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EVALUATION OF AIRCRAFT TURBINE
ENGINE REDESIGNS

by

Eugene G. Sudol, Jr.
and
Larry D. Price

June, 1990

Thesis Advisor: Paul M. Carrick

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The thesis reached the conclusion that the effects of CIP are more effectively assessed at the component level rather than at the system level. The thesis further demonstrated the logical and data collection difficulties encountered in the process of isolating the incremental benefits obtained from CIP expenditures.

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ABSTRACT

This thesis is a study of the Aircraft Turbine Engine Component Improvement Program (CIP). The study examines some of the problems associated with determining benefits accrued from CIP. The major thrust of the thesis was developing a component selection methodology and an analysis procedure for detecting changes in logistics parameters. The data source was the Engine Component Information Feedback Report (ECIFR). Data for this report come from aviation organizational level maintenance activities and squadrons. The thesis reached the conclusion that the effects of CIP are more effectively assessed at the component level rather than at the system level. The thesis further demonstrated the logical and data collection difficulties encountered in the process of isolating and measuring the incremental benefits obtained from CIP expenditures.

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I. INTRODUCTION

A. OBJECTIVES

The primary objectives of this thesis are:

- to examine the problem of associating Component Improvement Program (CIP) costs with accrued benefits
- to explore the funding trends for CIP and determine if they are appropriate
- to propose a methodology for observing and evaluating the effects of CIP on component logistics parameters
- to demonstrate the problems of using existing databases for evaluating the effects of CIP on component logistics parameters

The requirement to manage weapons systems on a life cycle basis grows more important as defense resources become more scarce. The ownership cost of an engine may exceed the original acquisition cost by two fold or greater.[1] This condition causes aircraft project managers to seek ways to reduce life cycle costs. Since CIP has more than just a safety objective, in its broader context, it might also be a means of significantly reducing ownership cost. To ensure that an appropriate amount of resources are allocated to CIP, the cost/benefit relationship must be examined.

[1] J. R. Nelson, "Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary.", The RAND Corp, Santa Monica, CA, March 1977, p. 27.

B. RESEARCH QUESTIONS

The most important question which the authors want to answer is: **Is there a positive relationship between expending CIP dollars and improving logistics parameters.** Specifically, is there an improvement which is statistically significant between a component population's Mean Time Between Failure (MTBF) before and after an expenditure of CIP resources and fleet implementation of an engine change proposal?

To assist in answering this inquiry, the following questions were used to guide the research effort:

- How does the budgeting process for CIP occur, that is, who are the key decision makers and what incentives do they face in allocating CIP resources?
- How are the benefits of CIP presently measured?
- What factors are influencing the existing levels of funding?
- What quantitative methods are currently used to determine efficient allocations?

C. THE AIRCRAFT COMPONENT IMPROVEMENT PROGRAM.

In this section of the thesis, the objectives and functions of the Aircraft Engine Component Improvement Program (CIP) are presented. Logical and intuitive justifications for CIP are discussed.

1. Goals

In accordance with Navy policy, the Aircraft Engine Component Improvement Program has three objectives[2]:

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[2] NAVAIR INST 5200.35; ser AIR-536; dated 25 Jan 1982.

- to maintain an engine design which allows the maximum aircraft availability at the lowest total cost to the government (primarily production and support cost)[3];

- to correct, as rapidly as possible, any design inadequacy which adversely affects safety-of-flight; and

- to correct any design inadequacy which causes unsatisfactory engine operation or adversely affects maintainability and logistic support in service.

To meet these objectives, the Aircraft Engine Component Improvement Program performs four functions. The first three functions are stated explicitly in the CIP acquisition plan and the fourth is stated implicitly throughout the official documentation and literature.[4] The four functions are:

- Problem Solving. The rapid investigation and resolution of fleet problems (safety, readiness, or operability).

- Problem Avoidance. An aggressive program of mission testing, analytical sampling of fleet hardware and engineering analyses designed to forecast hardware wearout rates, life limits, and problems before they occur in the fleet.

- Product Improvement. To develop and qualify design changes, repair procedures, and alternate sources (of parts and supplies throughout the life of an engine) where substantial savings in operation and support cost can be realized.

- Product Maturation: Provide an infrastructure (support facilities and experienced engineers) to mature the engineering design for newly developed and fielded engines.

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[3] It is not possible to simultaneously maximize aircraft availability at the lowest total cost. The objective would be more correct if stated as: Given a fixed amount of dollars, maintain an engine design which allows maximum aircraft availability.

[4] Aircraft Engine Component Improvement Program, Acquisition Plan (AP) No. A42-48-0-50 rev B, approved Aug 13, 1987. J. R. Nelson, et al. "Policy Options for the Aircraft Turbine Engine Component Improvement Program, Institute for Defense Analyses, Alexandria, VA, May 1987, chapter II.

2. Why a CIP For Aircraft Turbine Engines Should Be a Productive Expenditure

The Aircraft Turbine Engine Component Improvement Program is a sustaining engineering effort. The requirement for such a program exists for several reasons.

First, an aircraft turbine engine is an extremely complex mechanical device consisting of static and dynamic parts. Some moving parts are exposed to high speed rotational forces and other parts are subjected to rapid and repeated movement. Both dynamic and static components internal to the engine are exposed to significant stress which induces unexpected failures. CIP provides a mechanism to re-engineer the component and reduce these failures.

Second, both categories of parts are acted on by an extreme range of operating temperatures, ambient pressures, and ambient temperatures throughout an operating cycle. Such conditions contribute to rapid failure of poorly designed and engineered components and the eventual failure of even well designed and engineered components. In contrast to military engines, commercial aircraft engines encounter a reasonably stable and predictable operating environment. The operating envelope of a commercial engine can be characterized by start up, followed by a steady climb to cruising altitude, a gradual decent, landing, and engine shut down. Much of the operating cycle of a commercial engine can be viewed as "steady state," i.e., constant rate of climb, constant engine thrust, constant speed at a constant altitude, and constant rate of decent. "Transient" points such as changes in power setting are short intervals and occur during:

- start up
- take off
- transition to and from cruising altitude and speed
- landing
- engine shutdown

Military engines, out of necessity, encounter continually changing operating conditions which are more hostile to engine components than an operational environment analogous to the commercial conditions.

Third, it is only possible to effectively design an engine **after** the mission has been defined and the requirement for a new air platform exists. As a consequence of this restriction, aircraft turbine engines for military applications often enter the operational environment several years before they reach design maturity. Of the major systems which constitute a military aircraft, the powerplant historically requires the longest period of time to develop. The airframe, for example, can be engineered and adequately modeled using scale models and wind tunnels. Significant cost savings are realized during airframe development by using these techniques as opposed to requiring full scale operational engineering models. This is possible because the airframe is basically an air foil with a limited number of moving parts. Furthermore, the behavior of airframes moving through air is well understood and predicted accurately both in a mathematical sense and by engineering scale models.

Even if it were possible to design aircraft turbine engines using scale models, the power plant development process is inherently longer in duration.[5] Studies have estimated that an airframe design reaches maturity in four to six years, and the propulsion system in six to eight years.[6] A function such as CIP is required because an engine typically leaves full scale development (FSD) before maturity. When the requirement to bring a new aircraft on line by a particular date is driven by operational factors and the engine can not remain in FSD an optimal length of time, CIP provides a means to complete the design maturation process after an engine is brought into operational service.

Fourth, conscientious tradeoffs must occur in making the decision whether to bring an engine to maturity during Full Scale Development or after deployment via CIP. If, for example, one chooses to use FSD to bring an engine design to full maturity, the benefits of having a weapon system which meets all predetermined mission requirements must be weighed against the benefits of having the platform in the hands of the operators sooner. The longer the system remains in Full Scale Development, the more obsolete it will be when it becomes operational. The alternative is to shorten FSD and finish the maturation process with CIP. Given the opportunity, operators will frequently opt to use a weapon system that could, from an engineering view point, benefit from a longer FSD period. An operator would rather have a serviceable system that doesn't quite meet **all** specifications than wait an additional period of time. Practically speaking, there isn't any

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[5] Interview with Dr. R. Shreeve, Naval Postgraduate School, Monterey, CA, Department of Aeronautical Engineering.

[6] J. R. Nelson, et al, "Policy Options for the Aircraft Turbine Engine Component Improvement Program," Institute for Defense Analyses, Alexandria, VA, May 1987, p. II-3.

guarantee that the system will ever meet **all** specifications no matter how long full scale development continues. Furthermore, there are incentives for the program managers to field weapons systems on time and withing budget. Any attempt to keep an engine in FSD until maturity implies more time and money. Time and money are scarce resources to both program managers and operators.

Because of present design process constraints, operational service entry time requirements, and engine complexities, many undiscovered and potential failure modes remain dormant until the engine is actually used in an operational environment. The Aircraft Turbine Engine Component Improvement Program provides a systematic way to develop fixes for design deficiencies which occur during operational use.

Fifth, as a new weapon system such as an aircraft enters the operational inventory, it gives the users new capabilities. With these new capabilities, warfighters increase their effectiveness as they develop new tactics and maneuvers. Operators receive encouragement to do this. The new tactics and maneuvers, however, put the aircraft in an operating environment which may expose the engine to stresses, cycles, temperatures, and pressures that the design team could not have possibly anticipated. The new operating environment brings weaknesses of the engine's design to the surface. If the engine remained in the specified operating environment and design envelope, new weaknesses may not have surfaced. After the aircraft engine is fielded, FSD funds are no longer applicable. At the moment, CIP is the means to correct the weaknesses induced by new tactics. Thus, CIP provides a method of resolving engineering deficiencies that are revealed as a result of changes in the operating environment.

Finally, CIP can improve reliability and durability through accelerated engine testing. The purpose of accelerated engine testing is to discover deficiencies in design before the fleet does. By compressing the engine's life cycle in a simulated operational environment, a failure mode can be identified before it becomes a critical fleet problem. Unfortunately, not all key environmental factors, such as atmospheric pressure ratios, are fully simulated on the ground.

In summary, both logical and intuitive justifications exist to support a continuing engineering effort for aircraft engines. The Aircraft Engine Component Improvement Program currently fills this need.

3. Problems and Trends in CIP Funding

The Component Improvement Program is a program element of the military services' research, development, test, and evaluation (RDT&E) budgets. The service's RDT&E budgets are broken down into six major programs. They are: Technology Base, Advanced Technical Development, Strategic Programs, Tactical Programs, Intelligence & Communications, and Defensewide Mission Support. CIP is a line item in the Tactical Programs budget account.

In some instances, two or more of the uniformed services use the same engine or derivatives of the parent engine; for those engines, a lead service is designated to coordinate the establishment of priorities. Resource requirements are apportioned to individual services based projected usage of funds.

During budget formulation each service develops its individual CIP budget request. After the service budgets are reviewed and revised through the Planning, Programming, and Budgeting System (PPBS), tentative funding levels are used to form a budget proposal. During the spring of each year, meetings are held for those engine programs which have joint users. Based on the figures determined via PPBS, the lead service, in conjunction with the follower services, determines which engineering efforts receive priority for both common and unique problems. From these priorities and with the dollars available, a listing is made stating what tasks will be performed. The results of this meeting are then given to AIR 536 who incorporates these tasking priorities into its budget proposal to OPNAV.

