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ANALYSIS OF INTERMEDIATE LEVEL MAINTENANCE FOLLOWING F404-GE-400 ENGINE COMPONENT LIFE REDUCTIONS

by

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December, 1993

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Analysis of Intermediate Level Maintenance Following F404-GE-400 Engine Component Life Reductions

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I. INTRODUCTION

A. BACKGROUND

In the summer of 1993, General Electric announced significant reductions to the life limits of its F404-GE-400 turbofan engine. Engineering analysis had determined that 12 major components, comprising most of the engine's dynamic core, were not living up to their expected longevity. Reductions ranging from 14% to 64% and averaging 46% were imposed to reduce the possibility of in-flight catastrophic failures. Table 1.1 summarizes these reductions.

Component life reductions are not new to the F404. In 1991 the life limit of the low pressure turbine section was substantially lowered, causing many engine removals in a short span of time. The high removal rate and lack of available spares caused months of shortages throughout the fleet. [Ref. 1] The 1993 reductions, affecting more sections to a greater degree, have the potential to create even larger burdens on the logistics network supporting the engine.

Shortfalls in the F404 inventory are likely to have a broad impact throughout naval aviation. The engine powers the F/A-18 Hornet, an aircraft that has had a growing role in the Navy's force structure. Procured in the early 1980's as a replacement for the aging A-7 attack jet, program

TABLE 1.1 - NAVAIR SUMMARY OF LIFE REDUCTIONS (HRS)

COMPONENT	ORIGINAL LIFE	FY 94 LIFE	% LOST
FAN			
STAGE 1	5850	1870	62.3
STAGE 2	8770	2640	64.6
STAGE 3	4380	1440	61.1
AFT SHAFT	9030	4600	49.0
HPC			
STAGE 1-2	2240	1500	33.0
STAGE 3	7480	3470	53.6
STAGE 4-7	14560	12500	14.1
HPT			
DISK	10500	7200	31.4
COOL PLATE	2100	1600	23.8
LPT			
DISK	10520	6240	40.6
AIR SEAL	22030	17940	18.5
CON SHAFT	12370	6708	45.7

cancellations and budget constraints have forced the Hornet's mission to grow beyond its original design. By the mid-1990's, the F/A-18 will be the Navy and Marine Corps' primary attack and air superiority platform. These increased operational responsibilities have made engine reliability and availability key issues among Navy planners.

B. OBJECTIVES

At the time the 1993 life reductions were imposed, General Electric provided a forecast of the expected engine removal rate. [Ref. 2] This forecast, however, did not encompass several key aspects. Missing were critical planning items such as projected bare firewalls (grounded aircraft awaiting engines), engine turn-around-time (TAT), delays while awaiting parts (AWP) and repair capacity utilization. The objective of this thesis is to study the broader impacts of component life reductions as they relate to the Navy's ability to support the F404.

The research will focus on the engine repair process of the Aircraft Intermediate Maintenance Department (AIMD) at Naval Air Station (NAS) Lemoore. AIMD Lemoore was chosen for this study because of its proximity to the authors and its repair of a single type of engine. This simplified the data gathering efforts and modeling procedures described later in this chapter. Reductions in component life will be studied as they affect engine turn-around-time, back log inventory, and air field bare firewalls. Repair flow will also provide data for an assessment of capacity utilization. By analyzing the results of the study, a range of possible effects on the F404 repair process can be determined.

C. METHODOLOGY

This study will make use of several previous works and available maintenance data to analyze the engine repair flow of AIMD Lemoore. Computer simulation will be applied to construct a representation of the power plants work area. Simulation-generated data will first be compared against actual 1992 repair data to validate the model. Once validated, sensitivity analysis on engine arrival rates and awaiting part delays will be conducted. By studying the simulation output, the authors hope to learn how AIMD Lemoore should respond to F404 life reductions.

This thesis will focus on the following issues:

1. What elements are necessary to construct a valid working model of AIMD Lemoore power plants division?

2. What impact does lowering engine component life have on engine turn-around-time at this AIMD facility?

3. Will changes in engine induction rate significantly change engine repair times and the number of bare firewalls?

4. Will lower component life limits create substantial production bottlenecks in the F404 repair process at AIMD Lemoore?

D. PREVIEW

Chapter II provides background information on the Naval Aviation Maintenance Program, Aircraft Intermediate Maintenance Department organization, AIMD Lemoore operations, F404-GE-400 turbofan engine characteristics and an overview of the current engine logistics problems.. Chapter III discusses the simulation model and describes the development of the AIMD Lemoore model. Chapter IV discusses model validity and analyzes model results. Chapter V contains a summary, conclusions and recommendations for AIMD Lemoore.

II. BACKGROUND

This chapter provides background information about the Naval Aviation Maintenance Program (NAMP), the Aircraft Intermediate Maintenance Department at NAS Lemoore, California, the F404 engine and modules, and some logistics support problems already affecting the F404 repair process.

A. THE NAVAL AVIATION MAINTENANCE PROGRAM

The NAMP provides an integrated system for performing aeronautical equipment maintenance and all related support functions. The program is directed and sponsored by the Chief of Naval Operations (CNO) and is published as OPNAVINST 4790.2E in a six-volume series. The volumes address the maintenance policies, procedures, and responsibilities for the conduct of the NAMP at all levels of maintenance throughout naval aviation. The objective of the NAMP is "to achieve and continually upgrade the readiness and safety standards established by the CNO, with optimum use of manpower, facilities, material, and funds." [Ref. 3:p. 1]

1. Levels of Maintenance

The NAMP is founded upon the three-level maintenance concept which defines aviation maintenance as organizational (O-), intermediate (I-), and depot (D-) level maintenance. It provides management tools required for the efficient and economical use of personnel and material resources in performing maintenance. It also provides the basis for establishing standard organizations, procedures, and responsibilities for the accomplishment of all maintenance on naval aircraft and associated material and equipment.

Dividing the maintenance into three levels allows management to:

1. Classify maintenance functions by levels;
2. Assign responsibility for maintenance functions to a specific level;
3. Assign maintenance tasks consistent with the complexity, depth, scope, and range of work to be performed;
4. Accomplish any particular maintenance task or support service at a level which ensures optimum economic use of resources; and
5. Collect, analyze, and use data to assist all levels of management concerned with NAMP. [Ref. 3:p. 3-1]

a. Organizational Level Maintenance

O-level maintenance is usually performed by an operating unit on a day-to-day basis in support of its own operations. Blanchard (1992) states that:

> Maintenance at this level normally is limited to periodic checks of equipment performance, visual inspections, cleaning of equipment, some servicing, external adjustments, and the removal and replacement of some components. O-level personnel are usually involved with the operation and use of equipment, and have minimum time available for detailed system maintenance. [Ref. 4:p. 115]

The work performed at this level is to maintain assigned aircraft and aeronautical equipment in a full mission capable status while continually improving the local maintenance process. [Ref. 3:p. 3-1] Personnel assigned to this level generally do not repair the removed components, but forward them to the intermediate level. From the maintenance standpoint, the least skilled personnel are assigned to this function. O-level maintenance functions include inspections, servicing, handling, on-equipment corrective and preventive maintenance, including on-equipment repair and removal/ replacement of defective components, and records keeping and reports preparation. [Ref.3:p. 3-1]

b. Intermediate Level Maintenance

I-level maintenance is the responsibility of, and is performed by, designated maintenance activities in support of organizational activities. Blanchard (1992) states:

> At this level, end items may be repaired by the removal and replacement of major modules, assemblies, or piece parts. Scheduled maintenance requiring equipment disassembly may also be accomplished. [Ref. 5:p. 115]

The I-level maintenance mission is to enhance and sustain the combat readiness and mission capability of supported activities by providing quality and timely material support at the nearest location with the lowest practical resource expenditure. [Ref. 5:p. 3-1] Available maintenance personnel are usually more skilled and better equipped than those at the O-level and are responsible for performing more detailed maintenance. I-level maintenance consists of equipment material support such as:

1. Performance of maintenance on aeronautical components and related support equipment;

2. Calibration, by field calibration activities which perform I-level calibration of designated equipment;

3. Processing of aircraft components from stricken aircraft;

4. Technical assistance to supported units;

5. Incorporation of Technical Directives;

6. Manufacture of selected aeronautical components; and

7. Performance of on-aircraft maintenance, when required. [Ref. 5:p. 3-1]

c. Depot Level Maintenance

The highest level of maintenance is performed at naval aviation industrial establishments, called Naval Aviation Depots (NADEP's), on material requiring major overhaul or rebuilding of parts, assemblies, subassemblies, and end items. This level supports the accomplishment of tasks above and beyond the capabilities available at the I- and O-levels of maintenance. Blanchard (1992) expounds that:

> the D-level of maintenance includes the complete overhauling, rebuilding, and calibration of equipment as well as the performance of highly complex maintenance actions. [Ref. 4:p. 116]

D-level maintenance supports lower levels of maintenance by providing engineering assistance and performing maintenance that is beyond the capability of the lower level maintenance activities. [Ref. 5:p. 3-2] The use of assembly-line techniques in the depot facilities permits the use of relatively unskilled labor for a large portion of the workload, with a concentration of highly skilled specialists in such certain key areas as fault diagnosis and quality control. D-level maintenance functions may be grouped as follows:

1. Standard depot level maintenance of aircraft;
2. Rework and repair of engines, components and support equipment;
3. Calibration by Navy laboratories, as well as standards laboratories;
4. Incorporation of technical directives;
5. Modification of aircraft, engines, and support equipment;
6. Manufacture/modification of parts/kits;
7. Technical and engineering assistance by field teams; and
8. Age exploration of aircraft under reliability centered maintenance. [Ref. 5:p. 3-2]

B. THE AIRCRAFT INTERMEDIATE MAINTENANCE DEPARTMENT

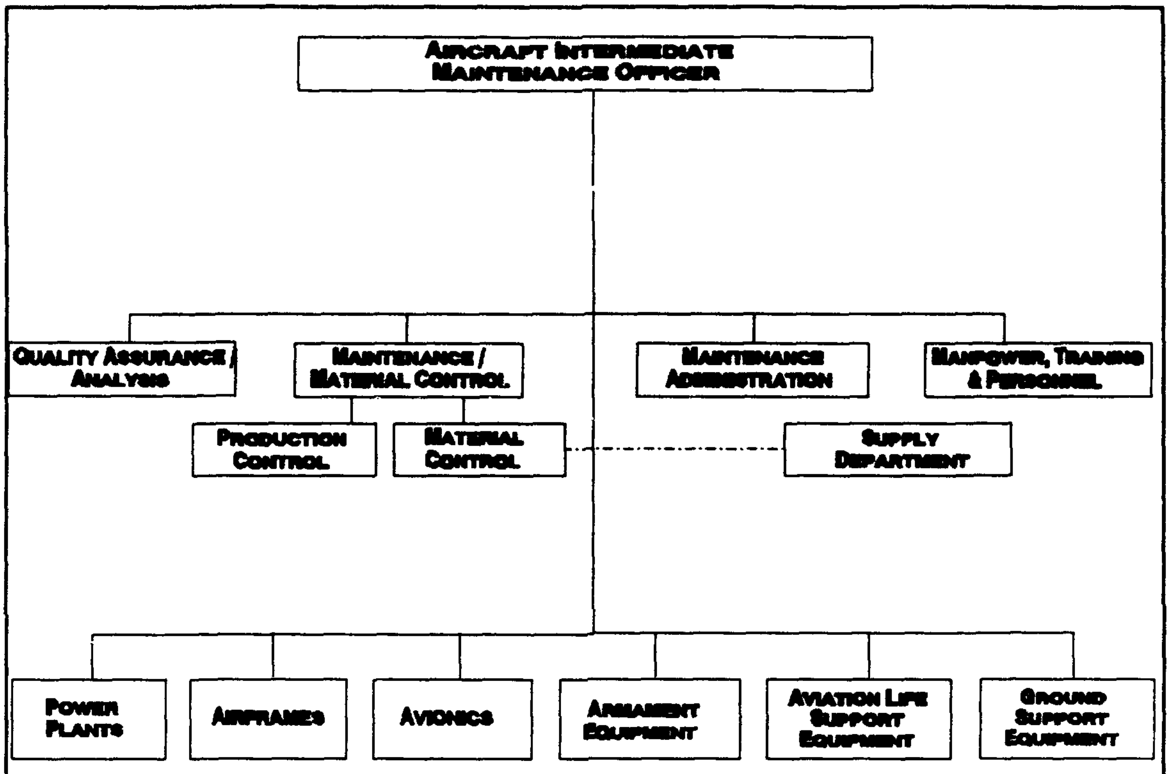
The Intermediate Maintenance Activity (IMA) comprises all departmental/organizational units responsible for providing I-level maintenance support ashore and afloat. Normally, an IMA consists of the aircraft intermediate maintenance department, the supply department, the weapons department, the public works department (ashore), and the engineering department (afloat). The AIMD, as an integral part of the IMA, is responsible for performing I-level maintenance functions on aircraft and aeronautical equipment located at the ship or station supported. [Ref. 5:p. 3-2] Thus, AIMDs ashore provide I-level maintenance to the squadrons based at Naval Air Stations.

