Designing for Sustainability & Upgradability in an Aerospace System

by

Spencer L. Lewis

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Submitted to the Aeronautical and Astronautical Engineering Department and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degree of Master of Science in Technology and Policy and Master of Science in Aeronautical and Astronautical Engineering at the Massachusetts Institute of Technology

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Signature of Author

Department of Aeronautical and Astronautical Engineering
May 5, 2000

Certified by

Professor Wesley L. Harris
Professor, Department of Aeronautical and Astronautical Engineering
Thesis Supervisor

Accepted by

Daniel D. Hastings
Professor of Engineering Systems and Aeronautics and Astronautics
Co-Director, Technology and Policy Program

Accepted by

Nesbitt W. Hagood, III
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

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Submitted to the Aeronautical and Astronautical Engineering Department and Technology and Policy Program on March 20, 2000 in partial fulfillment of the requirements for the Degrees of Master of Science in Aeronautical and Astronautical Engineering and Technology and Policy

ABSTRACT

The United States Air Force utilizes a significant amount of its budget to maintain its aerospace systems in operational condition. In order to reduce these costs, the Air Force has communicated to aerospace manufacturers a desire to reduce the overall costs of its aerospace system maintenance. This thesis investigates how the Air Force and Corporation Alpha, a leading manufacturer of aerospace engines, have adapted their design and development practices to make the EG10 fighter engine family more reliable, durable, and maintainable. I used the metric Unscheduled Engine Removals (UER) per 1000 Effective Flight Hours (UER/1000EFH) to compare the sustainability of different models of EG10 while investigating how the sustainment lessons of the EG10 have been incorporated into Corporation Alpha's latest product, the EG15-1. The analysis presented in this thesis will focus on the policies, technology, processes and tools, and final results of efforts to improve the sustainability of these engine systems. The final results show that the sustainability, as measured by the UER metric, have not increased beyond $10^6$ EFH with each succeeding generation of EG10 engine. This illustrates that improving aerospace system sustainability involves factors beyond the design phase of the system.

Thesis Supervisor
Prof. Wesley L. Harris

Professor of Aeronautical and Astronautical Engineering
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<td>AFB:</td>
<td>Air Force Base</td>
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<tr>
<td>ALC:</td>
<td>Air Logistics Center</td>
</tr>
<tr>
<td>AMT:</td>
<td>Accelerated Mission Tests</td>
</tr>
<tr>
<td>CAD:</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CALS:</td>
<td>Computer-Aided Acquisition and Logistics Support</td>
</tr>
<tr>
<td>CEA:</td>
<td>Cost Effective Analysis</td>
</tr>
<tr>
<td>CEDU:</td>
<td>Comprehensive Engine Diagnostic Unit</td>
</tr>
<tr>
<td>CEM:</td>
<td>Comprehensive Engine Management</td>
</tr>
<tr>
<td>CIP:</td>
<td>Component Improvement Program</td>
</tr>
<tr>
<td>DLA:</td>
<td>Defense Logistics Agency</td>
</tr>
<tr>
<td>DoD:</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>EFH:</td>
<td>Effective Flight Hours</td>
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<tr>
<td>EMDP:</td>
<td>Engine Model Derivative Program</td>
</tr>
<tr>
<td>ENSIP:</td>
<td>Engine Structural Integrity Program</td>
</tr>
<tr>
<td>FADEC:</td>
<td>Full-Authority Digital Electronic Controls</td>
</tr>
<tr>
<td>FSO:</td>
<td>Field Support Office</td>
</tr>
<tr>
<td>HQ AFMC/LG:</td>
<td>Headquarters Air Force Material Command</td>
</tr>
<tr>
<td>IPT:</td>
<td>Integrated Product Teams</td>
</tr>
<tr>
<td>ISP:</td>
<td>Initial Service Parts</td>
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<tr>
<td>LAI:</td>
<td>Lean Aerospace Initiative</td>
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<tr>
<td>LCCM:</td>
<td>Life Cycle Cost Model</td>
</tr>
<tr>
<td>LRU:</td>
<td>Line Repairable Units</td>
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<tr>
<td>LSI:</td>
<td>Lean Sustainment Initiative</td>
</tr>
<tr>
<td>MAJCOM:</td>
<td>Major Commands</td>
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<tr>
<td>MMH:</td>
<td>Maintenance Man-Hours</td>
</tr>
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<td>MIT:</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MSIP:</td>
<td>Multistage Improvement Program</td>
</tr>
<tr>
<td>MTBF:</td>
<td>Mean-Time-Between-Failure</td>
</tr>
<tr>
<td>MTBM:</td>
<td>Mean-Time-Between-Maintenance</td>
</tr>
<tr>
<td>OCM:</td>
<td>On Condition Maintenance</td>
</tr>
<tr>
<td>PPSIP:</td>
<td>Propulsion and Power System Integrity Program</td>
</tr>
<tr>
<td>R&amp;M:</td>
<td>Reliability and Maintainability</td>
</tr>
<tr>
<td>RCM:</td>
<td>Reliability Centered Maintenance</td>
</tr>
<tr>
<td>SA-ALC:</td>
<td>San Antonio Air Logistics Center</td>
</tr>
<tr>
<td>SER:</td>
<td>Scheduled Engine Removals</td>
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<tr>
<td>SPO:</td>
<td>System Program Office</td>
</tr>
<tr>
<td>TER:</td>
<td>Total Engine Removals</td>
</tr>
<tr>
<td>TER/1000EFH:</td>
<td>Total Engine Removals Per 1000 Effective Flight Hours</td>
</tr>
<tr>
<td>TOD:</td>
<td>Technical Order Data</td>
</tr>
<tr>
<td>UER:</td>
<td>Unscheduled Engine Removals</td>
</tr>
<tr>
<td>UER/1000EFH:</td>
<td>Unscheduled Engine Removals Per 1000 Effective Flight Hours</td>
</tr>
<tr>
<td>WPAFB:</td>
<td>Wright Patterson Air Force Base</td>
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Chapter I: Introduction

During fiscal year 1999, the United States Air Force was authorized to use over 24 billion dollars toward the operation and maintenance of its equipment¹. These funds represent almost double the amount that the Air Force spends on procuring new hardware, and represents over 30% of the total Air Force budget. This fact has led the Air Force to launch investigations into what policies and practices allow them to most efficiently utilize these massive operations and maintenance funds.

Given the Air Force's tremendous operations and maintenance budget, heavy competition exists to provide support services for Air Force aircraft. Moreover, Air Force officials want to minimize the funds used to operate their systems. One characteristic that determines how much effort and money aerospace system owners utilize to operate and maintain their systems is the system's sustainability. When a system is sustainable, the logistics, maintenance, and operations needs for that system have been optimized in order to minimize costs incurred by the owner of that system. Recently, the importance of system sustainability has increased because of pressure to reduce military spending while lengthening operational lives of aerospace systems.

Large Air Force operations and maintenance budgets and the heavy competition between civilian companies to support these operations have influenced the Air Force to gain greater understanding of aerospace system sustainability. This thesis examines how an American aerospace company designs sustainability into its products and what the results of those design efforts have meant to the users and maintainers of those systems.

The conclusions presented in this thesis are heavily based on case studies conducted of a series of fighter engine systems used by the Air Force and manufactured by a major American aerospace manufacturer, which shall be referred to as Corporation Alpha for the remainder of this thesis in order to maintain the company's anonymity. The engine systems studied will also be given the aliases EG10-1, EG10-2, EG10-5, EG10-9, and the newly developed EG15-1 in order to disguise further the identity of the Corporation Alpha. Collectively, the first four engine systems will be called the EG10 engine family.

1.1 Background Information

The Air Force fields hundreds of aerospace systems in order to fulfill its obligation to protect American interests and provide national security. Additionally, there exists a tremendous infrastructure that supports and maintains these aerospace systems. Purchasing and sustaining the hardware utilized by the Air Force and other military services has been a major industry in the US since before World War II.

Entering a new millennium with advanced technology and a dramatically changed international climate, however, has had a great impact on the military aerospace market. Dozens of technical advances occur each year that can potentially provide military aircraft with even greater capabilities. US aircraft are being pressed into completing a larger variety of missions in many different environments causing a general need to expand aircraft capabilities. However, expanding the capabilities of an aircraft type requires the Air Force to utilize large amounts of money on research and development. Decreases in the funds used to acquire and support new systems have forced the US aerospace industry to design systems that can be economically procured, operated, and upgraded. Figure 1.1
illustrates how the total funds allocated to the military over the past decade have decreased.

To compensate for its decreased budget, the US Air Force has been searching for methods to utilize each dollar as effectively as possible. The results of this search have led to vast changes in how the Air Force discharges its duties and how it spends its allocated funds. Repair and maintenance of US Air Force systems require billions of dollars annually, thus highlighting the sustainment of systems as a place to cut costs.

To further illustrate the financial situation faced by the Air Force in terms of operations and maintenance, Figure 1.2 illustrates the funds allocated for Air Force operations and repair since 1984. Of particular interest is the drastic decrease in funds that occurred in 1992 caused by DoD budget cuts.

Figure 1.1: Total US Air Force Budget Allocations vs. Fiscal Year

[Graph showing budget allocations from 1984 to 1998]

1.2 Thesis Motivation

The billions of dollars spent each year to sustain the Air Force's aerospace systems is the primary motivation for this thesis. Tight Air Force budgets mandate that every effort be made to minimize US funds spent on aerospace system sustainment. Minimizing the costs to procure replacement parts and perform maintenance tasks correctly would lead to savings in the Air Force budget. Additionally, because they perform vital roles in maintaining US security and policies worldwide, military aerospace systems must be maintained in peak condition to effectively perform their duties and safely convey their crews. This thesis seeks to provide the aerospace industry and the US Air Force guidance on how to best design systems for minimized sustainability costs.
Another motivation for my thesis results from the high pace of technical development within the aerospace industry. A system considered state-of-the-art often loses its technological edge to new developments soon after being fielded. Because aerospace system owners, particularly owners of military aerospace systems, want to have systems that outperform rival systems, upgradability in aerospace systems is an important characteristic. In this thesis, upgradability is a characteristic that refers to how much effort, whether in money or man-hours, a system requires to have some aspect of its capabilities improved (i.e. sustainability or overall performance) or have other capabilities added (i.e. ability to use another type of missile system). Military aerospace system owners have limited funding to procure upgraded products, so the aerospace industry cannot create upgraded systems that are excessively expensive, thus forcing those manufacturers to minimize the costs of upgrading systems. Through my thesis research, I seek to provide the aerospace industry and the Air Force with information on how to design systems to make future upgrades affordable.

Finding replacement parts for older systems has become a problem for a number of reasons. Manufacturers discontinue needed parts for military systems because it becomes unprofitable to continue creating the parts when the only buyer is the military, which only purchases the minimum number of parts necessary. For example, a corporation that manufactures microchips for F-15 aircraft may find it more profitable to steer its resources toward manufacturing commercial chips, as opposed to continuing military chip production. The market for manufacturing commercial microchips, in most cases, is tremendously larger than the market for a type of military microchip, and many military microchips are similar to at least one type of commercial microchip, thereby lowering the costs needed to switch from military to commercial production. The corporation in
question would be able to utilize the resources that it has more effectively by producing large numbers of commercial microchips as opposed to producing small numbers of military microchips. An additional event that will cause the military extreme difficulty in obtaining needed parts may occur when an original equipment manufacturer goes out of business. Either of these situations leaves the military in an undesirable and expensive position, which usually results in having the part custom produced as needed in low volume and at very high cost. Through research and data analysis, I will show that some of the problems created by parts obsolescence can be mitigated.

1.3 Hypothesis

The hypothesis of my thesis is that designing early for lean sustainment results in more affordable and agile life cycle options, and a greater flexibility for technical upgrades throughout the operational lifetime of a system. My thesis will investigate whether a system designed from its earliest design stages to incorporate sustainment ideas will demonstrate significant positive effects to members in that system's value stream. In regard to this thesis, value stream refers to the people and organizations involved with the entire life cycle of the system. These entities range from the system's original manufacturer to those that are responsible for disassembling the system and disposing of the components. More affordable and agile life cycle options include issues ranging from determining where a system will undergo major depot maintenance to how many technicians are required to fulfill the system's day-to-day maintenance needs. Flexibility for technical upgrades refers to the overall ability for a system to undergo improvements in some facet of its performance and or maintenance.

The thesis hypothesis will be investigated through researching the practices of the US Air Force and Corporation Alpha in regard to selected fighter engine systems.
Extrapolating from the thesis hypothesis, if the US Air Force and Corporation Alpha have improved their design practices, directing them toward design for lean sustainment, the costs of each progressing generation of the engines should decrease.

1.4 Key Research Questions

After the thesis hypothesis was selected, the next task was to determine the methodology for validating the hypothesis. I decided that the first step in validating the thesis hypothesis would be to develop a number of key research questions. The key questions selected are:

1. What does designing an aerospace system for sustainability entail?
2. What are the key design tools and processes utilized in designing an aerospace system for sustainability?
3. What impact does designing an aerospace system for sustainment have on all the agents in the system's value stream?
4. What are the enablers and barriers impacting designing aerospace systems for sustainability?
5. How does designing an aerospace system for sustainability impact the upgradability of an aerospace system?

The first of these questions, "What does designing an aerospace system for sustainability entail?" provides the key to the thesis by defining what in the design phases of an aerospace system will be searched for. Exhaustively defining a broad reaching term such as sustainability could require as much as six hundred pages; however, some initial parts of the definition can be stated briefly. Designing for sustainability would entail that the system's designers and other early value stream members were considering the long-term support needs of the system. The sustainability definition would also identify which
personnel and value stream members should be involved in the system's design. For example, the people responsible for providing depot-level maintenance to the system in fifteen years should certainly be included in the design activities of an organization designing its systems for sustainability.

