A SYSTEMS ENGINEERING DESIGN OF A RETIREMENT FOR CAUSE LIFE MANAGEMENT PROCESS FOR LIFE-LIMITED F110-GE-400 ENGINE PARTS

by

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Abstract

Extreme temperatures and high component rotational speeds within a gas turbine engine and design constraints limit engineers' ability to design all engine components to last for the expected service life of the engine. Under the United States Navy's current life management philosophy where life-limited engine parts are retired at their B.1 life, over $210 million (1995 dollars) worth of parts will be replaced with new parts before system retirement in 2010.

Using the systems engineering process, the retirement for cause methodology is adapted for use with and application to the Navy's F110-GE-400 engine. A preliminary retirement for cause system design is established, and all life-limited parts are evaluated for participation in the system. A life-cycle cost savings of $270 million is calculated for the four parts selected for management via the established retirement for cause system. Further, this life-cycle cost savings can be achieved with a maximum up-front investment of $4.57 million over two years. Methods for decreasing the up-front investment costs are discussed.

The retirement for cause system defined herein is a feasible and cost effective alternative to the Navy's current life management system for the selected F110-GE-400 engine parts. Flight safety and readiness are shown not to be degraded with implementation of the retirement for cause system. Limitations of this study consists primarily of data non-availability.

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List of Acronyms

ASO	Aviation Supply Office
CDP	Compressor Discharge Pressure
CL	Confidence Level
DCS	Detectable Crack Size
EC	Eddy Current
ENSIP	Engine Structural Integrity Program
FOD	Foreign Object Damage
FPI	Fluorescent Penetrant Inspection
GEAE	General Electric Aircraft Engines
HCF	High Cycle Fatigue
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IGV	Inlet Guide Vane
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LPT	Low Pressure Turbine
MPI	Magnetic Particle Inspection
NDI	Non-destructive Inspection
PMIC	Periodic Maintenance Information Card
POD	Probability of Detection
RFC	Retirement for Cause
RFI	Ready-for-Issue
RTS	Return to Service
TACs	Total Accumulated Cycles
TPM	Technical Performance Measure

List of Acronyms (continued)

USAF . . . . . United States Air Force
USN . . . . . United States Navy
UT . . . . . Ultrasonic

Introduction

Based on the current utilization rate for the F110-GE-400 engine, over $210 million (1995 dollars) worth of life-limited parts will be replaced with new parts before the year 2010. The useful life of these parts has been calculated under the guidelines set forth in the USN "safe life" life management philosophy. The USN has relied on this life management methodology to manage fatigue-prone parts on all naval aircraft and helicopter gas turbine engines since the start of naval aviation.

The USAF and others have argued that this life management philosophy does not take full advantage of advances in the understanding of how and when a crack initiates and how it propagates in a part. Additionally, there is no place is this life management philosophy (except on an exception basis in an emergency) to put to use the increasing advancing capabilities of non-destructive inspection techniques. In many instances, the necessary conservatism that is fundamentally embedded in the safe life method leads to higher operational costs than a structurally different method that embraces technological advancements and, thereby, less conservatism.

This paper will provide a preliminary design of a retirement for cause (RFC) life management system for some life-limited F110-GE-400 engine parts. The primary goal of this system design is to achieve a life cycle cost savings over current procedures without introducing additional risk to the USN F-14 fleet. To accomplish the stated objective, maximum safe utilization of certain selected F110-GE-400 life-limited engine parts will be sought.

Statement of Need

Most rotating parts and pressure vessels within an engine are life-limited. Material technology constraints, design weight constraints and immature life prediction techniques limit design engineers' ability to design parts capable of lasting for the life of the engine without failure. The culprits are the extreme mechanical and thermal stresses found within a gas turbine engine.

Low-cycle fatigue (LCF), creep fatigue, and, to a lesser extent, high-cycle fatigue (HCF) are the primary degraders of a particular part's useful life. These fatigue modes act to initiate and/or propagate cracks in a part. LCF is caused by high amplitude, low frequency loadings and unloadings. HCF, conversely, is the result of low amplitude, high frequency vibratory loadings. Creep is somewhat different. It is a dimensional change in a part, often referred to as "stretch", that is linked to the time that a part dwells at a particular loading condition.

All 22 of the F110-GE-400 engine life-limited parts that require removal after a given interval of service are limited by low-cycle fatigue. The life limits of these components are expressed in mission equivalency cycles known as Total Accumulated Cycles, or TACs.

The classical "safe life" life management philosophy is employed by the USN to ensure that each and every life-limited part is retired from service prior to failure. In this life management philosophy, engine usage profiles are combined with the operating conditions and material crack initiation characteristics of a particular part for the purpose of determining the point at which a minimum detectable crack could be expected to occur in 1 out of a population of 1000 parts.

The number of cycles at which 1 out of 1000 parts of a specific type will develop a minimum detectable crack is known as the B.1 life of that part. So, when an entire population of one component is retired at its B.1 life, 99.9 percent of the parts are retired with useful life remaining on them. Figure 1 illustrates the concept and reveals the effect of the applied conservatism. For safety reasons, since there is no way of knowing which one part out of a thousand will be the one (essentially, the "minus 3-sigma part") to develop a crack at the component's B.1 life, all parts must be retired at this time.

The cost of safety in this life management philosophy is high. Figure 2 shows that most parts have significantly more life remaining after retirement. In fact, over 80% of the parts retired at their B.1 life have 3 lifetimes remaining on them. Nevertheless, due to inadequate life prediction methodologies, both in terms of crack initiation and crack propagation, managing parts to their B.1 life has been the accepted method of guarding against critical in-service part failures for many years.

Based on the current usage rate of 45 TACs per month for the F110-GE-400 engine, more than $210 million (1995 dollars) worth of life-limited parts will be replaced with new parts before the year 2010 (see Table 1). Flight safety, life management, readiness, and the control and/or reduction of ownership costs are the top concerns of naval aviation. If ownership costs can be reduced without adversely impacting the other key concerns, then we should proceed in that direction.

Recent advances in analytical capabilities and the combination of analytical results with an ever-growing empirical database demand an evaluation of the utility of the RFC methodology for application to the F110-GE-400 engine. The USAF has calculated a life cycle cost (LCC) savings of over $1.2 billion (1986 dollars) as a result of implementing RFC on the F100

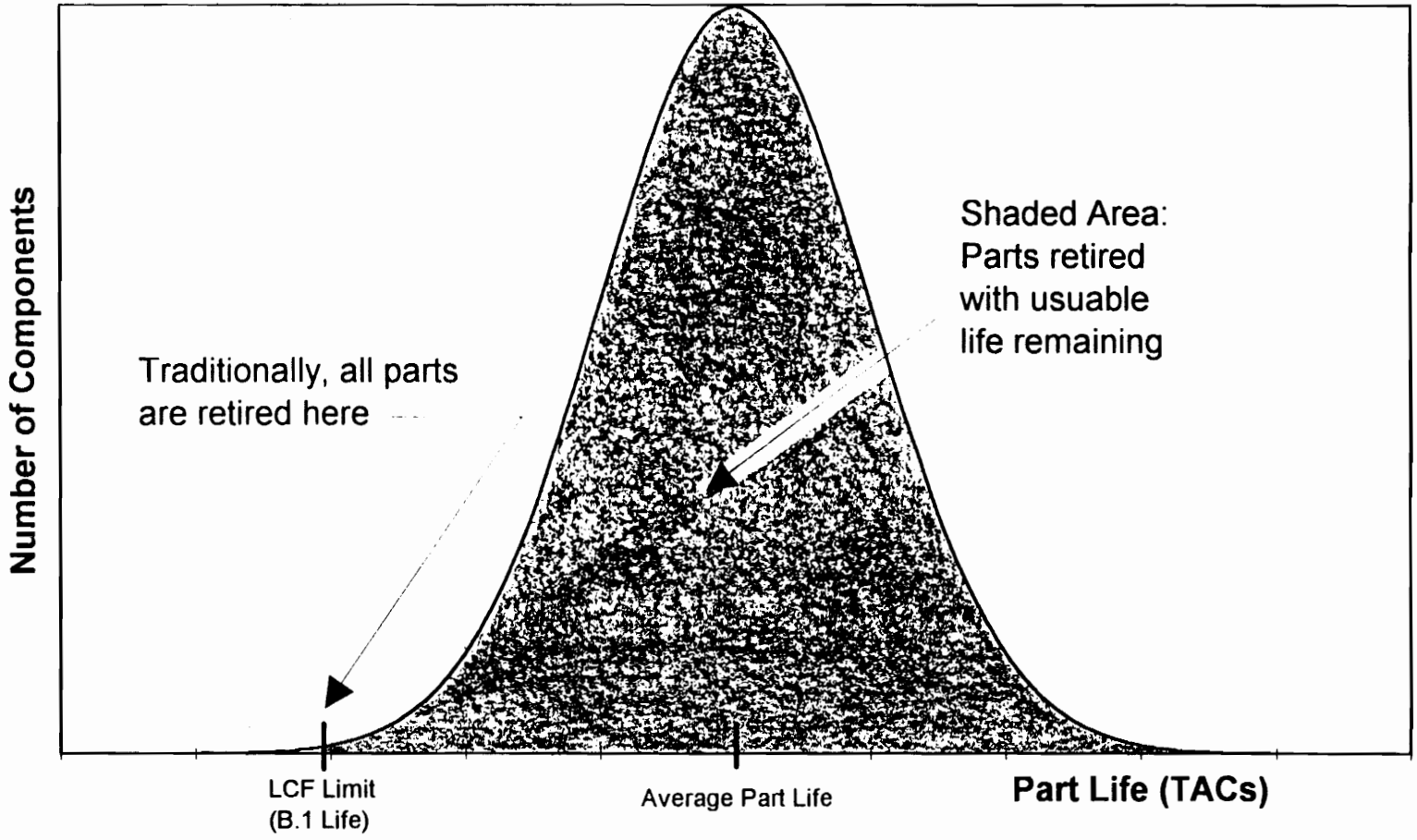

FIGURE 1: B.1 LIFE

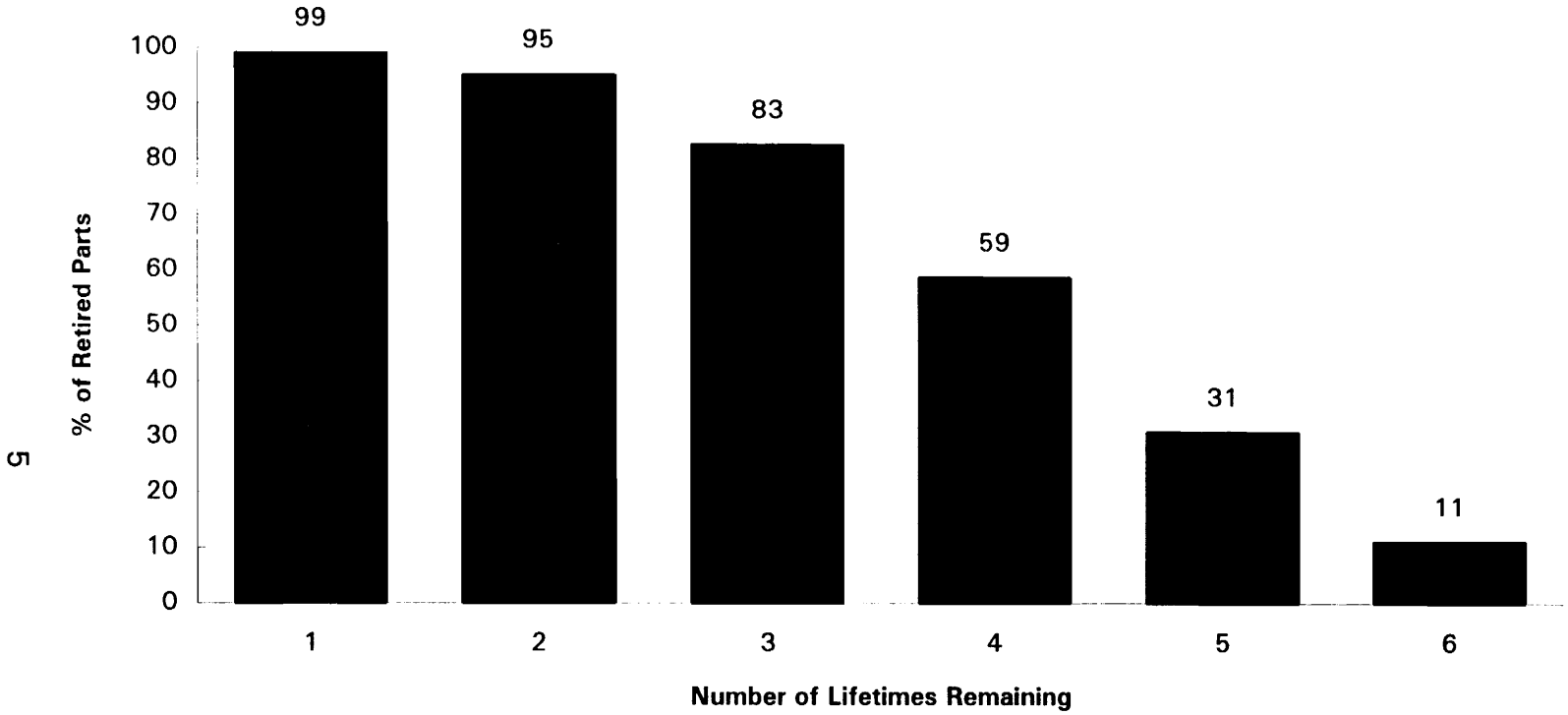

Figure 2: Lifetimes Remaining

TABLE 1: F110-GE-400 Life-Limited Parts Replaced at LCF life (1995 - 2010)

Part Nomenclature	Material	Cost *	Qty replaced	Total Cost
Fan Rotor Assembly				
1st Stage Fan Disk	Titanium 6-4	$20,368	245	$4,989,915
2nd Stage Fan Disk	Titanium 6-4	$48,750	353	$17,208,750
3rd Stage Fan Disk	Titanium 6-4	$27,627	1325	$36,607,100
Rear Fan Shaft	Titanium 6-4	$12,044	0	$0
Compressor Rotor Assembly				
1st & 2nd Stage Spool	Titanium 17	$36,857	0	$0
Forward Shaft Stub	Titanium 6-4	$5,693	0	$0
3rd Stage Compressor Disk	Titanium 17	$11,941	0	$0
4th - 9th Stage Spool	Inconel 718	$90,470	22	$1,990,349
Rotating Compressor Air Seal	Super INCL 718	$8,576	0	$0
Combustion Case Assembly	Inconel 718	$49,585	1660	$82,311,100
HPT Rotor Assembly				
HPT Forward Shaft	Inconel 718	$21,006	334	$7,016,031
HPT Forward Rotating Seal (M22)	Rene 95	$35,855	332	$11,903,979
HPT Forward Rotating Seal (M90)	Rene 95	$35,855	incl'd above	incl'd above
HPT Forward Rotating Seal (M48)	Rene 95	$35,855	incl'd above	incl'd above
HPT Forward Blade Retainer	Rene 95	$4,709	332	$1,563,428
HPT Disk	Rene 95	$73,549	333	$24,491,750
HPT Aft Blade Retainer (P05)	Rene 95	$5,952	452	$2,690,304
HPT Aft Blade Retainer (P03)	Rene 95	$5,952	incl'd above	incl'd above
HPT Aft Shaft	Inconel 718	$14,118	0	$0
LPT Rotor Assembly				
LPT 1st Stage Disk	DA 718	$19,565	0	$0
LPT 1st Stage Blade Retainer	Inconel 718	$3,022	452	$1,365,980
LPT 2nd Stage Disk	DA 718	$15,234	0	$0
LPT 2nd Stage Blade Retainer	Inconel 718	$2,596	332	$861,819
LPT Shaft	Inconel 718	$66,686	0	$0
LPT Seal Spacer	Rene 41	$23,530	764	$17,977,103
			TOTAL =	**$210,977,608**

* Costs include Aviation Supply Office standard 28% surcharge (1995 dollars)

engine.[1] Today, ever-looming defense fiscal constraints demand more capability from every defense dollar. Where possible, we need to get more for less.

If it is possible to reduce ownership costs for the F110-GE-400 engine by changing life management philosophies, the savings realized will be greater the sooner the switch is made. Since time must be allotted for the government budget planning cycle, required development efforts and production, introduction of the RFC system probably can not occur before January 1997.

It is hard to estimate the magnitude of government resources that would be available for such an effort at this time. What is important now is to conduct the study and construct as strong a case as the data will permit in argument for a change to a RFC life management philosophy. The USN will prioritize this effort and all other worthwhile development efforts of similar nature. Then, Congress will appropriate a sum of money to fund these worthwhile efforts. There will not be enough money to fund all of the efforts, no matter how worthwhile. This effort will be funded if its relative position on the list is high enough. It is likely that a low technical risk effort with the promise of significant LCC savings would fall high on the priority list for naval aviation. This statement is particularly true in the present. For the past several years the USN has devoted large sums of money in pursuit of gaining a better understanding of the lives of the life-limited components contained in its many aircraft. It is likely that this trend will continue into the future.

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[1]John A. Harris, Jr. and M.C. Van Wanderham, Retirement for Cause of the F100 Engine, West Palm Beach, FL, Pratt & Whitney, Advanced Engineering Operations, p. 528.

RFC and the F100 Engine

Plagued with critical life-limited F100 engine part failures in the 1970's, the USAF developed a new life management philosophy in the mid-1980's. This development effort was to provide the basis for eliminating the classical "safe life" life management philosophy. In its place a new system for retiring critical, life-limited rotating engine parts was to be inserted. In this system, a component would be retired from service when the economical safe life of that individual component was exhausted. A component's economical safe, useful life would be based on the unique cyclic life of that component, and not on a B.1 life for a population of parts of a specific type. A B.1 life dictates retirement of all parts in a population at a predetermined cyclic count, regardless of condition. Under this new system, individual parts would be removed from service when there is a specific reason (or cause) for retirement.

Retirement for Cause (RFC) was the result of the above development effort. RFC is a life management methodology that allows each individual component to be used to the full extent of its crack initiation fatigue life. Using an appropriately designed interval, life-limited parts are inspected. When a defect of a given size is detected, the component is removed from service. Fracture mechanics analysis of a part (with consideration given to material and geometry), the service cycle, and the overhaul/inspection interval determine the defect size at which the component is no longer considered safe for use.

In order to put the RFC methodology into practice the process by which fatigue eventually (if ignored) leads to part failure must be understood. This process is illustrated in Figure 3. For a period of time after a new part

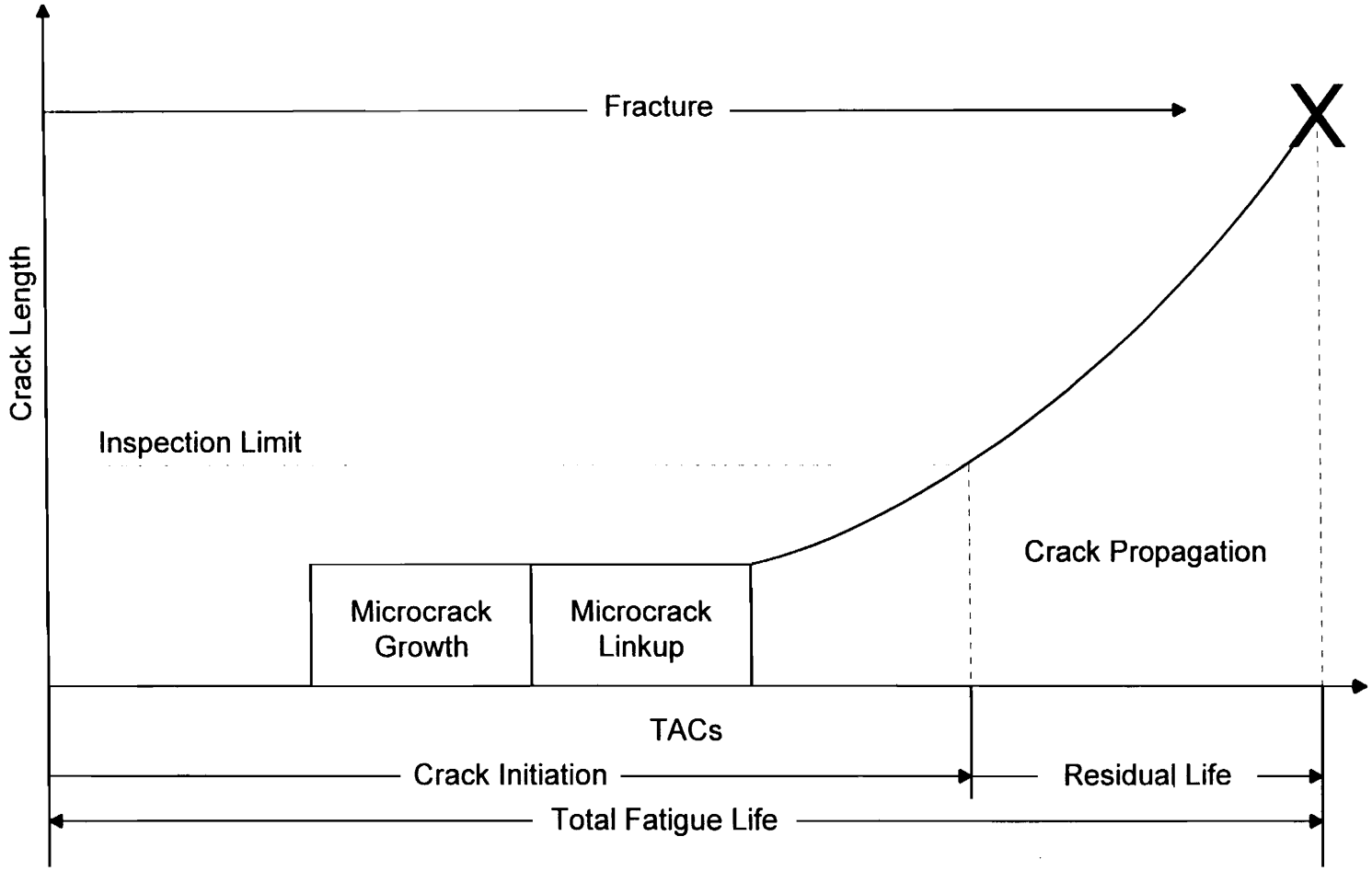

Figure 3: The Fatigue Process

is put into service, it operates with no cracking at all. Then, small microcracks begin to form. Next, these microcracks start to grow in size and link up with each other. The microcracks continue to propagate until, finally, they reach a size which is detectable. Presumably, this point would be the non-destructive inspection (NDI) limit in an RFC program. In any event, the point where a crack is large enough to be detected marks the end of the Crack Initiation Phase and the start of the Crack Propagation Phase in the fatigue process. If the part is allowed to continue to operate until completion of the crack propagation phase, part failure will result. Part failure occurs when the combination of the crack size and the operating stresses within the part exceed the material fracture toughness. The study of crack propagation is known as Fracture Mechanics.

Since failure of an engine rotating structural component leads to catastrophic engine failure and possibly loss of life and/or the aircraft, it must be avoided. However, there are many uncertainties in the life prediction process. There can be error or uncertainty in the stress analysis and models. The same can be said of the predicted temperature distributions and temperature models or any other analytical models. Also, part-to-part variation due to normal manufacturing variations introduce uncertainty into the life prediction equation. Perhaps the most uncertain variable is the field mission definition. Given all these uncertainties and the fact that all fatigue data have inherent fatigue initiation life scatter that may span two or more orders of magnitude[2], how are cataclysmic material failures best prevented? The safe life philosophy seeks to insure zero part failures by choosing a point

[2]J.A. Harris, Jr., et al., Concept Definition: Retirement for Cause of F100 Rotor Components, West Palm Beach, FL, Pratt & Whitney Aircraft Group, Government Products Division, September 1980, p. 9

at the lower end of the crack initiation distribution (i.e., the B.1 life) as the point at which to retire all parts.

How then, in the RFC system, is part integrity assured? How can the remaining life after the B.1 limit be safely extracted and used? Well, substantial consideration must be given to the determination of the return to service (RTS) interval. The RTS interval is the number of TACs between inspections. The value for this interval must be a balance of the cumulative cost of inspecting too frequently (too short of an interval) and the high cost of part failure (too long of an interval).

The crack propagation interval for each critical location on a part is determined by fracture mechanics. When choosing the RTS interval the assumption is made that a crack exists at the time of the inspection that is just smaller than the capability of the inspection to detect. A typical RTS interval for a component is one-half the smallest crack propagation interval on that part. As can be seen in Figure 4, if the part is found not to have any detectable cracks, then it is returned to service for another RTS interval. When a crack is detected and confirmed, then the part is retired from service.

