450	550	0.4737	0.5263			
123	555	0.4803	0.5197			
023M777	569	0.4868	0.5132			
126	574	0.4934	0.5066			
M819026	592	0.5000	0.5000			
107	595	0.5066	0.4934			
135M3451	597	0.5132	0.4868			
121M2578	597	0.5197	0.4803	600	0.478289	0.076610
068M1661	607	0.5263	0.4737			
119M2576	608	0.5329	0.4671			
074	619	0.5395	0.4605			
137M3453	638	0.5461	0.4539			
077M1563	660	0.5526	0.4474	700	0.441647	0.014119
122M2579	706	0.5592	0.4408	800	0.435411	0.132270
035M1133	821	0.5658	0.4342			
029M883	846	0.5724	0.4276			
113M2567	846	0.5789	0.4211			
128	849	0.5855	0.4145			
035M1133	853	0.5921	0.4079			
033M887	854	0.5987	0.4013			
104	860	0.6053	0.3947			
M3448	873	0.6118	0.3882			
038M1076	892	0.6184	0.3816	900	0.377819	0.146766
139M3456	906	0.6250	0.3750			
M2399	906	0.6316	0.3684			
065M1662	912	0.6382	0.3618			
061M1468	919	0.6447	0.3553			
097	921	0.6513	0.3487			

Table 6-1 (continued)

M2898	959	0.6579	0.3421			
125M2896	962	0.6645	0.3355			
116M2564	997	0.6711	0.3289			
141	1000	0.6776	0.3224	1000	0.322368	0.126745
090M1762	1007	0.6842	0.3158			
002M685	1026	0.6908	0.3092			
134M3450	1039	0.6974	0.3026			
079M1566	1082	0.7039	0.2961			
081M1569	1094	0.7105	0.2895			
046M1181	1096	0.7171	0.2829	1100	0.281509	0.196648
013M922	1115	0.7237	0.2763			
119M2576	1161	0.7303	0.2697			
017	1164	0.7368	0.2632			
023M777	1167	0.7434	0.2566			
114M2568	1171	0.7500	0.2500			
122M2579	1190	0.7566	0.2434			
102	1194	0.7632	0.2368			
138M3454	1195	0.7697	0.2303	1200	0.226151	0.224242
084M1759	1203	0.7763	0.2237			
062M1351	1211	0.7829	0.2171			
M3459	1214	0.7895	0.2105			
093M2382	1247	0.7961	0.2039			
016M896	1247	0.8026	0.1974			
124	1273	0.8092	0.1908			
082M1570	1298	0.8158	0.1842			
014M923	1299	0.8224	0.1776	1300	0.175438	0.378571
025M779	1302	0.8289	0.1711			
086M1761	1304	0.8355	0.1645			
031M884	1314	0.8421	0.1579			
100M2377	1318	0.8487	0.1513			
073	1320	0.8553	0.1447			
136M3452	1357	0.8618	0.1382			
051M1234	1381	0.8684	0.1316			
044M1006	1384	0.8750	0.1250			
085	1390	0.8816	0.1184			

Table 6-1 (continued)

M1758091	1391	0.8882	0.1118	1400	0.109022	0.084580
M3457	1412	0.8947	0.1053	1500	0.099801	0.267269
100M2377	1518	0.9013	0.0987			
063M1354	1572	0.9079	0.0921			
057M1302	1576	0.9145	0.0855			
034M1008	1577	0.9211	0.0789	1600	0.073127	0.418001
131M3447	1603	0.9276	0.0724			
123	1608	0.9342	0.0658			
118M2575	1638	0.9408	0.0592			
129M3445	1652	0.9474	0.0526			
042	1657	0.9539	0.0461	1700	0.042560	0.399345
105M2456	1738	0.9605	0.0395			
103M2385	1770	0.9671	0.0329			
011M693	1796	0.9737	0.0263	1800	0.025563	0.270020
092M1568	1831	0.9803	0.0197	1900	0.018661	0.125974
106M2457	2253	0.9868	0.0132	2000	0.016310	0.047034
041	2781	0.9934	0.0066	2100	0.015543	

Table 6-1 (continued)

