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Volume I

ENGINE COMPONENT RETIREMENT FOR CAUSE

VOLUME I - EXECUTIVE SUMMARY

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Air Force Wright Aeronautical Laboratories
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This program developed and integrated materials behavior characteristics, component life analysis, nondestructive evaluation and cost-risk technology to establish and demonstrate the retirement for cause maintenance concept as it applies to rotating components of military gas turbine engines. As such it provides the basis for elimination of classical time or cyclic life limits currently imposed for retirement of gas turbine rotor components by substituting a life management system in which each individual component is retired from service when the unique, economical safe life of that component is exhausted.

The methodology was demonstrated on and validated for the U.S. Air Force F100 engine's rotor components and has been implemented on that engine system by the USAF Air Logistics Command. Use of Retirement for Cause is projected to result in life cycle cost savings in excess of $1 billion for that engine system. The Retirement for Cause methodology developed is generic, and may be applied to not only other gas turbine engines, but to components of any life limited system.

This report presents an overview/summary of the development activity and its results.

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FOREWORD

This work was performed under the U.S. Air Force — Wright Aeronautical Laboratories, (Materials Laboratory) Contract F33615-80-C-5160 with the Project Number assigned as DARPA 3993. This contract program was initiated in August 1980, and was completed in February 1987. The Air Force Retirement for Cause Program Manager was Dr. W. H. Reimann (AFWAL/MLTC). The USAF Project Engineer for this contract was L. P. Zawada (AFWAL/MLLN). The work was performed by the Engineering Division and Government Products Division of Pratt and Whitney under the direction of the Retirement for Cause Program Management Office of the Materials Engineering and Technology Branch, (ED-S). Program Manager of Pratt and Whitney Retirement for Cause activities is J.A. Harris, Jr., reporting to M. C. VanWanderham, Manager, Mechanics of Materials and Structures. Technical Program Managers for this effort were C.G. Annis, Jr., B.A. Cowles, and J.S. Cargill. Project Engineers were D.L. Sims, R. White and R.L. Shambaugh.

This program was jointly sponsored by the Materials Sciences Office, Defense Advanced Research Projects Agency and the Materials Laboratory, Air Force Wright Aeronautical Laboratories. The contributions, support and cooperation of DARPA and the many U.S. Air Force participants are acknowledged as key factors in the success of the program.

The P&W Retirement for Cause Program Management Office also acknowledges the contributions of the many Pratt and Whitney organizations to the program.

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SUMMARY

Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase. Engine rotor component initiation life limits, usually expressed as operating cycles or time limits, are analytically determined using lower bound, 1 occurrence in 1000, low-cycle fatigue (LCF) characteristics. By definition then, 99.9 percent of the disks are being retired prematurely. Retirement for Cause (RFC) allows each component to be used to the full extent of its safe total fatigue life, retirement occurring when a quantifiable defect necessitates removal of the component from service. The defect size at which the component is no longer considered safe is determined through fracture mechanics analyses of the disk material and the disk fracture critical locations, the service cycle and the overhaul/inspection period.

The purpose of this program was to develop and to integrate materials behavior characteristics, component life analysis, nondestructive evaluation and cost-risk assessment technology to establish and demonstrate the retirement for cause maintenance concept as it applies to rotating components of military gas turbine engines. The methodology was demonstrated on, and validated for the rotor components of the U.S. Air Force F100 engine, and is being implemented on that engine system at the U.S. Air Force Air Logistic Command's San Antonio Air Logistics Center.

The goal of this effort was to provide the basis for elimination of classical cyclic, or time, life retirements currently imposed on gas turbine rotor components by substituting a system in which each individual component is retired from service when the economical safe life of that component is exhausted. In this system, the retirement of a component from service would occur when the unique cyclic life of that component has been utilized, as opposed to an arbitrary cycle or time count at which the entire population of components of a specific type are retired, regardless of condition. The individual component is therefore taken out of service when there is a specific reason (cause) for retirement.

A study conducted in 1979 indicated that realization of that goal could produce four major benefits for the U.S. Air Force, and indeed for all operators of military gas turbine engines:

- Direct life cycle cost savings resulting from utilization of components which would have been retired and consequently require replacement by new components, thus enabling more efficient use of logistic resources;
- Enhanced safety due to improved understanding of component capabilities and inspection;
- Provision of a management information system to enable evaluation of impact of maintenance options for specific components on system safety, cost and logistic requirements;
- Indirect cost savings resulting from reduction in use of strategic materials, reduction in energy requirements to process new components, reduction in space and administrative requirements associated with provisioning of components, and in mitigation of future inflationary pressures on costs of new components.

This program has met its goals.

The Retirement for Cause maintenance concept is presently implemented on USAF F100 rotor components at the San Antonio Air Logistics Center in conjunction with the F100 core upgrade program. A total of 23 fan, compressor, and low-pressure turbine rotor components will be managed under this philosophy. The F100 engine overhaul manuals (Technical Orders) have been revised to eliminate classical time to compliance (retirement) limits for those components, and incorporate RFC.

As a direct result of RFC, life cycle cost savings of $966 million are projected for the USAF F100-PW-100/200 engine systems over the period 1986 to 2005. An additional $655 million savings for which RFC is partially responsible (approximately 46 percent) also accrue from labor and maintenance fuel savings due to extension of the maintenance interval for the upgraded F100 core engine. These savings represent the highest return-over $1.2 Billion of any technology effort to date in the history of the Air Force Materials Laboratory (Air Force Wright Aeronautical Laboratories).

The technology and procedures developed under this program are generic. While the USAF F100 engine was used as the demonstration vehicle, and the concept was validated for that engine, the USAF TF30 engine was also reviewed. The technical basis has been established such that the procedure can be used on any gas turbine engine. The technical basis for probabilistic life analyses has also been established, and has been accepted. In addition, a number of the technical elements of the Engine Structural Integrity Program (ENSIP) were validated. Because of these activities, it is anticipated that Retirement for Cause will become the standard USAF procedure for logistics management of the life limited components of all future engines.

A major factor in the success of this program in taking Retirement for Cause from a concept to reality was the high level of coordination and teamwork maintained among the Government and industry organizations involved. From the inception of the program, all USAF and other Government organizations concerned with the development, operation and maintenance of gas turbine engines, and specifically the F100 engine, provided support, guidance, and management direction to the program. All corresponding Pratt and Whitney organizations were also involved in the performance of this effort, as well as its subcontractors, consultants and other USAF contractors. The primary vehicles for this interaction and coordination were executive, steering and working groups which met regularly during the seven year period of the program. The success of the program validates that program management approach.

SECTION II

INTRODUCTION

1. BACKGROUND

Historically, methods used for predicting the life of gas turbine engine rotor components have resulted in a conservative estimate of useful life. Most rotor components are limited by low-cycle fatigue (LCF) generally expressed in terms of mission equivalency cycles or engine operational hours. When some predetermined life limit is reached, components are retired from service.

The fatigue process for a typical rotor component such as a disk can be visualized as illustrated in Figure 1. Total fatigue life consists of a crack initiation phase followed by growth and linkup of microcracks. The resulting macrocrack(s) would then propagate subcritically until the combination of service load (stress) and crack size exceeded the material fracture toughness. Catastrophic failure would ultimately result had not the component been retired from service. To preclude such cataclysmic failures, disks have been typically retired at the time where 1 in 1000 could be expected to have actually initiated a short fatigue crack (0.03 inch). By definition then, 99.9 percent of the disks are being retired prematurely. This results from the fact that all fatigue data have inherent scatter. When considered with other uncertainties in any design system, e.g. stress analysis error, mission variability, fabrication tolerances, temperature uncertainty, the final life prediction is made using worst case conditions for an occurrence rate of 1 in 1000. When plotted on a life distribution curve as shown in Figure 2, this corresponds to approximately a -3 sigma lower bound. It is at this life that all fatigue life limited disks are removed from service. This procedure has successfully prevented catastrophic in-service failures. However, in retiring 1000 disks because one may crack, the remaining crack initiation life of the 999 theoretically good disks, (shaded area in distribution curve of Figure 2,) is not used. It has been documented that many of the 999 remaining retired disks have considerable useful residual life, as shown in Figures 3 and 4.

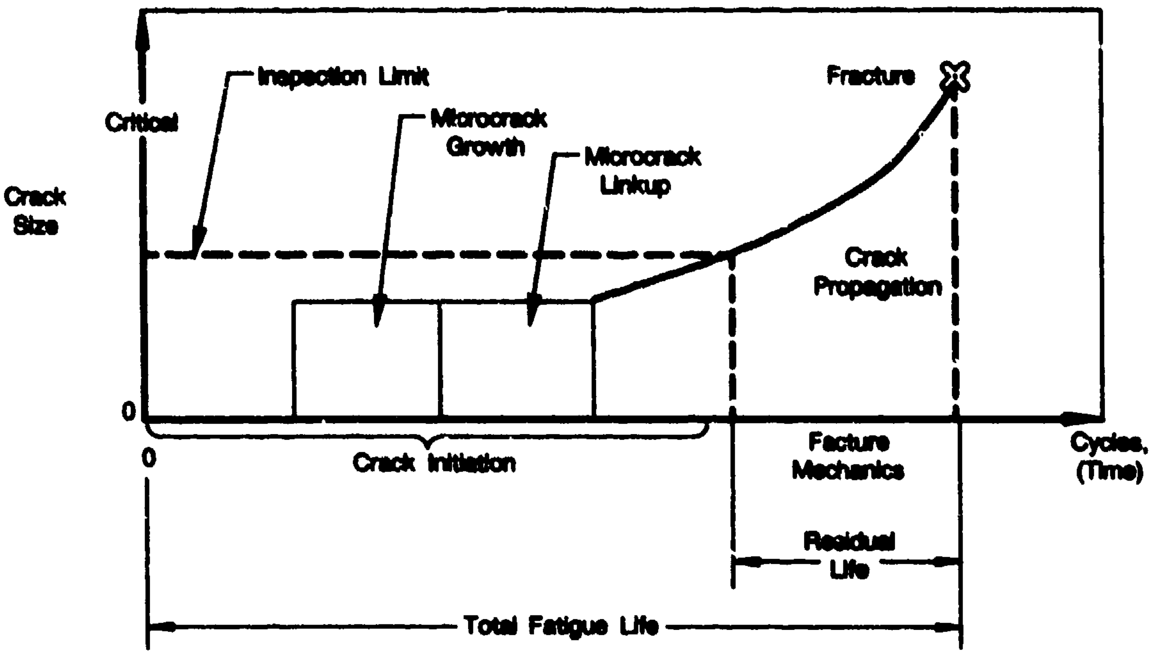


Figure 1. Total Fatigue Life Segmented Into Stages of Crack Development, Subcritical Growth and Final Fracture

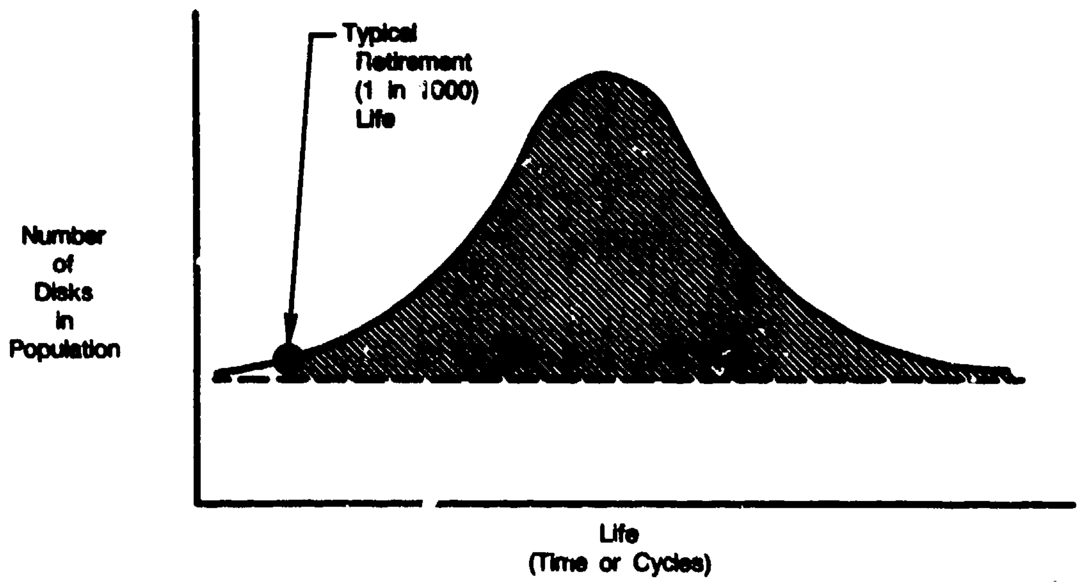


Figure 2. Historical Life Limit Methodology Precluded Use of All Available Life in a Population of Disks

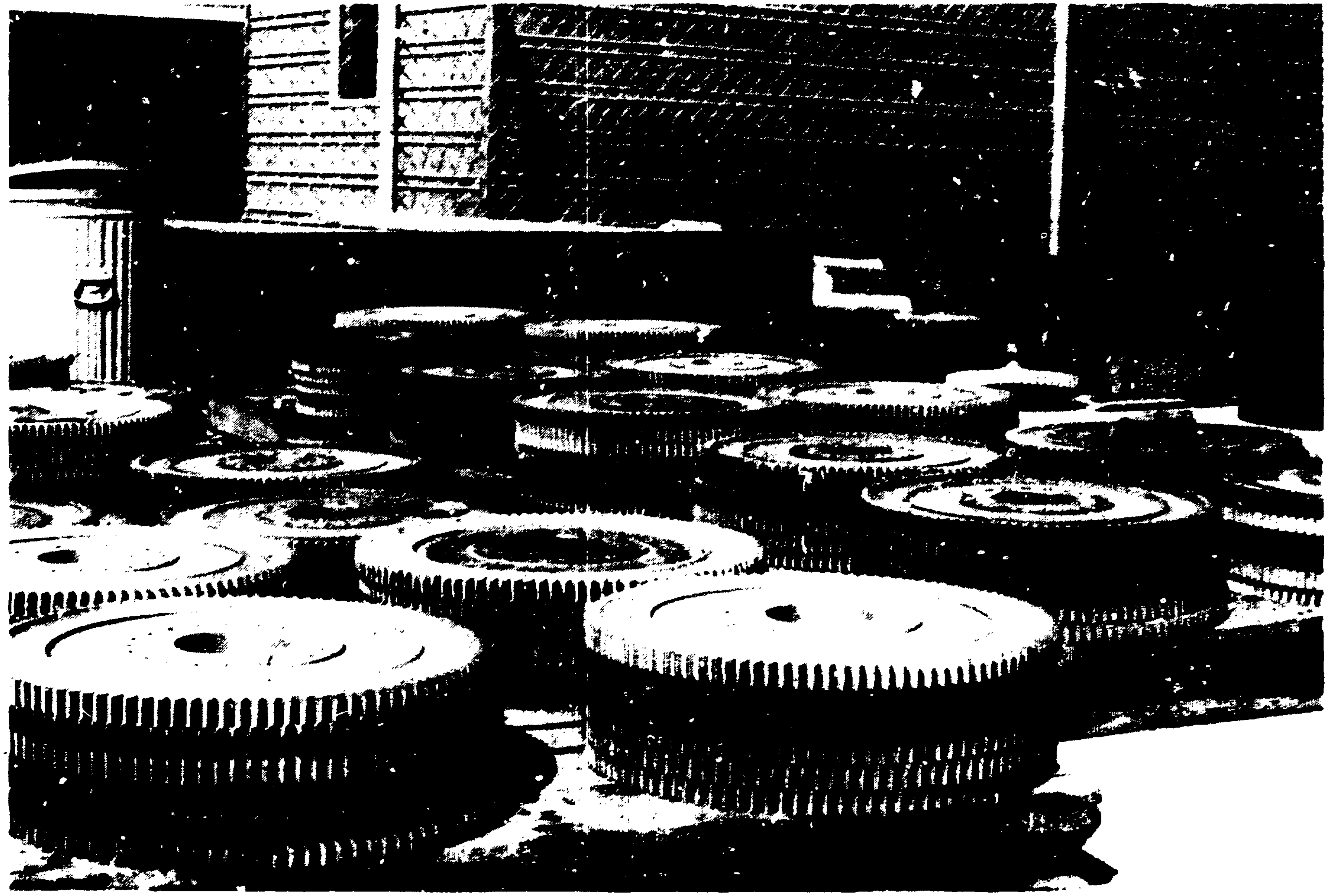


Figure 3. Many of These Disks Retired from Service Have Usable Life Remaining

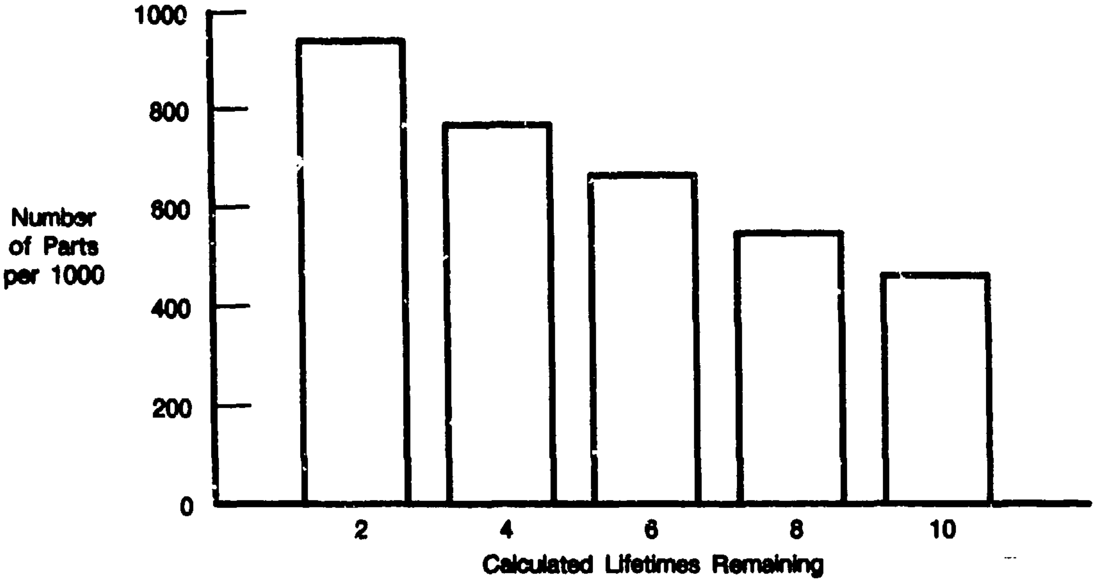


Figure 4. Useable Life in Excess of the Typical Components 1 in 1000 Retirement Life Can Be Significant for a Component Population

The ability to safely utilize the residual life in the population of 999 disks had been limited by the understanding of the fatigue and fracture process. Technology advances have now improved that understanding, resulting in the ability to eliminate or define the uncertainties in life prediction, thus enabling the Retirement for Cause approach. Economic pressure for efficient use of resources makes adoption of RFC procedures a necessity. Under the RFC philosophy, each of these retired disks could be inspected and returned to service. The return-to-service (RTS) interval is determined by a fracture mechanics calculation of remaining propagation life from a crack just small enough to have been missed during inspection. This procedure would be repeated, as shown in Figure 5, until the disk has incurred measurable damage, at which time it is retired for that reason (cause). RFC is a methodology under which an engine component would be retired from service when it had incurred quantifiable damage, rather than when an analytically determined minimum design life had been reached.