AIMDs provide direct support for squadrons by repairing and returning components sent to the AIMD, conducting non-destructive inspections (NDI) on squadron aircraft and equipment, providing a ground support equipment (GSE) pool, assisting with the incorporation of technical directives, and additional problem-solving activities. AIMDs also repair not ready-for-issue (NRFI) rotable pool items for the base supply department.

1. Organization

The NAMP provides a standard organization for all AIMDs regardless of their location or type(s) of aircraft supported. This standardization ensures effective management within a framework of authority, functions, and relationships necessary to achieve improvements in performance, economy of operation, and quality of work. [Ref. 5:p. 3-1] Work centers are the designated functional areas to which maintenance personnel are assigned. Typical work centers of an AIMD are maintenance/material control (production control), quality assurance, power plants, avionics, airframes, weapons, and administration/training. The standardized organization of AIMDs operates well due to the common basic skills, techniques, and capabilities required regardless of the type of aircraft supported.

Figure 2.1 provides the standard ashore AIMD organization chart set forth in the NAMP. The organizational



Source: NAMP Volume III

Figure 2.1 - AIMD Organizational Chart (Ashore)

chart is divided into three layers. At the top is the upper management and staff. The middle layer includes a link between AIMD and the base supply department. Although supply is not directly tied to the AIMD, the relationship is very important to ensure adequate AIMD support for its customers. The lowest layer of the organizational chart presents the production divisions. Of particular concern to this thesis is the Power Plants Division where engine repair takes place. It is this AIMD division that will be modeled to study any changes in the flow of engine repair caused by lowering component life limits. This work center will be described in greater detail later in this chapter. What follow are brief descriptions of some key AIMD work centers.

a. Maintenance/Material Control (Production)

The Production Control Department, under the auspices of the Maintenance/Material Control Officer, is responsible for the overall production and material support of the AIMD. [Ref. 5:p. 8-1] Some of the many functions included in coordinating the activities of the production divisions are:

1. Coordinating the production divisions to ensure efficient movement of components through the department;
2. Maintaining liaison with supported units and the supply department to ensure material requirements and workload are compatible;
3. Coordinating and monitoring the department workload and assigning priorities;
4. Reviewing maintenance data reports to ensure effective use of personnel and facilities. [Ref. 5:p. 8-1]

Numerous other responsibilities are assigned to the Production Control Department, all with the primary purpose of taking "the actions necessary to retain or restore material or equipment to a serviceable condition with a minimum expenditure of resources." [Ref. 5:p. 8-2] To achieve this objective, Production Control schedules the workload using procedures set by the Maintenance Material Control Officer and then coordinates and monitors the production divisions to ensure efficient use of resources.

b. *Material Control*

The Material Control Department works directly for the Maintenance/ Material Control Officer. Material Control centers are contact points within maintenance organizations where requirements for parts and materials are coordinated with the Supply Support Centers (SSC's). The Material Control Department provides the interface between AIMD and the base supply department and is responsible for material support to the production divisions. The Material Control Department forwards requisitions for parts and material to the supply department. Upon receipt, parts and materials are expeditiously routed to the requisitioning work centers by the Material Control Department. [Ref. 5:p. 8-93]

c. *Quality Assurance/Analysis*

> The Quality Assurance concept is fundamentally that of the prevention of the occurrence of defects. [Ref. 5:p. 7-1]

The Quality Assurance/Analysis (QA/A) Department is organized with a relatively small group of highly skilled personnel working to achieve the above goal using process monitoring and inspections. The analysis function of QA/A Department prepares statistical process control charts by gathering, analyzing, and maintaining information on the quality characteristics of products, the source and nature of defects, and their impacts on current operations. QA/A has additional specific functions including maintenance of the AIMD central technical publications library, monitoring calibration dates for support equipment, training production divisions on methods to improve the quality of their work and inspection techniques, and providing feedback information on goals and achievements. [Ref. 5:pp. 7-1 - 7-4]

d. Power Plants Division

The Power Plants Division of the AIMD is responsible for inspection, repair, and subsequent testing of damaged or non-operable gas turbine engines, accessories, and components. This includes engines used for flight, starting purposes, or auxiliary power. For engines, modules, or components requiring D-level repair or engineering investigation, the Power Plants Division is responsible for preservation and preparation for shipment. The Power Plants Division is also responsible for maintaining accurate engine records and logs and for compliance with applicable power plant bulletins. [Ref. 5:p. 11-1 - 11-11]

The Power Plants Division of each AIMD is classified as a first, second, or third degree repair activity for each engine type/model/series (T/M/S) that NAVAIR authorizes the activity to repair. The objective of the three degree gas turbine engine repair program is to provide the policy and procedures whereby maintenance activities can effectively accomplish their assigned engine maintenance responsibilities. [Ref. 5:p. 11-1] Descriptions of the degrees of repair are as follows:

(1) Third Degree Repair. Third degree is the simplest, least involved degree of I-level repair. This repair encompasses major engine inspections and the removal and replacement of modules for modular engines. Third degree repair includes the same gas turbine engine repair capability as second degree except that certain functions which require high maintenance man-hours and are of a low incidence rate are excluded. To qualify as a third degree repair site for a particular engine, the facility should receive and process between one and nineteen engines of one type per year." [Ref. 5:pp. 11-1 - 11-2]

(2) Second Degree Repair. Second degree repair includes all functions of third degree repair. In addition, this repair capability includes minor module repair through replacement of components or assemblies. The NAMP describes second degree repair as follows:

> Repair/replacement of turbine rotors and combustion sections, including afterburners; the replacement of externally damaged, deteriorated, or time-limited components, gear-boxes, or accessories, and minor repairs to the compressor section. Further, the repair or replacement of reduction gearboxes and torque shafts of turboshaft engines and compressor fans of turbofan engines, which are considered repairable within the limits of the applicable intermediate manual, shall be accomplished by second degree activities. [Ref. 5:p. 11-1]

To qualify as a second degree repair site for a particular engine, the activity should receive and process no less than twenty engines of one type per year. [Ref. 5:p. 11-2]

(3) First Degree Repair. First degree repair is the most complex of the three types of I-level repair. All repairs which are authorized as second or third degree can be completed by a first degree repair activity. In addition, first degree repair involves analytical disassembly to determine the extent of disassembly and repair required to return the engine to service. The NAMP states that this repair includes compressor rotor replacement/disassembly to the extent that the compressor rotor could be removed. In order to qualify as a first degree repair facility, the activity should receive and process no less than fifty engines of one type per year. [Ref. 5:pp. 11-1 - 11-2]

(4) Repair Beyond First Degree. Engines that have been subjected to extreme conditions, or which require rework or repair beyond the capability of a first degree intermediate level maintenance facility as defined in maintenance instructions are routinely sent to a D-level facility. Some examples include crash damaged engines, engines which are excessively corroded, and those that have life limited parts that cannot be removed at the I-level. [Ref. 5: p. 11-5]

(5) Manning and Training. The primary Navy enlisted specialty code for maintenance personnel assigned to the Power Plants Division is Aviation Machinist's Mates (AD). In addition, Aviation Electrician's Mates (AE) may be assigned to work centers such as the engine test cell. Authorized manning levels for the Power Plants Division, as well as the entire AIMD, are set forth in the OPNAV 1000/2 Manpower Authorization Document. This document is specifically tailored to meet the personnel skill requirements of Navy organizations, authorizing manning levels skill requirements. These skill levels are delineated by the Navy Enlisted Classification Code (NEC) system which identifies particular skills and training necessary for designated billets.

Maintenance technicians obtain NEC designations by attending technical training courses. AIMD Lemoore is a designated training center for the F404 engine, enabling technicians to earn the following NEC designations:

1. 6420: F404 First Degree Technician;
2. 6422: Jet Test Cell Operator;
3. 7166: Jet Test Cell Electrician; and
4. 6417: T400 F/A-18 Auxiliary Power Unit (APU) Technician. [Ref. 6:p. 45-47]

C. AIMD Lemoore

AIMD Lemoore is designated a first degree repair site for the F404-GE-400 engine used in the F/A-18 aircraft. [Ref.

7:Encl.(18)] The main maintenance/repair building houses the administrative offices, work centers, test stands, and storage space for work-in-process (WIP) engines, modules and support equipment. The aircraft engine maintenance area totals 54,690 square feet consisting of a main maintenance/repair building of 48,000 sq. ft. and three operational turbojet/fan engine test systems (test cell) of 6,690 sq. ft. Due to the age of one cell, and the noise abatement problems associated when running the outdoor cell, only one test cell is routinely used. [Ref. 8]

Organization of and manning for AIMD Lemoore Power Plants Division is shown in Figure 2.2. This figure reflects only

