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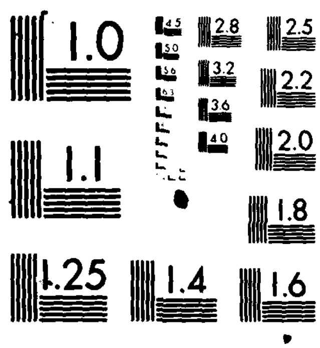

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LIFE FORECASTING AS A LOGISTICS TECHNIQUE

January 1982

ROBERT T. LUND, FLOYD R. TULER, and JOHN R. ELLIOTT
Center for Policy Alternatives
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

FINAL REPORT

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This document reports on a preliminary investigation of the use of reliability, nondestructive inspection (NDI) and life forecasting concepts in Army maintenance practice. The report includes the following major topics: (1) and overview of the Army Reliability Centered Maintenance (RCM) program, (2) brief discussion of NDI methods, (3) summary of life forecasting techniques, (4) alternatives for expanding use o f RCM by incorporating life forcasting methodologies, and (5) conclusions and recommendations.

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As part of its program to extend the lifetime and utility of military equipment the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, awarded a contract to the M.I.T.Center for Policy Alternatives for a preliminary study of life forecasting as a means of determining repair and overhaul strategies. This report summarizes the results of that study, which was conducted during 1981. The project was under the direction of Mr. Robert T. Lund, Senior Research Associate and Assistant Director of the Center. The major portion of the research was shared between Dr. Floyd R. Tuler, a consultant to M.I.T., and Captain John Elliott, who was a graduate student at M.I.T. and is now an instructor at U. S. Military Academy, West Point, NY.

The authors wish to thank Dr. Eric B. Kula, Mr. Norbert H. Fahey and Mr. Charles F. Hickey Jr. of AMMRC for their assistance and support during the study. Other members of AMMRC who provided valuable assistance were Dr. Edward M. Lenoe, Mr. George A. Darcy, and Mr. Richard Shea. We also wish to thank the personnel at the various readiness commands and depots with whom we visited in the course of the study. Those we met were, without exception, cooperative, helpful and interested in improving the effectiveness of their operations The results reported here are largely based on the information provided by these sources. We are grateful, too, to Ms. Sheila K. Bowen and Ms. Kathleen A. Brennan, Staff Assistants, for their assistance in the preparation of the report.

Although we have drawn on materials from a number of sources, the views presented in this report are those of the authors and do not necessarily represent the views of the Center for Policy Alternatives, Massachusetts Institute of Technology, or the U.S. Army.

September 1981

Robert T. Lund
Floyd R. Tuler
John T. Elliott

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LIFE FORECASTING AS A LOGISTICS TECHNIQUE

I. INTRODUCTION

In the past two decades the sophistication of military hardware and weapons systems has been increasing rapidly. Concommitant with increasing sophistication has been a corresponding increase in costs. Even though the defense budget is being expanded to upgrade dated weapons systems, military planners are becoming more and more cost conscious, for two reasons. The first reason involves the higher costs of weapons systems and of operating and maintenance manpower. To achieve a more effective defense system even with increasing budgets it is necessary to effect savings wherever possible without degrading mission reliability or readiness. The second reason stems from closer governmental and public scrutiny of military programs and expenditures to detect waste. This latter reason becomes all the more important at a time when other government branches are being forced to cut back on expenditures to meet the administration's budget goals.

One obvious area of possible savings is by achieving maximum service life from mechanical components or parts before replacing them. The problem lies in maximizing service life while avoiding unexpected or "catastrophic" failures whose large costs, mission success implications, and possible risk to human life are unacceptable. The optimal approach would be to predict service life accurately and replace a part just before it fails. Equally important, reliability of the equipment must be kept at a high level at the same time that service life is being extended. The importance of reliability has been stressed by Karger and Murdick:

> In the past decade, reliability has suddenly assumed major importance. Not only has it become of primary concern in the development of large weapons systems, but its emphasis is beginning to be reflected in the civilian market. Examples of the latter are the extended time guarantees on automobiles, refrigerators, etc. Industry has become reliability-conscious due, in part, to advancing technological developments and, in part, to recent wars which vividly emphasized the consequences of unreliability.

Unreliability results in excess costs and time wasted, introduces the psychological effect of inconvenience, and in certain instances jeopardizes personal and/or national security. The cost of unreliability is not only the cost of the failing item but also that of the associated equipment which is damaged or destroyed as a result of the failure. More importantly the primary equipment is worthless (for its intended purpose) until the failure has been repaired. This shutdown usually represents the greatest cost when dealing with a complex system. All of these result in losses of man hours which also may be very costly.[1]

It is this dual task of maintaining high equipment reliability while extending its service life that provides a major challenge to those charged with the responsibility for the upkeep and operation of the military arsenal. One approach to this challenge employed by the Army has been to adopt a well-tested and very successful system used by the commercial airlines, that of Reliability Centered Maintenance (RCM). RCM is a maintenance system designed to realize the inherent reliability of a system. The RCM logic procedure aids the decision on which components are to be replaced only after failure, replaced when a fixed time limit is reached, or inspected for condition during use and replaced before failure. For components in the latter category, appropriate nondestructive inspection (NDI) techniques must be identified or developed, and a life forecasting procedure applied to the results of the NDI. Service life, reliability, NDI, and life forecasting are interrelated topics, and none can be adequately discussed in isolation. Moreover, any procedure to forecast residual life must in its application, be considered in terms of the Army's overall RCM concept.

The project summarized in this report examined reliability, NDI, and life forecasting in the context of the Army's adopted maintenance concept. Under the sponsorship of the Army Materials and Mechanics Research Center (AMMRC) the MIT Center for Policy Alternatives had as its principal objectives a precursory examination of the use of NDI in current Army maintenance procedures and the identification of mechanical/structural systems (and components) for which application of NDI and related life forecasting techniques might provide significant advantage.

The study was conducted primarily by visiting Army and other groups concerned with maintenance and reliability of weapon systems, collecting and examining relevant documents, evaluating the information obtained, and formulating recommendations. This report of the study includes the following topics:

- an overview of the Army RCM program
- a brief discussion of NDI methods
- a summary of life forecasting methodologies
- alternatives for expanding RCM, incorporating life forecasting methodologies
- conclusions and recommendations

Appendix A lists the facilities and personnel visited. Short reviews of the statistical methods of reliability, and of applied fracture mechanics are also presented in appendices.

II. RELIABILITY CENTERED MAINTENANCE IN THE ARMY

Background

Decision logic and airline/manufacturer procedures for organizing scheduled maintenance programs for the Boeing-747 aircraft were developed in 1968 by representatives of various airlines constituting the Maintenance Steering Group. A more universal document, "Airline Manufacturers' Maintenance Program Planning Document - MSG-2", refined the earlier procedures and deleted specific reference to the Boeing 747 aircraft. MSG-2 decision logic became the basis for scheduled maintenance programs for commercial aircraft of the 1970's that were efficient, effective, and acceptable to the regulating authorities, the operators, and the manufacturers.

These new procedures were successfully applied by the Navy to their P-3 aircraft program. Consequently, the Department of Defense directed all services to apply the MSG-2 concept to new aircraft entering service in fiscal year 1977 and to in-service aircraft and all other military equipment by the end of fiscal year 1979.

The Department of the Army issued Program Objective Memorandum (POM) 78-82 establishing the requirement that the MSG-2 concept, under the name of Reliability Centered Maintenance (RCM), be incorporated on all Army weapon systems/equipment by the end of fiscal year 1979.

RCM uses decision logic to evaluate and construct maintenance tasks which are based on equipment function and failure models. RCM is based on the premise that maintenance cannot improve the reliability inherent in the design of the hardware; good maintenance can only preserve those characteristics.

In 1978, Martin Marietta Corporation published the results of an independent assessment of the Army's implementation of RCM.[2] To establish direction for the assessment, five candidate systems were examined for RCM activities. The candidate systems and the respective readiness commands were the UH-1H helicopter (TSARCOM), TOW Weapon System (MIRCOM), M-113 Armored Personnel Carrier (TARCOM), AN/VRC-12 Radio Set (CERCOM), and M-110 SP Howitzer (AARCOM). In addition, the AN/TPQ-37 Radar Set (ERADCOM) was chosen as an example for evaluation of RCM activities on a developmental system.

In its response to the requirement that RCM be implemented on all military commodities by the end of fiscal year 1979, the Department of the Army had contended that many aspects of RCM had already been implemented through maintenance improvement programs and policies that had been initiated before RCM was formulated. The Martin Marietta study examined these programs that contained or should have contained elements of RCM, and evaluated them with respect to the principles of RCM and MSG-2. Examples of these programs included the Army Oil Analysis Program, On-Condition Maintenance for aircraft, Project LEAP, Project Inspect, Preventive Maintenance and Checks Services (PMCS) Review, and DMWR Scrub.

Several important conclusions were drawn by Martin Marietta Corporation from these analyses and evaluations, the most important being that the Army had not developed a comprehensive RCM program for any product. Instead, Army RCM had been fragmented into a number of individual programs applied to a wide range of products, most significantly the PMCS Review, and the DMWR Scrub. Because of the scope and importance of the Martin Marietta Report, their complete conclusions and recommendations are listed below:

<u>Conclusions of the Martin Marietta Corporation</u>[2]

1. RCM has not been fully and accurately defined.
2. The Army has not implemented a comprehensive RCM program on any system or product.
3. Insufficient RCM guidance has been provided to Readiness and R&D Commands, and program planning has not been systematically developed.
4. Readiness commands do not have capability for developing Failure Modes and Effects Analyses (FMEA).
5. Accurate and dependable field or test data are generally not available.
6. RCM logic diagrams developed have been limited in scope and include complex rather than simple questions.
7. Instructional courses for RCM training have not reached the working level.