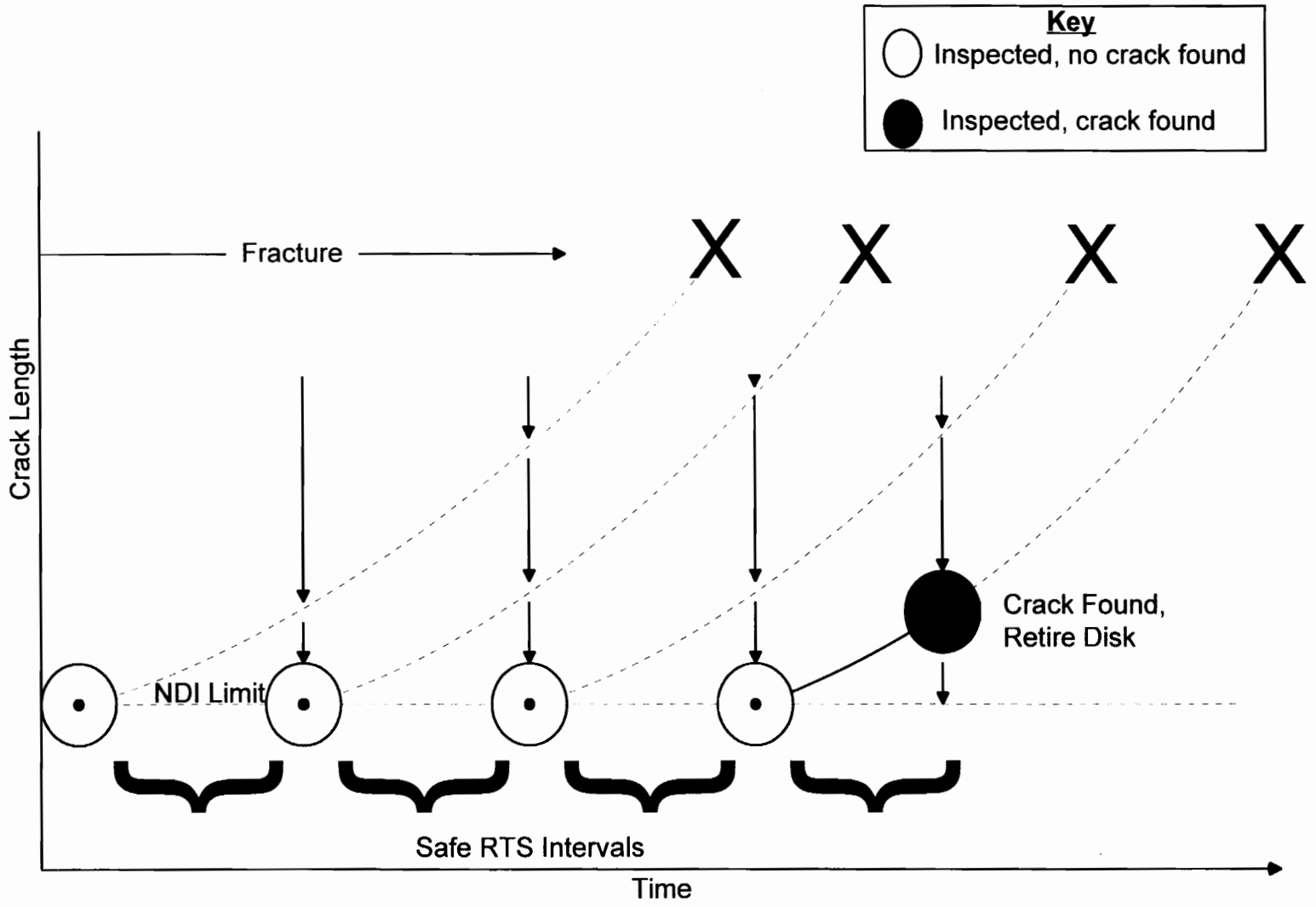

Figure 4: Return-to-Service Intervals

The F-14 Aircraft

In January, 1968 the Naval Air Systems Command recognized that the USAF F-111 could not be adapted for carrier operations and made a decision to pursue the development of a new fighter aircraft to combat the evolving USSR threat. A Request for Proposal was quickly issued, and proposals were received from five prominent aircraft manufacturers. In January, 1969 Grumman Aerospace Corporation was awarded a contract for the new F-14A.

Development, mock-up, and flight test proceeded at a rapid pace, and in May, 1972 Grumman delivered the first F-14A aircraft to the USN fleet. Over 500 aircraft have been manufactured since that time, most of which are still in operation today.

In November, 1987 a dramatically improved F-14A was delivered to the USN fleet. This aircraft was first designated as the F-14A(PLUS), and later as the F-14B. The most substantial improvement in this new aircraft was the incorporation of two General Electric F110-GE-400 turbofan engines as replacements to the original Pratt & Whitney TF-30 engines. The F110-GE-400 engines provided the F-14B with thirty percent more thrust and stall-free engine operation throughout the flight envelope.

In the early 1990's the F-14D was introduced to the USN inventory. This aircraft was also powered by F110-GE-400 engines. This aircraft offers significant improvements over the previous models by incorporation of a new state-of-the-art digital avionics system, a digital processing air-to-air radar system that is more advanced and more powerful than any other system in the world today, and a passive detection infrared search and track system.

The F110-GE-400 Engine

The F110-GE-400 engine (shown in Figure 5) is a dual rotor, mixed flow, augmented, turbofan engine. At its maximum rating (with full afterburner engaged) it produces 26,950 pounds of thrust at sea level, static conditions. The two rotor systems (one high pressure and one low pressure) are aerodynamically coupled, but are mechanically independent. The low pressure rotor system consists of three fan stages driven by a two-stage turbine. Variable inlet guide vanes (IGVs) are used on the fan. The high pressure system is made up of a nine-stage axial compressor which is driven by a one-stage turbine. The compressor utilizes variable inlet guide vanes and variable stator vanes on the first three stages.

The combustion chamber is a vaporizing, through-flow annular type with two spark igniters. The high pressure turbine is air-cooled, but the low pressure turbine is not. Support for the high pressure turbine rotor system is provided by two main bearings, while support for the low pressure system is provided by three. The augmenter has a daisy-type mixer and a variable area nozzle with a contoured exterior for drag reduction.

During operation of the engine, air is directed into the fan by the fan IGVs. The IGVs control airflow quantity and intake angle. The air passing through the fan is pressurized to a pressure ratio of 3.22:1 (at sea level, static conditions) and is sent into the engine core and into the annular fan duct.

The air that enters the core is further pressurized to a pressure ratio of 9.29:1 (at sea level, static conditions) for an overall compression pressure ratio of 29.9:1 (at sea level, static conditions). Air exits the compressor and is mixed with fuel sprayed from twenty fuel nozzles in the combustion

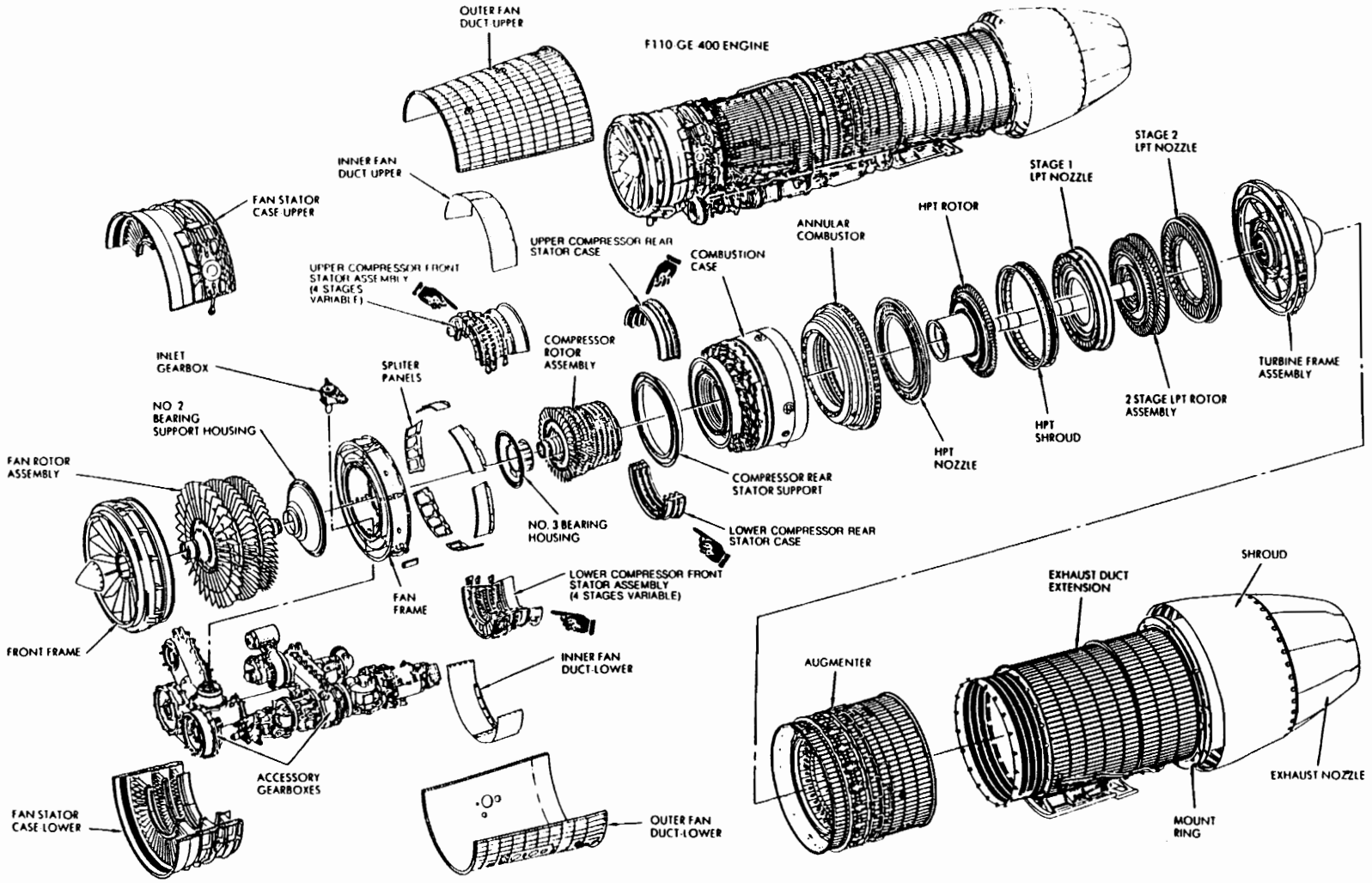

Figure 5: The F110-GE-400 Turbofan Engine

chamber. Hot gases from the combustion process expand through the turbine sections powering the fan and compressor. These gases continue to move past the turbine sections and into the augmentation chamber where they are mixed with air from the annular fan duct. During operation of the augmenter additional fuel is sprayed into this gas stream and ignited for additional thrust. The variable exhaust nozzle controls the exhaust gas expansion for improved thrust efficiency. Engine operation is maintained by controlling the high pressure rotor speed to balance aerodynamic and thermodynamic conditions.

Candidate Parts for the RFC System

The 22 critical, life-limited F110-GE-400 engine components and the material from which they are constructed are listed in Table 1. As can be seen from the table, the fan disks are all made from titanium, the high pressure compressor (HPC) components from titanium or inconel, the combustion case from inconel, the high pressure turbine (HPT) components mainly from Rene 95, and the low pressure turbine (LPT) components mostly from inconel or DA 718.

The cost listed for the each of the components in the table is the price that the Aviation Supply Office (ASO) would pay to the manufacturer of the part, plus 28 percent. Twenty-eight percent is the standard mark-up that ASO charges the USN fleet for the parts that it supplies. These prices do fluctuate with time and the quantity ordered, but the ones given in Table 1 are the prices the fleet would pay in January 1995 if they were to place an order. It should also be noted that ASO generally charges significantly more than a 28 percent surcharge for the components in the HPT and the LPT and for the combustion case assembly because of the large number of piece parts that are included in the purchase of these components. For conservatism and consistency, however, a 28 percent surcharge was assumed throughout this study.

The same components that were listed in Table 1 are enumerated again in the first column of Table 2. Table 2 summarizes the evaluation process that led to the determination of the feasibility of each of the candidates for participation in the RFC system. The next four columns in the table provide the calculated LCF life (i.e., the B.1 life), the corresponding removal interval as specified by the USN F110-GE-400 engine Periodic

Table 2: RFC Feasibility Worksheet

Part Nomenclature	Calc LCF Life	PMIC Removal as of JAN 95	Calc Average Propagation Int	Calc Minimum Propagation Int	Comment (RFC feasability)
Fan Rotor Assembly					
1st Stage Fan Disk	10,000 TAC	10,000 TAC	3,700 TAC	1,850 TAC	YES, inspect every 3000 TAC (see Note 1)
2nd Stage Fan Disk	6,300 TAC	6,300 TAC	6,900 TAC	3,450 TAC	YES, inspect every 3000 TAC
3rd Stage Fan Disk	2,200 TAC	6,000 TAC	5,950 TAC	2,975 TAC	YES, inspect every 3000 TAC
Rear Fan Shaft	100,000 TAC	100,000 TAC	28,000 TAC	14,000 TAC	NO, LCF life greater than system life
Compressor Rotor Assembly					
1st & 2nd Stage Spool	23,900 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
Forward Shaft Stub	38,000 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
3rd Stage Compressor Disk	62,400 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
4th - 9th Stage Spool	12,700 TAC	12,000 TAC	unknown	unknown	NO, LCF life approx same as sys life
Rotating Compressor Air Seal	24,300 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
Combustion Case Assembly	1,725 TAC	6,000 TAC	10,320 TAC	2,580 TAC	YES, inspect every 3000 TAC (see Note 2)
HPT Rotor Assembly					
HPT Forward Shaft	6,460 TAC	6,460 TAC	unknown	unknown	
HPT Forward Rotating Seal (M22)	4,100 TAC	4,100 TAC	680 TAC	340 TAC	NO, very low residual life
HPT Forward Rotating Seal (M90)	4,000 TAC	4,000 TAC	unknown	unknown	NO, very low residual life
HPT Forward Rotating Seal (M48)	15,000 TAC	15,000 TAC	unknown	unknown	NO, LCF life greater than system life
HPT Forward Blade Retainer	8,000 TAC	8,000 TAC	unknown	unknown	NO, residual life unknown
HPT Disk	7,600 TAC	7,600 TAC	1,900 TAC	950 TAC	NO, very low residual life
HPT Aft Blade Retainer (P05)	5,700 TAC	5,700 TAC	unknown	unknown	NO, residual life unknown
HPT Aft Blade Retainer (P03)	6,000 TAC	6,000 TAC	unknown	unknown	NO, residual life unknown
HPT Aft Shaft	69,000 TAC	69,000 TAC	7,800 TAC	3,900 TAC	NO, LCF life greater than system life
LPT Rotor Assembly					
LPT 1st Stage Disk	28,300 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
LPT 1st Stage Blade Retainer	5,620 TAC	4,000 TAC	unknown	unknown	NO, residual life unknown
LPT 2nd Stage Disk	51,300 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
LPT 2nd Stage Blade Retainer	8,090 TAC	8,000 TAC	unknown	unknown	NO, residual life unknown
LPT Shaft	41,400 TAC	16,000 TAC	unknown	unknown	NO, LCF life greater than system life
LPT Seal Spacer	3,750 TAC	4,000 TAC	unknown	unknown	NO, residual life unknown

Note 1: Inspect every 1500 TAC starting at 9000 TAC
Note 2: Min residual life exceeded slightly due to non-severe failure mode

Maintenance Information Cards (PMIC), the calculated average propagation life once a detectable crack has formed, and the associated calculated minimum crack propagation life for each of the parts.

The LCF lives and the crack propagation lives for the fan rotor, combustion case, and the HPT rotor (excluding the forward shaft) were updated in June 1994 based on several improvements. First, the operating conditions surrounding the component were revised based on new and more detailed mission profiles collected in 1993 via pilot interviews and actual measured flight data. Second, the analysis took advantage of analytical updates in the stress and thermal models. Finally, updates to General Electric's Life Analysis by Stress and Temperature Simulation (LASTS) program were incorporated. The LASTS program is General Electric's software for combining all of the information necessary to determine part lives and for generating the final part life numbers.

All of the known HPC and LPT lives as well as the life of the HPT forward shaft are based on dated mission profiles and analytical techniques. In fact, there is a known and significant difference between the 1993 mission profile data and the previous mission profile data which was generated in 1989 from computer simulations. The work to calculate the updated lives for these components is currently in progress with a scheduled completion date of June 1995.

F110-GE-400 Engine TAC Distribution

The fleet TAC distribution as of January 1, 1995 is shown in Figure 6. This distribution is a result of varying engine entry-into-service dates, maintenance requirements, and usage among the fleet operators. Currently,

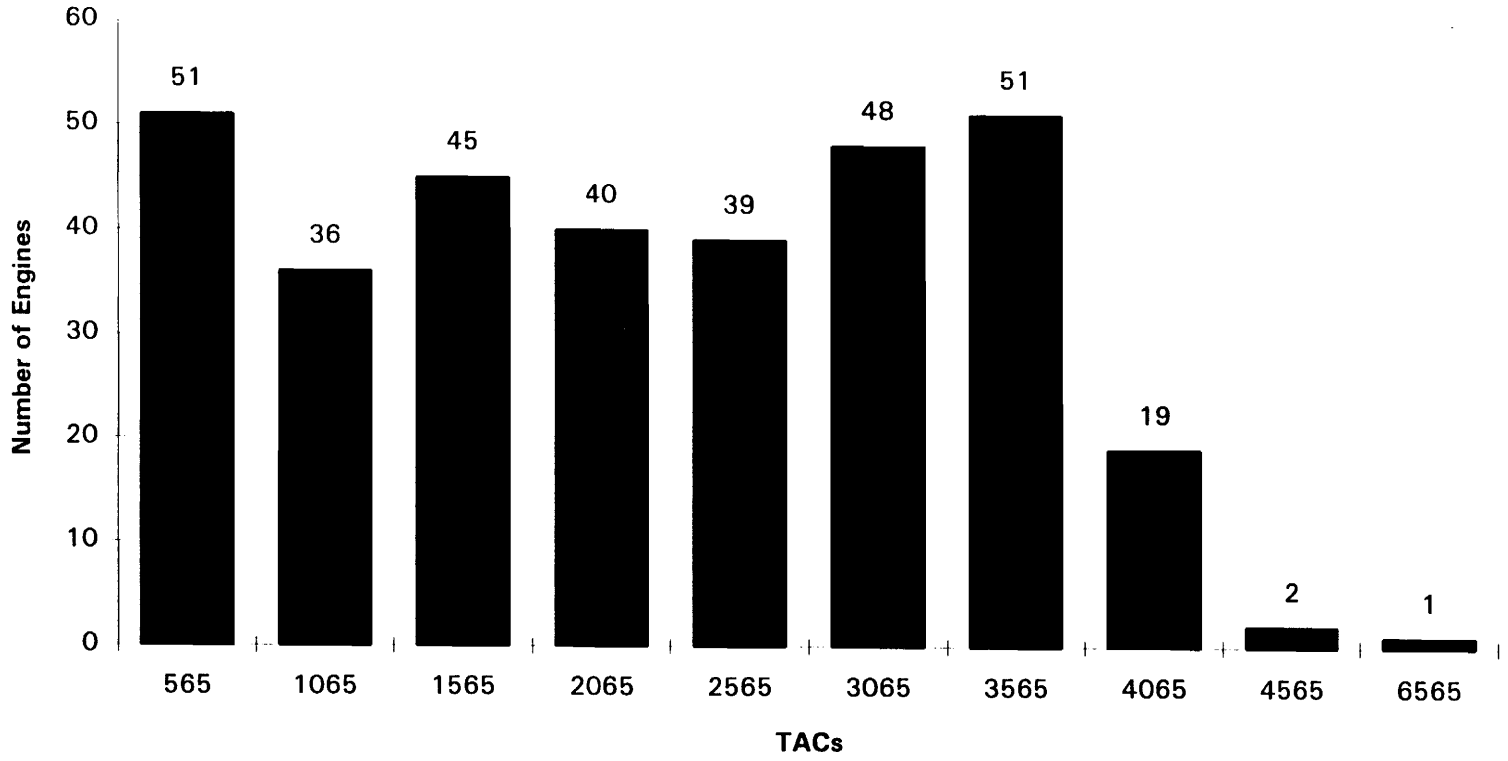

Figure 6: F110-GE-400 Engine TAC Distribution

the fleet is averaging 45 TACs per month. A distribution for each year up until system retirement is given in Table 3.

The Elimination Process

The first step in determining which parts might be feasible for participation in the RFC system was to eliminate from consideration all parts that have an LCF life longer than that of the F-14B/D system. On average, the F110-GE-400 engines have accumulated 2235 TACs ± 250 TACs as of January 1, 1995. The remaining service life of the F-14B/D is 16 years, and the fleet is currently averaging 25 flight hours per month. Since there are 1.8 TACs per flight hour, the average engine in the fleet is accumulating 45 TACs per month. Over the next 16 years, the average engine will accrue an additional 8,640 TACs.

Based on the above, in 2010 when the F14B/D retires, the average engine life usage will be 10,875 TACs ± 250 TACs. The engine life usage TAC distribution, however, will range from 9,205 to 15,205 TACs ± 250 TACs. Interestingly, the distribution is such that only 3 engines will have accumulated more than 12,705 TACs ± 250 TACs (i.e., 12,705 + 250 = 12,955 TACs at most). This result was rounded to 13,000 TACs and was set as the cut off point for RFC system feasibility. All parts with a B.1 life greater than 13,000 TACs were eliminated from the RFC candidate list. The final column in Table 2 indicates which parts were removed from the candidate list for having an LCF life greater than that of the anticipated system life.

The next step in the feasibility determination process was to evaluate the residual lives of the remaining candidates. All parts for which the

Table 3: F110-GE-400 Engine TAC Distribution

QTY ENGINES	END CY 1994	END CY 1995	END CY 1996	END CY 1997	END CY 1998	END CY 1999	END CY 2000	END CY 2001	END CY 2002
51	565	1105	1645	2185	2725	3265	3805	4345	4885
36	1065	1605	2145	2685	3225	3765	4305	4845	5385
45	1565	2105	2645	3185	3725	4265	4805	5345	5885
40	2065	2605	3145	3685	4225	4765	5305	5845	6385
39	2565	3105	3645	4185	4725	5265	5805	6345	6885
48	3065	3605	4145	4685	5225	5765	6305	6845	7385
51	3565	4105	4645	5185	5725	6265	6805	7345	7885
19	4065	4605	5145	5685	6225	6765	7305	7845	8385
2	4565	5105	5645	6185	6725	7265	7805	8345	8885
1	6565	7105	7645	8185	8725	9265	9805	10345	10885
avg eng	2235	2775	3315	3855	4395	4935	5475	6015	6555

QTY ENGINES	END CY 2003	END CY 2004	END CY 2005	END CY 2006	END CY 2007	END CY 2008	END CY 2009	END CY 2010
51	5425	5965	6505	7045	7585	8125	8665	9205
36	5925	6465	7005	7545	8085	8625	9165	9705
45	6425	6965	7505	8045	8585	9125	9665	10205
40	6925	7465	8005	8545	9085	9625	10165	10705
39	7425	7965	8505	9045	9585	10125	10665	11205
48	7925	8465	9005	9545	10085	10625	11165	11705
51	8425	8965	9505	10045	10585	11125	11665	12205
19	8925	9465	10005	10545	11085	11625	12165	12705
2	9425	9965	10505	11045	11585	12125	12665	13205
1	11425	11965	12505	13045	13585	14125	14665	15205
avg eng	7095	7635	8175	8715	9255	9795	10335	10875

residual life had never been calculated were removed from the candidate list. Then, the parts with very low residual lives (which would necessitate very frequent inspections) were removed. The final column in Table 2 also indicates which parts were removed for these reasons. The remaining parts were the combustion case and all three fan disks.

Determination of the RTS Interval

The "Calculated Minimum Propagation Interval" column in Table 2 shows the generally accepted RTS interval. The values in this column are 1/2 the average propagation interval for the fan disks and 1/4 the average propagation interval for the combustion case. The minimum interval for the combustion case is 1/4 the average vice 1/2 the average because crack growth testing for Cast and Hip Inconel 718 shows scatter from average to minimum of 4 instead of the usual 2.

If the objective was simply to choose an inspection interval for a single component, then the minimum propagation interval for each part would probably be accepted as its inspection interval. Implementing such an approach would mean engine removal, engine tear down, and component inspection at 1850 TACs, then again 730 TACs later, again 395 TACs later, again 475 TACs later, and again 250 TACs later. Clearly, such an approach would paralyze F-14 flight operations.

