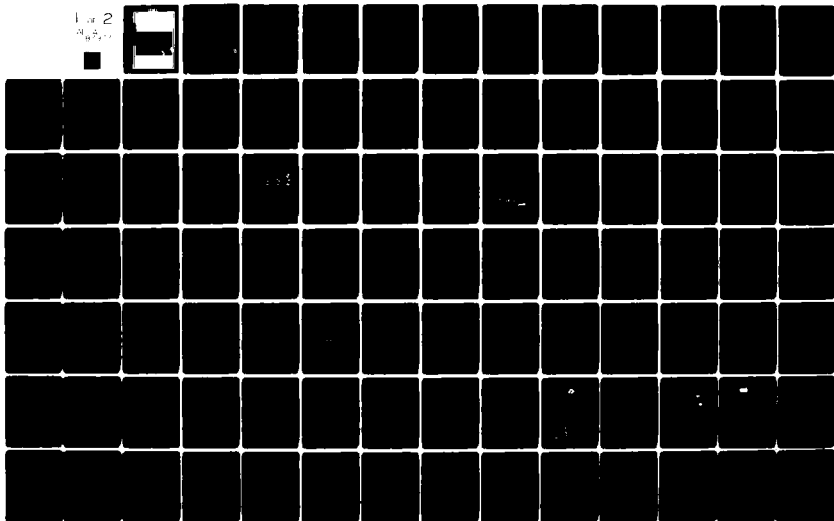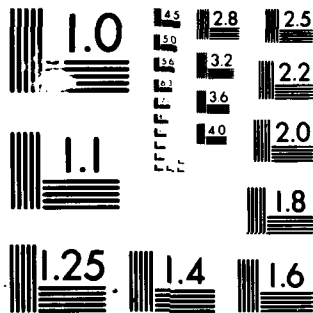AD-A087 977   ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC   F/G 21/5
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AGARD LECTURE SERIES No. 107

The Application of
Design to Cost and Life Cycle Cost
to Aircraft Engines

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Lecture Series No.107

THE APPLICATION OF DESIGN TO COST AND LIFE CYCLE COST

TO AIRCRAFT ENGINES

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 – Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;

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 – Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

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FOREWORD

All of the NATO nations are faced with a major concern for the growing cost of defence and the need to ensure that cost and performance are optimized. The requirements and related costs of weapon systems have come under close examination. The entire life cycle of a weapon system and its subsystems must be examined. The cost of design and development must now include not only the cost of production but also deployment, training, operational use, and support. The use of new technology and new management techniques are essential to obtaining the most for the available money.

The purpose of this Lecture Series is to examine the latest methodologies of cost/performance comparison and trade-offs for aircraft engines. Information will include data collection, analysis, modelling and estimating all development and operations costs. Also addressed will be contractual provisions and the costs related to incentives for performance and reliability. The latest applications in both government and industry will be covered, with examples and experiences from the military and civilian sectors.

R.W.ACKERMAN
Lecture Series Director

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1. Introduction

Traditionally, military procurements have emphasized unit cost as the major determining factor in systems acquisition. In the past, engineers were improving efficiency and reliability at ever-increasing cost factors, without regard to final unit cost or a total system view. As military budgets tightened, inflation increased, and cost overruns grew, the American Department of Defense began attempts to develop more realistic approaches to systems acquisition. Whereas previous procurements were judged on lowest cost-per-unit at delivery, the early 1960's brought the "Total Package Procurement" concept into the acquisition process. Although these early forerunners of Life Cycle Costing were generally unsuccessful attempts at viewing a total system cost, they laid important groundwork for today's Design to Cost/Life Cycle Cost principles.

At its very basic level, Design to Cost/Life Cycle Costing is simply the awareness of system and subsystem cost from the earliest conceptual studies to the end of system life: in other words, DTC/LCC is cost analysis, including design considerations which reduce cost, from "cradle to grave". LCC is based on groups of assumptions about the future and as long as these assumptions hold true, an accurate prediction of cost curves can be obtained. In the event that certain assumptions prove false, e.g. fuel costs, manpower predictions, etc., it is likely that the basic principles will hold true and that all systems will be affected by the unpredicted changes, not just a particular system under LCC study.

Thus, DTC/LCC is a viable tool relying on much more than just "crystal ball" methodology to achieve usable results. Increasingly, cost conscious governments are viewing the principles of DTC/LCC as invaluable in long-range planning and budgeting - in many instances, crucial to final system approval. LCC allows for a comparison of competing programs along several "phases" of the acquisition process and can be used to compare the basic logistics concepts of several competing contractors. This ability to carefully weigh alternatives can also produce decisions about equipment renewal needs and can control ongoing programs. Finally, an important application that is rapidly increasing in use, particularly within the American military community, is the selection of a prime contractor based on DTC/LCC data. Early U.S. DoD directives issued in the 1970's have met cultural resistance (e.g. engineers have traditionally designed systems to increase efficiency while ignoring cost), but a general trend toward acceptance has steadily expanded. Both buyer and seller see DTC/LCC as a commonsense, practical method for determining overall system cost and, increasingly, as a determinant in systems acquisition. It is as if the military establishment is applying principles from the private sector, a sector which has, for many years, used basic practical DTC/LCC concepts.

2. Lecture Series Summary

AGARD Lecture Series No. 107 will concentrate on applying DTC/LCC concepts to a major subsystem: the aircraft engine. As the program develops, it should become clear that these concepts must be applied to the total system in all its facets. The speakers from France, UK, and the U.S. represent both the customer who develops requirements (government procurement activities and the airframe manufacturers), and the engine manufacturer who designs propulsion systems to meet those requirements. The program will provide information on the latest techniques used within both government and industry as it relates to both military and civil aircraft engines.

The following are summaries of the presentations:

"Aircraft Turbine Engine Life Cycle Analysis" by Dr. J.R. Nelson, The Rand Corporation, USA: The presentation describes the methodology for life cycle cost analysis of aircraft engines. This process enables the weapon system planner to obtain visibility of cost, identify "drivers" that increase cost, and can lower capability. A most important point is developed by applying the methodology at the engine subsystem and aircraft system level to demonstrate that decisions about engine performance/schedule/cost must be made at the system level. The results of an extensive study of military and commercial engines are explained.

"Engine and Airplane Interaction in Design and Life Cycle Costs" by Mr. E.J. Jones, Ministry of Defence (Procurement Executive), UK: Based upon government requirements for military aircraft, an examination is made of the three main elements of aircraft costs: (1) Airframe Structure, (2) Propulsion, and (3) Equipment (Avionics). The potential for cost reduction is discussed as it applies to the main phases of a project programme (development, production, and operational life). The means of reducing engine costs at each phase will be covered. Emphasis will be on the complete aircraft system and, particularly, the interaction of engine and airframe which is a significant factor in choosing the means to reduce engine costs.

"U.S. Air Force Approach for Practical Management of Engine Life Cycle Costs" by Colonel R.E. Steere, USAF Aeronautical Systems Division, USA: Both technical and business practices applied to new gas turbine engines will be covered. The latest U.S. Defense Department approaches to influencing life cycle costs from exploratory development through phase-out technical and management activities, as well as business concepts and strategies will be explained. A new viewpoint being taken by the USAF Propulsion System Program Office is systems management of the life cycle process. Specifically, what can really be done today from a practical standpoint versus what may be possible tomorrow.

"Life Cycle Cost Programme for Military Engines" by Mr. Claude Foure, formerly with SNECMA, France: Presentation covers the various approaches leading to value engineering, reliability and maintainability studies, and direct engine operating costs. Cost prediction techniques will be discussed relating to their credibility, the effort needed for their development, and the decisions to be made on the basis of their results. Also covered will be trade-off factors, actions relating to fixed and revised targets with or without design changes. Finally, a look at measures of economy brought about by fuel cost uses.

