01WAC-2

Sustainment Measures for Fighter Jet Engines

Spencer L. Lewis
Massachusetts Institute of Technology

Wesley Harris
Massachusetts Institute of Technology

ABSTRACT

The US Air Force (USAF) has evolved a policy for the acquisition of fighter jet engines (FJE). In the 1970s and 1980s that policy placed a premium on FJE performance primarily measured by the metric: thrust/engine weight. In the 1990s, the USAF policy changed from an emphasis on performance to reduced life-cycle cost with a premium on sustainment. This paper reports the results of a study of how the USAF and Corporation Alpha (Alpha) have adapted their processes, practices, and policies to design, develop, manufacture, test, and sustain a family of FJEs. Each member of the family of FJEs is sequentially linked relative to insertion of technology designed to reduce sustainment costs.

In addition to the technology linkages, the development of the family of FJEs selected for this case study is also tracked relative to US Department of Defense and USAF policy and industry design, build, and maintain processes, methods, and tools. This paper discerns the complex, highly integrated manner that characterizes the interaction between (1) technology, (2) policy, and (3) manufacturing and sustainment tools to produce a family of FJEs with improving sustainment qualities and non-degrading performance.

The metric Unscheduled Engine Removals (UER) per 1000 Effective Flight Hours (UER/1000EFH) is used to compare the sustainability of each member of the selected family of FJEs. Our results are based on data obtained through a series of field interviews of USAF and civilian government personnel and Alpha personnel. The US government extensive database containing UER information is the primary source of MRO trends for the FJEs of this study. Our analysis shows that the family of FJEs sustainability, as measured by the UER metric, has <u>not</u> improved beyond 10^6 EFH for each succeeding generation in the selected FJE family. We conjecture that upstream policy, technology insertion, and manufacturing and sustainment tools are not the primary determinants of sustainability; the manner in which the FJE is used has the greatest influence on sustainability of FJEs.

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 equipment[1], an amount representing over 30% of the total Air Force budget. Tremendous operations and maintenance expenditures such as these have led the Air Force to launch investigations into what characteristics allow the most efficient usage of equipment and funds. One attribute being investigated is system sustainability, a characteristic that helps determine how much effort and money aerospace system owners employ to operate and maintain their systems. This paper examines the efforts of an American aerospace company to employ sustainment ideals and how those efforts have impacted system owners and maintainers. The conclusions presented in this paper are heavily based on case studies conducted on a series of Air Force fighter engine systems produced by an anonymous major American aerospace manufacturer, which shall be referred to as Corporation Alpha. The engine systems studied have been given the aliases EG10-1, EG10-2, EG10-5, and EG10-9, and will be collectively called the EG10 engine family.

Over the last decade, the Air Force has had to adapt its fleet of hundreds of aircraft and its operations infrastructure to a drastically changing world and staggering technical advancement. Additionally, Air Force aircraft are being called upon to complete a greater number of mission types while military budgets over the past decade have decreased[2]. Because of the billions of dollars spent annually, aerospace system operations and maintenance costs have been

[1] Office of the Under Secretary of Defense (Comptroller), "National Defense Budget Estimates for Fiscal Year 2000," March 1999, pp. 161.
[2] Office of the Under Secretary of Defense (Comptroller), "National Defense Budget Estimates for Fiscal Year 2000," March 1999, pp. 161.

highlighted as a prime place to increase efficiency and cut costs.

The billions of dollars spent each year to sustain the Air Force's aerospace systems is the primary motivation for this paper. Information will be presented to provide the aerospace industry and the US Air Force with guidance on how to best design systems for minimized sustainability costs.

Another motivation for this paper results from the high pace of technical development within the aerospace industry thus introducing a need for upgradability in aerospace systems. Upgradability is a characteristic that refers to how much effort, whether in money or man-hours, a system requires to have its capabilities improved (i.e. sustainability or overall performance) or have new capabilities added (i.e. ability to use another type of missile system). This paper seeks to provide the aerospace industry and the Air Force with information on how to design systems to make future upgrades affordable.

The third motivation stems from problems encountered while locating replacement parts for older aerospace systems. Manufacturers discontinue needed parts for military systems because it becomes unprofitable to continue manufacturing the parts when the only buyer is the military, which only purchases the minimum number of parts necessary. Similar problems occur when a part 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, this paper will show that some of the problems created by parts obsolescence can be mitigated.

In the context of the above environment, the objectives of this paper is to show *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*. Information and analysis will be used to illustrate whether a system initially designed to incorporate sustainment concepts will demonstrate significant positive effects to members in that system's value stream - referring to the people and organizations involved with the entire life cycle of the system. 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. Flexibility for technical upgrades refers to the overall ability for a system to undergo improvements in some facet of its performance and/ormaintenance.

To attain these objectives, five key research questions were developed to guide the research:

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 that system?

Through these questions, the information collected and analysis conducted will be presented to the reader thus exploring how designing for lean sustainment impacts the operations and cost of ownership of the system.