8. Navy and Air Force RCM programs contain elements which are potentially useful to the Army.
9. Some maintenance improvement programs have produced results that can be compared with RCM potential results objectives.
10. Development of new techniques for fault detection and location is needed, particularly for electronic equipment.
11. Audit trails of RCM decision and processing are not generally established.
12. RCM sustaining engineering has not received adequate development.
13. RCM terminology is confusing and usage has resulted in misunderstandings.
14. Monies to perform Logistic Support Analyses (LSA) and FMEA on development programs are not earmarked for that purpose.
15. RCM has not been implemented on a developmental system.
16. Analysis of exact cost benefits achieved from revised maintenance has not been feasible to date.

Recommendations of Martin Marietta Corporation[2]

It was recommended that greater in-depth study of RCM documentation be accomplished by the Army, including review of Navy program elements and the return on investment estimated by the Air Force from aircraft support equipment RCM studies. Additional recommendations were that the Army:

1. Develop and publish a formal RCM definition.
2. Develop complete and thorough RCM guidance and instructional courses, and disseminate these to the RCM working level.
3. Provide the resources (manpower and dollars) needed by Readiness Commands to obtain Failure Modes and Effects Criticality Analyses (FMECA).
4. Support acquisition of field operating and maintenance data.
5. Develop methodology for preparation of an RCM FMEA and require its usage on systems which will provide a good return on investment.
6. Require RCM decision logic diagrams for each type of system.
7. Develop a comprehensive RCM program for at least one major system in each command.
8. Retain all the successful RCM-related programs already in effect.
9. Develop new techniques in fault detection and location, particularly in electronic equipment.
10. Require documentation of RCM audit trails.
11. Require establishment of RCM sustaining engineering functions in each Readiness Command.
12. Establish a policy for systematically developing future RCM programs or modification.
13. Revise RCM terminology.
14. Select a valid developmental system for assessment of RCM implementation.
15. Dedicate monies for performance of LSA and FMEA to that end and do not allow them to be used for other activities.
16. Require RCM sustaining engineering to be implemented during the development phase of new systems.

Although no systematic attempt was made in this study to examine how far the Army had gone in implementing the Martin Marietta recommendations for RCM, our observations would indicate that a number of recommendations have been acted upon, but others remain as problems.

Organization of RCM Activities

The Deputy Chief of Staff for Logistics has overall responsibility for the Army RCM program and is the Chairman of the RCM Steering Group, which oversees Army efforts to develop and apply an equipment oriented maintenance strategy.

In addition to providing a representative to the RCM Steering Group, the Deputy Chief of Staff for Research, Development and Acquisition formalizes, incorporates, and assures application of RCM requirements in system development and acquisition.

A major role for implementation of RCM is assigned to the Army Material Development and Readiness Command (DARCOM). In 1979 the RCM responsibilities of DARCOM were enumerated in a letter issued by the Adjutant General[3]:

1. Incorporate RCM in the Logistic Support Analysis (LSA) Process for new materiel acquisitions. Establish and update, as required, procedures and methodologies, compatible with the LSA process and its record system (LSAR). Apply RCM in the form of full engineering analyses; i.e.:

    a. Perform failure modes, effects and criticality analysis (FMECA) to all maintenance significant items.
    b. Identify design deficiencies that preclude achievement of safety and reliability, availability and maintainability objectives.
    c. Apply RCM logic to all critical failure modes to establish the maintenance plan.
    d. Determine cost-effective maintenance procedures for all critical failure modes.
    e. Continue application of RCM to all product improvements.

2. Extend the Phased Maintenance Program to all first line aircraft and those aircraft programmed for input to future Army inventory. Incorporate an explicit RCM decision logic into the Phased Maintenance Program and provide an analysis of increased failure modes for the more complex assemblies.

3. Apply on-condition maintenance evaluations as a means of selecting aircraft and combat vehicles for depot overhaul or replacement based upon a cost-effective choice of on-condition evaluations or failure beyond the repair capabilities of the field Army activities, or, when justified by in-depth engineering and empirical analysis, by hard-time criteria.

4. Evaluate existing Depot Maintenance Work Requirements (DMWRs) to insure that maintenance procedures incorporate RCM principles. Diagnostic evaluations should be used to determine the type and extent of repair required.

5. Develop material inspection testing technologies and standards to detect premature deterioration and/or incipient failure of equipment and components.

6. Intensify component development efforts to improve field reliability and reduce maintenance burden.

7. Develop and update, as required, appropriate RCM decision logic, and guides for logic application.

8. Apply RCM decision logic and analyses to existing scheduled maintenance services for field maintenance significant items in order to eliminate unnecessary checks and services.

9. Perform an RCM cost-benefit analysis on a selected multi-commodity major weapon system comparing the costs and results obtainable by application of full engineering analyses, in accordance with (1) above to those obtainable by application of the field procedures logic and analyses in accordance with (8) above. Based upon the result of the cost benefit analysis, establish cost effective engineering RCM programs for high-density field weapon systems as applicable.

10. Carry out sustaining engineering programs for systems/equipment which have undergone RCM analyses to determine the effectiveness of the RCM program and apply continuing reliability and maintenance improvements as determined necessary.

11. Continue the Army Oil Analysis Program in accordance with AR 750-22.

12. Identify resource requirements for RCM programs in budget and POM submissions to support implementation and sustaining engineering.

13. Provide a representative on the the RCM Steering Group.

In conjunction with the directive for Army-wide implementation of RCM procedures, a number of pamphlets[4,5], regulations[6,7], and letters have been published. These publications present policies, responsibilities, and procedures for the development, establishment, and implementation of RCM as they relate to field and depot maintenance. Examples of actual applications are included. Specific guidelines are provided for deriving the detailed maintenance plan for systems or equipment undergoing logistic support analysis, and worksheets are provided for maintenance decisions.

Implementation of RCM

RCM logic has been applied to both field maintenance and depot maintenance. Scheduled preventive maintenance checks and services (PMCS) are determined by first analyzing the failure modes, effects, and criticality (FMECA) of the system and entering the results into an RCM logic diagram. The RCM logic for fielded equipment, shown in Figure 1, is designed to:

a. identify components in the system/equipment that are critical in terms of mission and/or safety,

b. provide a logical procedure to determine the feasibility and desirability of scheduled maintenance task requirements, and

c. provide supporting justification for scheduled maintenance task requirements.

Corresponding logic diagrams have been developed for depot overhaul and for system development.

The RCM program consists of three categories of maintenance, defined as hard-time limit, on-condition and condition monitoring. Hard-time limit maintenance is performed or items are replaced at some fixed interval such as calendar time, flying hours, miles driven, or rounds fired. On-condition maintenance is performed and items are replaced on a scheduled basis only after an evaluation of each item. Condition monitoring is utilized for items having neither hard-time limits nor on-condition maintenance as the primary maintenance process, and is accomplished on a non-scheduled basis. The item is monitored during normal operation of the system and replaced when deteriorating behavior or failure is observed.

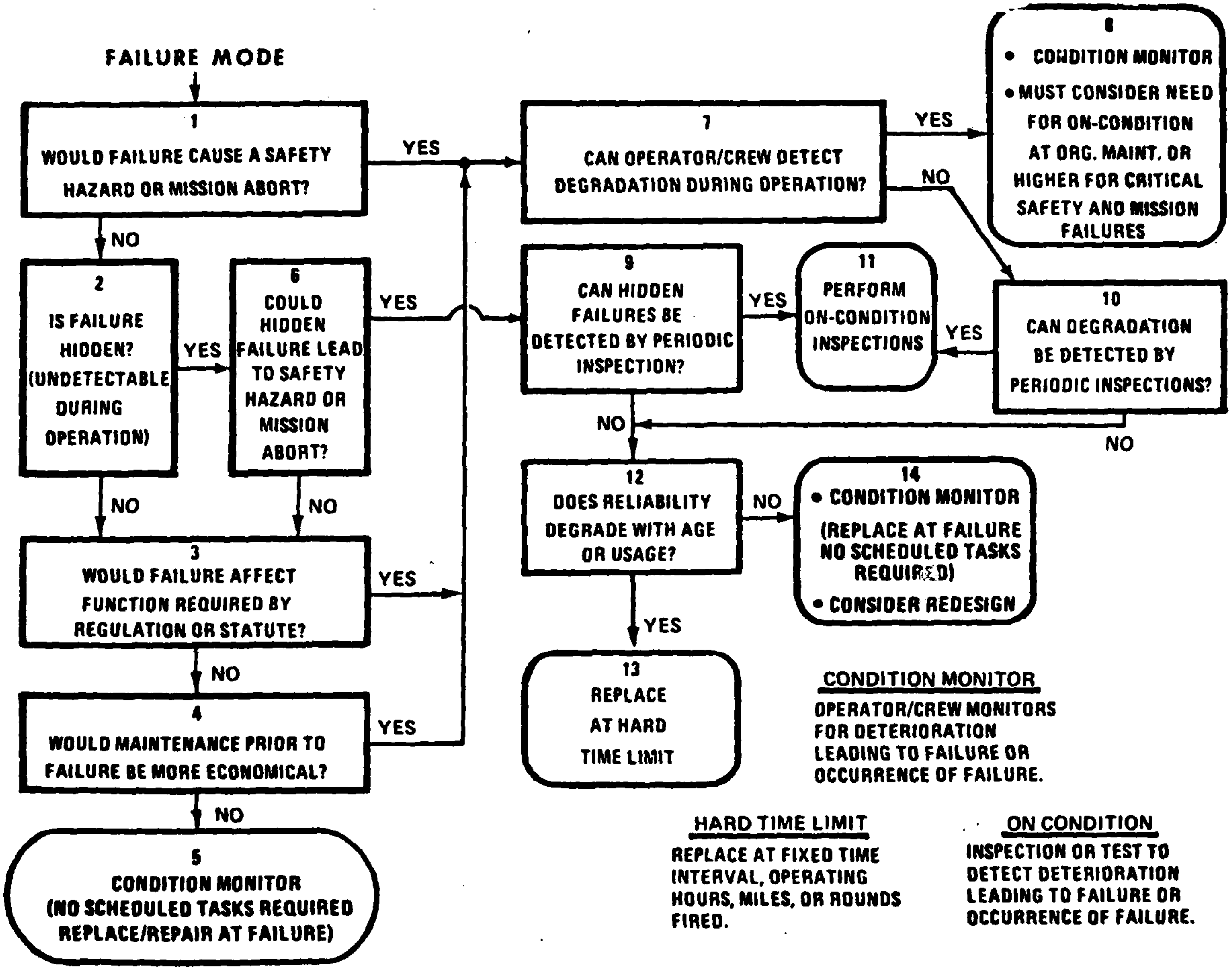

Figure 1: Reliability Centered Maintenance Logic Diagram

A maintenance Process Analysis Worksheet for following the RCM logic diagram is shown in Figure 2. The worksheet is used in field maintenance to record the data necessary to evaluate up to four failure modes and to arrive at a maintenance program.