A more integrated approach that views the engine as a whole and standardizes the inspection intervals for all 4 components is required. One approach might be to standardize the inspection interval for all 4 components at the lowest of the individual part RTS intervals (i.e., 1850 TACs). Although this approach is undoubtedly the most conservative, it was not

chosen. Instead an inspection interval of 3000 TACs was chosen. This RTS interval is slightly conservative for the second stage fan disk and is almost equivalent to the individual RTS interval for the third stage fan disk. However, 3000 TACs is greater than the minimum propagation lives for the first stage fan disk and the combustion case.

A slightly modified approach was chosen for the first stage fan disk that requires inspection every 3000 TACs up to and including the 9000 TAC inspection. Then, starting at 10,500 TACs, inspection is required every 1,500 TACs. The rationale on which this approach is founded takes advantage of the long LCF (B.1) life of the first stage disk. Based on the disk's LCF life of 10,000 TACs, no cracks should be detectable prior to 10,000 TACs. Also considered when formulating this approach was the fact that, due to the fleet TAC distribution, many engines will not reach 10,500 TACs prior to system retirement.

The decision to accept a 3000 TAC interval vice a 2,580 TAC interval for the combustion case was based wholly on the non-severe failure mode of this part. Failure of this part leads only to performance loss, not catastrophic failure as for the fan disks. The deviations from the generic RFC methodology discussed above are necessary to minimize the impact on engine, component, and man power availability. Failure analysis presented later in this report substantiates the chosen intervals for all 4 components.

Critical Locations and Flaws

Before proceeding further, a discussion of the critical locations and the corresponding detectable flaw sizes is warranted. Table 4 identifies all of the life limiting locations for each of the 4 parts identified for participation

Table 4: F110-GE-400 Engine Fan Disks & Combustion Case Critical Life Limited Locations and Associated Flaw Size

Critical Location	LCF Life (TACs)	Residual Life (TACs)	Flaw Size (mils)
First Stage Fan Disk			
Balance Pad Hole	14,000	10,000	10 x 30
Arm to Rim Fillet	43,000	8,100	10 x 30
Arm to Bore Fillet	>100,000	55,000	10 x 30
Dovetail Slot	10,000	3,700	10 x 30
Bore	10,000	3,800	10 x 30
Second Stage Fan Disk			
Forward Flange Bolt Hole	9,800	7,600	17.5 x 17.5
Forward Flange Scallop	28,000	6,799	17.5 x 17.5
Bore	23,000	4,500	17.5 x 17.5
Web	49,000	10,000	10 x 30
Dovetail Slot	6,300	6,900	10 x 30
Aft Flange Bolt Hole	>100,000	75,000	17.5 x 17.5
Third Stage Fan Disk			
Forward Flange Bolt Hole	19,000	8,400	17.5 x 17.5
Oil Drain Hole	6,600	4,100	10 x 30
Bore	29,000	5,000	17.5 x 17.5
Web	50,000	10,000	10 x 30
Dovetail Slot	2,200	5,950	10 x 30
Combustion Case			
Forward Flange Bolt Hole	4,400	41,000*	17.5 x 17.5
CDP Bleed Pad Aft Bolt Hole	1,800	14,000*	17.5 x 17.5
CDP Bleed Pad Fillet	1,725	10,320*	10 x 30
Inner Flange Bolt Hole	3,700	82,000*	17.5 x 17.5
Fuel Nozzle Pad Bore	3,100	13,000*	17.5 x 17.5
Ignitor Pad Bore	3,600	19,000*	17.5 x 17.5
Mid Flange Bolt Hole	3,200	8,000	17.5 x 17.5
Aft Cylinder Axial Weld	20,000	N/A	N/A

NOTES: Minimum residual life is 1/2 average residual life except as noted below.
*Minimum residual life is 1/4 average residual life.

in the RFC system. These same locations are also shown in the fan and combustion case diagrams presented in Figures 7 and 8, respectively. The locations specified are primarily areas having a stress riser such as a bolt hole, fillet radius, or a dovetail slot. Figure 9 presents a few sketches of typical rotor component flaw types.[3] It should be noted that the term "blade slot" that is used in the figure is equivalent to the "dovetail slot" term typically used in this report. Both terms refer to the slots in the disk where the blades are attached.

Each life limiting location has an associated crack initiation and crack propagation life as well as a detectable flaw size. It is important to note that the critical location on each part with the smallest minimum crack propagation life was used as the life limiting location for the part in the RFC system part feasibility analysis presented above. Critical locations having an LCF life greater than the anticipated system life of 13,000 TACs but a small minimum crack propagation life (e.g., the stage two fan disk bore) were not, however, considered during the RTS interval determination.

The only exception to the practice of using the smallest minimum crack propagation interval in order to determine the RTS interval was with the treatment of the third stage fan disk oil drain hole. The minimum crack propagation life at this location on the third stage disk is less than at the location used to determine the RTS interval (the dovetail slot). Since there was not enough information available to do a complete analysis of the oil drain hole and since the LCF life at the oil drain hole was 3 times greater than the LCF life at the dovetail slot, the dovetail slot was used as the life-limiting location for the third stage fan disk.

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[3]Harris, et al., Concept Definition: Retirement for Cause of F100 Rotor Components, p. 21.

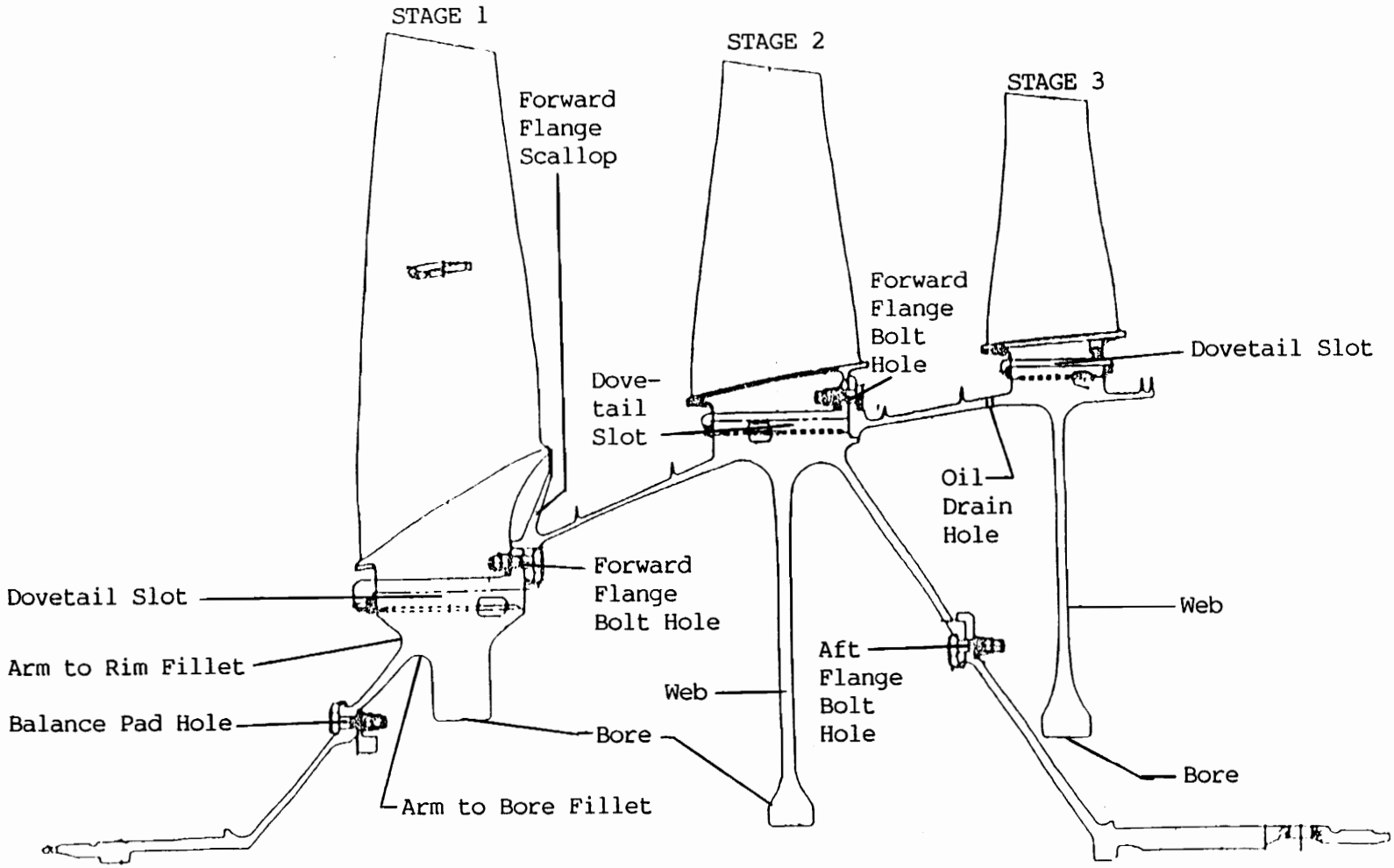

Figure 7: The F110-GE-400 Fan Rotor Assembly

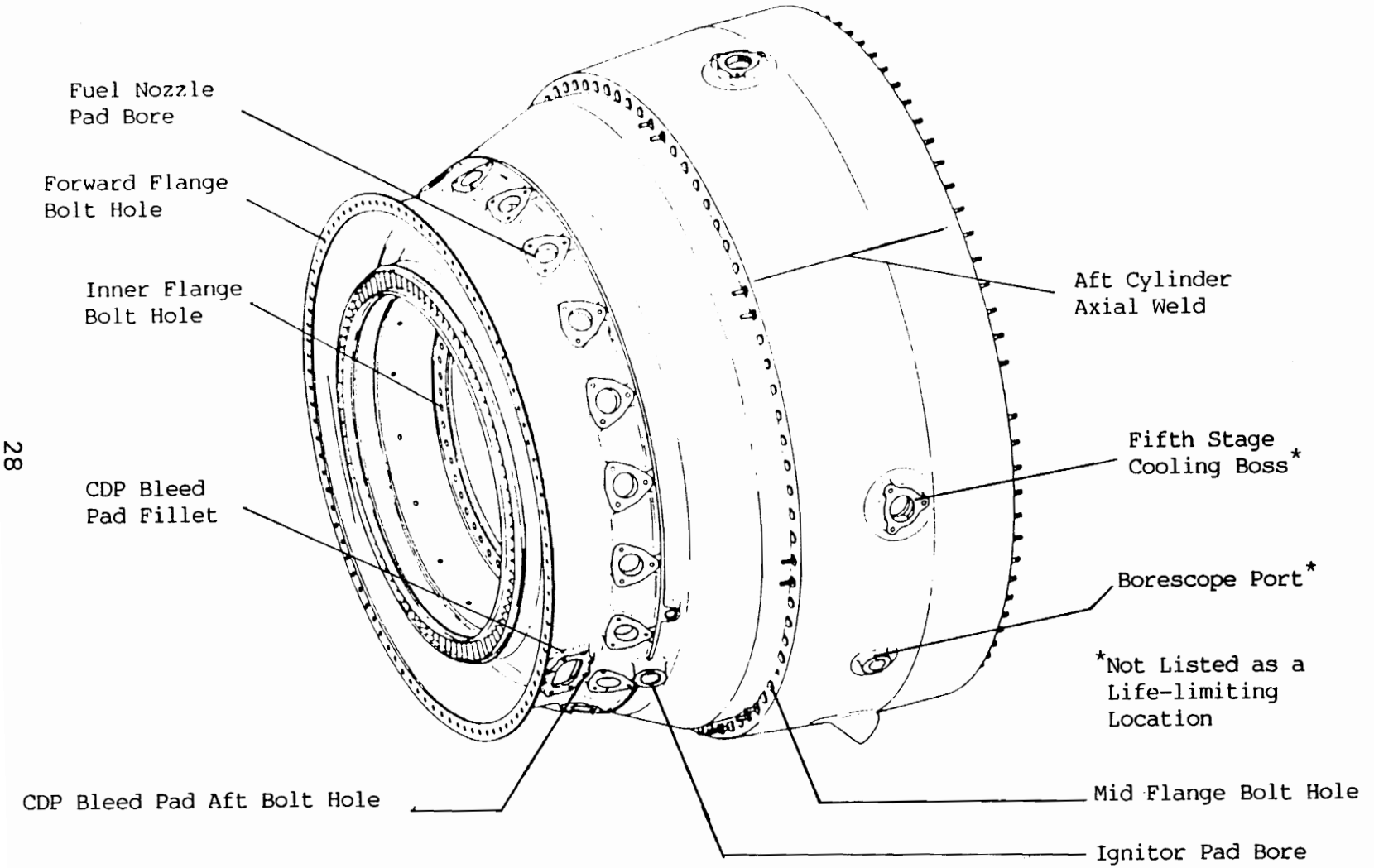

Figure 8: The F110-GE-400 Engine Combustion Case

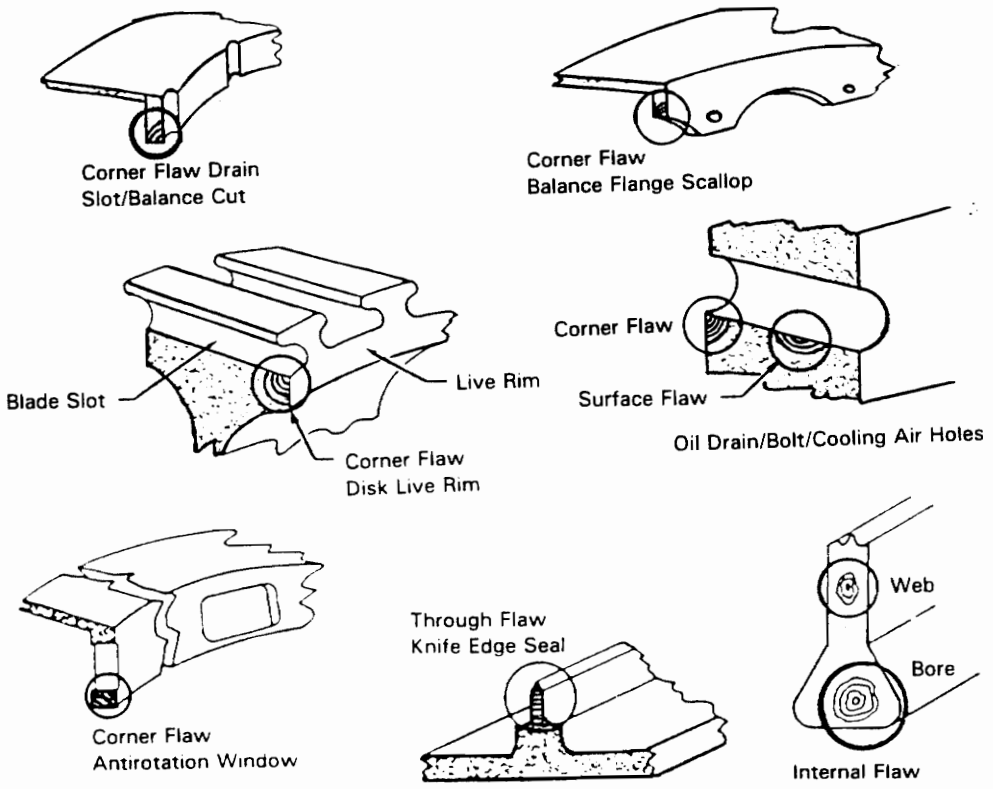

Figure 9: Typical Rotor Component Flaw Types and Locations

RFC System Inspection Scrap Rate

Now that the components that will participate in the RFC system have been selected, the inspection interval specified, and the critical locations and flaw types identified, a determination must be made of how many components will be found to have a crack when inspected. Table 5 (a)-(d) was constructed during the analysis of this question. Each one of the four tables yields a "Scrap Rate Profile" for one of the components.

All four tables were constructed in an identical manner, with the only exception being the 1,500 TAC interval for the first stage fan disk beginning after 9,000 TACs. The calculations are based on the standardized normal probability distribution. Since the normal curve is symmetric about the mean, the table of areas consulted for the standardized normal probability distribution[4] was a simplified listing, giving only the areas between zero and a specified number of standard deviations Z_o to the right of the mean. The areas in the table represent the probability that Z falls between zero and a given Z_o. The area between zero and a positive Z_o and the area between zero and a negative Z_o of the same absolute value are identical. Figure 10 illustrates.

Given that the LCF life is the point on the normal distribution that corresponds to 1 failure in a thousand, the area under the standardized normal distribution representing a failure is 0.0010. Using a standardized normal probability distribution table, the area representing the non-failures is

[4]William Mendenhall, et al., Statistics for Management and Economics, Boston, MA, PWS-Kent Publishing Company, 1989, p. 1040.

Table 5(a): Component Scrap Rate Profiles

1st Stage Fan Disk	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6	Inspect#7	Inspect#8
Original Parts											
TACs	2751	18501	10000	0	3000	6000	9000	10500	12000	13500	15000
Zo (the X of the normalized std distr)			3.09	-6.73	-5.63	-4.54	-3.45	-2.91	-2.36	-1.82	-1.27
P(0< =Z< =Zo)			0 4990	0.5000	0.5000	0.5000	0.5000	0.4982	0.4909	0.4656	0.3980
P(Z< =Zo)			0 0010	0.0000	0.0000	0.0000	0.0000	0.0018	0.0091	0.0344	0.1020
No. cracked parts (if only one inspection)				0.0000	0.0000	0.0000	0.0000	0.5976	3.0212	11.4208	33.8640
Rounded (No. cracked parts if one inspect)				0	0	0	0	1	3	11	34
No. of parts cracked during inspection int				0	0	0	0	1	2		
Parts (engines) not reaching next interval			0	0	0	0	132	127	70		
Parts requiring inspection at next interval			332	332	332	332	200	72	0		
Parts intro'ed at 10500 TAC											
TACs	2751	18501	10000					0	3000	6000	9000
Zo (the X of the normalized std distr)								-6.73	-5.63	-4.54	-3.45
P(0< =Z< =Zo)								0.5000	0.5000	0.5000	0.5000
P(Z< =Zo)								0.0000	0.0000	0.0000	0.0000
No. cracked parts (if only one inspection)								0.0000	0.0000	0.0000	0.0000
Rounded (No. cracked parts if one inspect)								0	0	0	0
No. of parts cracked during inspection int								0	0		
Parts (engines) not reaching next interval								0	1		
Parts requiring inspection at next interval							1	1	0		
Parts intro'ed at 12000 TAC											
TACs	2751	18501	10000						0	3000	6000
Zo (the X of the normalized std distr)									-6.73	-5.63	-4.54
P(0< =Z< =Zo)									0.5000	0.5000	0.5000
P(Z< =Zo)									0.0000	0.0000	0.0000
No. cracked parts (if only one inspection)									0.0000	0.0000	0.0000
Rounded (No. cracked parts if one inspect)									0	0	0
No. of parts cracked during inspection int									0	0	0
Parts (engines) not reaching next interval									1	0	0
Parts requiring inspection at next interval								2	1	1	1
Total parts insp at next int			332	332	332	332	200	72	1	1	1

Table 5(b): Component Scrap Rate Profiles

2nd Stage Fan Disk	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6
Original Parts									
TACs	2751	14801	6300	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-5.38	-4.29	-3.20	-2.11	-1.02	0.07
P(0 < = Z < = Zo)			0.4990	0.5000	0.5000	0.5000	0.4826	0.3461	0.0279
P(Z < = Zo)			0.0010	0.0000	0.0000	0.0000	0.0174	0.1539	0.5279
No cracked parts (if only one inspection)				0.0000	0.0000	0.0000	5.7768	51.0948	175.2628
Rounded (No. cracked parts if one inspect)				0	0	0	6	51	175
No. of parts cracked during inspection int				0	0	0	6	45	
Parts (engines) not reaching next interval			0	0	0	0	259	22	
Parts requiring inspection at next interval			332	332	332	332	67	0	
Parts intro'ed at 9000 TAC									
TACs	2751	14801	6300				0	3000	6000
Zo (the X of the normalized std distr)							-5.38	-4.29	-3.20
P(0 < = Z < = Zo)							0.5000	0.5000	0.5000
P(Z < = Zo)							0.0000	0.0000	0.0000
No. cracked parts (if only one inspection)							0.0000	0.0000	0.0000
Rounded (No. cracked parts if one inspect)							0	0	0
No. of parts cracked during inspection int							0	0	
Parts (engines) not reaching next interval							0	6	
Parts requiring inspection at next interval						6	6	0	
Parts intro'ed at 12000 TAC									
TACs	2751	14801	6300					0	3000
Zo (the X of the normalized std distr)								-5.38	-4.29
P(0 < = Z < = Zo)								0.5000	0.5000
P(Z < = Zo)								0.0000	0.0000
No. cracked parts (if only one inspection)								0.0000	0.0000
Rounded (No. cracked parts if one inspect)								0	0
No. of parts cracked during inspection int								0	0
Parts (engines) not reaching next interval								44	0
Parts requiring inspection at next interval							45	1	1
Total parts insp at next int			332	332	332	332	73	1	1

Table 5(c): Component Scrap Rate Profiles

3rd Stage Fan Disk	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6
Original Parts									
TACs	2751	10700	2200	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-3.89	-2.80	-1.71	-0.62	0.47	1.56
P(0 < = Z < = Zo)			0.4990	0.5000	0.4974	0.4564	0.2324	0.1808	0.4406
P(Z < = Zo)			0.0010	0.0000	0.0026	0.0436	0.2676	0.6808	0.9406
No. cracked parts (if only one inspection)				0.0000	0.8632	14.4752	88.8432	226.0256	312.2792
Rounded (No. cracked parts if one inspect)				0	1	14	89	226	312
No. of parts cracked during inspection int				0	1	13	75		
Parts (engines) not reaching next interval			0	0	0	0	243		
Parts requiring inspection at next interval			332	332	331	318	0		
Parts intro'ed at 3000 TAC									
TACs	2751	10700	2200		0	3000	6000	9000	12000
Zo (the X of the normalized std distr)					-3.89	-2.80	-1.71	-0.62	0.47
P(0 < = Z < = Zo)					0.5000	0.4948	0.4049	0.0239	0.3810
P(Z < = Zo)					0.0000	0.0052	0.0951	0.4761	0.8810
No. cracked parts (if only one inspection)					0.0000	0.0052	0.0951	0.4761	0.8810
Rounded (No. cracked parts if one inspect)					0	0	0	0	1
No. of parts cracked during inspection int					0	0	0		
Parts (engines) not reaching next interval					0	0	1		
Parts requiring inspection at next interval				1	1	1	0		
Parts intro'ed at 6000 TAC									
TACs	2751	10700	2200			0	3000	6000	9000
Zo (the X of the normalized std distr)						-3.89	-2.80	-1.71	-0.62
P(0 < = Z < = Zo)						0.5000	0.4948	0.4049	0.0239
P(Z < = Zo)						0.0000	0.0052	0.0951	0.4761
No. cracked parts (if only one inspection)						0.0000	0.0676	1.2363	6.1893
Rounded (No. cracked parts if one inspect)						0	0	1	6
No. of parts cracked during inspection int						0	0		
Parts (engines) not reaching next interval						0	13		
Parts requiring inspection at next interval					13	13	0		
Parts intro'ed at 9000 TAC									
TACs	2751	10700	2200				0	3000	6000
Zo (the X of the normalized std distr)							-3.89	-2.80	-1.71
P(0 < = Z < = Zo)							0.5000	0.4948	0.4049
P(Z < = Zo)							0.0000	0.0052	0.0951
No. cracked parts (if only one inspection)							0.0000	0.3900	7.1325
Rounded (No. cracked parts if one inspect)							0	0	7
No. of parts cracked during inspection int							0	0	
Parts (engines) not reaching next interval							2	72	
Parts requiring inspection at next interval						75	73	1	
Total parts insp at next int			332	332	332	332	73	1	