The research methodology presented in this paper is modeled after work completed in the MIT Lean Sustainment Initiative and Lean Aircraft Initiative with modifications made relating to this specific research topic. Based on these examples, the research conducted for this paper featured a literature search, development of a research framework, selection of relevant case studies, and arrangement of the data. The literature search stage focused on researching the history and trends of Air Force procurement policies. Following initial literature searches, a series of expert interviews were conducted among people within the aerospace industry, the Air Force, and MIT.

After completion of the literature search and the expert interviews, the case studies were selected. The EG10 engine family was selected because these systems had been created in quantities large enough that statistical data became relevant, upgraded versions of these systems were created every four to five years, and because data derived from studies of these engines would be of extreme benefit to the Air Force.

Table 1 illustrates some of the primary characteristics of each of the studied engine systems. The original EG10-1 and EG10-2 engines qualified for use within the Air Force in October of 1973 and featured system modularity as a primary design feature. Modularity allowed maintenance workers to separate different parts of the engine (i.e. diffuser, compressor, burner, turbine, and afterburner modules) from one another so that the parts could be worked on independently. Corporation Alpha improved on each version of the EG10 family's sustainability through incorporation of features such as improved reliability, increased durability, and inclusion of computerized diagnostic systems.

Engine	Completed Military Qualifications	Maximum Thrust	Number in USAF Inventory	Cost per Engine (millions)	Maintainability Innovation	Effective Flight Hours per Month
EG10-1	1973	23830	1579	2.65	Modularity	21
EG10-2	1973	23830	1094	2.67		25
EG10-5	1985	23770	1155	3.27	Increased Durability and Reliability	24
EG10-9	1989	29000	244	5.2	Computerized Diagnostic	40

TABLE 1: EG10 Engine Family Characteristics[1]

DATA SEARCH

EG10 AND EG15 MAINTAINABILITY DESIGN FEATURES - 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.[3]" Through the EG10 Maintainability Design Group, Corporation Alpha has endeavored to institute this definition into the EG10 engine family. Creation of this engineering group was mandated to improve the overall sustainment performance of the EG10-1 and EG10-2 engine systems after the Air Force expressed dissatisfaction with the system, and instituted competition to provide a replacement for the contract in the late 1970s and early 1980s. Through the experiences gleaned through this competition and the lessons learned from constant improvements to EG10 engines, Corporation Alpha has become a firm believer in sustainability. In their opinion, as long as a sufficient supporting infrastructure exists, systems designed effectively for sustainability will see savings in overall cost and manpower plus a more efficient sustainment pipeline. Sustainable engines demonstrate the characteristics of durability, survivability (surviving handling by maintenance technicians and the rigors of warfare), maintainability, reliability, reparability, and affordability.

Advances in available technology have greatly contributed to the increased sustainability of Corporation Alpha's systems. Through its tremendously increased thrust performance and incorporation of modular components the first EG10 engines demonstrated the cutting edge of engine technology. Fighter engine systems, however, represent extremely difficult systems to make sustainable because of their extremely harsh performance and operating requirements. The placement of Line-Replaceable-Units (LRU) and metrics such as Maintenance Man-Hours (MMH) and Mean Time to Removal represent methods of evaluating sustainability in fighter engines. Additionally, durability metrics such as individual part failure rates and number of removals also help measure sustainability. These metrics help drive advancements in technology that produce more durable materials, better thermodynamic models, and implementations of on-board diagnostic systems that lead to greater overall system sustainability.

Corporation Alpha has developed a number of processes and tools to aid the incorporation of sustainability into its systems. Some of these developments have been guided by military directives such as Designing and Developing Maintainable Products and Systems - MIL-HND-470A[4], which describes the processes that should be utilized to make new military systems maintainable, but other developments stemmed from internally produced mandates such as Corporation Alpha's Design Manual for Maintainability/Human Engineering. System sustainability is aided by computer-based tools such as Transom-Jack/Jane, stereo-lithography, and CATIA to help them design their systems for maintainability and older tools such as wooden system mock-ups. Many of these same tools help develop upgraded systems that are more transparent to users and maintainers of the aerospace system. One of the most impressive tools used by Corporation Alpha is their extensive Lessons Learned database. This database is accessible to engineers throughout the company intranet and provides them with knowledge from the many design projects that Corporation Alpha has participated in, thus allowing engineers to easily examine how design and operations problems have been solved in the past.

[3] Cooper, pg. 10

[4] Department of Defense Handbook MIL-HDBK-470A, Designing and Developing Maintainable Products and Systems, vol 1, August 4, 1997.

EG10 AND EG15 AIR FORCE MANAGEMENT - Case studies were conducted of the EG10 Engine Family Field Support Office (EG10 FSO) at Wright Patterson Air Force Base (WPAFB) to discover the Air Force's assessment of the sustainability performance of Corporation Alpha's products. A stark contrast in opinion between Air Force personnel and those at Corporation Alpha was quickly discovered. Where Corporation Alpha personnel stated that EG10 engines demonstrated good sustainability that was continuously improved upon, EG10 FSO personnel stated that the early EG10 engines initially demonstrated horrendous sustainment performance and that even the relatively modern EG10-9 demonstrated less than satisfactory sustainment performance. Through a series of upgrades, the earlier EG10-1 and EG10-2 engines have greatly increased their sustainment performance, but only to the point of remaining competitive with other engine systems.