The second question that must be addressed is, "What are the key design tools and processes utilized in designing an aerospace system for sustainability?" In this case, the term design tools refers to the information systems and computerized methods that system designers use to help visualize and predict performance characteristics throughout the entire life cycle of a given system. To be of value to the proposed thesis, investigation into the creation of these design tools must be conducted to determine the driving factors and criteria used to create the tool. This type of information would demonstrate those design characteristics that system designers want from their tools. That data can then be compared to the ideals of designing for sustainability determined by the first key research question.

The next key research question that must be answered is "What impact does designing an aerospace system for sustainment have on all the agents in the system's value stream?" This particular question can be divided into three separate questions to aid in understanding. The first, "What do the manufacturers and customers gain from designing systems for sustainability?" will help explore the reasons value stream members have for encouraging EDFLS in their designs. The second, "What are the disadvantages to designing systems for sustainability?" will determine the reasons why value stream members would be resistant to making the effort to design systems for sustainability. The third, "Where and how do the advantages and disadvantages of designing for sustainability
occur in the life-cycle of the aircraft?" will pin down exactly where, when, how, and to whom any advantages or disadvantages identified would take effect.

"What are the enablers and barriers impacting designing aerospace systems for sustainability?" is the primary question that will determine the exact advantages and disadvantages of designing systems for sustainability. In order to make the thesis effective, the causes for the enablers and barriers must be found including who initiates them, when they take effect, and why they are issues. Additionally, actions that have the potential to bolster the enablers and mitigate the barriers will be examined.

In order to link designing for sustainability to upgradability in aerospace systems, the primary question "How does designing an aerospace system for sustainability impact the upgradability of an aerospace system?" must be answered. The key upgradability issues do not need to be initially studied in great depth but merely identified and compared to the effects of designing for sustainability. Once these comparisons are made, upgradability issues that are impacted by designing for sustainability can be studied in greater depth.

1.5 Outline of Chapters

My thesis has been organized to best illustrate the information and conclusions derived from my research and data analysis. Chapter 2 will focus on the processes used to collect and organize data gathered throughout the thesis research process. This chapter features descriptions of the thesis research framework, procedures utilized to interview experts, methods used to select and conduct case studies, and the different types of research tools used.

Chapter 3 concentrates on a case study of Corporation Alpha's maintainability engineering group. This case study was used to collect both quantitative and qualitative
data on the policies and processes involved in an aerospace system manufacturer's efforts to develop US Air Force fighter engines. Chapter 3 will focus on ideas and opinions gathered during the case study in order to emphasize efforts that the manufacturer implemented to design systems for maintainability and sustainability. Further analysis of the collected information will be presented in Chapters 5 and 6.

Chapter 4 focuses on the ideas and opinions of the final owners of US Air Force fighter engines. Data presented in Chapter 4 originate from a case study conducted at the Air Force's Field Support Office (FSO) for the EG10 engine family.

Chapter 5 concentrates on bringing information from both Chapters 3 and 4 together, plus information gained during literature searches, into a format where each section of the research framework is displayed in chronological order. This format clearly illustrates the connections and interactions of the practices, processes, policies, and technology observed during my data gathering.

Chapter 6 presents actual maintainability data collected from San Antonio Air Logistics Center (SA-ALC) where EG10 engines undergo depot maintenance. Analysis of this data will demonstrate, if the thesis hypothesis is correct, that efforts needed to maintain these engines have indeed decreased with each subsequent generation of engines.

Chapter 7 will present the conclusions for the thesis by answering the key research questions listed previously. In addition, this chapter will give recommendations for further research to be completed on designing US Air Force fighter engines for sustainability and upgradability.
Chapter II: Research Methodology

In order to aid my thesis research, I followed a formal research methodology to guide information collection procedures and data organization. Previous theses created for the MIT Lean Aircraft Initiative (LAI) and Lean Sustainment Initiative (LSI) have served as the inspiration for the research methodology utilized in my work. LSI, an MIT research group, funded by the Air Force, and charged with investigating the Air Force's sustainment enterprise, is the primary sponsor of this research. This procedure has included an intensive literature search, followed by the creation of the thesis research framework, development of relevant case studies, arranging data contained within those case studies into the format of the research framework, analysis of collected data, and finally writing the thesis.

2.1 Research Methodology

The first step in creating this thesis was a thorough literature search of journals, theses, and other published sources related to the aerospace industry and design for sustainability in complex systems. Through this search, I familiarized myself with important issues and trends in both the military and civilian aerospace communities, investigated previous studies in the sustainment field, and identified individuals knowledgeable in aerospace system sustainability. Possibly the most important, purpose of the literature search was to increase my understanding of the sustainment industry itself. Although the literature search was primarily conducted during the beginning of my research process, it continued throughout the process in order to provide further insight into the thesis topic.
After exploring relevant literature, I conducted interviews of individuals knowledgeable in the sustainment of complex systems. These interviews supplemented information gained through the literature search and highlighted literature sources missed during earlier investigations. The experts interviewed were the designers and manufacturers of aerospace systems, various managers within the aerospace community, and those responsible for providing sustainment services to aerospace systems. In addition, professors and experienced researchers within the MIT community were interviewed.

The next step of thesis research was to select the specific aerospace systems to be studied. Because these systems would provide the majority of the content for the thesis, the selection of cases was a major step in the thesis creation process. In order to guide the case study selection process, four criteria were used:

1. Data from the system’s design stages and overall lifecycle must be accessible.
2. The system must have been produced and used in sufficient quantities to provide meaningful data.
3. There must be a large enough number of systems for statistical analysis methods to be effective.
4. The system must have been operational long enough for sustainability and upgradability to be a factor.

Using these selection criteria, I narrowed the possible case study candidates to fighter plane airframes, airborne radar systems, and fighter engines. The final decision was to study fighter engines. In addition to fulfilling the selection criteria, fighter engines are systems that undergo significant upgrades every four to five years after the deployment
of the original engine. Because of the relatively short time needed to commission upgraded engines, I could gather more data concerning upgradability in fighter engines.

2.2 Case Studies

After deciding to study fighter engines, I began the process of selecting a specific type of engine. One of the greatest considerations surrounding this decision was LSI's strong connection to the Air Force. First, any system selected must be a system relevant to, and preferably used by, the Air Force. Second, I wanted to make use of LSI's Air Force affiliations to obtain richer data than would be possible without such resources.

With these considerations in mind, I selected the engines from the Corporation Alpha EG10 engine family (i.e. EG10-1, EG10-2, EG10-5, and EG10-9 engine systems) and the Corporation Alpha EG15-1 engine. The EG10 series serves as the power plant for the Air Force's F-15 Eagle and F-16 Fighting Falcon aircraft.

The original EG10-1 and EG10-2 engines first qualified for use within the Air Force in October of 1973. Since that time, Corporation Alpha has improved upon the design of the engine culminating in the engine's latest variant the, EG10-9. Table 2.1 below illustrates important performance and maintainability characteristics of the engines in the EG10 family.
Featured in Table 2.1 are some innovations which are noteworthy from the perspective of engine sustainability. One of the most heralded innovations demonstrated by the EG10 program was the modularity featured in the EG10-1 and EG10-2 engines, which allowed removal of engine modules (i.e. diffuser, compressor, burner, turbine, and afterburner modules) by flight line technicians. In short, modularity allowed maintenance technicians to disassemble entire engines into their component. Additionally, technicians could replace the defective module with another module of the same type and reinstall the engine.

The EG10-5 engine was created to be both more durable and more reliable than the previous EG10 engines. This model also corrected problems hampering the operations of the EG10-1 and EG10-2 engines. Improvements such as replacement of the EG10-1's and EG10-2's unreliable 5000 part mechanical fuel control system with an electronic fuel control system greatly decreased failures of the critical engine components thus making the engine more reliable.

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3 The Engine Handbook 27-30
Increased electronic diagnostic capability in the EG10-9 engines allowed technicians to better diagnose and monitor the entire engine system thus cutting the time that each engine spent out of service. Through these diagnostic systems, engine performance and technical malfunctions were monitored while the engine was in operation. This data would then be transferred to the technicians, after undergoing further processing in some cases, to allow them to properly maintain the engine. Additionally, some of these diagnostic systems could be used while the engine was still within the aircraft thus eliminating the added expense of removing the engine.

2.3 Research Framework

In order to organize data collected during literature searches and case study interviews, I developed the research framework illustrated in Figure 2.1. Upon completion of the research stages of this thesis, the data collected was organized and placed within sections of the research framework presented in Figure 2.1 to discern relationships between practices, processes, technology, and policies observed. The following paragraphs describe each research framework category.
2.3.1 Policy

With regard to this thesis, policy refers to any guidance or influence exerted by an agency or person that impacts the decision making of those answering to the policymaking body in question. The guidance provided by policy makers can be literal directives involving the sustainment or design of systems, decisions on how much funding sustainment tasks will receive, or mandates on how the system in question will be utilized. Policy decisions, however, are often influenced by factors besides project sustainability performance, such as project leadership, national threats, and the country's political climate. These factors are illustrated in Figure 2.1.

A change in political climate within the United States can have a drastic impact on sustainment policy. One set of politicians may believe that funds are best spent on one project rather than another for reasons as simple as moving work to another region. Sometimes, decisions regarding changing a project's sustainment funding are based on
which politicians and areas support it as opposed to success and performance of the project.

New leadership may also cause changes in a project's sustainment policy. A leader with ideas, who has the charisma and influence to get those ideas implemented, can be responsible for bringing great improvements to any project, including projects relating to the sustainment of systems. Similarly, a leader's influence, bad decision making, or low popularity can take a project down a negative path. In any case, these actions seriously impact policies surrounding the project.

Since one of the primary purposes of the Air Force is to protect the United States and its international interests from enemies, potential threats also have a strong impact on Air Force maintenance and procurement policy. For example, one of the main reasons for the development of the original EG10 engines was to counter advance Soviet fighter technology in the 1970s. Depending on how serious DoD officials believe a threat to be, they have the power to enact policies to bolster development, but they could also restrict that development if they see the threat lessening. In either case, the status of a potential threat to the United States has great influence on the aerospace system development and upgrades.

2.3.2 Technology

As shown in Figure 2.1, I have theorized that policy directives drive the development of sustainment technology. By sustainment technology, this thesis refers to what has become technically possible to do with aerospace systems in the field of sustainment. An example of sustainment technology would be a device or technique that allows more accurate prediction of the operational life of a part or the development of routines capable of providing real time health estimates for a defense system.
In reference to sustainment technology, this thesis is mostly concerned with the behavior and actions of aerospace defense system manufacturers. The actions of these manufacturers are usually in direct reaction to policies promulgated by high authority levels in the Air Force or other relevant influential government agencies. As the policies handed down become stricter or more elaborate, the aerospace manufacturers respond by pushing forward what becomes possible in the field of sustainment. Technical advancements are usually results of intense research and development efforts that often, but not necessarily, occur in parallel with the company's efforts to provide better overall performance and fulfill the requirements of a defense contract. A manufacturer may also work to improve sustainment technology in order to create a more attractive product to the Air Force and convince them to provide the manufacturer with added funds for an improved defense system.

2.3.3 Processes and Tools

Similar to technical development, I have theorized that policy directives drive development of the processes and tools utilized in the design, manufacture, and sustainment of aerospace defense systems. Processes refer to the organizational, managerial, and material tracking techniques used to develop aerospace defense systems. These processes dictate how individuals interact and combine their talents to produce a product that fulfills customer needs. Often these techniques involve acquiring significant amounts of input from the customers themselves in order to insure that the product fulfills their needs.

The second part of this section refers to tools that aid in designing, manufacturing, and managing aerospace defense system development and maintenance. In the case of the products that this thesis examines, the majority of these tools are computer-based
technologies that organize data or simulate operations of aerospace defense systems. For example, Computer Aided Design (CAD) tools or complex logistics simulation routines are considered to be tools in this research. Because some processes often involve use of tools and visa versa, determining whether something is a process or a tool may be difficult. Therefore, processes and tools are considered in one section for this thesis. The differences between tools and processes are unimportant to the content of this work. What matters is the contribution that is made.

Processes and tools are utilized throughout the value stream of an aerospace defense system. Engineers, responsible for design and eventual production of a system, utilize processes and tools to better visualize and analyze their work while also reducing the need for expensive detailed models. On the other end of the value stream, technicians responsible for keeping the system operational utilize many processes and tools to accelerate and organize their work. Processes and tools may provide a technician with the ability to quickly diagnose the operational health of a system or provide that technician with the complete maintenance records for that system. As the policy requirements for aerospace systems become more demanding, processes and tools may improve to allow both engineers, flight-line technicians, and other value stream members to do their jobs better thus satisfying the increasing performance and maintainability requirements put forward by policy makers.

2.4 Results

More than any other part of the research framework, the results portion deals with the performance of the studied systems. Results refer directly to the sustainability performance of a system as observed by the owners of that system. Sustainment results can be measured via any number of metrics, including the number of times the system...
needs to undergo a given level of unscheduled maintenance or the amount of funding the owner of that system requires to keep the system operational. How the results are measured depends on the type of system and the final usage of the metric.

Qualitative data also provides vital information for this portion of the research framework. The results section will capture the user's impressions of the defense system and the results of relationships between contractor and user. These user impressions combined with the actual performance of the defense system influence future policy mandates as illustrated in the Figure 2.1.
Chapter III: EG10 and EG15 Maintainability Design Group

Corporation Alpha defines maintainability as "... the quantitative and qualitative system design influence employed to ensure ease and economy of maintenance and to reduce out-of-service time required for scheduled and unscheduled maintenance." During my evaluation of Corporation Alpha, the company's maintainability and human factors engineering group expanded on their company's efforts to design maintainability into its aerospace products. Unfortunately, due to proprietary considerations, the maintainability and human factors group could not fully reveal their reliability and maintainability (R&M) design techniques or how much usage of these techniques costs. I compensated for this omission through investigations of Air Force practices and examination of relevant literature.