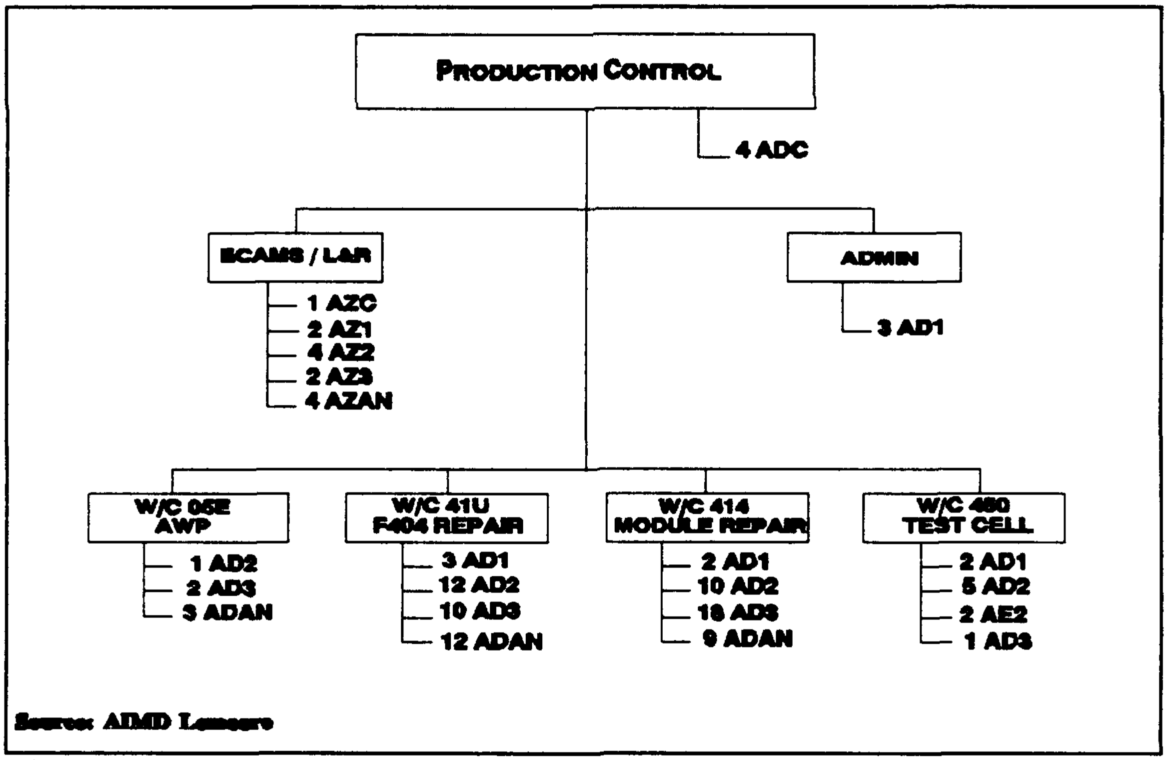


Figure 2.2: AIMD Lemoore's Power Plants Organization and Manning

actual assigned manning and does not include all personnel billeted by the manpower authorization document. [Ref. 8 and 9]

During the period from 1 October 1991 to 30 September 1992 AIMD Lemoore's Power Plants Division inducted 295 F404 engines and returned 287 of these engines to ready-for-issue (RFI) condition. This represents an average of 24.5 engine inductions per month and an RFI rate of 97.28 percent for the period.

D. F404-GE-400 ENGINE

1. Background

The F404 engine program began with the awarding of a development contract to General Electric (GE) in 1975. The F404 is derived from the YJ101, an engine that has the same technology as the F101 engine used in B-1A bombers. The basic YJ101 engine was scaled up approximately 10 percent for the F/A-18. [Ref. 10:pp. 2,025 - 2,036] Full development of the F404 engine was completed in 1980. Production began late in 1979, and by the end of March 1990, 1,900 engines were delivered to the Navy. The F404 is expected to be in service for 35 years. [Ref. 10:p. 4]

The F404 enhanced performance engine (EPE) is being installed in F/A-18C/D Lot 15 and later aircraft. The Enhanced Performance Engine (EPE F404-GE-402) was required as a result of additional weight of the newer F/A-18's. Design changes in the EPE correct many of the component life limit reductions addressed in this study. Because of their relativly small numbers, however, this thesis will ignore the different component life limits of the newer -402 engine.

The technique used to develop the F404 engine was a profound departure from former engine development programs. The F404 program approach stressed operational suitability, reliability, and maintainability whereas prior engine programs regarded performance and weight as the most important factors. [Ref. 10:p. 4] The engine was designed to have a high degree of reliability achieved through a cost-plus type contract, offering reliability and maintainability award fee incentives. [Ref. 10:p. 8]

2. Engine Characteristics

The F404-GE-400 turbofan engine is a low-bypass turbofan engine with augmented thrust provided by an afterburner. The engine is a modular construction, consisting of six major engine modules and an accessory gearbox. The engine consists of a three-stage fan, driven by a single-stage low pressure turbine and a seven-stage axial flow compressor driven in turn by a single-stage high pressure turbine. Continuous monitoring for critical malfunctions and parts life usage is provided by an In-Flight Engine Condition Monitoring System (IECMS). [Ref. 2:p. 1-2, Ref. 12:p. 1-1] This system maintains a record of engine operation as it affects various engine components and is transferred to the squadron database after each flight. Whenever the engine is sent to an I-level or D-level facility for maintenance, this record is transferred with the engine, enabling accurate tracking of all life-limited components.

The F404 engine is comprised of six main modules. These six modules are:

1. Fan Module;
2. High Pressure Compressor Module;
3. Combustor Module;
4. High Pressure Turbine Module;
5. Low Pressure Turbine Module; and
6. Afterburner Module.

Drawings of the engine and modules are presented in Appendix A.

3. F404 Reliability and Maintenance

a. Reliability

The F404 engine was designed with reliability and maintainability listed among the most important performance criteria during contract negotiations. Despite strict design goals and engine simplicity, the F404 has not met all planned reliability goals, though it has been significantly better than other Navy aircraft engines as shown in Table 2.1. Each performance measure represents average data for the three year period from 1987 to 1990.[1] [Ref. 10:p. 34]

TABLE 2.1 - FLEET EXPERIENCE WITH F404 AND OTHER ENGINES

Performance Measure	TF30 F-14	TF41 A-7	J79 F-4	F404 F/A-18	F404 Goals
MTBF (Hours)	33.7	24.4	29.4	67.4	>72.0
MTBMA (Hours)	14.3	10.1	13.9	19.0	>21.8
REM/1000 EFH	2.6	3.4	2.5	3.7	<2.0
MMH/EFH (Hours)	1.0	1.5	1.4	0.8	>0.5
MTTR (Hours)	5.1	5.8	8.9	6.2	<7.5

Source: Naval Air Systems Command

b. Maintenance

The maintenance plan for the F404 engine supports the Navy's Engine Analytical Maintenance Program (EAMP), which emphasizes reliability centered maintenance (RCM) and, to the maximum extent possible, utilizes an "on condition" maintenance policy. Blanchard (1992) states that RCM is:

> a systematic analysis approach whereby the system design is evaluated in terms of possible failures, the consequences of these failures, and the recommended maintenance procedures that should be implemented. The objective is to design a preventive maintenance program by evaluating the maintenance for an item according to possible failure consequences. [Ref. 4:p. 237]

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[1]MTBF . . . . mean time between failures
MTBMA . . . . mean time between maintenance actions
REM/1000 EFH . . removals per 1000 effective flight hours
MMH/EFH maintenance man-hours per effective flight hours
MTTR . . . . mean time to repair

In describing "on condition" maintenance, the F404 maintenance plan states:

> The on condition maintenance concept applies to all levels of maintenance on the F404 engines, modules, and components. This concept establishes maximum service life for certain parts so that reliable operations can be maintained throughout the life of the engine. To implement this concept, key life limiting parameters are monitored and cumulated by In-Flight Engine Condition Monitoring System (IECMS) for use by a Parts Life Tracking System (PLTS). Any engine part that is life limited will have its life specified in parameters calculated by IECMS. The PLTS consists of an on-board computer system and ground station computer that tracks all life limited parts by installation status (aircraft, engine, module, assembly) and updates the amount of life used for each part when usage data is input into the system. Life usage data input to PLTS is calculated and cumulated by the Enhanced Comprehensive Asset Management System (ECAMS) ground station. [Ref. 11:p. 26]

The modular construction of the engine facilitates the maintenance procedure. Each module can be assembled to or disassembled from the engine easily. This reduces engine down time by permitting replacement of a failed module, rather than holding the entire engine in a "down" status until the individual failed component can be repaired or replaced.

E. LOGISTICS PROBLEMS

1. Background

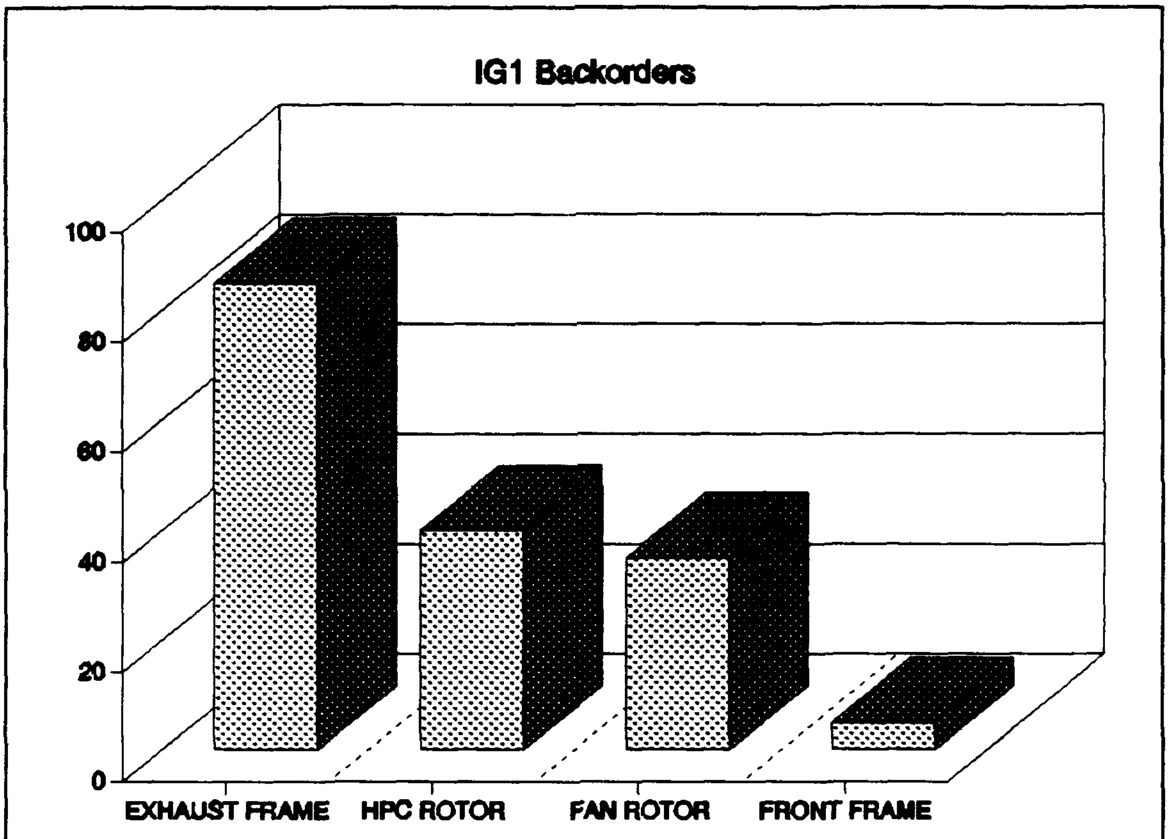
As long ago as 1980, NAVAIR personnel recognized that the lack of parts for both engine overhaul and assembly (component) repair contributed to the Navy's inability to maintain fully mission capable engines in the fleet. NAVAIRINST 4790.17, dated 3 September 1980, states:

> One of the major impediments to effective IMA jet engine repair has been the lack of RFI depot repairable assemblies as shelf stock. This has caused engines to be held at the IMA for excessive time awaiting parts, the expenditure of excessive man-hours in cannibalization, and the excessive use of depot customer service facilities. Engines needing only the replacement of a repairable assembly, which is not locally available, are being returned to the depot for repair rather than being repaired at the IMA. The net effect is a circumvention of the established maintenance and supply policies, with attendant loss of supply system demand visibility, and a general inability to effectively accomplish the jet engine intermediate maintenance program defined in the NAMP. Additionally, this lack of locally available repairable assemblies results in fewer RFI engines due to the increased "pipeline" time required for depot processing. [Ref. 13:p. 2]

Due to the Base Realignment and Closure Committee's decision to close the West Coast's F404 depot level repair facility at NADEP North Island, California, all maintenance actions listed in the F404 maintenance plan as D-level, as well as BCM actions from the first degree I-level sites, are sent to NADEP Jacksonville (JAX), Florida for repair. [Ref. 7:Encl. (18)] NADEP JAX is now the only aviation depot which provides organic F404 engine maintenance and repair capability within the Navy. This consolidation exacerbates the logistics support problem today in that all D-level maintenance is geographically located on the East Coast. AIMD Lemoore, and all other Pacific and West Coast repair facilities, suffer greatly increased transportation time for modules and engines from NADEP JAX due to the distance involved in shipping these assemblies.