"Logistics Forecasting for Achieving Low Life Cycle Costs" by Mr. G.I. Walker, General Electric Co., USA: This presentation examines engines designed under the DTC/LCC discipline. The "On Condition Maintenance (OCM)" concept is identified as a major contributor to the achievement of lower life cycle costs. This concept provides for reduced LCC by taking into consideration potential parts life (wear out characteristics and usage severity), and reduced maintenance workload. The information given relates to sophisticated methods for representing the dynamics of logistics systems inherent in such a maintenance philosophy. Also covered will be the use and impact of engine history recorders and parts tracking systems.

"Application of Design to Cost in Engineering and Manufacturing" by Mr. R.J. Symon and Mr. K.J. Dangerfield, Rolls Royce Ltd., UK: The presentation covers a procedure developed by Rolls Royce called Product Cost Control and its use to control the generation of costs during design and production phases. Examples will be given relating to implementation problems and solutions for controlling costs at the generation stage. Some examples of component design influenced by this procedure will also be provided. The results to date and a look at the next steps to be taken will be assessed.

"Turbine Engine Technology and Fighter Aircraft Life Cycle Costs" by Dr. F.A. Timson, Northrop Aircraft, USA: This paper discusses the fighter aircraft life cycle cost reductions being achieved through improvements in turbine engine technology. The engine characteristics that impact aircraft size are thrust-to-weight ratio and specific fuel consumption. Technology improvements in engines are reflected in aircraft that are resized (made smaller) to perform the same mission requirements. The cost analysis provided considers the savings in airframe design, production and maintenance costs, plus the savings resulting from lower fuel consumption. These savings are then available for application to further engine improvements.

"Evaluating and Selecting the Preferred Air-Breating Weapon System" by Mr. F.A. Watts, Boeing Aerospace Co., USA: This presentation provides a look at the big picture of cost versus need versus effectiveness. A top-down perspective of the applications of cost analysis and reduction is given to illustrate the basis and results of effective selection of alternatives. This is a philosophical, yet comprehensive, look at the real costs for weapon systems; a fitting conclusion to this lecture series on aircraft engines and the interrelationship of technology, costs, and defense needs.

AN APPROACH TO THE LIFE-CYCLE ANALYSIS
OF AIRCRAFT TURBINE ENGINES
by
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SUMMARY

This paper presents the results of a study that describes a methodology derived
from historical data for life-cycle analysis of aircraft turbine engines and ap-
plies that methodology at the engine subsystem and aircraft system levels. The
methodology enables the weapon-system planner to acquire early visibility of
cost magnitudes, proportions, and trends associated with a new engine's life cy-
cle, and to identify "drivers" that increase cost and can lower capability. The
procedure followed was to develop a theoretical framework for each phase of the
life cycle; collect and analyze data for each phase; develop parametric cost-
estimating relationships (CERs) for each phase; use the CERs in examples to as-
certain behavior and obtain insights into cost magnitudes, proportions, and
trends, and to identify cost-drivers and their effects; and examine commercial
experience for cost data and operational and maintenance practices.

SYMBOLS

ATBO = Average time between overhaul, hours
CAB = Civil Aeronautics Board
CIP = Component improvement program cost, millions of 1975 dollars
CPUSP = Current production unit selling price, thousands of 1975 dollars
DMQTC = Development cost to MQT, millions of 1975 dollars
DEVTIME = Development time from start to MQT, calendar quarters
EFH = Engine flying hour
EFHC = Engine flying hour consumed by operating fleet
EFHR = Engine flying hour restored to fleet by depot maintenance
IR&D = Independent Research and Development
KPRATE = Average production rate, 1000 engines/quarter*
KPUSP = 1000th unit production cost, millions of 1975 dollars
LCC = Life-cycle cost
MACH = Maximum flight envelope Mach number (measure of speed related to speed of sound)
MCDUM = Military-commercial dummy (1 = commercial, 0 = military)
MFRDUM = Manufacturer dummy (1 = Pratt & Whitney, 0 = others)
MQT = Model Qualification Test
MQTQTR = Man-rated 150-hr Model Qualification Test date, calender quarters (October
         1942 = 1)
MQTY = Total quantity produced, millions of units
MTBO = Maximum time between overhaul, hours
MVOLUME = Engine volume (maximum diameter and length, cu. in./10^6)
OPSPAN = Time since operational use began, quarters
PRQTYC = Production quantity cumulative cost at quantity purchased, millions of 1975
         dollars
QMAX = Maximum dynamic pressure in flight envelope, lb/ft^2
QTY = Quantity of production engines procured
RDT&E = Research, development, test, and evaluation
RMS = Resource Management System
SFCMIL = Specific fuel consumption at military thrust, sea-level static (SLS),
         lb/hr/lb thrust
TEMP = Maximum turbine inlet temperature °R
THRMAX = Maximum thrust (with afterburner if afterburner configuration), SLS, lb
TOA = Time of arrival
TOA26 = Time of arrival of demonstrated performance obtained from model derived using
        26 military turbojet and turbofan engines, calendar quarters
TOA37 = Time of arrival of demonstrated performance obtained from model derived using 26
        military and 11 commercial turbojet and turbofan engines, calendar quarters
ΔTOA26 = TOA26-MQTQTR, calendar quarters
TDC = Total development cost including MQT and product improvement, millions of 1975
      dollars
TOTPRS = Pressure term (product of QMAX × pressure ratio), lb/ft^2
WGT = Weight of engine at configuration of interest, lb

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* Several variables are expressed in what appear to be unusual units in order to obtain
significant figures in the computer output for various equations.

I. INTRODUCTION

Over the past several decades, the U.S. Department of Defense has placed increasing emphasis on understanding and assessing acquisition strategies and cost considerations in the development and procurement of new weapon systems. In the present era of budget constraints, and with an increasing share of the military budget devoted to operating and supporting forces in being, it has become even more important to be able to measure the contribution of both new and existing weapon systems to the overall defense posture in a life-cycle context--that is, their benefits relative to their total life-cycle costs.

Attention has recently focused on attempts to understand and predict total life-cycle costs for new weapon systems and important subsystems, including aircraft turbine engines. In this context, aggregation of costs is not enough; the key is to understand total life-cycle costs in terms of magnitude, distribution among cost elements, and trends over time relative to the benefits to be obtained. Such cost elements include not only those of acquisition (development and procurement) of a new weapon system, but also all the costs of operating and supporting the system in the field during its inventory lifetime. The latter costs, for both existing and proposed weapon systems, must be more clearly understood to make effective trade-offs during new developments and procurements.

OBJECTIVE OF THE STUDY

The study of the life-cycle analysis of aircraft turbine engines has a two-fold objective: (1) to develop a methodology for assessing life-cycle benefits and costs; and (2) to apply that methodology to improve understanding of policy options for engine acquisition and ownership.

The problem addressed is the weapon-system planner's lack of detailed information and a methodology to enable him to make early decisions concerning the selection of a new engine for a new weapon system, all within a life-cycle context. Accordingly, this paper presents information on and a methodology for life-cycle analysis, derived from the study of historical data on military and commercial engines, to provide a weapon-system planner with an early analytical perspective. This methodology, when backed up with appropriate data collection, should equip the weapon-system planner with improved early visibility of the magnitudes, proportions, and trends of costs associated with the various phases of an engine's life cycle. He should then be able to identify influential parameters that drive costs and exert leverages between life-cycle phases, and thus be able to assess trade-offs among quality, schedule, and cost in the search for policies appropriate to the various phases of a new engine's life cycle.

The major concern in this study, then, is to illuminate the entire life-cycle process for military aircraft turbine engines in terms of overall benefits and costs and their interactions. Commercial experience is also investigated to identify practices that the military might profitably adopt.

The procedure followed was to: (1) develop a theoretical framework for each phase of the life cycle, one feature of which was use of a technique for assessing the state-of-the-art advance represented by a new engine; (2) collect and analyze data for each phase; (3) develop and test parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends and to identify cost-drivers and their effects; and (5) examine commercial practice for cost data and operational and maintenance practices.