Between May 17, 1999 and May 18, 1999 I conducted a case study of the policies, technology, processes, and results related to Corporation Alpha's efforts to incorporate R&M into their systems. Corporation Alpha's maintainability and human factors group, composed of engineers specializing in the maintainability issues of the EG10 engine family and the EG15, hosted the interview process and provided the bulk of the research data.

In order to insure accurate recording of the statements and opinions of Corporation Alpha's maintainability group, my thesis advisor and I were both present during all interview sessions. After each session, we compared and contrasted our observations and made special note of issues we thought to be of particular importance. To add to the

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4 Cooper, pg. 10
collected information, the maintainability group at times provided documentation to support their statements.

3.1 Engine Systems
The first engines of the EG10 family, the EG10-1 and EG10-2, were the engines that originally powered two of the Air Force's front line fighter aircraft, the F-15 Eagle and F-16 Fighting Falcon, during the 1970s and 1980s. The Air Force experienced a number of difficulties with these early EG10 variants including in flight difficulties, which created especially dangerous situations for the single engine F-16 aircraft.

In response to Air Force complaints about the EG10-1 and EG10-2 engines, Corporation Alpha developed the EG10-5 engine that entered service in 1986 and later the EG10-9 engine that entered service in 1990. While also being designed to provide increased thrust, these engine systems were designed with maintainability as a major feature. According to Corporation Alpha's maintainability group, this focus on maintainability created an engine that was superior in flight and R&M performance to any other fighter engine system available.

Making systems capable of fulfilling customer desires and mission parameters has been the overarching goal of all the EG10 projects. To satisfy these obligations, each engine system has undergone a variety of changes, such as changes to the turbine stage, the exhaust generator, and other technical modifications. While some of these modifications have simply been to improve overall performance, many have been the result of efforts to improve the system's sustainability. Unfortunately, the exact development costs for the EG10 variants were proprietary information and could not be revealed.
The predecessor of the EG10 engine family, the EG15, will serve as the power plant for the Air Force's F-22 Raptor which is expected to enter service in 2001. During the EG15 development program, the engine's reliability, maintainability, and cost to operate were considered as vital to the engine's success as its operational performance and its stealth characteristics. The fact that the EG15 has fewer moving parts to make the engine more serviceable in the field and requires 40% less maintenance man-hours than the EG10 engines illustrates Corporation Alpha's efforts to improve the sustainability of their engines.

The EG15 design process differed greatly from the process used to design the EG10 engine variants in that the EG15 was designed under Integrated Product Teams (IPT) teams consisting of the Air Force and Corporation Alpha personnel, and there was more analysis and testing of components and systems under the Propulsion and Power System Integrity Program (PPSIP). The use of IPTs in the EG15 program was a strict requirement put forward by the Air Force.

3.2 Policy

The Corporation Alpha maintainability group stated that during the design phases of the EG10-1 and EG10-2 the Air Force did not emphasize engine R&M performance. The Air Force was only concerned with the pure performance of the engine and its procurement cost. However, once the EG10-1 and EG10-2 engines entered operation, the Air Force began to realize that the engine's unique modular construction would allow for different maintenance techniques and policies. The Air Force liked the new maintenance options, but they were unable to implement the ideas because the infrastructure did not exist within the Air Force to support them.
During the late 1970s and early 1980s, Air Force personnel decided to obtain an engine system that reduced the tremendous cost of ownership and relatively low reliability of the EG10-1 and EG10-2 engines in the Air Force's front line fighter aircraft. To promote the innovations needed to provide an improved engine system, the Air Force maneuvered both Corporations Alpha and Beta into creating new engine systems. The threat of competition motivated both companies, especially Corporation Alpha, to create new products that better addressed Air Force needs. By fostering a policy of competition, the Air Force was able to leverage both manufactures into creating superior products thus creating an extremely positive situation for the Air Force.

During the late 1980s and early to mid-1990s American aerospace engineering corporations, including Corporation Alpha, had to adapt to a dramatically different world environment in order to survive. In addition to significant military spending reductions, foreign aerospace manufacturers were taking away market share from the American aerospace companies. In 1990, American aerospace companies provided systems for 90% of the worldwide commercial aerospace market, but by 1995, this percentage had decreased to less than 70%\textsuperscript{5}. Aerospace customers were seeking alternatives to the traditionally long and expensive development timelines of the past, and the American aerospace companies had to change in order to survive. As a result, many aerospace corporations began to investigate how to streamline their processes utilizing tools such as concurrent engineering, IPTs, and improved risk assessment methods\textsuperscript{6}. Some of the tools utilized will be discussed further in Chapter 5.

\textsuperscript{5} Lang, pg. 28.
\textsuperscript{6} Funke, pg 15.
There exists a debate about incorporating maintainability into aerospace systems. Some believe that making the engine less maintainable can reduce the cost and weight of the engine system. However, the people in the Corporation Alpha maintainability group countered this belief by stating that the money saved will be overshadowed by the huge amount of money lost by not making the system maintainable. One of the engineers in the maintainability group stated that they could, "... build [an engine] for $1M less now without maintainability included, but it will cost more in the long term."

Corporation Alpha believes that if they effectively design their systems for sustainability they will see savings in overall cost and manpower plus a more efficient sustainment pipeline. However, the maintainability group clearly stated that the logistics pipeline providing replacement materials and parts to support the engine system must be pull driven in order for benefits of a truly sustainable engine to be realized. Contractor companies must be able to quickly respond to the military needs, and the military's infrastructure must be capable of quickly delivering necessary equipment and materials to operational squadrons. The Corporation Alpha maintainability group believes the only disadvantage in designing for sustainability may be the risk of lowered engine part availability. If the entire enterprise does not learn lean practices, this negative situation may occur.

3.2.1 Corporation Alpha Organizational Structure

During the EG10-1 and EG10-2 development phase, Corporation Alpha engineers worked in one of two teams, the project engineering team and the design and analysis team. The teams were composed of approximately 1500 engineers, each responsible for portions of Corporation Alpha's many projects. While this arrangement aided earlier sequential engineering processes where designs were moved from one engineer to another.
as work progressed, it hindered cross-discipline communication and prevented engineers from combining their skills.

Corporation Alpha design teams are currently organized into IPTs, Component Centers, and Module Centers. Through these different organizational structures, each Corporation Alpha project becomes the responsibility of an engineering team. The project's engineering team would be composed of engineers from different disciplines, such as maintainability, manufactureability, and performance characteristics, thus allowing each engineer to work within their specialty while also allowing him or her to contribute to the work of other team members. IPT teams and other new organizational structures began to be implemented during the design of the EG10-5 to better address maintainability and performance issues, and the usage of IPTs has continued to mature throughout both the EG10-9 and EG15 design programs.

In order to aid the design process, Corporation Alpha engineers receive formal IPT training. Their training includes conflict resolution methodology and methods of using disagreements as opportunities for design innovation. Another notable characteristic of Corporation Alpha IPTs is that the organization of the team itself is relatively flat, whereas one or two senior engineers dominated past teams. When presented with a task, first IPT members examine design requirements and parameters individually. Then, as a team, they write a formal contract for the task being examined and begin working out design details. Throughout the process, team members work to ensure that the final product will adequately meet all customer requirements.

Participation of others, such as the Air Force or Corporation Alpha subcontractors inside Corporation Alpha IPTs very depending on the issue being discussed. However, the Corporation Alpha maintainability group mentioned that personnel from the Air Force or
subcontractors are more than welcome to participate within the company's IPTs when necessary.

3.2.2 Maintainability/Human Factors Engineering Group

Corporation Alpha established its maintainability and human factors group during its efforts to design the EG10-5 engines for the Air Force. Each Corporation Alpha engineering project effort includes a maintainability and human engineering discipline group that functions as part of that system's engineering integrity team\footnote{Cooper, pg. 5}. They, with contributions from other engineering IPT groups, work to insure effective, timely, and economical accomplishment of identified program requirements.

A project's maintainability and human factors engineering group is charged with ensuring that new engine systems comply with customer and government maintainability regulations. Additionally, the maintainability and human factors group is charged with duties, such as improving product maintainability by implementing lessons learned and knowledge from field research. They also ensure that tools and other support equipment are designed properly from a maintainability and human factors perspective.

The Design Manual for Maintainability/Human Factors Engineering suggests implementing a number of major engineering design reviews early in the system's design stage and a critical design review performed just prior to freezing the design. These reviews insure that the new engine system will fulfill all customer requirements, including requirements for maintainability. If the system fails to satisfy any element of a review, the project is returned to the previous stage of its development. Because of the heavy competition and tight budgets affecting Corporation Alpha, it is likely that the
continuation of the project is called into question if it fails a review stage. Below are
details of the reviews listed in the design manual and a summary of their purposes as
quoted in the manual⁸:

- Preliminary Design Review - Conducted early in the design process after the
  component conceptual study is completed and the initial design materializes.

- Layout Review - Review of layouts or drawings normally performed by the
  maintainability engineer with the designer.

- Independent Design Review - Extensive design review conducted with members of the
  design team, the chief engineer's staff, and other disciplines as appropriate.

- Detail Design Review - Presentations to the customer when the design of a significant
  portion of the engine/component is complete.

- Mockup Review - Performed by maintainability engineers using wooden mockups or
  simulations and various laboratory rigs or models to verify component accessibility,
  clearances, wrench swing, and other features that are not definable on layouts,
  drawings, or computer generated electronic models.

- Critical Design Review - Performed near the end of a design process to determine if
  specified requirements are satisfied and if the design can be frozen so that procurement
  actions can be initiated.

- Maintainability Demonstration - Performed by maintainability engineering jointly with
  the procuring activity to determine whether specified maintainability contractual
  requirements have been achieved.

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⁸ Cooper, pg. 7
Corporation Alpha engineers believe including maintainability into designs as a means to fulfill a number of customer requirements. Engine systems possessing superior maintainability reduce the customer's need for depot, factory, and airline shop facility maintenance thus lowering total maintenance costs.

3.2.3 Engine Metrics and Characteristics

According to the maintainability group, sustainable engines demonstrate the characteristics of durability, survivability (surviving handling by maintenance technicians and the rigors warfighting), maintainability, reliability, reparability, and affordability. Different military services and manufacturers have different metrics for measuring R&M. For example, Corporation Alpha uses the following metrics to measure an engine's sustainability.

- Shop Visit Rate
- Unscheduled Engine Removals (UER)
- Mean-Time-Between-Maintenance (MTBM)
- In Flight Engine Shut Downs
- Mean-Time-To-Repair (MTTR)
- Maintenance Man-Hours (MMH) per Effective Flight Hour (EFH)
- Percent of Accurate Diagnoses

However, even with the multitude of metrics used to gauge system maintainability, neither Corporation Alpha nor any other organization produces standardized definitions for sustainment terminology. It is conceivable that two individuals or corporations utilize the same word to refer to different characteristics.

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9 Cooper, pg. 9
During the interviews, we engaged in discussions about the two engine maintenance schemes being considered by Corporation Alpha and the Air Force. These schemes are centered around the three levels of aerospace system maintenance shown in Table 3.1.

<table>
<thead>
<tr>
<th>Maintenance Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Level</td>
<td>Engine maintenance conducted on the flight line by technicians from the fighter squadron.</td>
</tr>
<tr>
<td>Intermediate Level</td>
<td>Maintenance conducted in shops on the squadron's home base that utilize heavier equipment that cannot be easily utilized on the flight line.</td>
</tr>
<tr>
<td>Depot Level</td>
<td>Major overhauls of the engines that are conducted at only one or two locations worldwide. Depot maintenance requires very heavy equipment and a large infrastructure.</td>
</tr>
</tbody>
</table>

### Table 3.1: Maintenance Levels

Both intermediate level and depot level maintenance involves usage of civilian and military labor. Aerospace industry and government leaders have been debating the merits of two-level maintenance, maintenance using only the organic and depot levels, versus three-level maintenance for over a decade. The EG15 engine was originally designed to have three levels of maintenance, but the Air Force executed a policy change that altered the requirements for the EG15 to utilize two-level maintenance, and Corporation Alpha adapted accordingly to fulfill Air Force requirements.

Corporation Alpha maintains the capability of designing their engines to be compatible with whatever maintenance scheme their customers wish to use. When the Air Force implemented a two-level maintenance scheme with the EG10-5, they were unable to support the weapon system because of an insufficient infrastructure. Cost benefit analysis studies are presently being done at Dulles AFB to determine which maintenance scheme is most effective. In the meantime, Corporation Alpha is looking into engine designs that
incorporate even greater modularity allowing the engine to be separated into various modules for maintenance with even less difficulty.

According to the maintainability group, Corporation Alpha has been taking steps to incorporate R&M characteristics into the designs of its engines since the beginning of the EG10 series. By this group's estimations, while the R&M characteristics and overall R&M effectiveness of the EG10-1 and EG10-2 engines were good, the engines developed afterward demonstrated tremendously improved R&M performance, as illustrated by the EG10's UER and MTBM metrics. However, the maintainability group emphasized that there was always room for improvement.

3.3 Technology

These first EG10 engines represented a tremendous technical advancement in fighter engine technology. First, they provided dramatically more thrust than previous fighter engines from Corporation Alpha or any of its competitors. Secondly, these engines were designed to allow its different subsections (e.g. turbine, compressor, combustor, afterburner, and etc.) to be removed and maintained separately. Before these EG10 engines, entire engine systems would be removed from operation and repaired. With the EG10 only one section needed to be removed. However, this new flexibility in engine maintenance led to logistical problems as personnel attempted to take advantage of engine modularity while the Air Force possessed an insufficient infrastructure to support the new practices.