2. Current Spares Procurement Outlook

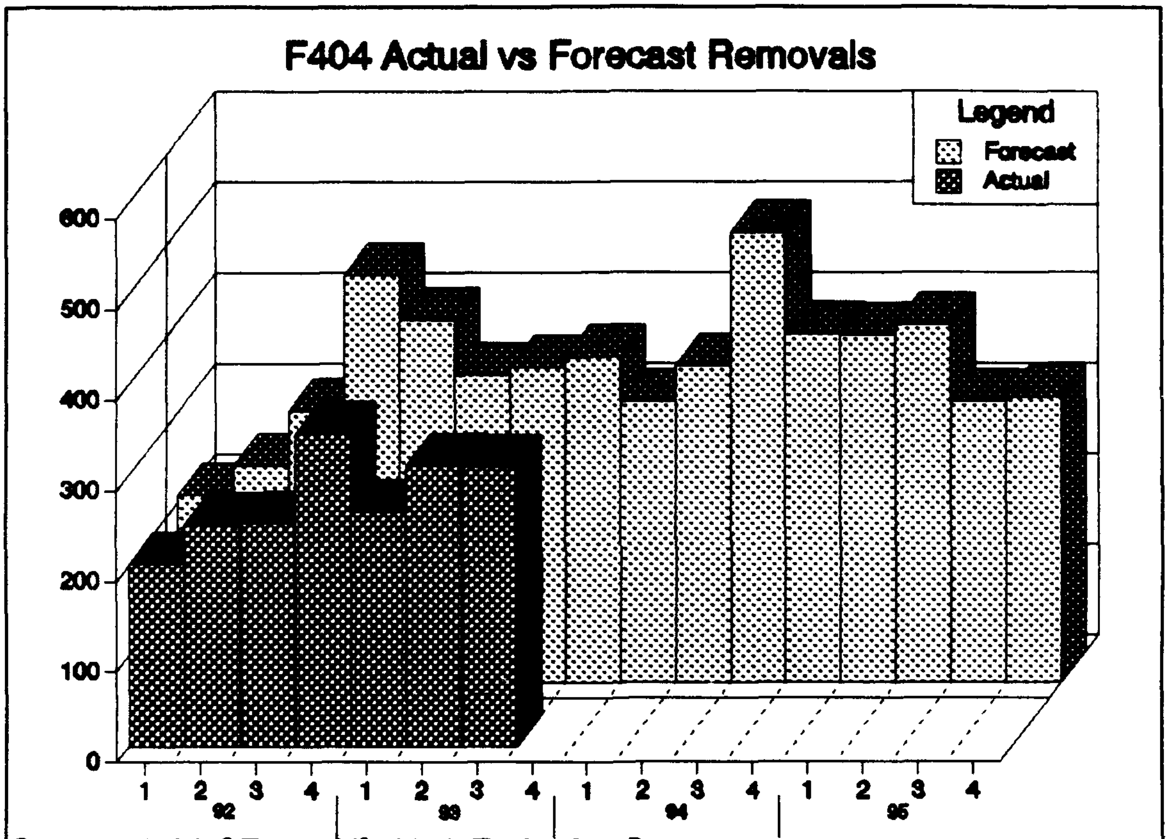
Lack of repair parts for components is still evident today as shown in Figure 2.3. [Ref. 13:p. 3] Adding to this problem is the long lead-times involved in the procurement of new parts and components, which can sometimes be as long as two years or more.



Source: F404-GE-400 Life Limit Reduction Summary

Figure 2.3 - Top F404 Logistic Shortages

This parts shortfall is further complicated by the life limit reductions in the fan disks, the HPT cooling plate, stage three LPT disk, and stage one and two spools in the HPC module caused by premature cracking. Incremental life limit reductions are scheduled through January 1994, which will result in an increased engine induction rate as shown in Figure 2.4. [Ref. 13:p. 3] The supply/repair parts posture thus far has been unable to respond quickly enough to this increased induction rate, and a substantial "buy" is not anticipated until mid-1994. [Ref. 14]



Source: F404-GE-400 Life Limit Reduction Summary
Figure 2.4 - F404 Actual vs Forecast Removals

Additionally, due to the modular design of both types of F404 engines, all -400 and -402 modules are physically capable of being mismatched. This modular design was intended to facilitate maintenance and repair, but the consequences of mixed module/component/part scenarios range from decreased life to engine failure. This further complicates the repair process, as each engine must be matched to its proper series/type components. Interchangeability of -400 and -402 components must be prevented to preclude potential disastrous results. [Ref. 13:p. 6]

Although the supply/repair parts posture should improve in the future, F404 repair is now heavily affected by life reductions in the Fan, HPC, HPT, and LPT modules. Weekly conference calls are being conducted to determine the distribution of limited parts. In addition, maintenance and support issues are being addressed in an attempt to minimize fleet impact. [Ref. 13:p. 5]

III. SIMULATION MODEL DEVELOPMENT

This study focuses on the flow of engines and modules being repaired at AIMD Lemoore following component life limit reductions. These reductions will alter the repair process by increasing the number of engine inductions at the AIMD, as well as increasing the rate and delay times for modules sent to the depot for repair. The authors developed a simulation model to determine if significant differences will occur in turn-around-times, capacity utilization, bare firewalls and inventory waiting for repair following component life limit reductions.

To develop a model of the AIMD, engine movement through the repair process is translated into SIMAN operating commands. The model uses a Poisson probability distribution to simulate engine interarrival times, and triangular distributions to model repair times. Each engine is separated into its six component modules for simultaneous repair, which permits the model to simulate multiple work centers. Throughout the simulation, statistics are collected to study the behavior of engines and modules as they flow through the AIMD.

A. OVERVIEW OF SIMAN

The simulation model, to evaluate the impacts of reductions in the life of engine components at AIMD Lemoore, was written in the simulation language SIMAN. A short description of the main features of SIMAN is provided below.

1. Model Frame

The SIMAN model provides a functional description of a real world system and the interactions between its various parts. It describes physical elements such as engines and modules, and their general flow through the repair process. In addition, the model depicts the logical interrelationships between system components. [Ref. 15: p. 62]

The basic structure of a SIMAN model frame has the following elements:

1. CREATE failed engine arrivals.
2. QUEUE to wait for engine and module repair.
3. SEIZE the repair work center when available.
4. DELAY for the repair and awaiting parts time.
5. RELEASE the repair work center for the next arrival.
6. TALLY the time in system (statistics).

2. Experiment Frame

The experiment defines variables, attributes, and other conditions which are imposed on the model. These include the length of the simulation, various initial conditions, resource availability, and the types of statistics collected. The experiment allows parameters to be easily changed without modifying the basic structure of the model. [Ref. 15:p. 85]

The basic structure of a SIMAN experiment frame includes the following elements:

1. QUEUES provides a name for each queue where engines or modules may have to wait for repair or parts.

2. RESOURCES provides the number of repair channels and spares available for use at the AIMD.

3. TALLIES provides descriptive statistics about data being recorded, for example, engine TAT, waiting times, etc.

4. DSTAT records time-persistent variables that includes the number of engines/modules in various queues, repair channel utilization, and spares utilization.

5. COUNTERS provides a total number of engines/modules undergoing some process during the course of the simulation.

6. SEEDS provides a seed for random number generation.

7. REPLICATE provides information regarding the length of the simulation and the warm-up period. This warm-up element allows the system to stabilize before usable statistics are generated for steady-state simulation.

3. Probability Distributions

In modelling real world environments, stochastic properties must be added to describe the effects of random fluctuations. [Ref. 16:p. 3] SIMAN has the ability to simulate stochastic behavior by generating random variables which influence the system.

Selection of an appropriate probability distribution is a critical task in designing the simulation model. [Ref. 16:p. 137] The following sections describe the properties of these distributions and the subsequent reason for their selection in this study.

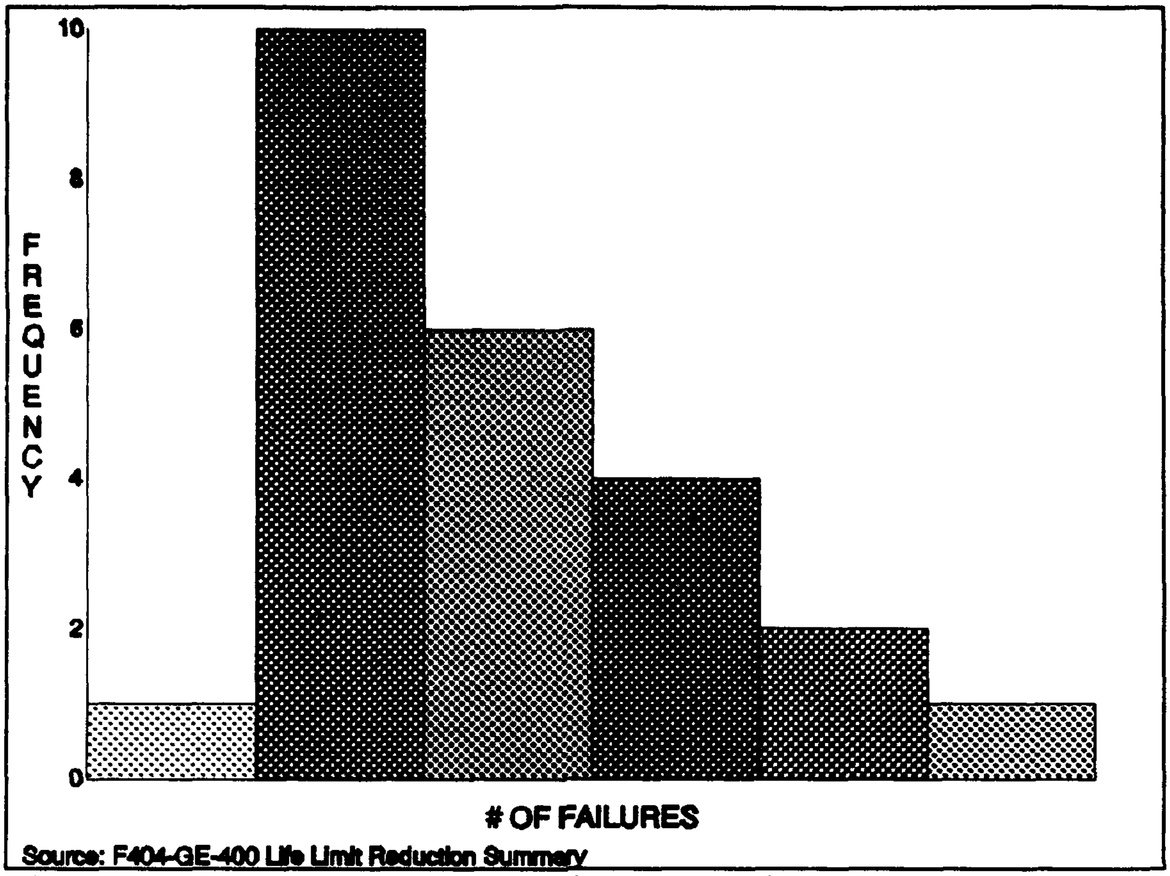


Figure 3.1 - AIMD Lemoore Engine Induction Data

The first distribution used in this study generates an arrival rate of engines at AIMD Lemoore AIMD. Figure 3.1 shows the frequency of F404 engine removals during FY91 and FY92. The pattern that emerges approximates that of the Poisson process. Figure 3.2 shows a typical Poisson distribution. In this Figure, x indicates the values for total engine removals during a year and p(x) represents the probability with which x removals occurred. The distribution function of Poisson is shown in the upper right-hand corner of Figure 3.2.