BACKGROUND

Aircraft turbine engines are a particularly promising subject for study because: (1) they are extremely important in weapon-system applications; (2) they are felt to be the pacing subsystem in aircraft weapon-system development; (3) they represent a large inventory and budgetary expense; (4) their 40-year history of continuing technological improvement furnishes a sizable (though fragmentary) data base for analysis; and (5) they could provide insights, from a subsystem viewpoint, across the life-cycle spectrum, that may be readily applicable to the weapon-system level. The subject also has an immediate practical urgency: Engines are a topic of considerable interest today because of problems arising in the operational inventory with aircraft grounded owing to engine-related problems.

RESULTS OF PREVIOUS STUDIES

Many past studies have attempted to shed light on the engine life-cycle process, and current studies within the military community tend to emphasize life-cycle cost estimates. The central question is, How much does it cost to acquire and own a new military engine over its life cycle? No previous study has been able to answer that question fully. It is obvious that the two major problems are: (1) accurately measuring what has already taken place; and (2) using such information to predict the future.

The most recent studies examined have been more qualitative than quantitative, or for the most part have addressed only a portion of the life cycle. (See, for example, Ref. 1.) Some previous studies have attempted to quantify operating and support costs and total life-cycle costs for specific engines, but no study to date has clearly and consistently defined all of the relevant cost elements and obtained their associated actual costs for any ongoing engine program. Furthermore, no methodology has been provided for predicting costs for new engines over the entire life cycle. The lack of data

is the persistent obstacle. For existing engines in the USAF inventory, studies of oper-
ating and support costs have been performed with cross-sectional data; in many cases,
they cover only a single fiscal year or even less. For a new engine, the procedure has
been to select a closely similar existing engine and use modified cross-sectional data
from that engine's current experience (usually at steady-state conditions) in an attempt
to project operating costs over the proposed engine's entire life cycle. The combined
lack of disaggregated, homogeneous, longitudinal data and of a reliable methodology for
projecting detailed cost estimates over a new engine's life cycle have frustrated attempts
to estimate life-cycle costs. Furthermore, none of these previous studies have attempted
quantitative calculations of the effect of state-of-the-art advances on life-cycle costs.

All these difficulties have led earlier studies to the erroneous conclusion that
engine base and depot maintenance costs are a relatively minor fraction of total life-
cycle costs for an engine--as little as one-tenth to one-fifth, with the range being af-
fected by whether or not fuel consumption attributed to a mission was considered within
the total cost estimate. These earlier studies suffered from the difficulty of defining
the cost elements associated with each of the phases of the life cycle, and ascertaining
whether these cost elements were consistent over time and whether all relevant cost ele-
ments were indeed included; their results further depended heavily on the data sources
and assumptions they employed. For instance, hourly labor rates used to estimate base
and depot labor costs will vary markedly, depending on the extent to which the direct
labor cost is burdened by applying appropriate overhead charges. Many studies have omit-
ted significant portions of the direct labor-hour cost burden. Another difficulty lies
in assuming that cross-sectional operating and support costs are average costs sustained
over the entire life cycle. The cross-section is likely to have been taken either during
the steady state of a mature engine or during its immature dynamic state; since neither
state is "average," a cross-section can seriously distort the estimate either up or down.
The impact of advanced technology is to bias cost estimates on the low side.

Previous studies have estimated engine ownership costs in a range of $20 to $200 per
engine flying hour. Recent data obtained for this study indicate that costs can be as
much as an order of magnitude higher (even after adjusting for inflation) for the newer,
high-technology engines for comparable mission objectives. It is possible that some pre-
vious cost figures were valid for earlier weapon systems at specific points in time, but
current systems are tending toward considerably higher average operating and support costs,
and future systems threaten to be even more costly if no actions are taken to change the
direction of this trend. Relying on older engine steady-state costs to directly reflect
new engine average costs over a 15-year time span can seriously underestimate future costs.

II. LIFE-CYCLE ANALYSIS

The life-cycle analysis of a new weapon system must be based on an understanding of
all phases of the life-cycle process, both separately and as they interact. Phases in-
clude concept formulation, validation, development, procurement, deployment, operational
use, and disposal. The life-cycle process extends over two to three decades, depending
upon the quality originally sought and the quality obtained, the length of time spent in
each phase, and the importance of the system in the inventory. The creation of a weapon
system involves many organizations within the Government, military service, and private
industry. While life-cycle analysis must be sensitive to institutional practices, the
central concern of this study is to develop a methodology that can be applied to benefit/
cost trade-offs at the subsystem and system level.

DEFINITIONS AND QUANTITATIVE MEASUREMENT OF BENEFITS AND COSTS

It is often extremely difficult to evaluate quantitatively the benefits to be gained
from a new weapon system. For example, the new system may incorporate a technical char-
acteristic that appears to provide a marginal improvement at best over a previous system,
but in reality creates a significant combat advantage--but how is that advantage to be
measured? In the commercial arena, the bottom line is profit earned for the service pro-
vided (where safety is one implied part of service), but it is far from easy to assign
a dollar-equivalent to the benefits a weapon system produces in a wartime environment.
In attempting benefit and cost assessments for engines, it must also be recognized that
analysis at the subsystem level must ultimately be related back to the system; engine
output must be measured in terms of its contribution to the weapon system. The true mea-
sures are the engine's impact on weapon-system availability and utilization, mission re-
liability, effectiveness, mobility, and inventory life. It is the task of the weapon-
system planner to transform the output measures dealt with in this study into their ulti-
mate value to the system; the methodology presented here should enable him to do so with
more confidence than has heretofore been possible.

DEFINING BENEFIT MEASURES FOR AIRCRAFT TURBINE ENGINES

The aircraft turbine engine has been characterized as one of the highly significant
inventions of the twentieth century. Certainly, no one can deny the tremendous importance
of the changes its military and commercial applications have wrought on our history and
the way we live. But everything comes with a price tag. It has been said, somewhat
wryly, that the only trouble with a turbine engine is that it weighs something, it gulps

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* Defense programs are not the only examples of this problem. See Ref. 2 for examples in
the energy sector.

fuel, it takes up space, it creates drag, and it breaks now and then. Like all other inventions, it has its benefits, and it has its costs.

Benefit measures for an engine hinge on its design, how it is used, and how it affects weapon-system quality. Quality is an extremely complex measure that defies absolute quantification in a military context. For an engine, it embraces the sum of the characteristics it is to contribute to a new weapon system (performance, durability, reliability, maintainability, safety), just as life-cycle cost is the sum of all cost elements. However, military quality is partly a subjective matter, more difficult to assess than cost. How much is an extra 50 miles per hour worth to a fighter aircraft? What is it worth to have the aircraft available more frequently? In the weapon-system context, it is possible--and necessary--to arrive at rational dollar figures for the answers, but subjective judgment will always enter the calculations.

In a life-cycle analysis, we seek to clarify, at least in part, the trade-offs among product quality, schedule, and total cost. When one characteristic of an engine is changed, other characteristics are affected. Since quality is a combination of many things, it is not certain that an improvement in one characteristic of quality necessarily leads to an overall improvement in quality for the end use desired. For instance, if performance is increased to the detriment of reliability, it is not clear that overall quality is improved if a higher performance aircraft is less available to perform its mission. In this study, quality is considered closely synonymous with performance in a military context, and engine performance characteristics will be related to the state of the art to assess schedule and cost impacts in selecting a new engine.

For military systems, quality has primarily meant performance, with other characteristics considered secondary. The goal commonly has been to obtain thrust at a minimum fuel consumption, weight, and installed volume, but other characteristics should be considered. (Commercial practice emphasizes safety, reliability, and cost.) Durability and reliability are so closely related that they are somewhat difficult to distinguish; but durability can be related to design life--the engine's continuing ability to perform the mission in the aircraft during its inventory lifetime. This may entail consideration of several system output measures: flying hours, sorties, takeoffs and landings, engine cycles (throttle movement), and calendar time. Reliability can be expressed as the engine's ability to be ready to go on any given mission and to perform it successfully. Measures of interest are engine removal rates, mission aborts, and time between scheduled base maintenance and depot repair visits. Maintainability is the ease with which the aircraft/engine combination can be maintained in the field. Safety can include design features that may appear to detract from performance--for example, designing engine casings so blades cannot go through them if they separate from the rotor. Such a feature increases engine weight but reduces the chance of substantial airframe damage. Environmental impacts include noise and smoke, which can be reduced at some penalty to engine performance.