The Materials and Aeropropulsion units of the Air Force Wright Aeronautical Laboratories (AFWAL) have been conducting in-house research and development activities in the RFC area since 1972. A joint study by the Metals Behavior Branch (AFWAL/MLLN), the Engine Assessment Branch (AFWAL/POTA), and the Directorate of Engineering, Aeronautical Systems Division, reference 1, was undertaken in 1975 to assess the state of the art of the technologies involved in RFC. This study addressed and utilized a TF33 3rd-stage turbine disk as a demonstration vehicle. As a result of this study, the technical requirements for implementing an RFC approach were identified. These technology requirements fell into four areas: stress analysis, crack growth analysis, nondestructive evaluation, and mechanical testing. Pratt & Whitney had also begun extensive research and development programs under corporate, IR&D, and government contract sponsorship in 1972 to identify and to develop the applied fracture mechanics and NDE technologies necessary to realize the RFC concept. In addition to the technical areas defined by the efforts discussed above, the broad areas of economics and logistics management also had to be incorporated and integrated before RFC could become a viable, implementable maintenance concept for managing life limited gas turbine engine components.

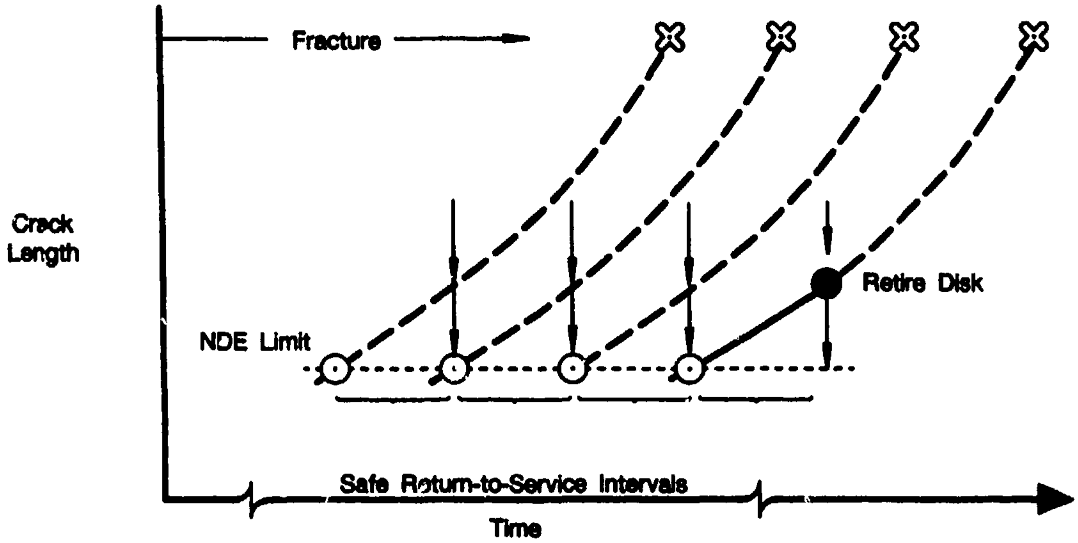


Figure 5. The Retirement for Cause Procedure Involves Inspection and Return-to-Service Until a Quantifiable Defect Is Found, Resulting in Retirement

The culmination of these preliminary activities was a study conducted by P&W in 1979 and 1980 under Defense Advanced Research Projects Agency (DARPA) and AFWAL sponsorship entitled "Concept Definition: Retirement for Cause of F100 Rotor Components," reference 2. This program was the first to consolidate and focus these disciplines on a specific engine system and to quantify the benefits and risks involved. The methodology and results of the study program have been discussed at many workshops and symposiums, and published in several articles, references 3, 4, 5, and 6.

Upon completion of the initial Concept Definition Study, AFWAL/Materials Laboratory established a major thrust in RFC with the goal of reducing the concept to practice with first system implementation to occur in 1986 on the F100 engine at the San Antonio Air Logistics Center (SAALC). P&W developed the probabilistic life analyses, integrated logistics/economic methodology, and RFC procedure to support this implementation. The RFC methodology is generic, and has direct applicability to fatigue life limited components of all gas turbine engines. While this program concentrated upon the F100 engine, the USAF TF30 engine system was also studied. The use of Retirement for Cause for a given engine application must be technically feasible. However, other factors, including economic desirability and compatibility with force maintenance/logistic structures must also be evaluated. Therefore, benefits of RFC must be weighed against, or in combination with, alternative procedures for each specific application before an implementation decision is made.

2. THE USAF RETIREMENT FOR CAUSE THRUST

The Air Force Wright Aeronautical Laboratories (AFWAL) had conducted a number of precursor technology activities prior to the inception of this program. In 1979, a Retirement for Cause Technical Thrust Area was established within AFWAL with Dr. W.H. Reimann of the Materials Laboratory as the Thrust Manager. An integrated development plan to reduce the Retirement for Cause concept to practice was established. The initial application, and vehicle for the reduction to practice, was the F100 engine. The development plan coordinated the activities of various units within the Air Force Systems Command, Air Force Logistics Command, Air Force Tactical Air Command and other Air Force, Department of Defense, and government agencies with those of the Air Force's contractor and consulting organizations. It also provided for independent review and consultation throughout the entire effort to assure the appropriateness, timeliness and efficiency of the activities.

In addition to the internal Air Force activities, the four contracted technology programs listed in Table 1 were conducted. A number of other Department of Defense contracted programs were also reviewed for application and/or incorporation of their technical results into the RFC Thrust Activities.

TABLE 1. MAJOR AIR FORCE RETIREMENT FOR CAUSE PROGRAMS

Name	*Type**	*Prime Contractor*	*Time Period*
Concept Definition: Retirement for Cause of F100 Rotor Components F33615-76-C-5172 Modified	6.2	Pratt & Whitney	1979-1980
Retirement for Cause Inspection System Design F33615-80-C-5049	6.2	Pratt & Whitney	1980-1981
Engine Component Retirement for Cause F33615-80-C-5160	6.2	Pratt & Whitney	1980-1987
Manufacturing Technology for Nondestructive Evaluation System for Implementation of Retirement for Cause Procedures for Gas Turbine Engine Components (AKA — RFC/NDE) F33615-81-C-5002	7.8	Systems Research Laboratories	1981-1987

*6.2 — Exploratory Development
7.8 — Manufacturing Technology

3. PROGRAM DESCRIPTION

The Engine Component Retirement for Cause program reported herein consisted of a 72 month technical effort with an additional period for final reports, reviews and debriefings. The program activities were divided into four phases with eleven major tasks and a total of 32 specific sub tasks. In addition to the primary technology tasks of the program, support tasks insured full coordination with the F100 Engine Program and with the other US Air Force sponsored nondestructive evaluation and Retirement for Cause related contract programs. The major elements of the program are shown schematically in Figure 6, together with statements as to their primary results/purposes. The activity conducted within each phase is summarized in the following paragraphs.

a. Phase I — Life Assessment Systems Development

This phase was the primary technology development activity of the program. The fracture mechanics, life, and economic analyses tools were developed, and the necessary data base for use of the tools was established. As F100 engine components were the primary application, the fracture mechanics and data base efforts addressed conditions and materials for that engine. The technology base development consisted of a series of state-of-the-art fracture mechanics studies aimed at producing analysis techniques and data for input to the life analysis systems. Materials characterization tasks provided quantitative information on the nature of defect population and crack propagation data for IN-100, Waspaloy, Titanium 6-2-4-6, and Astroloy, the materials of interest.

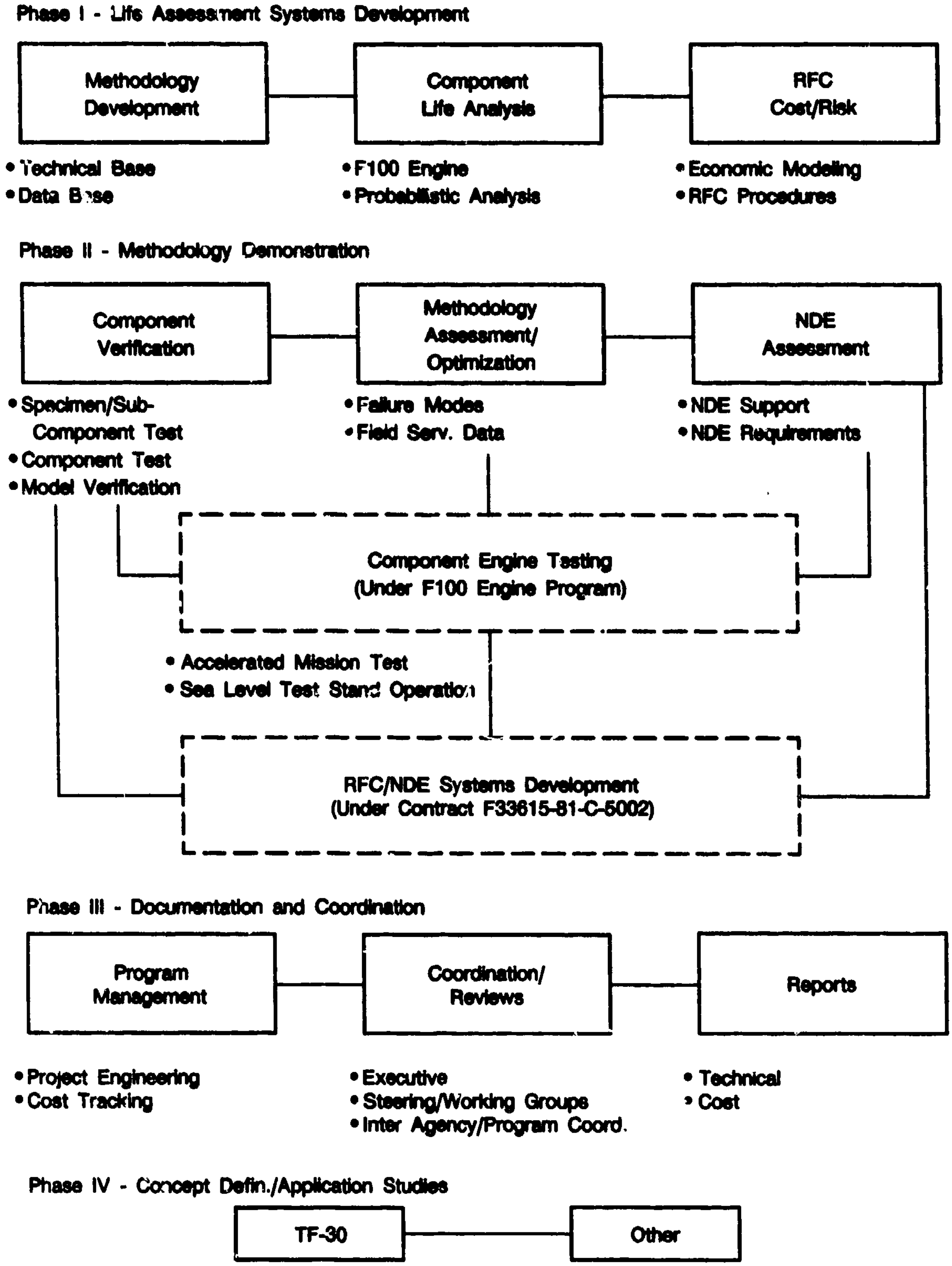


Figure 6. Program Phase and Major Task Structure With Summary of Results and Purposes

A probabilistic life analysis technique (PLAT) had been previously defined, (Reference 2) and was developed. The information generated in the technology base studies was used to refine this technique, or to provide inputs to the system. This probabilistic life analyses technique was then used in conjunction with thermal and stress analysis and nondestructive evaluation information to perform life prediction calculations and sensitivity studies on specific F100 engine components selected for Retirement-for-Cause. Results of these analyses were, in turn, employed in comparisons of cost versus risk and the life cycle cost calculations to establish strategies for implementation of RFC, and to provide management information necessary for cost effective maintenance decisions.

b. Phase II — Methodology Demonstration/Validation

This phase demonstrated the tools developed in Phase I by laboratory testing of specimens and subcomponents to verify the statistical aspects of the predictive models. In addition, spin-rig testing of turbine and compressor component assemblies verified the fracture mechanics tools. No engine or rig testing was conducted in the program. However, an Accelerated Mission Test (AMT) of a full F100 engine with purposely flawed components was conducted in the F100 Component Improvement Program. Technology activity in support of the AMT was provided, and the results were integrated into the RFC program. This test, equivalent to more than four years of service in the field, demonstrated fracture mechanics/life analysis tools under real engine operating conditions, and verified the laboratory specimen and component test results.

In addition to the laboratory and engine test results, information was obtained from F-15 and F-16 operating bases to confirm engine mission utilization, and from the San Antonio Air Logistic Center to assess field service performance of all F100 engine RFC Candidate Components. This information and data was used to verify and optimize the methodology.

While no development of NDE systems was conducted under this program, NDE support was provided during the methodology demonstration. Requirements for inspection of the candidate F100 RFC Components were defined, and were maintained current. This information was interacted with the Manufacturing Technology for RFC/NDE Systems program conducted by Systems Research Laboratories. In turn, information and results from that program were utilized in both the Methodology Demonstration and Life Assessment System Development Phases of this program.

c. Phase III — Documentation and Coordination

This phase provided for program management, project engineering, program reviews, and workshops, technical advisory services, and reports throughout the life of the program. It also provided the vehicle for the intense coordination activities among the various units of the Department of Defense, other government agencies, and the industrial and academic organizations involved. In addition to the normal contractual progress, status and final reports, special interim technical reports covering various aspects of the program were issued. These reports are listed in Table 2. A very large number of informational briefings at all levels of both the United States and allied nation governments were made, and aspects of the program presented at various technical conferences and symposiums.

TABLE 2. TECHNICAL REPORTS ISSUED UNDER THE ENGINE COMPONENT RETIREMENT FOR CAUSE PROGRAM

Title	*Identification*	*Date*
Position Paper: Validation of Retirement for Cause Methodology via Component Demonstration Testing	FR-14904*	June 1981
Application Study: Retirement for Cause of USAF TF30 Engine Components	AFWAL-TR-83--4020*	April 1983
Thermal Mechanical Fatigue Crack Growth	AFWAL-TR-84-4185	March 1985
Engine Component Retirement for Cause: Probabilistic Life Analysis Technique	AFWAL-TR-85-4075*	June 1985
Fracture Mechanics of Multiple Crack Initiations	AFWAL-TR-85-4110	Oct 1985

*Restricted Distribution Document

d. Phase IV — Concept Definition Studies

This phase provided for studies and consultations to determine the technical and economic feasibility of applying retirement for cause concepts to other propulsion systems. The most extensive effort was conducted on the USAF TF30 gas turbine engine. This study also provided for limited interaction with the Australian Department of Defense regarding the TF30 engines operated by the Royal Australian Air Force under the US-Australia Cooperative Research and Development Arrangement Number 79/703.

The results of the study of application of retirement for cause to the USAF TF30 engines were previously reported in detail and are only summarized in this report.

4. PROGRAM OPERATION

The technical and coordination activities of this program were accomplished in the time period August 1980 through February 1987 by a project team assembled from the Engineering and Government Products Divisions of Pratt and Whitney organized and directed by the Retirement for Cause Program Management Office (RFC/PMO) of the Materials Engineering and Technology Branch, Engineering Division, South. The program team also used a number of other organizations, outside of the government and United Technologies, to provide subcontract, consulting, and/or independent review effort throughout the program. Major organizations/individuals involved and the general area of their activities are listed in Table 3.

The program was organized and conducted using the phase-major task-subtask manager concept wherein specific responsibilities were defined. With USAF approval, a Master Planning and Control Document was developed and maintained throughout the program, which interpreted the statement of work in terms of task descriptions, approaches, objectives, schedules and resource allocations. This document was the primary tool for control and execution of the program.

TABLE 3. SUBCONTRACT, CONSULTING AND/OR REVIEW ACTIVITIES BY NON-GOVERNMENT ENTITIES FOR THE ENGINE COMPONENT RETIREMENT FOR CAUSE PROGRAM

Organization/Individual	*Subject of Activity*
Failure Analysis Associates Palo Alto, California	Probabilistic Life Methodology Support
Rockwell International Science Center Thousands Oaks, California	Statistical Methodology
Dr. A.F. Grandt, Jr. Purdue University	Multiple Crack Initiation/Growth Behavior
Dr. A.P. Berens University of Dayton Research Inst.	Nondestructive Evaluation Statistical Analysis
Dr. J.H. Griffin Carnegie-Mellon University	Stress/Life Prediction
Center for Nondestructive Evaluation Iowa State University	Nondestructive Evaluation Technology

A major factor in the successful conduct of the program was the program review activities. These consisted of working groups, steering groups, and/or executive groups. Regular meetings of these groups were held to resolve technical problems, and to provide evaluation, critique and management guidance by selected advisors from the government, industrial, (including P&W management), and academic communities. The purpose of the review activities was to focus the expertise and attention of those organizations and individuals responsible for technology development, engine development, system operation, and system maintenance upon the development of Retirement for Cause and its validation for, and application to, the F100 engine. Working groups addressed specific technical problem areas. The project group provided detailed presentations of the work performed to the steering groups; the steering groups discussed the work and made recommendations to the executive group, comprised of senior management personnel from the various organizations involved; the executive group review of the presentations and recommendations resulted in and/or confirmed the technical direction, decisions and conclusions of the program. This method of operation is shown in Figure 7. In addition to the primary objective of providing technical and managerial guidance to the program, the program review groups had four secondary objectives:

1. To ensure the program fully addressed all appropriate areas
2. To ensure continuing awareness and coordination throughout U.S. Air Force and appropriate government organizations
3. To define and assign specific responsibilities for execution of ancillary activities by government organizations
4. To assist in future aspects of RFC activities as applicable.

The organizations and agencies represented on the steering and executive groups, and participating in the program reviews are listed in Table 4.