The Air Force personnel interviewed seemed to believe that lean sustainment ideas could cut Air Force engine maintenance system costs without loss of service, but only if implemented correctly. Otherwise, it would remove the maintainer's ability to react to previously undiscovered failure modes that occur in the normal operation of the engine. Air Force personnel have already seen the results of drastic Air Force maintenance policy changes. During development of the EG10-1 and EG10-2 engine systems, the Air Force mainly considered engine sustainability and upgradability after it was already constructed and in the field. However, during development of the EG10-5 and EG10-9 engines, the Air Force has taken a more active role in determining how best to design engine systems for sustainment and in determining how the engine system will be used through out its life cycle. Additionally, the relationship between Corporation Alpha and the Air Force changed from a distrustful and distant producer/customer relationship to a relationship of cooperation focused on producing the best product possible.

Members of the EG10 FSO state that the most important technical innovation by Corporation Alpha in terms of engine sustainability was its development of engine modularity. This feature allows only parts of the engine to be sent off to depot and then be replaced with another module of that type thus providing maintainers with increased flexibility in how they maintain the engine system. Other technical innovations include increased refinement in how LRUs are positioned through analysis of individual part failure rates and accessibility requirements thus cutting MMH metrics. Also, engine systems have been designed with borescopes that allow technicians to examine parts of the engine without disassembling the engine and sometimes without even removing the engine from the aircraft.

Perhaps the strongest message communicated by the EG10 FSO was the importance of previous experiences to those managing an engine system. Through previous operational experience, maintainers are able to identify failure modes and prepare for the appearance of these failure modes in the rest of the engine fleet. Programs such as the Pacer engine program and the Accelerated Mission Test (AMT) program are focused on predicting and observing how engine systems behave over their operational lifetime.

The importance of such knowledge became extremely apparent through of difficulties that arose in maintaining the EG10-9 engine. Unlike its predecessors, the EG10-9 was purchased in much smaller numbers and over a relatively short three-year period. Because of this, the EG10-9 engine fleet gains flight hours significantly faster than other EG10 engines. The Pacer program, which runs a number of engines well ahead of the rest of the engine fleet to identify failure modes, is unable to stay ahead of the rest of the fleet because by the time the failure mode is identified and diagnosed, the rest of the fleet is experiencing that failure mode. Moreover, the fleet experiences the failure almost simultaneously, adding to the maintainability difficulties.

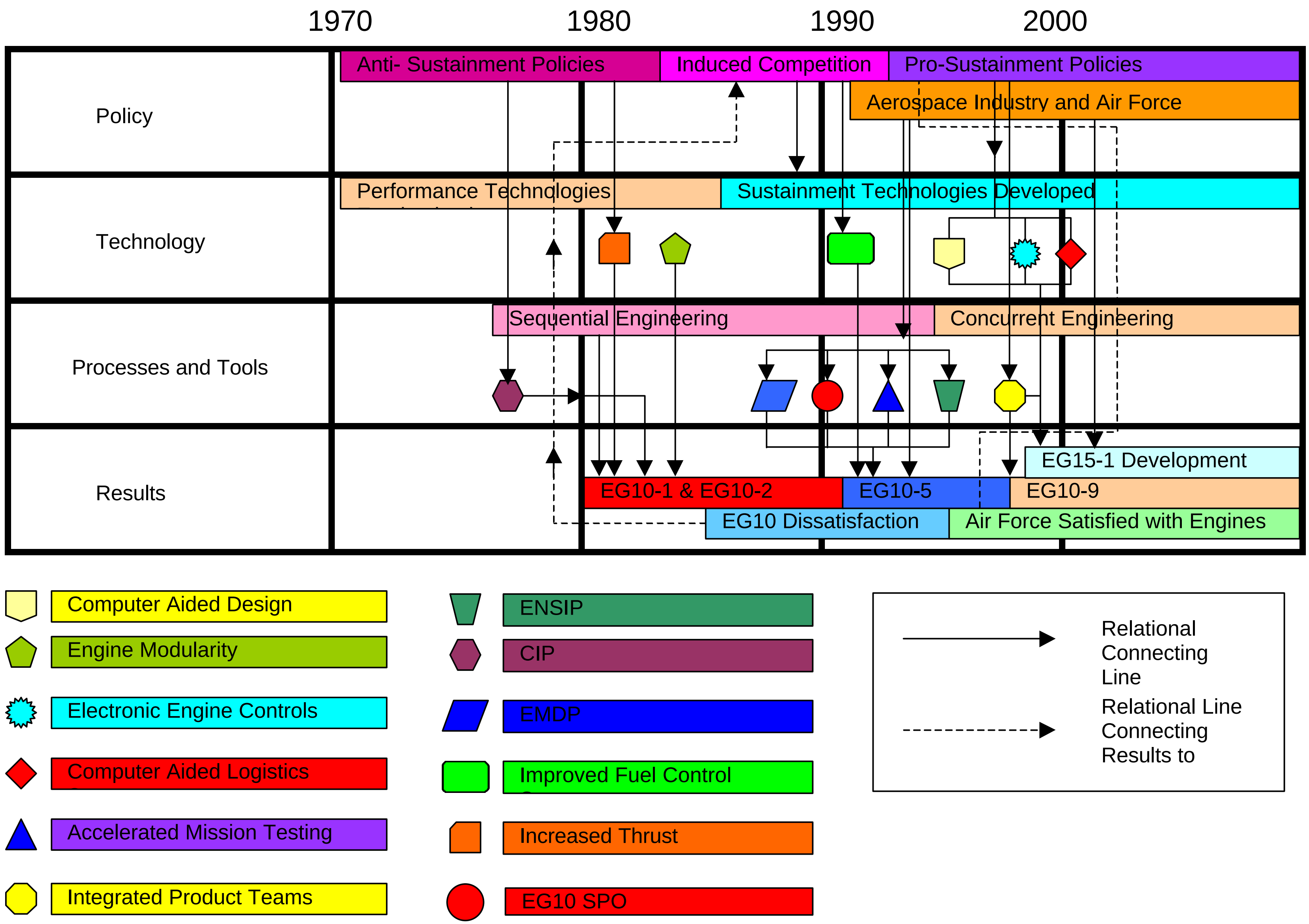
There has also been debate within the Air Force as to the best process to diagnose the maintenance needs of engines. Reliability Centered Maintenance determines engine system maintenance and replacement schedules through analysis of statistical and performance data collected from tests conducted during the development of the engine and from other engines already operational within the Air Force. However On Condition Maintenance, which dominated maintenance for the EG10-1, EG10-2, and EG10-5 engines, focused on using inspections to determine how maintenance for an engine system is scheduled. Conclusions have yet to be drawn as to which system is superior.