The time between events in the Poisson process is known to be exponentially distributed, so the mean time between engine failures (MTBF) can be modeled as being exponentially distributed with a mean of μ, the reciprocal of the MTBF. [Ref. 4:p. 30] This study will use the exponential distribution to model engine interarrival times. Figure 3.3

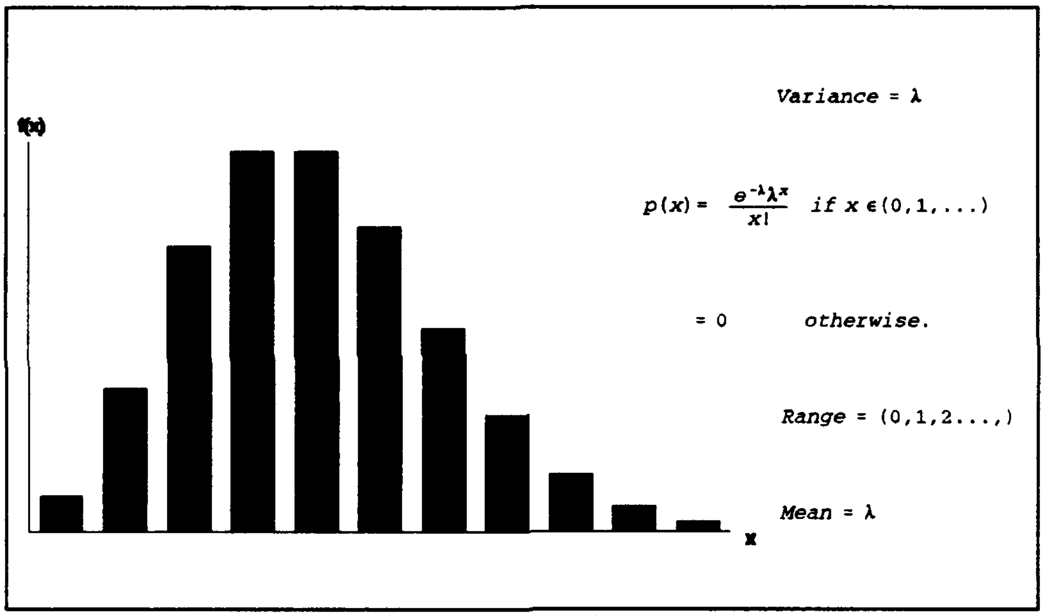


Figure 3.2 - Poisson Distribution.

provides an example of an exponential distribution where x represents time between removals and f(x) is the probability density function.

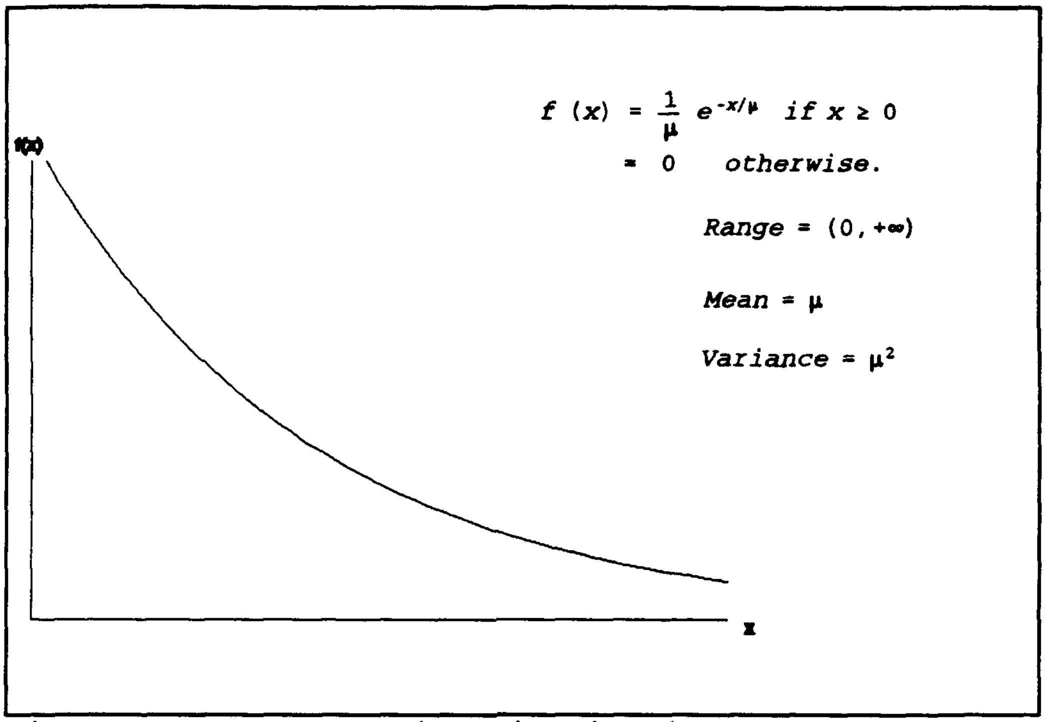


Figure 3.3 - Exponential Distribution.

The triangular distribution will be used to generate repair and waiting times. This simple distribution is easy to generate and is often used with limited data sets. [Ref. 16:p. 167] The triangular distribution is shown in Figure 3.4, defined by its three values of minimum, mode and maximum. The mode is the value most frequently seen for service or repair time. Based on conversations with AIMD Lemoore production managers, the minimum value is assumed to be 80% of the mean, while the maximum is assumed to be 140% of the mean.

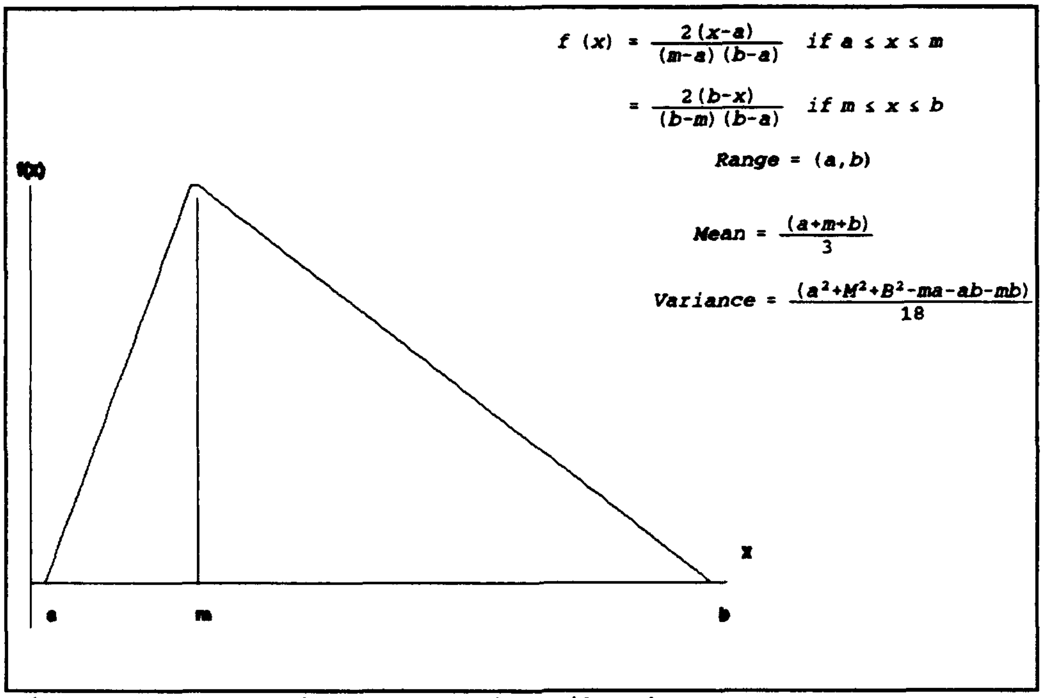


Figure 3.4 - Triangular Distribution.

B. MODEL ASSUMPTIONS

The simulation model attempts to recreate the AIMD environment as realistically as possible. Certain situations, however, were beyond the modeling capabilities of the authors. In addition, various data was unavailable to include in the research. The following list of assumptions were used to simplify the model and fill in missing data used in this experiment:

1. Engines inducted into the AIMD sometimes are disassembled only to the extent needed for repair of the non-RFI component or module, with RFI sections of the original engine remaining connected. Frequently, however, if an RFI module from a partially disassembled

engine is needed in another engine, the module will be used as a spare. In order to simulate the use of RFI modules as spares, the model assumes all engines are fully disassembled upon induction and all modules not needing repair are available as spares.

2. The simulation model operates 16 hours a day 5 days a week with an additional 8 hour shift on the weekend. The model ignores off-hours. Adjustments have been made in the arrival rate of engines to keep the total number of simulated engines inducted equal to the actual amount over a calendar year.

3. Each engine is disassembled into six separate modules prior to entering the repair process. Due to programming limitations, however, it was necessary to remove two modules from the simulation. Neither the combustor module nor the afterburner module were affected by reductions in component life limitations, so the authors felt it was reasonable to eliminate them from the model without adversely affecting the outcomes. Adjustments were made to reduce the available repair personnel resources.

4. The Navy's standard workweek includes 33.38 hours out of 40 available for productive work for shorebased activities. This model, therefore, assumes 83.45 percent of the assigned workers are available.

5. In using the triangular distribution, it is assumed the minimum value will be 80% of the mean. The maximum value will be 140% of the mean. This provides a reasonable approximation of the characteristic skewness seen in complex repair times [Ref. 8]

C. DATA COLLECTION

The data used in this research was gathered from a variety of sources. Aircraft Engine Management System (AEMS) and Naval Aviation Logistics Data Analysis (NALDA) databases were used to obtain engine interarrival times, AIMD repair times, depot (BCM) rates and average delays waiting for parts (ACWT/AWP).

Engine production supervisors at AIMD Lemoore power plant division provided information regarding inventory levels waiting for parts or repair, bare firewalls at NAS Lemoore, and personnel resources available in the repair centers. On-site visits also enabled the authors to construct a model of the power plant work center repair flow. General Electric engineers produced a forecast of expected engine removal rates for the upcoming quarters through March of 1995, resulting from a reduction in component life limits. [Ref. 13]

D. MODEL PARAMETERS

The following sections describe model parameters in detail. Data will be displayed along with its source in tabular form, followed by a narrative on how it was used in the model.

1. Interarrival Times

Engine removals at all activities serviced by AIMD Lemoore form an arrival pattern that approximates a Poisson distribution as shown in Figure 3.1. Based on this evidence, interarrival times are assumed to follow an exponential distribution. In FY92 AIMD Lemoore experienced an average of 24.5 engine induction per month. Using an average value of 4560 operating hours per year, this equate to an interarrival time of 14.3 hours. This model, therefore, incorporates an exponentially distributed engine interarrival time with a mean of 14.3 hours.