The most widely used output measure of ownership cost for a given engine is cost per engine flying hour. In the future, however, other measures may become more relevant. With the advent of the high cost of fuel, flying training may be accomplished in fewer flying hours. But pilots can make fuller use of these flying hours so as not to cut down on critical portions of their training. Thus, in the future, flying hours may decrease, but not the number of sorties, takeoffs and landings, and engine cycles; if so, cost per flying hour may not be an appropriate measure. The cost of maintaining the engine inventory may not decrease even though there is a decrease in flying hours and fuel cost. This is especially true if maintenance is staffed to handle peak workloads in wartime. Another measure is calendar time. The longer an engine is out in the field without major depot rework, the more opportunity it has to undergo corrosive and secondary damage. When it does finally return to the depot, the damage may be more extensive than might be expected on the basis of flying hours alone.

Although this study will primarily use engine performance characteristics to relate to state-of-the-art and life-cycle costs, and the engine flying hour as an output measure for ownership costs, future data collection efforts should encompass other benefit measures--notably, sorties, takeoffs and landings, engine throttle executions, and calendar time.

THE AIRCRAFT TURBINE ENGINE LIFE-CYCLE PROCESS

Just as there is a life-cycle process at the weapon-system level, there is also such a process at the subsystem level. The subsystems of an aircraft weapon system include the airframe, engine, avionics, armament, and support equipment. It must be clearly understood that optimizing engine quality/schedule/cost does not necessarily do the same for the system. In the final analysis, decisions must be made at the system level; however, understanding the subsystem level can aid in understanding the system level.

The life-cycle process of an aircraft turbine engine encompasses the entire spectrum of research, development, procurement, and ownership. The requirement for a new engine is tightly interwoven with the requirement for a new weapon system. Figure 1 depicts this process, which is iterative during the design phase and makes use of feedback from operational experience as well as expectations from new technology. The characteristics of the weapon system required to satisfy the military need combine airframe, engine, avionics, armament, and support subsystems technology; the particular selection of characteristics is based on technical considerations tempered by operational experience.

This study focuses on development, procurement, and ownership; it does not explicitly consider basic research or exploratory and advanced development, the reduction of new knowledge to hardware, or the testing of advanced prototypes. The process also includes independent research and development conducted by companies active in the field and research conducted under government contracts. The sum total of these activities constitutes the technological base for aircraft turbine engines.

DEFINING THE LIFE-CYCLE COST ELEMENTS[*]

The life-cycle cost of an aircraft turbine engine is the sum of all elements of acquisition and ownership costs. To enable effective trade-off decisions, detailed definitions of those elements are necessary, particularly in terms of what belongs under acquisition cost and what belongs under ownership cost. Table 1 lists those elements as they are used in this study. There are three columns in the table: (1) engine acquisition costs, comprising the RDT&E and procurement portions of the acquisition phase involving design, development, test, manufacture, and delivery to the field; (2) engine ownership costs, comprising operating and support maintenance costs for all base and depot activities; and (3) weapon-system-related costs for fuel and for attrition due to accidents and catastrophic failures.

Certain cost elements appear under both "acquisition" and "ownership," as for instance, ECP/mod/retrofit costs. In one situation they are in the "acquisition" column because they are associated with enhancement of performance or a change in requirement that should be attributed to acquisition. In another situation, they are associated with changes for correction of a deficiency and improvement of reliability and thus are attributable to ownership. Other costs appearing in both columns include AGE (common and peculiar), transportation, management, and training. These cost elements are not usually large in either acquisition or ownership (on-the-job training is significant, but difficult to separate from all other maintenance labor costs at the base or depot; also, initial recruitment training is not considered here). Facilities are usually a one-time expenditure and vary widely from program to program. They are included in the definition, but will not be considered further in this study. With the increasing complexity of new weapon systems, peculiar support equipment may become increasingly costly, particularly if it is considered to include software design and development as well as hardware, and if simulators and diagnostic systems are regarded as support equipment. This should be considered in future systems, particularly if engine health monitoring becomes an increasingly important factor in the design of new engines.

Engine attrition and fuel are classified as weapon-system-related because these cost elements depend primarily on the design and use of the particular weapon system. (Fuel consumption is a function not only of engine design but also of mission use; attrition rates depend on single-engine versus multi-engine application as well as other features.)

AIRCRAFT TURBINE ENGINE DATA

Researchers attempting a life-cycle study of a weapon system constantly run up against the same obstacle: obtaining all the relevant data required. The problem is much like trying to put together a jigsaw puzzle when some of the pieces are missing and other pieces seem to have wandered in from another similar puzzle. Not only must the researcher comb through a large number of data systems, but there is the additional problem of inconsistency of data sources--two different data systems not agreeing when both supposedly use the same data from the same basic source.

The data most readily available for ownership cost-estimating in this study have been aggregated, heterogeneous, and cross-sectional, that is, gross weapon-system level or engine-family cost totals for only a few fiscal years and sometimes inconsistently defined across those years. A sound life-cycle analysis requires disaggregated, homogeneous, longitudinal cost data broken down below weapon-system level into consistently defined categories and available over a considerable period of time, preferably at least ten years. In general, military practice is to save costs for about three to four years.

For engines, the contractor is the best source of RDT&E/CIP and procurement data, since he is in the best position to break out the detailed cost elements for each portion of the costs associated with a particular contract, and he saves cost data for many years. These data are valuable to him for analyzing new engine programs, whereas the military services, because specific contracts may cover a multitude of items procured by a lump-sum cost, are hard pressed to attempt a detailed breakout of costs long after the fact. For instance, an Air Force contract may include not only the procurement of whole engines, but some allotment to spare parts, management data, field support, and so forth.

The only source of all relevant ownership data is the using military service. It is critically important to obtain all relevant costs in a particular area. For instance, depot costs are a large expense for engines. The total depot cost includes not only overhaul of whole engines, but also repair of reparable parts for whole-engine overhaul, the cost of expendable parts, modifications, and the repair of components received

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[*] In this study, all costs are expressed in constant dollars. Discounting may change some of the findings, depending on the distribtuion of cost outlays over the time horizon of interest and the discount rate assumed.

directly from the field and returned to the field. Some of these costs have not been included in previous studies attempting to obtain total depot costs.

The operating base has similar data problems. This is one area in which specific weapon-system costs are significantly lacking. To obtain cost elements at the base, for example, the Resource Management System (RMS) is useful for costs associated with specific base cost centers. This system provides the cost associated with operating the engine shop. However, several difficulties hamper the collection of engine-related base costs: The engine shop is not the only source of labor related to engines; costs associated with the engine shop involve fixing all of the engines on a base, not merely the engine type of interest; and costs are not separated by weapon system. The analyst therefore must exercise care in obtaining the correct costs properly allocated, or apply some estimation technique that includes allocation.

III. AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS METHODOLOGY

Aircraft turbine engines have been one of the most successful inventions of the twentieth century. In revolutionizing certain aspects of military warfare and commercial travel, they have provided to military and commercial users very large benefits for the costs they have incurred. The benefits include higher performance, which is the primary objective for the military, and higher reliability, lower cost, and improved efficiency and productivity, which are usually the commercial objectives. Costs have included large and continuing expenditures in early research, exploratory development, advanced development, independent research and development, and the funding of development, procurement, product improvement, and maintenance for specific engine programs.

Military mission requirements have expanded so that fighter aircraft now fly faster and farther and at higher altitudes or very close to the ground; transports can lift more payload, fly over a longer distance, and take off and land in shorter distances. Commercial aircraft are much more productive today in terms of ton-miles delivered with the advent of wide-bodied jets powered by high-bypass turbofans compared to piston engine aircraft or even first-generation turbojets.