DATA ANALYSIS

This section 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. 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 1 illustrates some significant events and policy changes occurring between the 1960s and the beginning of year 2000 that impacted the design and maintenance of EG10 engine systems. Figure 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 section have impacted events in the policy section.

Figure 1: Research Framework Flow Chart



The information provided in Figure 1 is expanded upon throughout the remainder of this section. These detailed descriptions illustrate how given events impacted the EG10 development processes thus providing a more detailed understanding of how the topics presented throughout this paper intertwine with current Air Force and Corporation Alpha sustainment policies and practices.

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[5]. In reality, however, CIP money was utilized for projects that were so extensive that 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 funding was a bulk annual allotment used at the Air Force's discretion. To reestablish its oversight, 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. The usage of over $681 million CIP dollars within the EG10-1 and EG10-2 programs clearly illustrates the value of the CIP program.

ENGINE MODEL DERIVATIVE PROGRAM - The Engine Model Derivative Program (EMDP) was put forward by Congress in 1968 to correct what it saw as misuse of CIP funds while still providing means to conduct derivative engine system research and development[6]. 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, EMDP forced each new derivative idea in front of Congress. Because of the difficulty of procuring EMDP funding, EMDP funds went largely 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 Air Force's frontline fighter aircraft. By fostering competition, both corporations developed engines superior in performance and sustainability than the previous EG10 engines.

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, and insure that both 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 overrun. 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 largest reasons for the success of the EG10-5 development program[7].

One of the key motivators behind developing an upgraded engine system was to foster competition between Corporations Alpha and Beta. 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 was also responsible for surveying the war fighters 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 thus allowing them to contribute first-hand knowledge of flight-line engine maintenance procedures and difficulties. The SPO maintained a close relationship with the fighter squadrons to insure that the war fighter's interests were communicated to the manufacturers.

ENGINE STRUCTURAL INTEGRITY PROGRAM - Established in late 1978, the Engine Structural Integrity Program (ENSIP) is an Air Force program that focuses on improving an engine designer's understanding of engine system durability[8]. 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,

[5] Drewes pp. 92
[6] Drewes pp. 92
[7] Camm, pp. 14
[8] Camm, pp. 22

increased service readiness, and reduced life cycle costs.[9]" 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 was 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 from ENSIP provided a framework for managing problems and 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.

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 was tremendous since the engines had mainly been designed to provide high thrust without considering sustainability. In addition, problems such as dangerous in-flight stall stagnations appeared after the engine was fielded posing considerable danger to pilots, eventually forcing flight envelope limitations. 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 thus creating ill will between 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 among 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 Air Force fighter engine contract because, due to previous events, Corporation Beta had been effectively shut out of the military aerospace engine market. In order to win the contract and foil their competitor, both corporations designed engines that surpassed the Air Force's requirements. The warranties guaranteeing that the new engines were at least twice as durable as the earlier EG10 engines further illustrate drastic sustainment improvements[10].

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 fighter 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 an Air Force fighter/ground-attack 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.

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 Air Force dual engine fighters between 1978 and 1986[11]. Although the EG10 engines were not directly impacted through this program, the MSIP initiative led to major upgrades in fighter fire control systems, greater data processing ability, and numerous radar system upgrades.

RECOMMENDATIONS ON POLICY - In response to factors such as high aerospace system maintenance costs and war fighter 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 systems. The 1976 recommendation by the Air Force's Scientific Advisory Board and a 1980 recommendation given by the Comptroller General to Congress were two recommendations based on these studies. 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.