Unscheduled corrective maintenance at the depot level has also been rationalized through RCM procedures. The maintenance process at the depot level uses tests and inspections to determine the condition of an item prior to performing corrective maintenance. Tests and inspections are normally done within the guidelines of the Army Oil Analysis Program (AOAP) and preshop/postshop analyses to evaluate the condition or actual operation of an item prior to corrective maintenance.

Regulations require that AOAP records accompany the equipment when it is sent to the depot for repair and that preshop analyses should utilize diagnostic testing, nondestructive testing, and dimensional inspections to the fullest extent possible. Visual inspections should be used only when other techniques are inappropriate or uneconomical.[7]

The Unscheduled Maintenannce Sample Data Collection (UMSDC) Program covers aspects of reliability, maintainability and logistics of operational Army aircraft systems. The UMSDC system is based on forms coded in the field by Army mechanics for all unscheduled maintenance and scheduled replacements. Computer output products of the data base include the the statistics of breakdown events, maintenance actions, and component reliability and life characteristics. These output products are available from TSARCOM Product Assurance (DRSTS-QSM), St. Louis, Missouri.[15]

Examples of RCM Applications

A number of examples are presented in Army publications to illustrate RCM applications to maintenance procedures.[4,5,7] These applications include PMCS review of an automotive item, GOER (M520, M559, M553, and M877); phased maintenance revisions for the UH-1H Helicopter; and review and revision of Depot Maintenance Work Requirements (DMWR) of selected equipment, including the M110 Howitzer, UH-1H Helicopter, VRC-12

MAINTENANCE PROCESS ANALYSIS WORKSHEET

For use of this form, see DA PAM 750-40; the proponent agency is DARCOM.

1. MAJOR ITEM	2. PREPARED BY	
3. PREPARING ORGANIZATION	4. NOMENCLATURE	
5. PART NUMBER	6. DATE	7. REVISION NO.

8. FAILURE MODE(S)	A	B	C	D
9. CLASSIFICATION	A	B	C	D

NO.	LOGIC QUESTION		YES	NO	INFORMATION SUMMARY
1	WOULD FAILURE CAUSE A SAFETY HAZARD OR MISSION ABORT?	A			10.
		B			
		C			
		D			
2	IS FAILURE HIDDEN?	A			11.
		B			
		C			
		D			
3	WOULD FAILURE AFFECT FUNCTION REQUIRED BY REGULATION OR STATUTE?	A			12.
		B			
		C			
		D			
4	WOULD MAINTENANCE PRIOR TO FAILURE BE MORE ECONOMICAL?	A			13.
		B			
		C			
		D			
5	CONDITION MONITOR	A			14.
		B			
		C			
		D			
6	COULD HIDDEN FAILURE LEAD TO SAFETY HAZARD OR MISSION ABORT?	A			15.
		B			
		C			
		D			
7	CAN OPERATOR/CREW DETECT DEGRADATION DURING OPERATION?	A			16.
		B			
		C			
		D			
8	CONDITION MONITOR	A			17.
		B			
		C			
		D			
9	CAN HIDDEN FAILURES BE DETECTED BY PERIODIC INSPECTION?	A			18.
		B			
		C			
		D			
10	CAN DEGRADATION BE DETECTED BY PERIODIC INSPECTIONS?	A			19.
		B			
		C			
		D			
11	ON-CONDITION	A			20.
		B			
		C			
		D			
12	DOES RELIABILITY DEGRADE WITH AGE OR USAGE?	A			21.
		B			
		C			
		D			
13	HARD TIME	A			22.
		B			
		C			
		D			
14	CONDITION MONITOR	A			23.
		B			
		C			
		D			

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Figure 2: Maintenance Process Analysis Worksheet

Radio Set, and the M113 Armored Troop Carrier. In addition, RCM methodology has been applied to developmental systems such as the Pershing Missle.

Two examples of RCM applications were investigated directly by the MIT project team: the T53-L-13B engine for the UH-1H Helicopter and the M-60 Tank.

In fiscal year 1979 an RCM decision logic analysis of the T53-L-13B engine supported the elimination of the 1800 hour TBO (time between overhaul), and maintenance of the engine was placed on-condition. As of 1 July 1981, TSARCOM RCM records at Corpus Christi Army Depot (CCAD) showed that out of a population of 5563 T53-L-13B engines, 341 were operating beyond 1800 hours.[8] Actual times are as follows:

108 engines between 1800 and 2000 hours
102 engines between 2000 and 2500 hours
61 engines between 2500 and 3000 hours
40 engines between 3000 and 3500 hours
24 engines between 3500 and 4000 hours
6 engines beyond 4000 hours

The TSARCOM RCM Engineering Branch has been monitoring each of these "high-time" engines and currently there is no indication of a failure pattern. Under previous maintenance procedures, only 6.8% of these engines within the Army ran the designated TBO of 1800 hours, while many commercial engines were running to 4000 hours.

In conjunction with on-condition maintenance of the T53-L-13B engine, a telephone hot-line has been established to control premature return of engines for overhaul. If a problem cannot be corrected in the field with telephone assistance, a team is sent from CCAD to perform the repairs. Engines are approved for depot overhaul only if repairs cannot be completed in the field.

It is estimated that from 1979 to June 1981 approximately 10 million dollars have been saved through cost avoidance by running the 341

T53-L-13B engines beyond the old TBO of 1800 hours. In addition, approximately $5 million have been saved through cost avoidance by the telephone hot-line and CCAD field teams, permitting 53 engines to be returned to service rather than sent for depot overhaul.[8]

A complete review and rewriting of the DMWR for the M60 Tank incorporating RCM procedures was completed in the spring of 1981. During the summer of 1981, fifteen M60 tanks were to be selected and overhauled according to the revised DMWR. These tanks will be returned to the field and their subsequent service and maintenance records will be monitored and compared with vehicles overhauled according to the old DMWR or by "inspect and repair" procedures. Field personnel will not be informed as to which tanks have been overhauled under new RCM procedures.

The new RCM overhaul procedures for the T53-L-13B helicopter engine and the improved ability to collect, store, and analyze statistical records with the unscheduled Maintenance Sample Data Collection (UMSDC) Program have increased interest in parts integrity and traceability requirements. Traditionally, the Army has not required parts integrity in depot overhaul procedures. On the other hand, the Air Force and Navy require parts integrity for their helicopters, which are overhauled by the Army at the same facility. From engineering and reliability considerations, parts integrity in overhaul of a system or subsystem is necessary for determining component lifetime and monitoring failure rates. Parts integrity requirements, however, can be a definite factor in reducing overhaul throughput rates. It would seem possible and desirable to compare the Army system, not requiring parts integrity, with the Air Force and Navy system, requiring parts integrity, to quantify the costs and benefits of the two approaches.

III. NONDESTRUCTIVE INSPECTION METHODS

Background

Nondestructive inspection (NDI) techniques are used to detect flaws in materials in order to determine if a component can be placed in service or continue to be used once in service. The most commonly used NDI techniques include visual inspection, dye penetrants, magnetic particles, x-ray transmission, ultrasonics, and eddy current.[10, 11] The inspection techniques can be classified into two groups, namely direct and indirect methods. The direct methods are visual, penetrant, magnetic particles, and x-ray:

1. Visual inspection can be assisted by magnifying glass, low power microscope, lamps, and mirrors. It is used only where parts are easily accessible. Detection of small cracks usually requires much experience.

2. Penetrant inspection uses a colored liquid (penetrant) which is brushed on the material and allowed to penetrate into cracks. The penetrant is washed off and a quick-drying suspension of chalk is applied (developer). Remnants of the penetrant in the crack are extracted by the developer leaving colored lines. This method is used only at places easily accessible, and the sensitivity is of the same order as for visual inspection.

3. Magnetic particles inspection applies a layer of a flourescent liquid containing iron powder to the surface of the part under inspection. The part is placed in a strong magnetic field and observed under ultraviolet light. At crack locations the magnetic field lines are disturbed and this is highlighted by the magnetic particles. This method is only applicable to magnetic materials, and parts need to be dismounted and inspected in a special cabin. Also, because it is a sensitive method, notches and other irregularities often give indications.

4. X-rays are passed through a structure and recorded on film. Cracks, absorbing less X-rays than surrounding materials, are delineated by a line on the film. This method is used with great versatility and sensitivity. There are interpretation problems if cracks occur in fillets or at the edge of reinforcements, however, and small surface flaws in thick plates are difficult to detect.

The indirect methods are ultrasonics, eddy current and acoustic emmission:

1. Ultrasonic inspection uses a piezo-electric crystal probe which transmits high frequency sound waves into the material. The wave is reflected at surfaces and cracks and the input pulse and reflections are displayed on an oscilloscope. The distance between the first pulse and reflection indicates the position of a crack. Cracks can be distinguished easily from surfaces since reflections from cracks disappear when the direction of the wave is changed. Ultrasonic inspection is used on a wide range of types of parts, since a variety of probes and input pulses can be selected. However, information about the size and nature of the defect (which need not be a crack) is difficult to obtain by this technique.

2. Eddy current inspection passes alternating current through a coil to induce magnetically an eddy current in the metal part being examined. The eddy current in turn induces a current in a second coil. In the presence of a crack or defect the induction changes, so that the current in the coil is a measure of the surface condition. (In practice, a single coil is sometimes used.) This is an inexpensive method that is easy to apply, and coils can be made small enough to fit into holes. Eddy current inspection is a sensitive method when applied by skilled personnel, but little or no information about the nature and size of the defect is provided.