3.3.1 Maintainability Technology

Designing maintainability into complex systems such as gas turbine engines is a very challenging task, but for the EG10 engines and the EG15, the process has an added degree of difficulty. These engines serve as power plants for high performance fighter
aircraft, and on these aircraft, all characteristics, to a point, are optimized to maximize the aircraft's flight performance. Corporation Alpha designers must balance weight, performance, cost, and other characteristics with maintainability to achieve a balanced engine design. Among other practices, Corporation Alpha engineers combine their efforts and experiences in IPTs to achieve a design that satisfies all customer requirements. Additionally, Air Force personnel participate in these teams to insure that Air Force needs are satisfied.

Corporation Alpha's efforts can be illustrated by examining the placement of Line Replaceable Units (LRUs), engine components that can be removed and replaced by flight line technicians, on their engine systems. Removing and replacing LRUs account for many of the MMHs accumulated by fighter engine systems. The Air Force expects LRUs to require a minimum amount of effort to remove and replace while also having low MTTR characteristics. Each new generation of the EG10 engine has illustrated improvements in LRU design ranging from less cumbersome connections to error proofing LRU replacement tasks. The EG15's LRU features are particularly interesting because they can be serviced without removing the engine from the aircraft and have been specially designed to reduce technician workload in diagnosing and removing the parts.

3.3.2 Durability Technology

Durability is the characteristic that determines how well an aerospace system survives its operational environment and how long that system can be operated before requiring maintenance attention. This characteristic was particularly emphasized by Corporation Alpha's maintainability group as a factor in lowering the operational costs of an aerospace system. System durability drives how many maintenance man-hours a
system requires and how many new parts need to be purchased for the system annually. Essentially, the more durable the system, the less its owner needs to spend to operate it.

Corporation Alpha and the Air Force utilize many metrics to evaluate an engine system's durability including that engine's number of removals from the aircraft and the failure rates for individual parts. Advances in materials technology and improved thermodynamic models have led to significant increases in engine system durability. Additionally, the Air Force has initiated programs to improve the durability of its systems, such as the Engine Structural Integrity Program (ENSIP), which will be discussed in greater detail in Chapter 5.

Maintainability costs in Corporation Alpha's systems have also been reduced though utilization of fail-safe operational features and detection systems capable of quickly locating system degradations and malfunctions and through use of components requiring minimum amounts of preventative maintenance. Corporation Alpha engineers have also designed systems addressing the needs of flight line technicians by eliminating maintenance tasks that cause excess confusion.

3.4 Design Processes and Tools

Corporation Alpha personnel believe the company's overarching goal is to provide its customer with a quality product in a timely fashion and always at a value added cost. Corporation Alpha lists the primary considerations for maintainability to be\textsuperscript{10}:

- Assembly/Disassembly/Accessibility
- Fault Isolation, Testing, and Inspection
- Identification

\textsuperscript{10} Cooper, pg. 11-14
- Standardization
- Reparability

Corporation Alpha's efforts to incorporate sustainability into their engine designs have been guided by military directives such as Designing and Developing Maintainable Products and Systems - MIL-HND-470A\textsuperscript{11}, which describes the processes that should be utilized to make new military systems maintainable. Moreover, Corporation Alpha also utilizes an internally published Design Manual for Maintainability/Human Engineering to aid its R&M design efforts. According to the manual, the amount of maintenance a system requires is a function of its use, environment, durability, maintenance procedures, and engine design.

Corporation Alpha engineers utilize computer based tools such as Transom-Jack/Jane, stereo-Lithography, and CATIA to help them design their systems for maintainability. They also use older methods, such as building wooden system mock-ups, but such methods are being replaced with advanced software packages. Corporation Alpha suppliers have some access to these tools and the results that they produce, with larger suppliers having greater access than smaller suppliers.

3.4.1 Transom Jack/Jane

Transom Jack/Jane is a software suite that supplements and in many cases replaces creation of full wooden mockups to test the maintainability performance of engine designs. Through the Transom Jack/Jane program, Corporation Alpha personnel conduct human factors analyses to measure the degree of difficulty that technicians of various

sizes, shapes, and strengths have in performing a given maintenance task.

To facilitate their human factors analyses, Transom Jack/Jane creates a storyboard layout of male or female technicians, with physical characteristics predetermined by the design engineer, performing needed maintenance tasks on the engine. Transom Jack/Jane provides estimates on the difficulty of the maintenance task by analyzing the simulated technician's position and what percentage of his or her strength is required to complete the task. Transom Jack/Jane also shows the design engineers the simulated technician's field of view while performing the task.

3.4.2 Upgrade Process

Corporation Alpha often creates upgraded engines that incorporate improved performance to entice a customer into buying more of the product. Because of this policy, Corporation Alpha engineers must consider upgradability when they first begin to design the product. A maintenance group engineer stated "upgradability is a function of pure capitalism" while describing Corporation Alpha's policy toward incorporating upgradability into its systems. In the past it has been difficult to execute technical upgrades since everything in the engines are closely linked, making it difficult to just upgrade the system.

In order for an upgrade to be effective, it must be transparent to those maintaining the aircraft. When an engine upgrade is transparent, maintenance technicians do not have extreme difficulty when transferring from servicing the older version to servicing the upgraded version. Factors affecting system transparency include whether the upgraded model uses many of the same parts, particularly LRUs, as the older version, and if technicians need to learn many new maintenance procedures. In the case of a completely
transparent upgrade, the flight-line technician would be able to use the same tools and procedures on the upgraded system as on the previous model.

Processes used to decide which upgrades to implement include risk assessment, cost benefit analysis, and trade studies. In some ways, these processes are similar to the ones originally used to design the system. Corporation Alpha utilizes a number of methods to survey its customers as to what upgrades to incorporate into the next generation of engine system. These survey tools include lessons learned databases, the Propulsion and Power System Integrity Program (PPSIP), program reviews, Air Force IPTs, Corporation Alpha IPT trade studies, and Failure Reporting and Corrective Action System studies.

3.4.3 Suppliers

Corporation Alpha contracts many smaller corporations to provide the individual components needed for their complex engine systems, such as, turbine blades and individual LRUs. Problems experienced by these suppliers can have a great impact on Corporation Alpha's ability to fulfill its obligations to the Air Force. In fact, a series of labor strikes affecting Corporation Alpha suppliers in the late 1970s crippled the company's ability to produce EG10-1 and EG10-2 engines and eventually resulted in large amounts of ill will between Corporation Alpha and the Air Force.¹²

Because of the great effect that suppliers can have on Corporation Alpha's business, the company chooses its associates very carefully and attempts to monitor their performance. Corporation Alpha mainly relies on suppliers with whom it has a long history and that have good performance records. Prior relationships with Corporation Alpha also help to determine how much information sharing occurs between Corporation

¹² Drewes, page 84
Alpha and its suppliers. Corporation Alpha gives its suppliers access to its huge databases of project related knowledge. This depends, however, on the niche that they fulfill in the current operation, given that these suppliers often operate on a need to know basis.

3.4.4 Lessons Learned

Corporation Alpha maintains an extensive non-government funded lessons learned database incorporating information and experiences from all of the company's past projects to aid its IPT teams in negating and mitigating problems. Checking the lessons learned database is specifically marked on the designer's formal checklist of things to do when designing a system. The database is completely online, meaning that company personnel at any Corporation Alpha facility can look at the same lessons learned database. Because of proprietary considerations, I was unable to examine the database.
Chapter IV: EG10 and EG15 Air Force Management

On August 16th and 17th of 1999, my thesis advisor and I traveled to Wright Patterson Air Force Base (WPAFB) in order to collect data on the Air Force's opinion of EG10 R&M performance. I utilized LSI's connections in the Air Force to interview personnel in the Air Force EG10 Engine Family Field Support Office (EG10 FSO) and the EG15 System's Program Office (SPO).

Because the EG15 engine was still in the final stages of its development as opposed to the EG10 that was already in service, I chose to interview personnel concerned with the EG15 and the EG10 engines separately. Additionally, data gathered from Corporation Alpha led me to believe that the EG15 engine represented a dramatic enough change in technology to justify the time needed to interview its representatives separately in order to better focus upon the EG15's R&M characteristics.

4.1 EG10 Field Support Office

The EG10 FSO is responsible for ensuring that the EG10's maintenance needs are sufficiently met, thus ensuring that Air Force warfighters flying F-15 and F-16 aircraft are capable of effectively performing their missions. In the course of their duties, this office monitors how squadrons utilize the EG10 engines and how effectively EG10 depot facilities function.

The stark difference in opinion the EG10 FSO had in comparison to the Corporation Alpha maintainability group was one of the first things I made note of during the interviews. While members of the Corporation Alpha maintainability group stated how successful the entire R&M program for the EG10 engines had been, the EG10 FSO personnel for the most part disagreed. The FSO personnel complained that the EG10
engine had R&M problems ranging from high operating costs to frequent operational failures. Even after the large amount of experience that engineers and maintenance personnel gained from previous EG10 engines, the Corporation Alpha EG10-9 engines, at least according to the EG10 FSO, demonstrated the worst sustainment characteristics of any engine in the Air Force.

Despite criticism of Corporation Alpha products, the EG10 FSO did state that some of the EG10's R&M problems were at least partially due to Air Force policy. Two examples sited were the continued use of On Condition Maintenance (OCM) methods to determine what equipment required servicing and a premature switch to a two-level maintenance scheme for the EG10-5 engine.

FSO personnel also stated that Corporation Alpha has implemented, with the support of Air Force funds, technical improvements to EG10 engines. Now that many of the EG10-1 and EG10-2 engines have been upgraded to EG10-5E and EG10-5F models, these older engines are now demonstrating more acceptable sustainment characteristics. However, according to those interviewed, the R&M improvements that Corporation Alpha made to its engines were simply to allow their products to remain competitive with Corporation Beta products.

The EG10 FSO emphasized how development problems serve a beneficial function in weapon system development programs. Such events may include problems mating the engine system with the airframe, problems incorporating new technology into the engine, or problems resulting from the engine becoming too massive or too expensive. FSO personnel seemed to view these development problems as usual occurrences that lead to opportunities to improve the engine's performance or gain a greater understanding of
how the engine will operate in the field. The FSO personnel summarized this philosophy by saying "[the] unexpected is the routine" in developing a new system.

4.2 EG10 Development and Acquisition Policy

EG10 FSO personnel believe that lean sustainment concepts, if implemented properly, have the potential of greatly lowering system operating costs and improving overall system R&M. However, if these concepts are implemented incorrectly, maintainers will lose the ability to quickly react to operational surprises and surges because their supply chain would be so lean that there would not be room for adaptation. In other words, the system maintainer's support resources would be so customized to normal operating conditions, that changes in those conditions would cause the entire system to collapse. That would leave the engine fleet vulnerable to previously unknown failure modes capable of seriously decreasing engine system availability. Failure modes refer to malfunctions in the engine that occur during its life cycle because of normal use. Ideally, failure modes are recognized before the majority of the engine fleet encounters the problem so that preparations can be made to fix the problem without seriously lowering availability of the engine fleet. However, if the failure mode is not identified early and the engine fleet encounters the problem at approximately the same time, many engines may become unavailable during a short time period. The FSO group also added that in order to have a flexible sustainment scheme, the overall sustainment policy for the Air Force must be capable of adapting to the failure modes and individual eccentricities of each engine system.

4.2.1 Long Term Sustainability

During development of the EG10-1 and EG10-2 engines, the Air Force's policy toward long-term sustainment of fighter engines was to purchase the system and get it
operational as soon as possible. Under this policy, sustaining the engine became a concern only after the engine was operational within the Air Force. The fact that operational squadrons, the Air Force personnel that had dealt with and paid for an engine system's lack of maintainability, had limited input into the engine development process partially explains the existence of this early policy. Additionally, the relationship between Corporation Alpha and the Air Force was a sharply divided customer/buyer relationship that was often adversarial. Contract disputes and unsatisfactory sustainment performance in early EG10 engines led to the majority of the difficulties in the relationship. Moreover, the Air Force often rotated military personnel between different assignments disrupting the formation of good working relationships. This problem was exasperated by changes that Corporation Alpha made to its corporate structure.

When the EG10-5 engine was being developed, the large costs and poor availability of the previous EG10 engines motivated policy changes resulting in the Air Force giving greater consideration to the long-term sustainability of its engines\(^\text{13}\). Some personnel in both the Air Force and the aerospace industry had difficulty adjusting to these policy changes. During the EG10-5 and EG10-9 development programs, the Air Force became proactive in understanding the exact mission needs of its fighting squadrons and how those activities impacted the long-term sustainability of the engine system. Moreover, the adversarial relationship between Corporation Alpha and the Air Force was replaced with a sense of teamwork and the need to develop engines that satisfied all performance and sustainment criteria.

\(^\text{13}\) Camm, pg v
4.2.2 *EG10 Upgradability Policy*

According to the EG10 FSO, the Air Force previously did not consider upgradability in their requirements because they expected the product to fulfill all needs upon entering service. In addition, this group believed that none of Corporation Alpha's EG10 engines were designed to make production of future upgrades simpler. However, when manufacturers took the initiative to create an upgraded weapons system, utilizing that company's funds, the Air Force seriously considered purchasing the new variant.

Modifications are also made to engine systems after they are purchased by the Air Force, usually at a depot facility, through Component Improvement Program (CIP) directorates. Most CIP modifications are driven by a need to increase the engine's reliability and overall safety. Upgrades of the EG10-1 and EG10-2 engines to EG10-5E and EG10-5F engines, respectively, represent large-scale improvements that were managed through the CIP program.

The Air Force utilizes a Cost Effective Analysis (CEA) method to predict the costs of system upgrades. For example, using CEA, the EG10 FSO determined that it would cost $48M to upgrade the EG10-9's hot section in 1997. Apparently, there is no consistency to the cost of system upgrades, and the estimates from such prediction techniques are not very precise.