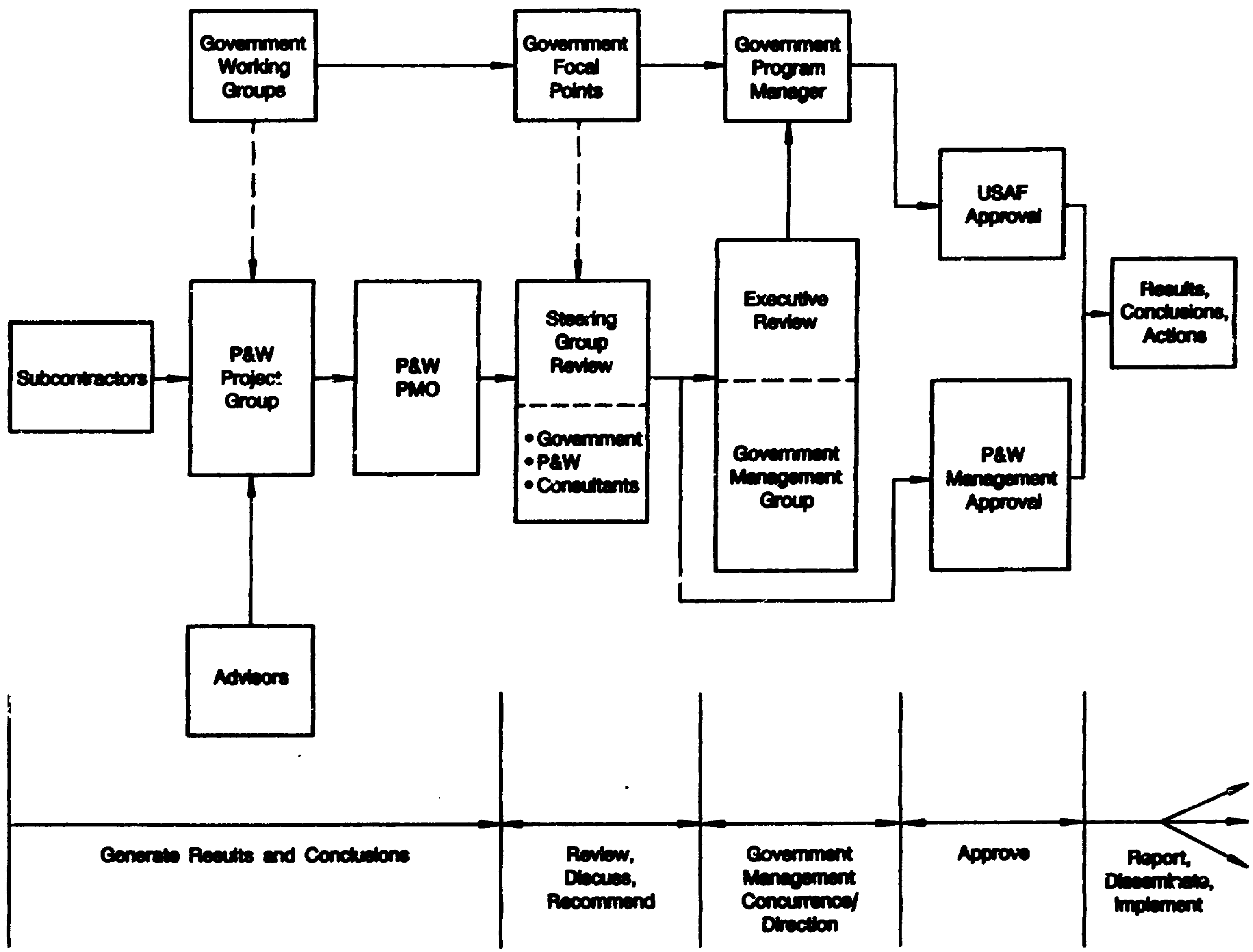


Figure 7. Functional Operation of the Engine Retirement for Cause Program

TABLE 4. PROGRAM REVIEW GROUP MEMBER ORGANIZATIONS

Under Secretary of Defense for Research and Engineering/DOD
- Defense Advanced Research Projects Agency — Defense Sciences Office

United States Air Force —
- Air Force Inspection/Safety Center
- Air Force Systems Command:
  - Aeronautical Systems Division
    - Tactical Engine Programs Office
    - Flight Systems Structures Division
    - Structural Durability Division
    - Logistics Engineering Division
    - Acquisition Logistics Division
  - Wright Aeronautical Laboratories
    - Materials Laboratory[1]
    - Aeropropulsion Laboratory
    - Flight Dynamics Laboratory
- Air Force Logistics Command:
  - Deputy for Propulsion Maintenance (Headquarters)
  - San Antonio Air Logistics Center
    - Directorate of Materials Management
    - Directorate of Maintenance
  - Oklahoma City Air Logistics Center
    - Directorate of Materials Management
    - Directorate of Maintenance
- Tactical Air Command
  - Deputy for Maintenance/Propulsion (Headquarters)

United States Army —
- Aviation Technology Directorate[2]
- Materials Technology Laboratory[2]

United States Navy —
- Naval Air Systems Command
  - Air Vehicle Division, Structures[2]
  - Production Management Division/Applied Technology[2]

National Aeronautics and Space Administration
- Lewis Research Center[2]

Federal Aviation Authority[2]

Pratt & Whitney — United Technologies Corporation
- Engineering Division[1]
- Government Products Division

Systems Research Laboratories, Inc.[2]

Notes 1 Program Management Responsibility
2 Coordination, Liaison or Advisory Role

5. RETIREMENT FOR CAUSE AND THE ENGINE STRUCTURAL INTEGRITY PROGRAM

There is occasional confusion regarding the relationship of Retirement for Cause (RFC) and the Engine Structural Integrity Program (ENSIP). The ENSIP is defined by Military Standard 1783 (USAF), and provides the basis for establishing the requirements, criteria, and methods for the design of gas turbine engines and/or components. Included is the requirement for damage tolerance in fracture critical parts, with fatigue crack initiation, (low cycle fatigue) life, and crack propagation life criteria. In addition, certain nondestructive inspection criteria are specified.

Retirement for Cause is a component life management methodology. It may be applied to any life limited engine component, regardless of the criteria used in the design of that component. Retirement for Cause and ENSIP both draw from the same technology base, and both involve similar component analyses. In many instances they are complimentary: i.e. damage tolerance concepts of ENSIP can be used in RFC, and probabilistic analysis techniques developed for RFC can be used in ENSIP. In fact, much of the technology base of ENSIP has been demonstrated, and has been validated by the Air Force's RFC programs.

The major difference between the two programs is the point in time of application. The Engine Structural Integrity Program is applied in the initial design and development phase of an engine program. Retirement for Cause is applied during the in-service, operational use, phase of an engine system. The use of the ENSIP philosophy for an engine design will greatly facilitate the use of RFC during its subsequent service life. As new engine systems entering the U.S. Air Force are being designed and developed under ENSIP criteria, RFC will emerge as the primary life limited component maintenance procedure.

In summary, use of RFC naturally accrues with an ENSIP designed engine; however, *an ENSIP engine design is not required in order to apply Retirement for Cause.*

SECTION III

THE F100 ENGINE

1. INTRODUCTION

The USAF F100 engine was chosen as the demonstration/validation vehicle for the Retirement for Cause (RCF) program. It is an augmented turbofan engine in the 25,000 pound thrust class with a thrust to weight ratio approximately 8 to 1. The engine became operational in the early 1970's in the F-15 aircraft at Luke Air Force Base, Arizona, and is currently in service around the world in the twin engine McDonnell Douglas built F-15, and the single engine General Dynamics built F-16 fighter aircraft. There are in excess of 3200 of these engines in the USAF operational inventory.

Development and sustaining engineering activity is conducted in support of USAF F100 engines under active Component Improvement Program (CIP) and Engineering Assistance to Production and Service (EAPS) programs managed by the San Antonio Air Logistics Center and the Tactical Engines Program Office, ASD/YZ. The activities under the RCF program would be closely coordinated, and in some cases could be integrated, with the CIP and EAPS efforts. The engine was chosen as the demonstration/validation vehicle to take advantage of that relationship. An additional reason for the selection of the F100 engine was that some of the rotating components of that engine would reach their 1 in 1000 low-cycle fatigue (retirement) limits in the time period coinciding with the validation of the RFC methodology, thus facilitating implementation.

This has occurred: the San Antonio Air Logistic Center implemented the RFC procedure for selected F100 components in 1985 via proofing techniques and in 1986 via nondestructive inspection techniques, and is continuing to phase additional F100 components into the process.

2. ENGINE DESCRIPTION

The F100 is an axial flow, low-bypass, high-compression ratio, twin-spool engine with an annular combustor and common flow augmentor. It has a three-stage fan driven by a two-stage, low-pressure turbine, and a ten-stage high-pressure compressor driven by a two-stage, high-pressure turbine.

The engine is equipped with a variable convergent-divergent nozzle based upon the balanced-beam concept. Nozzle area setting is a function of the engine control such that near optimum performance is provided at all operating conditions. The engine and its salient features are shown in Figure 8.

The engine consists of five major modules: fan, core (compressor, combustor, and compressor-drive turbine), fan-drive turbine, augmentor and exhaust nozzle, and the gearbox. The modular configuration is shown in Figure 9. Each module is completely interchangeable from engine-to-engine at the base and intermediate maintenance level.

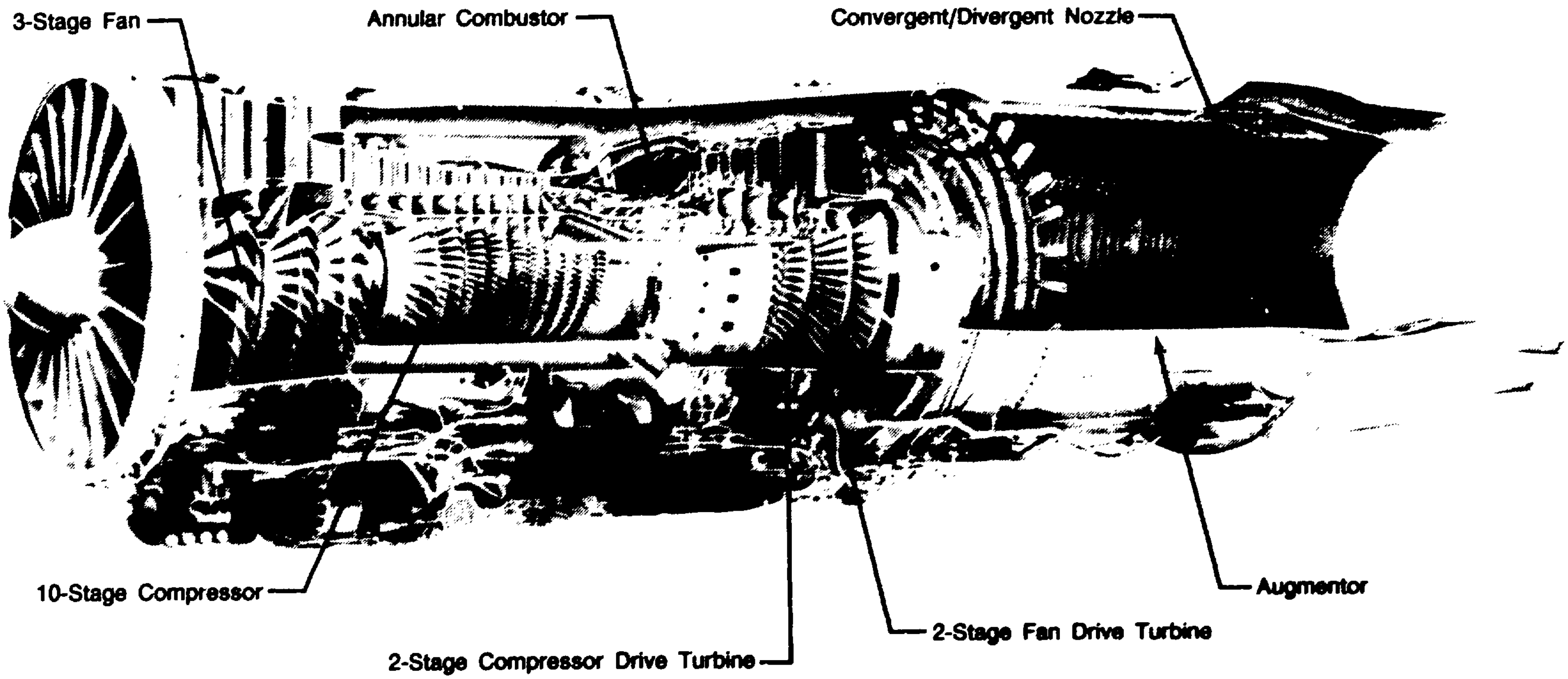


Figure 8. The F100 Turbofan Engine Which Powers the F-15 and F-16 Aircraft

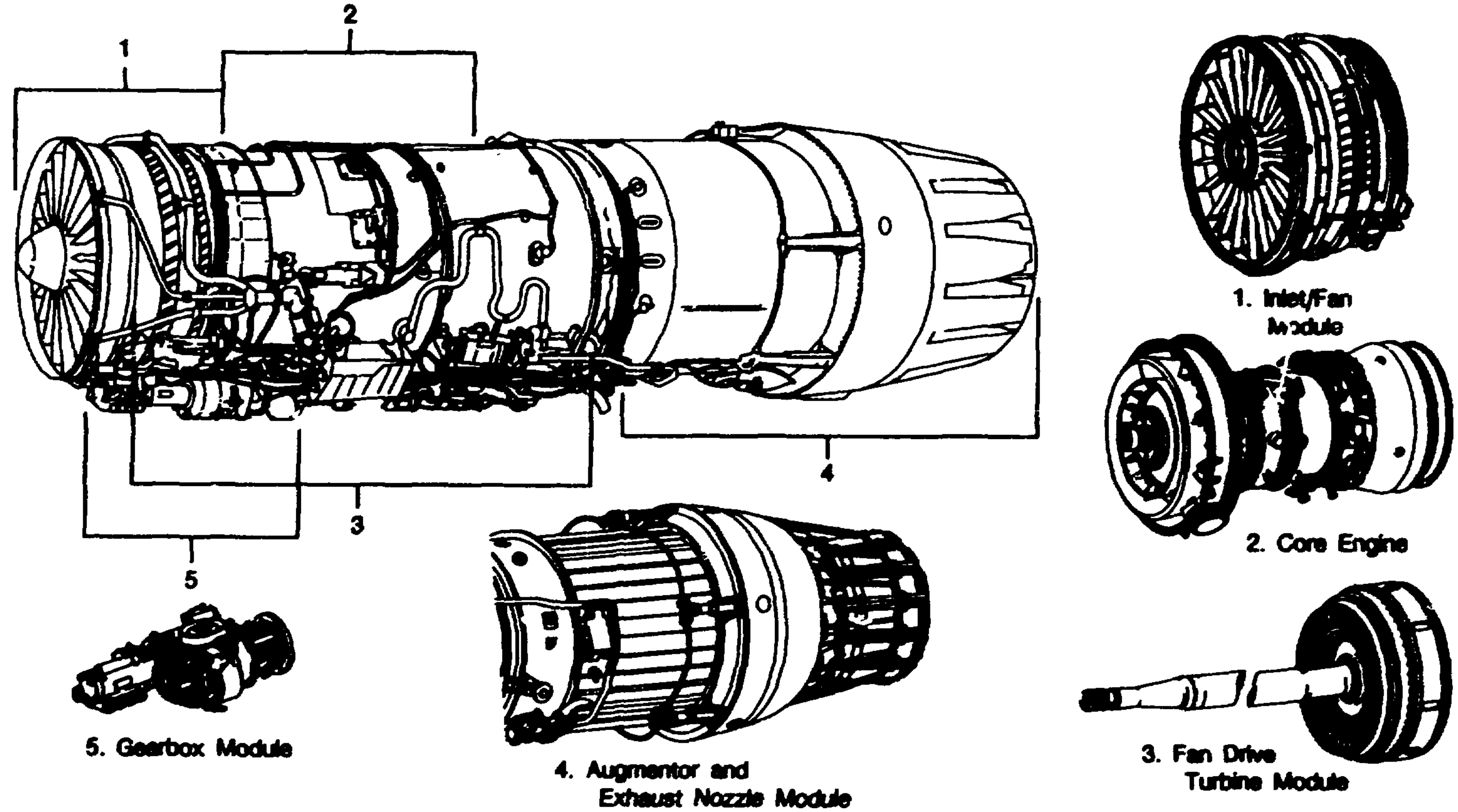


Figure 9. Modular Configuration of the F100 Engine

The modular approach was selected for the F100 engine so parts associated either functionally or physically can be removed as units. Modular construction has resulted in increased flexibility and reduction in the cost of maintaining the engine. Each module has its own scheduled maintenance rhythm, and is returned to the San Antonio Air Logistic Center for overhaul/refurbishment independent from the other modules which constitute an engine.

The fan, core, and fan drive turbine modules contain the disks and rim spacers/airseals considered for RFC. The core consists of two major rotating assemblies, the compressor (high-pressure compressor and the compressor drive turbine (high-pressure turbine, and each of these are considered separate items for the RFC maintenance concept.

There are at the present time five model variations in the F100 engine family, all derived from the same basic design and fitting within the same airframe envelope. All versions are similar in arrangement and concept, consist of the same five basic modules, and are maintained on a modular basis. The existing model variations and a brief description are:

1. *F100-PW100* — Original version of the engine for twin engine application in F-15 aircraft

2. *F100-PW200* — Original version of the engine for single engine application in F-16 aircraft

3. *F100-PW100 B/C* — Engine containing an upgraded core for F-15 aircraft. The letter suffix refers to accessory configuration

4. *F100-PW200B* — Engine containing an upgraded core for F-16 aircraft

5. *F100-PW220* — Engine with an ENSIP designed core, often called an Increased Life Core (ILC) engine. Deliveries of this engine began in 1986. It is the current production engine, deliveries of F100-100/200 models have been phased out

6. *F100-PW229* — An increased performance version engine. This engine has significant differences in the rotor due to its different airflow. At the present time this engine is in the full-scale development phase with production anticipated in the the 1989 time frame.

The Retirement for Cause activities of this program were originally directed at the F100-PW100/200 models. When the decision was made to upgrade the core engine, Retirement for Cause was incorporated as a part of the upgrade. It is anticipated that Retirement for Cause will also be used when the F100-PW220 and PW229 versions attain sufficient operational time.

3. F100 FORCE STRUCTURAL MAINTENANCE PLAN AND RETIREMENT FOR CAUSE

The critical nature of the F100 engine to the Air Force's F-15 and F-16 weapons systems made it important that the Air Force have the best possible visibility of structural maintenance needs and component life limits for the engine. Accordingly, an in-depth structural assessment was performed on this engine by a joint Air Force/P&W team. This effort, entitled "F100 Engine Structural Durability and Damage Tolerance Assessment" (F100 SAT), began in 1978, and concluded in early 1982. The assessment activities initiated by that effort are continuing under the F100 CIP and EAPS programs. These activities were the source of many of the detailed component analyses used in this program.

One of the primary objectives of durability and damage tolerance assessments is to define the inspection requirements necessary to protect the structural safety throughout the anticipated service life. A second primary objective is to establish economical modification/repair and upgrade options for those components where they may be needed. This includes establishing the technical feasibility of the options, defining the validation requirements, estimating the probable costs, and determining the post-modification/repair life limits and inspection requirements.

When the safety inspection requirements, and the repair/modification/upgrade requirements are defined, they are incorporated into the force structural maintenance plan for the engine, assuming aircraft are flown to a specific usage/environment spectra. As usage may change with time due to aircraft adaptation to new missions, tactics changes, or threat changes, continual review and updating of engine usage spectra is conducted. As changes occur, the component analyses and consequently the force structural maintenance plans are updated. During the time period of this program, two major revisions of the F100 force structural maintenance plans have occurred. The first revision resulted from a new mission analyses for the F-16 aircraft, aka F-16 Reanalysis; the second revision resulted from the decision to upgrade the core engine module of F100-PW100/200 engines.

The F100 structural assessment efforts are concerned with assuring that critical components safely reach their life limits, as opposed to safely exceeding the life limits, which is RFC. To assure this safety, the force structural maintenance plan defines component LCF limits and inspection intervals. Major depot maintenance actions are phased to correspond to the inspection intervals.

The maintenance actions and inspection intervals occur on a Total Accumulated Cycles (TAC) basis. Each installed engine is equipped with an events history recorder which monitors engine rotational speed excursions and other operational parameters. These parameters are used to calculate and count TAC's. The TAC count is applied to and tracked for each set of modules comprising an engine. At a specified TAC count, with tolerance windows to allow for opportunistic maintenance, individual modules are removed, and are returned to the depot for overhaul/inspection/refurbishment.

When the force structural maintenance plan was originally implemented, the fan and core modules were on an 1800 TAC depot maintenance interval or rhythm, and the fan drive turbine on a 2300 TAC rhythm. This was equivalent to more than four years of field service. As a result of CIP activities and the aforementioned F-16 reanalysis, the return-to-service interval for the fan and fan drive turbine was extended to 3000 TAC, however, the core remained on an 1800 TAC interval.