3. Accoustic emmission measures the intensity of stress waves emitted from the material resulting from plastic deformation at the crack tip and from crack growth. This inspection technique requires that the structure be under load, so that continuous surveillance is possible. Expensive equipment is required, however, and interpretation of the signals is difficult.

Other NDI techniques are being investigated. These include neutron radiography (Vought Corporation, Dallas), laser gauging, holographic interferometry, and X-ray tomography.

Major problems remain in using NDI results to provide quantitative flaw information that can be combined with fracture mechanics for life forecasting.[12] The ideal inspection technique would lead to a zero probability of rejecting a part for all flaws smaller than the critical size, and a probability of one that those with flaws larger than the critical size would be rejected. In reality, however, errors arise in the use of all techniques - some parts with flaws smaller than the critical size are rejected, and some parts with flaws greater than the critical size are accepted. Human fallibility is also an important factor. In each of the techniques the indication of a flaw must be detected by the inspector.

The Air Force has an on-going program [13] to develop an objective method for measuring NDI technician proficiency, a principal factor in reducing the quantitative capability of NDI. For example, almost 300 Air Force NDI technicians were recently checked with standardized preflawed specimens. The results showed that a one-half inch flaw was found only 50% of the time with 95% confidence. These poor results caused the Air Force to institute a program in which qualification kits are being prepared to test technicians throughout the Air Force.

The Army has a five year old program for certification of nondestructive testing personnel, established under DARCOM Regulation 702-22[17]. Under this program "minimum requirements are established for the training, examining, qualifying, and certifying DARCOM personnel for competence at appropriate levels in NDT methods applied for testing and inspection of an item of material." The methods included are eddy current, liquid penetrant, magnetic particle, radiography and ultrasonic testing. The Director of AMMRC is responsible for the management and technical direction of the program.

Observations by MIT Project Team Regarding NDI Implementation in Army Maintenance and Overhaul Procedures

The MIT project team visits to Corpus Christi Army Depot (helicopters) and Anniston Army Depot (tanks) did not confirm widespread use of NDI. We observed inspections that were primarily visual and dimensional, with only scattered use of dye penetrants and magnetic particles. No uses of ultrasonic or eddy current techniques were observed at either overhaul facility.

Although the function of DMWR's in calling out NDI applications was not pursued extensively, there were indications from our conversations with Army personnel that DMWR'S were frequently inadequate in this respect. If the DMWR were prepared by the contractor, the motivation for use of NDI techniques to extend product life was low. If prepared by an Army command, available NDI expertise might not be applied. The Product Assurance Director for each command must sign off on DMWR's. If not called for by the DMWR, NDI is not used by the depot, and even if desired by the depot, introduction of NDI procedures into a DMWR was said to be difficult. There appears to be little or no connection between AMMRC and the Product Assurance Directors.

Quality Readiness Reviews (QRR's) provide for review of the quality assurance provisions of the Technical Data Packages for major Army systems. Designated in advance of completion of system development by the Commanding General, DARCOM, these QRR's are administered by the project program manager. Only a few systems have been treated in this way in the three years this procedure has been in effect.

Regulation identifies AMMRC as the resource for assistance in developing and applying NDI techniques which, in conjunction with the Materials Predictive Technology (MPT) program, will serve to maximize system reliability by forecasting the remaining life for parts and components.[7] The project team did not meet depot personnel that were aware of this role for AMMRC, however.

Block 11 in the RCM logic diagram (Figure 1), calling for performance of on-conditioned inspections, is reached when there are hidden failures or degradation that can be detected by periodic inspection, but not by the operator or crew during operation. The hidden failures or degradation of concern, in this case, are those that can cause a safety hazard or abort the mission. We agree with the logic by which Block 11 is reached, but, unfortunately, once having arrived at this point, there is no RCM logic that enables one to "get out of the box." There is no systematic way of selecting appropriate inspection techniques or procedures. In the absence of such guidelines, the employment of life forecasting inspection techniques is likely to be haphazard and relatively unsophisticated. It would seem possible and desirable to extend the logic diagram to include selection criteria for the alternative NDI techniques available, so the preferred mode of inspection is normally chosen.

Recent developments in electro-optical pattern recognition techniques for use in other applications suggest that similar uses may be found for these techniques in NDI. The fact that all present NDI systems are highly dependent on the skills and attentativeness of the inspector provides ample justification for investigating such possibilities, particularly for critical components.

IV. LIFE FORECASTING METHODOLOGIES

In this section, we discuss five general life forecasting methodologies, whereby the results of NDI might be utilized. Each method is progressively a more expensive, difficult, and time consuming technique. With increasing sophistication, however, comes more opportunity to extend the operating lifetime of the part or component and to gain greater protection from premature or unexpected failure. Hence, we would expect the latter techniques to be applied to more expensive, safety critical or mission critical components. The five techniques to be discussed are:

1. Hard-time Retirement
2. Critical Flaw Size Criteria
3. Life Prediction After Discovery of a Flaw
4. Retirement for Cause (RFC)
5. Combined Analysis (CA)

We should note before proceeding that techniques 1 through 3 are in common use while techniques 4 and 5 are more experimental. In particular, the USAF is pursuing research on technique 4 at their laboratories at Wright-Patterson AFB and by contract to Pratt and Whitney Aircraft Group. We also note that this list is not exhaustive, but it contains both common techniques and techniques with promise for the future. Each technique is described in general terms with minimal mathematical references.

1. Hard-Time Retirement. This is the most commonly used life forecasting technique. Under this procedure, a mean-time-between-failure (MTBF) for a component is established using fracture analysis and data gathered from field use or laboratory testing. A safety factor is subtracted from this MTBF and the resulting figure represents the allowable time of use before a part is replaced. Components are retired when the hard-time limit is reached, regardless of condition.

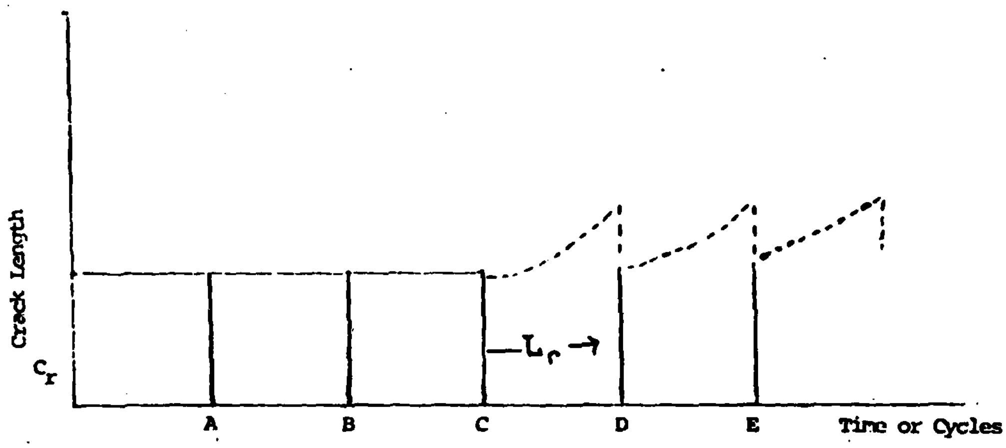
2. <u>Critical Flaw Size Criteria</u>. Under this procedure a sample of the type of components of interest is used to generate failure data. Failure here means verification of the existence of a critical flaw -- the nature of a the critical flaw is determined by the design of the part. NDI methods are employed in the generation of the failure data. The data are compared to generalized failure models and a fit is determined from among the models. Simple graphical and mathematical techniques are used to estimate the MTBF and hence the reliability of the component. Data gathered on products in service may also be used to estimate the MTBF for the component of interest.

Once a statistically reliable estimate of the MTBF for the failure models of interest is obtained, a safety factor can be subtracted and inspection intervals established. When a component is discovered during inspection to contain a flaw of critical size, it is removed from service and retired. Otherwise it is continued in service until some specified time (hard-time) or until a critical flaw is discovered. The essential difference between this approach and the hard-time retirement method is the use of NDI to inspect the component for flaws.

The advantage of both of these first two techniques is that they are relatively simple and inexpensive to apply. Moreover, they are conservative techniques that provide protection against catastrophic failures. They are, however, costly in terms of replacement parts. Many components will be discarded with a significant amount of useful life remaining. The disadvantage of this situation in the case of components with high dollar value is apparent.

3. <u>Life Prediction After Discovery of a Flaw.</u> This method is the first of three which allow continued used of a component with a flaw. Prediction of residual life is again based upon available failure data and fracture analysis.

The components of interest are assumed to have the traditional "bathtub" curve of lifetime distribution. As shown in Figure 3, Point A represents the end of the "break-in" period and B and C represent the end of intervals between inspections. (There are many inspections



C_r is the Critical Crack Length

L_r is the Residual Lifetime

Figure 3: Life Prediction after Discovery of Flaw

between A and B.) Point C also represents the theoretical beginning of the "wearout" period obtained from fracture analysis and laboratory failure data. Point D represents the laboratory-obtained prediction of time to critical flaw size or failure if a flaw is discovered at point C. If actual inspection of a component at Point C in its lifetime discloses a flaw, the remaining life (L_r) would extend to Point D, and the part would be replaced at D. If no flaw is seen at point C, however, the component would be returned to service and re-inspected at point D. In essence, the part is treated as if it were still at point B prior to the expected start of wear out. The inspection interval is chosen to be less than or equal to the time from flaw initiation to critcial size. The procedure is repeated until a flaw is found.

4. Retirement for Cause (RFC) . This technique is being developed by the Pratt and Whitney Aircraft Group for application to F100 gas turbine engine components under contract to the Air Force Material Laboratory and Air Force Wright Aeronautical Laboratories of the Air Force Systems Command at Wright-Patterson Air Force Base, Ohio. A short discussion of the work was recently published [14] and a final report on the current phase of this research was due to be completed in August 1981.

RFC exists in several variations, two of which will be discussed here. These techniques use historical data gathered on the individual component to modify the design crack length vs time (cycles) curve so that it takes into account the actual stresses and loads experienced by that particular component.