If the Congressional appropriation is different from the proposed budget, further coordination with the lead service takes place. Common and unique problems are re-prioritized and funds are reallocated among the tasks to allow the best utilization of the funds. If the congressional budget is the same as the proposed budget, then the program is executed as previously planned. The lead service bills the follower services for any of the common or unique tasks which are accomplished.

Each aircraft engine program engineer is responsible for putting together his or her budget and submitting it up the chain of command. The individual priorities are reviewed by a board in the NAVAIR organization which establishes a proposal for OPNAV. OP-514I prepares the final budget figures which are presented to OP-05. In OP-05, CIP competes against all other OP-05 RDT&E line items for funds.

Since 1985 there has been a significant decline in Navy funding for CIP (see Figure 1.1). The budgets since 1985 only provided sufficient dollars to meet engineering deficiencies which were classified as safety of flight related. The remaining dollars were

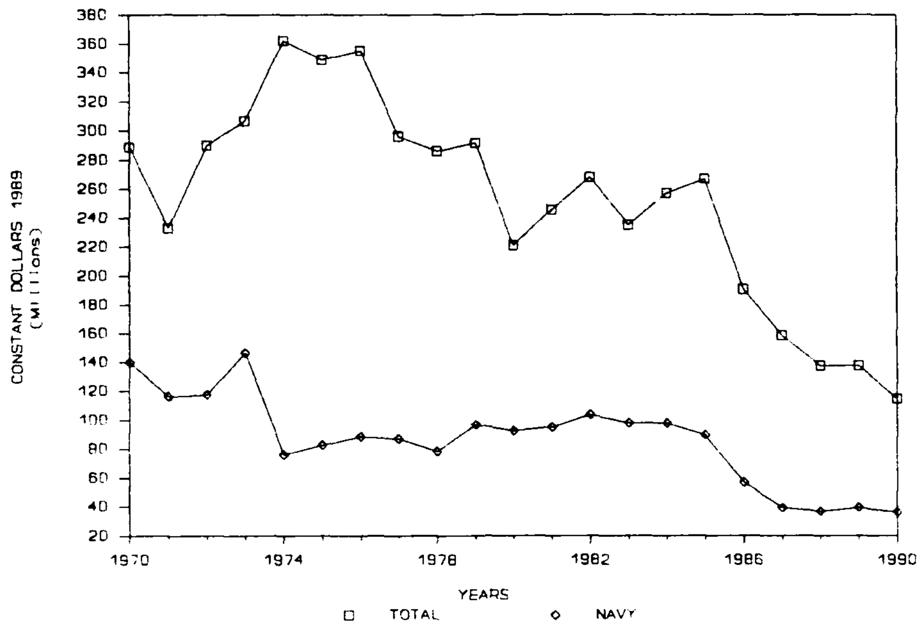

Figure 1.1 Navy and Total DoD CIP Budgets, FY70-FY90
Source: NAVAIR 536B

allocated to program overhead and maintaining the existing support facilities such as engine test cells. In essence, after meeting the safety of flight objectives and supporting the existing infrastructure, typically, there has not been any funding available to address other programmatic objectives. There have been few CIP efforts undertaken to specifically reduce life cycle cost. Some reductions in life cycle cost and benefits of the remaining goals have been realized, but only as a by-product of meeting a safety of flight need.[7]

There has been a constant level of funding for Navy CIP from 1988 through 1990. If the FY91 budget request for Navy CIP is approved without any adjustments, the

[7] Conclusions made by authors from interviews with NAVAIR and OPNAV personnel.

Navy will receive approximately $38.7M.[8] This would be a $2.69M increase in funding over 1990, ending a three year trend of zero growth in CIP.

Funding for CIP is also affected by the Foreign Military Sales (FMS) program. A foreign user of aircraft engines purchased from the United States also contributes to the respective CIP engine program based on the number of engines the user nation owns. The baseline figure for computing the FMS contribution is determined by the number of dollars spent by DoD for a specific engine CIP program divided by the number of engines in the U.S. inventory. For example, if the United States contributes $13,500,000 for CIP for the F-XXX engine program and owns 400, the baseline figure per unit engine is $13,500,000/400 or $33,750. To determine an ally's CIP contribution for the same engine, this figure is multiplied by the number of engines owned by the ally. If, for example, 60 engines are owned by various allied countries, their total contribution would be $2,025,000 (60 * $33,750), resulting in total funding for CIP of $15,525,000. The important relationship between FMS funding and CIP is that the more money the United States puts into a program, the more money an FMS user contributes. The money contributed to a CIP engine program by FMS is in addition to the CIP RDT&E funds appropriated by Congress.

Why did DON experience a substantial decrease in CIP dollars between 1985 and 1987? Four reasons which contributed to this problem were provided by OPNAV. These were:

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[8] 1989 constant year dollars

- overall tightening of the defense budget starting in 1986
- previous CIP management and assessment practices within OPNAV
- no effective method for briefing or educating senior managers about the long term benefits of CIP
- an inability to quantify the marginal benefit associated with the marginal expenditure of CIP funds.

The challenge facing Aircraft Engine Component Improvement Program managers in today's constricting defense budget is determining efficient levels of resources that allow CIP to accomplish its objectives without degrading operational, material, and mission readiness. An even greater concern in these austere times is the impact of significant decreases in funds for CIP.

Investigation of FY-90 congressional actions indicated only minor adjustments to the Navy CIP budget. For FY-90, the Navy requested $35.7M; it received $37.4M.[9] From this, the authors infer that if one wanted to increase the CIP budget, the increase must be requested and justified by the service during the planning and programming stages of PPBS. The drop in dollar resources for CIP experienced by the Navy between FY83 and FY90 is a problem caused by budgeting processes internal to the service. The problem is not apparently, the result of congressional cuts. The issue of CIP funding levels centers on the efficient allocation of RDT&E funds and the competition CIP faces from other RDT&E programs.

[9] then year dollars

In summary, the Component Improvement Program provides one method whereby the goals of continuing or sustaining engineering for aircraft turbine engines may be realized. The problems which must be solved before CIP will receive funding for all program objectives are:

- quantifying the marginal benefit of an expenditure of CIP funds
- ensuring that as key decision makers for CIP are replaced, these new managers understand the goals and functions of CIP

Without an effective solution to these problems, CIP becomes vulnerable to internal budgetary cuts.

D. SCOPE AND LIMITATIONS

The engineering complexities of aircraft turbine engines forced the research effort to focus on looking for benefits and changes at the component level rather than looking for benefits accrued by the engine at the system level. E·en after an engine subsystem or component has been re-engineered, the direct benefits of this engineering effort may not be discernable at the system level. For example, as one group of subsystems or components is improving in reliability, there are other subsystems or components whose reliabilities may be declining, creating a cancellation effect at the system level.

The ideal component for the purposes of this study possesses the following attributes:

- CIP resources were expended to provide a fix to an engineering deficiency
- the end product of the CIP effort resulted in an engine change proposal (ECP)

- APN funds were obligated to implement the ECP fleetwide
- the ECP has been in the fleet for a minimum of two years so that the benefits of the fix can accrue and the analysis can be based on actual experience rather than an engineer's best estimate
- data about the component are available to quantify the benefits.

E. ASSUMPTIONS

This thesis is written for:

- individuals who possess a working knowledge of the DoD and DoN resource allocation process,
- individuals who have an understanding of basic statistics, logistics engineering, and management theory.
- program item managers who prepare RDT&E budgets for upper echelon staff and Congressional review.

II. METHODOLOGY FOR SELECTING COMPONENTS

This Chapter explains the procedures and techniques used to identify data which would help determine whether there is a statistically significant difference between a component population's Mean Time Between Failure (MTBF) before and after an expenditure of CIP resources and fleet implementation of an engine change proposal. In other words, can a causal relationship between CIP and improved performance as measured by MTBF be demonstrated?

A. DESIGNING THE EXPERIMENT

Given the freedom to evaluate the effect of CIP funding on logistics parameters, how would one organize such an experiment?

First, a procedure which measures effectiveness must be formulated. In the context of this thesis, CIP effectiveness is defined as improvement in logistics parameters. The measure of effectiveness that will be used for the remainder of this thesis is increased MTBF because operating and support costs are largely affected by a component's MTBF[10].

Although CIP affects the overall readiness of an aircraft engine, it is difficult to assess discrete results as they affect total system performance. This is because as one

[10] Although this thesis uses MTBF, there are other logistics parameters which might be used as a measure of effectiveness for CIP. These are: maintenance dollars expended per component maintenance action, maintenance man hours per operating hour, in-flight aborts per 1000 flight hours attributable to this component, ground aborts per 1000 flight hours attributable to this component, Class 'A' mishaps per 1000 flight hours attributable to this component, and reduced number of aircraft required because of increased availability.

component's performance is deteriorating, another's may be improving, thereby offsetting the declining performance. Conversely, as one component's performance is improving as a result of CIP, the benefits may be offset by another component whose performance is deteriorating. Because of this intricate balance, the benefits of CIP must necessarily be assessed at a component level. The changes in a component's performance are not usually affected by changes in the performance of other components, except in the case of catastrophic or induced failures.

1. Ideal Environment

In an ideal environment one might use the following procedure:

- Test the hypotheses:

  H_o: CIP has no measurable effect on a component MTBF.
  H_f: CIP has a measurable effect on a component MTBF.

- Select a random sample of aircraft engine components of a statistically significant size for evaluation.

- Select those components that have been subjected to CIP funded re-engineering efforts.

- Compare changes in component MTBF at periodic intervals.

- Analyze the data and determine if the null hypothesis should be accepted or rejected. In other words, determine whether the MTBF changed significantly after subjecting a part to CIP.

2. Real World Constraints

Will the proposed methodology adequately assess the effectiveness of CIP funding in conjunction with real world constraints? What are the problems or inadequacies of this methodology? Does the operating environment restrict or bias the data?

Even after separating components into two sub-groups, one which has experienced CIP expenditures and the other which has not, this action may not truly isolate the effect of CIP funds for several reasons.

First, even though CIP dollars were spent to improve the characteristics of a component, the effort may prove fruitless because of circumstances beyond the control of the CIP Program Manager. For example, CIP may develop an engineering change proposal, but because CIP covers only the research and development part of the process, if APN funds are not released to implement the "fix", the intended benefits are not realized. In essence, the CIP funds become a sunk and unrecoverable cost.

The managers of APN accounts have several alternatives when it comes to allocating dollars. In the most general terms, they may designate funds to improve aircraft performance, increase aircraft warfighting capability, improve durability, or increase reliability. The first and second areas concern upgrading aircraft performance and the third and fourth areas concern reducing life cycle costs via improved logistics measures. There are tradeoffs between increasing aircraft performance or capability and increasing reliability and durability. Better reliability and durability may be foregone in an effort to achieve near term improved warfighting capability. In this case, the implied utility of CIP to APN managers is near zero.

Second, when there is a large investment in spare parts, there is a reluctance to dispose of these spare parts. Except in the case where CIP funded engineering changes involve safety issues, disposing of spare parts can be viewed as wasteful rather than as an irrelevant sunk cost. When the investment in spare parts is large and the improvements are in the areas of maintainability and reliability, there is a tendency to use the existing stock of old spares until it is exhausted. This practice extends the transition period of going from the old component to the new version. The time to realize benefits is spread out over a longer period making it more difficult to isolate the effects of the re-engineered component.