ACCELERATED MISSION TESTS - During the design of the EG10-1 and EG10-2 engines, ground test programs used to evaluate engine performance could not accurately predict engine or part reliability. First, the ground tests were relatively short, on the order of 150 hours, in comparison to the engine's total life cycle, thus

[9] U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, chart 36.

[10] Drewes, pp. 128

[11] McDonnell Douglas F-15 Eagle http://chan.csd.uwo.ca/~pettypi/elevon/baugher_us/f015.html

yielding limited information on long-term performance. Second, the tests were not based on how the engine would be operated in the field. Instead, they focused on evaluating the engine's maximum performance levels, thus only providing information about high-cycle fatigue characteristics. 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 new ground tests to better simulate long-term engine performance. 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 an AMT, the subject engine would be tested through an entire series of throttle settings designed to simulate the cycles it would encounter in actual service - including time spent at maximum, intermediate, and minimum thrust settings. AMTs are run for thousands of hours, stopping occasionally for system repairs and evaluation, thus duplicating operations over an engine's entire lifecycle. Because of the varying throttle settings and the length of the tests, AMTs accurately provide information on the engine's overall durability and reliability.

INTEGRATED PRODUCT TEAMS - Integrated Product Teams (IPT) became popular within Air Force and industry circles during the late 1980s and 1990s and largely impacted the EG10-9 development program. 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, were designed into each of its products.

IPTs bring together technically experienced individuals from many different backgrounds 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 engine modification processes[12]. It directed that the team should include personnel such as equipment specialists, quality assurance personnel, and financial representatives.

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[13]. 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.

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 neutral transfer protocols that allow different systems within and outside of the military to communicate seamlessly[14]. For example, the CALS program defines what software system will be used to electronically record scanned information. DoD estimates it will have a 20%-30% savings in its engineering, manufacturing, and support operations through usage of CALS directives[15].

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.

CALS directives affect aerospace system sustainability because they will allow easy capture and distribution of engine system data to both maintainers and manufacturers. Ideally, a manufacturing engineer will be able to use his or her workstation to examine the same information that an Air Force flight-line technician uses.

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*

[12] "Modification Planning and Management, March 31, 1995, Volume 1," [Online Document] Web DeskBook Edition, March 31, 1995, [cited April 4, 2000].

[13] Drouin, pp. 73

[14] Elwood, pp. 497

[15] Drouin, pp. 74

required life cycle processes, such as logistics support[16].

Previous attempts to improve industry performance during the 1980s focused 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 and focused only on their specified tasks[17]. While these efforts did lead to improvements, they were not as significant as industry leaders had hoped.

Concurrent engineering creates significant improvements 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, the product's development 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. All these points of view must be combined and traded in such a way that the important operational characteristics are optimized - including the system's overall cost, performance, durability, and maintainability.

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.

FINDINGS - 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, and 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.

However, technologies relating to R&M were not 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 the EG10-1 and EG10-2 designs evolved. While these engines out performed anything else available to the Air Force, initially causing high satisfaction, their poor reliability and maintainability coupled with a high cost of ownership eventually left the Air Force dissatisfied.

While it still operated with anti-sustainment policies, the Air Force did have in place mechanisms that allowed further aerospace system development, 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 EG10-5 system development. 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 create anything but low-level EG10 improvements.

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 EG10-1 and EG10-2 replacements that better met Air Force performance and sustainment needs. Due to competition, the new engines featured increased durability and both manufacturers made greater efforts to understand field operation and maintenance procedures.

Processes and tools were also augmented to allow the creation of more sustainable systems. The Air Force empowered organizations like the EG10 FSO to use previous engine development experience to mitigate future development problems. The Air Force and Corporation Alpha also changed their relationship from one of untrusting producers 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 later illustrated, 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 much more satisfied.

The technical sustainment improvements made to the EG10 engines were the results of active policy decisions. These policy decisions were directly influenced by strong leadership and the EG10's overall performance.

ENGINE SUSTAINABILITY METRICS

The previous sections 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 section will utilize quantitative analysis to illustrate the results of those efforts.

In order to quantitatively analyze the EG10 engine family, 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

[16] Hoffman, pp. 2

[17] Ellinger, pp. 421

judge the performance of their flight-line technicians. Based on information gathered, the metric Unscheduled Engine Removals per 1000 Effective Flight Hours (UER/1000EFH) was selected. 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 reason 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. The SA-ALC personnel are responsible for providing the depot level maintenance for the Air Force's fleet of EG10 engines.

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

The sections below illustrate data detailing EG10 family sustainability performance. 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.

To allow easier understanding of the data, most of the information presented in this section will involve the UER and TER metrics of the EG10-1 and EG10-5A engines. In some 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 single engine fighter aircraft as opposed to dual engine fighters. EG10-9 engines were also excluded because the number of operational Air Force EG10-9 is significantly less than the other EG10 engines, as illustrated in Table 1.

UNSCHEDULED ENGINE REMOVALS - Figure 2 illustrates UER/1000EFH metrics for EG10 engines, including the EG10-2 and EG10-5B engines, as a function of the fiscal year ranging from 1975 to 1999. 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 metric to decrease over time can also be seen with the polynomial data fit presented in Figure 3.