Table 5(d): Component Scrap Rate Profiles

Combustion Case	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6
Original Parts									
TACs	2404	9154	1725	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			3.09	-3.81	-2.56	-1.31	-0.06	1.18	2.43
P(0< =Z< =Zo)			0.4990	0.5000	0.4948	0.4049	0.0239	0.3810	0.4925
P(Z< =Zo)			0.0010	0.0000	0.0052	0.0951	0.4761	0.8810	0.9925
No. cracked parts (if only one inspection)				0.0000	1.7264	31.5732	158.0652	292.4920	329.5100
Rounded (No. cracked parts if one inspect)				0	2	32	158	292	330
No. of parts cracked during inspection int				0	2	30	126		
Parts (engines) not reaching next interval			0	0	0	0	174		
Parts requiring inspection at next interval			332	332	330	300	0		
Parts intro'ed at 3000 TAC									
TACs	2404	9154	1725		0	3000	6000	9000	12000
Zo (the X of the normalized std distr)					-3.81	-2.56	-1.31	-0.06	1.18
P(0< =Z< =Zo)					0.5000	0.4948	0.4049	0.0239	0.3810
P(Z< =Zo)					0.0000	0.0052	0.0951	0.4761	0.8810
No. cracked parts (if only one inspection)					0.0000	0.0104	0.1902	0.9522	1.7620
Rounded (No. cracked parts if one inspect)					0	0	0	1	2
No. of parts cracked during inspection int					0	0	0		
Parts (engines) not reaching next interval					0	0	2		
Parts requiring inspection at next interval				2	2	2	0		
Parts intro'ed at 6000 TAC									
TACs	2404	9154	1725			0	3000	6000	9000
Zo (the X of the normalized std distr)						-3.81	-2.56	-1.31	-0.06
P(0< =Z< =Zo)						0.5000	0.4948	0.4049	0.0239
P(Z< =Zo)						0.0000	0.0052	0.0951	0.4761
No. cracked parts (if only one inspection)						0.0000	0.1560	2.8530	14.2830
Rounded (No. cracked parts if one inspect)						0	0	3	14
No. of parts cracked during inspection int						0	0		
Parts (engines) not reaching next interval						0	30		
Parts requiring inspection at next interval					30	30	0		
Parts intro'ed at 9000 TAC									
TACs	2404	9154	1725				0	3000	6000
Zo (the X of the normalized std distr)							-3.81	-2.56	-1.31
P(0< =Z< =Zo)							0.5000	0.4948	0.4049
P(Z< =Zo)							0.0000	0.0052	0.0951
No. cracked parts (if only one inspection)							0.0000	0.6552	11.9826
Rounded (No. cracked parts if one inspect)							0	1	12
No. of parts cracked during inspection int							0	1	
Parts (engines) not reaching next interval							53	72	
Parts requiring inspection at next interval						126	73	0	
Parts intro'ed at 12000 TAC									
TACs	2404	9154	1725					0	3000
Zo (the X of the normalized std distr)								-3.81	-2.56
P(0< =Z< =Zo)								0.5000	0.4948
P(Z< =Zo)								0.0000	0.0052
No. cracked parts (if only one inspection)								0.0000	0.0052
Rounded (No. cracked parts if one inspect)								0	0
No. of parts cracked during inspection int								0	0
Parts (engines) not reaching next interval								0	0
Parts requiring inspection at next interval							1	1	1
Total parts insp at next int			332	332	332	332	73	1	1

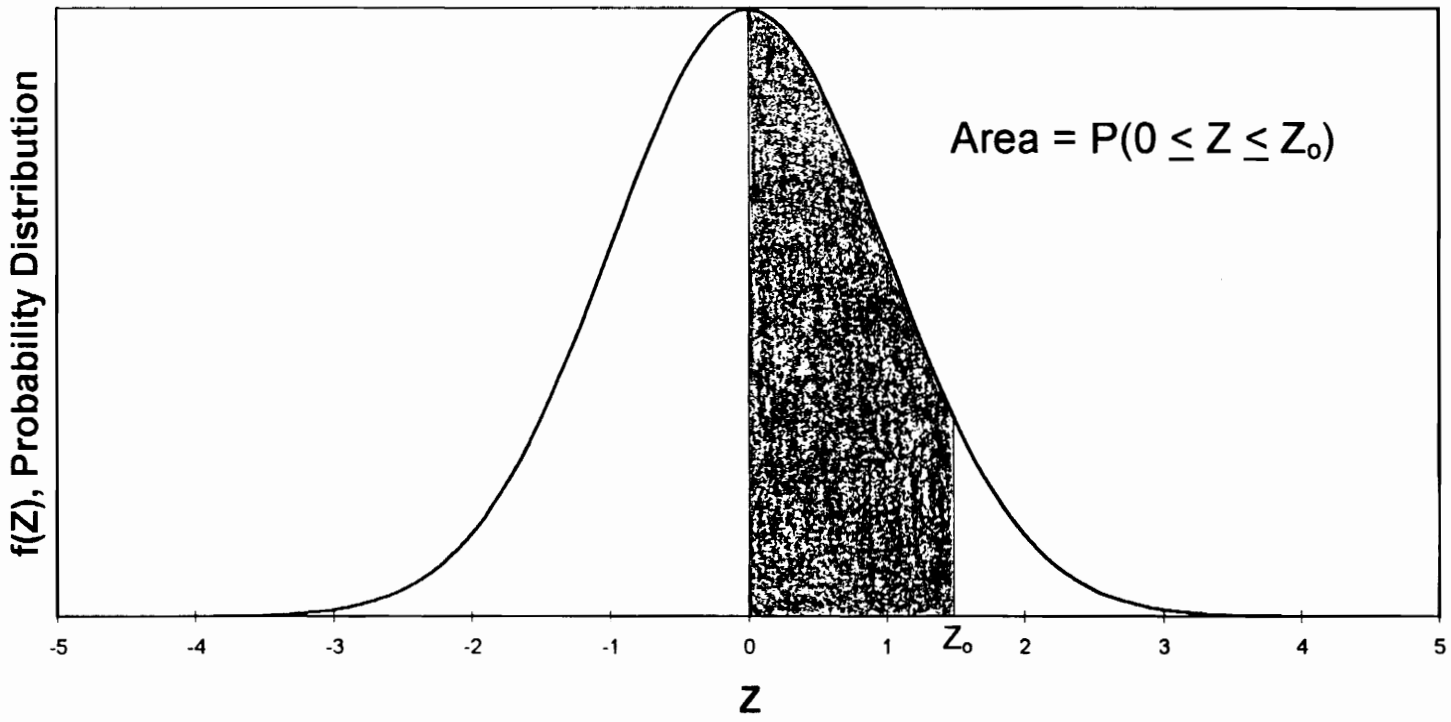

FIGURE 10: STANDARDIZED NORMAL DISTRIBUTION

0.4990 (or .9990 if the other side of the distribution is added to 0.4990). An area of 0.4990 corresponds to a Z_o[5] of 3.09.

The following equation is used to standardize given values of X_o[6] .

$$Z_o = \frac{X_o - \mu}{\sigma}$$

For application to this study:

- Z = the actual probabilistic life of a component in the standardized normal probability distribution
- Z_o = the calculated number of standard deviations on the standardized normal probability distribution corresponding to X_o
- X_o = the number of TACs on a component when it is inspected
- μ = the average crack initiation life (in TACs) of the component
- σ = the standard deviation (in TACs) corresponding to the distribution of crack initiation lives about μ

Using the third stage fan disk as an illustrative example (see Table 5(c)), the known information is the B.1 life and the average crack initiation life. Substituting these life numbers along with Z_o = 3.09 (corresponding X_o = B.1 life) into the above equation, and solving for σ yields the standard deviation for the crack initiation distribution. After determination of the standard deviation, the equation can be used to solve for the Z_o's corresponding to the number of TACs on the component when it is inspected (X_o), while μ and σ remain constant. The results from this effort are given on the second row of Table 5(c). The probability that the actual probabilistic

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[5]Ibid.

[6]Ibid, p. 238.

life of a component lies in the area between zero and the Z value corresponding to the number of TACs on the engine (Z_o) was obtained from the table of normal curve areas discussed above.

Having found the probability that $0 \leq Z \leq Z_o$, the probability that $Z \leq Z_o$ is obtained from the knowledge that:

(1) The total area under the standardized normal probability distribution is equal to 1.

(2) There is equal area on each side of the mean (i.e., zero) for the standardized normal probability distribution. The area on each side of zero is 0.5.

The probability that $Z \leq Z_o$ is the probability that any given part will have a crack when it is inspected at the TAC interval corresponding to Z_o.

The next line on the table gives the number of parts cracked at each inspection, assuming there is only one inspection. These numbers were obtained by multiplying the number of parts to be inspected by the probability of a crack in a part with a known TAC accumulation. Of course, recurring inspections are planned. So, the next calculation determines the number of parts that crack over the inspection interval by subtracting the cumulative total number of cracked parts found at the previous inspection point from the cumulative total number of cracked parts found at the current inspection point.

The next two rows on the table account for the fleet TAC distribution and the fact that not all parts will reach 12,000 or 15,000 TACs. The table assumes that the engines with the newest parts (i.e., replaced parts due to detection of a crack in the original) accumulate the most TACs.

Whenever a cracked part is found, it is replaced by a brand new part. These parts are then tracked along with (but separately from) all of the original parts. The introduction of new parts as used parts crack and tracking of those parts comprise the rest of Table 5(c).

The end result of this analysis was that 89 parts were found during inspection to have cracked. In the case of this part and also for the first and second stage fan disks (3 cracked and 51 cracked, respectively), none of the replacement components ever failed inspection. Such was not the case for the combustion case (see Table 5(d)). In the analysis of this component, 1 of the total 159 cracks detected was on a replacement part. On all calculations in Table 5(a)-(d), a 100 percent probability of crack detection was assumed. This assumption yields worst case results for LCC purposes. An analysis is presented later in this report which assesses the impact on the probability of part failure of a more realistic probability of crack detection value.

There are two other important assumptions regarding the determination of the scrap rate profile and the construction of Table 5(a)-(d) that require discussion. Both assumptions were necessitated by the unavailability of certain data.

The first assumption is that the distribution of crack initiation lives about the mean value is approximately the same for the three fan disks. This assumption is necessary because the average lives for the first and second stage fan disks have not yet been calculated by the engine manufacturer. The average life of the third stage fan disk (and of the combustion case), however, have been calculated. The assumption is based on the fact that all three fan disks are made of the same material (titanium 6-4), are of the same basic geometry, experience roughly the same degree of temperature and stress levels, and are life limited by the same location (the

dovetail slot). If one accepts this assumption, then the calculated standard deviation (from the known LCF and average lives) for the third stage fan disk can be transferred to the first and second stage fan disks. Subsequently, the average lives of the first and second stage fan disks can be calculated. At this point the crack initiation distribution profiles are fixed and are used as the basis for Table 5(a) and (b) calculations. Even if this assumption is not quite valid, it is postulated that it will yield conservative results because of the temperature increase from the first stage to the second stage to the third stage fan disk. Analysis of F404 fan disk life data supports this postulation.

The second assumption necessitated by the unavailability of data is that the most critical life-limiting location listed for each part in Table 4 drives the characteristic of the scrap rate profile. Under this assumption the scrap rate profiles are constructed based only on the probability of a crack initiating at the most critical location (i.e., the dovetail slots for the fan disks and the compressor discharge pressure (CDP) bleed pad fillet for the combustion case). The probability of a crack initiating and being detected during inspection for all other life-limiting locations is ignored.

The lack of average life data at the other critical locations required this assumption. If this data were available, then the crack initiation distribution profile for each of the life-limiting locations could have been modelled. Then, the general law of total probability (below)[7] could have been

$$P(a \text{ or } b \text{ or } c \ldots \text{ or } i) = 1 - (1 - P_a)\ (1 - P_b)\ (1 - P_c) \ldots (1 - P_i)$$

used to determine the probability that a given part would fail inspection.

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[7]Benjamin S. Blanchard and Wolter J. Fabrycky, Systems Engineering and Analysis, Englewood Cliffs, NJ, Prentice Hall, 1990, p. 357.

The second assumption, unlike the first one, does not yield conservative results. It is probable that the consideration of all critical life-limiting locations when determining each part's scrap rate profile would result in a significant increase in the number of cracked components at each inspection. The greatest effect would be seen on the combustion case scrap rate profile because there are several other locations with fairly low LCF lives.

The RFC System Life Cycle Process

The evolution of the RFC system from conception through system disposal is graphically displayed in Figure 11. All phases of the RFC system life cycle are included. The tasks associated with design, development, production, procurement, operational introduction, operational support, and system retirement are outlined. The figure shown is a tailored version of the one appearing in Figure 2.4 on page 22 of System Engineering and Analysis by Benjamin S. Blanchard and Wolter J. Fabrycky. The study conducted in this report focuses primarily on accomplishing those tasks set forth in blocks (1) and (2). Should the conceptual and preliminary design work contained herein indicate that the RFC system is feasible, then further work is required to carry forth this project into the detail design phase and on into production, procurement, and operational introduction.

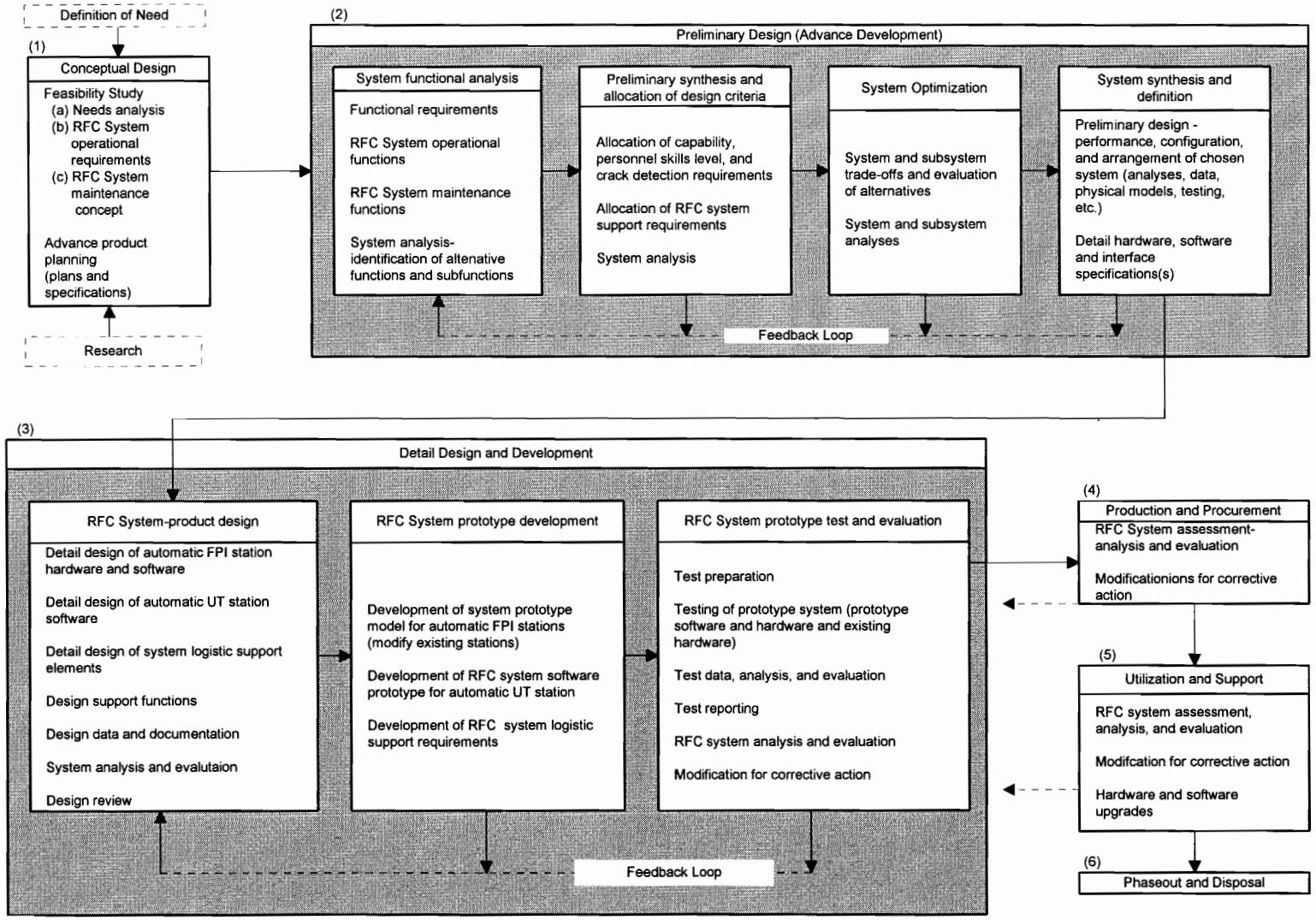

Figure 11: RFC System Life Cycle Process

Feasibility Study - Technical Approaches

The heart of the operational RFC system will be the non-destructive inspection (NDI) stations employed at the depot to inspect parts at regular intervals. NDI "is the analysis of materials without damaging or structurally altering the material being analyzed."[8] The most common NDI techniques are: Dye Penetrant, Magnetic Particle, Radiography, Ultrasonic, and Eddy Current Inspection. A brief description of the operational theory and capabilities, along with the advantages and disadvantages of each inspection method is presented below. The information presented here will serve as a basis for choosing the optimum technique for each part and geometric feature so that defect detection reliability is maximized and cost is minimized.

Dye Penetrant Inspection

Dye penetrant inspection, often referred to as florescent penetrant inspection (FPI), uses a combination of a florescent dye and a black light to identify cracks or discontinuities in the surface of non-porous materials. The material can be either metallic or nonmetallic, but the part must be thoroughly cleaned prior to inspection. After cleaning, a water-soluble florescent liquid is applied to the surface to be inspected. The dye can be sprayed or brushed onto the part or, if the part is not too large, the part can be dipped into a tank containing a dye.

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[8]Charles E. Dole,Fundamentals of Aircraft Material Factors, Redlands, CA, IAP, Inc., 1989, p. 153.

After a drying time sufficient to allow the dye to enter surface defects (usually about 30 minutes), the dye is rinsed under a black light to remove all surface penetrant. Next a developer is applied (via blotting) to bring back to the surface any penetrant that has entered a surface crack or defect. Following application of the developer, the part is dried in an oven at approximately 225° F. After completion of the drying process, the part is visually inspected under a high intensity black light in a dark area. Fatigue cracks will appear as florescent lines.

The primary advantages of this NDI technique include low cost, portability, high sensitivity for certain geometries, and the need for only minimal inspector skills. The main disadvantages are meticulousness with which a part must be cleaned and the requirement to remove surface coatings. Also, only surface flaws can be detected, and direct visual identification is required which means that no direct permanent record of the inspection results is available.

Magnetic Particle Inspection

In a magnetic particle inspection (MPI) a magnetic field is induced on a part constructed from a magnetic material in order to locate surface and near-surface sub-surface defects. The part is inserted into an electrified coil in order to locate cracks in the lateral direction. Cracks in the longitudinal direction are found by passing a current lengthwise through the part.

The part does not have to be nearly as clean for MPI as it does for FPI, although some gross cleaning is required. Also, thin surface coating has the effect of converting surface cracks into sub-surface defects; therefore, thin surface coatings need not be removed.

While inducing the magnetic field onto the part, florescent magnetic particles are sprayed over the surface of the part. Alternatively, the part can be dipped into a bath containing these particles prior to magnetic field induction. This "wet" method for application of the particles uses an oil or water bath containing suspended florescent magnetic particles. A "dry" method in which the colored magnetic particles are suspended in a finely sprayed powder is a somewhat less accurate alternative which offers greater portability.

After completion of the procedure using the wet method, the part is allowed to drain for a few seconds. It is then inspected under an ultraviolet black light in a dark area. As in the FPI, cracks will appear as florescent lines. The inspection for a part where the dry method was used is done under normal white light.

The principal advantages of this method are its sensitivity to small flaws in both the surface and the near sub-surface and the need for only moderate skills in the inspector. The big disadvantages are that MPI can only be used on magnetic parts. As with FPI, direct visual identification is required which means that no direct permanent record of the inspection results is available. Also, most surface coatings are thick enough to interfere with the technique and, therefore, must be removed. Additionally, the part must be demagnetized after the inspection is complete.

Radiography Inspection

Radiography uses X-rays or gamma rays to identify and locate flaws on and below the surface of a part. This inspection technique can be used on both metallic and non-metallic parts, but there is a limit on the effective depth that depends on the material and orientation of the part.

The radiography procedure requires a great deal of skill not only in the layout and orientation of the part and film, but also in the interpretation of the results. After the X-rays or gamma rays are released from a source, they travel in straight lines. When these rays come in contact with the part, they either pass through the part or are absorbed by the part. Those that pass through will create a shadowy picture on the film behind the part once the film is developed. When a gamma ray or X-ray encounters a crack or void in the part, less of the radiation will be absorbed by the crack or void than by the surrounding solid material. The corresponding increase in radiation that is allowed to pass through a defect shows up as a dark spot (a more exposed spot) on the film.

The advantages of this NDI method are usually outweighed by the disadvantages when other NDI methods will suffice. The primary advantages are its ability to detect both surface and sub-surface flaws in a part with very little part preparation. Also, unlike FPI or MPI, a direct permanent record of the results is obtained. The disadvantages include high cost, radiation danger, and the need for a highly skilled inspector/interpreter. Also, exposures from many different angles are often required due the highly directional nature of this method.

Ultrasonic Inspection

In ultrasonic (UT) inspection a piezoelectric transducer is used to convert a radio frequency electrical pulse into an ultrasonic vibration. Since these ultrasonic vibration pulses do not travel well through air, the part is either immersed in or covered with a fine film of water (containing an appropriate corrosion inhibitor). With both immersion and squirter technologies, the ultrasonic pulse travels through the water where it

encounters the part to be inspected. At each change in material and at every boundary, a portion of the pulse is reflected and refracted.

After emitting a pulse the transducer waits for a return echo, then it sends another pulse. The return echo is converted back into an electrical pulse which will show a pip for each boundary and each flaw encountered. This NDI technique is capable of locating all surface and internal cracks and flaws regardless of material or part thickness. However, it is used primarily for detecting internal volumetric flaws and voids.

This NDI technique is well suited to automation. Once a scan plan for each type of part is developed, the inspector need only set up the inspection and monitor its progress. As the test proceeds a computer can compare results against those expected from an unflawed part. If a discrepancy occurs, the inspector can be notified. Alternatively, or simultaneously, a plot of the part can be produced for evaluation by the inspector or as a direct permanent record.

The advantages of this NDI method are many. For a wide range of part thicknesses and sizes, this method is sensitive to small defects both on the surface and within a part. Also, little part preparation is required, and the process is relatively easily automated. The main disadvantage is that a highly skilled inspector is required to interpret results. Also, since the inspection is directional, the orientation of the flaw is relevant.

Eddy Current Inspection

An eddy current (EC) inspection can be used to locate (but not identify) flaws contained in the surface and in the material below the surface down to about a 1/4 inch depth. Since this NDI method relies on the

interpretation of eddy currents induced on the part, it can only be used with parts made of metal or metal alloys that are conductive.

An electrical current is sent into a probe which is held near the part to be inspected. The electrical current in the probe sets up a magnetic field around the probe. This magnetic field initiates circulating electrical currents in the metallic part. These electrical currents, in turn, set up a secondary magnetic field about the area in the part being inspected. The effects of this secondary magnetic field on the probe can be interpreted by the EC device. Flaws, material thickness changes, and geometric boundaries all register on the eddy current read-out because the EC device detects anything that distorts or compresses the induced eddy current.

EC inspection, like UT inspection, is well suited to automation. As in UT inspection, once a scan plan for each type of part is developed, the inspector need only set up the inspection and evaluate any discrepancies from the results expected from an unflawed part.

The primary advantage of this inspection technique is its ability to focus on small areas with good sensitivity to small defects in both the surface and sub-surface of a part. Other advantages include the requirement for only minimal part preparation, the capability to automate the inspection process with relative ease, portability, and moderate cost. The main disadvantages are that the surface must be accessible to the probe, rough surfaces detract from the sensitivity, it is time consuming to use on large areas, and it can only be used on metallic parts. Additionally, a highly skilled inspector is required, and it is difficult to use on parts with a varying cross section.

System Operational Requirements

RFC System Mission Definition

The most fundamental mission of this system is to provide a means (previously not available for the F110-GE-400 engine) to utilize the unique fatigue life of individual parts. This objective will be accomplished through a solid understanding of:

(1) The component's material behavior with respect to crack propagation

(2) The operating conditions experienced by the component along with the associated temperature and stress distributions

(3) Engine usage

(4) The logistics and maintenance systems involved

(5) The NDI systems involved (capabilities and limitations)

The NDI equipment that would be introduced and used to implement the RFC methodology would be required to operate for one 8-hour shift per day, 5 days a week. The above is based on the inspection interval, the current TAC accumulation rate, the number of engines, and the number of parts for which RFC is feasible.

RFC System Performance Parameters

Processing Speed

As shown in the calculation below, the RFC system must be capable of processing 20 parts per month (5 engines per month).

$$\frac{(332\ engines)(4\ parts/engine)}{(3000\ TACs)/(540\ TACs/yr)(12\ mon/yr)} = 20\ parts/mon$$

Detection Capability

Detection capability refers to the ability of the NDI equipment to detect cracks of critical size (sizes defined previously in this report).

Detection Accuracy

A 90 percent probability of detection with a 50 percent confidence level is currently achievable with top-of-the-line automated NDI equipment.

RFC System Use Requirements

The daily utilization time for the NDI equipment is 8 hours per day, 5 days per week assuming the current fleet TAC accumulation rate of 540 TACs/month.

Increases or decreases in F14B/D sorties due to wartime operations or decreased operational funding, respectively, could affect the TAC accumulation rate in the future. In turn, the utilization rate of NDI equipment and all other RFC system elements would be affected accordingly. Also, utilization of the NDI equipment for purposes other than to support the RFC system should be possible and should be investigated for cost sharing purposes.