In the early 1980's time frame, development activity aimed at improving durability and operability produced a revised design of the core engine. This was an ENSIP design known as the Increased Life Core (ILC). This core became the basis for the F100-PW220 model. It was apparent that the benefits of the ILC were desirable for the F100-PW100/200 engine cores. A study conducted in 1984 indicated that retrofit of the existing F100-PW100/200 engines with a new ILC was not cost effective; however, several of the features of the ILC could be incorporated that would greatly enhance the existing fleet of F100-PW100/200 core engines.

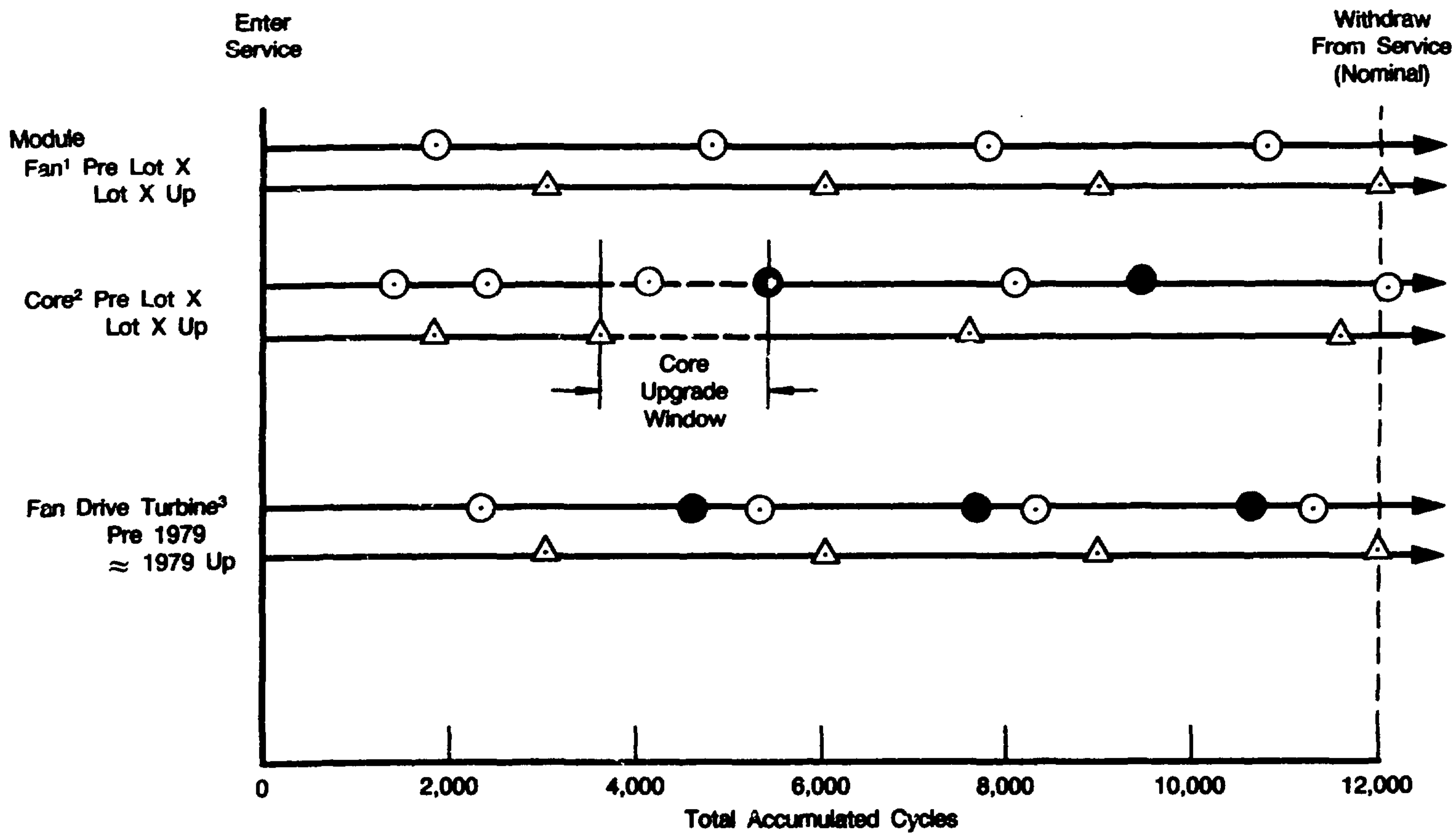
The result of this activity was the definition of a core upgrade package. Major elements of this package include a new, damage-tolerant, high-pressure turbine, modifications to the diffuser/combustor, and modifications to the remote control variable vanes and airseals of the high-pressure compressor. The existing high-pressure compressor rotor is retained. The result of the core upgrade is an increase in the core engine module return-to-service interval from 1800 to

4000 TAC. The majority of core engines will be upgraded at their 3600 to 4100 TAC depot visit; the balance at the 5400 TAC depot visit.* To enable the HPC rotor to return-to-service for 4000 TAC, the Retirement for Cause procedure is utilized for many of the disks and airseals. This is because many HPC components would reach their classical LCF retirement limits in the period 3600 to 8100 TAC. The depot visit rhythm of the current force structural maintenance plan is shown schematically in Figure 10.

Retirement for Cause is applied to selected components at the module depot visit coincident with classical LCF retirement limits, or at the visit immediately prior to return-to-service for an interval in which the limit would be reached. For the F100 engine, as for most engines, RFC is compatible with force maintenance plan, thus requiring no revision of maintenance intervals, and in fact, presenting additional options for fleet life management decisions. The current F100 force maintenance plan provides for no actions which would sustain field operations beyond 12000 TAC. As this is equivalent to approximately 25 years of service, it is anticipated that F100-PW100/200 engines would be phased out of the operational inventory by the end of that time.

Throughout the RFC program, close coordination was maintained between the RFC program group and the P&W and Air Force units responsible for the support of the F100 engine to assure that the development and implementation of the RFC procedure would not impact the maintenance rhythm. No adverse impact on weapon system readiness has occurred due to incorporation of RFC.

*Some early core engines-preproduction lot X — had intermediate depot visits at 1300 and 2300 TAC. These core engines were returned- to-service for 1800 TAC after the 2300 TAC depot visit. These engines would return to depot at 4100 cycles, and would receive the core upgrade at that time. A similar situation exists due to extension in intervals for fan and fan drive turbine modules resulting in some irregularities in rhythm of the force structural maintenance plan.



Notes: 1. Nominal Δ 3,000 TAC After First Depot Visit
2. Nominal Δ 1,800 TAC Until Upgrade: Δ 4,000 TAC Thereafter
3. Nominal Δ 3,000 TAC - Change Effective Early 1984

Figure 10. F100-PW100/200 Force Structural Maintenance Plan Scheduled Depot Visit Rhythm

SECTION IV

RESULTS

1. PROGRAM OBJECTIVE

The objective of this program was to provide a cost effective component management/maintenance methodology for fatigue life limited gas turbine engines systematized in a form that could be implemented at Air Force engine logistic centers. While generic in nature, this program was directed towards the USAF F100 engine, specifically the various disks and air seals/spacers that comprise the prime rotor structure. The technical effort consisted of executing a series of tasks to obtain this objective by accomplishing the following:

1. Development of a probabilistic life analysis system and the means of using that system to assess economic factors

2. Review, expansion and formatting of the fatigue and fracture mechanics technology base and its supporting materials characterization data to enable accurate residual life analyses for the probabilistic life analysis system

3. Demonstration of the validity of the technology base and the RFC methodology by laboratory testing of specimens, subcomponents and components, by actual engine testing of selected components, and by monitoring the behavior of components in the USAF F100 operating fleet

4. Selection and analyses of specific F100 engine components

5. Economic analyses to document the benefits and risks associated with RFC of the selected F100 engine components

6. Interface and assistance in the implementation of RFC for the F100 engine, and for application to other engine systems.

The results of the major activities are summarized in the following paragraphs. Detailed results on a task by task basis are documented in other Air Force Wright Aeronautical Laboratories technical reports issued under this contract.

2. METHODOLOGY REVIEW

The general background and reasons for this program were discussed in Section II of this report. The methodology was originally defined in a precursor program conducted in 1979 to 1980, Reference 2. That methodology did not change as a result of this program; some aspects of it are reviewed here to fix the context for reporting of the program results.

Referring to Figure 5, Section II, it can be seen that the RFC concept is based on fracture mechanics and nondestructive evaluation. Nondestructive evaluation is used to ascertain the presence or absence of defects in critical locations on a component. Fracture mechanics is used to predict the crack propagation life at every critical location from a defect size below the NDE limit of reliable crack detection. Given that the technology exists to accurately do these two things, a third factor impacts the decision making process: is RFC economically beneficial?

a. Economic Considerations-Propagation Margin

Economic benefits of RFC are a function of the return to service interval-crack propagation life relationship. If the return to service interval were short, relative to crack propagation life, high costs may be incurred due to frequent return of modules or engines for depot inspection/overhaul. If the return to service interval were long relative to crack propagation life, high costs may be incurred due to in-service failure. The relationship between the return to service interval, and the crack propagation life, is defined as the propagation margin, and is illustrated in Figure 11.

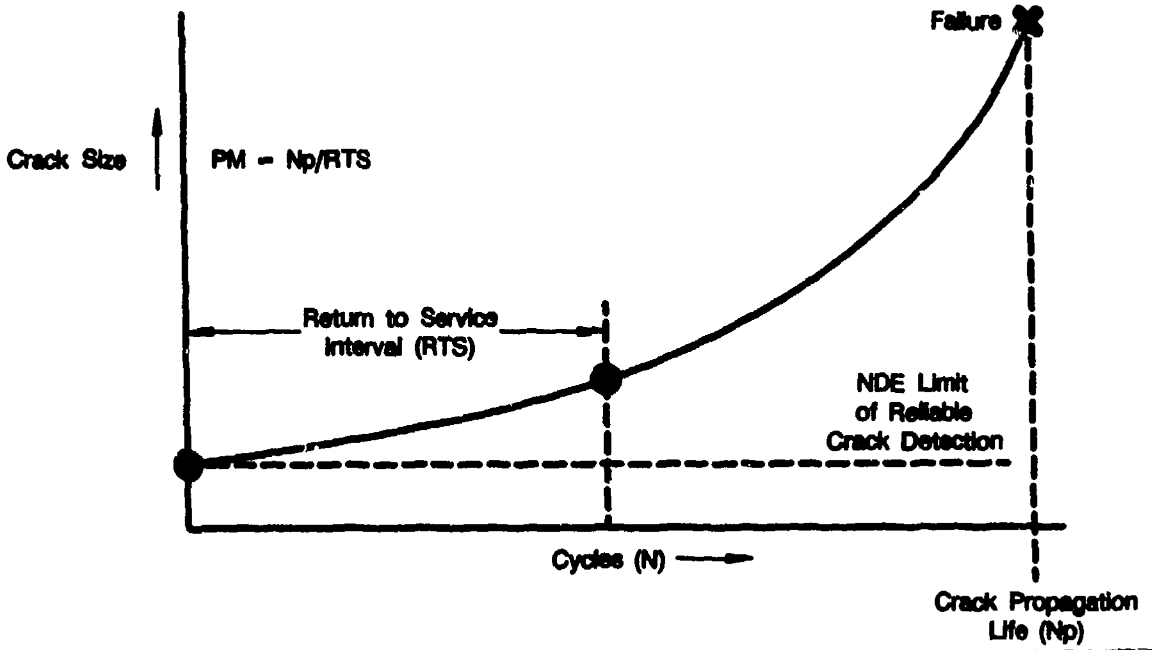


Figure 11. Propagation Margin, (PM), Defines the Relationship Between Crack Propagation Life and Return-to-Service Interval. This Example Illustrates a Propagation Margin of Two

Applying a propagation margin assures safety in utilizing the remaining initiation life in each component, recognizing that some uncertainties may still exist. This is done by determining the crack propagation life, Np, at every critical location on a component from a defect of a size barely small enough to be missed during inspection. The return to service interval, RTS, is then established by conducting life cycle cost analyses to determine the most economical propagation margin, PM, to apply to the shortest Np, thus RTS = Np/PM. In this context, propagation margin is akin to a safety factor. Life cycle cost versus propagation margin is plotted for each individual component and combined to determine the most economical interval to return an engine or module for inspection. An example is shown in Figure 12.

b. The RFC Procedure

The RFC flow chart, Figure 13, illustrates a simplified view of how this maintenance concept is utilized. When an engine or module is scheduled for maintenance, an economic analysis is performed on the engine or module, i.e., fan, compressor, high turbine, or low turbine, identified as a participant of the RFC maintenance program. If the module has already been in service for several inspection intervals, the probability of finding cracked parts may be great enough to make reinspection economically undesirable, and specific components of that module are retired without being inspected. This is determined by the economic analysis at decision point one and is one of three possible decisions. An unscheduled engine removal, UER, may bring a module out of service that is more economical to return to service for the remainder of its inspection interval than to inspect and release it for a new full interval, the second possible decision at point one. The remaining choice at point one is to tear down the module and inspect the parts. During inspection, there again are three possibilities, (decision point two). If no defects are found, the part is returned to service. If the disk is found to be flawed, it is retired. The third choice is to investigate modification or repair of a flawed part. An economically repairable part may be repaired and returned to inspection, decision point three.

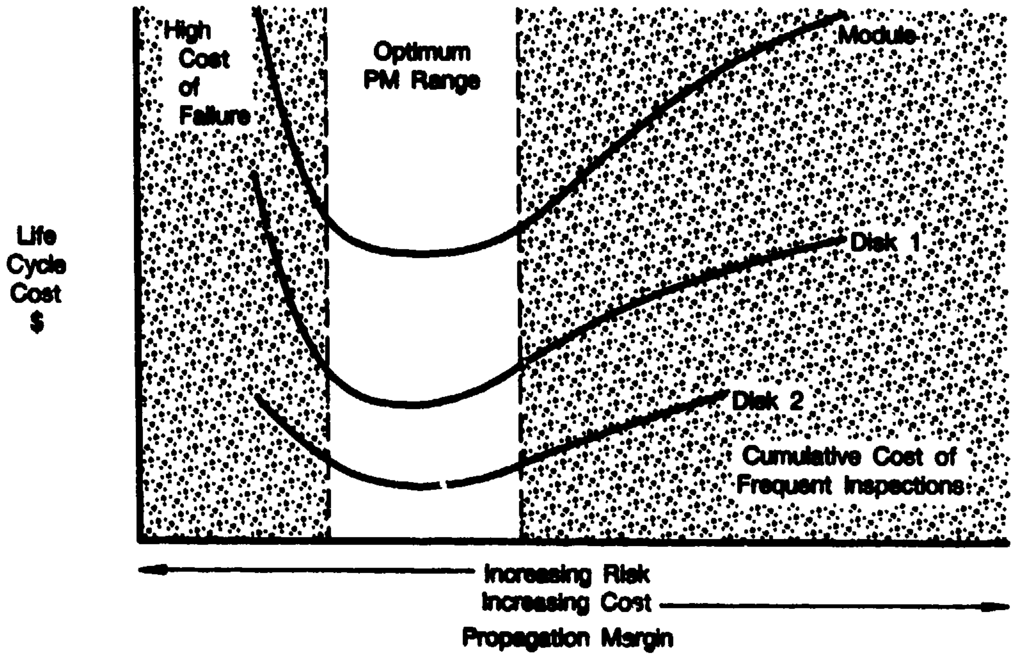


Figure 12. Propagation Margin Is Determined from an Economic Balance Between High Cost of Failure and Cumulative Cost of Frequent Inspection/Overhaul

c. F100 Engine Application

The RFC methodology discussed in the preceding paragraphs presents a generic view of the process. In practice, return to service intervals may be based on more than inspection considerations. In the case of the F100-PW-100/200 engines, maintenance rhythms were already established, and propagation margin/life cycle cost evaluations were conducted corresponding to those intervals. For future applications, however, a priori RTS analyses could be a major factor in establishing an initial force structural maintenance plan.

In following the RFC procedure shown in Figure 13, the module economic analyses, decision point 1, was performed for the high pressure turbine unit of the core engine as part of the core upgrade program. This analyses indicated that the probability of finding cracked parts in the HPT by 5400 TAC was high, therefore, these units will be retired without inspection at the scheduled depot visit in the 3600 and 5400 TAC window. They will be replaced with the ILC (F100-PW220) HPT unit as part of the Core Upgrade Program. At the present time, fan, HPC and LPT modules bypass point 1 and go directly to point 2, inspection. As the USAF F100 engine fleet ages, and engines are phased out of the inventory, the economic analysis step will be introduced for all modules.

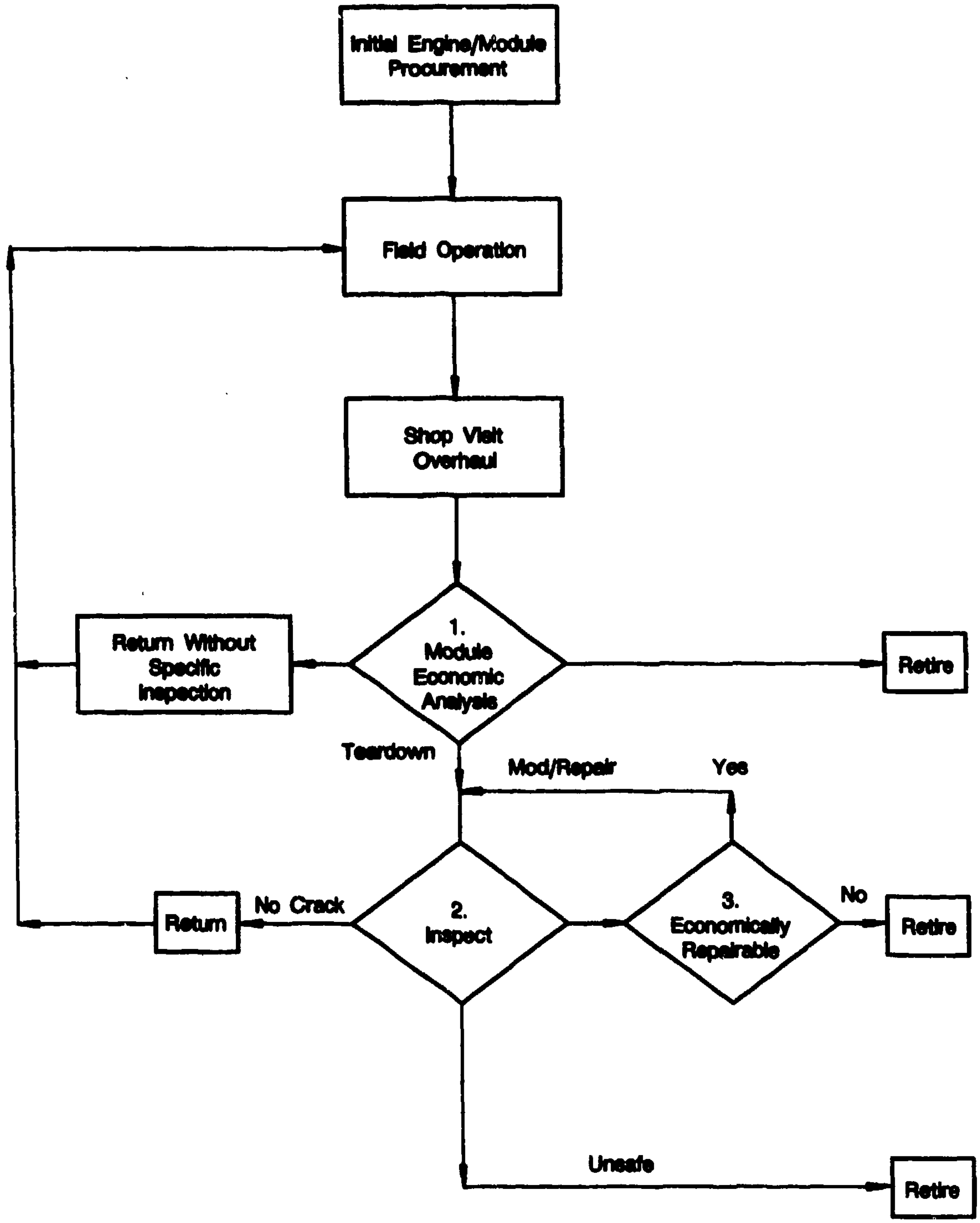


Figure 13. Retirement for Cause Procedure Flow Chart

3. PROBABILISTIC LIFE ANALYSIS TECHNIQUE

Utilization of the total available life of a component requires the consideration of fatigue crack propagation. The fracture mechanics approach to estimating component service life is based on the assumption that materials contain inherent initiation sites, that fatigue cracking could begin at those sites, and that fatigue failure may occur as a result of progressive growth of one or more of those crack defects into a critically sized flaw. Thus, the prediction and monitoring of crack growth as a function of cycles (or time) becomes one of the basic requirements of the life analysis system. To utilize such an approach in practice requires quantitative information on materials behavior, component stress and nondestructive evaluation capabilities. Most of the parameters which provide this information cannot be defined as a single value, but must be described by a probability distribution, similar to that shown in Figure 2. In order to obtain a deterministic life prediction, given these distributions, the conventional approach has been to use worst case assumptions for all parameters. Employing all worst case assumptions necessarily results in a conservative estimate of the service life of a component population.