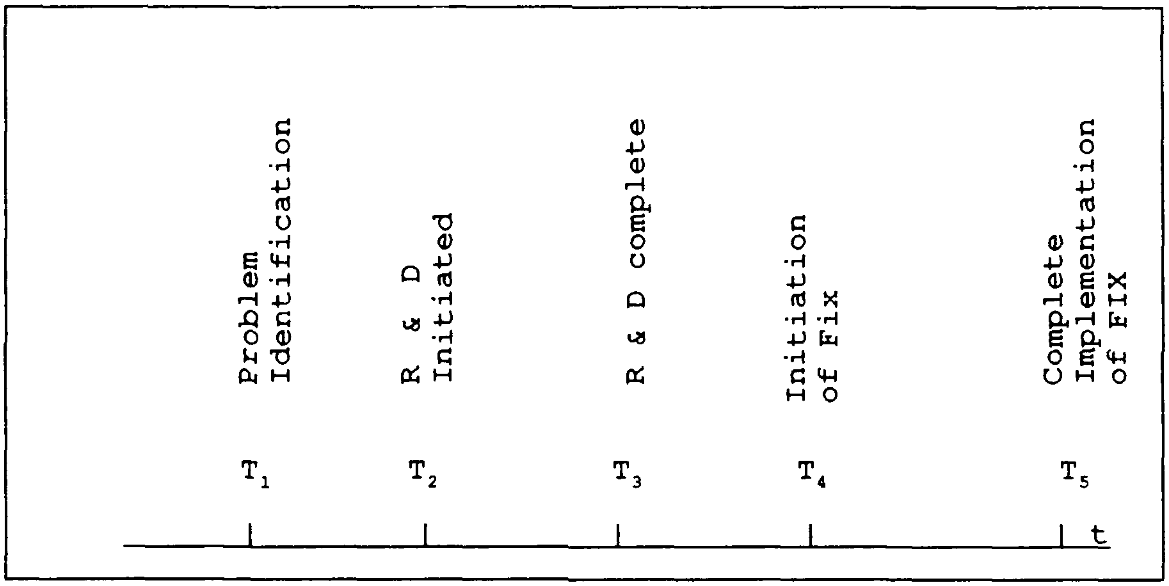

Figure 2.1 Generic CIP Milestone Timeline

Third, the steps of the CIP process do not occur instantaneously; time is required for research and development. Likewise, the benefits do not appear instantaneously; rather, they accrue over time. The generic life of a component, relative to CIP, is shown in figure 2.1. T_1 is the point when a problem is discovered. T_2 is when CIP begins to research and design a solution for the problem. At T_3 the R&D is complete. The implementation of the fix starts at T_4 and it is fully fielded at T_5.

We assume that there is no observable change in MTBF prior to T_4. MTBF is measured both at T_4 and again after T_5. For the purposes of this study, components were chosen which were believed to have data available for all points on the time line. Discussions with individual engine program managers indicate that it takes a minimum of two years to go from T_1 to T_5. In non-emergency situations it may take ten years or longer. The variable length of time from T_1 to T_5 makes it difficult to predict when the effects of CIP will manifest themselves.

The above constraints indicate that one must consider more than just two categories of components relative to CIP. At least four categories are identified:

- Components for which no CIP funds have been expended for redesign
- Components which have been re-engineered with CIP funding but because of insufficient APN funding, they have not experienced the effects of the CIP expenditures
- Components which have been re-engineered with CIP funding and are still in a transition period or awaiting fleet wide implementation of the solution
- Components which have been re-engineered with CIP funding and have completed the time-line from problem identification to full implementation of the solution.

Even with a variety of categories in which to place a component, it is often difficult to determine the correct one. Sometimes more than one category is correct for a component if several engineering efforts overlap.

B. METHOD USED

To overcome the difficulties associated with identifying and categorizing components which have been re-engineered or "improved", components were selected which met the following criteria:

- The component has exhibited a significant reduction in its failure rate (MTBF has increased).
- There was an expenditure of CIP funds for Engineering, Research and Development
- The component has gone through the CIP milestone timeline from problem identification through complete installation
- Sufficient time has elapsed since the ECP was completely fielded (T_5) to detect a change and observe a trend in the component MTBF

A flow diagram of the logic used to identify candidate components is presented in Figure 2.2.

The data used in this study spanned the years from 1979 through 1989.[11] The purpose of the data search was to identify components that were "maintenance drivers" and had been subject to CIP. A component was considered to be a "maintenance driver" if it had a low MTBF, relative to other components of the same engine. "Maintenance drivers" were identified from the 1979-1982 historical data records. The list of

[11] The data for this thesis come from a document known as the Engine Component Information Feedback Report (ECIFR). The ECIFR is a database compiled from aviation maintenance (3-M) data and is used to monitor logistics parameters for aircraft engines. The data used to generate the ECIFR are maintained by NAVAIR. The data found in the ECIFR database were believed to contain sufficient detail to facilitate analysis of aircraft engine logistics parameters at the component level.

"maintenance drivers" was compared to 1989 ECIFR data to determine if the component was still a "maintenance driver". If the component remained a "maintenance driver" it was not considered. If a component was no longer a "maintenance driver" it was considered for further analysis.

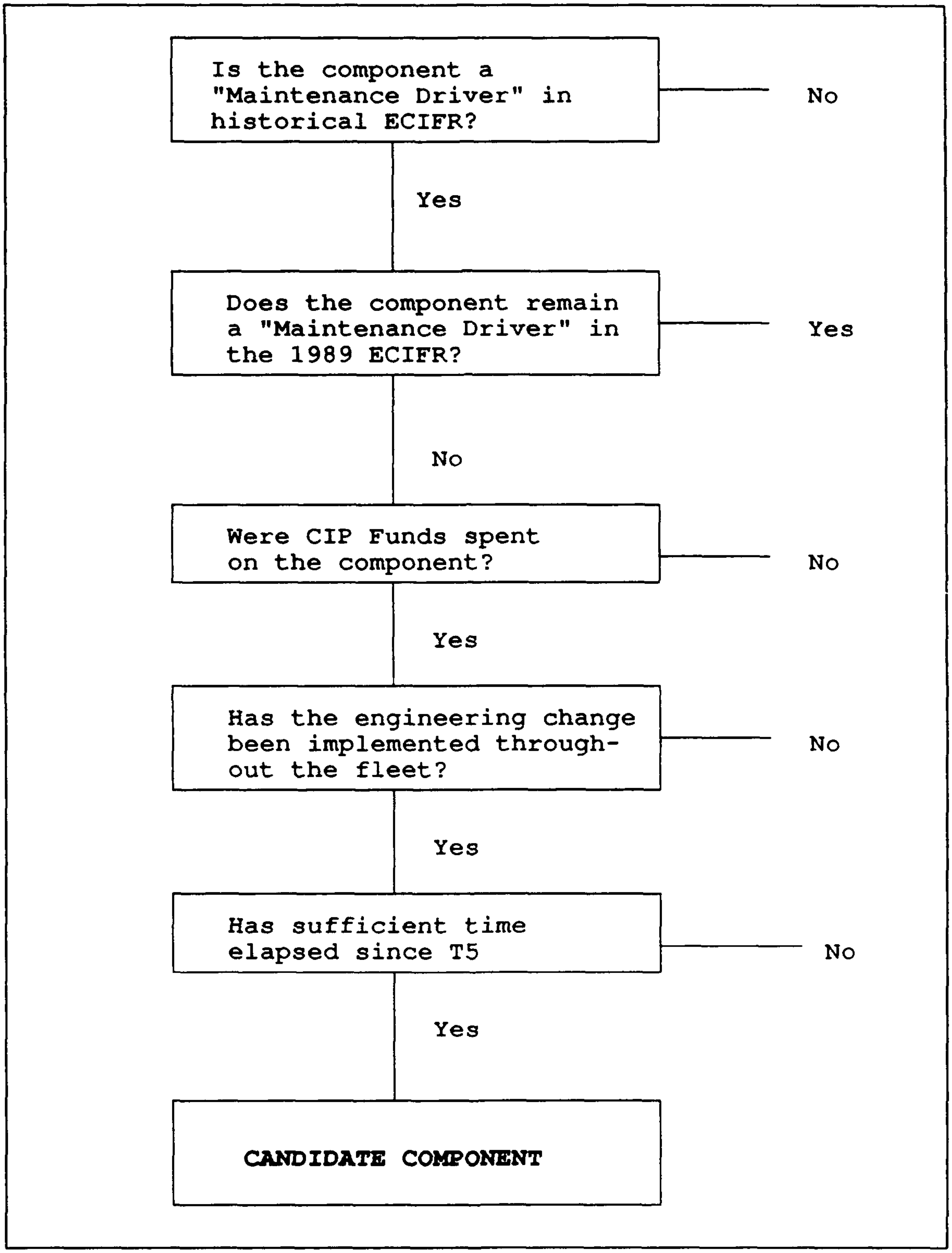

Figure 2.2 Component Selection Logic Diagram

Through discussions with the engine program managers both at NAVAIR and at the contractor's facility, the authors were able to determine if the component had benefitted from the expenditure of CIP funding. If the component was not a beneficiary of CIP funding, it was not added to the list of candidate components. After a list of candidate components was compiled, the year and month in which T_4 and T_5 occurred were determined with the help of the engine program managers. At this point an analysis of component MTBF would be conducted using the procedures found in Chapter III.

C. ASSUMPTIONS ABOUT THE METHODOLOGY

This methodology makes the following assumptions:

- Any favorable growth in MTBF is a direct result of CIP expenditures and not the result of a more favorable operating environment. The severity of operational demands on the engine is assumed to remain constant.
- Several years may lapse from the time a problem is identified until the solution is fully fielded.
- Because of the rationale used to select candidate components, any negative impact CIP expenditures may have had on any MTBF are ignored.
- The methodology considers only benefits which are measurable and quantifiable; it ignores any intangible benefits accruing to operators or any increased "utility."
- In the absence of CIP, MTBF was in steady state and would have remained constant.
- The data have built-in biases such as the amount of input error made by the maintenance data processors. This bias and others are assumed to remain constant over time.
- All failures are independent; there are no induced failures.

III. THEORETICAL FRAMEWORK FOR DETECTING CHANGES IN MTBF

This Chapter discusses the theory which supports the following conclusion: changes in MTBF are more easily detected at the component level rather than at the system level. The terms and parameters used in the discussion are explained to enhance further understanding of the research problems. Included in this explanation are the mathematical relationships among the parameters addressed. Finally, an example using a hypothetical system is provided to illustrate the principles of the model.

As the reader will note from the example that follows, large improvements in component parameters generate relatively small improvements in system parameters. Therefore, when attempting to determine the benefits of CIP, it is critical to evaluate them on the component level rather than on a system level. Otherwise, any improvement in a logistics parameter becomes lost in the "noise" of the system's complexity.

A. FRAMEWORK DEVELOPMENT

A weapons system is an assemblage of integrated subsystems. For the purposes of this thesis, the system is an aircraft. An aircraft is the integration of four major subsystems: the airframe, the powerplant, the electronics suite, and the payload. Each subsystem is a combination of component weapons replaceable assemblies (WRAs) and sub-replaceable assemblies (SRAs).

The attributes of the system are an aggregation of the attributes of its subsystems. Similarly, the attributes of a subsystem are an aggregation of the attributes of its component parts.