RFC System Deployment and Setup Requirements

All NDI equipment and associated personnel will be located at Tinker Air Force Base in Oklahoma City, Oklahoma. All organic depot level maintenance for all variants of the F110 engine (including the -400 series) is currently performed at Tinker. Also, the USAF Engine Structural Integrity Program (ENSIP) has generated much experience at Tinker in the NDI of F110-GE-100 parts.

The depot has the flexibility to increase its staffing to accommodate the slight increase in labor it would experience for the tear down of rotor assemblies and combustion cases. Also, a requirement for highly skilled NDI inspection technicians and NDI maintenance personnel exists. It is not necessary here to define the additional personnel requirements in terms of numbers of persons, but only to recognize that depot labor hours at the appropriate rates for these functions must be accounted for in the life cycle cost analysis.

Additional personnel will be required at the Intermediate level of maintenance (I-level) to support increased workload caused by more frequent and extensive engine tear downs. The I-level has the capability to tear down 5 engines per month even though it takes about 180 man hours to disassemble and reassemble an F110-GE-400 engine. As will be discussed shortly, the 3 fan disks and the combustion case are the only F110-GE-400 life limited components for which it is economically feasible to manage using the RFC system.

It requires approximately 55 man hours to remove the fan rotors (only) from the engine. These are currently removed an average of every 2500 TACs (mainly due to Foreign Object Damage, or FOD). The combustion case assembly is rarely removed prior to reaching its LCF life. In fact, due to

economic considerations the USN is currently managing risk on this item by not retiring (and hence not removing) this item until more than double its LCF life. It requires approximately 145 hours to remove the combustion case assembly. So, if we assume a slightly decreased FOD rate, the return-to-service interval (i.e., inspection interval) of 3000 hours proposed in this study will increase I-level labor by 125 hours per engine times 5 engines per month. Another 4 people would be required at I-level to meet the increased workload. The cost of the additional personnel should be recorded in the LCC calculations, but with the knowledge that, in practice, the cost of military personnel will not be charged to the RFC System.

The Organizational level of maintenance (O-level) has the capability to remove/install five engines per month. This procedure requires an average of about 46 man hours of labor. Current on-wing time averages around 350 flight hours. No additional manpower requirements at the O-level are anticipated for the support of the RFC system.

The F110-GE-400 engine, at 25 percent spared, is one of the highest spared engines in the USN. Consequently, no additional assets should be required to support engines undergoing inspection.

Transportation systems for the movement of engines, assemblies, and parts between levels of maintenance and within a maintenance department are well established and acceptable as is for incorporation into the RFC system. The incorporation of the RFC system is anticipated to have no effect on the established transportation systems.

January, 1997 is the target date for system deployment, but the RFC system can be introduced anytime thereafter as long as its implementation can be justified in terms of LCC.

RFC System Operational Life Cycle

The RFC system and all of its elements will remain in place until retirement of the F-14B/D aircraft from the USN inventory. The anticipated retirement date for the F-14 B/D aircraft and, therefore, the F110-GE-400 engine and the RFC system elements is at the end of 2010.[9] For the purposes of this study no decline (in engine inventory or in engine or RFC system usage) at the end of the service life is assumed. This assumption is made primarily on the basis that a certain size force level is necessary to maintain pilot proficiency and to meet operational commitments.

RFC System Effectiveness Factors

If a LCC savings can be achieved via the RFC system without adversely impacting fleet readiness or safety, then the RFC system should be implemented. So, the system effectiveness factors are:

(1) LCC savings
(2) Fleet readiness
(3) Flight safety

[9]Dan Alexander, F-14 Deputy Assistant Program Manager, Air, Naval Air Systems Command, private telephone interview, Arlington, Virginia, February 6, 1995.

RFC System Operational Environment

The NDI stations are the only additional equipment necessary to implement the RFC system. The equipment hardware and much of the software is off-the-shelf and has been designed to operate in a factory environment. It is planned to locate this equipment and the personnel necessary to support its operations and maintenance at the Tinker depot. The consistency between the design and operational environment indicates that environment should not pose any technical or programmatic risk in RFC system implementation.

Packaging, shipping, and handling for NDI equipment and software should be in accordance with normal commercial practices for this type of equipment. It is anticipated that the following requirements will be met by normal commercial practices;

(1) Sufficient packaging (to include wood and/or cardboard boxes with styrofoam inserts) shall be provided to preclude damage to hardware as a result of ordinary handling during shipping via plane, ship, or truck.

(2) Software and software tapes shall be marked as "Magnetic Field Sensitive" and shall be packaged to preclude damage due to weather and magnetic fields such as might be generated by a package-tracking scanner during shipping.

(3) Hardware packaging shall be resistant to inclement weather.

(4) Hardware and software shall not be left in direct sunlight during the shipping process.

RFC System Maintenance Concept

The NDI equipment located at the Tinker depot are the only elements of the RFC system that require the development of a maintenance concept. Currently the USAF contracts out all maintenance (scheduled and unscheduled) that is beyond the level of the operator to a private contractor. The only maintenance responsibilities that remain organic are operational check out and verification of calibration (calibration procedures are automatic). The remainder of the maintenance responsibilities (from minor servicing to major repair) are performed on-site by a technician provided by the maintenance contract.

Currently the USAF has a service contract in place that covers all maintenance requirements of the system including technicians, spares, and supply support. Contract coverage is 24-hours/day with a maximum of 24 hours permitted for the contractor to respond to emergencies. The contract coverage is provided for 4 EC2C semi-automatic eddy current machines and 12 RFC-ECIS fully-automatic eddy current machines. It is intended to extend the coverage of the service contract to include the machines required to implement the RFC system for USN F110-GE-400 engines.

The on-site technician is responsible for all scheduled maintenance including servicing of the robotics (adjustments and repair), changing of o-rings (in the robotics), checking the concentricity of the turn tables, changing the oil, and calibrating the electronics. All scheduled maintenance is done on-site. Unscheduled maintenance is conducted on-site by the contract technician via repair of the broken component or replacement with a good spare. Any repairable parts whose repair is beyond that of the technician

may be returned to the manufacturer for repair (if feasible) and returned to the spares pool after completion.

To assist the technician, all of the automatic NDI equipment has built-in test capability that can diagnosis a fault down to the component level. Also, there is no requirement for organic specialized support equipment to conduct any scheduled or unscheduled maintenance.[10]

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[10]David Medina, Non-Destructive Inspection Process Engineer, United States Air Force, Tinker Air Force Base Depot, private telephone interview, Tinker Air Force Base, OK, February 24, 1995.

RFC System Functional Analysis

Earlier in this report the need was defined. Then, the need was translated into operational requirements, and a top-level maintenance concept was described. Now, the systems engineering process demands the use of the functional approach as a basis for further defining the operational and maintenance requirements. The functional analysis yields results that can be used as qualitative and quantitative design requirements. The process is an iterative one and is accomplished in this study by the use of the functional flow diagram. Figure 12 (a)-(k) presents the functional flow diagram for the RFC system. Level one, two, three, and four operational functional flow diagrams and level one maintenance functional flow diagrams are shown. In keeping with this phase of the systems engineering process, the emphasis of the functional analysis was to specify actions required to meet objectives so as to serve as a baseline for the definition of hardware, software, personnel, maintenance, and logistic support requirements.