To circumvent this difficulty, the problem can be treated probabilistically. A closed form analytical solution which takes into account all the required probabilities is far too complex to be practical. The behavior of a population of engine disks and/or spacers over time is a problem of this type. With so many events and parameters influencing the entire population, analytical formulations to describe mutual interaction become intractable.

An alternative solution is to employ computer simulation techniques. This was the approach used in this program and resulted in an analysis system called Probabilistic Life Analysis Technique (PLAT). The PLAT simulator integrates statistics, fatigue, fracture mechanics, nondestructive evaluation and engine component management into a cohesive entity. This was done by constructing a model of the entire component life cycle in terms of statistical elements representing individual aspects of the life cycle. In particular, the life cycle is divided into elements whose behavior can be quantified in terms of probability distributions of life controlling parameters for each of the possible states of the life cycle. The interrelationships among elements are also incorporated in the model.

The PLAT simulator is comprised of the following elements:

1. Initial material quality (inherent defect distributions)
2. Crack initiation behavior
3. Crack size versus propagation life (a versus N behavior)
4. Crack propagation variability
5. Stress analysis (including temperature and manufacturing tolerance) variability
6. Mission (usage) severity
7. Nondestructive evaluation variability.

Details of the development, operation, and verification of this simulator were reported in AFWAL-Technical Report-85-4075, and will not be discussed in this report. However, in summary, the simulator evaluates each feature of a component, combines individual feature results to present results for a single component and then computes occurrence rates for significant events such as parts removals, initiated cracks, inspection results, failures, etc. for a fleet of components. All of the information is established in terms of the occurrences at the beginning, during and/or at the end of a return to service interval. An example output showing results of a PLAT analyses of the F100 7th-stage HPC disk is shown in Figure 14 for a fleet size of 1000 engines.

Implicit in the elements of the simulator, and in its evaluation of the F100 RFC components, is the requirement for accurate definition of input values and distributions. A number of the activities described in Section II and illustrated in Figure 6 were conducted to provide that input information. Phase I of this program was, in fact, structured for that purpose: developing materials and component information; resolving fracture mechanics — crack growth prediction questions, and establishing procedures for use of PLAT generated results in economic analyses. In this program, the PLAT simulator was used to evaluate 17 of the selected F100 retirement for cause rotor components, and results were coupled into the life cycle cost/risk analyses. For these components, the return-to-service (overhaul) rhythm was fixed as shown in Figure 10. The real potential for this tool, however, is not retirement for cause per se, but is two fold: evaluating impact of changes in the usage — maintenance senarios for existing engine/weapon systems (What — if games); and investigating effects of virtually all engine component life controlling parameters in the design stage of new engine/weapon systems. In these regards, PLAT represents a new generation of analytical tools for use in making component and engine design and maintenance decisions.

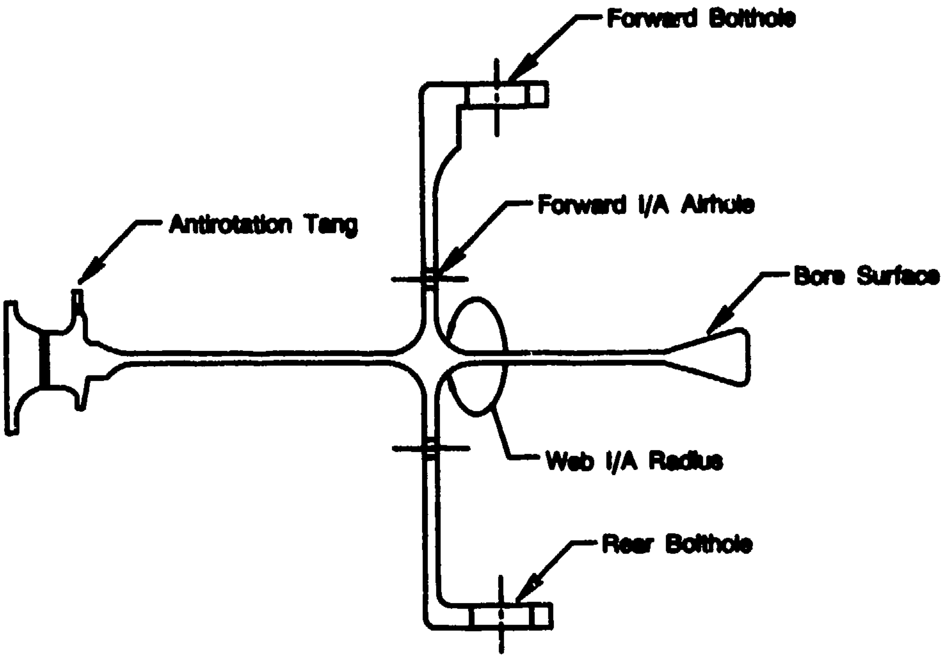
4. THE TECHNOLOGY BASE

It may seem incongruous that an effort to use the available crack initiation life inherent in a population of rotor components would emphasize fracture mechanics — crack propagation — knowledge as a requisite. Crack initiation phenomena are not completely understood, and the predictive ability is not precise. That is why traditionally lower bound limits are used, (Section II). The fracture mechanics — NDE approach of retirement for cause does not require knowledge of the exact crack initiation life of a component. The concern is *if* a crack initiates in a service interval, is this growth predictable with enough precision to give assurance that the part could not fail prior to the completion of that interval? Should a crack have initiated, the inspection process at the end of the interval would then result in the retirement of that part long before failure could occur. The use of a propagation margin builds additional safety into the process. The understanding of how a crack will behave, if present, therefore, becomes the paramount concern in applying RFC.

At the inception of this program, a member of fracture mechanics activities had been conducted giving high confidence in the ability to accurately predict crack growth. In particular, the Hyperbolic Sine (SINH) procedure for modeling crack growth rate had been developed and validated. It was used extensively in this program. There did exist, however, some concerns and data gaps which conceivably could technically limit the application of RFC to specific F100 (or other) engine components.

The technology base activities were conducted early in the program to assure that there were no insurmountable unknowns-"show-stoppers",-in the methodology. These tasks were conducted to:

1. Investigate the impact of fracture mechanics technology concerns on current life predictions
2. Evaluate the adequacy of current predictive methodology for RFC applications
3. Provide additional data for RFC probabilistic (PLAT) life predictions.



a. Six Features Analyzed

Event	Occurances at TAC Interval 1,800	3,600	7,600	11,600[4]
Number of Disks	1,000	1,000	1,000	1,000
Number Inspected	1,000	1,000	1,000	1,000
Inspection Errors	0	0.7	0.8	0.4
Replaced Disks	0	3	4	3
RTS Disks[1]	973	757	540	249
Reworked Disks[2]	27	243	460	751
Failures	0	0	0	0
Failure Probability[3]	0	0	0.0002	0.0003

Notes
1. Returned to Service After Inspection
2. Reworked and RTS. Rework is Planned as Part of a 4,000 Cycle Upgrade
3. Probability During Interval Ending at Designated TAC
4. Engines Normally Retired at this TAC. Results Shown for Information Only

b. Results of PLAT Analysis - Occurrances are Per 1,000 Disks

Figure 14. F100-PW100B/200B 7th-Stage, High-Pressure Compressor Disk Probabilistic Life Analysis

While generic in nature, the activities addressed the materials (IN 100, Titanium 6-2-4-6, Waspaloy and Astroloy) and conditions present in the F100 engine, and built upon previous Air Force Materials Laboratories sponsored materials behavior programs. Major results are summarised in the following paragraphs; detailed approaches, support activities, data and results are included in other reports issued under this program.

a. Statistics of Fracture Mechanics

Among the variables contributing to the statistical nature of a probabilistic life analysis system is the variability in the crack propagation rate data base. A crack growth curve (da/dN versus ΔK) is not uniquely defined for a given set of operating conditions; rather, a statistical distribution describes the variability in crack growth rate about a curve representing mean behavior.

Such inherent variability has numerous sources. Among these are variations in chemistry, fabrication, heat treatment, and microstructure. All such statistical sources are collectively described by the single distribution about the crack growth rate curve.

A methodology to define and assess the effects of this variability (scatter) in crack propagation on residual life was developed in conjunction with work under AFWAL contract F33615-80-C-5189, References 7 and 8.

It was found that the variability in crack propagation rate data may be described by a log-normal probability distribution. That is, for a given value of applied stress intensity range (ΔK), the corresponding crack growth rate (da/dN) follows a log-normal distribution about a mean value of da/dN, as shown in Figure 15. This variability results in a maximum/minimum crack propagation life range of approximately 2, (as opposed to a crack initiation range of 10 or greater), for the four materials of concern, and is accounted for by the addition of a Z(x) term to the Hyperbolic Sine model. This is a standard statistical technique, and is totally adequate for this application.

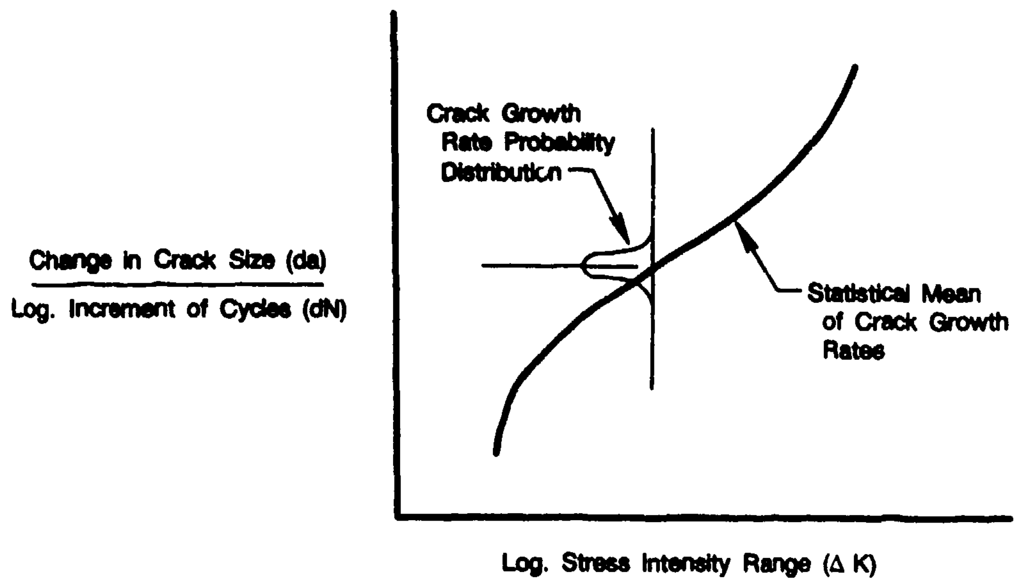


Figure 15. Variability In Crack Propagation Rate Is Defined By a Log Normal Probability Distribution

b. Fracture Mechanics of Multiple Crack Initiation

Applied fracture mechanics is predicated on a uni-parametric relationship between the status of the stress field surrounding a crack as expressed by K, the stress intensity factor, and the dynamic response of the crack, da/dN. Currently available handbook solutions for K have proven to be adequate for nearly all singly occurring cracks. In real components, however, several cracks may initiate more or less simultaneously within a stress riser, e.g. bolthole, slot, then synergistically propagate toward link-up, and subsequently behave as a single macrocrack. Only after link-up can these be addressed in the conventional manner. The problem of multiple crack initiation, link-up and propagation is nearly intractable with analytical treatment, therefore an empirical approach was used. A variety of crack initiation configurations, Figure 16, representing the range of senarios which might occur in an engine component were tested. Existing life prediction tools, by modeling the resultant crack growth in two stages, were found to adequately (actually somewhat conservatively) predict the residual life of the four materials of concern for F100 component RFC applications. This effort was completely documented in AFWAL Technical Report (TR) 85-4110, Reference 9.

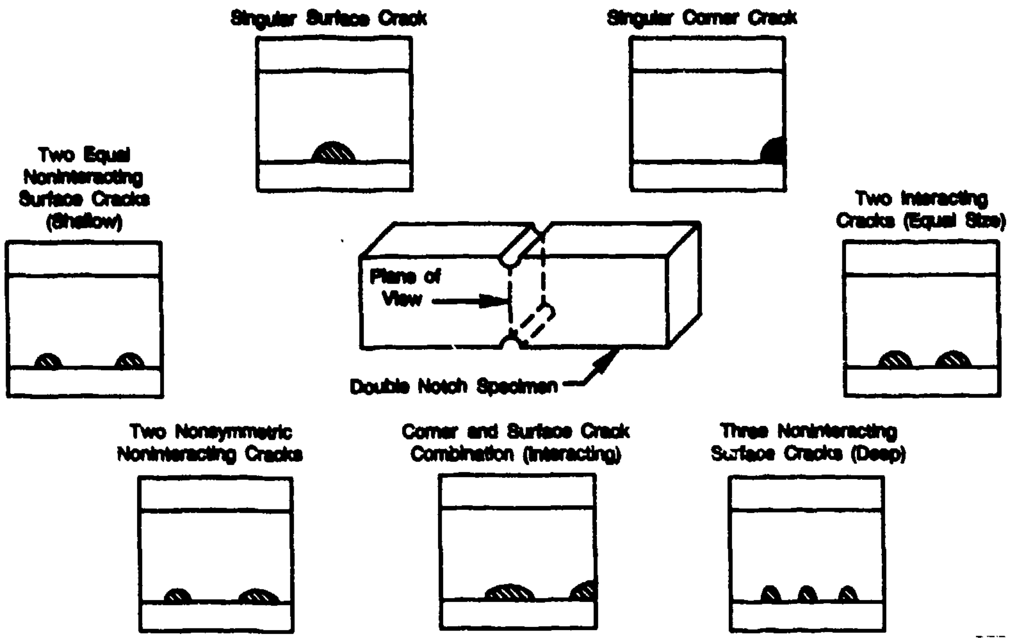


Figure 16. Existing Predictive Tools Adequately Predict Crack Growth from a Variety of Multiple Crack Initiations in a Typical Component Stress Riser

c. Thermal Mechanical Fatigue Crack Growth

It has been shown that thermal mechanical fatigue crack propagation is one of the primary failure modes in cooled turbine airfoils, i.e. blades. This raised a concern as to the effect that the temperature-load range conditions which exist near the rim of a turbine disk may have upon the adequacy of the crack growth predictions for potential flaws in that area of a disk. Traditionally, these crack growth predictions are made using isothermal crack growth data at the temperature corresponding to the maximum loads expected to exist. In general, the predictions are accurate, or at least conservative. The purpose of this effort was to conduct an experimental program to assess the adequacy of using isothermal (constant temperature, load cycling), crack growth data for predictions of gas turbine disk life. This effort was not an exhaustive investigation of thermal mechanical fracture mechanics, but focused upon materials and conditions typical of disks in an advanced tactical fighter engine such as the F100.

The specific objectives were: to evaluate any differences in crack growth rate in the materials Astroloy and IN100 between isothermal and thermal mechanical cycling, and to assess the impact these differences, if any, might have upon the implementation of the RFC concept for these materials. Using the existing interpolative Hyperbolic Sine Model (SINH) the method of evaluation was to compare crack growth rate (da/dN versus ΔK) data generated under isothermal conditions with data for the same materials tested under in-phase (maximum tensile load at maximum temperature) and out-of-phase (maximum tensile load at minimum temperature) thermal mechanical cycling. It was found that the existing Hyperbolic Sine Model accurately predicted crack growth under TMF cycling when: 1) isothermal data at the highest temperature of the in-phase TMF cycle, and 2) isothermal data at the lowest temperature of the out-of-phase TMF cycle, were used. Therefore, no significant difference in crack growth rate prediction capability existed which would impact the application of RFC for the conditions found in disks or airseals/spacers of the F100 engine.

This effort was completely documented in AFWAL Technical Report, TR 84-4185, Reference 10.

d. Small Crack/Stress Field Synergism

Most experimental studies are made with large cracks to determine the fatigue crack growth rates and the threshold stress intensity on the basis of linear elastic fracture mechanics (LEFM) concepts. Very often, the fatigue life of a turbine component made of high yield strength material is dominated by initiation and growth of very small cracks, which usually initiate at geometric stress risers such as holes and notches. Both crack-tip plasticity associated with localized yielding and size effects associated with the lack of a continuum at small-size scale may effect the crack propagation behavior of small cracks.

There is a unique stress intensity below which a crack will not grow. This is the threshold stress intensity, K_{TH}. Normal procedure has been to extrapolate large crack (>0.040 inch) data to very low growth rates to establish this point as shown in Figure 17. Some investigations have suggested that small crack (0.005 inch) growth behavior, particularly in the near threshold region, may be different, and that current linear elastic fracture mechanics methods are not applicable in certain materials.

Testing methods were developed to enable precise determination of the threshold stress intensity and to establish crack growth rates for small cracks. This data was compared to long crack data. Results indicate no significant differences in residual life predictions exist when using small crack/threshold data as opposed to normal procedures for the materials of concern, and the behavior of those materials in F100 components is adequately described by the LEFM techniques used in RFC.

e. High-Cycle Fatigue/Low-Cycle Fatigue (HCF/LCF) Interaction

Many gas turbine engine components are subjected not only to low-cycle fatigue and creep-fatigue type loading conditions, but to high-cycle or frequency, low amplitude vibratory fatigue (HFF) loads. This is particularly true in rotating components such as disks and spacers where the effect of superimposed vibrational stresses associated with airfoil vibration could have an adverse influence on crack growth rate.