The first version is similar to the life prediction techniques of the previous section. Based on fracture analysis and generated failure data, a crack length vs time model is generated - as shown in Figure 4. Inspection intervals are established so that an undetected flaw cannot propagate to failure in the period between overhauls. Note point R on the diagram, which is the normal hard-time retirement point. Based upon the data, the component would ordinarily be discarded at this point.

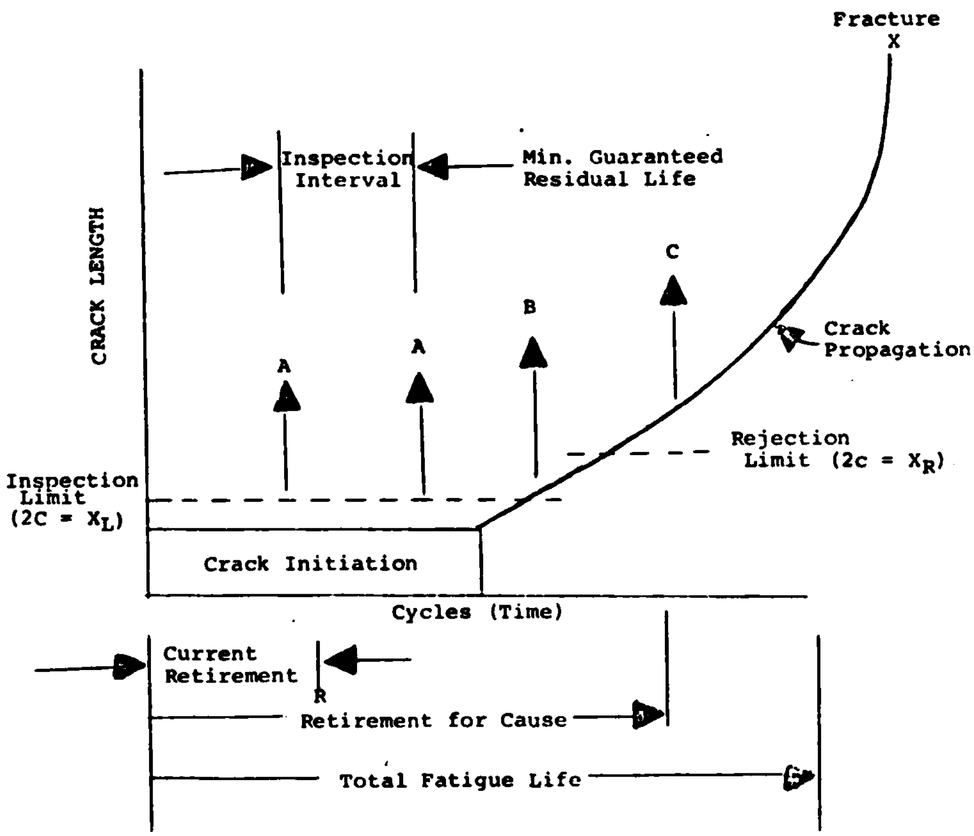


Figure 4: Residual Life Prediction as Applied to Retirement-for-Cause

Source: Reference 16

Under RFC if no cracks are detected the component is returned to service. Inspections are continued until point B is reached, point B being the time when a crack is monitored until the first inspection at which it is beyond the rejection limit (Point C). The component is then removed and discarded. At each inspection where no flaw is detected, the prediction is that the component has a residual life at least equal to the next inspection interval.

A more complex variation of RFC is to use the results of inspections to redraw the crack length vs time (cycles) curve. The actual material properties and the actual stresses and loads encountered in field use of a component seldom have the exact values predicted in design or in the testing process in the laboratory. If a given component has a hypothetical crack length vs time curve (or equivalently, a probability of failure vs time curve) of the shape of the solid line in Figure 5, its actual field use may reveal that although wearout or crack initiation has begun as expected, subsequent inspection indicates that the rate of propagation is slower than anticipated (dotted line in Figure 5). In this variation of RFC, the field inspection data would be used to redraw the curve and extrapolate it to a new retirement time. This procedure is repeated after each inspection, thus providing more refined estimates of remaining life with each inspection. Our example is for the case of a component under lighter than expected loads and thus slower crack propagation. A similar procedure is followed for components under heavier than expected loads.

This latter procedure is expensive, sophisticated mathematically, and time consuming. However, for expensive components such as F100 turbine disks the procedure allows maximum use of the component based on actual service life, while providing an acceptable margin of safety. Computer-aided analytical techniques speed the computations.

5. Combined Analysis. As a final illustration of life forecasting methodologies, the method of Failure Analysis Associates will be briefly discussed.[9] Their method, called Combined Analysis (CA), attempts to overcome errors in life prediction with a modification of the RFC

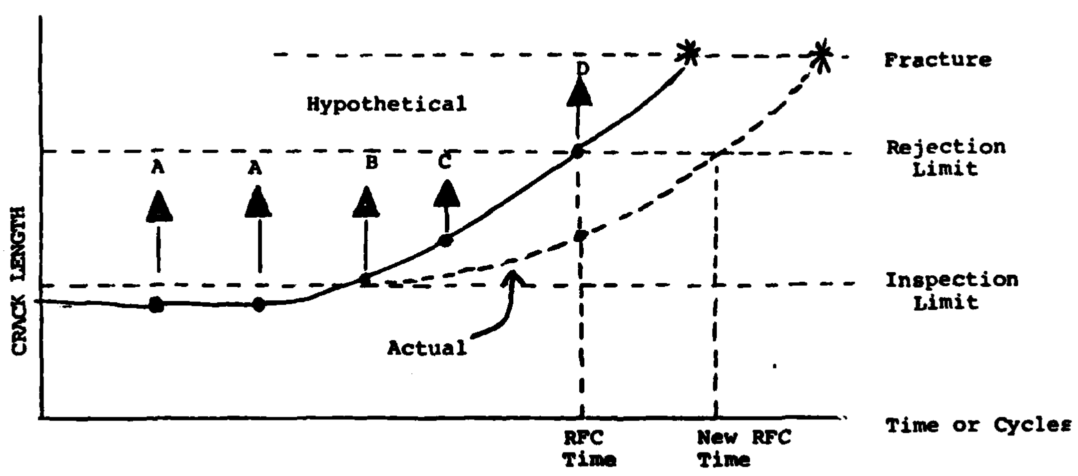


Figure 5: Retirement-for-Cause Recalculation from Actual Inspection Date

procedure described above, making more direct use of past operating experience (as reflected in inspection information) to establish the RFC strategy. In this approach an incomplete engineering model is calibrated against all available in-service data. The mathematics of CA is the same as that of mathematicalregression analysis, but the formulation and use of CA in practice utilizes engineering judgments. The formulation of the engineering model, specification of known and unknown parameters, and details of solving for unknown parameters from test and field-derived data must be accomplished in a way that minimizes the impact of uncertainties upon CA-based decisions. The method, according to the authors, can also be used for probabilistic calculations outside of fracture mechanics or mechanical engineering fields.

CA uses the minimum amount of engineering modeling required to supplement the routine statistical analysis of actual in-service data on the frequency and severity of crack occurrance, and failure. Consider a hypothetical but realistic population of turbine rotors. Conventional design life is established to assure an acceptably low failure rate. A significant fraction of rotors, say 10%, will crack but not fail, while the balance will not even develop cracks during the conventional design life. An RFC procedure, based upon probabilistic fracture mechanics alone would establish a conservative life extension model based on an accurate stress analysis and a "safe" distribution of crack propagation lives, N_p. Combined Analysis, on the other hand, does not require accurate stress calculations if adequate substitute data are available, such as would be obtained in field inspections. CA uses all available in-service data on N_p and initiation life, N_i, along with appropriate laboratory data on engineering models which relate N_i, N_p and failure life N_f. CA procedures constantly account for new data by refitting and, if required, reformulating the original engineering models from the augmented data set. Errors in the model or in materials data are not as influential in CA as in probabilistic fracture mechanics RFC approaches, because CA provides continued calibration with actual experience. Further, while design approaches often incorporate "fudge" factors to account for actual test and field data, CA provides a more systematic and formal basis for incorporating actual performance data into the life prediction model.

V. ALTERNATIVES FOR IMPLEMENTING LIFE FORECASTING IN ARMY MAINTENANCE

Although our observations were limited in this preliminary study, we have identified several opportunities for an expanded role for life forecasting and applications of NDI within the general framework of the Army RCM concept. These opportunities fall into four broad categories: organization and communication, personnel, applications to specific systems and components, and technique development.

The first two areas - those of organizational and personnel opportunities - were not specifically mentioned in the charter of this study, yet they impact heavily on the success of any RCM program. It would have been impossible within the scope of this limited project to investigate all the problems of managing, training, and motivating individuals concerned with RCM and NDI, or of insuring responsive communication between the providers of NDI techniques (i.e. AMMRC) and users (i.e. depots and field maintenance units). However, we did make some observations on these topics during our visits to various locations and we offer them here. These and related subjects are currently being addressed in more detail by the Tri-Service NDI Steering Committee.

1. Organization and Communication. During the MIT project team visits to engineering and overhaul facilities, we observed a general lack of awareness concerning the opportunities and benefits to be derived from modern NDI. Futhermore, we encountered few individuals who were aware of the NDI expertise within AMMRC or that the services of AMMRC were available to present or potential users of NDI. NDI is not universally applied in the Army and individual users seem to utilize or develop techniques without the assistance, coordination, or approval of any central authority. This situation in the Army strongly contrasts with that in the Air Force, where the NDI Program Office at Kelley Air Force Base has direct program involvement in all Air Force commands and certifies all Air Force NDI personnel.

Except for AMMRC's responsibility for the management and technical direction of the NDT Certification Program [17], AMMRC's role as the proponent agency for NDI in the Army is generally not clearly understood, nor is information about this role widely disseminated. It would be possible to strengthen AMMRC's role through workshops, roving "technical ambassadors" and a regular newsletter directed towards problems and solutions, new techniques, and reccommended applications. The newsletter should also establish means for return communication from field maintenance and depot personnel.