Figure 2: EG10 UER/1000EFH vs. Fiscal Year

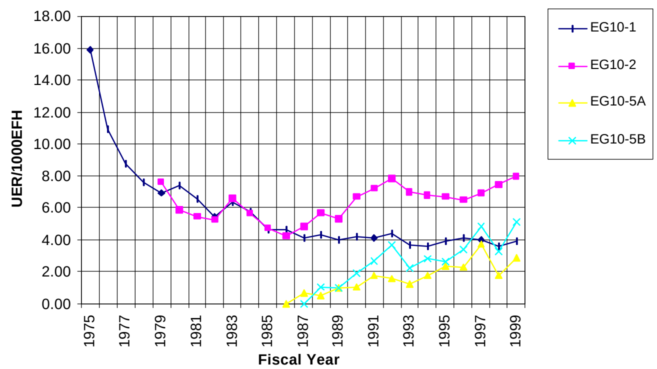
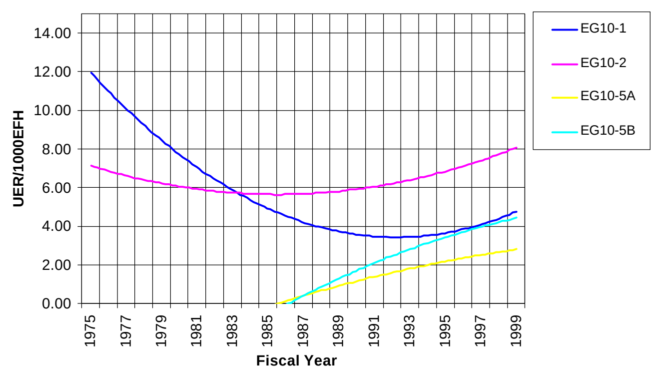


Figure 3: Polynomical Fit of EG10 UER/1000EFH vs. Fiscal Year



Upon examination of Figures 2 and 3 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 4 and 5 that only plot the EG10-1 and EG10-5A UER/1000EFH metric.

Figure 4: EG10-1 and EG10-5A UER/1000EFH vs. Fiscal Year

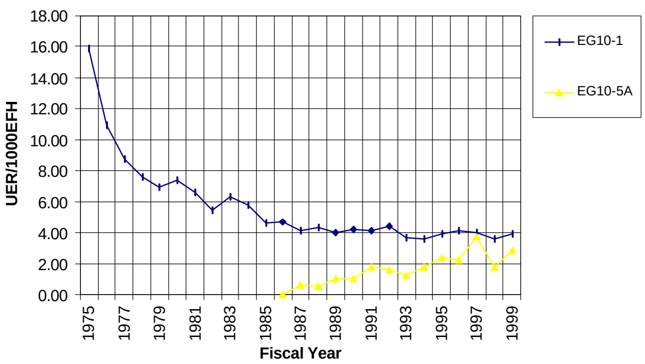
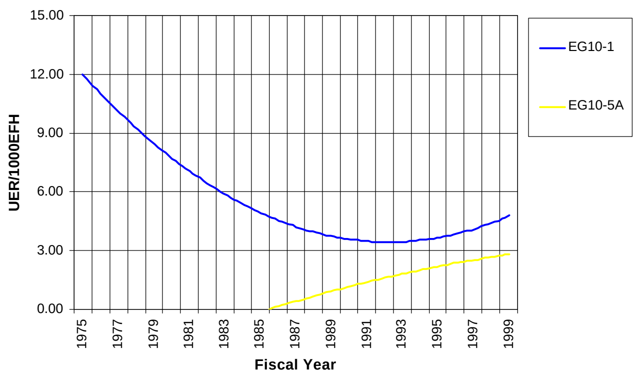


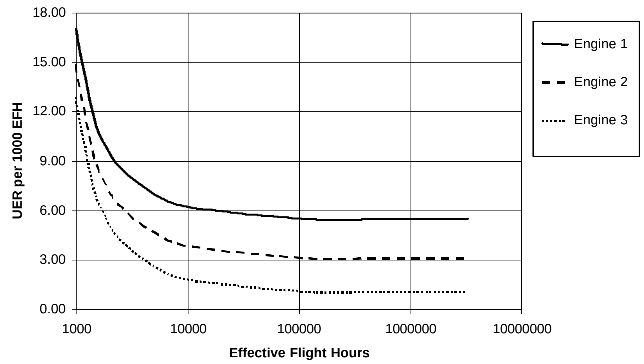
Figure 5: Polynomical Fit of EG0 UER/1000EFH vs. Fiscal Year



This behavior is far from what was expected from engine systems where 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 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?