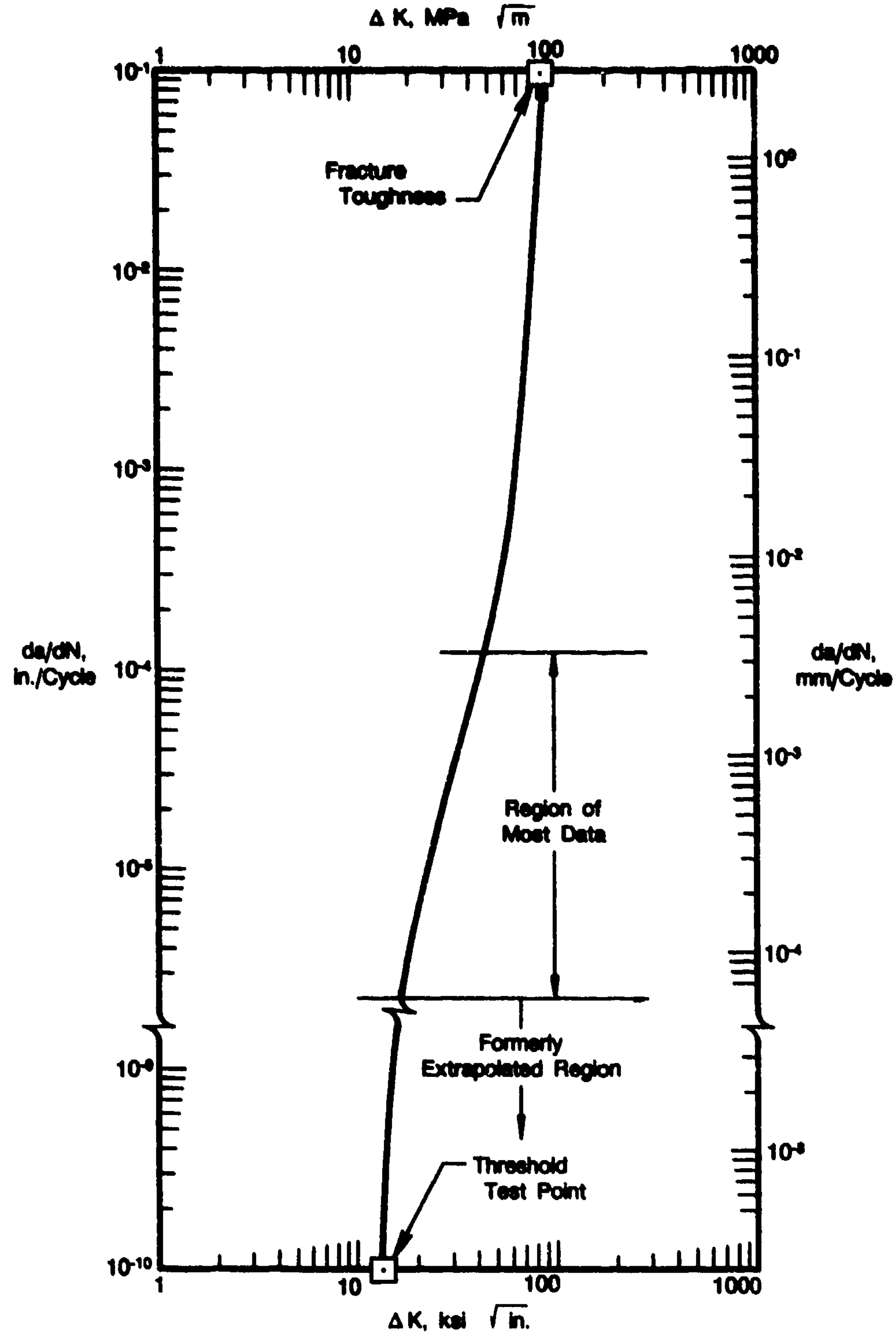


Figure 17. Typical Crack Growth Rate (da/dN) Stress Intensity Range (ΔK) Curve. Significant Portion of Life Is in the Formerly Extrapolated Region

A current ENSIP compatible analytical approach for determining the effects of small-amplitude high frequency fatigue loading on calculated LCF crack growth rates of engine components is based on the threshold stress intensity for HFF, $K_{TH(HFF)}$. Once the maximum vibratory stress amplitude is determined for a particular component and operating condition, the maximum crack size used in determining the crack growth life is limited so that $K_{TH(HFF)}$ is not exceeded. This approach limits crack lengths to sizes for which a direct effect of vibratory loading does not occur, that is below the $K_{TH(HFF)}$ for HFF propagation. It does not account for interactions or synergistic effects of low amplitude vibratory loading on fatigue crack growth rates.

Testing was conducted on IN 100 and titanium 6-2-4-6 using a test method developed based on work conducted at AFWAL (AFWAL/MLLN). Testing utilized both a pure LCF cycle and a LCF-creep (dwell) cycle with and without superimposed vibratory loading as shown in Figure 18. Comparison of life predictions made using crack growth data for each case showed no appreciable difference in life below the predicted $K_{TH(HFF)}$. As expected, above the $K_{TH(HFF)}$, crack growth rate is faster with superimposed vibration. As the analytical approach used for predicting residual life does not take any credit for life above the $K_{TH(HFF)}$, it is entirely adequate — and conservative — for F100 component analysis. Also, the predicted $K_{TH(HFF)}$ values agreed with the observed onset of increased crack growth rate due to HFF, thus validating the analytical approach.

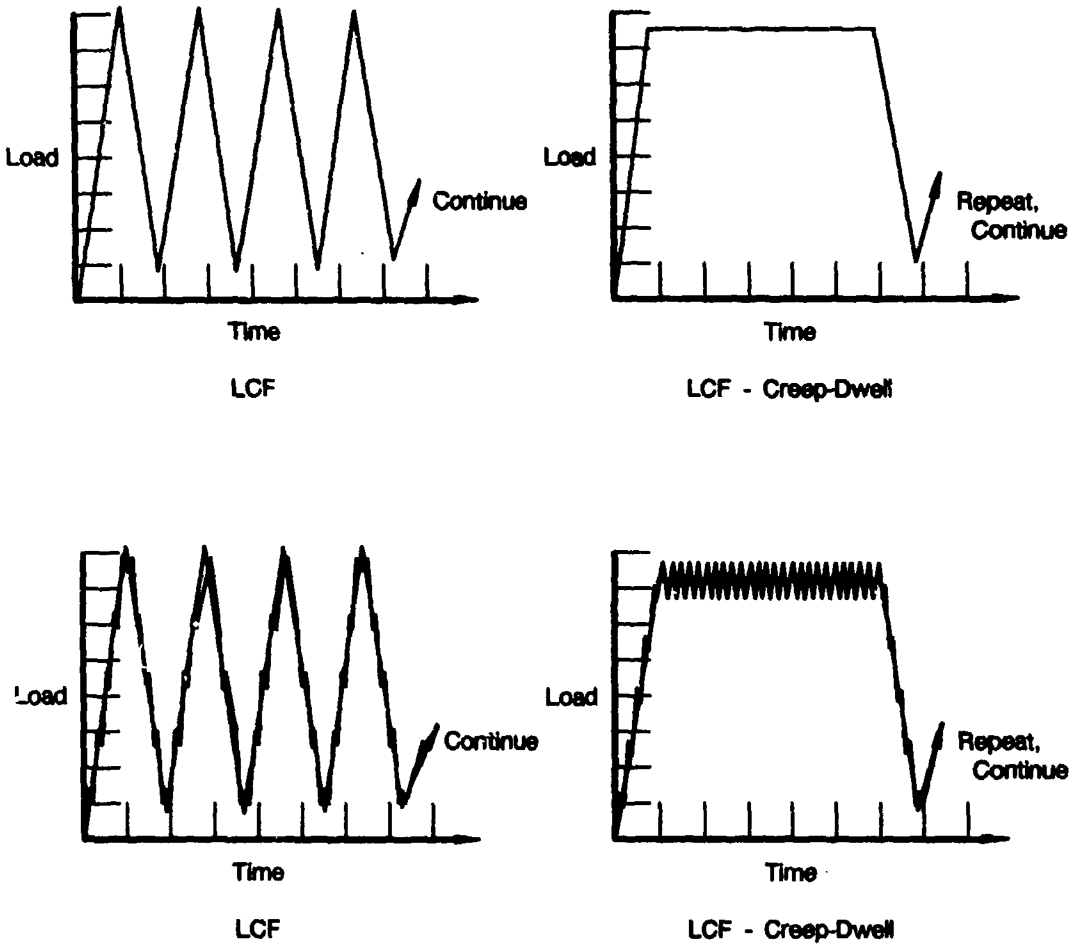


Figure 18. Schematic Depicting LCF and LCF-Creep-Dwell Loading Schemes With (Lower) and Without (Upper) Superimposed High Frequency Vibratory Loading

f. Initiation Distribution Studies

A vital element of the PLAT simulator is the initial material quality — the distribution of intrinsic material defects that may act as initiation sites. Another element of the simulator then uses this information to generate crack initiation behavior. This study had two stages: first, parameters describing defect size distributions were defined for each of the four RFC materials; second, the defect sizes were correlated with LCF life to quantify flaw size classifications. The PLAT initiation behavior element accounts for intrinsic material defects by debiting life according to the initial flaw classification. Flaws can be classified in three categories:

1. A defect so small that its influence on crack initiation is within the normal LCF initiation behavior (refer to Figure 2), i.e. $a<A_1$

2. A defect large enough to diminish LCF capability but too small to behave as a propagating crack, i.e. $A_1 <a<A_2$

3. A defect so large that it behaves as a propagating crack at the onset, i.e. $a>A_2$.

Approximately 580 fatigue specimens of IN 100, titanium 6-2-4-6, Waspaloy and Astroloy were subjected to fractographic and LCF life correlation analyses. These specimens included a variety of types, test conditions, and heats of each material, therefore the resulting analysis data are truly representative of the materials nature. This data, in its statistical form, were incorporated in the PLAT simulator. An example of the information is shown in tabular form in Table 5.*

TABLE 5. EXAMPLE OF INITIATION DISTRIBUTION STUDY RESULTS FOR RFC MATERIALS[1]

Material	*Mean Defect Size (Inch)*	*A_1 Size (Inch)*	*A_2 Size [2] (Inch)*	*Anomolies Frequency Orgin Site (%)*
IN-100	0.0009	0.001	0.005	65
Ti6-2-4-6	0.0004	0.0005	0.005	13
Waspaloy	0.0005	0.0008	0.005	22
Astroloy	0.0005	>0.0015	0.005	15

Notes: 1 All sizes are approximate
2 Arbitrary cut off size for conservatism in crack growth life analysis. Actual A_2 sizes may be larger.

g. Mission Studies

Rotating components of a military gas turbine engine commonly experience extremely complex loading spectra. Major and minor throttle excursions as well as sustained flight define engine disk loading sequences that interact synergistically and complicate the component life prediction procedure. Since the specific goal of RFC is to use the available life of individual engine components, it is important to assess the component damage incurred under representative mission spectra accurately.

A fundamental requirement for this assessment is definition of loading histories that are representative of the anticipated mission usage. Mission analysis data are commonly collected from pilot interviews and events history recorders. Data of this type was compiled for F100

* This effort was also complimented by activity under AFWAL Contract F33615-79-C-5074, "Effects of Defects in Powder Metallurgy Superalloys."

engine performance in F-15 aircraft and F-16 aircraft. While similarities in usage exist for these two aircraft, characterization of separate performance histories is warranted. Aside from the obvious benefits of accurately defining mission severity, recording the sequences of mission loads is important. This is necessary to predict the effect of loading sequence on crack growth in engine components that are candidates for RFC. In conjunction with F100 Component Improvement Program activities, definition of mission profiles was obtained and maintained current throughout the program. This resulted in mission usage severity distributions development for use in PLAT and in guidance for materials characterizations and for the development of synergistic crack growth models.

h. Materials Characterization

A large crack propagation data base existed for the materials used in the F100 RFC components. Some conditions had not been investigated thoroughly and new conditions were established as a result of the mission studies discussed previously. Approximately 90 crack growth rate tests and fractographic analyses were conducted to complete the data base for all conditions identified. In addition, test results from other activities in the technology base were incorporated. Results of the materials characterizations were used to generate, or to refine the crack growth models used for component life analyses. In total, over 200 crack growth tests were conducted and modeled.

5. METHODOLOGY DEMONSTRATION AND VALIDATION

Implementation of the RFC methodology requires the systematic, coordinated application of several disciplines. Materials behavior, detailed and accurate component stress/strain analyses, fracture mechanics probabilistic life analysis, and reliable NDE techniques are necessary to evaluate the potentially critical locations of each component. Retirement for Cause integrates these constituents to enable maximum utilization of component service life capability. However, before application to an active engine system, the methodology must be demonstrated, qualified and validated. This was done for the RFC methodology, and for the F100 engine system. Laboratory specimen, subcomponent and component, and full-scale engine tests were conducted, and the status of components in the USAF F100 engine fleet was monitored to assess and qualify the validity of the methodology.

The methodology demonstration and validation activities had four primary objectives:

1. Provide component demonstration tests for selected components
2. Substantiate statistical aspects of the RFC methodology
3. Provide an RFC model demonstration
4. Validate the process for implementation for the F100 engine system.

These objectives had to be accomplished within reasonable time and cost. Ideally numerous tests of each RFC component, either in an engine or under simulated engine conditions, would be used for substantiation. However, the high costs associated with engine component cyclic testing precluded performance of the required number of tests for significant statistical substantiation. As specimen and subcomponent tests adequately represented critical variables, and could be economically tested in quantities necessary to substantiate statistical aspects of the RFC life predictions and methods, this approach was used. When coupled with selected laboratory and engine component tests, and the component field history from the large engine fleet, the methodology would be verified. The demonstration and validation process was based on the following:

1. Selected component tests for substantiation of stress analyses, mean crack growth predictions, fracture path and other component geometric feature related variables

2. Specimen/subcomponent tests for evaluation of the statistical/probabilistic aspects of the RFC model, life predictions, and laboratory demonstration of the RFC model

3. Field data analyses for support and correlation of the above.

Nondestructive evaluation support was provided using the best available laboratory techniques to minimize the uncertainty in NDE, and to provide maximum sensitivity for evaluating the accuracy of the life predictions and the contributors to life prediction uncertainty. Information obtained from the NDE evaluation was incorporated into AFWAL Contract F33615-81-C-5002, (Table 1) as were the RFC component inspection requirements.

The objectives of this effort were accomplished, thus facilitating implementation. Because of the successful demonstration/validation of the RFC methodology, the RFC process was incorporated in the F100 Core Upgrade Program, resulting in accelerated implementation by the San Antonio Air Logistic Center.

a. Component Testing and Analysis

The primary purpose for component testing is to verify the component analysis and RFC mean predictions. Substantiating the component analysis includes assessment of the accuracy of component stress analyses and crack growth behavior for actual geometries. Substantiation of RFC mean predictions includes evaluation of stress analyses, mean predictions of crack growth rates, geometric feature cracking sequences, inspection intervals and variation in behavior from one critical location to another within the same component. No actual engine testing was conducted by this program. However, full support of the Aeronautical Systems Division Tactical Fighter Engines Office, ASD/YZ, and the P&W F100 Organization enabled the RFC-PMO to incorporate and integrate RFC component demonstration activities with F100 Component Improvement Program activities, thus greatly enhancing the scope of the verification effort.

Specific RFC program sponsored component tests included laboratory spin tests under simulated engine conditions of ten components of seven configurations. When coupled with the F100 Component Improvement Program spin tests and Fracture Critical Parts Engine Accelerated Mission Test, a total of 19 RFC components were subjected to the detailed test/analyses demonstration. In this manner, all RFC materials, generic geometries, and engine module/part types were represented by either engine or laboratory tests. The component demonstration test matrix is shown in Table 6.

TABLE 6. F100 COMPONENT TEST MATRIX INCORPORATING BOTH F100 ENGINE AND RFC PROGRAM EFFORTS FOR RFC ANALYSIS SUBSTANTIATION

Module	*Engine Test*[1]	*CIP Test*	*RFC Test*[3]	*Material*	*Component*
Fan		1[2]		Ti6-2-4-6	2nd-Stage Disk and Hub
		1[2]		Ti6-2-4-6	3rd-Stage Disk
		1[2]		Ti6-2-4-6	2-3-Airseal/Spacer
Compressor (HPC)	1		2	Waspaloy	7th-Stage Disk
			2	Waspaloy	8th-Stage Disk
	1			IN100	9th-Stage Disk
			1	Waspaloy	12th-Stage Disk
			1	IN100	13th-Stage Disk
			2	Waspaloy	7th-Stage Airseal/Spacer
	1			Waspaloy	10th-Stage Airseal/Spacer
	1			Astroloy	11th-Stage Airseal/Spacer
	1		1	Astroloy	12th-Stage Airseal/Spacer
			1	IN100	13th-Stage Rotor Spacer/Cone
High-Pressure Turbine (HPT)	1	1[4]		IN100	1st-Stage Disk
	1	1[4]		IN100	2nd-Stage Disk
	1	1[4]		Astroloy	1st-Stage Blade Retainer (TOBI)
	1	1[4]		IN100	2nd-Stage Blade Retainer (1-2 Spacer)
Fan Drive Turbine (LPT)	1			IN100	3rd-Stage Disk
	1			IN100	4th-Stage Disk

Notes:
1 1800 TAC minimum after flawing
2 3600 TAC minimum after flawing
3 12,000 TAC minimum after flawing
4 Continuation in laboratory of engine test components

Except for the fan disks, the components tested had been previously used in engine service. However, all components contained multiple, nominally identical, limiting features. Through the cooperation of SAALC and P&W resident Air Force organizations, a high number of components obtained and tested *had already exceeded their LCF retirement limit,* and had been removed from service prior to use in this program.

Because RFC is concerned with component behavior if a flaw were present, all components had either natural or induced flaws prior to testing. Crack progression was measured during periodic inspections using surface replication; aspect ratios were determined from post test fractography.

The crack size observed from the testing was compared to the predicted crack size for each feature for at least one return to service interval.* Where more than one of each component was tested, and/or several nominally identical features, e.g. boltholes, were flawed, all data was compared to the same prediction. An example, the 7th-stage HPC air seal/spacer, is shown in Figure 19.

* Engine testing was conducted for 1800 TAC, the then RTS interval for the core module. With the upgrade, the core RTS went to 4000 TAC. RFC sponsored spin testing was conducted to at least 12,000 TAC.