The attainment of military or commercial performance, reliability, and efficiency levels requires the judicious use of available technology in determining not only the level of performance or reliability that can be attained, but when and at what cost. Performance, schedule, and cost must be considered in a total context at the system level. Performance and reliability are tied together by the schedule. There is a trade-off between increased performance or improved reliability with regard to the available technology at a specific point in time. If improved levels of both performance and reliability are desired, then additional technology is necessary and more time is required to achieve that level of technology maturation. This is evident from comparing the military and commercial experience, although currently commercial objectives are approaching those of the military in some aspects of performance as well as in attempts to maintain high reliability.

In looking at the history of the development of specific engine subsystems and aircraft systems, it can be seen that evolutionary improvements have been obtained during the past four decades. It appears that the benefits of new engine subsystems in specific applications, such as military fighter aircraft or commercial transports, have indeed been worth the technology R&D support. Thus, the overall evolutionary trend of aircraft turbine engine technology is providing substantial benefits for the costs that have been incurred, and this is true in both military and commercial applications.

There are two levels at which benefits and costs for engines are usually analyzed: (1) the macro-subsystem level (the overall engine's performance and installation in the aircraft system), and (2) the micro-component level (the part or component's impact on the engine and on the aircraft). At the macro-subsystem level, parametric analysis is usually employed to select the appropriate design point for a new system prior to extensive engineering design. The available data base of historical engine programs is utilized to obtain parametric relationships. At the micro-component level, detailed engineering analysis is usually employed in evaluating whether an anticipated improvement in cycle performance, or materials, or a new design technique for a particular part or component may be expected to provide a positive benefit. In both approaches value judgment plays a large role.

This section will present the methodology for a parametric life-cycle analysis of aircraft turbine engines. An example of a performance/schedule/cost parametric analysis at the engine subsystem/aircraft system level for the F100 engine and F-15 aircraft will be provided.

PERFORMANCE/SCHEDULE/COST CONSIDERATIONS*

The approach employed in this analysis is to use a proxy for the state-of-the-art advance in engines. The proxy is a time trend of a particular set of aircraft turbine engine characteristics at the U.S. military 150-hour Model Qualification Test (MQT) date. A multiple regression technique was used to obtain the equation that predicts the trend of the 150-hour MQT; the significant variables were thrust, weight, turbine inlet

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* For a more detailed description of the methodology, see Ref. 3.

temperature, specific fuel consumption, and a pressure term that is the product of the pressure ratio and the maximum dynamic pressure of the engine's operating envelope--all important performance and technology measures. The initial efforts in obtaining a trend for military engines concentrated primarily on performance measures since they were most readily available and the military process has been essentially performance-oriented. Many additional variables were examined but did not add significantly to the quality of the model obtained.

The data base for this approach consisted of 26 turbojet and turbofan engines spanning a 30-year time period of aircraft turbine engine history (1942 to 1972). Some of the technological highlights of this time period are shown in Table 2. Although sporadic surges of technological advance have occurred at various times in specific areas, the overall trend has been one of reasonably steady evolution. Time can therefore be used as a proxy for evolutionary change when evaluating performance/schedule/cost trade-offs in the selection of a new engine for a new aircraft.

The 26 engines in the data base are shown by date of start of development in Table 3; the detailed data appear in Table 4. The model and the data points are portrayed in Fig. 2. The 26 points are plotted by the number of quarters of years from an arbitrary origin, October 1942, when the first U.S. turbojet-powered aircraft flew. The equation obtained is displayed in the figure.

The statistical qualities of the model are very good, as is shown by the R^2 and the standard error; the F and t tests for the model and coefficients were also extremely significant. Perhaps most important, all the variables have entered into the relationship in a manner consistent with theoretical considerations and operational experience.

As will be shown in the cost analysis to follow, the continuing development of engines after the completion of the MQT when they have entered operational military service is often more costly than the entire development program up to the MQT. As an illustration of the application of the time trend technique, an analysis was made of the additional technological growth of 13 engines after their original MQT. It would be expected intuitively that the growth version of an engine already in production would have limited design flexibility, because many of its features are constrained by the existing hardware and production capabilities. Hence, technology improvement for updated engines should be slower than that for new engines. This expectation is borne out by Fig. 3, portraying post-MQT technology growth for 13 engines. The left-hand point of each pair of points is the original MQT engine, and the right-hand point is the most improved version. The connecting line indicates the rate of technological growth for each engine relative to the state of the art. All engines showed growth curves of less than 45 degrees.

To compare commercial experience with the military, a commercial engine data base of 11 points was also obtained. The detailed data for these engines are in Table 5. The results for the 11 data points relative to the time trend are shown in Fig. 4. The commercial trend line lies below and appears to be approaching the 45-degree-line military model as time increases. The implication is that commercial engines are more "conservative" than their performance-oriented military counterparts. It also appears that the commercial line is converging with the military model, indicating that commercial engines may approach military engines in the future. Indeed, some engine designers feel that commercial technology could surpass military technology in the future, especially if noise abatement and smoke elimination requirements are explicitly considered. All commercial engines were direct derivatives of military programs until development of the Pratt & Whitney JT9D. The JT9D is the first example of a major new aircraft turbine engine entering commercial service with no prior military experience. Another possible factor is the absence of new military programs in the early 1960s.

The 11 commercial engines were then added to the data base of 26 military engines, and an equation was obtained that uses the combined 37-point data base. A dummy variable (MCDUM) was employed for the commercial engines to differentiate them from the military. The results are shown in Fig. 5. The indication is that the commercial engines are more conservative than military engines because of their higher reliability goals. The dummy variable has a positive value of about ten quarters, indicating that commercial engines are about 2-1/2 years behind military engines.

The relationship obtained for the performance characteristics sought by the military or commercial user over time can serve as a proxy for the measurement of the state of the art with time. In this analysis, not only the time trend but also a time difference (the characteristics sought at a certain date compared with when those characteristics were expected to arrive) are employed in a series of cost models to obtain a life-cycle cost for engines. These models are useful to ascertain the cost effect of not only the trend of the state of the art, but also whether a particular engine is "pushing" the state of the art relative to the trend of time and how that might affect cost.

Table 6 presents the models obtained to date.[*] The state-of-the art trend (time of arrival) is shown with the other important characteristics sought in an engine, as discussed above. In addition to all of the models having statistical significance, the variables entering the models are perceived to behave correctly with regard to theoretical relationships; they corroborate the experience of the designers and users that the

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direction of the variables is correct, giving additional confidence to the validity of the models. This is true for all the models presented. For instance, in the state-of-the-art trend, where it is expected that technology will be improving with time, turbine inlet temperature is a highly desirable characteristic in an engine; it has indeed improved with time, and we do have a positive coefficient for how it enters the time trend relationship. Variables that would be expected to be reduced with time, such as weight and specific fuel consumption, have negative coefficients. Thrust is positive; the average thrust size of engines has been growing with time.

We use time trend parameters (TOA and ΔTOA) in the cost models. For instance, a model for development cost has been obtained. Here, the development cost of the engine to the 150-hour MQT is a function of the development time period (how long the engine was under development), thrust (the physical size of the engine), the Δ time trend (how the engine compared to the time trend), and the complexity of the engine (Mach number measuring the flight environment). All of these variables enter positively, all having the effect of increasing the development cost of the engine. We see similar results in looking at production costs. We show several ways of achieving development and production costs. Thus, a method for trading off the acquisition performance/schedule/cost for a new engine is presented.

To complete an analysis of engine life-cycle cost, models for depot and base costs are required. These two areas are principal cost elements in ownership of engines (in addition, whole spare engines and CIP are also considered part of ownership in this study). Note that these two models each use a different definition of engine flying hour, the utilization measure that was used for engine ownership costs. Costs incurred at the air base depend on "consumed" flying hours, the flying hours "restored" by the depot; that is, the depot repairs engines and restores flying time to the engines and returns them to the user. In a steady-state situation of supply equal to demand, the user is demanding (consuming) in the field and the depot is supplying (restoring) to flying status. Thus, in a steady-state situation, consumed and restored flying hours would be approximately the same. A problem arises in the analysis because the life cycle is dynamic. Furthermore, we have only limited cross-sectional data at the depot (for a year or two) and in any given year the consumed and restored flying hours can be very different. For instance, in the initial phase of a program when new engines are being introduced, the fleet may be flying at a higher rate, yet not many engines would be showing up at the depot until time is accumulated on them. Thus, consumed flying hours are much higher than restored hours. Also, across the total program, consumed hours would exceed restored hours because when an engine is finally condemned and disposed of, it has some flying hours on it (it is not sent back to the depot to be restored to zero time before being thrown away). Thus, more hours are consumed than restored during the engine life cycle. In any particular year, however, more engine hours may be restored in the depot than consumed in the field (for example, a major modification program may cause engines to be sent to the depot for repairs even though they have accumulated relatively few hours). Thus, these two measures are important to understand and keep separate; in the depot, the restored flying hour is the preferred unit for tracking depot costs, and at the base, the consumed flying hour is the preferred unit for tracking base costs.