4.3 Technology

EG10 FSO members believe that usage of modular components represents Corporation Alpha's most significant R&M development in engine design. Through modularity, a single module, rather than an entire engine, is sent to depot shops. The FSO personnel also mentioned that Corporation Beta achieves similar R&M benefits through use of shop replaceable units. In the event of an unexpected failure in one of the modules,
engine technicians endeavor to replace the failed module with a module that possesses approximately the same amount of estimated reliable flight hours as the remainder of the engine. This is a necessary practice because the technicians want to avoid removing an entire engine for just one module's scheduled maintenance whenever possible. The personnel at the FSO described this as keeping the modules "flying in formation."

EG10 FSO personnel also believe that the positioning of LRUs are critical R&M design considerations. LRUs are parts that flight line technicians often remove from the engine, sometimes without removing the engine from the aircraft. EG10 FSO personnel believe factors that influence LRU placement should include the reliability of the units, and the projected failure modes of the units. Moreover, designers should take into account what parts and locations technicians need to have access to while inspecting the engine and which components will be manipulated most frequently.

Another important maintainability feature is the inclusion of borescope inspection capability into the engine design. Borescopes allow engine maintainers to inspect the internal mechanisms of engine systems without separating the individual modules thus significantly reducing time needed to service the engine. Engine designers have also incorporated various electronic components that provide data allowing for faster inspections and simplified monitoring of engine performance.

4.4 Processes and Tools

Perhaps the strongest message communicated by the EG10 FSO was the importance of previous experiences to those managing an engine system. As an engine type accumulates operational hours, the failure modes of that engine are identified, and once encountered, Air Force technicians can prepare to cope with the problem within the remainder of the engine fleet. Through the Pacer engine program, some engines of each
type are operated within the aircraft of operational squadrons more than twice as long as
other fleet engines in an attempt to identify that engine type's failure modes. Additionally,
Accelerated Mission Tests (AMT) that forecast long-term engine operation characteristics
and analytical condition inspection tally sheets that record the condition of all operational
engines throughout their operational cycles both provide information to analysts who to
predict maintenance behavior for Air Force's engines. The accuracy of these predictions,
in the case of the EG10-9, has increased greatly as the engine has been utilized throughout
the Air Force.

A comment of particular note was that the small number of EG10-9 engines in Air
Force inventory created difficulties with the Pacer program and the EG10-9 program in
general. While EG10-9 engines used in the Pacer program are stopped and diagnosed, the
other engines within the fleet quickly accumulate flying hours. The Pacer program's main
goal is to identify failure modes well before the rest of the engine fleet encounters them,
but the quick rate that EG10-9 fleet engines accumulate flying hours severely limits the
time between identification of a problem and when the problem affects all Air Force
EG10-9. This problem is exasperated by the fact that the EG10-9 engines were procured
over a relatively short three-year period whereas the other EG10 engines were procured
over periods of about ten years. As a result of this difference in procurement policy,
EG10 FSO members mentioned that all the Air Force's EG10-9 engines tend to encounter
failure modes and other operational problems at nearly the same time. The Air Force has
to quickly diagnose the problem, determine a way to correct it, and distribute necessary
material to squadrons in order to avoid serious decreases in engine availability. With the
previous EG10 engines, the Air Force had far more time to react to such occurrences
because of the large number of such engines in the Air Force's inventory.
The experience that engine technicians and managers gain from older engine systems should also be considered as a useful tool in managing engine sustainment. For example, the EG10-9 engines have many parts in common with the other EG10 engines and their design purposefully utilizes equipment and configurations used in the previous EG10 engines. Therefore, many of the lessons learned from previous EG10 engines carry over into the EG10-9. The need for previous experience with derivative engine systems caused some of the personnel that we spoke with to be concerned about the sustainment performance of a brand new engine such as the EG15.

One of the processes that the Air Force has been trying to implement to increase sustainability in their engines is Reliability Centered Maintenance (RCM). RCM determines engine system maintenance and replacement schedules through analysis of statistical and performance data collected from tests conducted during the development of the engine and from other engines already operational within the Air Force. This maintenance scheme attempts to predict which maintenance tasks and parts the engine requires before the engine requires them. RCM, which allows squadrons to better forecast system availability and part requirements, replaced OCM as the maintenance scheme for the EG10-9 engines and will soon do so for the EG10-5 engines.

Through OCM, which has dominated maintenance for the EG10-1, EG10-2, and EG10-5 engines, maintenance schedules are determined primarily by inspections of the engine system. OCM was the field maintenance practice that was in effect when the Air Force attempted to replace three-level maintenance with two-level maintenance in the EG10-5 engine. In the late 1990's, the DoD Director of Engineering, with the support of military engine product group managers and the MAJCOMs, led the change from using
OCM to RCM. The Air Force is conducting studies to compare RCM and OCM practices in greater detail and to determine the most effective methods of implementing RCM.

Like Corporation Alpha, the Air Force has also utilized IPTs to aid creation of better maintenance practices for its engine systems. Some IPT work involves flight line technicians visiting the manufacturers, and visa versa, to better design engines for maintainability. However, the FSO mentioned that IPTs have only been in use since the early 1990s.

Another program, previously mentioned in Chapter 3, that has been used to increase sustainability in engine systems is ENSIP. ENSIP is a procedure that has been in operation for the past ten years and is the first procedure that a completed engine system must undergo to clear it for Air Force service. Through ENSIP, tests are conducted to determine the durability characteristics of the engine, such as the fracture mechanics of its individual parts\textsuperscript{14}. This program was designed by personnel at WPAFB to diagnose engine maintenance characteristics and overall engine durability.

Computer simulation models of internal engine operations that roughly predict engine sustainment performance and Air Force maintenance infrastructure simulations that illustrate how well squadron maintenance and material needs will be fulfilled during a given time period are also useful tools in determining the sustainment needs of engine systems. However, the EG10 FSO communicated that these techniques were very limited and not very accurate. They seemed to believe that prior experience was the best way to predict engine sustainment requirements.

\textsuperscript{14} AF Instruction 21-104; Selective Management of Selected Gas Turbine Engines; 1 July 1998 - Attachment 2.
4.5 Results

The EG10 FSO believes that the EG10-9 engine delivers good reliability and maintainability performance, although it ranks below the Corporation Beta HF15-5 engine in R&M performance. The FSO's opinion was formed through tracking of metrics, such as MTBF, Actual-Time-On-Wing, and engine removal rates. However, there have still been maintainability problems with EG10-9 engines. During 1992, an F-15E squadron from Lacon Heath, England, experienced maintainability difficulties with its EG10-9 engines while flying Gulf War missions. The problem occurred because the squadron was flying missions that were not included in the original EG10-9 AMT engine tests. Additionally, at the time of the Gulf War, the EG10-9 engine had not been in service for long and some of the failure modes for the engine were still being identified.

Moreover, the EG10 FSO believes that the ENSIP program could be improved by placing greater emphasis on part inspectability. Damages occurring on some engine parts are too small to be easily detected in the field. If technicians suspect that the part has experienced such a hard to detect damage condition, the technician removes the part so that detailed inspection procedures can be used to determine if the suspected damage condition actually exists. However, these tests are usually expensive and it often takes a long time before the diagnostic is performed. While the part waits for the needed diagnostic procedure, another part is often ordered to replace it. If the part had been easier to inspect, funds used to purchase a new part or even conduct the diagnostic procedure could have been utilized elsewhere.

4.6 EG15 System Program Office

After my interview with the EG10 FSO, I turned my attention to collecting information from the Air Force SPO responsible for overseeing the acquisition and
development of one of Corporation Alpha's latest military engines, the EG15-1, which will power the Air Force's F-22 Advanced Tactical Fighter. The EG15 will not only provide the F-22 with an impressive 35,000 pounds of thrust but will also incorporate features to make the engine extremely maintainable. The list below contains but a few of the EG15's many positive maintenance characteristics.

- Technicians require only a few common tools to maintain the engine.
- Color-coded electrical wiring is used to decrease maintainer confusion.
- Captive fasteners are used to prevent any loose fasteners from disconnecting and damaging the engine.
- Interchangeable parts between the right and left engines.
- Borescope ports are used to aid technicians inspecting the engine.
- The mean replacement time for the engine is approximately 90 minutes.

So far, the personnel that I interviewed at the EG15 SPO seem to be satisfied with the maintainability of the engine, although they are very aware that the true test of the EG15's maintainability characteristics will come when the engine is fielded in 2001.

4.7 EG15 Policy

According EG15 SPO personnel, the acquisition policy of the Air Force has drastically changed over the past decade. Now the Air Force wants engines that are maintainable and affordable. This policy was very prevalent in the EG15's development and in the F-22's development in general. The leaders of the EG15 SPO were adamant about the program fulfilling both the engine's performance goals and its maintainability goals. The personnel with whom I spoke believe that the only disadvantage of designing a system for long-term sustainability is that it would disturb the methods many use to do
their design and support tasks, thus causing irritation despite the fact that overall sustainment services would be improved.

In the opinion of EG15 SPO personnel, a sustainable system should be capable of functioning at optimum performance levels under normal environmental and operational conditions. They also believe that a sustainable system requires an engineering integrity program to ensure the quality of that system. A specific ENSIP document has been developed, as opposed to relying on military standard documents, to address the progress of the entire F-22 program, including the EG15 engine. A prime item performance specification is also used to specify the performance requirements for the entire F-22 program. This document mandates inspection of all subsystems and how those tasks will be managed and documented.

EG15 SPO personnel also mentioned that in order to design a sustainable system both contractors and development managers must be acquainted with the military development environment so as to mitigate any developmental problems that may arise. As mentioned by the EG10 FSO, problems occur between manufacturers and the Air Force for reasons as simple as differences of opinion and working style - a problem further compounded by the transfer of personnel every few years. Additionally, in order to further avoid development problems, managers must also be aware of prior military and manufacturer development experiences.

An interesting opinion was stated during my investigations regarding the difference between how developers view sustainability versus how higher officials, at the Pentagon for example, view it. According to EG15 SPO personnel, high level officials believe that the life cycle of an engine or other complex system is strictly linear and can be easily predicted - much like a home appliance. However, military systems experience
surges of extreme operational activity and different forms of use that make their operational environment tremendously more complex. In the opinion of those I spoke with, one must understand this added complexity to create good sustainment policy for complex systems.

Another opinion stated was that some of the older management systems operating within the Air Force's maintenance structure would not be capable of dealing with next generation military systems such as the EG15. For example, the Defense Logistics Agency (DLA), which is the organization responsible for acquiring and delivering the majority of the Air Force's replacement parts and equipment, will apparently have difficulty providing services for the EG15 and the F-22. The DLA utilizes older information systems that are incompatible with the high technology systems that will be used to help determine the maintenance needs of the EG15. One person at the EG15 SPO stated the problem would be similar to operating state of the art equipment off of a ten-year-old computer. The DLA simply would not be able to respond quickly enough to the F-22's needs.

Other organizations that the EG15 SPO believes will have problems with the latest technology are the Air Logistics Centers (ALC). The ALCs cannot process large amounts of complicated data from other sources, such as fighter squadrons and defense system manufacturers. In order to share information with the ALCs, others have needed to process data into simpler formats that the ALCs can decode because of their lagging information technology. EG10 SPO personnel also believe that the ALCs will have difficulty consistently providing services of the quality required by the Air Force's high technology programs.
The users of the engine must be involved early in the system's design stages in order to communicate requirements to the manufacturer clearly. According to EG15 SPO, engine users were very active in the EG15's development from the very beginning. For example, the Air Force participated in developing the specific organizational requirements document (a document that was primarily developed by the contractor in the past) and closely inspected every aspect of the EG15 proof of concept before approving development of the engine.

Like their counterparts at the EG10 FSO, the personnel at the EG15 SPO also commented on the possible maintenance strategies and structures under which the EG15 would be maintained. When the EG15 program began in the late 1980s, the Air Force maintained its engines utilizing the three-level maintenance scheme. In order to improve the maintainability performance of the EG15, in 1996 the Air Force decided to field the EG15 under a two-level maintenance scheme instead, despite the fact that the two-level scheme tried with the EG10-5 engine failed. EG15 SPO personnel stated that the current plan is to utilize an augmented two-level scheme that makes very limited use of larger base level shops until the EG15 and its support structure matures enough to support the full two-level scheme. The EG15's maintenance scheme will also feature use of regional maintenance centers positioned at strategic areas around the globe. Combined with high-speed delivery methods, such as overnight air transport, the regional maintenance centers could quickly fulfill the parts needs of any military base or squadron worldwide. Usage of regional maintenance centers and rapid transportation of materials represent some of the primary ideas behind making two-level maintenance successful.
4.7.1 Upgradability

From the opinions expressed during the interview with EG15 SPO personnel, attention has been given to EG15 upgradability, at least from the Air Force's point of view. In order to regulate engine upgrades, an engineering integrity program will be used in place of the CIP to determine what modifications will be made to the engine system after its deployment. Apparently, the CIP has resulted in great expense and delays in making modifications to engine systems, possibly because of the large amount of oversight inserted into the program by Congress in the 1970s. The EG15's integrity program will provide a method of determining needed modifications to the EG15 based on the operational and maintenance performance of the engine. The EG15's engineering integrity program will fund and manage all EG15 modifications designed to improve overall engine performance.

The engine will also undergo a tenth-year midlife upgrade with other smaller modifications to be handled through CIP. However, all modifications to specifically address performance deficiencies will be dealt with through the engineering integrity program. The formalized plans concerning EG15 upgradability, according to the EG15 SPO, resulted from the strong leadership and vision of Air Force policy makers. The end result is that the long-term sustainability of the EG15 has been a driving priority throughout the EG15 development program.