2. Repair Times

The repair times used in the AIMD model were obtained from FY-92 NALDA data records and are shown in Table 3.1. The

TABLE 3.1 - REPAIR TIMES (HRS)

Work Center	Task	Module	Mean Service Time
O-Level	Engine Removal	Engine	3.82
O-Level	Engine Install	Engine	5.74
41U	Engine Assy/ Disassy	Engine	37.30
414	Fan Repair	Fan	42.97
414	HPT Repair	HPT	26.38
414	LPT Repair	LPT	57.23
414	HPC Repair	HPC	33.46
414	CMB Repair	CMB	14.29
413	AB Repair	AB	18.83

Source:FY-92 NALDA Data Reports

repair times are mean values, using a weighted average to calculate average service times for both engines and modules. The frequency of each work unit code failure by engine/module was multiplied by the average repair time. These figures were then summed and divided by the total number of removals for each engine/module to obtain the weighted average service times.

3. Engine and Module Repair Channels

The capacity of the AIMD to repair engines is largely based on the available personnel and equipment resources labeled in the model as repair channels. At NAS Lemoore the number of repair channels is determined by maintenance man hours available, since work center capacity is not limited by equipment. The assigned number of personnel in each work center are not available for productive work 100 percent of the time due to time off taken for lunch, breaks, meetings, training, sickness, and vacations. The simulation model operates 16 hours a day, 255 days a year, equaling the 4080 available maintenance man hours per year typical at NAS Lemoore.

To determine the number of channels for each work center during each shift, the number of technicians is multiplied by the productivity factor (.8345), then divided by the channel size of two or three people, depending on the work center. This number was further reduced by 35% to account for the removal of two modules from the model (determined through discussions with power plant supervisors). Once the number of available man hours per work center was calculated and converted into an equivalent number of repair channels, the result was rounded off to the nearest integer. Table 3.2 provides the number of available repair channels for the SIMAN models.

4. BCM Rates for Engine and Modules

Some maintenance actions cannot be completed by the AIMD for a variety of reasons including administrative and

TABLE 3.2 - REPAIR CHANNEL CALCULATION

Work Center	**Channel Calculation**
41U Engine Day Assembly/Disassembly	23*.8345*.65/3= 4.15 rounded to 4
41U Engine Night Assembly/Disassembly	14*.8345*.65/3= 2.53 rounded to 3
414 Module Repair Day	24*.8345*.65/2 = 6.51 rounded to 7
414 Module Repair Night	16*.8345*.65/2 = 4.34 rounded to 4
450 Test Cell Day	7*.8345*.65/3 = 1.25 rounded to 1
450 Test Cell Night	6*.8345*.65/3 = .9 rounded to 1

lack of equipment or expertise. The simulation model uses the BCM rates shown in Table 3.3 to simulate routing a percentage

TABLE 3.3 - BCM RATES

Component	**BCM Rate**
Engine	.0271
Fan Module	.1232
HPT Module	.3105
LPT Module	.0625
HPC Module	.2632
CMB Module	.0092
AB Module	.0001

Source:FY-92 AEMS Data Reports

of engines and modules to the depot for repair. These BCM rates were obtained from the FY92 AEMS data reports. [Ref. 17]

BCM rates for FY93 and FY94 were derived from General Electric estimates of engine removal rates. Engine removals in FY93 and FY94 above those experienced in FY92 were assumed to be for high-time repairs caused by lowering component life limits. Replacement of these high time components are beyond the maintenance capability of the AIMD, necessitating transfer to the depot. This increase in depot-level repairs is reflected in the higher BCM rates.

5. Awaiting Parts Time and Average Customer Wait Time

Engines and modules being repaired at the AIMDs must often wait for parts after they are disassembled. This delay is recorded as awaiting parts time. When an engine or module is sent to the depot for repair, a replacement is ordered from the supply system. The average customer wait time (ACWT) is the time needed to obtain the replacement. The average delay times for AWP and ACWT were obtained from FY-92 AEMS data reports. They are shown in Table 3.4.

The increase in depot-level repairs in FY93 and FY94 is expected to have a direct impact on ACWT. [Ref. 18] High time component repair involves the replacement or rework of precision, high-cost parts. Long lead times are normally required for any increases in production rates. Logistics managers do not expect additional replacement inventory to arrive before the third quarter of FY94. The anticipated increases in ACWT have been estimated from 25% to 200%. Multiple simulations will be performed to cover this range of

TABLE 3.4 - AWAITING PARTS/AVG. CUSTOMER WAIT TIME (HRS)

Component	AWP	ACWT
Engine	---	221
Fan Module	792	298
HPT Module	168	278
LPT Module	72	317
HPC Module	720	180
CMB Module	672	185
AB Module	96	238

Source:FY-92 AEMS Data Reports

ACWT. No effect on AIMD AWP is expected as a result of lowering component life limits.

6. Engine and Module Spares

Conversations with officials at NAS Lemoore indicated that the AIMD does not receive spares to augment its repair operations. For all practical purposes, afloat commands and in-theater repair sites receive all available spare assets. The AIMD does, however, have an average of 60 non-RFI engines in storage waiting for parts. These non-RFI engines frequently contain one or more RFI modules which can and do get used as spares. Using these assets provides faster repairs in the short run, but typically creates more delays in the long run. [Ref. 9]

Including these assets in the model proved difficult due to the lack of data regarding their use. The model assumes that all engines inducted will be fully disassembled, making available any module not requiring repair.

7. Module Failure Percentages

Once an engine is inducted into AIMD, a detailed engine logbook review is conducted to identify any high time components. This may result in multiple maintenance actions against more than one module regardless of the original reason for engine removal.

When an engine is inducted for repair, the model breaks the engine down into the six modules. Modules are then directed to the appropriate work center for repairs or to the spare pool if no repair is needed. If the work center is empty, the failed module enters service. If the repair shop is full, the failed module waits in a queue until the center is available. Table 3.5 provides the module failure

TABLE 3.5 - FAILURE RATE

Component	PERCENT FAIL
Fan Module	46.78%
HPT Module	64.41%
LPT Module	48.81%
HPC Module	25.76%
CMB Module	36.61%
AB Module	69.15%

Source: FY-92 AEMS Data Reports

percentages for the period from 1 October 1991 to 30 September 1992, obtained from FY-92 AEMS data reports.

E. AIMD MODEL

The AIMD simulation starts with a sequence of entities (engines) arriving at the repair facility. The CREATE block generates the need to remove an engine followed by an appropriate delay simulating actual removal. At this point the engine branches to both a repair process and an engine replacement process.

The replacement process begins with an aircraft engine queue. Here the aircraft with the engine removed looks for a spare engine at the QUEUE block. If an RFI engine is available, the aircraft "takes it" at the SEIZE block, followed by another delay for installation. If a spare is not available, however, then the aircraft remains grounded and waits in the queue for the next available spare.

At the same time the aircraft is looking for a spare engine, the non-RFI engine is sent to either one of two places by another BRANCH block. It is either sent to the depot for repair or it is inducted into the AIMD.

All BCM'd engines are delayed an appropriate amount of time to simulate average customer wait time, the time it takes for the supply system to deliver a replacement spare. Once received, the spare is made available to the next aircraft waiting in the replacement process queue.

Engines inducted into AIMD are delayed to match ECAMS data with a Navy-wide database. Once the databases are matched, the engine proceeds to work center 41U, where it is disassembled as soon as the center has available space (repair channel). The engine is again delayed for inspection and disassembly before it is released and sent to its next destination.

At this point, the separate modules are branched to their respective module spare pools or module repair work centers depending on their status. Those needing repair are either BCM'd or repaired at the AIMD. BCM'd modules are delayed until supply issues an RFI spare, at which point the RFI module replenishes the spare pool. Repaired modules also replenish the pool following appropriate delays at a work center (repair channel), for parts and actual repair work.

As the four modules undergo their various procedures, the model looks for a group of separate RFI segments to assemble as a total engine. Once four different modules are available, the process must wait for work center availability, followed by the actual reassembly procedure. From here the assembled engine waits for an available test cell where it will be given required checks before returning to the replacement process queue.

IV. MODEL VALIDATION AND ANALYSIS

This chapter will present an analysis and the results of the simulation model. As part of the analysis, validation of the model will demonstrate that the simulation generates reasonable outputs that approximate actual AIMD Lemoore operations. This will be done through a tabular comparison of simulation outputs and FY-92 historical data.

A. MODEL VALIDATION

Simulation results were compared with actual AIMD Lemoore data to help determine model validity. FY-92 NALDA data provided engine arrival rates, delays for repair or work-in-process (WIP), AWP delays and BCM rates used in the simulation model. Averages of AWP and WIP delays were collected during 5 simulation runs to ensure the model was generating correct delays for repair times. Output generated by the model was also compared against actual AIMD Lemoore production statistics. These included the number of items inducted, repaired and BCM'd, module turn-around-times and the number of aircraft waiting for engines.

1. Awaiting Parts Comparison

Table 4.1 provides a comparison of simulated and actual AWP delay times averages from 5 simulations. The model generated delays with averages similar to those of actual AWP times.

TABLE 4.1 - AWAITING PARTS TIME COMPARISON

Maintenance/ Supply Factors	Simulation Results	NALDA Data	Difference Simulation & NALDA
Fan AWP	789.86	792.00	2.14
HPC AWP	724.30	720.00	4.30
HPT AWP	166.85	168.00	1.15
LPT AWP	72.13	72.00	0.13
CMB AWP	674.01	672.00	2.01
AB AWP	95.58	96.00	0.42

Source:Developed from NALDA data & averages of 5 simulations

2. Work-in-process Comparison

Table 4.2 compares simulated and actual WIP time averages. The simulation again generated delays with averages similar to the actual data.

TABLE 4.2 - WORK-IN-PROCESS TIME COMPARISON

Component Repair Time	Simulation Results	NALDA Data	Difference Simulation & NALDA
Fan WIP	64.07	42.97	21.10
HPC WIP	36.39	33.46	2.93
HPT WIP	28.73	26.38	2.35
LPT WIP	60.97	57.23	3.74

Source:Developed from NALDA data & averages of 5 simulations

3. Items Repaired and BCM Actions

Table 4.3 compares the simulation output of the total AIMD items repaired against the actual data. Table 4.4 shows

TABLE 4.3 - COMPARISON OF ITEMS INDUCTED/REPAIRED

Item Inducted Repaired	Simulation Results	NALDA Data	Difference Simulation & NALDA
Eng Inducted	301.00	295.00	6.00
Eng Repaired	284.20	287.00	2.80
Fans Repaired	117.40	121.00	3.60
HPTs Repaired	126.20	131.00	4.80
LPTs Repaired	135.10	135.00	0.10
HPCs Repaired	53.30	56.00	2.70

Source:Developed from NALDA data & averages of 5 simulations

that simulated BCM actions closely matched that of the actual data.

TABLE 4.4 - COMPARISON OF BCM ACTIONS

Component BCM'd	Simulation Results	NALDA Data	Difference Simulation & NALDA
BCM Engines	10.4	8.00	2.4
BCM Fans	17.3	17.00	0.3
BCM HPTs	62.6	59.00	3.6
BCM LPTs	10.9	9.00	1.9
BCM HPCs	22.8	20.00	2.8

Source:Developed from NALDA data & averages of 5 simulations

B. RESULTS AND ANALYSIS

This section provides FY93 and FY94 estimates of engine and module turn-around-times, capacity utilization and bare firewalls at AIMD Lemoore. Highlights of simulation output will be discussed along with tabular presentations available in the Appendices A through D.

1. Turn-around-time (TAT)

Appendix A shows the impact a decrease in component life limits could have on TAT. Turn-around-time is defined as the delay of an engine or module from the moment it is removed from service to the moment it is ready for issue (RFI). Increases in TAT resulting from changes in ACWT were seen in the engine but not in the four affected modules. Increases in engine TAT up to 15.5% resulted when ACWT was increased by 100% to 200% above the FY92 baseline values. Lower engine TAT was observed when ACWT increased 25% to 75% above the baseline. Induction rate appeared to have little impact on TAT.