The key independent variables for depot and base costs are time between overhaul and current unit selling price of the engine. At the depot, the average time between overhaul (ATBO) is of interest--when an engine actually comes in to be fixed. At a base, the maximum time between overhaul (MTBO) is of concern since it is the policy that sets how long an engine can stay in the field before it is mandatory for it to be returned to the depot for overhaul. This is of interest at the base because the base keys its scheduled periodic inspection, which is a major part of the propulsion shop workload, to the MTBO. It is also interesting to note that the engine unit selling price indirectly brings into the cost relationships the state of the art in terms of TOA and ΔTOA because they were utilized in determining the production unit price. Thus, the time of arrival technique is indirectly represented in the depot and base cost estimation models.

IV. PARAMETRIC ANALYSIS AT THE ENGINE SUBSYSTEM/AIRCRAFT SYSTEM LEVEL

How have the costs of fighter engines changed over the past decades? Does technology improvement have a payoff? The F-15 will be presented as an example of subsystem/system level analysis intended to provide some insight into the value of engine technology improvements. But first the performance/cost trends of fighter engines will be discussed.

ENGINE SUBSYSTEM LEVEL ANALYSIS

Figure 6 presents a hypothetical baseline program to calculate on a common basis life-cycle costs for various fighter aircraft engines employed in the 1950s, 1960s, and 1970s. Costs are in constant 1975 dollars; no discounting has been employed in this example, nor are any costs allocated for fuel or attrition due to a specific application. The engines were all "advanced" for their time.

Using the models derived, Fig. 7 presents a comparison of life-cycle cost breakdowns for these hypothetical engine programs. In spite of increases in development and procurement costs of engines (in constant dollars) from one decade to the next, the ownership cost portion dominates and tends to represent an increasingly larger portion of the total. Depot maintenance cost, the largest cost, is the reason for this trend. Miscellaneous costs were estimated to be approximately 3 percent of total costs for this example. The table indicates that total life-cycle cost has more than doubled from the 1950s to the 1970s and that the depot is accounting for an increasing portion of that larger cost. It

must be remembered that the 1970s engine is significantly more advanced in technology, and is larger in thrust and faster in Mach number, than the 1950s engine, and those improvements are what the military is paying for in attempting to obtain better weapon systems.

When these engines are normalized to the trend of technology advance and the same thrust and Mach number as the 1950s engine, the second set of bars is obtained (Fig. 8). Analysis reveals that present engines with higher technological content are more expensive than their older counterparts. But what is not revealed by this figure is what the improved technology is buying: lighter, smaller, more efficient engines. These highly desirable characteristics can only demonstrate their value in a specific weapon system. We now turn to such an example.

AIRCRAFT SYSTEM LEVEL ANALYSIS

The objective at the system level is to determine how engine technology improvements interact with specific mission requirements and system/subsystem specifications to obtain the "best" possible design. It was necessary to seek assistance from an airframe manufacturer to obtain the necessary understanding of how system/subsystem interactions depend on a specific mission requirement. McDonnell-Douglas provided assistance in examining an air superiority mission requirement. The Rand engine life-cycle models and Rand airframe RDT&E and procurement models were then utilized, together with the airframe information on system design and fuel consumption for the particular mission requirement, to determine the costs that are given here.

Certainly, "optimum" answers were not obtainable for the time and effort involved in this illustrative analysis, but this example can give system-level trade-off considerations, which in turn improve the perception of the usefulness of the subsystem results.

The F-15 air superiority mission was investigated at the system/subsystem level. This illustrative analysis is of limited scope. A total optimization study for each particular mission requirement, variation of engine thrust/weight, engine thermodynamic cycle, and aircraft configuration would have resulted in a very complex analysis.* For this example, a range of engine thrust/weight ratios was studied for a family of state-of-the-art engines of the 1960s, 1970s, and 1980s. For analytical simplicity. the thermodynamic cycle of the F100 engine was used throughout the analysis and a fixed procurement of twin-engine aircraft at a constant airframe technology was an additional ground rule.

Figure 9 presents the results of the variation of parametric aircraft takeoff gross weight designs with changes in engine thrust/weight ratio for the McDonnell-Douglas F-15 air superiority mission payload and performance. The improvement obtained in reducing aircraft takeoff gross weight as thrust/weight ratio is doubled is particularly evident. The design point for the F-15 is shown. It is seen that a considerably smaller aircraft gross weight (and engine thrust size) results as engine thrust/weight increases. It should be noted that further improvements in thrust/weight ratio apparently provide much less reduction in airframe takeoff gross weight for this particular air superiority mission. Aircraft trade-offs assume equal reliability and availability.

A hypothetical system baseline program is presented in Fig. 10. In this case, the fuel costs and airframe development and procurement costs are also discussed. For this F-15 air superiority mission, the F100 engine was calculated to consume 1250 gallons of fuel per average flight hour (at 44 cents per gallon) with fuel consumption at other engine thrust/weight design points scaled to the thrust of the engine. At a thrust/weight ratio of four, for example, the aircraft takeoff gross weight is double that of a thrust/weight ratio of eight. Fuel consumption was scaled to thrust level. The number of airframes procured is consistent with the number of engines being procured. RDT&E and procurement costs assume fixed airframe technology; no airframe operating and support costs were estimated. Again, in this case the airframe technology remained constant and only the thrust/weight ratio varied.

The cost results for the air superiority mission at selected engine thrust/weight values corresponding to aircraft gross weight are presented in Fig. 11. The thrust/weight ratio of eight is the design point for the F-15. The figure indicates that for the air superiority mission requirement, increasing the engine thrust/weight ratio lowers the total system costs, even though more technology is required, resulting in a more expensive engine. Total cost comprises the engine life-cycle cost, airframe RDT&E and procurement cost, and fuel cost. The cost is lower when using the more advanced engine because the physical size and weight of the engine and airframe are reduced, resulting in a smaller airframe to achieve the same mission. Improvement in thrust/weight from eight to twelve results in little additional cost reduction because the size of the airframe is not reduced as much and because the specific fuel consumption is the same (only the thrust/weight ratio for the engine is varied). Figure 12 shows a second set of bar charts in which a 50 percent improvement in ATBO/MTBO for the engine is presented. Again, notable savings for the engine are achieved, particularly because of cost reduction at the depot. Thus, in this particular air superiority mission, it would appear that use of advanced technology, resulting in a 50 percent increase in ATBO/MTBO, would reduce costs more than if the same technology advance were used to increase the thrust/weight

* An extensive study investigating variations in all these areas would normally be accom-

ratio from eight to twelve. Overall, advanced technology (from 1950s to 1970s) apparent-
ly saved several billion dollars in this one fighter application in terms of gross weight
reduction of the aircraft system, and further savings are possible if aircraft turbine
engine endurance as well as performance can be appreciably improved.

V. COMMERCIAL CONSIDERATIONS

What lessons can be learned from commercial experience that might be relevant to
the military? The primary concern of an airline is to make a profit, and the primary
operational benefit measure for an airline is aircraft utilization. For engines, utili-
zation is usually expressed in flying hours or operating cycles. The commercial flying-
hour experience is considerably different from the military. The airlines follow estab-
lished routes with known demand rates for flying-hour segments and takeoffs and landings
over a given calendar period. The U.S. military has varying requirements, except perhaps
for a portion of the fairly well-scheduled airlift fleet. The airlines accumulate engine
operating hours faster than the military, even for comparable aircraft. The airlines fly
about three times more hours in a given year than the airlift fleet aircraft, and ten
times more than supersonic fighter aircraft. But are there commercial operational and
maintenance practices that the military might consider to improve their capabilities?