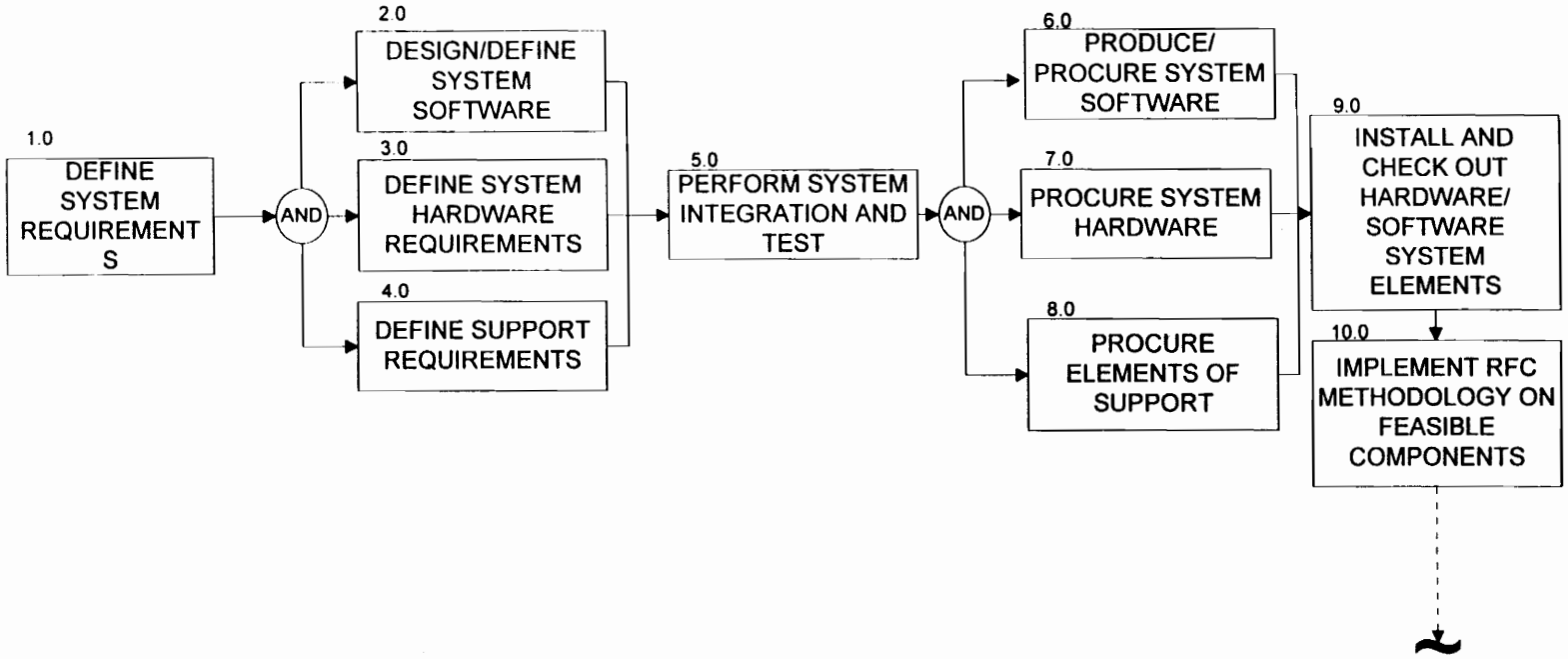

Figure 12(a): Functional Flow Diagram
Operational Level 1

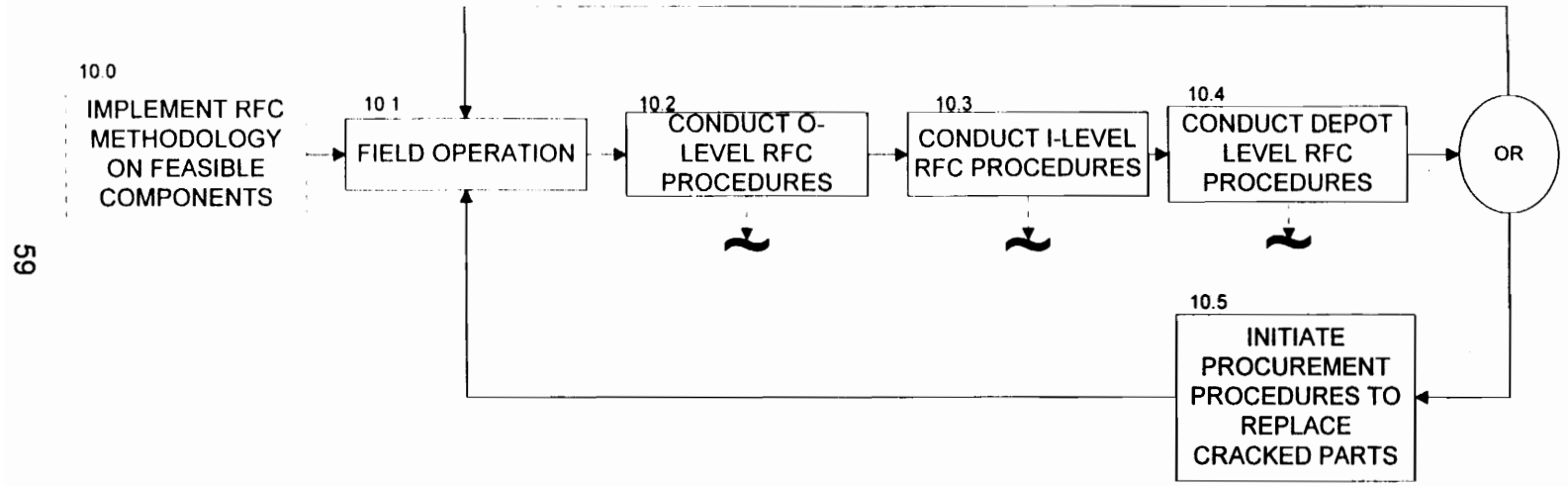

Figure 12(b): Functional Flow Diagram
Operational Level 2

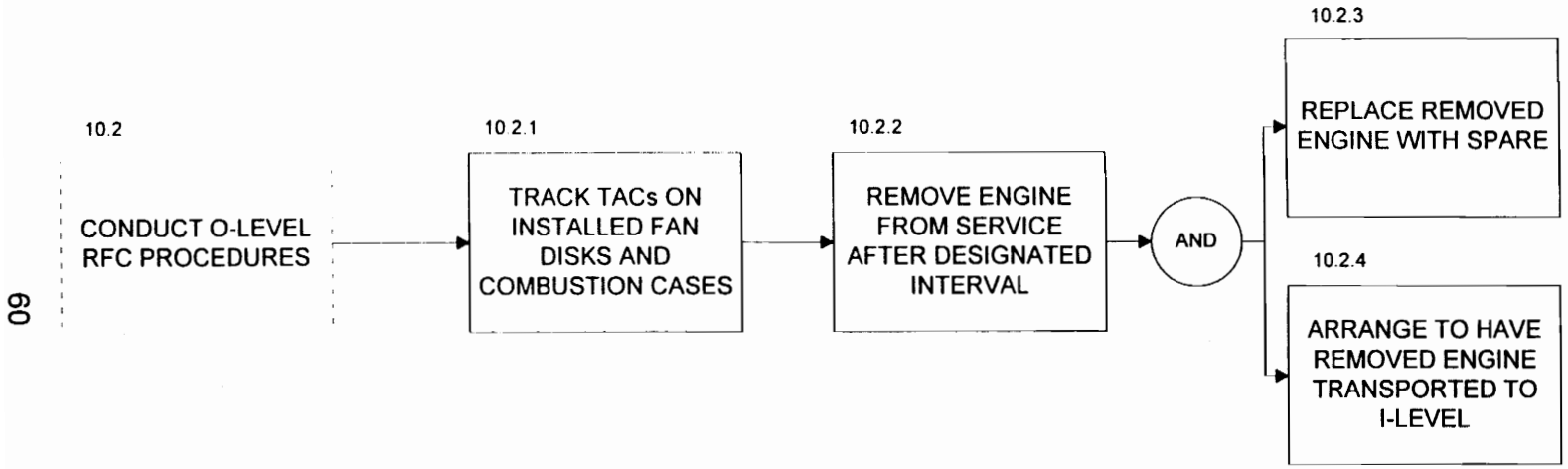

Figure 12(c): Functional Flow Diagram
Operational Level 3

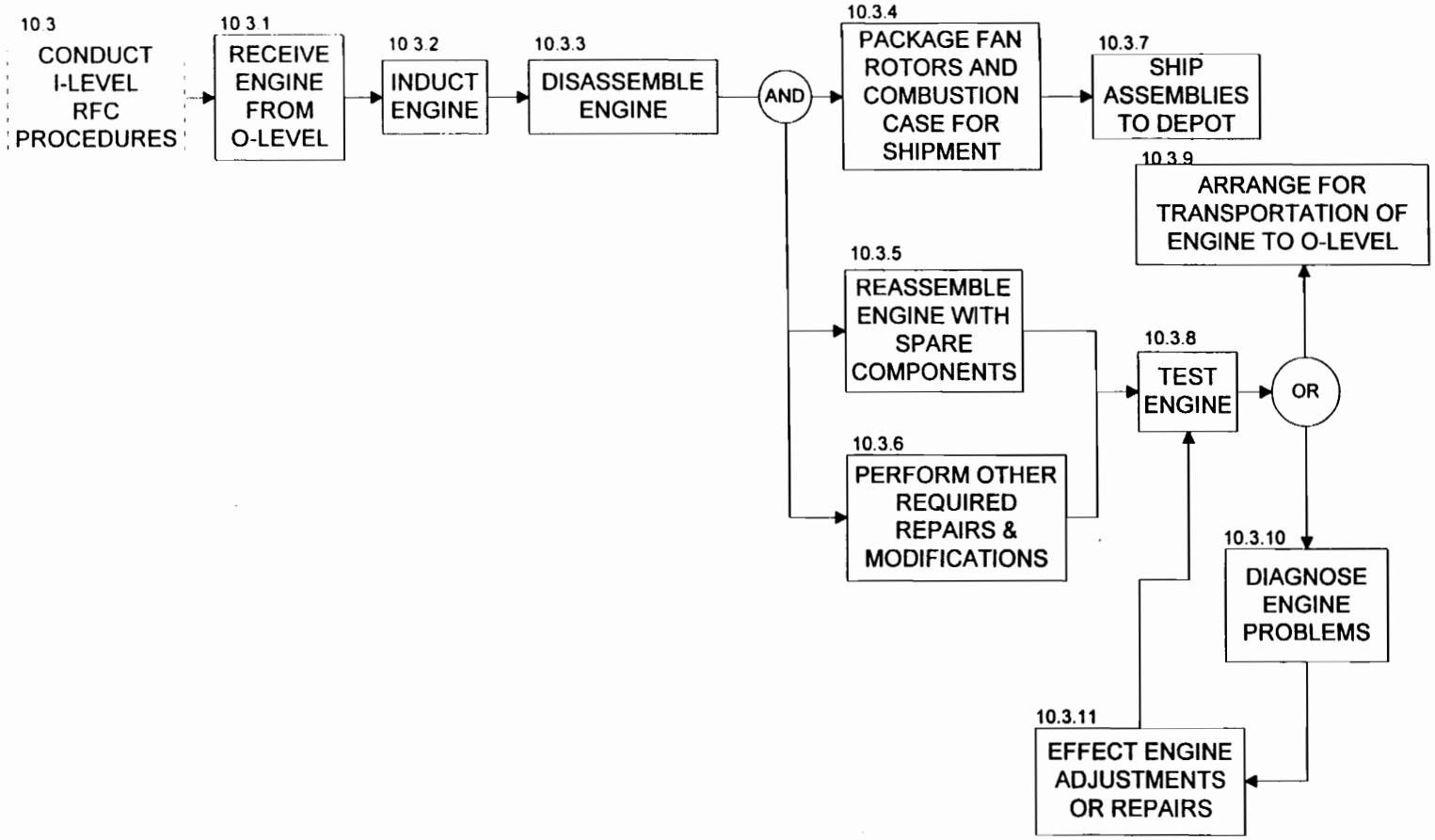

Figure 12(d): Functional Flow Diagram
Operational Level 3

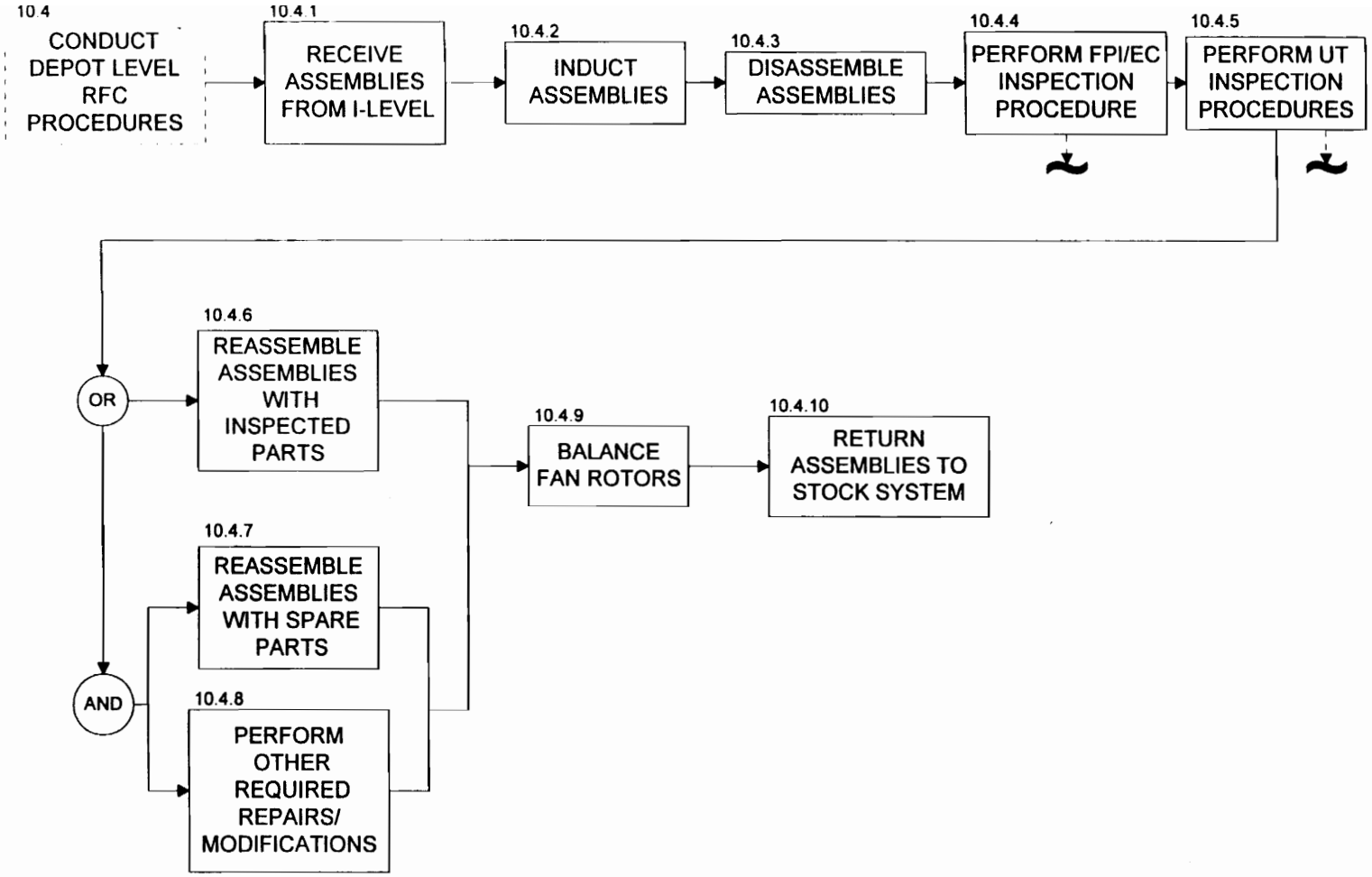

Figure 12(e): Functional Flow Diagram
Operational Level 3

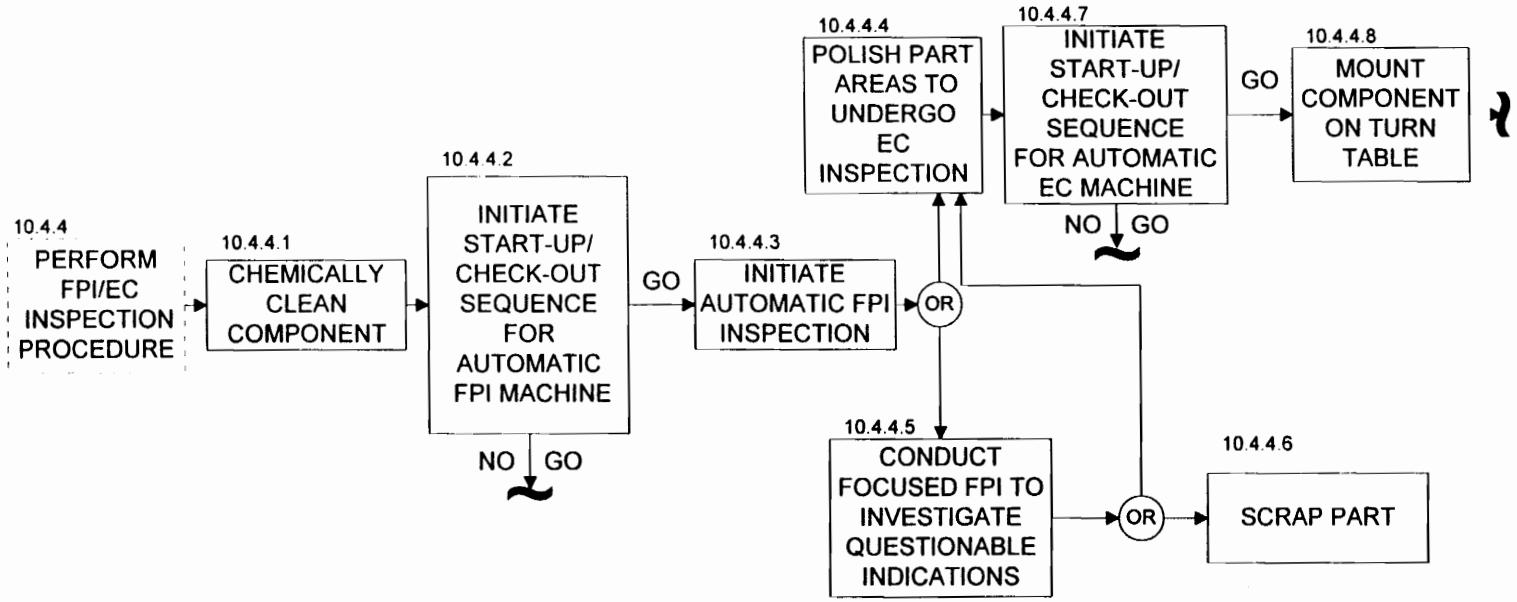

Figure 12(f): Functional Flow Diagram
Operational Level 4

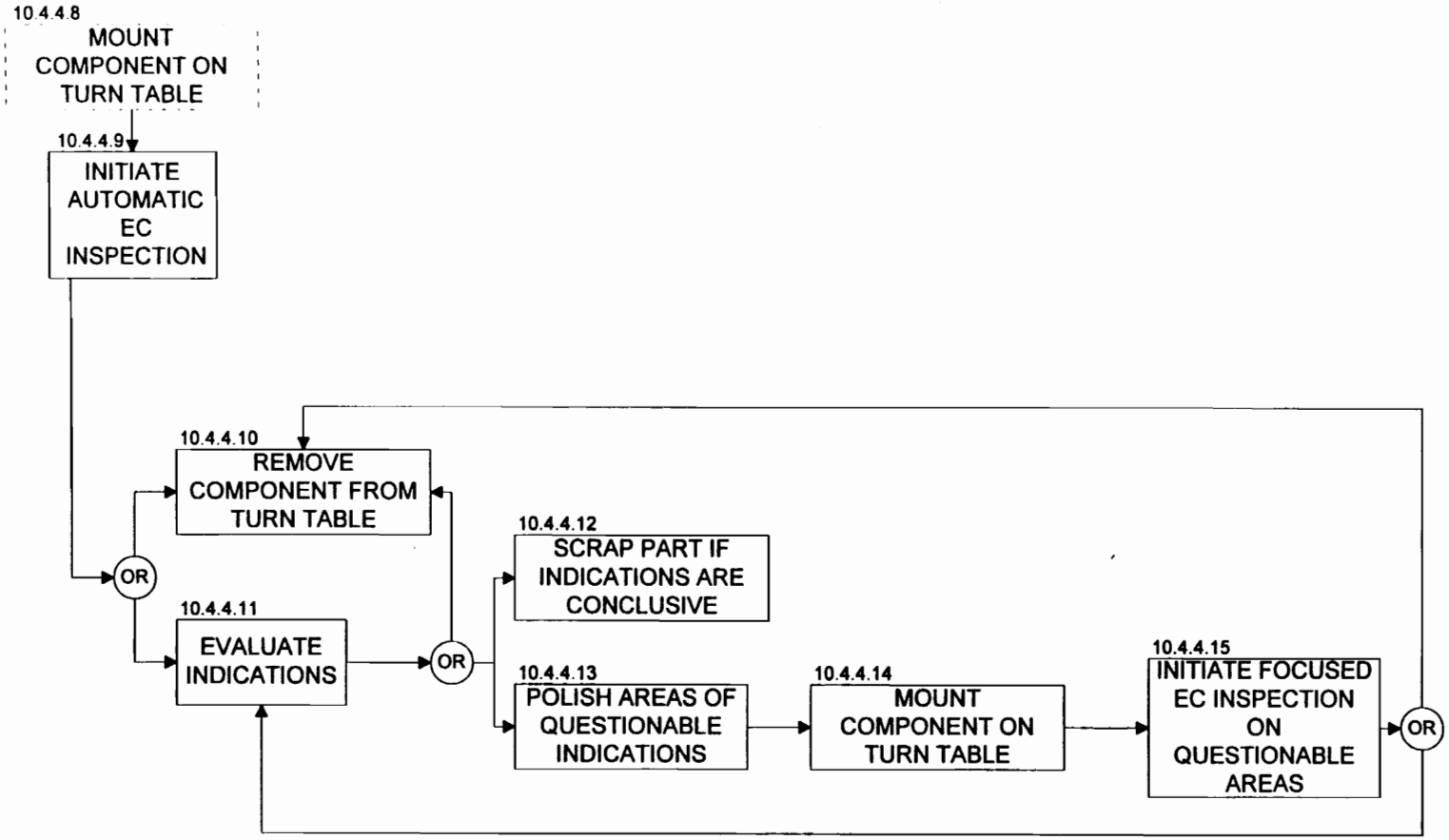

Figure 12(g): Functional Flow Diagram
Operational Level 4

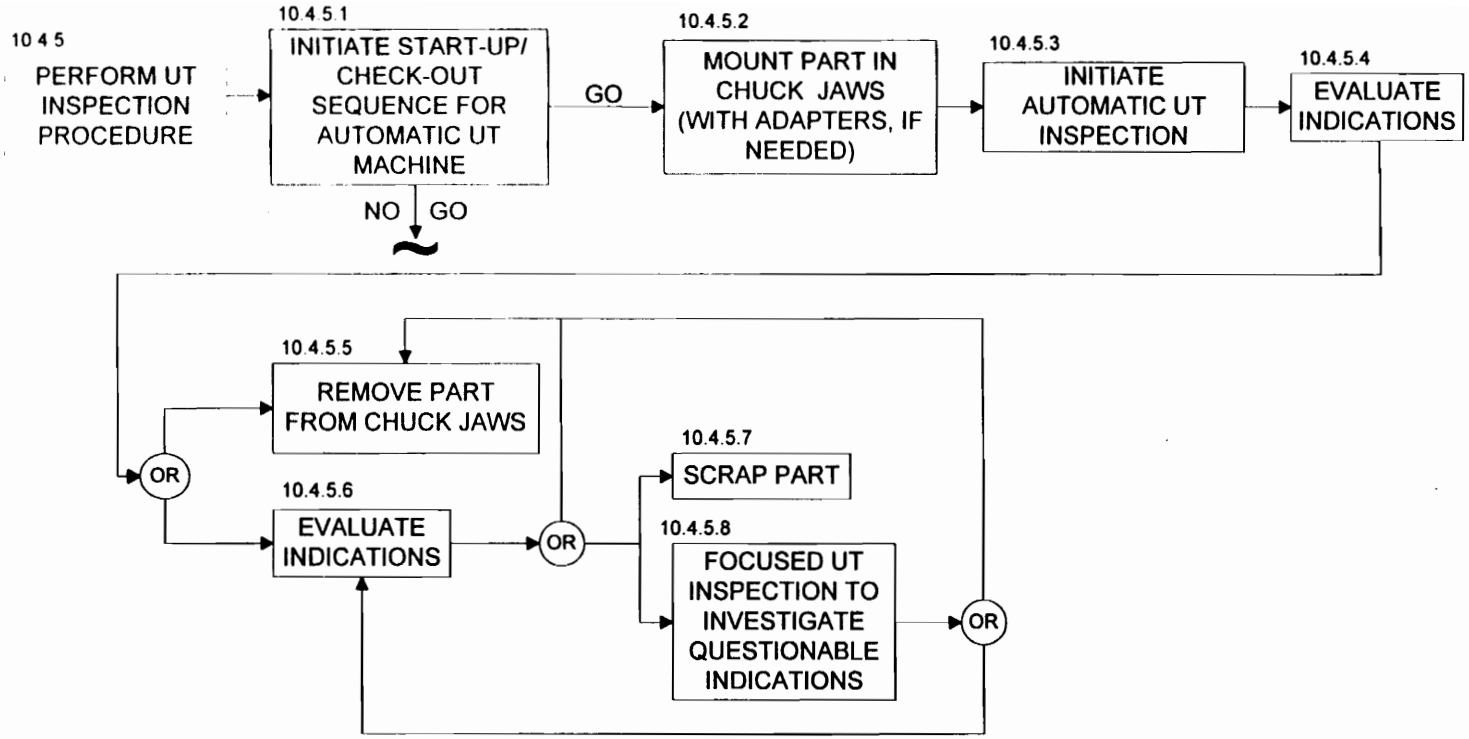

Figure 12(h): Functional Flow Diagram
Operational Level 4

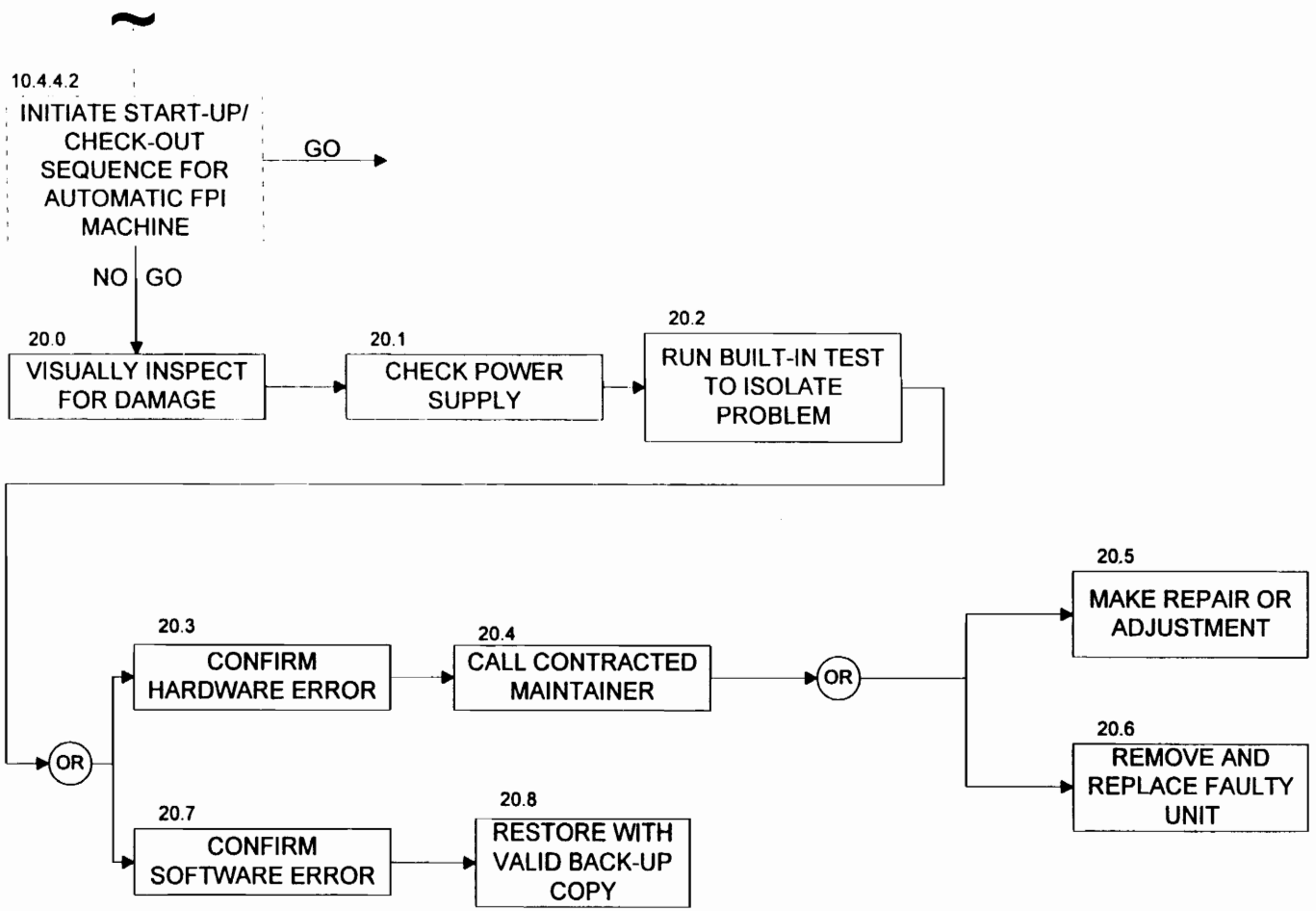

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Figure 12(i): Functional Flow Diagram
Maintenance Level 1

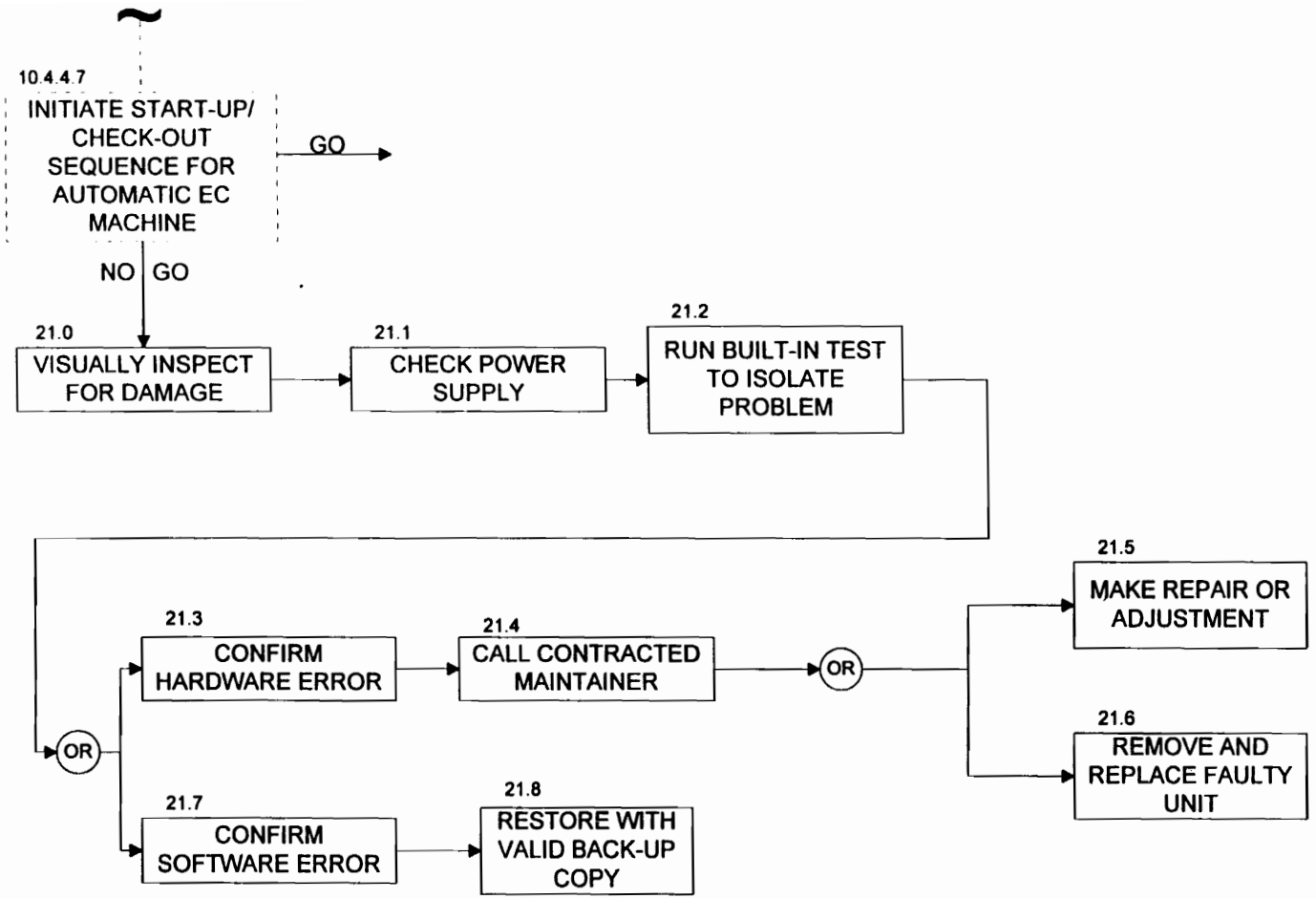

Figure 12(j): Functional Flow Diagram
Maintenance Level 1

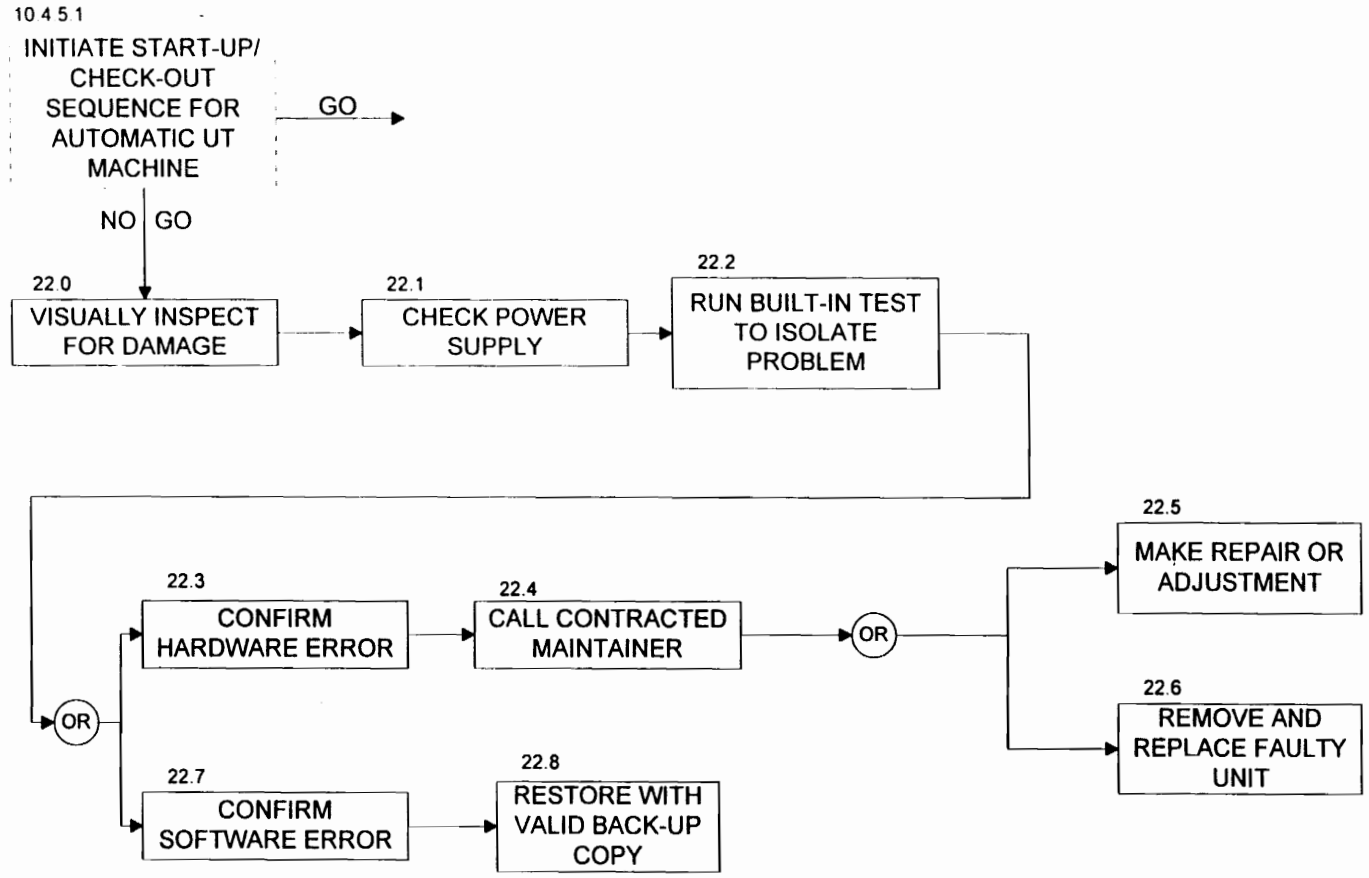

Figure 12(k): Functional Flow Diagram
Maintenance Level 1

Requirements Allocation

The traceability of top-level system requirements is illustrated in Figure 13. The RFC system level requirements are life cycle cost savings over the safe life methodology, conservation of F-14 fleet readiness, and preservation of F-14 flight safety. The life cycle savings are rigorously detailed and discussed in the following life cycle cost section of this paper, and so are not included here.

Fleet readiness is a term used to describe the instantaneous percentage of full operational capability of a particular weapon system. In the case of the F-14, it refers to the number of aircraft that are available to the President to deal with a situation at any given instant compared to the full number of USN F-14s. The availability of spares; the overall degree, amount, and timing of pilot training; the availability of scarce support equipment; the maintenance burden; and the availability of ready-for-issue (RFI) engines are among the many factors that affect readiness.

The RFC system technical performance measure (TPM) that most directly translates into readiness is RFC system capacity. The RFC system capacity requirement is derived directly from the current F110-GE-400 engine fleet TAC distribution and expected TAC accumulation rate. Both pieces of information were extracted from a database maintained by General Electric Aircraft Engines (GEAE) called the MEETS database.

In order for the implementation of the RFC system not to adversely affect F-14 readiness, the system must be capable of processing at a rate of 60 inspections per month. The NDI equipment responsible for handling this capacity will be one automated FPI, one automated EC, and one automated UT machine. Each part will be inspected by each of the machines, and each

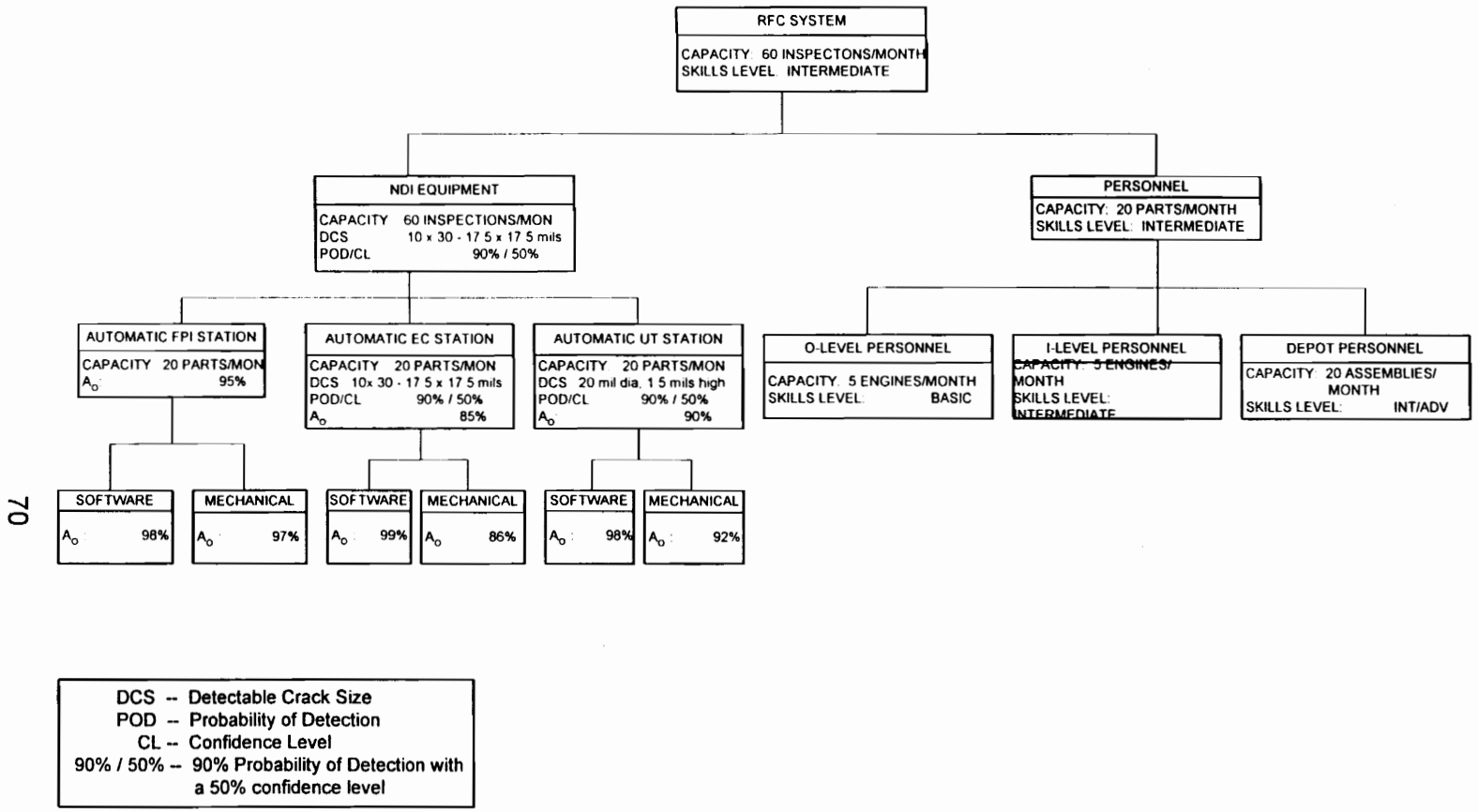

Figure 13: Requirements Allocation

of the three machines will be capable of processing 20 parts per month. The longest of the 3 inspections (the EC inspection) takes an average of 6.6 hours to perform, and with a operational availability of 85 percent for the EC machine this inspection can be thought of as taking 7.6 hours to perform. With approximately 20 workdays in a month and a processing rate of a little better than one part per day (assuming one 8-hour shift), the 20 parts per month capacity requirement can be met. Table 6: EC Inspection Times

Table 6: EC Inspection Times

Part	Inspection Time
Stage 1 Fan Disk	5.0 hours
Stage 2 Fan Disk	1.8 hours
Stage 3 Fan Disk	3.6 hours
Combustion Case	16.0 hours
AVERAGE	6.6 hours

gives the number of hours required to inspect each of the fan disks and the combustion case. The values were based on the length of time it takes the USAF to inspect these exact same parts. The USAF values were then expanded to include inspection of the additional critical locations required under the RFC system.