Engine TAT can initially be seen to decrease, followed by an increase, as ACWT climbed 75% above the FY92 baseline. This is a result of shorter module repair queues at as the BCM rates increase. As ACWT increases 75% above the baseline, the longer delay at the depot impacts the availability of spares at the AIMD. This creates a shortage of RFI modules available for engine build-up.

Fan and HPT modules demonstrated TAT may not be significantly impacted by changes in ACWT, induction rate, or BCM rate. This is due to the insignificant changes in the number of Fans and HPTs waiting to be repaired. The FY92 average of .19 Fans and .39 HPTs was reduced to .13 and .26

respectively in FY94. This negligible change resulted in relatively no impact on either Fan or HPT TAT.

Higher induction rates and longer ACWT delays resulted in even lower TATs in the HPC and LPT. The HPC TAT went from the baseline value of 1,168.6 to 912.9 in FY94, while the LPT TAT decreased from 242.3 in FY92 to 225.1 in FY94. This can be attributed to the higher BCM rate, eliminating some demands on the AIMD repair system. With less modules being delayed while waiting for an available work center, these modules could get through the system quicker.

The number of HPC modules awaiting repair decreased from a baseline of 3.74 HPCs to .53 HPCs in FY94, while the LPT saw reductions from 1.09 LPTs to .49 LPTs in FY94. No significant relationship between HPC TAT reduction and ACWT increase was apparent, possibly due to the relatively large HPC fluctuations in delay times. The LPT module experienced TAT reductions from 2% and 8% with no apparent correlation between ACWT and TAT.

2. Queue Lengths

Changes in queue lengths are listed in Appendix B. These changes reflect how reductions in component life limits affect the number of modules waiting for repair or parts. Queue lengths were measured for each module waiting for repair. The bare firewall queue will be discussed below.

FY92 baseline data and subsequent simulation runs showed the number of modules waiting to enter work center 414 generally remained below 2. These queues remain small due to the apparent balance between induction rate and BCM rates. As the number of engines arriving at the AIMD increases, a proportionally equivalent number of modules are BCM'd due to the need for high time repair.

3. Modules Awaiting Parts

Appendix C lists the number of modules waiting for parts. With the exception of a .52% rise in the HPC module, changes in ACWT and engine interarrival time resulted in reductions of modules awaiting parts. These decreases ranged from .2% up to 11.4% with no apparent connection to changes in ACWT. The number of modules awaiting parts in FY93 AWP appeared somewhat larger than FY94 values, indicating that the relationship between induction rates and BCM rates shifted creating fewer modules awaiting parts in FY94.

4. Work Center Utilization

Work center utilization rates help determine if sufficient capacity exists to support engine and module repair as arrival rates change. Monitoring utilization rates is one means of identifying production bottlenecks or excessive capacity.

Appendix D shows AIMD Lemoore work center utilization rates generated from the simulation model of the three major work centers. AIMD production officials verified that the

FY92 baseline figures were representatives of the actual activities.

Work Center 414 consistently shows utilization rates in excess of 100%. This may possibly be explained by SIMAN software operations which may allow the number of entities to exceed the number of resource channels. As repair channel resources are reduced to reflect lower night shift and weekend operations, the model may allow engines to remain in repair. This could make it possible to have more than a one-to-one assignment of jobs for a short period of time following shift changes. While these values are not truly representative of actual repair channel utilization, a direct relationship can be identified as the induction rate changes.

414 utilization rate changes were not apparently related to changes in ACWT. Decreases ranging from 7.4% to 9.4% were recorded in FY93, with reductions ranging from 3.5% to 7.0% recorded in FY94. Overall reductions can be attributed to higher BCM rates for modules inducted at the AIMD, placing less demand on the repair center. Higher FY94 values indicate that BCM rates were offset by the induction rate during this period causing slightly higher utilizations.

41U utilization was seen to increase from a baseline of 56.8% to a high of 76.3% in FY94. ACWT delays appeared to have little impact on the utilization rate. With the highest increases recorded in FY94, it was clear that induction rate had the greatest impact on 41U. This is easily explained by the fact that all modules, regardless of their BCM rates, must go through this work center.

Test cell utilization of 450 changed from 16.8% in FY92 to a high of 22.7% in FY94. In this work center as well, ACWT appears to have no effect on utilization rates. Likewise, utilization rate appears directly related to induction rate. This, too, can be explained as a result of more engines being repaired as the induction rates go up, requiring more engines to be checked in the test cell.

5. Engines Repaired/BCM'd

Appendix E shows the effect of reduced component life limits on the number of engines repaired or sent to the depot. A increase is seen in the number repaired, as higher induction rates caused the flow of engines through the AIMD to increase. At the same time, BCM rates are lowered to maintain the total number of engines BCM'd the same in all periods. This is due to the assumption that BCM actions, resulting form catastrophic failures, would not be affected by the lower component life limits.

Engines repaired increased from a baseline of 308 in FY92 to a high of 417 in FY94. Average increases of 22% in FY93 and 35% in FY94 appeared to be directly dependent on induction rate increases. No apparent correlation between ACWT and numbers repaired was observed. BCM values also increased, ranging from a baseline of 10.4 to a high of 21.

No apparent correlation existed between any increasing parameters.

6. Modules BCM'd

Appendix F shows the number of modules BCM'd rose throughout FY93 and FY94. The LPT's and Fans experienced increases in excess of 400%. These increases combined with higher ACWT delays had a significant impact on the overall repair capability of AIMD Lemoore.

Chapter III described how engines reassembled at AIMD Lemoore rely on module spare pools replenished by AIMD and depot repair. In as much as Lemoore depends on the depot for spare modules following BCM actions, any increase in depot repair times will directly affect AIMD repair capability.

The number of BCM'd fans grew from a baseline of 17 to a high of 97 in FY94, an increase of over 450%. HPTs BCM'd went from 62 to 96, an increase of 54%. HPCs BCM'd grew 182% from a baseline of 23, and LPTs rose from 11 to 56, an increase of 414%. In all cases, induction rate appeared to have the greatest effect on the number of modules sent to the depot, while ACWT delays had no apparent impact.

7. Bare Firewalls

Bare firewalls are an indication of the number of aircraft awaiting engines. As more engines are removed, greater demands are placed on the repair system to supply RFI replacements. Delays in BCM'd engines and modules generate increasing queues of aircraft waiting for engines. Appendix

G indicates that bare firewalls grew from a baseline of 33.7 to a high of 54.1 in FY94. This indicates indicates that both ACWT and induction rates have a direct impact on the number of bare firewalls.

The number of bare firewalls is perhaps the most significant statistic collected in this study. Each bare firewall can represent an F/A-18 aircraft grounded for lack of an engine. The cost associated with this asset is in excess of $30 millon per aircraft. In addition, the loss in readiness and training must also be factored. The simulation forecasts an increase of 60.7% above baseline in the number of bare firewalls, which could represent 45% of the aircraft stationed at NAS Lemoore being grounded.

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The focus of this thesis has been to determine the effects that lowering component life limitations will have on the repair of F404 engines at AIMD Lemoore. Using simulation, the investigation looked at the effects of lowering component life limits on turn-around-time, capacity utilization, queue lengths, items repaired and bare firewalls. The results of the simulation demonstrated that AIMD Lemoore engine production flow will not be greatly affected by component life limit reductions. Our simulation also showed that a significant increase in grounded aircraft due to bare firewalls occurred when ACWT delays and induction rates were increased by the amounts forecasted by the APML and GE engineers. In addition, the amount of modules BCM'd due to high time repairs created a substantial increase in depot-level work. Increases of over 400% were observed in some cases.

B. CONCLUSIONS

The following conclusions provide answers to the research questions stated in Chapter I. In particular, the conclusions address the impacts on TAT, WIP, BCM rates and work center utilization when component life limits were reduced. These impacts estimated using simulation models provide strong indications that lowering engine component life limits will have a significant impact on engine production and bare firewalls. The simulation model furnished the following evidence.

1. Model Validity

For model validation, the simulation results of the current repair times provide an accurate system of AIMD Lemoore's engine production capabilities.

2. Engine and Module Turn-around-time

Engine and module TATs increase since reduced engine component life results in higher engine induction rates and ACWT delays. Simulation results showed that TAT will significantly increase only when ACWT delays approach 200%.

3. Bare Firewalls

An increase in aircraft grounded due to lack of RFI spare engines resulted from lowering component life limits. Increased removal rates combined with increased ACWT contributed to a potential increase of bare firewalls of as much as 60.7% above the baseline model value of 33.7.

4. Utilization

The AIMD's work center utilization rates remain below maximum capacity, and no bottlenecks developed as a result of lowering component life limits. However, the trend indicates that, as additional engines are inducted, a small increase in capacity utilization does take place. Excess repair capacity at the AIMD appears to absorb this small increase with minimal effect on overall production.

Additional simulation runs were performed with increased and decreased Work Center 414 repair channels. As additional capacity was added, capacity utilization rates decreased as anticipated. This had no effect, however, on TAT or bare firewalls. Decreasing capacity, on the other hand, had a dramatic effect on both TAT and bare firewalls. Using FY94 data, the elimination of a single 414 channel produced increases in engine TAT to 1,240 hours and bare firewalls to 97, from 488.5 and 33.7, repectively. Additional eliminations of Work Center 414 channels created too many modules for the software to manipulate, terminating the simulation.

C. RECOMMENDATIONS

1. AIMD Capacity

AIMD capacity to repair modules in 414 must be maintained at a level that prevents the work center's waiting queues from building beyond current levels. If these queues are allowed to grow, substantial delays in engine TAT will occur combined with large increases in bare firewalls. Current 414 operating capacities appear delicately balanced with the work flow. Normal variations in induction rates could cause this balance to shift, creating substantial delays in the repair systems.

A possible guard against induction rate fluctuations would be an investment in additional 414 capacity. Three to six more workers could add one to two more channels, bringing capacity utilization levels down to 90% and 85% respectively. This could benefit the system by preventing large increases in modules waiting for repair and the subsequent grounding of aircraft due to bare firewalls.

2. Depot Repair Flow

The model demonstrates that the AIMD is not significantly affected by changes in component life limits. The reason for this is that the depot absorbs most increases through higher BCM rates. The number of modules BCM'd rose by over 400% in some instances. Recent depot consolidation has reduced the excess capacity available for D-level repair, which under some conditions could result in an unstable system. [Ref. 14]

Much of the D-level information used in this study was based on assumptions made by depot managers and engine manufacturer forecasts. Actual depot repair capacity and its response to changes in induction rates are recommended as a future research area.

3. Additional Simulation Applications

The value of simulation as an analysis tool for complex systems was evident in this study. As consolidation and base closures continue, D-level and I-level systems will undergo significant changes. AIMD Lemoore, for example, will change from a single-type engine repair facility to one servicing four different types of engines by the mid-1990's.

Simulation could be used in early planning stages to help determine optimal repair center layouts and manning levels. Similar applications could be used in the upcoming consolidations at NAS Oceana and Marine Corp Air Station Beaufort. As new aircraft are introduced and others are retired, AIMD tasking will change significantly. Simulation can be applied to assist with early planning and decision making.

4. Supply Lead Time

Increases in TAT and the number of bare firewalls can be attributed to the depot's inability to increase production in a timely manner. The F/A-18's importance in the Navy's strategic mission makes significant logistics shortfalls unacceptable. Aviation logistics support services must be adequately funded to procure enough excess capacity to avoid future shortfalls. Comprehensive sensitivity analysis studies should be conducted to determine which logistics factors have the greatest impact on readiness.