CSD Pump Cumulative Experience Data

Operating Experience Calculations

Cumul. Failures	Cumul. Oper. Exper.	Regressed Points
1	456	-7.48754
2	1362	-6.30185
3	3762	-3.16096
4	6146	-0.04100
5	7182	1.314815
6	11886	7.470971
7	12032	7.662043
8	12177	7.851805
9	12897	8.794074
10	15042	11.60125
11	16462	13.45961
12	17167	14.38225
13	17447	14.74868
14	18142	15.65824
15	18556	16.20004
16	18830	16.55863
17	19102	16.91459
18	19912	17.97465
19	22458	21.30661
20	22724	21.65473
21	22724	21.65473
22	24034	23.36914
23	24554	24.04966
24	24554	24.04966
25	24554	24.04966
26	25443	25.21310
27	25695	25.54290

Regression Output:

Constant		-8.08431
Std Err of Y Est		5.663880
R Squared		0.983556
No. of Observations		152
Degrees of Freedom		150
X Coefficient(s)	0.001308	
Std Err of Coef.	0.000013	

Table 6-2

CSD Pump Cumulative Experience Data

28	26195	26.19725
29	26691	26.84637
30	27429	27.81220
31	30113	31.32476
32	31323	32.90830
33	31803	33.53648
34	32041	33.84795
35	32159	34.00238
36	33095	35.22733
37	33211	35.37914
38	35396	38.23866
39	36422	39.58140
40	36761	40.02505
41	36985	40.31820
42	37540	41.04453
43	37540	41.04453
44	38848	42.75632
45	38956	42.89766
46	39491	43.59782
47	40127	44.43015
48	42017	46.90361
49	42537	47.58414
50	43258	48.52771
51	43564	48.92818
52	44675	50.38215
53	44875	50.64389
54	45172	51.03258
55	46348	52.57162
56	46736	53.07940
57	47600	54.21012
58	48075	54.83175
59	49109	56.18496

Table 6-2 (continued)

CSD Pump Cumulative Experience Data

60	49481	56.67180
61	50125	57.51460
62	53310	61.68283
63	54840	63.68516
64	55107	64.03458
65	56075	65.30141
66	58772	68.83099
67	58858	68.94354
68	58943	69.05478
69	59279	69.49451
70	61188	71.99283
71	61188	71.99283
72	62160	73.26489
73	62640	73.89307
74	63035	74.41001
75	64127	75.83912
76	64512	76.34297
77	65880	78.13328
78	66105	78.42774
79	66253	78.62143
80	66253	78.62143
81	66973	79.56369
82	67044	79.65661
83	67814	80.66432
84	69125	82.38003
85	70621	84.33786
86	73703	88.37129
87	81293	98.30438
88	82918	100.4310
89	82918	100.4310
90	83107	100.6783
91	83355	101.0029

Table 6-2 (continued)

CSD Pump Cumulative Experience Data

92	83416	101.0827
93	83776	101.5538
94	84543	102.5576
95	85645	103.9998
96	86443	105.0442
97	86443	105.0442
98	86773	105.4760
99	87151	105.9707
100	87257	106.1095
101	89233	108.6955
102	89386	108.8957
103	91136	111.1859
104	91283	111.3783
105	91619	111.8180
106	92512	112.9867
107	93110	113.7693
108	95045	116.3017
109	95573	116.9927
110	95659	117.1052
111	96457	118.1496
112	98343	120.6178
113	98463	120.7748
114	98580	120.9279
115	98732	121.1269
116	99435	122.0469
117	99579	122.2353
118	99614	122.2811
119	99886	122.6371
120	100150	122.9826
121	100246	123.1082
122	101269	124.4471
123	101269	124.4471

Table 6-2 (continued)

CSD Pump Cumulative Experience Data

124	102023	125.4338
125	102723	126.3499
126	102750	126.3853
127	102828	126.4873
128	102878	126.5528
129	103118	126.8669
130	103210	126.9873
131	103254	127.0448
132	104031	128.0617
133	104511	128.6899
134	104568	128.7645
135	104676	128.9058
136	104693	128.9281
137	105029	129.3678
138	106619	131.4486
139	107375	132.4380
140	107427	132.5061
141	107439	132.5218
142	107725	132.8961
143	107775	132.9615
144	108045	133.3149
145	108157	133.4614
146	108192	133.5072
147	108678	134.1433
148	108838	134.3527
149	108942	134.4888
150	109047	134.6262
151	109891	135.7307
152	113200	140.0612

Table 6-2 (continued)

Spearman Coefficient Calculations

Spearman Calculations:

Sorted CP(f)	Sorted Rank		Data Rank	Difference Squared
0.014119	7		1	36
0.047034	20		2	324
0.055056	4		3	1
0.076610	6		4	4
0.084580	14		5	81
0.125974	19		6	169
0.126745	10		7	9
0.129828	2		8	36
0.132270	8		9	1
0.137240	3		10	49
0.196648	1		11	100
0.146766	9		12	9
0.165296	5		13	64
0.196648	11		14	9
0.224242	12		15	9
0.267269	15		16	1
0.270020	18		17	1
0.378571	13		18	25
0.399345	17		19	4
0.418001	16		20	16
			Total:	948

Spearman Rank Correlation Coefficient: 0.287218

Table 6-3

Overhaul Efficiency Calculations

Serial Number	Time to Removal	Removal Reason	Life Span Improvement Post Ovhl	# Ovhls	# Ovhls Impr. Life	# Ovhls Decr. Life
001M683	1278	Time	0	0	0	0
002M685	1026	F	0	0	0	0
003M690	102	F	15	1	1	0
003M690	117	F	0	0	0	0
005M668	323	F	-298	1	0	1
005M668	25	F	0	0	0	0
007M691	1449	Time	0	0	0	0
008M692	399	F	0	0	0	0
011M693	1796	F	0	0	0	0
012M694	189	F	0	0	0	0
013M922	1115	F	-583	1	0	1
013M922	532	F	0	0	0	0
014M923	1299	F	-1127	1	0	1
014M923	172	F	0	0	0	0
015	370	F	0	0	0	0
016M896	1247	Time	-1244	1	0	1
016M896	3	F	0	0	0	0
017	1164	F	-810	1	0	1
017	354	F	-306	1	0	1
017	48	F	0	0	0	0
019A	1747	Time	0	0	0	0
019M898	281	F	0	0	0	0
020	349	F	0	0	0	0
021M001	305	F	0	0	0	0
023M777	1167	F	-988	1	0	1
023M777	179	F	390	1	1	0
023M777	569	F	0	0	0	0
024	274	F	61	1	1	0

Table 6-4

Overhaul Efficiency Calculations

024	335	F	0	0	0	0
025M779	1302	F	0	0	0	0
028M882	366	F	-135	1	0	1
028M882	231	F	0	0	0	0
029M883	846	F	0	0	0	0
031M884	1314	F	-1142	1	0	1
031M884	172	F	0	0	0	0
033M887	854	F	0	0	0	0
034M1008	1577	F	0	0	0	0
035M1133	821	F	32	1	1	0
035M1133	853	F	-729	1	0	1
035M1133	124	F	0	0	0	0
038M1076	504	F	388	1	1	0
038M1076	892	F	0	0	0	0
039M1073	472	F	0	0	0	0
040M1075	1795	Time	-1334	1	0	1
040M1075	461	F	0	0	0	0
041	2781	F	0	0	0	0
042	1657	F	-1485	1	0	1
042	172	F	0	0	0	0
043	379	F	0	0	0	0
044M1006	1384	F	0	0	0	0
046M1181	1096	F	-1015	1	0	1
046M1181	81	F	0	0	0	0
047	276	F	0	0	0	0
051M1234	1381	F	0	0	0	0
052M1235	505	F	-121	1	0	1
052M1235	384	F	-90	1	0	1
052M1235	294	F	0	0	0	0
054M1237	3271	Time	0	0	0	0
055M1300	1795	Time	0	0	0	0
057M1302	1576	F	-1439	1	0	1

Table 6-4 (continued)

Overhaul Efficiency Calculations

057M1302	137	F	0	0	0	0
057M1349	1807	Time	0	0	0	0
060M1355	458	F	-241	1	0	1
060M1355	217	F	0	0	0	0
061M1468	919	F	0	0	0	0
062M1351	1211	F	554	1	1	0
062M1351	1765	Time	0	0	0	0
063M1354	1572	F	-1414	1	0	1
063M1354	158	F	248	1	1	0
063M1354	406	F	0	0	0	0
064M1659	181	F	0	0	0	0
065M1662	912	F	-793	1	0	1
065M1662	119	F	0	0	0	0
067M1470	532	F	-445	1	0	1
067M1470	87	F	0	0	0	0
068M1661	328	F	279	1	1	0
068M1661	607	F	0	0	0	0
073	1320	F	0	0	0	0
074	619	F	-492	1	0	1
074	127	F	0	0	0	0
075	1189	Time	-1058	1	0	1
075	131	F	140	1	1	0
075	271	F	0	0	0	0
077M1563	660	F	0	0	0	0
078M1664	1794	Time	0	0	0	0
079M1566	1082	F	0	0	0	0
080M1567	503	F	-269	1	0	1
080M1567	234	F	0	0	0	0
081M1569	1094	F	0	0	0	0
082M1570	1298	F	-1056	1	0	1
082M1570	242	F	-162	1	0	1
082M1570	80	F	0	0	0	0