As implied above an important factor that influences capacity and, therefore, readiness is the operational availability of the inspection stations. The operational availability of the software for the automatic EC station and

the automatic UT station is 99% and 98%, respectively[11]. The operational availability of the EC station (software and mechanical) is between 85%[12] [13] and 90%.[14] The lower number was used for the purposes of conducting a worst-case analysis. The operational availability of the UT station is 90%.[15] The operational availability of the software for the automatic FPI machine is assumed to be similar to that of the EC and UT machines. A value of 98% was chosen. Although unknown, the operational availability of the FPI station is assumed to be 95% because of the significant reduction in complexity as compared to the EC and UT machines.

The final significant factor that requires consideration before leaving the topic of readiness is the level of staffing at the O, I, and depot levels of maintenance. The personnel must be available to process 20 parts per month. At the O-level, this requirement manifests itself in the need to remove and replace 5 engines per month. At the I-level, 5 engines per month must be torn down to the assembly level and rebuilt. Finally, at the depot, 20 assemblies per month must be torn down, 20 parts per month must be cleaned and inspected, and 20 assemblies per month must be rebuilt. The RFC personnel required to perform these tasks is discussed in

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[11]Wally C. Hoppe, A General Discussion of the Retirement for Cause Inspection System, Dayton, OH, Systems Research Laboratories, Inc., NDE Systems Division, p. 536.

[12]Ibid.

[13]Medina interview.

[14]Robert Marker, Non-Destructive Inspection System Installation and Repair Technician, Systems Research Laboratories, Inc., private telephone interview, San Antonio, TX, March 8, 1995.

[15]Ibid.

the RFC System Deployment and Setup Requirements subsection of this paper.

The TPMs that most directly translate into flight safety are the NDI equipment's detectable crack size (DCS) and probability of detection (POD) parameters. It is not required that cracks of a size below that of the DCS limit be detected; however, all cracks of the DCS limit or greater must be able to be detected.

The DCS range (10 x 30 to 17.5 x 17.5 mils) represents cracks of the same approximate size formed in different locations. A DCS of 10 x 30 mils is required for surface cracks, and a DCS of 17.5 x 17.5 mils is required for corner cracks. The DCS limits for the F110-GE-400 engine were set by the smallest crack size that is considered reliably detectable (via manual inspection) in each of the critical locations in each of the components. The initial crack sizes were determined by the engine manufacturer and are given for each of the critical locations of the three fan disks and the combustion case in Table 4. A DCS of either 10 x 30 mils or 17.5 x 17.5 mils is required in all critical locations.

Experience has shown that with automated EC equipment, cracks down to the size of 2-3 x 5-7 mils can be reliably detected (at 90% probability of detection with a 50% confidence level (CL)).[16] Due to the noise associated with the grain boundaries in titanium the crack size that can be detected at 90% POD / 50% CL is 6-7 x 11-14 mils. Despite the slightly degraded performance associated with titanium the actual DCS is still below the 10 x 30 or 17.5 x 17.5 mils DCS requirement.

Experience has also shown that a 20 mil diameter void that is 1.5 mils thick and buried 1 inch deep is detectable with an automated UT machine

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[16] Ibid.

with a 90% probability of detection at a 50% confidence level. Currently the engine manufacturer has not identified the critical size for internal voids in F110-GE-400 engine parts. For the purposes of this study, it is assumed that the UT machine's void detection capability is sufficient.

The POD TPM of 90%/50% means that a crack corresponding to the DCS limit will be detected 90% of the time with a 50% confidence level. In other words, if 10 cracks are present, chances are that only 9 will be found. The chances of crack detection are correlated with crack size. However, different cracks of the same size can have significantly different crack detection probabilities.[17] A probability of detection distribution is formed about the mean probability of detection. The mean probability of detection corresponds to the 50 percent confidence level (i.e., 50 percent of the probability of detection distribution is above the mean value and 50 percent is below (see Figure 14). Ninety percent of the distribution must be above the NDI detection threshold (i.e., the DCS limit) to obtain a 90 percent probability of detection (see Figure 15). The line with positive slope in Figure 15 is established from test specimens with known flaws that are otherwise exactly the same as the parts to be inspected. The value of this TPM corresponds with the capability of today's technology.[18]

With the chosen inspection interval of 3000 TACs, a worst-case analysis (see Table 7) conducted for the third stage fan disk and the combustion case yielded no part failures over the expected remaining service life of the F-14. The analysis was conducted using 90% POD on these two components because the LCF and crack propagation lives for the third stage

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[17]Alan P. Berens, NDE Reliability Data Analysis, Dayton, OH, ASM International, 1988, p. 689.

[18]Marker, interview.

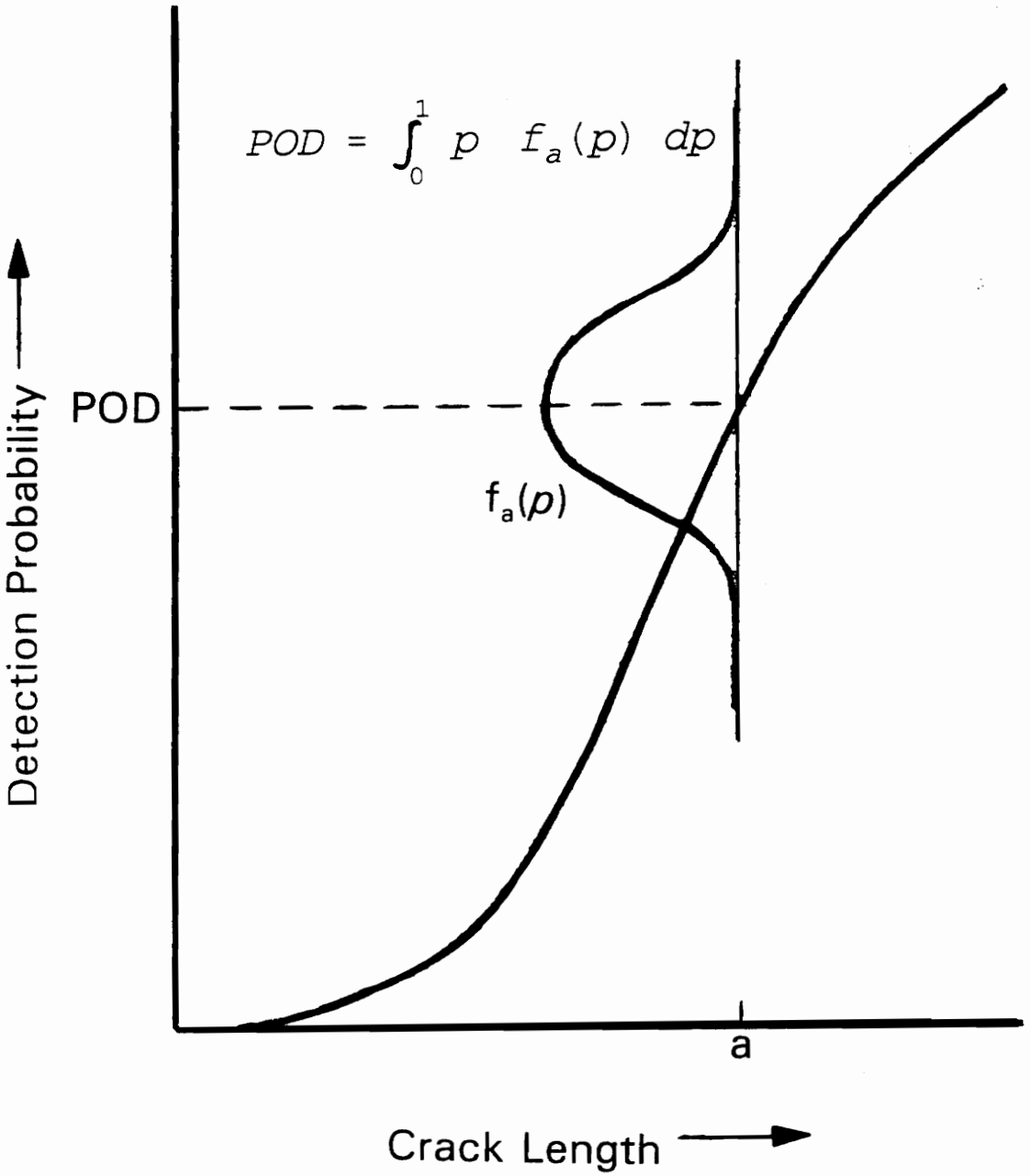

Figure 14: Detection Probability Distribution

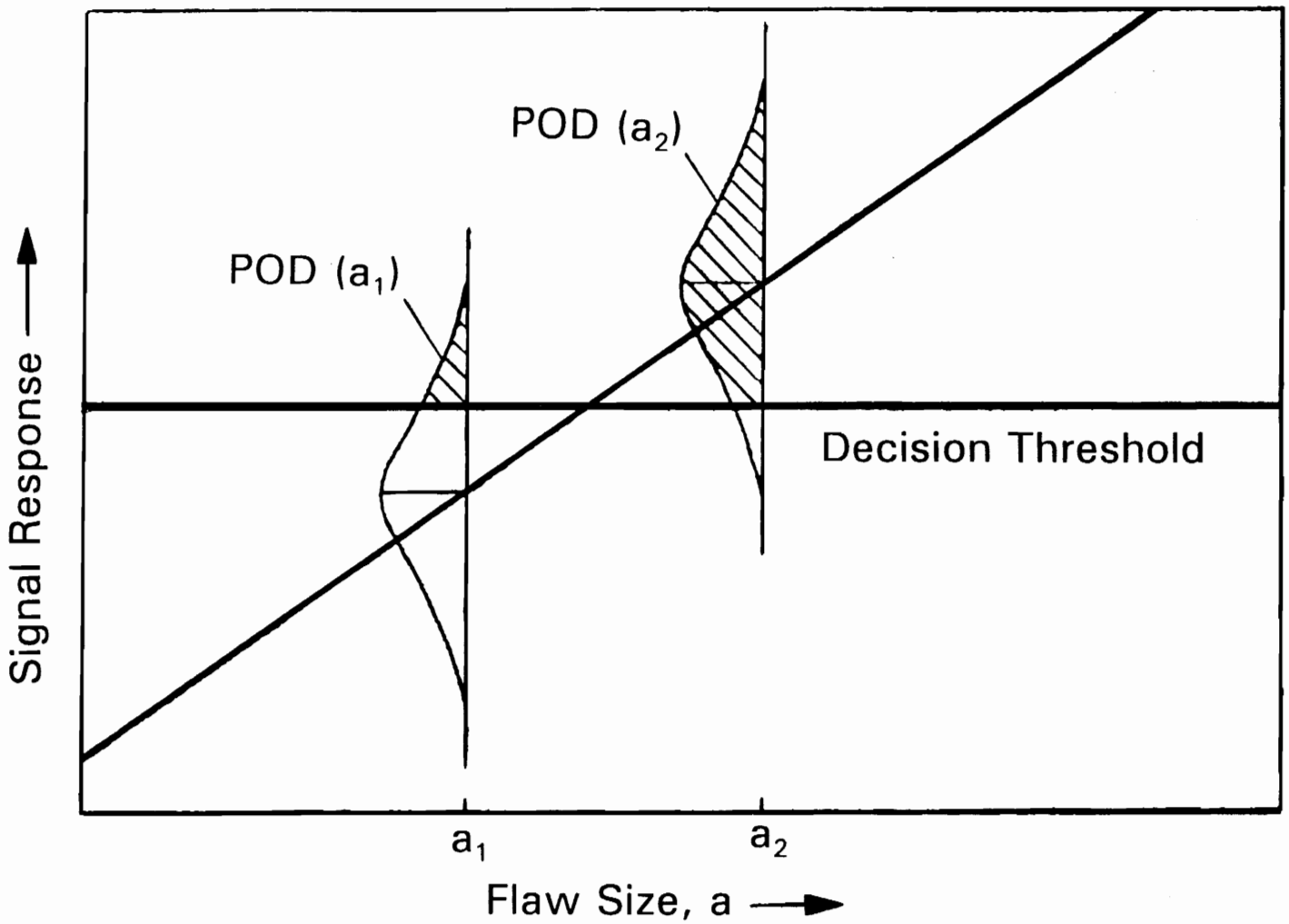

Figure 15: Probability of Detection Calculation Schematic

Table 7: Effect of Detection Capability on Probability of Part Failure

3rd Stage Fan Disk	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6
Original Parts (the worst case)									
Cracked Parts Analysis									
TACs	2751	10700	2200	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-3.89	-2.80	-1.71	-0.62	0.47	1.56
P(0< =Z< =Zo)			0.4990	0.5000	0.4974	0.4564	0.2324	0.1808	0.4406
P(Z< =Zo)			0.0010	0.0000	0.0026	0.0436	0.2676	0.6808	0.9406
No. cracked parts (if only one inspection)				0.0000	0.8632	14.4752	88.8432	226.0256	312.2792
Rounded (No. cracked parts if one inspect)				0	1	14	89	226	312
No. of parts cracked during inspection int				0	1	13	75		
Parts (engines) not reaching next interval			0	0	0	0	243		
Parts requiring inspection at next interval			332	332	331	318	0		
Failed Parts Analysis									
TACs	3714	16650	5175	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-4.48	-3.68	-2.87	-2.06	-1.25	-0.44
P(0< =Z< =Zo)			0.4990	0.5000	0.5000	0.4979	0.4803	0.3944	0.1700
P(Z< =Zo)			0.0010	0.0000	0.0000	0.0021	0.0197	0.1056	0.3300
Cracked parts missed at each inspection int				0.0000	0.1000	1.3100	7.6310		
Number of Failed Parts				0.0000	0.0000	0.0028	0.1503		
Rounded (Number of Failed Parts)				0	0	0	0		

Combustion Case	Std Dev	Avg Life	LCF Life	Inspect#1	Inspect#2	Inspect#3	Inspect#4	Inspect#5	Inspect#6
Original Parts (the worst case)									
Cracked Parts Analysis									
TACs	2404	9154	1725	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-3.81	-2.56	-1.31	-0.06	1.18	2.43
P(0< =Z< =Zo)			0.4990	0.5000	0.4948	0.4049	0.0239	0.3810	0.4925
P(Z< =Zo)			0.0010	0.0000	0.0052	0.0951	0.4761	0.8810	0.9925
No. cracked parts (if only one inspection)				0.0000	1.7264	31.5732	158.0652	292.4920	329.5100
Rounded (No. cracked parts if one inspect)				0	2	32	158	292	330
No. of parts cracked during inspection int				0	2	30	126		
Parts (engines) not reaching next interval			0	0	0	0	174		
Parts requiring inspection at next interval			332	332	330	300	0		
Failed Parts Analysis									
TACs	4909	19474	4305	0	3000	6000	9000	12000	15000
Zo (the X of the normalized std distr)			-3.09	-3.97	-3.36	-2.74	-2.13	-1.52	-0.91
P(0< =Z< =Zo)			0.4990	0.5000	0.5000	0.4969	0.4834	0.4357	0.3186
P(Z< =Zo)			0.0010	0.0000	0.0000	0.0031	0.0166	0.0643	0.1814
Cracked parts missed at each inspection int				0.0000	0.2000	3.0200	12.9020		
Number of Failed Parts				0.0000	0.0000	0.0094	0.2142		
Rounded (Number of Failed Parts)				0	0	0	0		

fan disk and combustion case are lower than those of the first and second stage fan disks. Since the greatest risk of failure should lie with the components having the shortest lives, the analysis was not repeated for the first and second stage disks.

From the discussion above it is clear that the system level requirement for readiness of the F-14B/D weapon system has been quantified in terms of RFC system capacity. The capacity TPM was then allocated to lower levels in the system. Readiness is not degraded with the values derived for the RFC system capacity and the related subsystem capacity allocations.

The discussion above also quantified the requirement for flight safety. The two TPMs chosen for this requirement were POD and DCS. The values chosen for these allocated requirements are realistic and sufficient, and analysis indicates favorable flight safety numbers - zero failures.

Life Cycle Cost Analysis

A life cycle cost analysis was performed for budgetary purposes. The analysis details the costs and savings involved with the January, 1997 implementation of an alternative (i.e., the RFC system) to the current safe life methodology. The narrow results of the feasibility analysis precluded the need for an alternative evaluation study.

First, all of the activities that will generate costs throughout the life cycle of the RFC system were identified. Next, the life cycle costs associated with those activities were categorized into cost categories. A cost was then assigned for each category based on the required manpower, materials, data, etc. Finally, the costs for each category were projected into the future on a year-by-year basis over the applicable portion of the life cycle. The results from this effort are presented in the upper portion of Table 8 . In this cost summary all of the costs are in constant (1995) dollars.

The lower portion of Table 8 is a presentation of the results of the application of inflation. A constant ten percent inflation factor was assumed (see the last line in Table 8). Since the RFC system essentially involves only a one-time purchase, the application of learning curves is not relevant and was not performed.

All calculations in Table 8 were performed in EXCEL. All costs/savings for each category have been summed both horizontally and vertically. The cost/savings for each major phase and for the entire system have been summed in the same manner. A bar chart presenting the year-by-year actual cost by major system phase is shown in Figure 16.

Table 8: F110-GE-400 Engine RFC System Cost Summary

COST STREAM BY PROGRAM YEAR, CONSTANT DOLLARS

COST CATEGORY	1995 YEAR 1	1996 YEAR 2	1997 YEAR 3	1998 YEAR 4	1999 YEAR 5	2000 YEAR 6	2001 YEAR 7	2002 YEAR 8	2003 YEAR 9
RFC SYSTEM COST	**$780,000**	**$3,788,330**	**($9,586,132)**	**($6,582,461)**	**($5,484,170)**	**($12,215,083)**	**($6,438,010)**	**($7,887,866)**	**($10,521,790)**
RESEARCH AND DEVELOPMENT COST	$780,000	$533,330	$0	$0	$0	$0	$0	$0	$0
System Management	$60,000	$90,000	$0	$0	$0	$0	$0	$0	$0
Data Development	$310,000	$0	$0	$0	$0	$0	$0	$0	$0
Engineering Design	$200,000	$150,000	$0	$0	$0	$0	$0	$0	$0
Design Documentation	$40,000	$60,000	$0	$0	$0	$0	$0	$0	$0
System Software	$150,000	$50,000	$0	$0	$0	$0	$0	$0	$0
System Test & Evaluation	$0	$183,330	$0	$0	$0	$0	$0	$0	$0
PRODUCTION COST	$20,000	$3,245,000	$0	$0	$0	$0	$0	$0	$0
Production Mgmt	$0	$25,000	$0	$0	$0	$0	$0	$0	$0
Industrial Engr & Operations Anal	$20,000	$20,000	$0	$0	$0	$0	$0	$0	$0
Procurement/Manufacturing	$0	$3,200,000	$0	$0	$0	$0	$0	$0	$0
Transportation/Installation (included in purchase price)	$0	$0	$0	$0	$0	$0	$0	$0	$0
OPERATION & MAINT SUPPORT COST	$0	$10,000	($9,586,132)	($6,582,461)	($5,484,170)	($12,215,083)	($6,438,010)	($7,887,866)	($10,521,790)
System Life-cycle Mgmt	$0	$10,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000
System Operations	$0	$0	$559,680	$559,680	$559,680	$559,680	$559,680	$559,680	$559,680
System Distribution/Transportation	$0	$0	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000
Engine Component Retirements at LCF life that are not performed	$0	$0	($10,303,937)	($7,300,266)	($6,401,975)	($12,932,888)	($9,002,529)	($8,805,671)	($11,239,595)
Engine Component Replacements (failed inspection)	$0	$0	$0	$0	$0	$0	$1,846,714	$0	$0
System Maintenance	$0	$0	$78,125	$78,125	$78,125	$78,125	$78,125	$78,125	$78,125
System Modifications	$0	$0	$0	$0	$200,000	$0	$0	$200,000	$0
RETIREMENT & DISPOSAL COST	$0	$0	$0	$0	$0	$0	$0	$0	$0
Disp of Non-repairable Sys Elements (covered in service contract)	$0	$0	$0	$0	$0	$0	$0	$0	$0
System Retirement	$0	$0	$0	$0	$0	$0	$0	$0	$0

COST STREAM BY PROGRAM YEAR, INFLATED DOLLARS (assumes a constant 10% interest rate)

COST CATEGORY	1995 YEAR 1	1996 YEAR 2	1997 YEAR 3	1998 YEAR 4	1999 YEAR 5	2000 YEAR 6	2001 YEAR 7	2002 YEAR 8	2003 YEAR 9
RFC SYSTEM COST	**$858,000**	**$4,583,879**	**($12,758,142)**	**($9,636,723)**	**($8,834,998)**	**($21,645,127)**	**($12,547,681)**	**($16,911,585)**	**($24,810,381)**
RESEARCH AND DEVELOPMENT COST	$836,000	$645,329	$0	$0	$0	$0	$0	$0	$0
System Management	$66,000	$108,900	$0	$0	$0	$0	$0	$0	$0
Data Development	$341,000	$0	$0	$0	$0	$0	$0	$0	$0
Engineering Design	$220,000	$181,500	$0	$0	$0	$0	$0	$0	$0
Design Documentation	$44,000	$72,600	$0	$0	$0	$0	$0	$0	$0
System Software	$165,000	$60,500	$0	$0	$0	$0	$0	$0	$0
System Test & Evaluation	$0	$221,829	$0	$0	$0	$0	$0	$0	$0
PRODUCTION COST	$22,000	$3,926,450	$0	$0	$0	$0	$0	$0	$0
Production Mgmt	$0	$30,250	$0	$0	$0	$0	$0	$0	$0
Industrial Engr & Operations Anal	$22,000	$24,200	$0	$0	$0	$0	$0	$0	$0
Procurement/Manufacturing	$0	$3,872,000	$0	$0	$0	$0	$0	$0	$0
Transportation/Installation	$0	$0	$0	$0	$0	$0	$0	$0	$0
OPERATION & MAINT SUPPORT COST	$0	$12,100	($12,758,142)	($9,636,723)	($8,834,998)	($21,645,127)	($12,547,681)	($16,911,585)	($24,810,381)
System Life-cycle Mgmt	$0	$12,100	$26,620	$29,280	$32,220	$35,440	$38,980	$42,880	$47,160
System Operations	$0	$0	$744,934	$819,372	$901,644	$991,753	$1,090,816	$1,199,954	$1,319,725
System Distribution/Transportation	$0	$0	$79,860	$87,840	$96,660	$106,320	$116,940	$128,640	$141,480
Engine Component Retirements at LCF life that are not performed	$0	$0	($13,714,540)	($10,687,589)	($10,313,582)	($22,917,078)	($17,545,929)	($18,879,359)	($26,502,865)
Engine Component Replacements (failed inspection)	$0	$0	$0	$0	$0	$0	$3,599,246	$0	$0
System Maintenance	$0	$0	$103,984	$114,375	$125,859	$138,438	$152,256	$167,500	$184,219
System Modifications	$0	$0	$0	$0	$322,200	$0	$0	$428,800	$0
RETIREMENT & DISPOSAL COST	$0	$0	$0	$0	$0	$0	$0	$0	$0
Disp of Non-repairable Sys Elements (covered in service contract)	$0	$0	$0	$0	$0	$0	$0	$0	$0
System Retirement	$0	$0	$0	$0	$0	$0	$0	$0	$0
F/P,i = 10%,n = 1 to 10	1.100	1.210	1.331	1.464	1.611	1.772	1.949	2.144	2.358