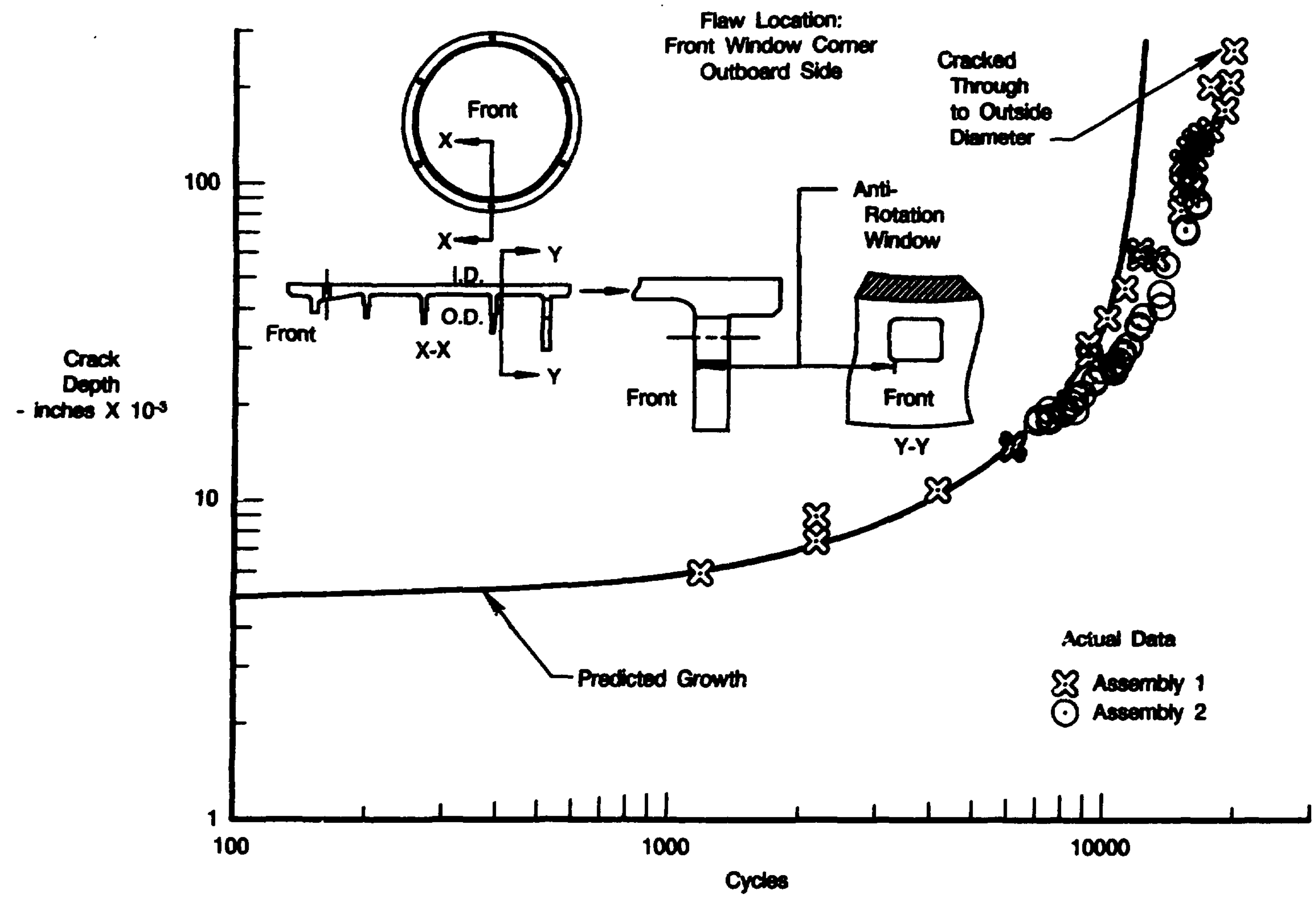


Figure 19. Predicted Crack Growth Versus Actual Data for 7th-Stage Air Seal/Spacer. Note Log Scale

More then 50 total features on the tested components were evaluated in this manner. A number of the features also had multiple examples. The actual and predicted mean crack growth were in good agreement, and in many cases predicted growth rates were faster than actual growth rates (conservatism). This validated the fracture mechanics analysis and life prediction methodology. In many cases, the actual cyclic life of flawed components greatly exceeded not only the maximum return to service intervals but the total life expectancy of the F100 engine system! The 8th-stage high-pressure compressor disk was one example. Prior to use of RFC, this component would have been retired from service at approximately 5000 TAC. A retired 8th-stage HPC disk was obtained. This disk was subjected to an additional 6100 cycles before it was purposely flawed. After flaws were introduced, the disk was installed into a 7th/8th stackup which was spin cycled to failure, with periodic crack growth inspections. The disk accumulated an additional 21,000 cycles before the 7th-disk in the stackup failed. This totals more than six times the nominal retirement life, and almost three projected weapon system lives.

It is recognized that the limited number of component tests conducted does not provide full statistical validity. However, collectively, the results certainly build confidence in the analysis procedures used for RFC of the selected F100 engine components.

b. Specimen/Subcomponent Testing and Analysis

The purpose of the specimen/subcomponent testing was two fold: substantiation of life prediction and statistical methods with representative geometries and conditions, and provision of a laboratory demonstration of the RFC process. To accomplish both of these purposes, a sufficient number of tests for statistical evaluation is required.

As previously stated, the high cost and time required for engine component cyclic tests, even in a laboratory facility, precluded performing the number of tests needed for significant statistical substantiation. Alternatively, sufficient quantities of specimens/subcomponents could be economically tested while adequately representing enough variables to provide substantiation for statistical aspects. As a result, specimen/subcomponent configurations were designed, Figure 20, for the RFC component critical locations to be simulated.

The specimen/subcomponent test plan included all the relevant materials and generic geometries. The tests also used appropriate mission cycles, with sufficient duplicate tests for statistical evaluation, (approximately 110 total tests). The specimen/subcomponent test matrix was sized to permit statistical evaluation of each variable at the lowest level, so that the cause of prediction errors could be isolated to material, geometry or cyclic condition. The specimen/subcomponent testing was carried out in accordance and simultaneously with the laboratory demonstration of the RFC model.

Eight duplicate tests were conducted for each material, configuration and mission cycle. This number of duplicate tests was selected in conjunction with program consultants, (see Table 3), to accomplish the objectives of the test, and was a sufficient sample size to statistically distinguish errors in mean life predictions for the sample if the actual results were more than 33 percent too low or more then 50 percent too high (conservative) relative to the mean predicted life. Differences in mean behavior of these magnitudes are statistically significant at a level of 0.05, (95 percent). Similarly, differences in dispersion of the actual and predicted results are also statistically significant at the 95 percent confidence level if the observed standard deviation of the sample differs from the expected standard deviation by more than approximately 50 percent.

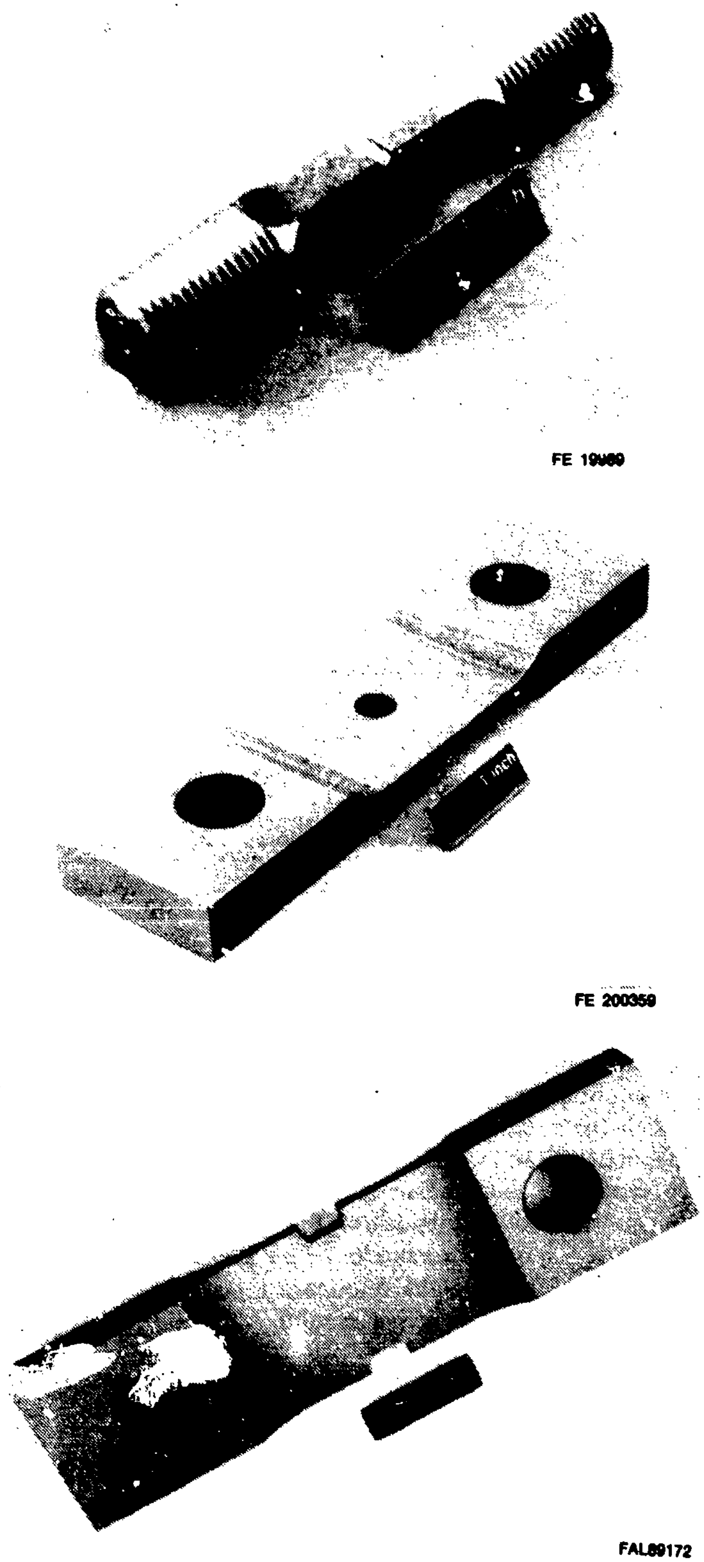


Figure 20. Generic Specimen/Subcomponent Types Used to Verify the RFC Process

During testing, frequent inspections were performed using the best available laboratory techniques to verify crack growth data predictions, and results plotted against a mean prediction for remaining life. An example is shown in Figure 21. When coupled with the duplicate tests for the same conditions, statistical verification of the methodology was obtained.

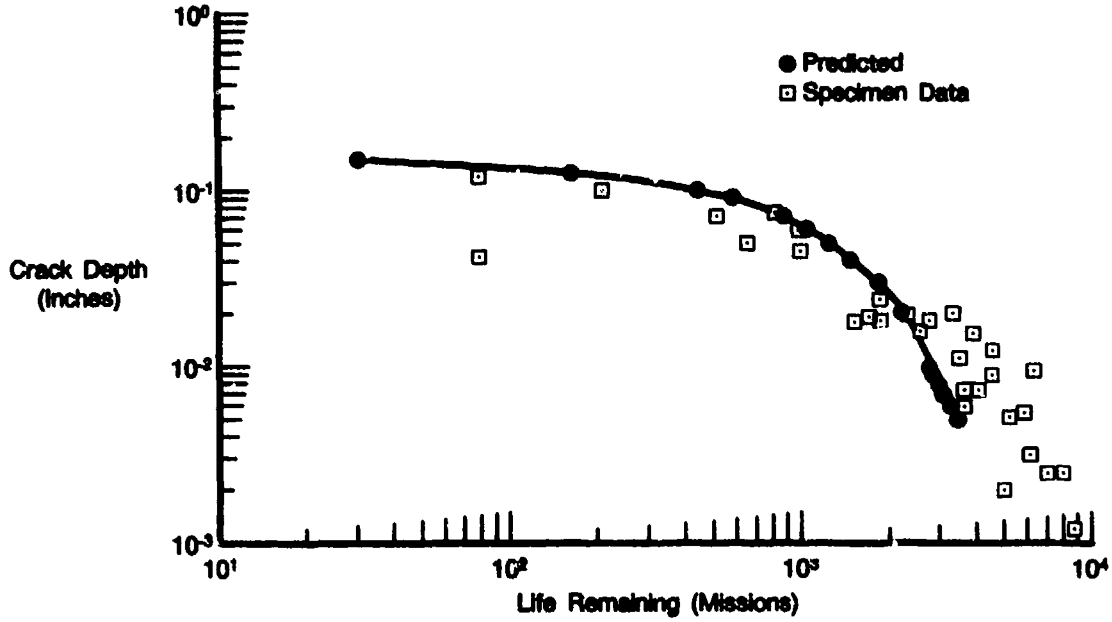


Figure 21. Actual Versus Predicted Remaining Life for a Specimen Verification Test Simulating the 8th-Stage High-Compressor Disk Rim, Waspaloy Material, 600°F Mission Cycle

In addition to statistical verification, the same tests also demonstrated the RFC procedure. For this aspect, the PLAT analyses was conducted for each test type. Based on the results of that analyses, a return-to-service interval was selected, the specimen/subcomponent was cycled through that interval, and a blind inspection was conducted. These blind inspections were performed by a group not associated with the testing using the same procedures employed for engine overhaul. Based on the blind inspection results, a return-to-service or retire decision was made, and the cycle-inspect sequence repeated. Even when a retire decision was made, this process was continued to evaluate the accuracy of the decision. The possible outcomes for a decision are listed in Table 7. An example of the decisions made for an 8th-stage high-pressure disk rim subcomponent is listed in Table 8, for the eight duplicate tests of that configuration/condition, showing the accurate, somewhat conservative results.

TABLE 7. SUMMARY FOR POSSIBLE OUTCOMES FOR RETIREMENT FOR CAUSE DECISIONS

Decision Prior to Interval	*Results in Interval*	*Decision Evaluation*
Retire	Failure	Correct - Accurate
Retire	Interval completed, No Failure	Conservative - Low Cost for Inaccuracy
Return to Service	Interval completed, No Failure	Correct - Accurate
Return to Service	Failure	Incorrect - High Cost for Inaccuracy

TABLE 8. RETIREMENT FOR CAUSE DECISION SUMMARY FOR 8TH-STAGE HIGH-PRESSURE COMPRESSOR DISK RIM SPECIMEN VERIFICATION TEST. SAMPLE SIZE WAS 8, NOMINAL INTERVAL WAS 1800 MISSIONS

Decision Prior to Interval	*Result in Interval*	*Number of Occurrances by Interval*						
		6	*7*	*8*	*14*	*16*	*25*	*Total*
Retire	Failure	1	0	0	0	0	0	1
Retire	Interval Completed	1	2	2	1	1	1	7
Return to Service	Failure	0	0	0	0	0	0	0
Return to Service	Interval Completed	1	2	2	1	1	1	7
Actual Accumulated Missions (Thousands)		10.6	12.4	14.2	24.8	28.4	44.3	

Note: No predicted failure activity prior to interval 6.

It should be noted that the laboratory exercise of the RFC model was structured to verify the RFC process. Therefore, the return-to-serivce intervals, and total life were tailored for the demonstration testing, and not necessarily for the life of the corresponding engine component. This enabled an evaluation of the RFC-PLAT process itself, independent of the F100 engine application.

It was found that initiation life predictions were conservative. Recognizing the conservatism, the demonstration showed that the RFC process itself functions well, is viable, and gives confidence that it will result in safe, efficient use of life inherent in engine components.

6. F100 ENGINE RETIREMENT FOR CAUSE COMPONENTS

The Retirement for Cause concept was initially evaluated for all prime rotor components of the F100 engine using the existing deterministic analyses, and retirement lives. As the force structural maintenance plan was changed, (reference Section III), and PLAT analyses became available, the rotor components were continually reviewed to establish applicability.

a. Component Selection Criteria

There are two primary criteria used to select F100, or any other engine, rotor components for RFC implementation. These criteria must be sequentially applied:

- Component low cycle fatigue life at any location is less than the anticipated system life;
- Component crack propagation life at all locations must be greater than the return to service interval with an appropriate Propagation Margin.

The critical locations considered for each of the two criteria may not be the same and that is why the criteria are applied sequentially. The LCF limiting locations may not be those with the most limiting crack propagation life. It is important that the actual analytical lives be used in application of the criteria. Often the component retirement limits reflected in an engine Technical Order, Overhaul manual may have other factors involved. While all factors must be assessed, the criteria requires use of the most accurate life calculations available.

The projected life of the F100-PW100/200 engine system is 12,000 TAC. As engines/ modules reach that life it is anticipated that they would be removed (retired) from active service.

Thus in applying the first criteria any component with an LCF life, at any location, less than 12,000 TAC would be an RFC candidate.

After complete review, the Executive Group established additional guidelines for use of the Propagation Margin in the second criteria. Any component with a Propagation Margin of two or greater would meet the criteria. If the Propagation Margin was less than two, but greater than one, appropriate PLAT and/or risk analyses would be conducted. Based on the risk assessment, a final decision to include or exclude a component was made. The Propagation Margin calculations were based on the return to service interval of the module containing the component i.e., fan, core or fan drive turbine, (reference Sections III and IV).

It is emphasized that both criteria must be applied in sequence. Failure to meet both criteria removes a component from consideration for RFC. For example, a component with a LCF life greater than 12,000 TAC would not be retired in the life of the system, therefore RFC is not applicable and normal overhaul safety inspections would suffice. Conversely, for a component with a LCF life less than 12,000 TAC, but a low propagation margin, RFC is also not applicable, assuming no change in return to service interval, and the component would be retired and replaced at its LCF limit.

There are two additional factors that should also be considered in applying the selection criteria. If the cost of conducting the necessary component inspections exceeds the cost of a new replacement component, it is not economically feasible to apply RFC. If replacement components were not available-at any cost-in the required time period, RFC may be necessary regardless, in order to maintain force readiness. These factors were also accounted for i   ecting F100 RFC components.

b. Retirement for Cause Components

At the present time, 23 fan, high-pressure compressor and fan drive turbine disks and air seal/spacers are F100-PW100BC/200B (upgraded core) RFC components. Should a core not receive an upgrade, and be maintained on .n 1800 cycle rhythm as an F100-PW100/200 model version, an additional seven high-pressure compressor (HPC) and high-pressure turbine (HPT) components could be managed under the RFC process. As it is planned that all USAF F100-PW100/200 core engine modules will be upgraded, it is doubtful that RFC will ever be used for these seven components. That option, however, exists.

The F100 Retirement for Cause Components are listed in Table 9, together with return to service interval and material.

Currently, the upgraded core engine's 10-, 11- and 12th-stage HPC air seals and high-pressure turbine unit will not reach their life limits prior to removal of the F100-PW100B-C/200B engines from active service, and therefore are not included in Table 9. Should circumstances warrant extending the system life, RFC could be used. That option also exists. If system life extension were required, other F100 components, in addition to those discussed in this paragraph, could also be managed with the RFC process.

c. Nondestructive Evaluation Techniques

Coupled with fracture mechanics analyses, reliable production oriented nondestructive inspection techniques are required. The inspection requirements for each critical feature for each RFC component were established. The appropriate NDE techniques to meet those requirements are also listed in Table 9, and are of four types: proof test, eddy current, ultrasonic, and focused fluorescent penetrant.