Table 6-4 (continued)

084M1759	1203	F	-970	1	0	1
084M1759	233	F	29	1	1	0
084M1759	262	F	0	0	0	0
085	1390	F	0	0	0	0
086M1761	1304	F	-795	1	0	1
086M1761	509	F	0	0	0	0
088M1755	168	F	0	0	0	0
090M1762	1007	F	0	0	0	0
092M1568	1831	F	0	0	0	0
093M2382	1247	F	-966	1	0	1
093M2382	281	F	0	0	0	0
095M2379	544	F	0	0	0	0
097	921	F	0	0	0	0
098M2384	1772	Time	0	0	0	0
100M2377	1318	F	200	1	1	0
100M2377	1518	F	0	0	0	0
102	1194	F	0	0	0	0
103M2385	1770	F	0	0	0	0
104	860	F	-509	1	0	1
104	351	F	0	0	0	0
105M2456	1738	F	-1697	1	0	1
105M2456	41	F	0	0	0	0
106M2457	2253	F	0	0	0	0
107	195	F	400	1	1	0
107	595	F	0	0	0	0
109M2459	1797	Time	0	0	0	0
110M2482	243	F	-85	1	0	1
110M2482	158	F	-2	1	0	1
110M2482	156	F	0	0	0	0
111M2563	185	F	0	0	0	0
113M2567	338	F	508	1	1	0
113M2567	846	F	0	0	0	0

Table 6-4 (continued)

Overhaul Efficiency Calculations

114M2568	1171	F	0	0	0	0
116M2564	997	F	0	0	0	0
118M2575	1638	F	-1526	1	0	1
118M2575	112	F	0	0	0	0
119M2576	1161	F	-553	1	0	1
119M2576	608	F	0	0	0	0
120M2577	1733	Time	0	0	0	0
121M2578	597	F	-202	1	0	1
121M2578	395	F	0	0	0	0
122M2579	1190	F	-484	1	0	1
122M2579	706	F	0	0	0	0
123	1608	F	-1053	1	0	1
123	555	F	0	0	0	0
124	1273	F	-974	1	0	1
124	299	F	0	0	0	0
125M2896	962	F	0	0	0	0
126	441	F	133	1	1	0
126	574	F	0	0	0	0
127M2901	1172	Time	0	0	0	0
128	849	F	0	0	0	0
129M3445	1652	F	0	0	0	0
131M3447	1603	F	0	0	0	0
134M3450	1039	F	-489	1	0	1
134M3450	550	F	0	0	0	0
135M3451	597	F	-468	1	0	1
135M3451	129	F	0	0	0	0
136M3452	1357	F	0	0	0	0
137M3453	638	F	-411	1	0	1
137M3453	227	F	0	0	0	0
138M3454	1195	F	0	0	0	0
139M3456	906	F	0	0	0	0
141	1000	F	0	0	0	0

Table 6-4 (continued)

Overhaul Efficiency Calculations

143M3460	1705	Time	0	0	0	0
144M3461	82	F	-73	1	0	1
144M3461	9	F	0	0	0	0
M1356	2240	Time	0	0	0	0
M1758091	1391	F	0	0	0	0
M2399	906	F	0	0	0	0
M2898	959	F	0	0	0	0
M3448	873	F	0	0	0	0
M3457	1412	F	-1119	1	0	1
M3457	293	F	0	0	0	0
M3459	1214	F	0	0	0	0
M819026	592	F	0	0	0	0
Totals:			-27775	57	14	43

AVERAGE LIFE LOSS PER OVERHAUL: 487 HOURS

Percent Experiencing Shorter Subsequent Life: 75.4%

Percent Experiencing Longer Subsequent Life: 24.6%

Table 6-4 (continued)

CHAPTER SEVEN

RELIABILITY TRENDING MODEL

All maintenance programs are dynamic in nature. Therefore, it is useful to establish feedback mechanisms to provide information concerning the direction of reliability trends. Ideally, all failure rate trends will be downward, representing improving reliability. Of course, as aircraft systems age beyond a certain point, new reliability problems may surface that were previously unknown. A good tracking system can quickly identify undesirable trends, and may even assist with problem identification and solution.