Attributes of a system, subsystem, or component are initially estimated during the design phase before field data become available. Through user input field data are collected to evaluate reliability and other logistics parameters. After field data are accumulated, a comparison of the parameters from each set is made to measure the difference between design data and field data. If field data are determined to be more accurate, they should be used to revise projected life cycle costs and expected performance attributes.

B. PARAMETERS AND DEFINITIONS

When defining logistics functions, support costs, reliability and maintainability attributes, a component can be characterized by the following parameters:

- MTBM. Mean time between maintenance. It is a function of both MTBF ($MTBM_p$) and $MTBM_c$. Equal to $1/(\Sigma\lambda+\Sigma fpt)$. Expressed in terms of time per maintenance action.

- MTBF ($MTBM_c$). Mean time between failures or mean time between corrective maintenance actions. The average time between failures for a component, subsystem, or system. Usually expressed as operating hours per failure, i.e. 1000 hours/failure.

- λ or failure rate. The rate at which units fail, usually expressed as failures per operating hour, i.e. .001 failures/hour. λ is equal to 1/MTBF.

- $MTBM_p$. Mean time between preventative maintenance. The average time between preventative maintenance actions. usually expressed as hours between maintenance actions, i.e. 1000hrs per preventative maintenance action.

- fpt. frequency of preventative maintenance. The rate at which units require preventative maintenance, expressed in units of preventative maintenance action per time. fpt is equal to $1/MTBM_p$.

- Mct. Mean corrective maintenance time. The mean active maintenance time required to restore a system, subsystem, or component to an operational status after a failure has occurred. It is expressed in terms of time per corrective maintenance action.

- Mpt. Mean preventative maintenance time. The mean active maintenance time required to perform preventative maintenance. It is expressed in terms of time per preventative maintenance action.

- Mean active maintenance time. The wrench turning time required to perform maintenance, includes both Mpt and Mct. It is computed as a frequency weighted average. $M=[\Sigma(\lambda*Mct)+\Sigma(fpt*Mpt)]/\Sigma(\lambda+fpt)$.

- MMH/OH Mean maintenance hours per operating hour. The average direct maintenance man hours per operating hour.

- MM$/OH Mean maintenance cost per operating hour.

- Reliability is the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions.

C. FORMULAE AND PARAMETER RELATIONSHIPS

$\lambda_{System}=\Sigma\lambda_i$

$MTBF=1/\lambda$

$\lambda=1/MTBF$

These relationships assume that failures are random and independent from one component to another.[12]

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[12] Complete derivations of the above formulae can be found in Blanchard, B. S., Logistics Engineering and Management, Prentice-Hall, Englewood Cliffs, NJ, 1986.

D. MATHEMATICAL RELATIONSHIPS FOR A SIMPLE MODEL

To explain how a change in the failure rate, λ, of one component might affect an entire system, the following hypothetical four subsystem aircraft is given as an example. This example illustrates the concept that large changes in component parameters do not necessarily translate into large changes in system parameters; in fact, the opposite is true. Large changes in component parameters result in relatively small changes at the system level. The weapons system in Figure 3.1 integrates the four major aircraft sub-systems in a series configuration.

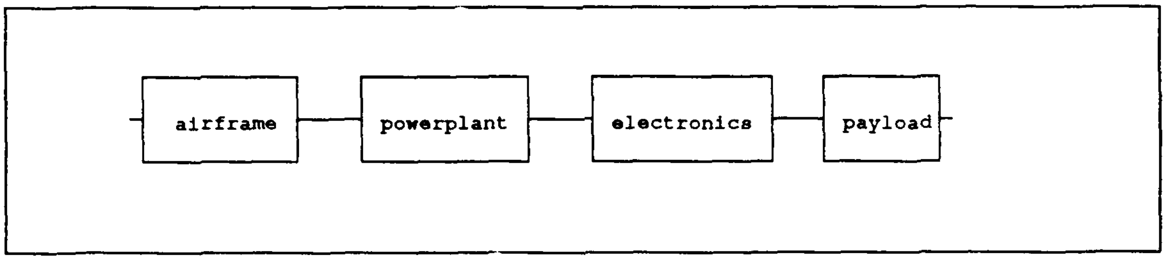

Figure 3.1 Airborne Weapons System Schematic.

1. Failure Rate Analysis

In the following example, each sub-system consists of 100 components in series. Such an assumption is an over simplification of an actual aircraft which consists of thousands of components both in series and in parallel. Components configured in parallel are usually identical in structure or provide a backup capability to another component. For example, on a multi-engine aircraft the engines are in parallel with each other, but as a whole, the propulsion system is in series with the payload. The failure rate of the aggregate propulsion system can be expressed as a single parameter. The assumption of a series system is made to reduce the mathematical complexity and demonstrate that large changes in λ at the component level yield substantially smaller changes in the failure rate at the system level.

The failure rate, λ, for each component will be assumed to be equal to the failure rate for every other component, i.e., $\lambda_{1,1}=\lambda_{1,2}=\lambda_{1,3}=...=\lambda_{4,100}$; for each subsystem $\lambda_{subsystem}=\Sigma\lambda_i=100\lambda$; for the whole system $\lambda_{system}=\Sigma\lambda_{j(subsystem)}=4*100\lambda=400\lambda$. Given the relationships above (p. 26), $MTBF_{sub\text{-}system}=1/(100\lambda_i)=0.01MTBF_i$, and $MTBF_{system}=1/(400\lambda_i)=0.00025*MTBF_i$. Assume CIP resources are expended. This action changes the failure rate of only one component and leaves all other failure rates constant. If the failure rate of the one component improves by a factor of 2, i.e. doubling the MTBF, that is $\lambda'=.5\lambda$ then $\lambda_{subsystem}=99.5\lambda$ and $\lambda_{system}=399.5\lambda$.

For the above example and using the assumptions, decreasing the failure rate for a single component by 1/2 results in only a 0.5 percent improvement at the subsystem level and only 0.125 percent improvement at the system level. If it was possible to reduce the failure rate of a single component infinitely, i.e. $\lambda'=0$, then $\lambda_{sub\text{-}system}=99$ and $\lambda_{system}=399\lambda$ resulting in a 1.0 percent improvement at the sub-system level and a 0.25 percent improvement at the system level.

Using the same example, as above, with four major sub-systems, let each sub-system consist of 100 components; assume all λ's are equal but one. Let one component have a failure rate equal to one hundred times that of the other ninety-nine components, $\lambda'=100\lambda$; then, $\lambda_{sub\text{-}system\ a}=199\lambda$, $\lambda_{sub\text{-}system\ b}=100\lambda$, $\lambda_{sub\text{-}system\ c}=100\lambda$, $\lambda_{sub\text{-}system\ d}=100\lambda$. When resources are expended and λ' is decreased by a factor of two, then λ'' becomes $.5\lambda'$ which is the same as 50λ. This change can be observed at the sub-system and system levels. $\lambda_{sub\text{-}system}$ becomes 149λ which is a 25 percent change in the subsystem failure rate and λ_{system} becomes 449λ which is a 10 percent change in the system failure rate.

In the extreme case, assume λ' decreases infinitely, i.e., λ"=0. When this change is reflected in sub-system and system parameters $\lambda_{sub\text{-}system}$=99λ, which is a 49.7 percent change in the failure rate occurs and λ_{system}=399λ, which is a 20 percent change in the failure rate.

2. Influences of Changes In Failure Rates

It is apparent that even large reductions in failure rates at the component level may only translate into very small changes in overall system parameters. Changes in failure rate (λ) may be very difficult to detect at the system level and more easily observed at the component level. Even if a component is the driving force behind a sub-system failure rate, the effect of changes at the component level may still remain undetected at the system level.

In summary, the authors conclude that the effects of CIP are likely to be undetected at the system level and should be appraised at the component level.

E. TECHNIQUES FOR DETECTING THE CHANGES IN MTBF.

To evaluate the effect of CIP efforts, the following assumptions are made:

- This effect will trickle down, up, and through the sub-system and system levels. A change in the failure rate of a component will result in a change in the failure rate at the sub-system and system level. It has been shown that the changes at the sub-system and system levels are so small they may be undetectable.
- Based on previous discussion, the effect cannot be detected at the system level; it is lost in the random noise associated with the operating characteristics of a sub-system or system. It can only be detected at the component level.

To evaluate the expenditure of CIP funds, a candidate component must be selected. The characteristics of the candidate component are then examined to see if there is a statistically significant change in one or more characteristics. The data available from the ECIFR make it possible to evaluate failure rate, MTBF, MTBR, and/or MMH/OH. MTBF is analyzed by the model and techniques of this thesis because operating and support costs are largely affected by a component's MTBF.

1. Analysis by Graphic Representation of Data

a. Graphic Plots of Time Versus MTBF

One method of detecting a change in the MTBF would be to plot time in months against observed monthly MTBF. There are three general trends which one might observe when using this technique. MTBF could either be decreasing, remaining constant, or improving over time. A component could exhibit any or all combinations of the above during its life time. Figure 3.2 illustrates what a data plot might look like for a component during its life-cycle. The MTBF is relatively constant from months 1-13. During months 13-17, there is a transition to a lower MTBF. It becomes relatively stable again between months 17-28. At month 28 there is a transition to a higher MTBF. At month 31 the MTBF appears to remain relatively stable for the remainder of the data.

b. Graphic Plots of Cumulative Engine Flight Hours Versus Cumulative Failures

A second method of identifying a change in MTBF would be to detect a change in the failure rate, λ. Given the relationships $\lambda=1/MTBF$ and $MTBF=1/\lambda$, it

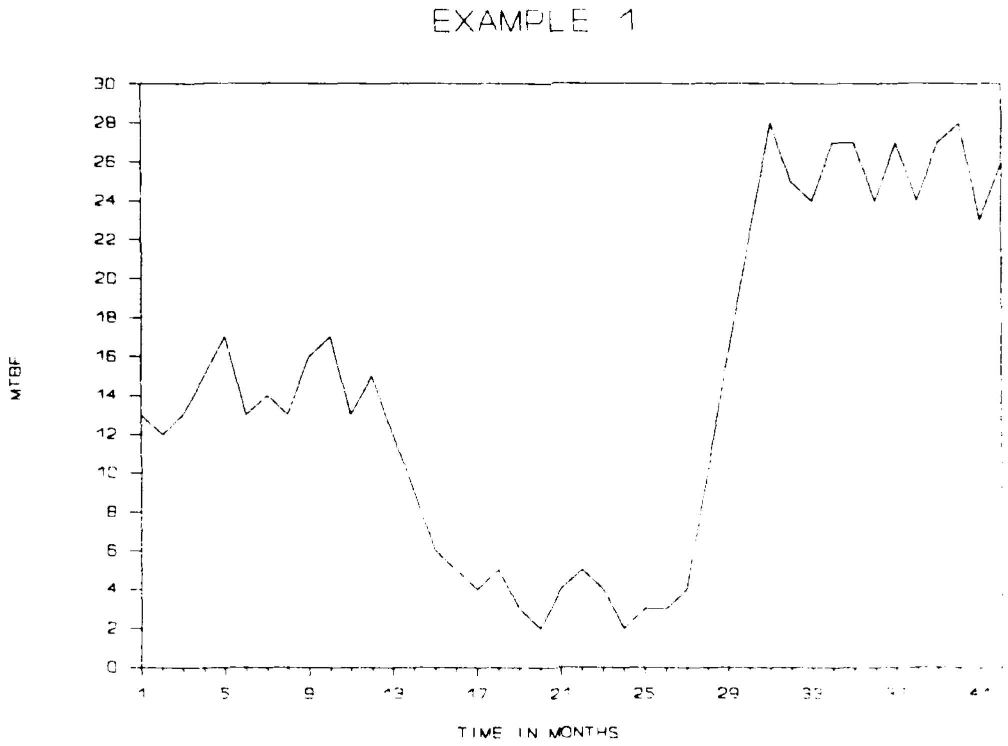

Figure 3.2 Changes in MTBF During a Component's Life-cycle.

follows that a change in the MTBF will be reflected as an inverse change in the failure rate. Specifically, as the MTBF increases, λ decreases; as MTBF decreases, λ increases.