2. Personnel. The MIT project team observed what seemed to be a shortage of engineering, field and depot personnel trained in NDI and in life forecasting techniques. If such a shortage actually does exist, this should warrant a comprehensive program within the Army to recruit, train, motivate, and monitor qualified personnel. The monitoring function is particularly critical to insure a uniform standard of performance among inspectors, because the ultimate success of NDI and life forecasting techniques rests upon the ability of inspectors to detect and describe flaws accurately. One option is for the Army to participate in the Air Force program for testing and evaluating the effectiveness of its NDI personnel. In like manner, engineeers responsible for application of life forecasting techniques need to be recruited and trained for their assignments in the commands.

3. Application to Specific Systems and Components. With RCM presently being implemented throughout the Army, primary opportunities exist in modifying DMWR's and technical manuals for additonal weapons systems and vehicles. As discussed in the previous section, Block 11 of the RCM ligic diagram requires inspection of various components which can only be accomplished by NDI methods, providing extensive opportunities for using presently available techniques. However NDI techniques vary greatly in expense and testing time. Some judgment must be exercised in deciding which techniques to apply and to which components, and this calls for a set of selection criteria. In particular, the most rewarding (a) are extremely expensive, (b) have long lead times in the replacement system, (c) are mission/safety critical, or (d) have high volume and can be inspected inexpensively.

a. Expensive Items. The rationale here is obvious. With high cost items, it is important to use the item for its full service life. Use of NDI (even high cost NDI) and life forecasting can effect a large monetary savings, even with only moderate alility to forecast life.

b. Items with Long Lead Times. Long lead time items are likely items for NDI because an accurate knowledge of remaining life will avoid "surprise" failures and resulting extended downtime for a system while a replacement component is obtained. Items with long lead times are frequently over - or understocked - in a supply system with resulting increased costs. An accurate picture of service life with a responsive reorder policy may substantially reduce these costs.

c. Mission/Safety Critical. The failure of certain components in a system can result in mission abort or endanger human life. These components frequently are expensive, as well. It may not always be possible to avoid catastrophic failure of such components when there are sudden, unusual stresses or loads. NDI and life forecasting can prevent failure, however, that arises from lack of knowledge of the true character (presence or absence of flaws) of the component and of its residual service life. Such items often are replaced at hard-time limits with substantial margins of safety. This practice is conservative, but it is usually not cost effective, especially with expensive components. RCM logic in conjunction with NDI can provide an effective method for assuring readiness and safety at lower cost by shifting the replacement criteria from hard-time limits to on-condition maintenance.

d. Low Cost, High Volume Items. Low cost items produced in large quantities are good targets for NDI and life forecasting applications only when the techniques can be set up inexpensively and conducted with low labor and material cost.

Recommendations for parts now in service that should be subject to NDI and life forecasting should come from Army maintenance and overhaul personnel who are directly concerned with the operation and upkeep of weapons systems. These recommendations should be directed to engineers and metallurgists who can evaluate the effects of wear, delamination, fatigue, etc., and institute NDI following the RCM logic diagram. We believe these personnel should be consulted even for recommendations for parts that may be used to demonstrate or test the techniques. Not only are these the experts on what can go wrong, but they are also the people who eventually will be involved in use of the techniques. Their early involvement will engender a positive attitude toward RCM.

One of the tasks of the M.I.T. project was to recommend candidate parts for application of NDI and life forecasting techniques. With the caveat of the preceding paragraph in mind, and on the basis of only limited discussions with maintenance and overhaul personnel, we suggest the following problem parts for which applications of NDI and life forecasting should provide recognizable benefits:

a. Detection of corrosion and cracking around the boltholes of the cover plate and flanges of the main gear box on the UH-1H Helicopter, without loosening the bolts and breaking the seals.

b. Detection of corrosion and wear on gear mating surfaces in the gear boxes on the UH-1H Helicopter, without complete disassembly.

c. Determination of the residual life of starters and generators in tanks and other combat vehicles.

d. Detection of cracking in the helicopter rotor link which is the connecting pin of the pitch rotor control system.

4. Technique Development. The MIT project group observed a lower level of utilization of NDI and life forecasting techniques in Army overhaul and maintenance activities than is generally found in the Air Force or comparable commercial industries. In contrast, however, the level of Army expertise in NDI and life forecasting is at the level of the state-of-the-art at facilities such as AMMRC. As discussed earlier, this divergence can best be alleviated through increased awareness at the engineering, field and depot level of the availability of this expertise

and through a more aggressive policy at AMMRC for distributing information and finding specific "real life" applications. In most cases, the primary technological problem is to adapt existing techniques to specific items.

Current Army and Air Force programs in technique development should be matched with specific component items. These include the mobile neutron radiography system developed by the Army, which offers particular advantages for detection of corrosion. The Air Force development of retirement-for-cause (RFC) should be followed closely and a preliminary identification of potential applications for Army weapon systems should be conducted.

The stress placed on training inspectors in detection techniques as a means of assuring higher probabilities of early flaw discovery is appropriate, given the existing NDI technologies. Each technique is heavily dependent upon the capabilities and motivation of the human involved. Long-run considerations, however, would recognize that the problem of human fallibility will always constitute a limit on the reliability of NDI techniques as long as an inspector is part of the detection loop. Such considerations would argue for the development of automated flaw detection methods that would reduce or eliminate dependence on humans for this part of the task.

Computer-based pattern recognition techniques have made substantial progress in various applications, such as cell recognition systems, photo-reconnaissance, photographic enhancement, optical character reading, and in robot vision systems. Similar systems, used in combination with existing NDI techniques, could provide more consistent, faster, and more reliable detection of incipient flaws, thus reducing the inspection limit and the level of uncertainty attached to RCM approaches. It is recommended that the Army explore means of employing various computer-augmented vision and pattern-recognition approaches in parts inspection processes.

VI. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The preliminary study described in this report examined life forecasting as a means of determining repair and overhaul procedures under the Army's Reliability Centered Maintenance Program. Our conclusions and recommendations are based primarily on information obtained from Army documents and from our observations and discussions during visits to several Army and Air Force maintenance and overhaul facilities. Summarized briefly below are what we found and what we recommend.

Findings

- In the overhaul facilities we visited, NDI techniques were not being widely used. Visual methods of inspection predominated. NDI is apparently less used by the Army than by the Air Force or by some commercial operations such as airline maintenance.

- Experimental programs now under way in several commands (for example, the M60 tank program and the T53-L-13B Helicopter engine program) are expected to provide useful insights into the organization and implementation of Army RCM procedures.

- The Quality Readiness Review procedure appears to be an appropriate means of establishing the adequacy of the Technical Data Package for an Army System. Use of the procedure to date, however, has been limited only to major systems.

- AMMRC's role in RCM is not widely known among the overhaul and maintenance engineering personnel visited.

- Performance monitoring of Army inspection personnel appears to be uncoordinated, and a shortage of NDI-trained manpower exists. Air Force experience indicates that inadequate attention to human performance in inspection can produce serious degradation of RCM methods.

- The difference in helicopter engine overhaul philosophy between the Army on the one hand and the Air Force/Navy on the other presents an opportunity to evaluate the relative merits of parts integrity and traceability as an overhaul requirement.

- The logic diagram for selecting the appropriate RCM strategy would be more useful if NDI technique selection criteria and steps were added.

Recommendations

Based on the foregoing observations we recommend the following course of action:

- o A broader dissemination of knowledge of and applications for NDI techniques in the Army is needed. This calls for a more aggressive program on the part of AMMRC, including workshops, presentations, visits, a newsletter, and similar techniques.

- o A coherent program for performance monitoring of inspection personnel should be established. Air Force practices for monitoring NDI technician proficiency could be used as guidelines.

- o While primary emphasis should be placed on the implementation of currently available NDI techologies, the continued development of new techniques, such as neutron radiography, or procedures, such as the Air Force Retirement for Cause method, should be encouraged.

- o The emergence of computer-based vision systems, image processing and pattern recognition, and the proven ability of computers to manage machine functions suggest that it should be entirely feasible to establish computer-integrated nondestructive inspection processes that remove the human inspector for the fault detection loop. Such systems should be more reliable, more consistent and faster than conventional NDI procedures. The functions that might be performed under computer control would include:

  - Loading and manipulating parts
  - Controlling process steps
  - Sensing results
  - Evaluating findings (critical, non-critical, rate of change)
  - Communicating results
  - Calling for technician/engineer review
  - Setting re-inspection schedules
  - Recording data for future use.

Computer-integrated NDI (CINDI IS A HANDY ACRONYM) could be an important contributor to greater manpower productivity, more reliable equipment performance and lower replacement cost.

- A study should be made of the relative merits of the Army system of helicopter overhaul vs. that of the Air Force and Navy at the Corpus Christi depot. The principal focus of the study should be on parts integrity and traceability.

- Candidate parts for demonstration of NDI and life forecasting techniques should be nominated by field and depot maintenance personnel. Based on our contacts with these people, we suggest the following:

  - Cover plate and flanges of main gear box of the UH-1H helicopter (corrosion and cracking).

  - Gear mating surfaces in UH-1H helicopter gearbox, without disassembly (corrosion and wear).

  - Starters and generators in tanks and other combat vehicles.

  - Connecting pin of the pitch rotor control system (cracking).

- Block 11 of the RCM logic diagram (shown as Figure 1 on Page10) should be expanded into an NDI technique selection diagram, as an aid in the selection of appropriate NDI methods for parts on which on-condition inspections is required.