4.8 EG15 Technology

The EG15 engine is being optimized in ways that were impossible for the older EG10 family of engine systems. While some of the tools utilized to design the EG15 have

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15 Drewes, pp 92
been used on other complex systems, such as computer modeling tools, the tools used on the EG15 have been specifically tailored for the needs of the program. The EG15's Full-Authority Digital Electronic Controls (FADECs) and Comprehensive Engine Diagnostic Unit (CEDU) represent technical innovations particularly relevant to the R&M performance of the EG15\textsuperscript{16}. FADEC control units are used to control and optimize engine performance during flight. Given the pilot's throttle setting and the condition of the engine, the FADEC controls the engine's fuel supply, operations, and airflow characteristics to provide optimum performance. The FADEC also monitors engine performance and is capable of detecting anomalies in engine performance. The FADEC communicates failure events to the CEDU that can be accessed by flight line technicians using a standard handheld device.

4.9 EG15 Processes and Tools

Developing the EG15 involved usage of recently developed tools and processes, including computer intensive techniques, to achieve better design results than previously obtained. Participants in the EG15 program tested tools and processes early in the development stage to forestall any development problems. With the development of the EG15, they began testing both process and tool interactions early, hoping to encounter and solve problems before the engine was fielded. The EG15 utilized very complex analytical processes and computer aided simulations in its design that the EG10 engines did not.

Corporation Alpha utilized the Air Force Life Cycle Cost Model (LCCM) to estimate total system costs for the EG15 through 2030. This document served as the primary document in all Air Force and Corporation Alpha negotiations. The LCCM

\textsuperscript{16} Rea, pg. 25
attempted to predict the life cycle costs of the engine based on estimates of its sustainment metrics, such as, MTTR and UER. Besides providing a tool for determining the cost of the system, the LCCM is also an invaluable tool in attempting to predict the EG15's needs throughout its life cycle.

Other new procedures will also be utilized to aid maintainers on fielded EG15 systems. Technical Order Data (TOD) are manuals that list, in great detail, the tools and procedures required when performing maintenance tasks on the EG15. Supposedly, with use of TODs, removing complex electronic equipment from the EG15 will require as few as fifteen minutes. The Air Force will also utilize Comprehensive Engine Management (CEM) to track parts of the EG15 so that maintainers possess the latest information concerning the inventory of items related to the EG15's operation. Moreover, CEM will allow maintainers to examine the entire history of a part, thus giving them more useful information useful.
Chapter V: Research Analysis

This chapter provides an analysis of data concerning the policy, technology, processes and tools, and results of Air Force and Corporation Alpha efforts to develop the EG10 engine family and the EG15 engine. The data presented in the following sections was derived from analysis of case studies; numerical data collected from personnel at Kelly AFB in San Antonio, Texas, and literature sources.

Figure 5.1 illustrates some of the significant events and policy changes occurring between the 1960s and the beginning of year 2000 that impacted the design and maintenance of the EG10 and EG15 engine systems. The events presented in Figure 5.1 are divided into the same divisions as the research framework used in this thesis. A full description of each component (Policy, Technology, Processes and Tools, and Results) has been presented in Chapter 2. Figure 5.1 illustrates elements of engine sustainment policy, technology, processes and tools, and results, and how those same elements impacted the entire engine sustainment infrastructure. For example, one can easily see that the EG10-1 and EG10-2 engines were developed and used when sequential engineering methodologies were prevalent and the Air Force still implemented non-sustainment focused ideology. Additionally, dotted links have been used to highlight points where events in the results sections have impacted events in the policy section.

The information provided in Figure 5.1 is expanded upon throughout the remainder of this chapter. These detailed descriptions illustrate how given events impacted the EG10 and EG15 development processes thus providing a more detailed understanding of how the topics presented throughout this thesis intertwine into current Air Force and Corporation Alpha sustainment policies and practices.
Figure 5.1 Research Framework Flow Chart

1970

Policy

- Anti-Sustainment Policies
- Induced Competition
- Pro-Sustainment Policies
- Aerospace Industry and Air Force Cooperation

Technology

- Performance Technologies Emphasized
- Sustainment Technologies Developed

Processes and Tools

- Sequential Engineering
- Concurrent Engineering

Results

- EG10-1 & EG10-2
- EG10-5
- EG10 Dissatisfaction
- Air Force Satisfied with Engines

Legend:

- Computer Aided Design
- Engine Modularity
- Electronic Engine Controls
- Computer Aided Logistics Support
- Accelerated Mission Testing
- Integrated Product Teams
- ENSIP
- CIP
- EMDP
- Improved Fuel Control System
- Increased Thrust
- EG10 SPO

Relational Connecting Line
Relational Line
Connecting Results to Policy
5.1 Component Improvement Program

During the 1960's, the Component Improvement Program (CIP) was created to address maintainability and reliability problems that were recognized after an engine system was deployed. CIP resources were only to be used to fund small engine component improvements - in essence CIP was only meant to fund engine upgrades\textsuperscript{17}. However, in reality, CIP money was utilized for projects that were so extensive they were practically full development projects. Congress saw this usage of CIP funding as a way to avoid their oversight of new engine developments since CIP was provided as a bulk amount of money from year to year that could be utilized for whatever CIP administrators deemed appropriate. To reestablish its oversight over major engine development programs, Congress restructured the CIP to limit the scale of projects that could be funded without prior congressional approval.

Despite Congress's restructuring efforts, the CIP program has still been utilized throughout the EG10 program to fund many needed improvements. These improvements have included reorganizing the placement of LRUs in order to simplify maintenance tasks and replacing various components with more reliable and durable equipment. An idea of the usefulness of the CIP program is illustrated by the fact that in 1985 over $681 million dollars of CIP funds were distributed to the EG10-1 and EG10-2 programs alone.

5.2 Engine Model Derivative Program

The Engine Model Derivative Program (EMDP) was put forward by congress in 1968 to correct what it saw as abuses in the use of CIP funds\textsuperscript{18}. In order to provide a

\textsuperscript{17} Drewes pg 92
\textsuperscript{18} Drewes pg 92
means of researching and developing derivative engine systems, Congress put into place the EMDP. However, the EMDP process was very bureaucratic and had to compete with other military priorities before receiving approval. Where previously derivative engine development programs relied on CIP funds, which was a lump sum that could be distributed on the discretion of direct managers, EMDP forced each new derivative idea in front of Congress. Because of the difficulty of procuring EMDP funding, EMDP funds went unused until the late 1970s.

In 1978, the Air Force persuaded Congress to release EMDP funds to aid Corporation Beta's development of an alternate engine to the EG10-1 and EG10-2 thus forcing Corporations Beta and Alpha to compete for the contract to develop a better engine system for the F-15 and F-16. By fostering competition, both corporations developed engines superior in performance and sustainability than the previous EG10 engines.

5.3 Propulsion System Program Office

The Propulsion System Program Office (SPO) was organized in 1977 in order to oversee the development of the EG10-5 engine and its rival engine system, the HG15-1 developed by Corporation Beta. The Propulsion SPO was responsible for insuring that both the competing engine systems fulfilled the Air Force's performance and sustainability needs. This organization of engineers and managers was responsible for negotiating contracts between the Air Force and engine manufacturers while assisting manufacturers to solve system development problems, such as system integration issues and cost overruns. In many ways, the purpose of the SPO was to insure that the EG10-1's and EG10-2's development problems did not reoccur with the new engine systems. The
SPO also negotiated contract disputes between Air Force and manufacturer personnel, thus further insuring creation of a quality product.

The majority of SPO personnel were veterans of previous engine system development projects and were already well acquainted with the many challenges an engine development program faces. This previous experience among the team members was one of the most valuable resources in the success of the EG10-5 development program.19

The Propulsion SPO also had the added responsibility of overseeing the competition between Corporations Alpha and Beta. One of the key tools behind developing an upgraded engine for the Air Force was to foster competition between these two large aerospace manufacturers thus producing a superior engine. In addition to other duties, the SPO needed to coordinate efforts with both corporations to insure that both engines fit basic Air Force requirements. The Propulsion SPO also played a vital role in determining exactly how to divide the final contracts for the new engines based on the results of the final fly-off competition.

The SPO not only interacted with the engine manufacturers but also with the warfighters that would eventually make use of the new engine's capabilities. The SPO was responsible for surveying the warfighters in order to determine what their needs were in terms of maintainability and performance - especially compared to the EG10-1 and EG10-2 engines. Some SPO personnel had previously served with operational fighter squadrons as technicians and were able to bring first hand knowledge of difficulties faced

19 Camm, page 14
on the flight line. The SPO maintained a close relationship with the fighter squadrons to insure that the warfighter's interests were communicated to the manufacturers.

5.4 Engine Structural Integrity Program

The Engine Structural Integrity Program (ENSIP) is an Air Force program launched in the late 1970s that focuses on improving an engine designer's understanding of engine system durability. Prior to ENSIP, engine designers possessed a less structured view of engine system durability and had a mind set that they could design their systems to not fail which is not the case. ENSIP provided "an organized and disciplined approach to the structural design, analysis, development, production, and life management of gas turbine engines with the goal of ensuring engine structural safety, increased service readiness, and reduced life cycle costs." This was done by directing designers to perform tasks such as identifying possible catastrophic failure points, accurately characterizing the engine's material properties, simulating the thermal and dynamic stresses that the engine would undergo, and determining how the engine's structure would interact with the aircraft and other systems.

Once the analysis tasks were complete, developers engineered their systems to minimize the chances of catastrophic failures. In addition to lessening the risk of these failures, this analysis also helped to provide the system owners with data for scheduling inspections and maintenance. The system owners, using data gained through ENSIP, now had a better probability of identifying potential failures before they impacted the system and could arrange their supply chain to provide needed parts. In addition, data

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20 Camm, page 22
from ENSIP provided a framework for managing problems or needed enhancements through the CIP program. If a new mission needed to be performed or a new material became available, designers would utilize the information and steps from the original ENSIP program to institute the needed changes. The ENSIP program brought greater understanding to the EG10-5 development program and can be credited with much of the R&M improvements seen in that engine system.

5.5 Impact of Competition

As mentioned earlier, the Air Force encountered multiple problems with its EG10-1 and EG10-2 engines. Despite the fact that these engines satisfied all the Air Force's performance needs, other problems outside of strict flight performance thoroughly clouded the Air Force's opinion of these engines. For example, the cost of ownership for the EG10-1 and EG10-2 were tremendous. The engines had been designed to provide high thrust as opposed to being durable. In addition, problems such as dangerous in flight stall stagnations appeared after the engine was fielded posing considerable danger to pilots, eventually forcing them to limit their flight envelope. The Air Force believed that Corporation Alpha should be responsible for correcting the problems with the engines while Corporation Alpha believed that the Air Force should provide funding to repair the problems. This difference in opinion resulted in ill will forming between the Air Force and Corporation Alpha officials. To create even more problems, two Corporation Alpha suppliers experienced labor strikes which crippled Corporation Alpha's ability to build EG10 engines and caused great skepticism to form in the minds of Air Force officials about relying on one company to provide all the engines for its front line fighter aircraft.
Air Force officials decided to entertain proposals from both Corporations Alpha and Beta for an engine to replace the EG10-1 and EG10-2. Corporation Beta leaped at the opportunity to obtain even part of the lucrative F-15 and F-16 engine contracts because, due to previous events, Corporation Beta had been effectively shut out of the military aerospace engine market. Conversely, Corporation Alpha wanted to continue to be the sole supplier of F-15 and F-16 engine systems. In order to win the contract and foil their competitor, both corporations designed engines that more than fulfilled the Air Force's requirements. The warranties that both engines had of being at least twice as durable as the earlier EG10 engines illustrates the amount of improvement that occurred\(^{22}\).

Despite the fact that Corporation Beta succeeded in procuring 75% of the 1985 development contract, totaling 120 engines, Corporation Alpha was not completely forced-out of the F-15 and F-16 engine market because the company still provided support services to the EG10 engines it had already built for the Air Force. In fact, Corporation Alpha later produced the EG10-9 for the F-15E aircraft. Fostering competition between these two rivals resulted in a tremendous benefit for the Air Force, which received superior high quality engine systems that addressed all their sustainment needs at very competitive prices.

5.6 Multistage Improvement Program

The Multistage Improvement Program (MSIP) illustrates that Air Force policy makers at least partially understand the necessity of aerospace system upgradability. The MSIP program was conceived during development of the second generation of F-15's, the

\(^{22}\) Drewes, page 128
C and D models, between 1978 and 1986\textsuperscript{23}. Although the EG10 engines were not directly impacted through this program, the MSIP initiative led to major upgrades in the F-15's fire control system, greater data processing ability, and numerous radar system upgrades.

5.7 Recommendations on Policy

In response to factors such as high aerospace system maintenance costs and warfighter complaints, the Air Force commissioned studies to increase understanding of how complex military technical systems are developed. In the late 1970s and the early 1980s, some studies released findings that emphasized the need for Air Force designers and managers to increase focus on system ownership costs, including the maintainability, structural integrity, reliability, and durability of the systems. Two recommendations resulting from these studies were the 1976 recommendation by the Air Force's Scientific Advisory Board and a 1980 recommendation given by the Comptroller General to Congress. These opinions illustrate changing attitudes within the Air Force, and the government in general, toward focusing not just on raw system performance but also the system's cost of ownership.

5.8 Accelerated Mission Tests

During the design of the EG10-1 and EG10-2 engines, ground test programs that were used to evaluate the performance of engine systems could not accurately predict engine or part reliability. First, the ground engine tests were relatively short, on the order of 150 hours, in comparison to the engine's total life cycle, thus yielding no information as to how the engine would perform over a long period of time. Second, the tests were

\textsuperscript{23} McDonnell Douglas F-15 Eagle http://chan.csd.uwo.ca/~pettypi/elevon/baugher_us/f015.html
not based on how the engine would be operated in the field. The tests centered on evaluating the engine's maximum performance levels, thus only providing information about engine high-cycle fatigue characteristics. However, fielded engines function at numerous throttle settings, and often these throttle settings are quickly and drastically changed depending on the pilot's requirements thus making low-cycle fatigue extremely important.