This chapter will provide a brief example of a typical reliability trending model using actual data obtained from the ACMS data base. There are numerous variations to the techniques presented, and experience with the specific component or system will indicate which model design should be optimum.

ATF3 REMOVAL RATE TREND MODEL

The example presented is based on monthly removal data for the Garrett, ATF3-6-4C Turbofan engine. This engine is used on the HU-25 Falcon Fanjet, and is the same engine upon which the previously analyzed CSD pump is mounted. It is an advanced design, high-bypass turbofan engine that is just now reaching the mature stage. The engine has been in extensive fleet operation since about 1982. Numerous modifications have been made to the engine to improve performance and reliability.

Table 7-1 is a sample reliability trending model based on monthly removal rates and aircraft hours. This model was designed using a personal computer and standard spreadsheet software. All removals under the ACMS are classified by reason into four categories: Time, Trouble, Cannibalization, and Other.

INPUT VALUES

The only required input values are: total aircraft hours flown during the month, total engine removals, and a categorical listing of those removals by reason. All of this data is available from the ACMS data base. These values can be manually input monthly or a program can be written to automatically update this data. The computer will generate a trend rate, a 2 sigma alerting limit, and an alert notification in the event that the computed monthly value exceeds the established alert limit.

COMPUTATIONS

To recognize that there are two engines per aircraft, the engine hours are computed by multiplying the aircraft hours by a factor of two. The mean-time-between-removal for trouble, (MTBR Trbl), is computed by dividing the engine hours for the month by the number of removals for trouble. The removal rate is expressed per 1000 hours, and is computed by dividing MTBR Trbl into 1000.

The computer then performs a linear regression of removal-for-trouble rate versus the month, using only the last 12 months of data. This establishes the reliability trend. Using the regression coefficient and constant, the predicted point value for the trend is then calculated.

The computer also calculates the standard deviation of the last 12 months of removal-for-trouble data. A predetermined multiple of that standard deviation is then added to the predicted point value to establish an alert limit. In this case, a multiple of 2 was chosen. If the limit is exceeded by the calculated rate for that particular month, then "ALERT" is indicated in the alert column.

GRAPHIC REPRESENTATION

Figure 7-1 is a graphic representation of this trending model. The overall trend is indicated on the graph, although not shown on the spreadsheet model. The downward slope might confirm the improvements in reliability expected of a maturing system. Some of the previously demonstrated measures of statistical significance could be calculated to confirm this perception of an improving trend.

MODEL VARIATIONS

Several variations to this model should be considered and, based on actual usage, adopted to derive optimum results. For instance, the trend could be derived by linear regression of all data, not just the past twelve months. Removals for "other" reasons could be included. The alert level could be set at lower or higher factors to the standard deviation, depending on the desire to accept alerts caused by chance alone, and not truly indicative of an actual trend change.

Another consideration in modifying the model is that by using a multiple of the sample standard deviation, we account only for the variability of the data about the regression line, and do not take into consideration the uncertainties involved in estimating the line itself.

Although slightly more complex, there is a method to compute the alert limit that should be more sensitive and consistent. This method takes into account the uncertainty involved in the derivation of the regression line itself.

To compute this deviation, we use the variance defined by the standard error of the estimate. The standard error of the estimate (SEE) is produced by most computer software packages when performing linear regression analysis. The variance formula is given by:

$$\sigma^2 = \frac{\sum_1^n r_i^2}{n-2} * \left[1 + \frac{1}{n} + \frac{(t_{n+1} - \bar{t})^2}{\sum_1^n (t_i - \bar{t})^2} \right]$$

or;

$$\sigma^2 = \text{S.E.E.} * \left[1 + \frac{1}{n} + \frac{(t_{n+1} - \bar{t})^2}{\sum_1^n (t_i - \bar{t})^2} \right]$$

Where: S.E.E. = standard error of the estimate.

For any predetermined, fixed period over which the regression might be performed, the sum of the terms inside the parentheses will assume a constant value. For the example of a twelve month period, the formula will simplify to:

$$\sigma^2 = \text{S.E.E.} * 1.42$$

Then:

$$\sigma = (\text{S.E.E.})^{\frac{1}{2}} * 1.19$$

To apply this method, the derived standard deviation is again multiplied by some factor and added to the estimate to establish the alerting limit.