If the cumulative number of failures is plotted against operating time, the curve described by the data points can provide insight into the history of the failure rate. The slope of the curve (df/dt) at any point is the failure rate, λ, at a given time. There are five general shapes of curves that data could possibly trace. These are shown in Figures 3.3 through 3.7.

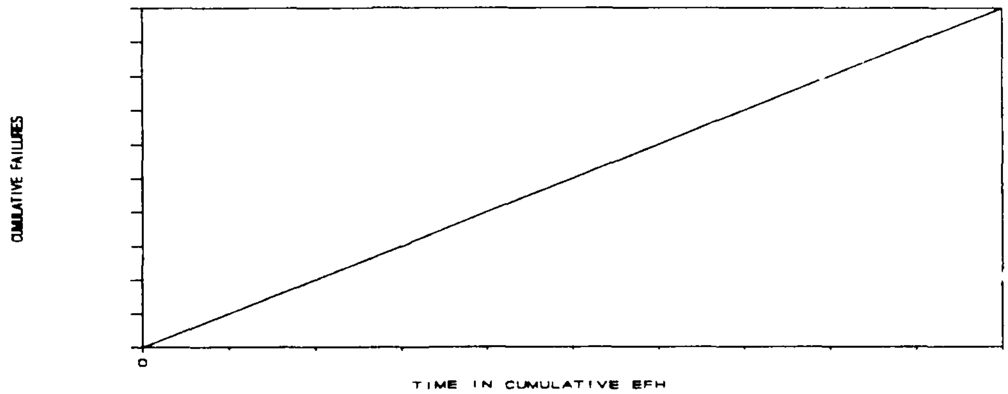

Figure 3.3 Straight Line

A line with a constant slope indicates a component with a constant failure rate and MTBF.

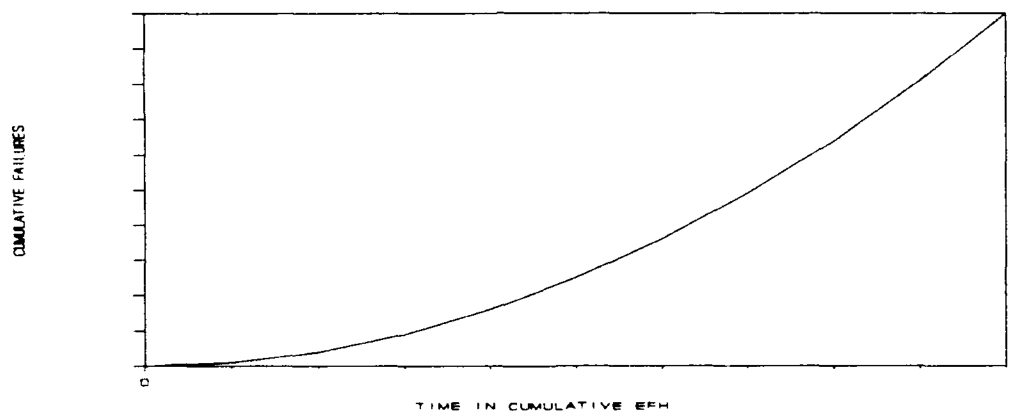

Figure 3.4 Increasing Curve

This curve shows a component with a continuously increasing failure rate or a continuously decreasing MTBF.

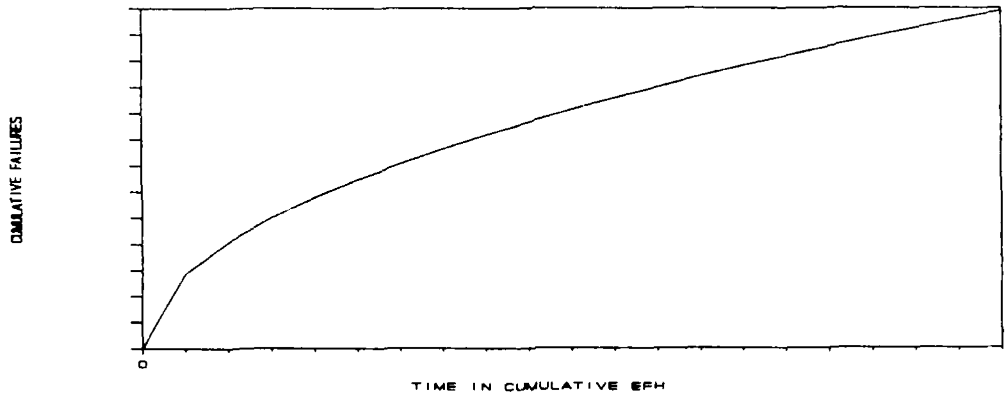

Figure 3.5 Decreasing Curve

This curve indicates a component with a continuously decreasing failure rate or a continuously increasing MTBF.

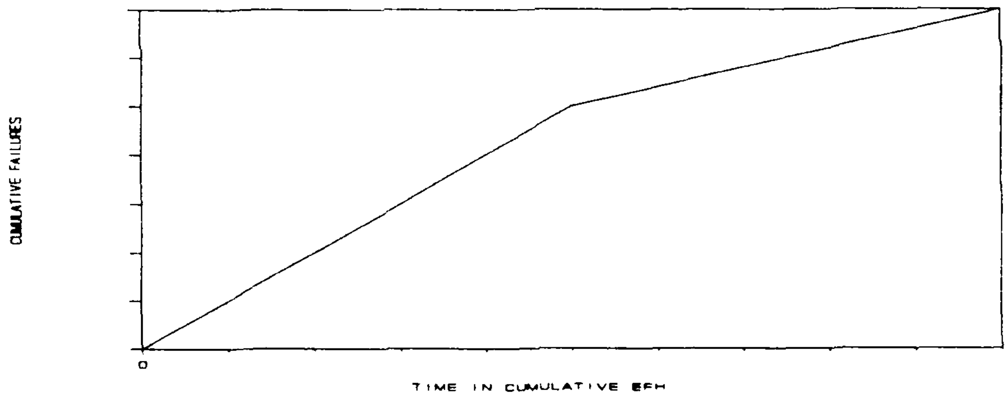

Figure 3.6 Kink downward

This curve shows a component with a constant failure rate until the bend in the curve. Beyond the kink the failure rate **decreases** to a **lower** constant value.

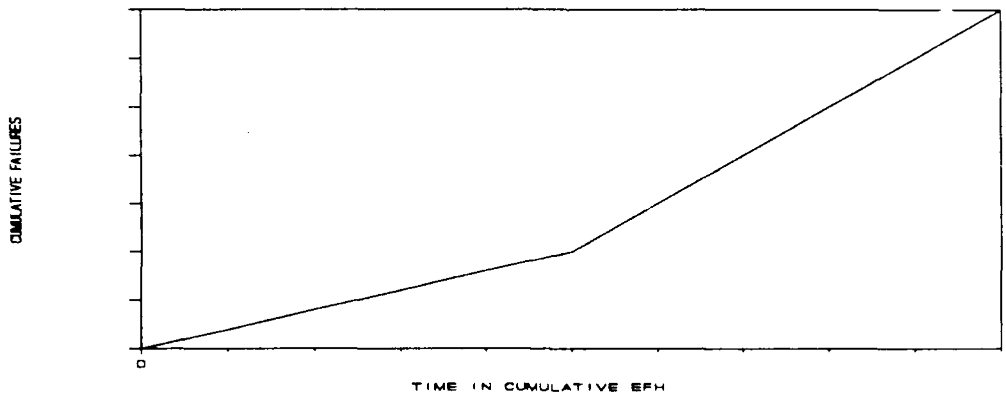

Figure 3.7 Kink Upward

This curve again shows a component with a constant failure rate until the bend in the curve. In this case the failure rate **increases** (beyond the kink) to a **higher** constant value.

Over time, an actual component's failure rate may show any combination of the above graphs depending on where the component is in its life cycle and its continuing engineering efforts. These graphs provide a tool which help determine the trend a particular component is following relative to MTBF and failure rate λ.

Example: Using the data from Tables III.1 and III.2, two graphs have been constructed. For the first graph, time in months versus MTBF is plotted; for the second graph, cumulative engine flight hours is shown versus cumulative failures. The data in Tables III.1 and III.2 were generated for illustration purposes only and have no relationship to any actual engine components.

Month	MTBF	Month	MTBF
1	5	13	13
2	4	14	12
3	6	15	13
4	3	16	19
5	2	17	17
6	6	18	13
7	7	19	18
8	4	20	13
9	2	21	16
10	3	22	17
11	3	23	13
12	4	24	15

Table III.1 Observed Monthly MTBFs.

cumulative failures	cumulative flight hours	cumulative failures	cumulative flight hours
8	343	91	4282
14	710	93	4588
19	995	96	4927
25	1232	99	5163
32	1539	103	5430
40	1775	107	5710
49	2096	110	5915
57	2433	112	6168
65	2732	114	6456
73	3065	115	6717
80	3527	119	7040
87	2899	121	7389

Table III.2 Cumulative Failures and Engine Flight Hours.

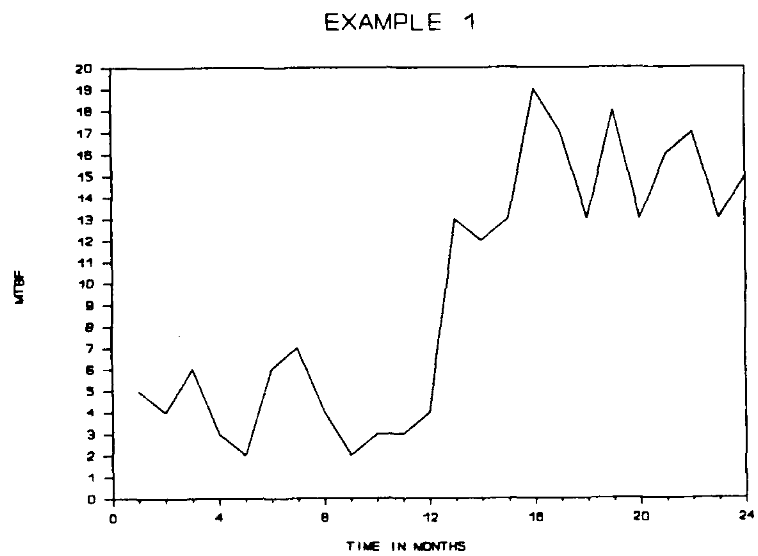

Figure 3.8 Observed Monthly MTBFs

From Figure 3.8, one could conclude that at approximately month 13 there was a significant increase in the component MTBF. After month 12, the MTBF remained relatively constant over time. In this example, CIP did in fact result in an increase in the component MTBF.