Table 8 (Continued): F110-GE-400 Engine RFC System Cost Summary

COST CATEGORY	2004 YEAR 10	2005 YEAR 11	2006 YEAR 12	2007 YEAR 13	2008 YEAR 14	2009 YEAR 15	2010 YEAR 16	TOTALS TOTAL CONSTANT $ COST
RFC SYSTEM COST	**($8,449,643)**	**($8,830,799)**	**($8,316,203)**	**$2,210,212**	**($9,074,016)**	**($7,919,892)**	**($6,779,279)**	**($101,106,802)**
RESEARCH AND DEVELOPMENT COST	$0	$0	$0	$0	$0	$0	$0	$1,293,330
System Management	$0	$0	$0	$0	$0	$0	$0	$150,000
Data Development	$0	$0	$0	$0	$0	$0	$0	$310,000
Engineering Design	$0	$0	$0	$0	$0	$0	$0	$350,000
Design Documentation	$0	$0	$0	$0	$0	$0	$0	$100,000
System Software	$0	$0	$0	$0	$0	$0	$0	$200,000
System Test & Evaluation	$0	$0	$0	$0	$0	$0	$0	$183,330
PRODUCTION COST	$0	$0	$0	$0	$0	$0	$0	$3,265,000
Production Mgmt	$0	$0	$0	$0	$0	$0	$0	$25,000
Industrial Engr & Operations Anal	$0	$0	$0	$0	$0	$0	$0	$40,000
Procurement/Manufacturing	$0	$0	$0	$0	$0	$0	$0	$3,200,000
Transportation/Installation (included in purchase price)	$0	$0	$0	$0	$0	$0	$0	$0
OPERATION & MAINT SUPPORT COST	($8,449,643)	($8,830,799)	($8,316,203)	$2,210,212	($9,074,016)	($7,919,892)	($5,819,279)	($104,705,132)
System Life cycle Mgmt	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$290,000
System Operations	$559,680	$559,680	$559,680	$559,680	$559,680	$559,680	$559,680	$7,835,520
System Distribution/Transportation	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$840,000
Engine Component Retirements at LCF life that are not performed	($9,167,448)	($9,548,604)	($9,034,008)	($7,119,903)	($9,991,821)	($8,637,697)	($8,841,520)	($128,327,862)
Engine Component Replacements (failed inspection)	$0	$0	$0	$8,612,310	$0	$0	$2,304,436	$12,763,460
System Maintenance	$78,125	$78,125	$78,125	$78,125	$78,125	$78,125	$78,125	$1,093,750
System Modifications	$0	$200,000	$0	$0	$200,000	$0	$0	$800,000
RETIREMENT & DISPOSAL COST	$0	$0	$0	$0	$0	$0	($960,000)	($960,000)
Disp of Non-repairable Sys Elements (covered in service contract)	$0	$0	$0	$0	$0	$0	$0	$0
System Retirement	$0	$0	$0	$0	$0	$0	($960,000)	($960,000)

COST CATEGORY	2004 YEAR 10	2005 YEAR 11	2006 YEAR 12	2007 YEAR 13	2008 YEAR 14	2009 YEAR 15	2010 YEAR 16	TOTALS TOTAL ACTUAL $ COST
RFC SYSTEM COST	**($21,918,374)**	**($24,823,670)**	**($26,096,245)**	**$7,629,652**	**($34,463,113)**	**($33,081,389)**	**($35,277,331)**	**($269,534,227)**
RESEARCH AND DEVELOPMENT COST	$0	$0	$0	$0	$0	$0	$0	$1,481,329
System Management	$0	$0	$0	$0	$0	$0	$0	$174,900
Data Development	$0	$0	$0	$0	$0	$0	$0	$341,000
Engineering Design	$0	$0	$0	$0	$0	$0	$0	$401,500
Design Documentation	$0	$0	$0	$0	$0	$0	$0	$116,600
System Software	$0	$0	$0	$0	$0	$0	$0	$225,500
System Test & Evaluation	$0	$0	$0	$0	$0	$0	$0	$221,829
PRODUCTION COST	$0	$0	$0	$0	$0	$0	$0	$3,948,450
Production Mgmt	$0	$0	$0	$0	$0	$0	$0	$30,250
Industrial Engr & Operations Anal	$0	$0	$0	$0	$0	$0	$0	$46,200
Procurement/Manufacturing	$0	$0	$0	$0	$0	$0	$0	$3,872,000
Transportation/Installation	$0	$0	$0	$0	$0	$0	$0	$0
OPERATION & MAINT SUPPORT COST	($21,918,374)	($24,823,670)	($26,096,245)	$7,629,652	($34,463,113)	($33,081,389)	($32,787,091)	($272,473,786)
System Life-cycle Mgmt	$51,880	$57,060	$62,760	$69,040	$75,960	$83,540	$51,880	$716,800
System Operations	$1,451,810	$1,596,767	$1,756,276	$1,932,015	$2,125,665	$2,337,783	$1,451,810	$19,720,325
System Distribution/Transportation	$155,640	$171,180	$188,280	$207,120	$227,880	$250,620	$155,640	$2,114,100
Engine Component Retirements at LCF life that are not performed	($23,780,360)	($27,242,167)	($28,348,717)	($24,577,905)	($37,948,936)	($36,079,660)	($40,626,784)	($339,165,572)
Engine Component Replacements (failed inspection)	$0	$0	$0	$29,729,694	$0	$0	$5,977,707	$39,306,647
System Maintenance	$202,656	$222,891	$245,156	$269,688	$296,719	$326,328	$202,656	$2,752,734
System Modifications	$0	$570,600	$0	$0	$759,600	$0	$0	$2,081,200
RETIREMENT & DISPOSAL COST	$0	$0	$0	$0	$0	$0	($2,490,240)	($2,490,240)
Disp of Non-repairable Sys Elements (covered in service contract)	$0	$0	$0	$0	$0	$0	$0	$0
System Retirement	$0	$0	$0	$0	$0	$0	($2,490,240)	($2,490,240)
F/P,i = 10%,n = 1 to 10	2.594	2.853	3.138	3.452	3.798	4.177	4.595	

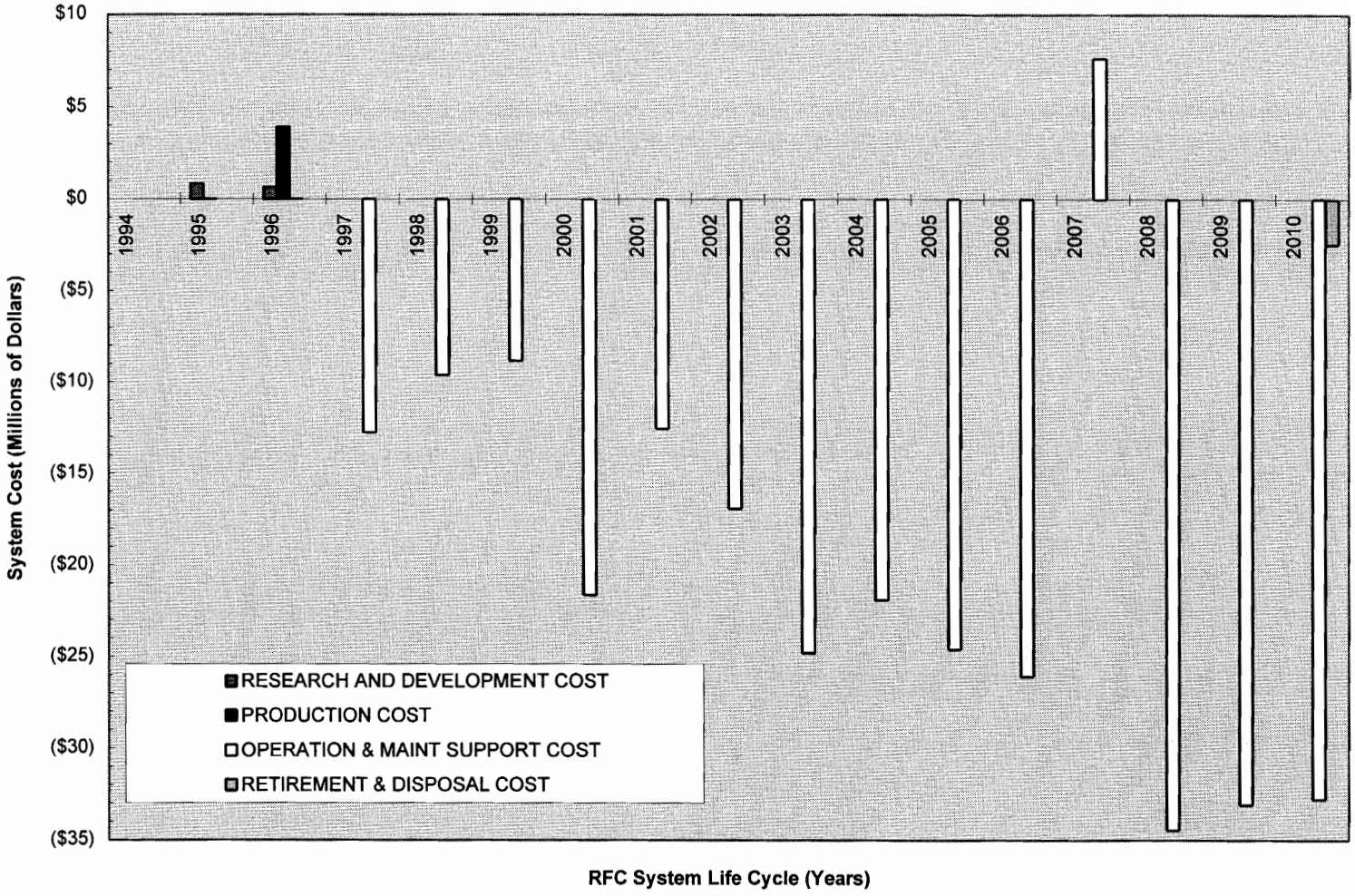

Figure 16: RFC SYSTEM COST PROFILE

A few brief notes detailing how the cost for each category was assigned is given below.

Research and Development

System Management:

Required Personnel	Man Years(1995/1996)
Technical Lead & Acquisition Planner	0.25 / 0.25
Technical Expert (NDI machines)	0.50 / 1.00
Contractor Mgmt	0.25 / 0.25
In-service Engineering	0.20 / 0.30

One man year = $50,000. Man year requirements were assumed based on experience.

Data Development:

$300K (assumed value based on experience) - Calculate minimum and average LCF and residual lives for fan disks and combustion case based on most up-to-date methods for internal voids.

$10K (assumed value based on experience) - Calculate average LCF and residual lives for first and second stage fan disks.

Engineering Design:

Costs for 1995 and 1996 are assumed for USN contribution toward adaption of automated FPI machine to allow inspection of fielded parts. Automated FPI capability currently exists for new parts only.

No costs were allocated for the design of EC or UT machines since these machines are essentially off-the-shelf purchases. Also, the EC probe design cost is included in the price of the probes.

Design Documentation:

The U.S. government already owns the documentation for the automated EC machines.

$20K - Assumed purchase price for existing automated UT machine documentation.

$80K - Assumed development and purchase price for automated FPI machine documentation.

System Software:

$200K - Estimated software development cost for the automated UT machine[19]

EC inspection software already exists for the USAF F110-GE-100 engine parts. No additional software development costs are required because the -400 and -100 life limited engine parts are identical.

Costs for development of FPI inspection software are included in the engineering design costs given above.

System Test and Evaluation:

$146,330 - purchase price for one of each of the fan disks and one combustion case.[20]

$20,000 - estimated costs for other test specimens

$17,000 - Manpower estimate (2 test engineers for 2 months effort at $50K/man year)

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[19]Ibid.

[20]Alex Garcia, F110 Engine Item Manager, Aviation Supply Office, Engine Branch, facsimile, Philadelphia, PA, February 7, 1995.

Production Cost

Production Management:

$25,000 - Assume one-half man year is required in 1996. Since virtually all the hardware has been produced before, most of the effort in this category will be directed toward software integration.

Industrial Engineering and Operational Analysis:

$20,000/year for 1995 and 1996 - assumed minimal effort for production planning and manufacturing engineering.

Procurement/Manufacturing:

$1,000,000 - cost of 1 automated EC machine[21]

$200,000 - cost of 1 set of unique F110-GE-100/-400 EC probes[22]

$1,500,000 - cost of 1 automated UT machine[23]

$500,000 - assumed cost of one automated FPI machine

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[21]Marker, interview.

[22]Ibid.

[23]Ibid.

Transportation/Installation:

Equipment delivery charges and installation (including pass-off testing and validation) are included in the purchase price of the machines.

Operation and Maintenance Support Cost

System Life-cycle Management:

$10K (1996) and $20K (1997 - 2010) - assumed costs at the depot.

System Operations: (1997 - 2010)

$190,080/year - Depot cost for 2 NDI inspectors based on a depot labor rate (for highly skilled personnel) of $120/hour, 6.6 hours inspection per part (assuming that inspectors concurrently control the automatic FPI, EC, and UT inspection stations), and a rate of 20 parts per month.

No additional costs at O-level associated with removal of engines because no additional workload is anticipated based on current F110-GE-400 on-wing time.

$120,000/year - Cost of 4 additional people at I-level to disassemble engine to remove fan and combustion and then

reassemble engine. The cost for a man year at I-level is estimated at $30K.

$21,600/year - Cost at depot for personnel to clean and prep parts for inspection based on a depot labor rate of $60/hour, 1.5 hours cleaning time per part[24], and a rate of 20 parts per month.

$228,000/year - Cost at depot for personnel to disassemble and reassemble fan rotor and combustion case assemblies based on a cost of $2400 and $1400 to disassemble and reassemble a F110-GE-400 fan rotor assembly and combustion case assembly, respectively.[25] This cost is also based on a rate of 5 fan rotor assemblies and 5 combustion case assemblies per month.

System Distribution/Transportation:

There is no cost associated with shipment of an engine from O-level to I-level because of relative proximity.

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[24]Joanna Mason, F404 Engine Project Engineer, memorandum to USN Commander Grirard, June 29, 1993.

[25]John Peterson, F110 Engine Cognizant Field Activity Logistician, USN Physical Support Detachment, Norfolk, private telephone interview, Norfolk, VA, February 28, 1995.

$60,000/year - Cost for shipment of fan ($500/shipment) and combustion case ($500/shipment) from I-level to depot[26] based on an I-level tear down rate of 5 engines/month.

Engine Component Retirements at LCF Life that are not performed:

The values assigned vary year to year. The values were determined by calculating the year in which each of the fan disks and the combustion case would be retired based on each component's individual LCF life, current fleet TAC distribution, current fleet TAC accumulation rate, and expected service life of the F-14B/D aircraft.

Engine Component Replacements (failed inspection):

The values assigned vary year to year. The values were determined by calculating the year in which individual fan disks and combustion cases would be retired based on a detected crack, current fleet TAC distribution, current fleet TAC accumulation rate, expected service life of the F-14B/D aircraft, and the relevant crack prediction probability distribution.

System Maintenance:

$78,125/year - The USAF currently has a complete service contract with Systems Research Laboratories to maintain all of

[26]Ibid.

their 16 automated NDI machines. The value of the contract is $0.5M.[27] Extension of the contract to include the USN NDI equipment is calculated on a per machine basis.

System Modifications:

$800,000 total cost - Although no modifications are planned, $200K is budgeted every third year as a contingency for unforeseen needs.

Retirement and Disposal Cost

Disposal of Non-repairable System Elements:

The cost for this function is included in the maintenance service contract.

System Retirement:

$960,000 - Assume that 30% of original NDI equipment acquisition cost can be recouped at F-14B/D service life in 2010.

From the calculation results shown in Table 8, the implementation of the RFC system is determined to result in a total life cycle cost savings of $270 million. The plot shown in Figure 16 clearly indicates that the savings

[27]Medina, interview.

are realized in the Operation and Maintenance Support Phase of the RFC system. Obviously it is the savings incurred by not retiring the fan disks and combustion cases at their B.1 life that results in the massive savings shown.

One noteworthy point regarding the Figure 16 plot relates to the net cost (vice savings) indicated in 2007. It was not possible to pinpoint a year in which an inspected component would fail inspection. Instead, a determination was made regarding how many parts would fail at a particular inspection interval based on the fleet TAC distribution and TAC accumulation rate. The average engine was used in order to determine a year in which to assess the inspection failures and resulting component replacement costs.

The result of this methodology was a grouping of engine component replacement costs in the years when the average engine reaches 6000, 9000, and 12000 TACs. Therefore, the sudden cost spike in 2007 is seen to be merely a manifestation of the method of assigning costs and not a true cost spike. The cost shown in 2007 and the reduced savings shown in 2001 and 2010 would, in fact, be distributed in some way to the other years. However, it is considered extremely unlikely that the actual distribution would affect the end result of this study noticeably.

RFC System Milestones

The major milestone dates required to implement the RFC system by the January, 1997 planned introduction date are shown in Table 9 below. The schedule's most aggressive area is the time allotted for the USN to plan, study, decide in favor of, and commit funds to the RFC system. It will still be cost effective, however, for the USN to implement the RFC system for several years to come if the dates shown here are not able to be met.

Table 9: Major RFC System Milestones

COMPLETE	RFC CONCEPT DEFINITION
JUN 1995	RECEIVE REMAINING LCF AND RESIDUAL LIFE UPDATES FROM ENGINE MANUFACTURER
JUL 1995 - JUL 1995	CALCULATE AVERAGE LIVES FOR PARTS PARTICIPATING IN THE RFC SYSTEM
AUG 1995 - AUG 1995	CONFIRM PARTS' PARTICIPATION IN RFC SYSTEM (BASED ON ACTUAL AVERAGE LIVES)
AUG 1995	INITIATE RFC SYSTEM (COMMIT FUNDING)
SEP 1995 - MAR 1996	DESIGN OF FPI AND UT STATION SOFTWARE. DESIGN OF ANY REQUIRED FPI STATION HARDWARE.
APR 1996	ORDER SYSTEM HARDWARE AND SOFTWARE
APR 1996 - SEP 1996	PRODUCTION OF NDI EQUIPMENT, SOFTWARE, AND TEST SPECIMENS
OCT 1996 - OCT 1996	DELIVERY AND INSTALLATION OF NDI EQUIPMENT
NOV 1996 - DEC 1996	SYSTEM TESTING AND EVALUATION
JAN 1997	RFC SYSTEM DEPLOYMENT
JAN 1997 - DEC 2010	RFC SYSTEM OPERATION
DEC 2010	RFC SYSTEM RETIREMENT

Conclusions

The "retirement for cause (RFC) system" is a feasible alternative to the current safe-life methodology for the management of the F110-GE-400 engine three fan disks and combustion case. Based on the assumptions and limitations of this study, a life-cycle cost (LCC) savings of $270 million will be achieved if the RFC system is operated from January, 1997 until F-14B/D system retirement in 2010. Further, this LCC savings is achieved without adversely impacting readiness or flight safety at a maximum up-front investment (non-recurring cost) of just over $4.5 million (1995 dollars).

The first of two primary limitations encountered in this study was the non-availability of up-to-date crack initiation and crack propagation lives for all life-limited engine parts. Data for twelve out of twenty-two parts is not current and is in the process of being updated. This fact impacted this study's ability to definitively state that only four parts are feasible for participation in the RFC system. In fact, if the updates to the crack initiation and crack propagation data show that more parts fit the criteria for admission into the RFC system, then a greater LCC savings will be achieved. The shorter the crack initiation life and the longer the crack propagation life, the greater is the LCC savings.

The second primary limitation in this study was the non-availability of complete crack propagation data for all life-limiting locations on the four parts selected for participation in the RFC system. The residual life at the most limiting location of an average first and second stage fan disk was derived from knowledge of the minimum crack propagation life of these two disks at that location and the standard deviation associated with the third stage fan disk crack propagation data at that same location. Applying the

crack propagation data standard deviation of the third stage fan disk to the first two stages is believed to yield conservative LCC savings.

Since even less data was available on all the other critical locations than was available for the most limiting location, only the most life-limiting location on each part was considered in this study. The impact of considering only the most critical life-limiting location is an inflation of the calculated LCC savings. Consideration of all life-limiting locations would result in shorter parts' lives and, therefore, increased costs (or reduced LCC savings).

One other assumption that affects both the LCC savings and the up-front investment costs is that eddy current and ultrasound inspection stations are not available for use with F110 engine parts and, therefore, must be procured. Since the depot at Tinker Air Force Base (where all Navy and Air Force F110 engines are maintained) has 12 fully automated eddy current machines currently in operation, it is almost certain that enough extra capacity exists to satisfy the Navy's requirement without the purchase of any additional eddy current equipment. If the above is true then the up-front investment costs would be reduced by $1.2 million to a total of just over $3.3 million (1995 dollars).

It might also be feasible to utilize ultrasound equipment currently located at Kelly Air Force Base and, thereby, eliminate the requirement to purchase such equipment at Tinker. Such a strategy would reduce the up-front investment costs by $1.5 million to a total of just over $1.8 million (1995 dollars). The disadvantages associated with shipment of parts off-site for inspection include increased LCCs, turn around times, and handling damage. Also, unique software for the F110 engine would have to be integrated into the mainframe computer at Kelly Air Force Base that currently contains the F100 unique software. Maintaining all the required software to

process both F100 and F110 engine parts may not be possible without computer system hardware modifications. Also, modification of the ultrasound equipment to enable effective inspection of the F110 engine part geometries may be necessary. One further disadvantage is that the expertise specific to the F110 engine is not available on-site at Kelly for problem resolution.

One final point that needs to be emphasized is that significant LCC savings can still be realized even if the planned RFC system implementation date of January, 1997 can not be met. For example, if the RFC system were implemented in January, 2002, a LCC savings of over $200 million could still be achieved.

Recommendations

In order to solidify the actual LCC savings that would be realized by the implementation of the RFC system, certain assumptions and limitations of this study need to be validated and/or removed. First, the LCF and residual lives at each critical location on each life-limited part need to be based on the most up-to-date missions and stress, temperature, and life prediction analytical techniques. This effort is funded, and results are expected in June, 1995. When these lives are available, an examination should be made to determine if any other parts qualify for participation in the RFC system. The addition of more life-limited parts (especially expensive parts that have low B.1 lives and, therefore, require frequent replacement) to the RFC system will increase LCC savings if the length of the inspection interval can be maintained.

A very important factor in substantiating the LCC savings of this study is the determination of the actual average crack initiation lives of the first and second stage fan disks. The more the actual average crack initiation lives vary from the ones calculated in this study, the greater the impact on LCC savings. Also, the average crack initiation lives at all critical locations, not at just the most critical one, must be calculated so that a proper part scrap rate profile (at inspection) can be determined based on the general law of total probability. Using all critical locations to the determine the scrap rate profile for a part instead of just the most critical location will likely reduce LCC savings (especially with respect to the combustion case).

The general law of total probability must also be applied to the safety analysis (i.e., the probability of part rupture analysis) that was performed in this study. The impact to safety is expected to be slight, and flight safety is

expected to remain acceptable. If, however, future work reveals a flight safety concern, then the use of a hard component life limit might be necessary to alleviate it.

Recommendations for Future Research

Flight safety and LCC savings can be increased by fine tuning the RFC system. Increasing the return-to-service (RTS) interval by reducing the variance in the crack propagation data will reduce LCCs. It may or may not be possible to reduce the variance in crack propagation data. If this task is to be accomplished then basic material research to advance the analytical understanding and calculation methods of crack propagation will be required. This research must be combined with specific component spin pit testing to validate and enhance the analytical crack propagation models. The increase in quantity of data will also serve to reduce the crack propagation variance.

A reduction in the variation of material characteristics from part to part will also reduce the variation in crack propagation data. A study to quantify the benefits of such an effort should be undertaken.

Improvement in the definition of the mission profile is another area that would enhance flight safety and optimize the RTS interval, thereby maximizing LCC savings. A flight recorder placed on each aircraft could record exact mission profiles for each engine. The actual mission experience of a particular part could be used instead of a generic mission profile applied to all parts in all engines. Systems that perform this function are available today. The AH-1W Supercobra utilizes the Structural Data Recording System to monitor exact stresses experienced by the airframe structure during each flight. Based on the data collected for each aircraft, the life remaining of the structural components is decremented from a starting point of 100 percent down to zero, where the components are retired. A study to determine the LCC benefit of taking advantage of the mission profile

variance by installing the necessary recording equipment onto the F-14B/D aircraft should be conducted.

A final recommendation is to continuously update the analytical stress, temperature and life prediction methodologies. Faster and more capable computers will make the time-consuming computational programs of today (and of the future) economical to use on a routine basis. Also, as our understanding of crack initiation and crack propagation grows and is applied in conjunction with advances in modelling techniques, the accuracy of the analytical models will be elevated.

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