Figure 6: Ideal UER/1000EFH Representation



In order to answer these questions, personnel at the EG10 FSO at WPAFB were contacted. 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 quickly bring, what was at the time, the Air Force's newest fighter into operation to counter advanced Soviet fighter aircraft[18]. Due to the rushed production cycle, Initial Service Parts (ISPs), which are usually reworked for increased durability before the engine is fielded, were used in fielded engines thus causing high UER metrics. 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 contributed to the engine's high UER metrics since it was extremely prone to failure because of its over 5000 mechanical parts. 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 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 engines 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 that appeared as the engine gained EFHs in the Air Force fleet forcing EG10-5A UER metrics to increase. Additionally, the fact that over time engine components wear out partially explains why the EG10-5A UER/1000EFH metric increases.

Part wear is also a reason that both the EG10-1 and the EG10-5A UER/1000EFH metrics approach 5 UER/1000EFH. EG10-5A components were designed

[18] Drewes, pp. 9

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 EG10-5A components thus countering increased component durability. 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.

Another interesting behavior is the tendency for the EG10-1 and EG10-5A UER metrics to be lower than the same metric for the EG10-2 and EG10-5B engines as can be seen in Figure 3. This behavior inspired investigations that uncovered the fact that engines of single engine fighter aircraft, such as the EG10-2 and EG10-5B, tend to have a greater number of unexpected engine removals than engines operating in fighters with two engines, such as the EG10-1 and EG10-5A.

In addition to examining the UER/1000EFH metric against fiscal year, this metric versus total accumulated flight hours of the entire engine fleet was also examined. Figure 7 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 8. The TER metrics were used to further examine the engine removal behavior.

Figure 7: EG10 UER\1000EFH vs. Effective Flight Hours

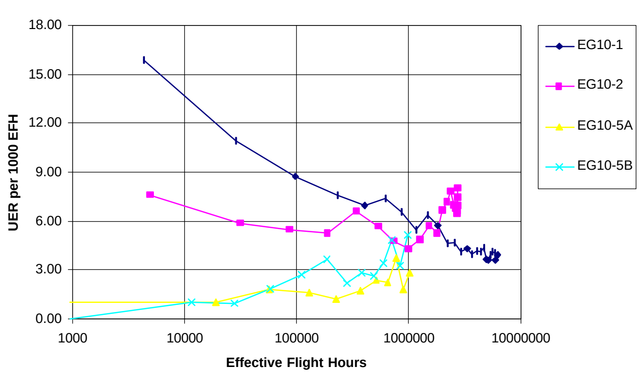
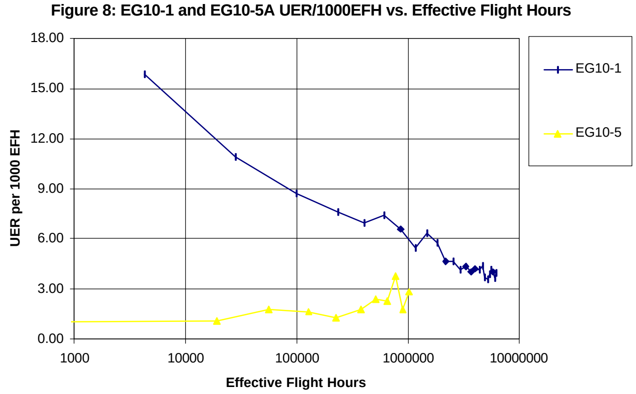


Figure 8: EG10-1 and EG10-5A UER/1000EFH vs. Effective Flight Hours



TOTAL ENGINE REMOVALS - Figure 9 illustrates the TER metric for the EG10-1 and EG10-5A engines measured against fiscal year while Figure 10 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 clearly appears. This behavior confirms the information obtained from both 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 9: TER/1000 Hours vs. Fiscal Year

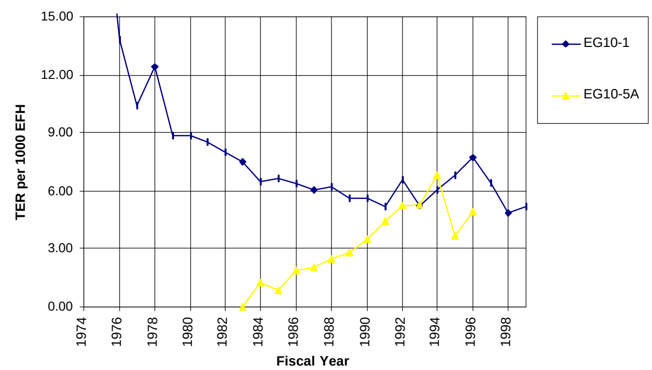
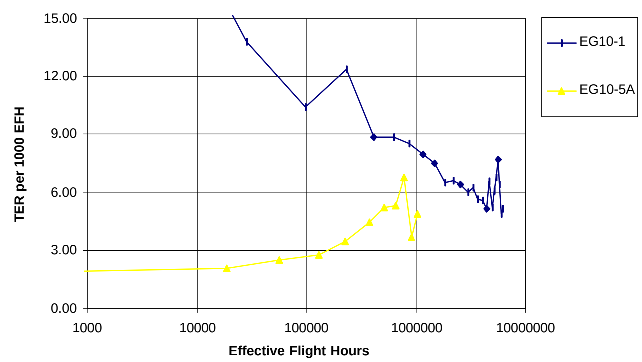


Figure 10: Effective Flight Hours vs. TER/1000 Hours



CONCLUSIONS AND RECOMMENDATION

Judging from the data collected, designing early for lean sustainment does not necessarily result in more affordable and agile life cycle options, and a greater flexibility for technical upgrades throughout the operational lifetime of a system. 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.