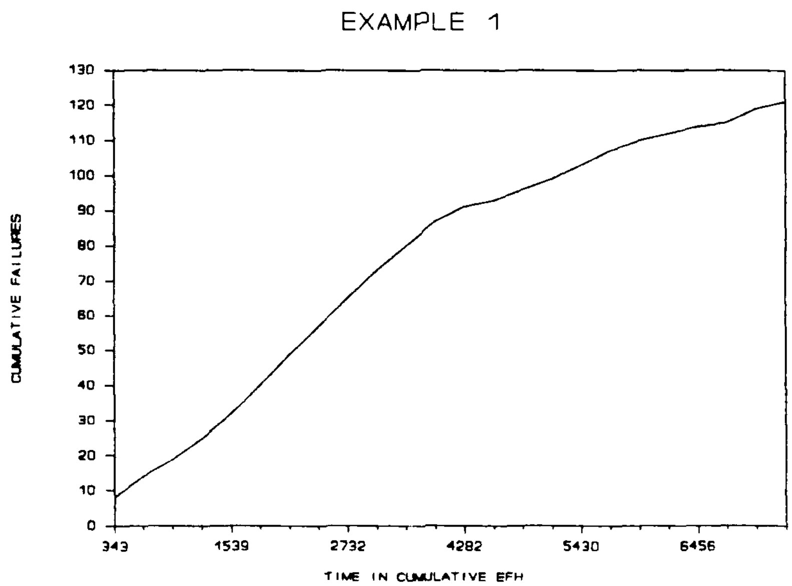

Figure 3.9 Cumulative Failures Versus Cumulative Engine Hours

Figure 3.9 most resembles a kink downward plot which means that the failure rate was constant until approximately 4,282 cumulative engine hours. After 4,282 cumulative hours one could conclude that CIP decreased the failure rate (λ) to a lower constant value.

2. Analysis by ANOVA (Analysis of Variance)

A function of CIP is to reduce the life cycle cost of components. One could compare a population of component MTBFs before and after CIP engineering because life cycle cost is inversely related to MTBF. If there was a change in the population's MTBF, and it was due to CIP, then it would be possible to quantify the change in terms of dollar savings.

One technique for detecting a change in the mean of a population of components is ANOVA. In general terms at the component level, a change in a parameter's value may be detected by testing the hypothesis that the central tendency of the sample populations is the same, or the central tendency of the sample populations is different. In more common mathematical notation, the above statement is written as:

H_o: $\mu_1=\mu_2=\mu_3...$

H_1: not all μ_i are the same.

The computations for an analysis of variance problem are usually summarized in tabular form as shown in Table III.3.[13]

Table III.3 Analysis of Variance for One-Way Classification

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Computed f
Factors	k-1	SSA	$s_1^2 = \frac{SSA}{k-1}$	$\frac{s_1^2}{s^2}$
Error	k(n-1)	SSE	$s^2 = \frac{SSE}{k(n-1)}$	
Total	nk-1	SST		

Example: Using the data from Table III.1, test the hypothesis $\mu_1 = \mu_2$ at the 0.05 level of significance. [i.e., that there is only a probability of .05 that $\mu_1=\mu_2$]. MTBFs for months 1-12 make up the first sample population; MTBFs for months 13-24 make up the second.

[13] For a more rigorous explanation of ANOVA consult R. E. Walpole and R. H. Myers, Probability and Statistics for Engineers and Scientists, Macmillan Publishing Company, 1985.

Table III.4 Analysis of Variance for the Data in Tables III.3 and III.4.

```
SOURCE       DF          SS          MS           F         P
FACTOR        1      704.17      704.17      163.69     0 .000
ERROR        22       91.83        4.17
TOTAL        23      796.00


LEVEL         N        MEAN       STDEV
MTBFa        12       4.083       1.692
MTBFb        12      14.917       2.392

POOLED STDEV =        2.043

INDIVIDUAL 95 PCT CI'S FOR MEAN
BASED ON POOLED STDEV
---+---------+---------+---------+--------
 (--+--)
                                 (--*--)
---+---------+---------+---------+--------

  4.0       8.0        12.0       16.0
```

The results of the ANOVA are found in Table III.4.[14] Before any meaningful interpretation of the data can be made, one must know the upper bound of the critical region. The upper bound is determined by knowing the level of significance α, the degrees of freedom for factors v_1 or k-1, and the degrees of freedom for error v_2 or k(n-1). Once this information is known, the upper bound of the critical region can be obtained from a standard table of Critical Values of the F Distribution [$F_{(\alpha, v1, v2)}$]. For $F_{(0.05, 1, 22)}$ the value of the upper bound is 4.3. If the relationship $f_{(data)} > f_\alpha$ is true, then the null hypothesis (Ho) should be rejected. In this example, 168.9>4.3; therefore, the null

[14] Table III.4 and subsequent Anova tables were generated using the statistics software package Minitab.

hypothesis is rejected and the alternative is accepted. Interpretation of the data findings mean that there is a difference in population means as a result of CIP at a 95 percent confidence interval (CI).

Once a change has been detected in a logistics parameter and it is known that CIP was the cause of the change, the task becomes one of quantifying the net benefits in terms of life cycle cost reductions and dollar savings.[15]

[15] For methods to quantify benefits readers should consult a life cycle cost reference such as; Blanchard, B. S., Design and manage to Life Cycle Cost, Matrix Press, 1978; Blanchard, B. S., Logistics Engineering and Management, Prentice-hall, 1986; Life-Cycle Cost Model Final User's Manual and Operating Instructions, Vol. I, Planning Research Corporation, PRC-R-1225, Arlington, VA; or Equipment Designer's Cost Analysis System, Systems Exchange, 5504 Garth Avenue, Los Angles CA 90056.

IV. ANALYSIS

In this Chapter, the results are explained which were obtained by using the model and techniques of this thesis in conjunction with ECIFR data.

A. OBJECTIVES

The objectives of the analysis are:

- to determine if the effect of expending CIP resources was large enough to be detected by an observable change in component MTBF.
- to demonstrate if an observed change in MTBF was in agreement with the model in Chapter III.
- to determine if the change was statistically significant at the 95 percent confidence interval by using the ANOVA technique.
- to show that there is a positive relationship between CIP and MTBF improvements.

B. PRESENTATION OF DATA

Figures 4.1, 4.2 and Table IV.1 are illustrations of data from an actual engine component which met the selection criteria discussed in Chapter II. This particular component helps demonstrate the complex nature of isolating the benefits of a single CIP action from other factors such as overlapping CIP efforts.

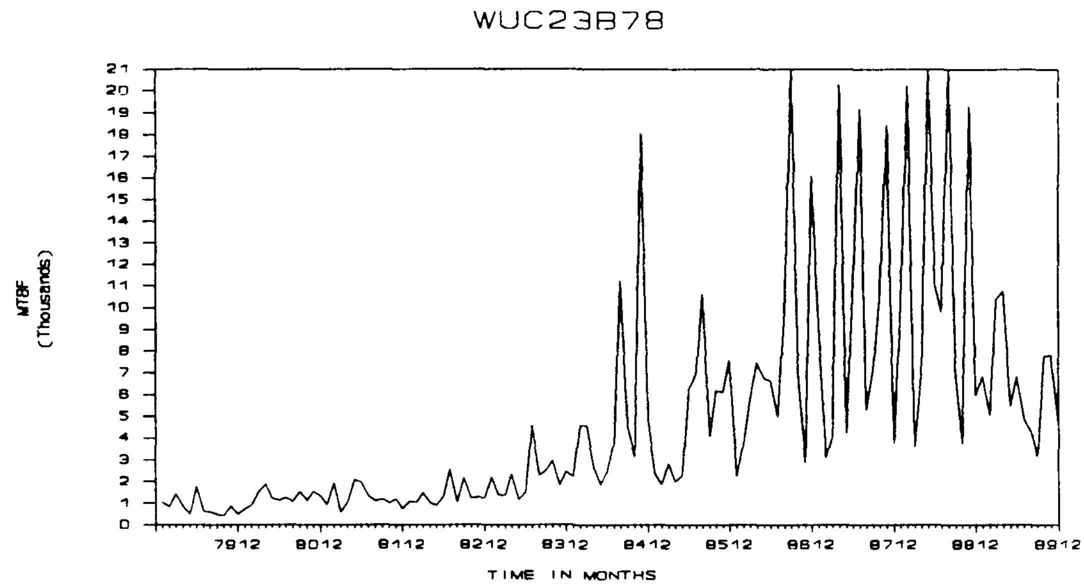

Figure 4.1 Afterburner Igniter Fuel Valve Observed Monthly MTBF

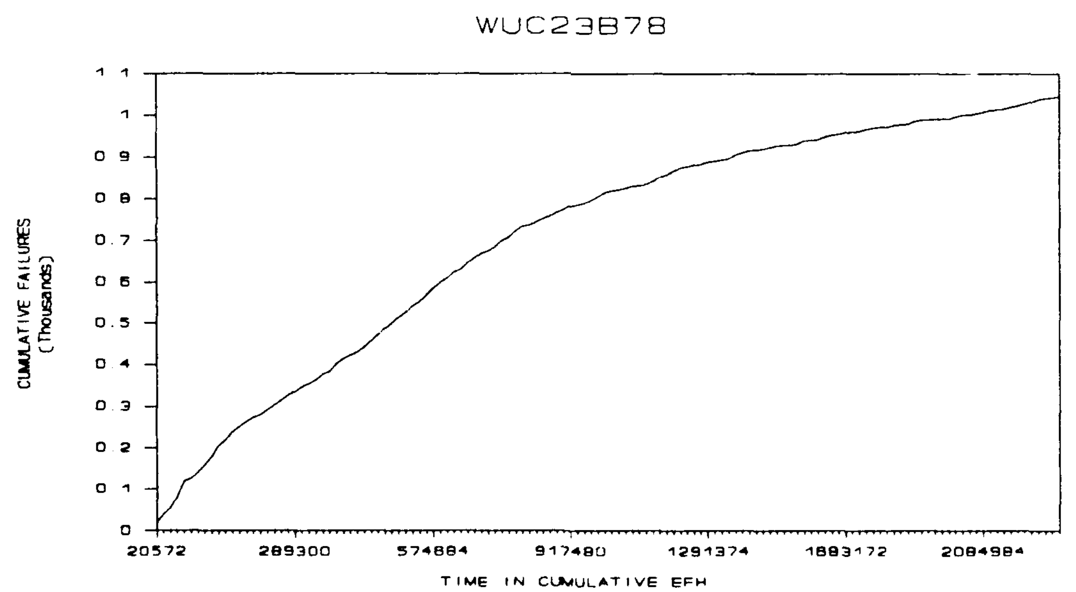

Figure 4.2 Afterburner Igniter Fuel Valve Cumulative Failures Versus Cumulative Engine Hours.

The component represented by the above Figures is the TF30 Afterburner Igniter Fuel Valve. The TF30 is produced by Pratt & Whitney and is the power plant for the F-14 Tomcat. The F-14 Tomcat was introduced into the fleet in the early 1970's. The data set for the Afterburner Igniter Fuel Valve is without break, but because the TF30 became operational in the early 1970's, the entire life of the component's MTBF is not represented.