APPENDIX A

Turn-around-time Comparison Table

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
ENGINE					
488.48	25 %	448.53	- 8.20	451.14	- 7.64
	50 %	470.23	- 3.69	455.79	- 6.69
	75 %	490.52	- 0.42	480.62	- 1.61
	100 %	501.35	+ 2.63	500.08	+ 2.37
	150 %	542.18	+ 10.99	556.31	+ 13.89
	200 %	564.39	+ 15.54	562.80	+ 15.21
FAN MODULE					
988.72	25 %	980.51	- 0.830	981.78	- 0.702
	50 %	985.15	- 0.361	982.97	- 0.582
	75 %	982.07	- 0.672	982.97	- 0.582
	100 %	980.46	- 0.835	980.10	- 0.872
	150 %	983.45	- 0.533	982.59	- 0.620
	200 %	985.52	- 0.323	983.81	- 0.496
HPT MODULE					
288.69	25 %	285.92	- 0.959	288.17	- 0.180
	50 %	286.08	- 0.904	287.46	- 0.426
	75 %	288.28	- 0.142	287.14	- 0.537
	100 %	286.53	- 0.748	287.22	- 0.509
	150 %	287.39	- 0.450	287.54	- 0.398
	200 %	284.48	- 1.458	286.95	- 0.603

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
HPC MODULE					
1168.6	25 %	903.68	- 22.67	1027.2	- 12.10
	50 %	976.67	- 16.42	1021.3	- 12.60
	75 %	949.73	- 18.73	958.79	- 17.95
	100 %	934.60	- 20.02	927.86	- 20.60
	150 %	937.38	- 19.79	1090.8	- 6.67
	200 %	974.97	- 16.57	912.97	- 21.87
LPT MODULE					
242.26	25 %	221.87	- 8.42	233.68	- 3.54
	50 %	225.78	- 6.80	229.33	- 5.34
	75 %	228.64	- 5.62	227.68	- 6.02
	100 %	228.15	- 5.82	225.43	- 6.95
	150 %	232.11	- 4.19	236.76	- 2.27
	200 %	234.00	- 3.41	225.07	- 7.09

APPENDIX B

Modules in Repair Queues

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
FAN					
.190	25 %	.130	- 31.6	.173	- 8.9
	50 %	.141	- 25.8	.143	- 24.7
	75 %	.147	- 22.6	.147	- 22.6
	100 %	.142	- 25.3	.142	- 25.3
	150 %	.154	- 18.9	.160	- 15.8
	200 %	.134	- 29.5	.143	- 24.7
HPT MODULE					
.386	25 %	.195	- 49.5	.275	- 28.8
	50 %	.237	- 38.6	.266	- 31.1
	75 %	.272	- 29.5	.258	- 33.2
	100 %	.263	- 31.9	.235	- 39.1
	150 %	.271	- 29.8	.296	- 23.3
	200 %	.209	- 45.9	.256	- 33.7
HPC MODULE					
3.740	25 %	.393	- 89.5	1.824	- 51.2
	50 %	1.266	- 66.1	1.763	- 52.9
	75 %	.913	- 75.6	1.007	- 73.1
	100 %	.694	- 81.4	.673	- 82.0
	150 %	.807	- 78.4	2.610	- 30.2
	200 %	1.175	- 68.6	.533	- 85.7

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
			LPT MODULE		
1.090	25 %	.393	- 63.9	.754	- 30.8
	50 %	.542	- 50.3	.613	- 43.8
	75 %	.589	- 46.0	.563	- 48.3
	100 %	.582	- 46.6	.483	- 55.7
	150 %	.706	- 35.2	.821	- 24.7
	200 %	.729	- 33.1	.491	- 55.0

APPENDIX C

Modules Awaiting Parts

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
FAN MODULE					
23.04	25 %	20.73	- 10.03	21.98	- 4.60
	50 %	21.32	- 7.47	21.04	- 8.68
	75 %	21.38	- 7.20	21.19	- 8.03
	100 %	21.31	- 7.51	21.96	- 4.69
	150%	21.29	- 7.59	22.58	- 1.99
	200 %	20.90	- 9.29	21.25	- 7.76
HPT MODULE					
5.34	25 %	4.73	- 11.42	4.96	- 7.12
	50 %	4.75	- 11.05	5.07	- 5.06
	75 %	4.81	- 9.93	4.95	- 7.12
	100 %	4.87	- 8.80	5.03	- 5.81
	150 %	4.94	- 7.49	4.99	- 6.55
	200 %	4.83	- 9.55	5.14	- 3.75
HPC MODULE					
9.64	25 %	8.79	- 8.82	9.22	- 4.46
	50 %	9.69	- 0.52	8.98	- 6.85
	75 %	8.87	- 7.99	9.57	- 0.73
	100 %	8.87	- 7.99	9.39	- 2.59
	150 %	8.77	- 9.02	9.62	- 0.21
	200 %	8.83	- 8.40	9.06	- 6.02

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
LPT MODULE					
2.39	25 %	2.19	- 8.37	2.32	- 2.93
	50 %	2.21	- 7.53	2.29	- 4.18
	75 %	2.17	- 9.21	2.16	- 9.62
	100 %	2.12	- 11.30	2.18	- 8.79
	150 %	2.21	- 7.53	2.25	- 5.86
	200 %	2.14	- 10.46	2.21	- 7.53

APPENDIX D

Utilization Rate

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
41U					
.568	25 %	.690	+ 21.5	.763	+ 34.3
	50 %	.692	+ 21.8	.762	+ 34.2
	75 %	.694	+ 22.2	.760	+ 33.8
	100 %	.690	+ 21.5	.756	+ 34.7
	150 %	.692	+ 21.8	.758	+ 33.5
	200 %	.690	+21.5	.762	+ 34.2
450					
.168	25 %	.205	+ 22.0	.227	+ 35.1
	50 %	.205	+ 22.0	.226	+ 34.5
	75 %	.207	+ 23.2	.227	+ 35.1
	100 %	.205	+ 22.0	.224	+ 33.3
	150 %	.207	+ 23.2	.226	+ 34.5
	200 %	.205	+ 22.0	.227	+ 35.1
414					
1.195	25 %	1.083	- 9.4	1.149	- 3.8
	50 %	1.106	- 7.4	1.127	- 5.7
	75 %	1.096	- 8.3	1.104	- 7.6
	100 %	1.090	- 8.8	1.118	- 6.4
	150 %	1.107	- 7.4	1.153	- 3.5
	200 %	1.084	- 9.3	1.111	- 7.0

APPENDIX E

Engines Repaired or BCM'd

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
ENGINES REPAIRED					
308	25 %	375.9	+ 22.0	417.0	+ 35.4
	50 %	376.7	+ 22.4	416.1	+ 35.1
	75 %	378.2	+ 22.8	415.4	+ 34.9
	100 %	376.3	+ 22.2	412.3	+ 33.9
	150 %	378.5	+ 22.9	414.2	+ 34.5
	200 %	376.5	+ 22.2	415.9	+ 35.0
ENGINES BCM'd					
10.4	25 %	21.3	+ 104.8	19.0	+ 82.7
	50 %	19.5	+ 87.5	18.9	+ 81.7
	75 %	18.3	+ 75.9	19.4	+ 86.5
	100 %	19.9	+ 91.3	21.6	+ 107.7
	150 %	17.9	+ 72.1	20.1	+ 93.3
	200 %	19.3	+ 85.6	18.2	+ 75.0

APPENDIX F

Modules BCM'd

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
FANS BCM'd					
17.3	25 %	76.0	+ 339.3	95.0	+ 449.1
	50 %	75.2	+ 334.7	93.0	+ 437.6
	75 %	77.5	+ 347.9	97.1	+ 461.3
	100 %	73.4	+ 324.3	89.1	+ 415.0
	150 %	77.7	+ 349.1	95.8	+ 453.8
	200 %	73.9	+ 327.2	90.3	+ 421.9
HPTS BCM'd					
62.6	25 %	86.4	+ 38.0	96.5	+ 54.2
	50 %	86.3	+ 37.9	94.6	+ 51.1
	75 %	86.4	+ 38.0	94.0	+ 50.2
	100 %	80.0	+ 27.8	93.4	+ 49.2
	150 %	85.4	+ 36.4	94.8	+ 51.4
	200 %	84.2	+ 34.5	96.7	+ 54.5
HPCS BCM'd					
22.8	25 %	53.8	+ 136.0	64.5	+ 182.9
	50 %	51.4	+ 125.4	64.5	+ 182.9
	75 %	51.0	+ 123.7	62.6	+ 174.1
	100 %	52.5	+ 130.3	62.3	+ 173.2
	150 %	53.1	+ 132.9	62.7	+ 175.0
	200 %	56.4	+ 147.4	61.4	+ 169.3

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
LPTS BCM'd					
10.9	25 %	47.0	+ 331.2	54.8	+ 402.8
	50 %	42.4	+ 289.0	52.5	+ 381.7
	75 %	44.0	+ 303.7	55.4	+ 408.3
	100 %	43.6	+ 300.0	56.1	+ 414.7
	150 %	43.3	+ 297.2	54.9	+ 403.7
	200 %	41.3	+ 278.9	56.0	+ 413.8

APPENDIX G

Bare Firewalls

FY 92 (Baseline)	% ↑ in ACWT	FY 93	Percent Change	FY 94	Percent Change
ENGINE					
33.682	25 %	38.661	+ 14.8	42.772	+ 27.0
	50 %	40.636	+ 20.6	43.322	+ 28.6
	75 %	42.502	+ 26.2	45.827	+ 36.0
	100 %	43.593	+ 29.4	47.771	+ 41.8
	150 %	47.297	+ 40.4	53.276	+ 58.1
	200 %	49.463	+ 46.9	54.135	+ 60.7

APPENDIX H

List of Abbreviations

ACWT	Average Customer Waiting Time
AD	Aviation Machinist's Mate
AE	Aviation Electrician's Mate
AEMS	Aircraft Engine Management System
AFB	Afterburner Module
AIMD	Aircraft Intermediate Maintenance Department
APU	Auxiliary Power Unit
AWP	Awaiting Parts
BCM	Beyond the Capability of Maintenance
CMB	Combustor Module
CNO	Chief of Naval Operations
D-level	Depot Level (Maintenance)
EAMP	Engine Analysis Maintenance Program
EPE	Enhanced Performance Engine
FY	Fiscal Year
GSE	Ground Support Equipment
HPC	High Pressure Compressor Module
HPT	High Pressure Turbine Module
I-level	Intermediate Level (Maintenance)
IECMS	In-Flight Engine Condition Monitoring System
IMA	Intermediate Maintenance Activity
JAX	Jacksonville, Florida
LPT	Low Pressure Turbine
MTBF	Mean Time Between Failure
NADEP	Naval Aviation Depot
NALDA	Naval Aviation Logistics Data Analysis
NAMP	Naval Aviation Maintenance Program
NAS	Naval Air Station
NAVAIR	Naval Aviation
NAVAIRSYSCOM	Naval Air Systems Command
NDI	Non-Destructive Inspection
NEC	Navy Enlisted Classification (Code)
NRFI	Not Ready for Issue
O-level	Organization Level (Maintenance)
OPNAVINST	Operations, Naval Aviation Instruction
PLTS	Parts Life Tracking System
QA/A	Quality Assurance/Analysis
QA	Quality Assurance
RCM	Reliability Centered Maintenance
RFI	Ready For Issue
SSC	Supply Support Center
T/M/S	Type/Model/Series
TAT	Turn-Around-Time
W/C 450	450 (Engine Test Cell)
W/C 414	414 (Module Repair)
W/C 41U	41U (Engine Disassembly and Reassembly)
WIP	Work-In-Process

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