This method is technically more correct and, in the long run, should produce more consistent results. In this example, using a factor of 2 produced no alerts, while a factor of 1 duplicated the single alert provided by the sample standard deviation method. The use of this S.E.E. method in setting the alert limit should be considered a superior one, particularly when the data exhibits a well defined trend.

USE OF MODEL

This type model should be useful for monitoring items such as powerplants, pumps, generators, and any other serial number tracked components that generate enough meaningful removal data to justify the tracking effort. Based on a two sigma alert limit, and assuming a normally distributed removal rate function, there is approximately a 5% probability that an alert might be caused by chance variation alone. By varying the sigma multiplier, and using a standard "Z" value table, this probability can be manipulated as desired.

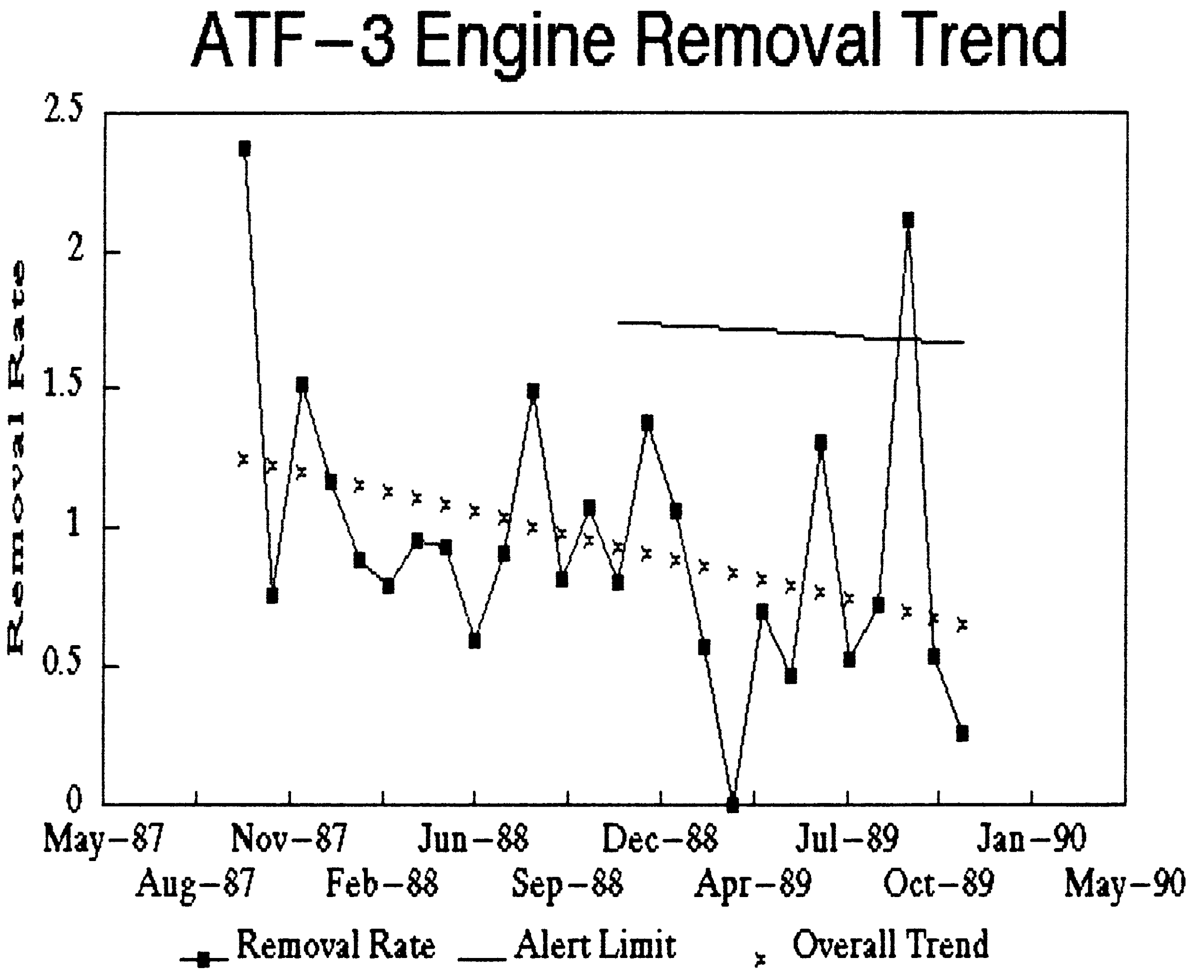
Using the programmers available at the ACMS mainframe, an automatic alerting model such as this should be easily designed and monitored. Should alerts occur, a quick investigation might determine causation.