In the 1970s, Air Force propulsion SPO managers instituted ground tests that more accurately simulated the operation of an engine throughout its lifetime. Designers used information from active fighter squadrons to determine throttle usage for expected mission types (e.g. air-to-ground missions, air-to-air missions, and escort missions). During these AMTs, the subject engine would be tested through an entire series of throttle settings designed to simulate the cycles it would encounter in actual service, thus including time spent at maximum, intermediate, and minimum thrust settings. AMTs are run for thousands of hours, stopping occasionally for system repairs and evaluation, in order to duplicate operation over an engine's entire lifetime. Because of the varying throttle settings and the length of the tests, AMTs accurately provide insight into engine durability and reliability.

5.9 Integrated Product Teams

IPTs became popular within Air Force and industry circles during the late 1980s and 1990s and had great impacts on both the EG10-9 and EG15 development programs. Corporation Alpha, learning from Air Force complaints about the R&M characteristics of previous engine systems, utilized IPTs to insure that all engine characteristics, including flight performance, sustainability, and durability, are designed into each of its products.
IPTs bring together technically experienced individuals from many different backgrounds in order to create teams that are knowledgeable of all customer needs and system characteristics. In the case of Corporation Alpha's products, Air Force personnel also participate in the IPTs to better insure that Air Force needs are satisfied.

Research also revealed that the Air Force has been attempting to implement IPT practices. For example, a March 1995 Modification Planning and Management Directive described in great detail how Air Force IPTs should be established to guide modification of engine systems. It directed that the team should include personnel such as equipment specialists, quality assurance personnel, and financial representatives.

5.10 Computer-Aided Acquisition and Logistics Support

In 1985 and 1988 the Deputy Secretary of Defense issued a memorandum calling for standards to be established that would allow different military units and outside contractors to be able to share maintenance and performance information electronically. Prior to this directive, the military and its contractors had either relied on paper documents or stand-alone computer systems to record system performance data and specifications. In order to share information with other units, the information would either have to be photocopied or directly inputted into the other unit's computer system. Either option required large amounts of time. Moreover, when a specification was changed, new documents would have to be copied and distributed. Often, units would operate with an outdated specification since there were significant delays in distributing new specification documents.

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25 Drouin, pp. 73
The Computer-Aided Acquisition and Logistic Support (CALS) program is an initiative that seeks to establish the infrastructure necessary to allow military units and contractors to share information electronically without need for complex translation routines. CALS defines the standards for a neutral transfer protocol that allow different systems within and outside of the military to communicate seamlessly\textsuperscript{26}. For example, the CALS programs define what software system will be used to electronically record scanned images of information previously existing on paper. Through CALS, documents only need to be inputted once and then transmitted to anyone who needs it allowing simpler information distribution. DoD estimates it will have a 20\%-30\% savings in its engineering, manufacturing, and support operations through usage of CALS directives\textsuperscript{27}.

CALS has already had an impact on the industries supporting DoD. Manufacturers need to utilize CALS protocols in order to submit design changes, suggestions, or bids for DoD contracts. Forcing contractors to CALS standards should also bring benefits to large military manufacturers because they, like the military itself, need to share large amounts of information with different parts of their organization.

The CALS program affects the sustainability of aerospace systems because it will greatly increase the capture useful information by those maintaining and manufacturing aerospace systems. Ideally, an engineer of a major aerospace manufacturer will be able to use workstations to examine the same information that an Air Force flight line technician uses. Moreover, the information that is obtained will be more current.

\textsuperscript{26} Elwood, pp. 497
\textsuperscript{27} Drouin, pp. 74
5.11 Concurrent Engineering

During the late 1980s, concurrent engineering gained popularity as a method of reducing production costs and increasing the quality of complex engineering systems within civilian industries and the military. In the 1988 version of a military specification, concurrent engineering was defined as:

...a systematic approach to creating a product design that considers all elements of the product life cycle from conception through disposal. In doing so, Concurrent Engineering simultaneously defines the product, its manufacturing processes, and all other required life cycle processes, such as logistics support.28

Previous methods attempting to improve industry performance during the 1980s focused mainly on individual sections of the product development process, thus lessening focus on the project as a whole. These methods also did not completely solve the problems of sequential engineering where development personnel functioned in an assembly line fashion by focusing on just their piece of the product and then handing off the work to the next section.29 In essence, these initiatives attempted to optimize the processes needed to complete the sections of a project and then combine them together. While these efforts did lead to improvements, they were not as significant as industry leaders had hoped.

Concurrent engineering brings about significant improvement by ensuring that the entire product and its lifecycle are considered during each stage of development. In order to achieve a successful concurrent engineering project, first the product's development

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28 Hoffman, pp 2
29 Ellinger, pp 421
process must be extremely well understood. During the process, all participants must also remain aware of how different individuals within the new system's value stream will view the product and insure that production requirements reflect those points of view. Finally, to achieve a successful product, all these points of view must be combined and traded in such a way that the important operational characteristics of the system are optimized - including the system's overall cost, performance, durability, and maintainability.

My research discovered a great interest within military and civilian sectors toward implementing concurrent engineering ideals into product development. A central idea behind concurrent engineering is thinking about the product's entire life cycle, which naturally includes the sustainability of that product. Concurrent engineering forces all participants to step back from their particular facet of a project and consider all of the goals of the system. Military and civilian interests in concurrent engineering methods hint at the increased importance of maintainability in current systems.

5.12 Research Analysis Summary

From the 1960s to the end of the 1970s the Air Force operated under policies that, from a modern point of view, were policies that did not emphasize sustainability. In various parts of this thesis, I have illustrated how these non-sustainment policies caused problems for new aerospace systems. Often, in the rush to get a system operational, the long-term needs of that system were overlooked making it expensive to own and difficult to maintain. Such policies focusing on greater operational performance led to technical breakthroughs that led to drastic improvements in the capabilities of aerospace systems. In Figure 5.1, it is shown that policies encouraging performance centered technologies resulted in the EG10-1's and EG10-2's increased thrust.
However, technologies relating to R&M were not similarly pursued because it was not considered to be of vital importance at the time. The processes and tools used at the time, specifically sequential engineering practices, were also not optimized to allow consideration of the entire system and its life cycle. It was under these conditions that the designs for the EG10-1 and EG10-2 engines evolved. These engines out performed anything else available to the Air Force, initially causing high satisfaction, but eventually those same engines left the Air Force very dissatisfied because of high cost of ownership and poor reliability and maintainability. The results from the EG10-1 and EG10-2 development projects led to changes in Air Force policy.

While it still operated with anti-sustainment policies, the Air Force did have in place mechanisms that allowed further development of its aerospace systems such as EMDP and CIP. However, these mechanisms, at least during most of the 1970s, were difficult to exploit due to heavy bureaucracy. The EMDP program existed for nearly ten years before it was used to spur the development of the EG10-5 engine system. Before dissatisfaction with EG10-1 and EG10-2 engines became an issue, the leadership and vision did not exist to fully exploit programs such as CIP and EMDP to bring anything but low level EG10 improvements into existence.

The Air Force then changed its policies to encourage system sustainability as much as overall operational performance, and, as a result, a number of changes were made within both the Air Force and the aerospace industry. In the case of engine systems, the Air Force's policy changes were initiated by instigating competition between Corporations Alpha and Beta to design replacements for EG10-1 and EG10-2 engines in order to insure creation of an engine system that fully fulfilled Air Force performance and sustainment needs. These two aerospace companies were very receptive to the Air Force's
needs once competition was induced since Corporation Beta wanted desperately to have a part of the fighter engine market and Corporation Alpha needed to put forward a strong effort to insure they did not lose production of the EG10 engines. As a result, durability was increased in the new engine systems and greater efforts were made to understand how the engine would be used and maintained before it was actually deployed.

This new emphasis on durability began to inspire creation of system sustainability technology. For example, the complicated EG10 mechanical fuel control system was replaced with a far more reliable and durable electronic fuel control system which, according to personnel at San Antonio, partially led to improved sustainability in the EG10-5 engine.

Moreover, processes and tools were also augmented to allow the creation of more sustainable systems. For example, this was the time when Corporation Alpha began to change its internal organization to better address what its customer, in this case the Air Force, wanted. Additionally, the Air Force empowered organizations like the EG10 FSO to more readily bring previous engine development experience and knowledge into new engine development in order to mitigate program difficulties. The Air Force and Corporation Alpha also changed their relationship from one of untrusting customers and buyers to a relationship of partners trying to create the best engine possible.

Under these programs, the EG10-5 engines were designed. As will be illustrated in Chapter 6, at least initially, the new engine satisfied Air Force desires for a more sustainable engine. The EG10-5 eliminated many of the problems suffered by the EG10-1 and EG10-2 engines such as in flight stall stagnations and problems with the fuel control system. Additionally, because efforts were made to better understand how the
engine would be utilized in the field, the squadrons using the engines were more satisfied with how they were able to maintain their systems.

The Air Force's pro-sustainment policies did not cease upon completion of the EG10-5 project. Both Corporations Alpha and Beta wished to continue producing engines for the F-15 and F-16 aircraft, and, in order to do that, they had to continually improve the sustainability of their engines. Due to the Air Force's strong emphasis on sustainability, the two corporations installed a number of new features, such as electronic monitoring systems, in order to make their engines more sustainable while also implementing processes such as concurrent engineering, IPTs, and usage of CAD. It was in the midst of these innovations that the EG10-9 engine was designed.

As the research framework diagram in Figure 2.1 illustrated, the technical sustainment improvements made to the EG10 engines were all the result of active policy decisions that led to the creation of operational systems. Moreover, these policy decisions, again illustrated in Figure 2.1, were directly influenced by the results of good leadership and the EG10's performance.
Chapter VI: Engine Sustainability Metrics

The previous chapters have concentrated on detailing the efforts and policies that Corporation Alpha and the Air Force have utilized to improve the R&M of their systems. This chapter will utilize quantitative analysis to illustrate the results of those efforts.

In order to quantitatively analyze the EG10 family of engine systems, it was necessary to collect maintainability performance metrics. The Air Force utilizes many metrics to gauge the reliability, maintainability, and durability of their aerospace systems and to indirectly judge the performance of their flight line technicians. One of the most important decisions of my research process was determining which of these metrics to use in the investigation of my thesis hypothesis. The final decision was heavily based on interviews conducted both at Wright Patterson AFB and with Corporation Alpha's maintainability group. Based on information gathered, I choose the number of Unscheduled Engine Removals per 1000 Effective Flight Hours (UER/1000EFH). A UER refers to removing an engine from the aircraft for purposes other than its regularly scheduled maintenance, such as an unexpected engine malfunction or failure.

An engine removal indicates that flight line technicians were unable to perform a needed maintenance or repair task on the engine while it was still installed within the aircraft. Upon removal, the engine is sent to a maintenance shop, either at the intermediate or depot level, where the needed work can be completed. A UER indicates when such removals were not previously scheduled for the engine. Intermediate and depot maintenance tasks force the engine owner, usually an Air Force squadron, to use its monetary resources to pay for the maintenance task, thus adding to the life cycle cost of the engine system. However, while engine removal indicates a need for some level of maintenance, it is important to note that not all engine problems require removing the
engine from the aircraft. Another motivation for selecting EG10 UER/1000EFH metrics is that this metric indicates when the engine was not functioning inside an aircraft. The longer an engine remains functional in the aircraft, the greater value it has to its owner.

UER/1000EFH metrics for the Air Force's fleet of EG10 engines were provided by personnel at SA-ALC located at Kelly AFB in San Antonio, Texas. SA-ALC personnel are responsible for providing the depot level maintenance for the Air Force's fleet of EG10 engines and has been chosen to be the depot maintenance center for the EG15-1 engine. Personnel at SA-ALC were contacted after the interviews conducted on WPAFB at the suggestion of the EG10 FSO group.

In order to add greater depth to the engine maintainability comparisons and provide another view on the maintainability performance of the engines, I have also examined the number of Total Engine Removals per 1000 Effective Flight Hours (TER/1000EFH) to supplement the UER/1000EFH metric. The Total Engine Removal (TER) metric combines all reasons for engine removal, including UERs and Scheduled Engine Removals (SERs), engine removals that had been planned for well in advance, into one metric.

The sections below will illustrate features of the data relating to my hypothesis. Some of the figures present trend lines fitted to the engine metric data to provide readers with an approximation of the trends for that metric. The trend lines were calculated utilizing functions in the Microsoft Excel® software package. Appendix A contains charts that provide a greater understanding of the ideas presented in this chapter.

To allow easier understanding of the data, most of the information presented in this chapter will involve the UER and TER metrics of the EG10-1 and EG10-5A engines. In many cases, EG10-2 and EG10-5B engines will be excluded because they are slightly
modified versions of EG10-1 and EG10-5A engines and operate in F-16 aircraft as opposed to F-15 aircraft. EG10-9 engines were also excluded because the number of EG10-9 engines operating in the Air Force is significantly less than the other EG10 engines, as illustrated in Table 2.1.