OPERATIONAL PRACTICE

Commercial operational practices and procedures also differ from those of the mili-
tary. Operationally, the airlines require pilots to devote considerable "tender loving
care" to their aircraft. The throttle is used only to the extent made necessary by gross
weight, field length, altitude, and temperature for takeoffs and landings. On almost all
Air Force aircraft, there is no way to determine how much "hot-time" the engine accrues
during a known mission profile, although there has been some initial work on engine diag-
nostic systems that count throttle excursions. (The F100 engine on the F-15 aircraft has
such a counter, but it is not yet working well in operational practice.) Squeezing out
the last percent of power is considered very costly to engine hot-section life. Airlines
require flight crews to monitor engine performance in flight and to supply data for trend
analysis of engine performance after each flight. Careful throttle management enables
the airlines to achieve important dollar savings by trading performance for temperature
(and thus parts life). The Air Force could do the same. Since the military operation
of an engine is even further up on the higher end of the power curve (approaching maximum
performance), even a nominal reduction in throttle excursions could yield a significant
improvement in parts life.

MAINTENANCE PRACTICE

Commercial maintenance practice has been extolled as an example the military might
emulate. Airline maintenance practice today has turned away from the military's "hard-
time" philosophy (certain actions are taken at certain times regardless of how well the
engine is operating) toward what is generally termed on-condition maintenance.

There is some semantic confusion concerning the meaning of on-condition maintenance.
Current airline maintenance procedures fall into three areas: maintenance of life-
limited, high-time parts; condition monitoring of certain nonsafety-of-flight parts for
which there are no fixed time limits; and on-condition maintenance of critical safety-
of-flight parts that require regular periodic inspections. Various airlines cause con-
fusion by using these terms somewhat differently, but in general they distinguish be-
tween on-condition maintenance and condition-monitored maintenance by the level of in-
spection activity and the effect of the part on safety of flight.

The intent of the on-condition maintenance program is to leave the hardware alone
as long as it is working well and symptoms of potential problems are not developing.
This philosophy is not one of "fly-to-failure" when safety-of-flight items are involved.
This maintenance program is expected to reduce the shop visit rate, determine which
parts are causing removals and at what time intervals, increase the engine's accumulation
of flying hours and cycles by maintaining its availability on-wing, reduce secondary
damage resulting from serious failures, and maintain and improve the normal distribution
of failures expected for engines.

Prolonging the interval between shop visits for maturing commercial engines is
equivalent to increasing the average time between overhauls in the military. The result
of this action is to prevent the truncation of the engine overhaul distribution caused
by fixing the maximum allowable operating time between overhauls and the subsequent large
increases in engine removal rate when maximum hard-time overhaul is reached. Commercial
practice could therefore provide insights to the military on what parts are determining
failure rates and how CIP funds might best be apportioned among various engine problems.

On-condition maintenance has several specific requirements: (1) periodic on-aircraft
inspection of engine safety-of-flight areas at ground stations (borescoping, X-ray, oil
sampling and analysis, careful examination of the engine); (2) engine performance checks
and data gathering in flight, where the data are used for trend analysis at a central
data-processing center (usually at the main overhaul facility) to anticipate problems
before they occur; and (3) tracking of critical parts by part number to keep account of
the amount of operating time and operating cycles the parts have undergone.

When an engine problem is discovered or anticipated from trend analysis, the engine
is removed from the airframe and repaired at a base if possible (by replacing a part or

module, which is then returned to the shop); or the entire engine is sent back to the shop; or the aircraft is scheduled for a flight to the maintenance base so that the engine can be removed and another engine installed overnight with no loss of scheduled flight time. It is estimated that 90 percent of engine repair activity is performed at the shop; very little fixing of hardware is done at bases except removal and replacement of engines or modules or of major parts easily reached with minimum disassembly. (The base also performs other tasks primarily concerned with ground inspections, and handles lube, oil, and maintenance associated with day-to-day activities.) It may be asked why the Air Force cannot operate in this manner. The reason is that the airlines operate in a relatively stable peacetime environment. Some Air Force units may be able to operate in a similar manner, but others must be prepared to be self-sufficient in an overseas wartime contingency and thus are required to maintain a larger labor force at the base level.

When a commercial engine is returned to the shop, the data system is expected to furnish the engineering and maintenance people with records of how much operating time has accumulated on particular parts so they can judge whether to fix only the part that is broken (or that they anticipate will break shortly) or to fix other parts as well while they have the engine in the shop. They attempt to rebuild the engine to some minimum expected operating time.

Newer commercial engines are of modular design. Modular means that the engine can be readily separated into major subassemblies. The intent is to add flexibility to maintenance procedures at the shop and at the base. Engines can be removed and replaced overnight and modules can be "swapped out" at a base in several days, with only the modules returned to the shop for repair. One result is that airlines turn engines around faster than do U.S. military depots (15 to 30 days versus 45 to 90 days) and consequently require substantially fewer spare engines.

The U.S. Air Force has begun to procure modular-designed engines; the F100 engine on the F-15 is an example. The Air Force is implementing a modular engine maintenance information system like that of the airlines for keeping track of the operating time on parts and for helping in decisions concerning the operating life appropriate for each module and engine. The Air Force will have to be able to do this kind of analysis at the depot and base if it plans to adopt the commercial maintenance philosophy regarding modular engines and, especially, regarding on-condition maintenance.

Maintenance experience and skill levels are very high in airline central shops. Most mechanics are FAA-qualified, have a long continuity in service, and with their years of experience get to know the individual engines and aircraft, since the fleet is not so large for a given airline. The civilian labor force at the Air Force depot also has considerable continuity of service, but the base inventory and the current practice of completely disassembling an engine during overhaul and reassembling it with different parts prevents them from getting to know individual engines--besides which, the engine changes its identity every time through the depot. It is not clear how much of an edge this gives the airlines, but airline people consider it substantial. The commercial work force is also more flexible about scheduling overtime during peak periods and laying off during slumps. The military depot does not have this flexibility in the short term.

Several airline officials have expressed concern that they have gone too far too fast with on-condition maintenance as applied to current high-bypass-engine experience. Their worry is that they might be merely postponing certain problems to a later date. They believe they are obtaining more operating hours, but at a cost. When an engine finally does return to the shop, more has to be done to it in terms of parts replacement than if it had come in sooner. The problem is to determine the "optimum" point. The military attempt to do so by setting an engine MTBO at some point that the user and supplier believe is the optimum in terms of operational availability on the one hand, and the amount of work required when it is returned to the depot, on the other hand. The choice lies between the two extremes; a short-fixed-time philosophy is one, and on-condition maintenance running to failure or close to the anticipated point of failure is the other. There may be some optimum intermediate point derived from a combination of hard-time and on-condition maintenance, and this optimum could vary, depending upon the individual airline or military situation. One airline's (or service's) optimum is not necessarily another's because of differences in route structure and operating conditions (mission), utilization of the fleet, economic environment, and so forth. At any rate, it would appear desirable for the military to move away from its strict hard-time philosophy, but no doubt there is some point on the on-condition maintenance spectrum beyond which it may not be desirable to go for the sake of economic efficiency. Appropriate data are required to assist in seeking this optimum.

COMMERCIAL ENGINE COSTS

What does it cost the airlines to own and operate their commercial engines? Do they do a better job at cost control than their military counterparts? These questions are more difficult to answer than would first appear, even though manufacturers preserve a great deal of engine cost data over a period of time for their cost analyses. (Airlines are also required to provide certain cost data to the Civil Aeronautics Board (CAB), separated into certain cost categories.)