After talking with both Pratt & Whitney program engineers and Navy CIP engine managers, the authors learned that the Afterburner Igniter Fuel Valve was the recipient numerous CIP efforts during the period which the data covers (no fewer than three times but not more than ten times). In this situation, how does one distinguish or weight increases in MTBF among all of the ECPs which have taken place.

By Figure 4.1, one can see that there has been a change in the MTBF of the Afterburner Igniter Fuel Valve from approximately 1,000 hours in 1982 to in excess of 6,000 hours in 1989. Because there were multiple CIP efforts affecting the MTBF of the Afterburner Igniter Fuel Valve, there was no abrupt change in the MTBF at any point in the graph. The plot of MTBF versus months indicates that there was a steady increase in the MTBF throughout the life of the component. The observations from Figure 4.1 are confirmed by Figure 4.2. Figure 4.2 also demonstrates that the component has had an increasing MTBF and a decreasing λ throughout the data set.

Since the Afterburner Igniter Fuel Valve has been re-engineered multiple times, one could surmise that there would not be any obvious demarkation of changes in MTBF.

One would expect to see gradual changes in MTBF caused by the overlap of different ECP's. This expectation is substantiated by Figures 4.1 and 4.2.

Table IV. 1 Afterburner Igniter Fuel Valve ANOVA

WUC 23B78

SOURCE	DF	SS	MS	F	p
FACTOR	2	1.296E+09	648198144	41.00	0.000
ERROR	129	2.039E+09	15809329		
TOTAL	131	3.336E+09			

LEVEL	N	MEAN	STDEV
MTBFa	22	1008	421
MTBFb	52	2482	2768
MTBFc	58	8276	5372

POOLED STDEV = 3976

```
INDIVIDUAL 95 PCT CI'S FOR MEAN
BASED ON POOLED STDEV
---+---------+---------+---------+---
  (----*-----)
        (--*---)
                         (---*--)
---+---------+---------+---------+---
   0      3000      6000      9000
```

Using Figure 4.2, the data were divided into three sub-sets. The first sub-set included the data from January 1979 to October 1980 (300,600 EFH); the second contained data from November 1980 to February 1985 (1,143,826 EFH); and the third contained data from March 1985 to December 1989 (2,302,322 EFH). From Table IV.1, one could conclude that at the 95 percent confidence level there was not a statistically significant difference between sub-sets 1 and 2. There was, however, a statistically significant difference between sub-sets 1 and 3, and, sub-sets 2 and 3.

C. CONCLUSIONS

In summary, one can make the following conclusions about CIP and the Afterburner Igniter Fuel Valve:

- the affect of CIP resources was detected and observed in Figure 4.1 by the continual increase in component MTBF from 1979 to 1989.
- the trend in failure rate illustrated in Figure 4.2 is consistent with the model in Chapter III (see Figure 3.5).
- there is a statistically significant difference between 2 of 3 Afterburner Igniter Fuel Valve data sub-sets (see Table IV.1).
- the more CIP resources which were expended on the Afterburner Igniter Fuel Valve, the more the failure rate decreased and MTBF increased (see Figures 4.1 and 4.2).

The analysis clearly shows that there is a positive relationship between MTBF improvement and CIP. The changes in MTBF for the Afterburner Igniter Fuel Valve are detected as they are predicted by the methodology and analytical procedures of this thesis.

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The original goal of this thesis was to provide managers of the Component Improvement Program with a tool that would quantify the benefits of CIP. One of the original assumptions underlying the research effort was that CIP funding needed a significant increase rather than an incremental increase. As the research effort continued, it became obvious to the authors that quantifying the benefits of CIP was an extremely complex process.

First, the budgeting process within DON was examined. The drop in CIP funds between 1983 and 1987 was the result of internal Navy management. An attempt was made to determine if this decline in budget was appropriate or if another method to justify CIP funding level requests was required. We believe a tool to help budget managers associate the costs and benefits of CIP is required. This tool should be designed to assist budget managers in determining an efficient allocation of resources for the Component Improvement Program.

After discussions with NAVAIR and OPNAV personnel, it seemed logical to search for CIP benefits which accrued at the component level, rather than at the system level. A theoretical discussion was presented concerning why the effects of observable benefits became diluted as they filtered through the component, subsystem and system structure of an engine. This discussion supports the intuition that the component level is the correct place to assess CIP benefits.

The tools for selecting and analyzing a component's MTBF were developed and validated in Chapters II, III and IV. As a result of developing this procedure, the problems of normalizing the ECIFR data against the CIP milestone timeline became evident. There exists some evidence that there is a database structuring problem; that is, data from the ECIFR are not collected in a format compatible with the previously mentioned timeline.

Without the ability to normalize the ECIFR data, it is impossible to effectively determine the level of change in component MTBF which has occurred as a result of specific CIP activities.

The most significant accomplishments made by the authors were:

- analysis of the problems involved in developing a methodology for selecting candidate components for study.
- use of the analysis of variance for one-way classification as a technique for discriminating between sample means of component MTBF; this technique is applicable to other logistics parameters.
- development of formats for graphing ECIFR data in its existing form and explanation of the significance of these graphs.

A deeper understanding of the Component Improvement Program process was achieved. By producing a procedure for analyzing ECIFR data and other logistics parameter data, this thesis has clearly paved the way for additional research. This thesis has provided a comprehensive bibliography which lists other publications about CIP and continuing engineering. The bibliography eliminates the need to extensively research background and historical information.

B. CONCLUSIONS

The effects of CIP can only be evaluated at the component level. Because of the complex interactions of components and their intricate relationships, the effects of CIP are lost in the random noise of a system. The effects of a single CIP expenditure are so small when examined at the system level they become insignificant; therefore, engine parameters should not be tracked at the system level but at the component level.

Sub-optimization of dollar resources is occurring. Because different individuals with different incentive structures are responsible for managing and executing the funds required to take an aircraft from "cradle to grave," the Navy is accepting a suboptimal expenditure of resources. Many tradeoffs take place when designing and operating an aircraft. A **single** individual (or organization) should be responsible for making those tradeoffs. The same individual should also be responsible for executing the budget and supporting the weapon system. One goal should be to achieve the most "effective and reliable" system within a given budgetary constraint which includes RDT&E, APN, and O&M,N dollars. Because of the way the United States Navy currently manages funds, each appropriation manager is optimizing the use of his funds largely without regard to the impact on the managers of other appropriations. If one individual or organization were responsible to manage an allocation of funds whose purpose was "cradle to grave" support of a weapon system, he/she could make the tradeoffs necessary to ensure the optimal use all funds and still meet the system's mission objectives.

Currently OP-05 is responsible for programming and planning allocations between different appropriation resources; however, by the time field data reach the decision maker in OP-05 it is homogeneous. There is not enough detail to allow the resource manager to make a rational decision which achieves the most "effective and reliable" system within a given budgetary constraint.

We conclude from this project that the method of data collection plays a critical role in developing the capability to measure the effects of CIP on logistics parameters and quantifying the benefits of CIP itself. Once the correct format of data is available, it should be possible to calculate the net benefits in dollar terms.

The component we selected for analysis demonstrates the difficulties in measuring the incremental benefits from additional CIP expenditures. Our objective was to assess the consequences of a CIP expenditure as soon as possible after the installation of an ECP. However, if evaluation is based on the existing data, an accurate assessment is unlikely until a very large amount of program time has elapsed.

Perhaps it is best to recognize that it is probably not possible to measure CIP productivity using active engine programs. Rather, CIP productivity might best be assessed by looking at "retired" engine programs. One could then assess the value or utility of continuing a component improvement program from a life-cycle-cost basis rather than on a year to year incremental basis.

C. RECOMMENDATIONS

The following recommendations are provided as a means of further achieving the objectives stated in Chapter I.

The authority for "cradle to grave" management of an aircraft should be consolidated in one program management office. This action would allow optimal tradeoffs to be made and the impact of these tradeoffs to be evaluated across the entire spectrum of a weapon system life cycle. Tradeoffs could be made which consider impacts on reliability, maintainability, operability, operating and support cost, production and retro-fit cost, and weapon system effectiveness.

The Aircraft Turbine Engine Component Improvement Program should be returned to the Aircraft Procurement, Navy (APN) appropriation. This initial step would overcome the sub-optimization problem. It would allow the appropriation manager to evaluate tradeoffs such as conducting a CIP effort and not providing the funds to implement the engine modifications.

If CIP is to remain a separate RDT&E line item it should be split into three sub-line items. The first proposed line item would contain the funding needed to accomplish safety of flight objectives. The second proposed line item would contain the funding needed to achieve the remaining objectives of CIP. The final proposed line item would contain the funding needed to support CIP program management and infrastructure. This recommendation suggests a means to show how much money is being spent on safety of flight items and program management and how little is being spent on the remaining CIP objectives.

A more indepth follow-on study should be conducted using the methodology and techniques discussed in Chapters II and III. Component selection criteria must be strictly followed. Once components are identified, NAVAIR engine program engineers should determine the dates when the component reached each of the CIP timeline milestones. Disregard any component where T_4 and T_5 are not identified.

Students who are in the Operations Research, Computer Systems Management, Financial Management, Material Logistics Support Management, and Aeronautical Engineering Curriculums should be recruited to study the Component Improvement Program further. Because of the multi-faceted nature of the Component Improvement Program, students in each of these curricula would be able to improve on this base of knowledge. A Computer Systems Management student could provide useful insight into a database design that would facilitate analysis using the methods of this thesis. A Material Logistic Support Management student could evaluate the effects of CIP on a life-cycle cost basis. A Financial Management student could develop a methodology for determining the efficient allocation of funds for the Aircraft Turbine Engine Component Improvement Program given current real world budgetary constraints. An Operations Research student could develop other analytical techniques to evaluate or determine optimal tradeoffs between recommendations which other disciplines might make. Finally, an Aeronautical Engineering Student might provide insight into the specific problems of aircraft engine design and support. The Aircraft Turbine Engine Component Improvement Program is a multi-disciplined program; therefore, the study of CIP budgeting should be open to the above disciplines.

D. AREAS FOR FURTHER RESEARCH

Research should be conducted to determine if CIP is the causative factor in the improvement of MTBF. This thesis clearly demonstrates a positive relationship between the expenditure of CIP funds and improvements in MTBF. It remains to be shown that the expenditure of CIP resources was the cause of the improvement in MTBF.

A cost savings analysis should be conducted on the J52 Power Plant Change (PPC) 290. A claim is made by the J52 program engineer that if PPC 290 was incorporated, the O&M,N savings which might accrue from installation would also make it possible to procure a new radar system for the A-6. Instead, the decision appears to be to buy a new radar system and forego the O&M,N savings that could be achieved by incorporating PPC 290. The apparent driver in this decision is the unavailability of funds to do both simultaneously. If the PPC were installed first, it might save enough money to pay for the radar system, too.

The component sample size of this study should be expanded. With a sufficiently large sample size it may be possible to quantify the point where marginal benefits of CIP equal the marginal cost of CIP. In an economic sense, this is the proper allocation of funds for the Component Improvement Program.

Alternative sources of data should be studied to apply to the model contained in this study.

The effects of optimizing the use of funds at the appropriation level should be evaluated. These data should be compared this to what might happen if a fixed amount of funds had been used optimally over the life-cycle of the system.