6.1 Unscheduled Engine Removals

Figure 6.1 illustrates UER/1000EFH metrics for EG10 engines, including the EG10-2, EG10-5B, and EG10-9 engines, as a function of the fiscal year ranging from 1975 to 1999. Figure 6.1 alone illustrates some of the sustainability behaviors mentioned during interviews with both Corporation Alpha's maintainability group and the EG10 FSO. The EG10-1 engine data illustrates that as the engine system matured, its UER/1000EFH metrics significantly decreased. The reason for this trend is that as EG10-1 engine systems matured, their maintainers became familiar with the characteristics of the engine, such as its failure modes, thus allowing them to better predict when an engine needed to be removed. The tendency for the UER/1000EFH to decrease over time can also be seen with the polynomial data fit presented in Figure 6.2.
Upon examination of Figures 6.1 and 6.2 it is observed that the UER/1000EFH metric trends downward for the EG10-1, and to some extent the EG10-2, while the same metric for the EG10-5A engines trends upward. Additionally, this metric appears to be converging to an asymptote of approximately 4 UER/1000EFH for both the EG10-1 and EG10-5A engine systems. This converging behavior is even more visible in Figures 6.3 and 6.4 that only plot the EG10-1 and EG10-5A UER/1000EFH metric.
This behavior is far from what was expected from engine systems where the overall sustainability has been improved with each new engine model. If the sustainability of each generation of EG10 were improved, one would expect that the UER metric would trend downward in a similar fashion for each engine toward a lower UER metric than the metric approached by the preceding generation. Figure 6.5 illustrates an example of such ideal behavior. Examination of the UER metric raises two questions:

1. Why did the EG10-5A engines approach the UER asymptote from below instead of above like the EG10-1?

2. Why do these engine systems appear to approach the same UER metric despite the fact that the EG10-5A engines were designed for increased sustainability?
In order to answer these questions, I contacted personnel at the EG10 FSO at WPAFB. The reason that the EG10-5A engine exhibited a positive UER/1000EFH slope while the EG10-1 engine had a negative slope lie partially in how the engines were procured by the Air Force. The EG10-1 engines were rushed from their prototype stage into full production in order to bring the F-15 into operation quickly to counter advanced Soviet fighter aircraft\textsuperscript{30}, and, due to the rushed production cycle, Initial Service Parts (ISPs) were used in fielded engines. ISPs are usually reworked to be more durable before the engine is fully fielded, and, because of these ISPs, the EG10-1 engine posted extremely high UER ratings. However, as the engine grew older, ISPs were steadily replaced with more durable components through the CIP. This, combined with other R&M related modifications, drove the UER metric down until it approached 5 UER/1000EFH.

Personnel at SA-ALC also mentioned that the EG10-1's fuel control system

\textsuperscript{30} Drewes, page 9
contributed to the engine's high UER metrics since this component was made of over 5000 mechanical parts that were extremely prone to failures. In fact, this mechanical fuel control system still causes many of the UERs that current EG10-1 engines experience today. The EG10-5 eliminated this problem by replacing the original mechanical fuel control system with an electronic version that used far fewer moving parts thus highly improving the EG10-5's operational reliability.

Unlike older EG10 versions, the EG10-5A engine represented an upgrade to the existing and fielded EG10-1 engine. Where the EG10-1 was seriously impacted by the performance of its prototype ISPs, the EG10-5 engines were built with parts that were meant to be used in fielded engine systems thus making the early UER metrics for the EG10-5A engines low. Although the EG10-5A was a derivative of the previous EG10, it still possessed new failure modes which appeared as the engine gained EFHs in the Air Force fleet forcing EG15 UER metrics to increase. Additionally, the fact that over time engine components wear out partially explains why the UER/1000EFH metric increases for the EG10-5A engines.

Part wear is also a cause for both the EG10-1 and the EG10-5A UER/1000EFH metrics approaching 5 UER/1000EFH. Engine components are designed to function for a given amount of time under given operating conditions (assuming that something else within or outside the engine does not breakdown). EG10-5A components were designed to be more durable than the EG10-1 components, but in order to provide greater thrust, the EG10-5A will often operate at higher temperatures than the EG10-1. These higher temperatures create a harsher operating environment for the EG10-5A components thus countering the improved durability of its parts. In essence, the harsher operating environment and added component durability balanced in such a way that the EG10-5A
developed UER performance similar to the EG10-1 over time.

The EG10-9 engines in general did not exhibit improved UER metrics compared to the EG10-5 engines, but there are explanations for this occurrence. The EG10 FSO explained that the EG10-9 engines, for the most part, fly drastically different profiles compared to the other EG10 engines because the engine is mostly used in the F-15E Strike Eagle aircraft which flies ground attack missions in addition to performing in the fighter role. This data confirms some of the statements made by EG10 SPO personnel.

Another interesting behavior is the tendency for the EG10-1, EG10-5A, and EG10-9A UER metrics to be lower than the same metric for the EG10-2, EG10-5B, and EG10-9B engines as can be seen in Figure 6.2. This behavior inspired investigations which uncovered the fact that the engines operating the single engine F-16 tend to have a greater number of unexpected engine removals than the engines operating in the F-15.

In addition to examining the UER/1000EFH metric against fiscal year, I also examined the metric versus total accumulated flight hours of the entire engine fleet. Figure 6.6 illustrates the UER metrics for the various EG10 engine variants. Examination of the data in this format revealed many of the same conclusions as the charts comparing UER/1000EFH to fiscal year. However, the EG10-1 and EG10-5A UER trend lines did not appear to approach the same asymptote in these charts, as shown in Figure 6.7. I utilized the analysis of TER metrics to further examine the engine removal behavior of these engine systems.
Figure 6.6: EG10 UER/1000EFH vs. Effective Flight Hours

Figure 6.7: EG10-1 and EG10-5 UER/1000EFH vs. Effective Flight Hours
6.2 Total Engine Removals

Figure 6.8 illustrates the TER metric for the EG10-1 and EG10-5A engines measured against fiscal year while Figure 6.9 measures that same metric versus EFH. These charts show tendencies very similar to the tendencies illustrated in the UER charts, but in the case of these charts, a tendency for the engines to reach 6 TER/1000EFH as they approach $10^6$ EFH appears clearly when the TER metric is measured against both fiscal year and EFH. This behavior confirms the information obtained both from the EG10 FSO and the personnel at SA-ALC that the engines do approach a common engine removal metric. This seems to imply that the engines have similar sustainment performance as total EFH approaches $10^6$ regardless of increased sustainment design.

Figure 6.8: TER/1000 hours vs. Fiscal Year
Figure 6.9: Effective Flight Hours vs. TER/1000 hours

- EG10-1
- EG10-5A
Chapter VII: Conclusions and Recommendation

The previous chapters have documented investigations and data analyses used to determine what impact designing jet fighter aircraft engines for sustainability has on the engine's performance. These investigations have yielded a number of conclusions and insights. In this chapter, those conclusions will be detailed followed by suggested research directions that may enhance understanding of the impact of design for sustainability.

7.1 Conclusions

Judging from the data collected and examined, the overall thesis hypothesis has been disproved. The EG10 upgraded variants did not demonstrate significant sustainment improvement in regard to the UER metric. In fact, many of the engines approached approximately the same sustainability performance, depending on the aircraft that the engine operated in, despite the increased efforts by the Air Force and Corporation Alpha to increase engine sustainability. This observation is counterintuitive to what would be expected from systems that have been supposedly designed to be more sustainable with each new generation.

I can only speculate as to the reasons for this behavior. My main theory for explaining the EG10 engine's sustainability characteristics is that as the engines were modified and components were made more durable the thrust of the engines were also increased thus countering the added durability. While increased thrust led to improved flight performance, the increased power also required the engine to operate at higher temperatures when the added thrust was utilized than previous engine models. Higher temperatures create a harsher operating environment for engine components requiring
more durable components to provide the same sustainment performance as the components of previous engine models. If this theory is correct, efforts to increase durability and sustainability are countered by owner usage of increased flight performance.

Based on statements taken from the EG10 FSO and SA-ALC, there appears to be a balance, at least in terms of engine systems, between total engine performance and overall sustainability that must be considered when designing and procuring complex aerospace systems. This would imply that one can trade increased performance in an engine system for decreased sustainability and visa-versa. If such a balance point between sustainability and performance exists, drastic improvements in sustainability performance may be possible by adjusting the system's operations as opposed to improving the design. For example, a squadron flying EG10-1 engines may be able to decrease the amount spent on sustaining their engines by restructuring their flying patterns, especially during training. Such a change would reduce funds needed to improve the engine thus allowing that particular squadron to cut its overall costs. This type of conclusion would suggest that serious attention be directed to how the squadrons use their engines and if those squadrons are properly balancing their performance needs with their sustainment needs.

Another conclusion formed from my thesis research is that designing sustainability into aerospace systems requires usage of teams composing of the system value stream members (e.g. manufacturers, final owners, and maintenance personnel). The EG10-1 and EG10-2 development programs demonstrate how adversarial relationships between manufacturers and buyers hinder the development of a sustainable engine system. Conversely, the design stages for later models of EG10 engines and the
EG15 utilized processes such as IPTs and concurrent engineering to ensure that all value stream members effectively communicated their requirements and that these suggestions were considered during the system design process. The importance of team organizations to the design of these engines is also demonstrated through operations of the EG10 FSO during development of later EG10 versions. This group of experienced individuals guided the later EG10 development programs and effectively avoided or mitigated many sustainment problems.

A thorough understanding of the characteristics and operations of systems must also be emphasized while designing complex aerospace systems. In the cases of the EG10-1 and EG10-2, neither the Air Force nor Corporation Alpha demonstrated great understanding of how the engine would be utilized in the field thus leading to warfighter dissatisfaction and high UER metrics. However, this deficiency in understanding was corrected during the EG10-5 development program through implementation of new policy directives through programs such as AMT and ENSIP that emphasized accurately predicting how the engines would be used in the field. Once the concepts of durability and accurate operations modeling were understood and implemented, the removal metrics, suggesting overall engine sustainability, for EG10-5 engines and their predecessors showed improvement in comparison to the earlier EG10 models.

My research has also led to the conclusion that the Air Force and Corporation Alpha at least partially understand the importance of upgradability to the operation of their aerospace systems. The Air Force has programs such as MSIP and CIP that provide funding mechanisms for modifications to existing systems. Moreover, programs such as CALS are utilized to keep both Air Force personnel and aerospace industry manufacturers aware of the latest system requirements and performance metrics. While
Corporation Alpha personnel stated that the company understood and designed upgradability into their systems, this thesis failed to find actual evidence that it made their systems easier to upgrade. Corporation Alpha did attempt to improve their products to entice the Air Force into purchasing new engines and these newer engines have been thoroughly examined from a human factors point-of-view, but this does not indicate an effort to make the engines easier to upgrade.

7.2 Research Recommendations

The conclusions of this thesis leave questions that should be answered in order to provide greater understanding of design for sustainability in aerospace systems. The first suggestion is to conduct further research seeking to determine the results of adjusting a system's operational performance in relation to its sustainability. In essence, this research would seek to discover if an owner can restructure how the system is utilized to achieve better sustainability performance without excessively sacrificing mission goals or utilizing extra funds to modify the system. The data presented in this thesis only hints that such actions would be possible, but this hint provides more than enough justification for further research. Possible methods of conducting this research include continued interviews of Air Force and aerospace industry personnel. Additionally, further aerospace system case studies may demonstrate the existence of a tradeoff between performance and sustainability.

Another possible research direction would be to examine the sustainment features of another system, such as, air born radars or avionics packages. Unlike engine systems, avionics and radar systems do not experience increased wear-and-tear when they are upgraded. Where engines with increased durability were also exposed to harsher operating conditions because of the increased thrust included in the engine design,
avionics and radar systems operate under the same conditions, no matter how much performance is improved. This characteristic would eliminate any possible tradeoffs existing between system sustainability and the way users operate the system although the tradeoff may still exist in terms of how often the system is utilized.

Informative research would also come from an investigation on how well the Air Force's system modification programs, such as MSIP and CIP, fulfill warfighters needs. This may involve measuring the time elapsed between submission of a modification proposal and when that modification is implemented with fielded systems. Through such research, Air Force and aerospace industry opinions could be collected on how well these programs fulfill warfighter needs and how easy or difficult they are to use as a means to modify existing systems.

Finally, the last research suggestion is to conduct sustainment research of systems operating within one Air Force unit as opposed to all the systems operational within the entire Air Force fleet. An example of such research would be to examine the UER metrics from a single squadron over its existence while correlating where and how the squadron used the engines. Research such as this would present another point of view on designing systems for sustainability thus providing policy makers more useful information.

7.3 Concluding Remarks

While this thesis does not answer all questions involving designing aerospace systems for sustainability, it has offered an insight that, through more research, can lead to a far more profound understanding into not only how aerospace systems should be designed for sustainability, but also how these same systems should be used. Additional focused research on this subject may provide policy makers both within the Air Force and
the aerospace industry with information on how to better satisfy the needs of the warfighter and how to cut system operating costs. In closing, this thesis has, at the very least, demonstrated that system sustainment involves factors beyond designing for sustainment.
Bibliography


"F-22 Chronology (Including F119 engine dates)," [Online document], February 2, 2000, [cited March 14, 2000], Available HTTP:
http://www.geocities.com/CapeCanaveral/Hall/7674/Chronology.htm

"F-22 History," [Online document], November 4, 1999, [cited March 14, 2000], Available HTTP:
http://www.lmasc.lmco.com/f22/history.html


"McDonnell Douglas F-15 Eagle," [Online document], [cited November 4, 1999], Available at:
http://chan.csd.uwo.ca/~pettypie/elevon/baugher_us/f015.html


"Pratt & Whitney F119-PW-100," [Online document], [cited November 4, 1999], Available at:
Related Readings


Appendix A

Figure A.1: EG10 UER/1000EFH vs. EFH

Figure A.2: Polynomial Fit of UER/1000EFH vs. EFH
Figure A.3: EG10 TER/1000EFH vs. EFH

Figure A.4: Polynomial Fit of TER/1000EFH vs. EFH
Figure A.5: EG10 TER/1000EFH vs. Fiscal Year

Figure A.6: Polynomial Fit of EG10 TER/1000EFH vs. Fiscal Year
Figure A.7: EG10 SER/1000EFH vs. EFH

Figure A.8: Polynomial Fit of EG10 SER/1000EFH vs. EFH
Figure A.9: Polynomial Fit of EG10 SER/1000EFH vs. Fiscal Year

Figure A.10: Polynomial Fit of EG10 SER/1000EFH vs. Fiscal Year