The main theory for explaining the EG10 engine family's sustainability characteristics is that as the engines were modified and components 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. Higher temperatures create harsher operating environments, and, in order to obtain sustainment performance similar to previous engines, the higher thrust engine must have more durable parts. 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 could trade increased performance 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. 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 the 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 sustainable engine systems. Conversely, the design stages for later models of EG10 engines utilized processes such as IPTs and concurrent engineering to ensure that all value stream members communicated effectively and that their suggestions were considered equally during the system design process. The importance of team organizations to the design of these engines is also demonstrated through the actions 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 war fighter dissatisfaction. However, this deficiency in understanding was corrected during the EG10-5 development program through implementation of new policy directives and the actions of programs such as AMT and ENSIP that emphasized accurately predicting how the engines would be used in the field.

Both 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 paper failed to find actual evidence that it made their systems easier to upgrade. Corporation Alpha does 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.

While this paper 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 war fighter and how to cut system operating costs. In closing, this paper has, at the very least, demonstrated that system sustainment involves factors beyond designing for sustainment.

REFERENCES

Camm, Frank. The Development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of Risk. 1993.

Cooper, W.C., Littlefield, A. H., and McCurry, G.E., Design Manual for Maintainability/Human Factors Engineering, Number FR-9607, Revision R2, © United Technologies Corporation 1996.

Department of Defense Handbook MIL-HDBK-470A, Designing and Developing Maintainable Products and Systems, vol 1, August 4, 1997.

Drewes, Robert W, The Air Force and the Great Engine War. Washington, DC: National Defense University Press, 1987.

Drouin, Bernadette, "CALS: An Essential Strategy for Paperless Interchange of Technical Information for Manufacturing - Current and Future Standards," CompEuro '93, 'Computers in Design, Manufacturing, and Production', Proceedings, 1993, pp. 73 -78.

Ellinger, Robert S. *When Do You Start to Design R&M into a Product? Concurrent Engineering, CALS, and the R&M Engineer*, 1994 Proceedings Annual Reliability and Maintainability Symposium.

Elwood, George, P. "What is CALS All About," AUTOTESTCON '93, IEEE Systems Readiness Technology Conference. Proceedings , Sept. 1993 , pp. 497 -500.

The Engine Handbook: Turbofan, Turbojet, Turboshaft/Turboprop, Reciprocating, and Small Gas Turbines, 1991 Edition, Directorate of Propulsion Headquarters Air Force Logistics Command.

Hoffman, Dennis R, "An Overview of Concurrent Engineering," Annual Reliability and Maintainability Symposium, Anaheim, CA, January 19-22, 1998, Proceedings, Piscataway, NJ, Institute of Electrical and Electronics Engineers, Inc., 1998, pp. 1-7.

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

"Modification Planning and Management, March 31, 1995, Volume 1," [Online Document] Web DeskBook Edition, March 31, 1995, [cited April 4, 2000], Available HTTP: http://web.deskbook.osd.mil/scripts/rwisapi.dll/@WebDADSearch.env?CQ_SESSION_KEY=JVTXQLDMUBOE&CQ_QUERY_HANDLE=124131&CQ_CUR_DOCUMENT=2&CQ_VIEW_TEXT=YES&CQ_SAVE[MDI]=YES#FIRSTHIT

Office of the Under Secretary of Defense (Comptroller), "National Defense Budget Estimates for Fiscal Year 2000," March 1999.

U.S. Air Force, Aeronautical Systems Division Deputy for Propulsion, 1982, chart 36.

CONTACT

Spencer L. Lewis
Wesley L. Harris
77 Massachusetts Avenue, 33-410
Cambridge, MA 02139
spencell@alum.mit.edu
weshar@mit.edu

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFB:	Air Force Base
AMT:	Accelerated Mission Tests
CALS:	Computer-Aided Acquisition and Logistics Support
CEA:	Cost Effective Analysis
CIP:	Component Improvement Program
DoD:	Department of Defense
EFH:	Effective Flight Hours
EMDP:	Engine Model Derivative Program
ENSIP:	Engine Structural Integrity Program
FJE:	Fighter Jet Engines
FSO:	Field Support Office
IPT:	Integrated Product Teams
ISP:	Initial Service Parts
LRU:	Line Repairable Units
MMH:	Maintenance Man-Hours
MIT:	Massachusetts Institute of Technology
MSIP:	Multistage Improvement Program
MTBF:	Mean-Time-Between-Failure
MTBM:	Mean-Time-Between-Maintenance
R&M:	Reliability and Maintainability
SA-ALC:	San Antonio Air Logistics Center
SPO:	System Program Office
TER:	Total Engine Removals
TER/1000EFH:	Total Engine Removals Per 1000 Effective Flight Hours
UER:	Unscheduled Engine Removals
UER/1000EFH:	Unscheduled Engine Removals Per 1000 Effective Flight Hours
USAF:	United States Air Force
WPAFB:	Wright Patterson Air Force Base