The impact of "fully funding" the CIP program should be evaluated, i.e., zero funding shortfalls. Is the program executable? Can the contractors support the program? Do the contractors have on staff or access to the technical and management expertise to support a "fully funded" CIP program.

APPENDIX

This Appendix contains the data used to generate the graphs and ANOVA tables in chapter 4.

RAW DATA FROM ECIFR			COMPUTED DATA		
DATE	FAIL	EFH	MTBF	CUMEFH	CUMFAIL
			WUC23B78		
7901	20	20572	1033.6	20572	20
7902	20	17100	855.0	37672	40
7903	16	22584	1411.5	60256	56
7904	26	22176	852.9	82432	82
7905	38	18536	487.8	100968	120
7906	6	10476	1746.0	111444	126
7907	16	9730	608.1	121174	142
7908	18	10580	587.8	131754	160
7909	20	9564	478.2	141318	180
7910	28	12154	434.1	153472	208
7911	12	10434	869.5	163906	220
7912	20	9782	489.1	173688	240
8001	13	9648	742.2	183336	253
8002	11	9852	895.6	193188	264
8003	9	13528	1503.1	206716	273
8004	7	12972	1853.1	219688	280
8005	12	14786	1232.2	234474	292
8006	13	14736	1133.5	249210	305
8007	11	13628	1238.9	262838	316
8008	12	12688	1057.3	275526	328
8009	9	13774	1530.4	289300	337
8010	10	11300	1130.0	300600	347
8011	9	13878	1542.0	314478	356
8012	8	10558	1319.8	325036	364
8101	14	12888	920.6	337924	378
8102	7	13366	1909.4	351290	385
8103	18	10504	583.6	361794	403
8104	12	12536	1044.7	374330	415
8105	7	14436	2062.3	388766	422
8106	9	17830	1981.1	406596	431
8107	12	16090	1340.8	422686	443
8108	14	15576	1112.6	438262	457
8109	15	17952	1196.8	456214	472
8110	15	15000	1000.0	471214	487

RAW DATA FROM ECIFR			COMPUTED DATA		
DATE	FAIL	EFH	MTBF	CUMEFH	CUMFAIL
8111	13	15336	1179.7	486550	500
8112	14	10530	752.1	497080	514
8201	14	15118	1079.9	512198	528
8202	14	14504	1036.0	526702	542
8203	11	16396	1490.5	543098	553
8204	17	17054	1003.2	560152	570
8205	16	14532	908.3	574684	586
8206	13	16914	1301.1	591598	599
8207	11	28088	2553.5	619686	610
8208	14	14552	1039.4	634238	624
8209	7	15032	2147.4	649270	631
8210	16	19356	1209.8	668626	647
8211	11	14120	1283.6	682746	658
8212	11	13648	1240.7	696394	669
8301	7	15272	2181.7	711666	676
8302	10	13946	1394.6	725612	686
8303	15	20296	1353.1	745908	701
8304	8	18572	2321.5	764480	709
8305	15	17566	1171.1	782046	724
8306	10	15028	1502.8	797074	734
8307	3	13700	4566.7	810774	737
8308	9	20478	2275.3	831252	746
8309	7	17452	2493.1	848704	753
8310	6	17780	2963.3	866484	759
8311	10	18378	1837.8	884862	769
8312	6	14752	2458.7	899614	775
8401	8	17866	2233.3	917480	783
8402	4	18406	4601.5	935886	787
8403	4	18410	4602.5	954296	791
8404	6	16138	2689.7	970434	797
8405	10	18640	1864.0	989074	807
8406	8	19628	2453.5	1008702	815
8407	5	19138	3827.6	1027840	820
8408	2	22440	11220.0	1050280	822
8409	4	18058	4514.5	1068338	826
8410	6	18900	3150.0	1087238	832
8411	1	18028	18028.0	1105266	833
8412	3	14568	4856.0	1119834	836
8501	8	19074	2384.3	1138908	844
8502	8	14918	1864.8	1153826	852
8503	7	19796	2828.0	1173622	859
8504	9	18086	2009.6	1191708	868
8505	8	18292	2286.5	1210000	876
8506	3	18814	6271.3	1228814	879
8507	3	20826	6942.0	1249640	882
8508	2	21230	10615.0	1270870	884
8509	5	20504	4100.8	1291374	889
8510	3	18534	6178.0	1309908	892

RAW DATA FROM ECIFR			COMPUTED DATA		
DATE	FAIL	EFH	MTBF	CUMEFH	CUMFAIL
8511	3	18320	6106.7	1328228	895
8512	2	15100	7550.0	1343328	897
8601	9	20154	2239.3	1363482	906
8602	5	19186	3837.2	1382668	911
8603	4	23130	5782.5	1405798	915
8604	3	22310	7436.7	1428108	918
8605	3	20292	6764.0	1448400	921
8606	3	19916	6638.7	1468316	924
8607	4	19928	4982.0	1488244	928
8608	2	19878	9939.0	1508122	930
8609	0	19412	21000.0	1527534	930
8610	3	20854	6951.3	1548388	933
8611	7	20096	2870.9	1568484	940
8612	1	16058	16058.0	1584542	941
8701	2	18124	9062.0	1602666	943
8702	6	18836	3139.3	1621502	949
8703	5	20378	4075.6	1641880	954
8704	1	20276	20276.0	1662156	955
8705	5	21016	4203.2	1683172	960
8706	2	21362	10681.0	1704534	962
8707	1	19172	19172.0	1723706	963
8708	4	21226	5306.5	1744932	967
8709	3	21488	7162.7	1766420	970
8710	2	20936	10468.0	1787356	972
8711	1	18434	18434.0	1805790	973
8712	4	15088	3772.0	1820878	977
8801	2	19154	9577.0	1840032	979
8802	1	20216	20216.0	1860248	980
8803	6	21590	3598.3	1881838	986
8804	3	21002	7000.7	1902840	989
8805	0	22180	21000.0	1925020	989
8806	2	22152	11076.0	1947172	991
8807	2	19594	9797.0	1966766	993
8808	0	20916	21000.0	1987682	993
8809	3	20924	6974.7	2008606	996
8810	5	18692	3738.4	2027298	1001
8811	1	19322	19322.0	2046620	1002
8812	3	17856	5952.0	2064476	1005
8901	3	20508	6836.0	2084984	1008
8902	4	20082	5020.5	2105066	1012
8903	2	20718	10359.0	2125784	1014
8904	2	21510	10755.0	2147294	1016
8905	4	21932	5483.0	2169226	1020
8906	3	20464	6821.3	2189690	1023
8907	4	19468	4867.0	2209158	1027
8908	5	21384	4276.8	2230542	1032
8909	6	19022	3170.3	2249564	1038
8910	3	23394	7798.0	2272958	1041

RAW DATA FROM ECIFR				COMPUTED DATA	
DATE	FAIL	EFH	MTBF	CUMEFH	CUMFAIL
8911	2	15614	7807.0	2288572	1043
8912	3	13750	4583.3	2302322	1046

BIBLIOGRAPHY

Alexander, Arthur J.; "The Cost and Benefits of Reliability in Military Equipment"; The RAND Corporation, Santa Monica, CA, December 1988.

Birkler, J. L. and Cote, S. M.; "Forecasting of Developmental Expenditures and Test Hours for Gas Turbine Engines": Air Vehicle Technology Department, Naval Air Development Center, Warminister, PA; 28 April 1975.

Birkler, J. L. and J. R. Nelson; "Aircraft Turbine Engine Monitoring Systems: Overview and Lessons Learned From Six Case Studies"; RAND Corp, Santa Monica, CA; May 1979.

Blanchard, B. S.; Logistics Engineering and Management; Third Edition, Prentice-Hall, Englewood Cliffs, NJ; 1986.

Gebman, J. R., D. W. Mclver and H. L. Shulman; "A New View of Weapon System Reliability and Maintainability (Executive Summary)"; RAND Corp, Santa Monica, CA; January 1989.

Geron, John D., MAJ, USAF; "Contracting for the Component Improvement Program (CIP) for Military Aircraft Engines"; Defense Systems Management College, FT Belvoir, VA; May 1975.

Harmon, Bruce R. et al; "Assessing Acquisition Schedules for Tactical Aircraft"; Institute for Defense Analysis, Alexandria, VA; February 1989.

Harmon, Bruce R. et al; "Military Tactical Aircraft Development Cost" (5 volumes); Institute for Defense Analysis, Alexandria, VA; September 1988.

Hines, William W. and Montgomery, Douglas C.; Probability and Statistics in Engineering and Management Science; Second Edition, John Wiley & Sons, Inc.; New York; 1980.

Francke, K. P.; "Users' Manual, Cost Effectiveness Analysis Model for Program Task Plans and Engineering Change Proposals"; Air Force Systems Command, Wright Patterson Air Force Base, OH; "For Official Use Only"; Draft.

Marks, Kenneth E. and Hess, Ronald W.; "Estimating Aircraft Depot Maintenance Cost"; RAND Corp, Santa Monica, CA; July 1981.

Nelson, J. R.; "An Approach to the Life Cycle Analysis of Aircraft Turbine Engines"; RAND Corp, Santa Monica, CA; November 1979.

Nelson, J. R.; "Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary"; Rand Corp, Santa Monica, CA; March 1977.

Nelson, J. R.; "Life-Cycle Analysis of Aircraft Turbine Engines"; Rand Corp, Santa Monica, CA; November 1977.

Nelson, J. R.; Harmon, B. R.; and Tyson, K. W.; Policy Options for the Aircraft Turbine Engine Component Improvement Program", Institute for Defense Analyses, Alexandria, VA May 1987.

Ryan, B. F., B. L. Joiner and T. A. Ryan, Jr.; Minitab Handbook, Second Edition; PWS-KENT Publishing Company, Boston; 1985.

Verma, Rajiv S., 1LT, USAF; "The Use of Cost Estimating Relationships Versus Accounting Models for Estimating Maintenance and Repair Cost: A Methodology Demonstration"; Air Force Institute of Technology, Wright Patterson Air Force Base, OH; September 1987.

Vess, Jack E., "An Analysis of Maintenance Cost Reduction in Operational Naval Aircraft Through Reliability and Maintainability Improvements" Master's Thesis, Naval Postgraduate School, Monterey, CA, June 1988.

Walpole, R. E. and R. H. Myers; Probability and Statistics for Engineers and Scientist, Third Edition; Macmillan Publishing Company, New York; 1985.

"Acquisition Plan AP No. A42-48-0-50 Rev B for Aircraft Engine Component Improvement Program"; Naval Air Systems Command, Washington, D. C.; August 1987.

"Component Improvement Program Technical Evaluation Plan"; Naval Air Systems Command, Washington, D.C.; draft.

"Policy Guidelines and Responsibilities for the Administration of the Aircraft Engine Component Improvement Program"; NAVAIR Instruction 5200.35; Naval Air Systems Command, Washington, D.C.; 25 January 1982.

"Program Management Plan for the Engine Component Improvement Program"; Air Force Systems Command, United States Air Force, Acquisition Support Division. Wright Patterson Air Force Base, OH; 10 March 1989.

"Program Management Directive for Engines Component Improvement Program(CIP)"; Headquarters U.S. Air Force, Washington, D.C.; 3 February 1989.

"Return on Investment Analysis Program User's Guide"; Naval Air Systems Command (AIR-536), Washington, D.C.; September 1989.

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