TABLE 9. F100 ENGINE RETIREMENT FOR CAUSE COMPONENTS

Module	*Component*	*RTS Interval (TAC)*	*Material*	*NDE Technique**
F100-PW 100B-C/200B (Upgraded Core) Engines				
Fan	1st-Stage Disk and Hub	3000	Ti6-2-4-6	Cryo Proof
	2nd-Stage Disk and Hub	3000	Ti6-2-4-6	Cryo Proof
	3rd-Stage Disk	3000	Ti6-2-4-6	Cryo Proof
	2nd-Stage Airseal (2-3 Spacer)	3000	Ti6-2-4-6	EC
Core/HPC	4th-Stage Disk	4000	Ti6-2-4-6	EC
	5th-Stage Disk	4000	Ti6-2-4-6	EC
	7th-Stage Disk	4000	Waspaloy	EC
	8th-Stage Disk	4000	Waspaloy	EC
	9th-Stage Disk	4000	IN 100	EC/UT
	10th-Stage Disk	4000	Waspaloy	EC
	11th-Stage Disk	4000	IN 100	EC
	12th-Stage Disk	4000	Waspaloy	EC
	13th-Stage Disk	4000	IN 100	EC/UT
	13th-Stage Rotor Spacer	4000	IN 100	EC/UT
	4th-Stage Airseal	4000	Ti6-2-4-6	FPI
	5th-Stage Airseal	40[illegible]	Ti6-2-4-6	FPI
	6th-Stage Airseal	400[illegible]	Waspaloy	FPI
	7th-Stage Airseal	4000	Waspaloy	FPI
	8th-Stage Airseal	4000	Waspaloy	EC
	9th-Stage Airseal	4000	Waspaloy	FPI
Fan Drive Turbine	3rd-Stage Disk	3000	IN 100	EC/UT
	4th-Stage Disk	3000	IN 100	EC/UT
	4th-Stage Airseal (3-4 Spacer)	3000	Waspaloy	EC
F100-PW100/200 (Nonupgraded Core) Engines All of the Above Plus:				
Core HPC	10th-Stage Airseal	1800	Astroloy	FPI
	11th-Stage Airseal	1800	Astroloy	FPI
	12th-Stage Airseal	1800	Astroloy	FPI
Core HPT	1st-Stage Disk	1800	IN 100	EC/UT
	2nd-Stage Disk	1800	IN 100	EC/UT
	1st Blade Retainer (TOBI)	1800	Astroloy	EC
	2nd Blade Retainer (1-2 Spacer)	1800	IN 100	EC

*EC - Eddy Current Feature Inspection
UT - Ultrasonic Zone Inspection
FPI - Fluorescent Penetrant Inspection (Focused)

Note: All components receive standard whole field FPI during the engine/module overhaul process.

Proof testing techniques at cryogenic temperatures are used for the three fan disks. The cryo-proof process for disks was developed in conjunction with the Aeronautical Systems Division and San Antonio Air Logistics Center. Under this process, a fan disk is spun to an overload speed while at cryogenic temperature. If a deleterious defect were present, the disk bursts: if not, the disk is certified for its next return to service interval.*

All components receive standard fluorescent penetrant inspection (FPI) during the overhaul process to detect gross surface defects. Focused FPI, using sensitive penetrants examined under magnification is used for some features on HPC airseals, where flaw size requirements are less stringent.

*The cryogenic proof testing technique of inspection was not introduced by the F100 engine. Certain aircraft and spacecraft airframe components were, and still are, being inspected with this technique prior to its use on F100 fan disks.

Eddy current and ultrasonic techniques are used where critical surface and/or subsurface (internal volumetric defect) inspections are required. Specific inspection requirements were established by this program for each component location or zone and interacted with Systems Research Laboratories Inc. (SRL), the developer and producer of the automated eddy current/ultrasonic inspection system for RFC under USAF Contract F33615-81-C-5002. Continuous coordination between the P&W RFC group and SRL was maintained. The resulting advanced state-of-the-art NDE system has been installed and is now operational doing RFC inspections at the San Antonio Air Logistics Center.

With RFC, (as with any safety oriented inspection), it is not the smallest flaw that can be found that may cause a problem, but the largest flaw that can be missed. To ensure adequacy of the RFC inspection processes, extensive reliability analyses were conducted. Results of these analyses, in the form of Probability of Detection (POD) distributions were then incorporated in the PLAT component analyses. The RFC/NDE system produced by SRL has the highest in-production reliability of any inspection system produced yet. It is totally adequate for implementation of RFC for F100 engine components. When coupled with Propagation Margin, this high POD minimizes the effect of inspection uncertainty on component life.

7. ECONOMIC ANALYSES

The underlying fracture mechanics/life prediction and nondestructive evaluation technology basis of RFC has been demonstrated/validated. There are no technical reasons why RFC can not be used as a priori intention, as opposed to an after-the-fact necessity, for engine maintenance. However, there must be a reason *to use* RFC. The primary premise for using RFC is that it will significantly reduce the cost of ownership of a engine system. Life Cycle Cost (LCC) savings are the means of measuring the reduction in cost of ownership.

A number of LCC models were evaluated for use in assessing RFC for the F100 engine system. In conjunction with the USAF Tactical Engines Programs Office, (ASD/YZ), a LCC model had been developed under the F100 Component Improvement Program called, appropriately, the F100 LCC Model. This model simulates fleet build-up/retirement/annualized costs and accounts for all elements in the Joint Air Force/Industry Standard LCC Model criteria. This model was selected for use in the RFC program. A major element of the model is the Support Cost Model. It is this aspect of LCC of a system that RFC impacts. The F100 LCC Model is shown schematically in Figure 22.

Initially, integration of the probabilistic life assessment (PLAT) and LCC models was envisioned. This approach was abandoned due to prohibitive computer size and computational time requirements. Consequently, slight modifications of the LCC program were made to accept required information from PLAT and other sources as data sets. For the RFC components receiving a probabilistic analyses, PLAT results were used. Conventional analysis data were used for the balance.

a. Life Cycle Cost Savings

Life Cycle Cost analyses were conducted for two scenarios for the F100 upgraded core fleet: baseline, with components retired and replaced with new components at their LCF limits; and RFC of the 23 components. The difference in the two analyses results is the LCC savings for RFC. In addition, as RFC makes possible a cost effective core engine upgrade, the cost savings for the reduced number of core engine overhauls was also established.

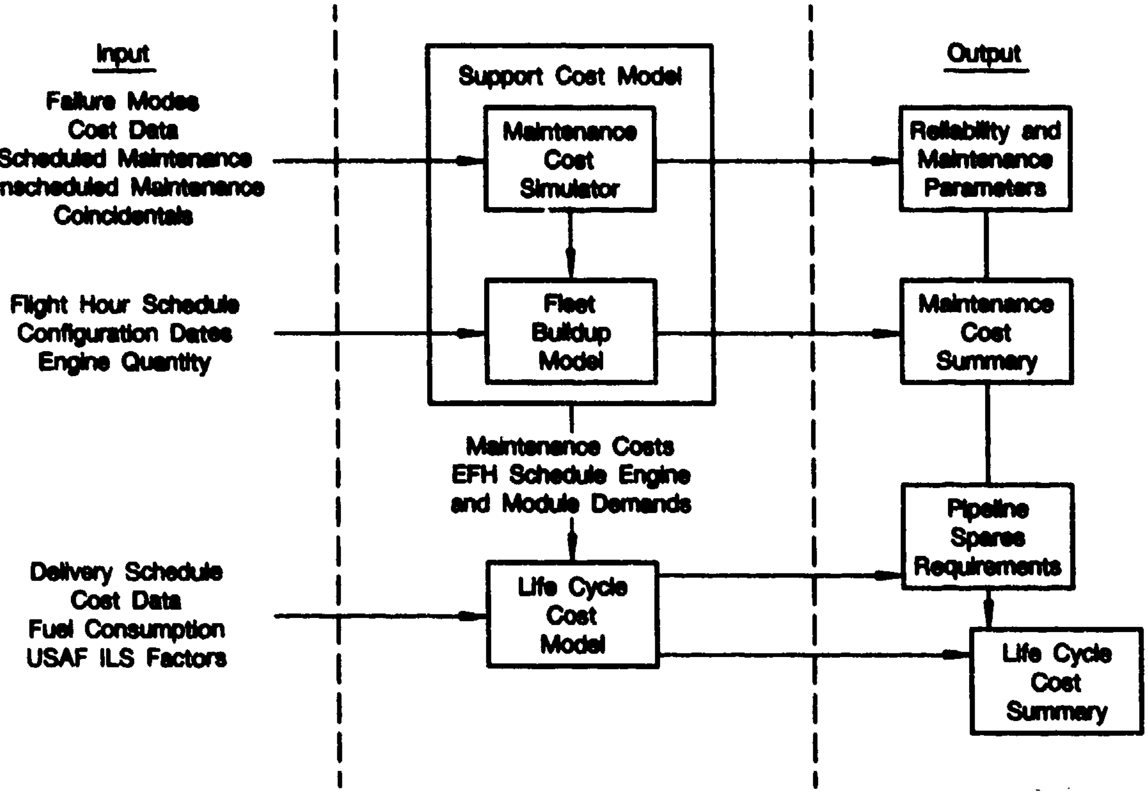


Figure 22. Schematic of the F100 Life Cycle Cost Model Used to Evaluate RFC

Life Cycle Costs analyses are predicated upon various ground rules and assumptions concerning events in the future. These include aircraft/engine utilization rates, scheduled and unschedule maintenance events, engine delivery schedules, engine/module retirement rate, labor requirements and many others. Ground rules and assumptions for this study were developed in conjunction with the Tactical Engines Program Office (ASD/YZ) Air Logistics Command Headquarters, Acquisition Logistics Division, San Antonio Air Logistics Center and AFWAL, and used with their concurrence. All costs were based on and are reported in fiscal year 1986 dollars.

The LCC savings for the F100-PW100BC/200B fleet are $966.2 million due to parts cost avoidance for a nominal 12,000 TAC engine life. These savings are delineated by module and component in Table 10. In addition, $655.2 million is saved because of approximately 9600 fewer scheduled core engine overhaul visits for the fleet over its projected life. This reduction results from the extension of the core engine return-to-service interval from 1800 to 4000 TAC due to the upgrade. RFC is responsible for a part of this savings. As discussed in Section 3.3, the upgrade is accomplished as a package entity. The cost of that package would increase by a factor of 1.7 to 1.8 if RFC were not used. Therefore, it is postulated that RFC is responsible for a proportionate amount of the savings due to the fewer core engine overhaul visits. With this premise, RFC can be credited with approximately $303 million of the overhaul visit cost avoidance.

TABLE 10. F100 ENGINE COMPONENT RETIREMENT FOR CAUSE LIFE CYCLE COST SAVINGS FOR UPGRADED CORE ENGINES IN CONSTANT 1986 DOLLARS

		LCC Savings in $ Million		
Module	*Component*	*F100-PW100B-C*	*F100-PW200B*	*Total*
Fan	1st-Stage Disk and Hub	58.6	38.1	96.7
	2nd-Stage Disk and Hub	47.4	30.8	78.2
	3rd-Stage Disk	42.1	27.4	69.5
	2nd-Stage Airseal (2-3 Spacer)	11.7	7.6	19.3
	Fan Sub Total	159.8	103.9	263.7
Core/HPC	4th-Stage Disk	12.7	8.3	21.0
	5th-Stage Disk	26.9	17.5	44.4
	7th-Stage Disk	17.4	11.3	28.7
	8th-Stage Disk	15.7	10.2	25.9
	9th-Stage Disk	30.2	19.6	49.8
	10th-Stage Disk	11.7	7.6	19.3
	11th-Stage Disk	45.4	29.5	74.9
	12th-Stage Disk	21.9	14.3	36.2
	13th-Stage Disk	32.5	21.1	53.6
	13th-Stage Rotor Spacer	19.1	12.4	31.5
	4th-Stage Airseal	6.8	4.4	11.2
	5th-Stage Airseal	8.2	5.4	13.6
	6th-Stage Airseal	4.7	3.1	7.8
	7th-Stage Airseal	6.4	4.1	10.5
	8th-Stage Airseal	4.8	3.1	7.9
	9th-Stage Airseal	4.9	3.1	8.0
	Core/HPC Sub Total	269.3	175.0	449.3
Fan Drive Turbine (LPT)	3rd-Stage Disk	75.4	49.0	124.4
	4th-Stage Disk	56.7	36.8	93.5
	4th-Stage Airseal (3-4 Spacer)	24.4	15.9	40.3
	LPT Sub Total	156.5	101.7	258.2
	Total	585.6	380.6	966.2

The gross savings due to RFC must be debited by the investment costs required to enable its use. These cost accrue due to development, equipment and facility expenses to enable its application. A total of $52.5 million (FY 1986 dollars) including the NDE and cryo spin equipment and facilities, are considered RFC investment costs in this analysis and are deducted from the LCC savings.

With the above premises, the use of Retirement for Cause for the upgraded core USAF F100 engine fleet produces a net life cycle cost savings in excess of 1.21 billion dollars.

b. Cost and Risk Sensitivity Studies

Sensitivity studies were conducted to evaluate the impact of variations in the ground rules and/or assumptions used in the LCC analysis. The fan drive turbine (LPT) module was used for these sensitivity studies. It was selected because PLAT analyses had been conducted for all of the RFC rotor components in that module; therefore failure rates, replacement rates, intervals, etc., were available.

For these studies, actual failure rates were used. This technique is useful in studies only. In reality, a part either fails or it does not; there is no such thing as 0.001 failure. The cost of a failure was set very high. When multiplied by a failure rate, costs could be assigned to a "partial failure" for comparison purposes.

Propagation margin versus LCC for the three RFC rotor components of the LPT module and the module summation are plotted in Figure 23 using the process described previously. As propagation margin (PM) decreases, costs go up due to increased failure rates. As PM increases, failure rate approaches zero. Once the costs of failure reaches a minimum, LCC are driven by costs associated with the increased number of depot visits/overhauls/inspections. This is as expected. It is interesting to note that the results of this analysis support the Propagation Margin guidelines, set before the analysis was conducted. A propagation margin in the range 1.5 to 2.5 appears to be optimum. Most of the F100 RFC components are in this range; some have higher propagation margins.

Propagation margin is inversely related to return to service (RTS) interval. From Figure 23, the relationship between length of RTS interval and LCC can be inferred. As RTS interval increases, risk, and thus cost of failures, increases. Sensitivity studies of LCC savings verses RTS interval for the LPT indicate maximized savings for an interval length of 2500 to 3500 TAC. The current interval for the LPT is 3000 TAC.

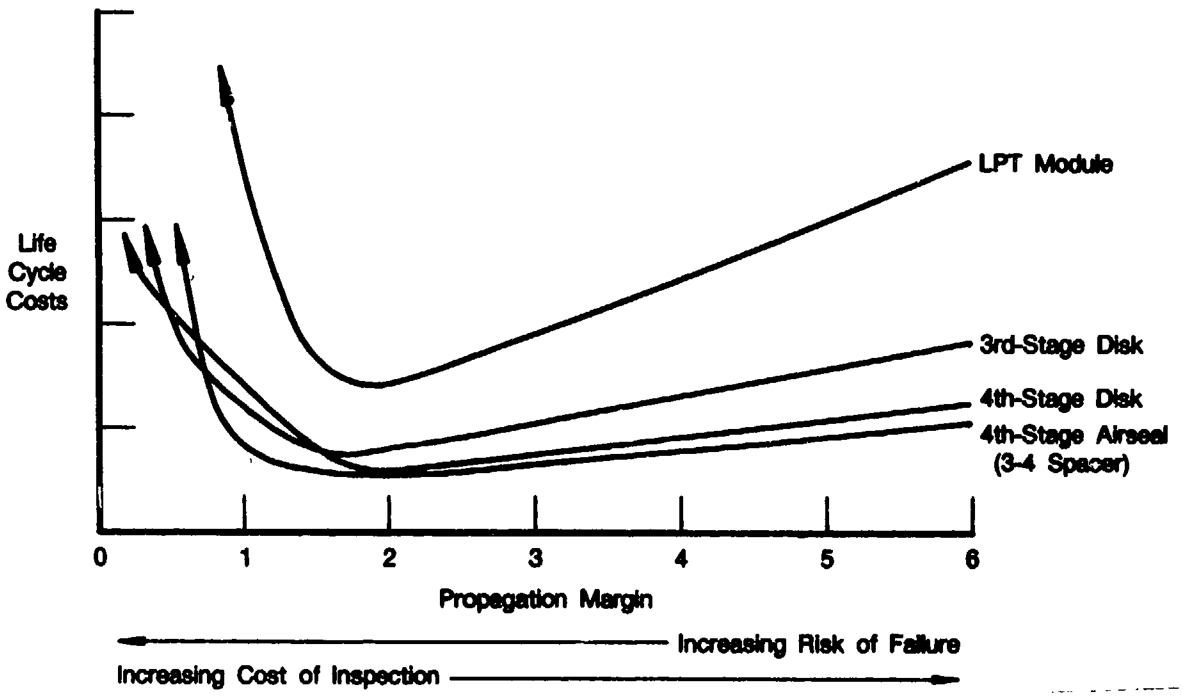


Figure 23. Propagation Margin Versus LCC for F100 Fan Drive Turbine Module

Life cycle cost savings were relatively insensitive to inspection costs. Variation of the inspection costs from 1/2 to 2 times the base for the three LPT components results in less than a 5 percent change in total LCC savings for these components. This is because the inspection costs of the component are very low relative to the costs of replacement components.

Replacement component cost, however, is a major factor. Life cycle cost savings for the LPT vary directly, almost linearly, with the costs of the component. Increasing the costs of the three LPT components by 50 percent yields a 51 percent increase in LCC savings. As replacement component cost avoidance is the major factor in the LCC benefits of RFC, this was also expected.

A similar relationship exists between LCC savings and the number of LPT modules managed under RFC. Should the LPT modules of the F100-PW220 engines be included, (approximately 1500 additional) the savings increase from $258 million to $377 million.

Life cycle cost savings are sensitive to many factors. Only a few parameters were evaluated herein, and then within the ground rules and assumptions initially established. Other weapon system factors, not directly related to the specific components evaluated, may have influences that mitigate these results.

8. APPLICATION TO OTHER ENGINES — THE TF30

The feasibility of applying a RFC maintenance approach to the rotor components of the USAF TF30 engines was evaluated. Unlike the F100 engine, the TF30 is significantly advanced in life cycle. Therefore, in addition to determining the technical feasibility, the economic desirability of performing RFC was assessed in conjunction with other maintenance options. The TF30-P3 and P100 engine models were studied in detail. Because of simularities in the rotor components, the P7 and P9 models were included by extrapolation of P3 data and results.

Three scenarios were evaluated:

1. Perform RFC on current engine components
2. Incorporate "full life" redesigned components in engines
3. Incorporate redesigned components and perform RFC on remaining eligible components.

The basis for comparison was the effect on projected life cycle costs of the engine. The baseline situation consisted of the current engines with continuation of the existing engine design and maintenance procedure throughout the engine system projected service life. The impact of each senario on LCC was compared to the baseline to evaluate benefits. In addition to these comparisons, sensitivities to fleet size, fleet utilization life, and propagation margin were determined. It was found that applying RFC resulted in LCC savings for all TF30 engine models, but incorporation of redesigned components produced higher LCC savings than use of RFC. As expected, LCC savings were maximized when RFC was applied to the redesigned engines. Extension of the weapon system retirement life also favored incorporation of redesigned components.

This effort was completely documented in AFWAL Technical Report, TR 83-4020, Reference 11.

SECTION V

CONCLUSIONS

Engine Component Retirement for Cause is technically valid and economically desirable. The benefits are so significant that RFC was implemented for components of the F100 engine as this technology contract program was being completed. It is anticipated that RFC will become the standard procedure for maintenance management of life-limited components of all future USAF gas turbine engines, and potentially for any fatigue life-limited system.

In addition to the LCC savings, there are other, less tangible benefits. For the F100 engine alone, it is estimated that more than 3500 tons of strategic material use is avoided over the total engine system life by not producing the quantities of spare parts that would have been required prior to RFC. In this regard, while not the primary objective, RFC evolves as one of the largest of the strategic material conservation efforts.

Another intangible benefit is the change in perception of and attitudes toward damage tolerance and probabilistic concepts that occurred over this programs duration. This, too, speaks well for future engine systems.

This program demonstrated that RFC is viable for the F100 engine. It is strongly emphasized, however, that to use RFC for other engines, thorough knowledge and understanding of the materials behavior, component operating conditions, engine use, and logistics/ maintenance systems involved are required to avoid undesirable consequences.

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