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APPENDIX A: FACILITIES AND PERSONNEL VISITED

Complete reports of the visits to maintenance and overhaul faclities conducted by the MIT project team were presented in the two Interim Reports for this project.[A1,A2]. Visits were made to:

TSARCOM, Maintenance Engineering Branch, St. Louis, Missouri (18 February 1981)

Personnel visited: Bill Masters, Branch Chief
Doug Danforth, NDT Specialist

Corpus Christi Army Depot, Technical Analysis Division and Production Division. (19 February 81)

Personnel visited: Earl E. Juleg, Division Chief for Technical Analysis
Don Wells, Division Chief for Production

TARCOM, Quality Assurance Testing Branch, Detroit, Michigan (3 March 1981)

Personnel visited: David Gamache and Chester Kedzior

MRSA, Maintenance Division, Lexington, Kentucky (4 March 1981)

Personnel visited: Earl Crisp, Division Chief
Jim Eastwood
Gene Zajicek
Larry Geldmeier

Anniston Army Depot, Anniston, Alabama (5 March 1981)

Personnel visited: Robert Cheekwood, Quality Control Chemist
Jerry Bell, Engine Planning Section of Planning, Production and Control
Hubert Suggs, Coordinator of RCM program at Anniston

Mechanical Failure Prevention Group (MFPG). Annual Meeting No. 33 held at National Bureau of Standards, Gaithersburg, Maryland (21-23 April 1981)

Air Force NDI Program Office, Kelley Air Force Base, Texas (27-28 May 1981)

Personnel visited: Colonel James R. Griffin
Squadron Leader Collin Harris
John Petru

TSARCOM, Reliability Centered Maintenance and Depot Engineering Support Division, Corpus Christi Army Depot, Corpus Christi, Texas (29 May 1981)

Personnel visited: Clifford E. Sims, Division Chief
Frank M. Smejkal
Mike Manguia
Richard A. Cardinale

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APPENDIX B: MATHEMATICS AND STATISTICS OF RELIABILITY

The statistical methods behind reliability is an area of great current interest and active research. Here we give only a brief "conversational" introduction to the mathematics of reliability analysis. Several sources have been used in preparing this section and a more complete discussion can be found in the references. (B.1-B.9) We note that all of our discussion is directed toward the reliability analysis of individual components and not the reliability of systems - a more complicated topic which is not necessary for this report.

Definition of Reliability

Reliability is a quantitative concept. It is the probability that if an item is put to use under specified operating conditions, it will perform its intended function for a specified interval. (The interval can be time, miles, cycles, rounds, etc.)

How is reliability computed? To answer that question, let us consider the the meaning of 'probability'. If an experiment is performed under identical conditions N times, and a particular result occurs A times, the probability of A's occurrance, P(A), is defined as the limit of the ratio A/N as N becomes infinite, i.e.

$$P(A) = \lim_{N \to \infty} A/N$$

In practice we perform the experiment some reasonably large number of times and use the resulting ratio, A/N, as an estimate of the true probability to predict the outcome in the future.

We often express reliability by mean time between failure (MTBF). MTBF is given by:

$$MTBF = \frac{\text{Total Time in Service}}{\text{Total Number of Failures}}$$

MTBF is the average time it takes a component of a particular type to fail.

Failure Rate

A key reliability parameter is the failure rate. Failure rate is a measure of the number of failures experienced per unit of time, i.e. failures per hour or failures per 1000 hours, etc. When a number of units are being tested, the failure rate is computed from

$$\text{Failure rate} = \frac{\text{No. of failures in t / Average No. of units under test in t}}{t}$$

Defined this way, failure rate is relative rate, i.e., its dimensions are failures per unit under test per increment of time.

Suppose now we compute the failure rate and it is approximately constant over some significant interval. When this constant failure rate occurs in nature, it leads to a mathematical expression for reliability called an exponential function. For a constant failure rate, a, the reliability, R, for any mission time, t, is given by the function $R = \exp(-at)$.

Mean Time Between Failures (MTBF)

Returning now to our discussion of the mean time between failures (MTBF), for items which have an exponential reliability function, i.e. constant failure rate, MTBF is the reciprocal of failure rate. Thus the MTBF is given by

$$\text{MTBF} = \frac{1}{a}$$

When referring to the reliability of a system or a piece of equipment, MTBF is useful because it relates readily to mission length. For example, consider a system which has a typical mission length of 10 hours and a tentative reliability requirement of 0.9. We would like to know (1) how large the MTBF for this system should be, and (2) how sensitive mission reliability is to variations in MTBF. If our piece of equipment has an exponential reliability function, then we know that:

$$\text{Reliability} = \exp(-at) = \exp(-t/\text{MTBF}) = \exp(-10/\text{MTBF})$$

Soving this equation for MTBF gives us:

$$\text{MTBF} = -10/\ln(0.9) = 94.9 \text{ hrs.}$$

we could also have found the answer by referring to a graph of the curve of $R = e^{-10/\text{MTBF}}$. The curve would also indicate that to improve system reliability much above 0.9 requires a large improvement in MTBF; this <u>might not</u> be worth the cost and effort.

Limitations of the Exponential Reliability Function

Not all items exhibit rates which are constant over some portion of their life. Electrical components and some other parts usually do and the exponential reliability function which results is very convenient to handle mathematically. But many items exhibit failure rates which increase or decrease with time because of some physical process such as wear, corrosion, or work hardening. <u>When the failure rate is not approximately constant, the exponential expression for reliability is inapplicable</u>. In such cases other mathematical functions such as the Weibull, the normal, log-normal, extreme value distribution must be used.

Hazard Rate

Given a population of units which fail, are not repaired, and an arbitrary observation time period, the hazard rate is defined as the failure rate per unit time at any given lifetime.

$$\text{The failure rate per unit time} = \frac{\text{Number of failures we expect during a unit of time at a given lifetime}}{\text{Number of items exposed to failure at the same lifetime}}$$

Alternatively, hazard rate may be thought of as the probability that a unit will fail in a time period given that it has survived to the beginning of the period. Thus, the term hazard rate is a very descriptive label, i.e., it provides a measure of the "hazard" encountered in operating through the given time period.

Hazard rates may not be constant over the life of units and components. Rather, hazard rates may exhibit increasing, decreasing, constant, and combinational shapes. Several general causes for these shapes are wearout, infant mortality, and random failure for the first three shapes, respectively. The combination of these shapes, i.e, a more general model, supposes that all systems have elements of wearout, infant mortality, and random failure and exhibit the hazard rate commonly referred to as the "Bathtub Curve" (Figure B.1). This curve assumes a high but diminishing failure rate during the break-in period of a component (infant mortality), a constant failure rate over the useful life (random failure) and an increasing failure rate at the end of its life (wearout period).

A more rigorous view of the hazard or failure rate is given by Mann Schaefer and Singpurpwalla [B.9]

> The measure of an equipment's reliability is the infrequency with which failures occur in time. A failure distribution represents an attempt to describe mathematically the length of the life of a material, a structure, or a device. There are many physical causes that individually or collectively may be responsible for the failure of a device at any particular instant. At present it is not possible to isolate these physical causes and mathematically account for all of them, and therefore, the choice of a failure distribution is still an art. If one tries to rely on actual observations of time to failure to distinguish among the nonsymetrical probability functions, he is still faced with a problem because nonsynthetic distributions are importantly different at the tails and actual observations are sparse, particularly at the right-hand tail, because of limited sample size.
>
> In view of these difficulties, it is necessary to appeal to a concept that makes it possible to distinguish between the different

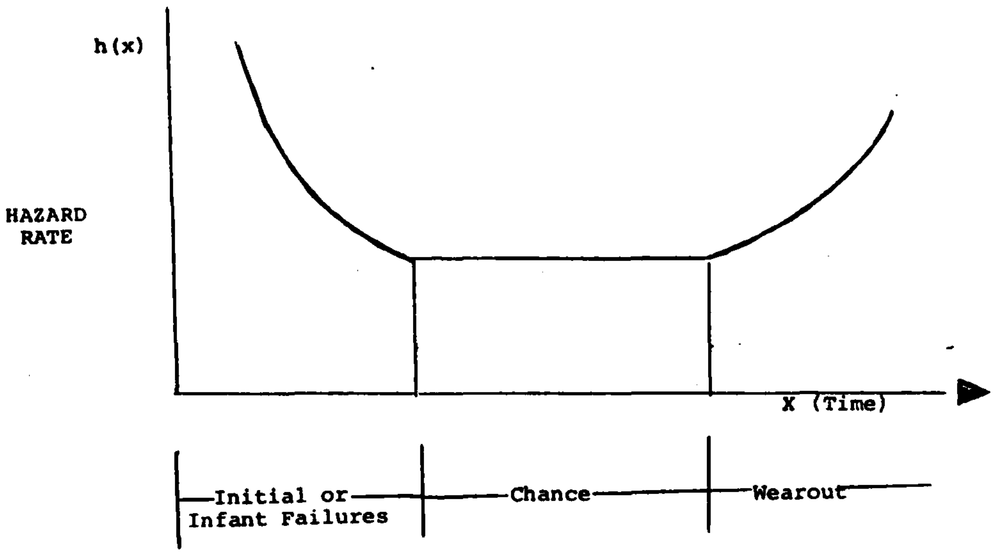

Figure B. 1.: The Bathtub Curve

distribution functions on the basis of a physical consideration. Such a concept is based on the failure-rate function, which is known in the literature of reliability as the hazard rate. In actuarial statistics the hazard rate goes under the name of force of mortality, in extreme-value theory it is called the intensity function, and in economics its reciprocal is called Mill's Ratio.

Let F(x) be the distribution function of the time-to-failure random variable X, and let f(x) be its probability density function. Then the hazard rate, h(x), is defined as:

$$h(x) = \frac{f(x)}{1-F(x)}$$

Here 1-F(x) is called the reliability at time x and will be denoted by either R(x) or $\bar{F}(x)$. The hazard rate, which is a function of time, has a probabilistic interpretation; namely, h(x)dx represents the probability that a device of age x will fail in the interval (x,x +dx), or

$$h(x) = \lim_{\Delta x \to 0} \left[\frac{\text{P[device will fail in interval } (x, x+\Delta x) \text{ given it has survived up to } x]}{\Delta x} \right]$$

On the basis of physical considerations, one is at liberty to choose the functional form of h(x) for a particular device. Once this is done, a differential equation in h(x) is obtained, from which f(x) and F(x) can be recovered.