The conscientious use of such a model could quickly identify undesirable trends, assist in investigating causation, and improve overall aircraft reliability.

Table 7-1

ATF-3 Trending Model

DATE	TIME	TRBL	CANN	OTHER	TOTAL REMOVALS	MTBR Trbl	MTBR ALL	ENG HRS	ACFT HRS	REMOV. RATE	TRBL RATE	PREDICTED RATE	PREDICTED (+2 Sigma)	ALERT
01-Oct-87	0	7	7	1	15	423	197	2962	1481	5.064	2.363			
01-Nov-87	1	5	2	4	12	1308	545	6538	3269	1.835	0.765			
02-Dec-87	0	5	0	1	6	660	550	3300	1650	1.818	1.515			
02-Jan-88	0	4	2	2	8	858	429	3432	1716	2.331	1.166			
02-Feb-88	0	3	1	3	7	1121	481	3364	1682	2.081	0.892			
04-Mar-88	3	3	5	1	12	1263	316	3790	1895	3.166	0.792			
04-Apr-88	0	3	14	0	17	1041	184	3124	1562	5.442	0.960			
05-May-88	0	3	3	3	9	1071	357	3214	1607	2.800	0.933			
05-Jun-88	0	2	1	0	3	1683	1122	3366	1683	0.891	0.594			
06-Jul-88	1	3	1	0	5	1095	657	3284	1642	1.523	0.914			
06-Aug-88	0	5	1	0	6	671	559	3354	1677	1.789	1.491			
06-Sep-88	0	3	0	3	6	1227	613	3680	1840	1.630	0.815			
07-Oct-88	0	4	1	0	5	932	746	3728	1864	1.341	1.073			
07-Nov-88	0	3	0	2	5	1238	743	3714	1857	1.346	0.808	0.8417655	1.897404	
08-Dec-88	1	5	3	2	11	728	331	3638	1819	3.024	1.374	0.8354451	1.891084	
08-Jan-89	1	4	3	2	10	945	378	3780	1890	2.646	1.058	0.8291246	1.884764	
08-Feb-89	0	2	1	1	4	1759	880	3518	1759	1.137	0.569	0.8228042	1.878443	
11-Mar-89	0	0	2	4	6	0	725	4348	2174	1.380	0.000	0.8164838	1.872123	
11-Apr-89	1	3	0	2	6	1417	708	4250	2125	1.412	0.706	0.8101634	1.865802	
12-May-89	0	2	1	2	5	2152	861	4304	2152	1.162	0.465	0.8038430	1.859482	
12-Jun-89	0	5	1	0	6	764	637	3822	1911	1.570	1.308	0.7975226	1.853162	
13-Jul-89	0	2	1	2	5	1882	753	3764	1882	1.328	0.531	0.7912022	1.846841	
13-Aug-89	2	3	1	2	8	1369	513	4106	2053	1.948	0.731	0.7848818	1.840521	
13-Sep-89	3	8	2	2	15	475	253	3796	1898	3.952	2.107	0.7785614	1.834200	*ALERT*
14-Oct-89	4	2	0	2	8	1860	465	3720	1860	2.151	0.538	0.7722410	1.827880	
14-Nov-89	1	1	1	2	5	3918	784	3918	1959	1.276	0.255	0.7659206	1.821560	
15-Dec-89														
15-Jan-90														
15-Feb-90														
18-Mar-90														



Source: ACMS Data Base

Figure 7-1

CHAPTER EIGHT

CONCLUSION

After researching the RCM field, I believe there are some significant opportunities for the application of RCM techniques to the United States Coast Guard aircraft maintenance programs.

Prior to beginning my research, and knowing very little about maintenance program design, particularly with respect to RCM techniques, I surmised that the Coast Guard was probably in the dark ages when it came to designing an efficient maintenance program. After extensive review, I found that this was not the case. Of course there are always areas for improvement, but in general, the areas that I analyzed showed that the Coast Guard had been very astute in deciding what tasks should be done, and how often. I did not locate a specific source of this astuteness, but it was generally pervasive. I interviewed numerous maintenance managers, and none of them claimed any knowledge of RCM. Nonetheless, many of the RCM concepts had previously been applied to modify the more mature maintenance programs. I did not review the newest maintenance program, that of the HH-65A "Dauphin" helicopter, because I did not have access to the data base containing the specifics of that aircraft's program. I did thoroughly review the maintenance program for the HU-25 "Falcon" fanjet, and found many modifications that had already been made in compliance with RCM guidelines.