To aid the choice of h(x), three types of failures generally have been recognized as having a time characteristic. The first one, called the initial failure, manifests itself shortly after time x = 0 and gradually begins to decrease during the initial period of operation. A good example of this type is seen in the standard human mortality table, in which it is assumed that up to the age of 10 years a child can die of hereditary defects but, having lived past this age, is almost certainly free of such defects. The second one, called chance failure, occurs during the period in which a device exhibits a constant failure rate, generally lower than that prevailing during the initial period. The cause of this failure is attributed to unusually severe and unpredictable environmental conditions occurring during the operating time of the device. For example, in human mortality tables, it is assumed that deaths between the ages of 10 and 30 years are generally due to accidents. The third type, called the wear-out failure, is associated with the gradual depletion of a material or with an accumulation of shocks, fatigue, and so on. Again, in human mortality tables, after the age of 30 years an increasing proportion of deaths are attributed to old age. The three types of failures have been classically represented by the bath tub curve, (Figure 1) wherein each of the three segments of the curve represents one of the three time periods: initial, chance, and wear-out.

It was stated above that, given the functional form of h(x), the f(x) and the F(x) could easily be determined and after mathematical manipulation we may derive the following equation:

$$f(t) = h(t)\exp[-\int_0^t h(x)dx]$$

Hazard rate plots as shown in Figure B.1 depict the failure of components and systems as allowed to fail from a new condition. While the hazard rate graph does not directly show how many units have failed, survived, nor the percentage that survive to a particular age (measured as the number of time increments the unit is in operation), it does, however, explicitly show the percentage of presently surviving units that will fail in the next time increment.

Failure Distributions As a final part of our discussion, we will briefly introduce five useful failure distributions. These are the exponential, Weibull, Gamma, log normal, and the Birnbaum - Saunders distributions. We will not (because of complexity) discuss mixed composite, extreme value, competing-risk or multivariate distribution models).

1. The Exponential Distribution

The probability density function (p.d.f.) of the exponential distribution can be obtained either from the hazard rate concept or by considering the waiting time between arrivals in a Poisson process. Our p.d.f. of x, where x denotes the time interval between successive failure (or "shocks"), is given by

$$f_x(x) = a\exp(-ax)$$

More generally, if

$$h(x) = 0 \quad , 0 \leq x \leq A$$

and $\quad h(x) = a \quad , x \geq A$

then $\quad f_x(x) = a\exp[-a(x-A)], x \geq A$

$$f_x(x) = 0 \quad , x < A$$

and $\quad F_x(x) = 1 - \exp[-a(x-A)], x \geq A$

$$F_x(x) = 0 \quad , x < A$$

Often A is referred to as the <u>shift</u> or <u>threshold</u> parameter. We note that the exponential distribution can be chosen as a failure distribution if and only if the assumption of a constant hazard rate is justified.

2. <u>The Weibull Distribution.</u>

The Weibull distribution is perhaps the most popular parametric family of failure distributions at the present time. Its applicability to a wide variety of failure situations was discussed by Weibull (1951); it has been used to describe vacuum-tube failures (Kao, 1958) and the ball-bearing failures (Lieblein and Zelen, 1956). Whereas applicability of the exponential distribution is limited by the constant hazard rate assumption, the family of Weibull distributions provides for increasing and decreasing rates as well. We note that the Weibull distribution is an extreme value distribution in that it is the limiting distribution of the minimum of independent random variables.

The distribution is given by

$F_b(x) = 1 - \exp[-(ax)^b]$ for $x \geq 0$, where $a, b > 0$ and the hazard rate takes the form

$$h(x) = f(x)/\bar{F}(x) = ab(ax)^{b-1} \text{ for } x > 0$$

Thus the Weibull distribution is IFR for $b \geq 1$ and DFR for $0 < b \leq 1$; for $b = 1$, $F_b(x) = 1 - \exp[-ax]$, the exponential distribution, which is both DFR and IFR. We note the following characteristics of the hazard function $h(x)$:

- $h(x) \uparrow \infty$ for $b > 1$ and $\downarrow 0$ for $b > 1$ as $x \rightarrow \infty$

- the parameter b is called the <u>shape</u> parameter; as b increases the hazard rate (failure rate) rises more steeply and the probability density becomes more peaked.

- the parameter a is called the <u>scale</u> on <u>location</u> parameter; the distribution depends on a and x only through their product ax.

3. <u>The Gamma Distribution</u>

The gamma distribution is a natural extension of the exponential distribution and has sometimes been considered as a model in life-test problems (Gupta and Groll, 1961). It can be derived by considering the time to the k + h successive arrival in a Poisson process or, equivalently, by considering the k-fold convolution of an exponential distribution.

The p.d.f. is given by

$$g_{a,b}(x) = \frac{a^b x^{b-1} e^{-ax}}{\Gamma(b)} \qquad \text{for } x \geq o \text{ and } a,b \quad o$$

and $\quad (b) = (b-1)!$ is the gamma function.

Thus the distribution is given by $G_{a,b}(x) = \int_o^x g_{a,b}(t)dt$ and for b = positive integer $G_{a,b}(x)$ may be written in closed form:

$$G_{a,b}(x) = 1 - \sum_{i=0}^{b-1} \frac{(ax)^i}{i!} e^{-ax} \qquad \text{for } x \geq 0$$

We note the following characteristics of gamma function:

- the distribution $G_{a,b}$ is DFR for $0 < b < 1$ and IFR for $b \geq 1$

- for b = 1, $G_{a,b} = 1-e^{-at}$, an exponential distribution

- h(x) a for a 1 and h(x) a for a 1 as x

- as with the Weibull family, as the shape of the parameter b increases the probability density becomes more peaked.

- a is a scale parameter

D. The Logarithmic Normal Distribution

Until recently, the logarithmic normal (log-normal) distribution received little attention in the statistical literature - its applications being mainly in small-particle statistics, economics, and biology. Of late, however, because of its wide applicability to reliability problems, especially with respect to maintainability and certain types of fracture problems, its use has increased.

The log-normal distribution implies that the logarithms of the lifetimes are gaussian (normal) in distribution, hence the easiest derivation is accomplished with a simple logarithmic transformation. Other, more difficult derivations are accomplished by considering the hazard rate or by considering a physical process wherein failure results from fatigue cracks (this latter derivation makes the log-normal distribution more acceptable for failure problems).

If we let X be the time to failure random variable of a device and let $T = \log_e X$ be gaussian with parameters μ and σ then we can show that the log-normal p.d.f. for X is given by:

$$g_X(x) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{\log x - \mu}{\sigma}\right)^2\right], \quad x > 0$$

$$g_X(x) = 0 \qquad\qquad , \text{ elsewhere}$$

We customarily write this as : $X \sim \Lambda\,(\mu, \sigma^2)$. We note that the hazard rate, h(x), of the log-normal distribution is an increasing function of time followed by a decreasing function, and can be shown to approach zero for large lifetimes and at the initial time.

5. The Fatigue-Life Model (Birnbaum - Saunders Distribution)

The derivation and characteristics of the fatigue-life model are too long and complicated to be presented here but because of its importance it bears mentioning. We quote the opening paragraph of Section 4.11 of Mann, Schafer, and Singpurwalla[B.9] and refer the interested reader to that book and others for further discussion.

> To characterize failures due to fatigue crack extention, Birnbaum and Saunders (1969) proposed a life distribution based on two parameters. This distribution, for a non-negative random variable, is derived using considerations from renewal theory, via an idealization of the number of cycles necessary to force a fatigue crack to grow past a critical value. A distribution such as this, which is obtained from considerations of the basic characteristics of the fatigue process, is more persuasive in its implications that any other distribution chosen for ad hoc reasons, such as goodness of fit tests and the like. The reasonableness of the appraoch used to derive this model is indicated by its ability to offer a probabalistic interpretation of Miner's (1945) rule. a deterministic rule that attempts to predict the fatigue life of a speciman under repeated cyclic loading, Birnbaum and Saunders (1968). Freedenthal and Shinozuka (1961) , on the basis of heuristic engineering considerations, have presented a distributional form akin to the model given by Birnbaum and Saunders, and have also substantiated the validity of their model using several sets of fatigue data. It is for these reasons that a presentation of the basic approach used by Birnbaum and Saunders in doing this model is believed to be useful.

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APPENDIX C: APPLIED FRACTURE MECHANICS

Fracture mechanics, through a combination of energy considerations and stress analysis, provides a formalism for describing crack propagation in structural components.The bibliography lists references in increasing order of difficulty. (C.1-C.4)

Briefly, cracks in a structural/mechanical component can be characterized by the stress intensity factor K which is proportional to the applied stress σ and the square root of the crack length a:

$$K = \sigma \sqrt{\alpha \pi a}$$

where α is a factor depending on the type of loading and the geomety of the crack and the structure. Unstable fracture occurs when K equals the critical stress intensity factor K_c, known as the fracture toughness. The fracture toughness is a function of material properties, section size, and operating environment.

At the outset of unstable crack growth which occurs before general yielding the fracture stress σ_f for a specified crack size a or the critical crack size a_c for a specified stress σ may be determined:

$$f = \frac{K_c}{\sqrt{\alpha \pi a}}$$

$$a_c = \frac{1}{\alpha \pi} \left(\frac{K_c}{\sigma}\right)^2$$

For the cases of time-dependent fracture, such as fatigue or stress corrosion cracking, the failure time t_f of a part containing a crack of a specified initial size can be determined by integrating the crack growth equation for the particular case.

As an approximation

$$\frac{da}{dt} \text{ or } \frac{da}{dn} = AK^n,$$

where the constants A and n depend on the type of loading and crack growth, material properties, and environment. The failure time, for example, can be calculated from

$$t_f = \int_0^{t_f} dt = \int_{a_i}^{a_c} \frac{da}{AK^n}$$

After substitution for K, the failure time is:

$$t_f = \frac{1}{A(\sigma\sqrt{\alpha\pi})^n} \left[\left(\frac{1}{a_i}\right)^{\frac{n}{2}-1} - \left(\frac{1}{a_c}\right)^{\frac{n}{2}-1} \right]$$

Usually, $a_c >> a_i$ so that the lifetime is not sensitive to the final crack length but, instead, is strongly dependent on estimations of the initial crack size. The small critical crack sizes associated with higher strength materials and the uncertainties associated with the NDI methods for defection of small flaws lead to assumption of "worst-case" conditions in general fracture mechanics analyses. The fracture toughness of the material is usually assumed to be the lowest possible value for the particular conditions. In addition, the critical crack size for design calculations is often chosen to be the maximum crack size that might be undetected by NDI equipment or that an NDI operator might not detect.

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