The major area that I found still needing improvement was the development of a structured and consistent method of modifying the maintenance programs. The present system for modification is, at best, random. Although the more mature programs seem to have been significantly modified, I'm sure that it did not occur in the most efficient or timely manner. Given the recent addition of the HH-65 aircraft to the fleet, and the present transition to the HH-60J aircraft, there will be significant opportunities to fine tune these new programs. Of course, even a mature program needs to remain dynamic, but new programs should present vast opportunities for efficiency and reliability enhancements.

The formal integration of reliability-centered-maintenance concepts into the overall maintenance program may require the addition of resources, but based on the experience of civilian industry, the investment should prove to be very cost effective.

APPENDICES

APPENDIX 1

COAST GUARD AIRCRAFT

RESOURCES

Coast Guard Aircraft

FIXED WING:

HC-130H (Hercules)	31	
HU-25(A/B/C) (Falcon)	41	
E-2C (Hawkeye)	2	
RG-8A (Recon)	2	
Subtotal:	76	

ROTARY WING:

HH-3F (Pelican)	36	
CH-3E (Jolly Green)	6	
HH-65A (Dauphine)	96	
HH-60J (BlackHawk)	32	Note (1)
Subtotal:	170	
Total Aircraft:	246	

NOTE: (1) These aircraft will be delivered beginning in March of 1990.

Source: USCG Fact File 1989-90

APPENDIX 2

ACMS

MAINTENANCE PROCEDURE

CARD

U.S. COAST GUARD AVIATION COMPUTERIZED MAINTENANCE SYSTEM	HU-25 **322.0**

AIRCRAFT NUMBER	OPERATING ACTIVITY	MAINTENANCE ACCOMPLISHED				MAINTENANCE DUE			
		DATE			A/C HOURS	DATE			A/C HOURS
		MO	DAY	YEAR		MO	DAY	YEAR	

SERIAL NUMBER TRACKED ITEM - ALL INFORMATION REQUIRED

ITEM 1	CMS CODE	ACTION	DESCRIPTION	CEINUM
☐ DUE	291173	REM / INST	CSD HYDRAULIC PUMP LH	25-2910-002

☐ SCHEDULED ☐ UNSCHEDULED

This card is used to report maintenance performed on this **AIRCRAFT** SERIAL NO

PART OFF

CSD HYDRAULIC PUMP SERIAL NO.

PART NO______________________

REASON REMOVED: TIME__ TROUBLE__ CANNIBALIZATION__ OTHER__

COMPONENT STATUS. RFI__ NON RFI__

TECHNICIAN'S SIGNATURE ______________ TECHNICIAN'S ID ____________ QUALITY ASSURANCE SIGNATURE ______________

PART ON

CSD HYDRAULIC PUMP SERIAL NO.

PART NO______________________

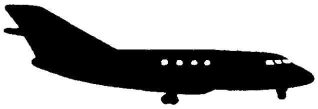
TECHNICIAN'S SIGNATURE ______________ TECHNICIAN'S ID ____________ QUALITY ASSURANCE SIGNATURE REQ'D ______________

MAN HOURS : AD______.__ AE______ __ AM______.__ AT______ __ ASM______ __ OTHER______.__

REMARKS. ____

____

REVIEWED BY	LOG YN	DATA ENTRY COMPLETED	



REFERENCES

1U-25A-2
29-50-21-401

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APPENDIX 3

MAINTENANCE PROGRAM

REVISION FORM

MAINTENANCE PROGRAM REVISION RECOMMENDATION

Aircraft Type:____________________ Report No.____________

ATA CHAPTER AFFECTED:_____________________

Originator:________________________ Date:__________________

SUBJ:___________________________________ UNIT:________________

PROPOSAL: (recommended change to existing program)

PRESENT PROGRAM: (existing program)

JUSTIFICATION:

AREAS AFFECTED:

__ Maintenance Procedure Cards
__ Maintenance Text Card
__ Supply (AR&SC CG-298)
__ Tooling and Equipment
__ ACMS Maintenance Schedule

REVIEW AND COMMENTS:

Engineering Officer:

____________________.
(signature)

ACMS Aircraft Type Analyst:

____________________.
(signature)

Prime Unit:

____________________.
(signature)

Commandant (G-EAE):

APPROVED/DISAPPROVED

____________________.