Because accounting practices, operations, and economics vary among airlines, however, only the individual airline will know fully what its costs are under its own accounting practices, route structure, operating conditions,

conditions. Therefore, difficulties arise in attempting to use airline cost data directly. The purchase price of an engine that an airline reports to CAB may reflect the cost of the entire pod, which is the total installed engine in its nacelle ready for mounting on the aircraft wing, or it may reflect the bare engine and certain spare parts. It may also include, as in the case of reported Air Force contract prices, spare parts and accessories, technical data, and field service costs. Thus, it may be difficult to use the aggregated data reported to CAB to arrive at standardized procurement costs that will be comparable among the commercial airlines. At least an estimate can be obtained, however, if it is known whether the purchase was for a bare engine or a podded engine, and if some idea can be gained of what additional costs are involved in the purchase price.

The matter of proprietary information can be a further stumbling block. To gather information on military engines for this study, it was necessary to go to the manufacturers for disaggregated, homogeneous, longitudinal data. They were willing to supply military data on a proprietary basis, but they were not willing to supply commercial cost data at all, except in the most unusual circumstances and then only on a very limited basis.

In sum, the analyst faces the dual difficulty of determining the content of the CAB data and of obtaining information the airlines and manufacturers consider highly proprietary. Thus, the major problem in comparing commercial and military engines is generating comparable costs. At present, the most pressing need is to understand what the commercial cost data actually include; nor is it sufficient to do so for only a one-year or two-year cross-section. Cost analysts in both the engine industry and the airline industry agree that five to seven years worth of historical data are needed to gain a reliable picture of the trend for a particular piece of equipment. This appears to be true for both technical and economic reasons.

Analysis of Available Data

Figure 13 depicts an approximation of typical 14-year life-cycle costs for the older first- and second-generation commercial turbojet and turbofan engines. New third-generation high-bypass engines may be different in terms of cost magnitude and proportions, and their life-cycle may be extended to cover their higher costs, with depreciation spread over more years--perhaps 16 rather than 14. The figure reveals that 75 to 80 percent of cost is ownership. It should be recalled, however, that the procurement cost of the engine includes allocations for development and IR&D, and certain ownership cost (spare parts purchases) also includes, besides CIP and warranty add-ons, a charge for development; consequently, acquisition and ownership costs are not cleanly defined even for airlines. It is interesting to note from the figure than an airline buys an engine twice over in spare parts alone during its operational lifetime.

Data obtained from five commercial airlines in the course of this study indicate that the older and smaller turbofan engines such as the JT8D and the JT3D are costing between $500,000 and $100,000 per shop visit for engines that have been operating for 2000 to 4000 hours, while the newer and larger high-bypass engines such as the CF6, JT9D, and RB-211 are costing between $100,000 and $200,000 (1975 dollars) per shop visit for engines that have been operating for 1000 to 2000 hours. The cost range appears to be affected by the size of the engine, the state of the art, engine maturity, usage since the last shop visit, and airline policy on refurbishment to some minimum operational time prior to the engine's next shop visit. The costs are quite different from those obtained from the military for comparable engines with similar operating experience. Airline shop costs are apparently fully burdened* and reflect around 90 percent of base and shop costs combined. At the military depot, a cost increment of at least 50 to 100 percent must be added to the major overhaul cost to obtain the total depot cost per engine processed in a given year.

What does it cost to maintain a commercial engine? From the data presented, ownership constitutes 75 to 80 percent of total life-cycle cost (not including fuel). The first- and second-generation commercial engines are estimated to have a peak cost of around $40 to $80 per flying hour for ownership and $50 to $100 per flying hour total (all costs are expressed in 1975 dollars). Steady-state costs with the advent of maturity fall to a range of $20 to $30 per flying hour for engine maintenance. Peak costs appear to be two to three times steady-state costs. A total of about 35,000 to 45,000 operating hours in a 14- to 16-year period is expected. New third-generation high-bypass engines will peak at well over $100 per flying hour if the same percentage breakdown applies. The airlines hope that long-term steady-state ownership costs can be reduced to around $40 to $50 per flying hour when maturity is attained for these new-generation engines. Since these engines are of higher technology, with at least twice the thrust and considerably improved specific fuel consumption, they are expected to be well worth the higher cost to the airlines in the service they will provide with the new wide-bodied transports.

In examining the available commercial cost data over a number of years, a general cost profile trend is distinguishable. A hypothetical cost profile is shown in Fig. 14. It presents expected cost patterns on the basis of consumed and restored engine hours with peak, average, and steady-state values indicated. Also shown are two general problem areas that seem to occur in engine maturation: an early peak (occurring usually

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* Including all allocated materials, back shop labor, and overhead, except for major modifications, which are treated as investment rather than operating expense.

because of problems in the hot section in the engine's maturation) and later on, an additional hump on the way to steady-state conditions (some cold-section problems tend to show up later). Shop visit rates show the same pattern (leading the reported cost data by six to nine months because of reporting delays). The JT9D, operating since 1970, apparently is approaching maturity and will be an interesting example to watch as an indicator of cost differences between the current generation of high-bypass engines and previous generations' experience. It does appear that the high-bypass engines are at least twice as costly to operate. The question still to be answered by the operators is whether or not they will be as profitable as expected in the long term. They were expected to return their investment and increase airline profits when they were purchased in the late 1960s. The difficulty has been the slower than expected increase in air transportation growth in the early 1970s. One indication that things may be different for a high-bypass engine is that some airlines are now using 16 years as the depreciation period for tax purposes rather than 14 years, because these newer engines are not accumulating flying time as rapidly as the older engines at similar points in their life cycle. Consequently, the extra time is needed to achieve the expected 35,000 to 45,000 operating hours on the hardware.

In short, it is possible to construct a cost profile for the life cycle of an engine. The data examined here are consistent with the general trend indicated regarding maturation and steady-state operation. This commercial cost profile of peak, steady-state, and average costs should be helpful in attempting to understand overall military life-cycle costs, which should behave similarly (at perhaps a higher cost level). The use of only cross-sectional data to estimate costs for a given engine can be misleading if the engine's relative position in its overall life cycle is not understood, and if the data are heavily weighted to the steady-state situation, when overall average costs are needed to determine overall life-cycle cost.

VI. ENGINE MONITORING SYSTEMS

How can operational data be obtained for users to understand day-to-day problems and costs, for military planners to obtain required data for engine life-cycle cost models, and for the engine designer to obtain the feedback necessary to improve current designs and future generations of engines? The use of engine monitoring systems has received increasing emphasis lately, with these objectives in mind. The experiences gained from several military and commercial aircraft turbine engine monitoring systems over the last decade and a half were examined in this light (see Ref. 4). Table 7 lists the six systems examined. They span the gamut of military and commercial, U.S. and British, and fighter and transport applications. The examination reveals that two different approaches to engine monitoring have evolved in attempts to achieve the varied goals of improved day-to-day engine operations, maintenance, and management, while reducing long-term support costs and providing feedback to engine designers. The first approach concentrated on the short-term day-to-day operations, maintenance, and management practices and was usually accomplished by recording in-flight data in a snapshot mode, i.e., a few seconds of data either at predefined performance windows or when certain engine operating limits are exceeded. The second approach focused on the long-term design-oriented cost reductions through improved knowledge of the engine operating environment. To achieve the design-oriented benefits, data must be recorded continuously on at least a few aircraft at each operational location for each type of mission.

U.S. monitoring systems have initially focused on short-term maintenance-oriented benefits, whereas the British initially developed a system that focused on long-term, design-oriented benefits. The benefits of each are listed in Fig. 15. From a life-cycle analysis viewpoint, it would seem that both types of benefits are worthy of consideration in any new monitoring system. Both countries are now moving in that direction.

In addition, ongoing engine duty-cycle research being conducted by the U.S. military services was also reviewed. This research demonstrates that neither the services nor the engine manufacturers have a clear idea of fighter aircraft engine operational usage--i.e., of power requirements and throttle transients on actual mission flight profiles. Figures 16 and 17 present one example for a U.S. Navy fighter, comparing the design power required cycle and actual mission power required cycles during operation. As a result of this lack of knowledge of the correct duty cycle, engine parts life has generally been overestimated and expected life-cycle costs have been understated. While this situation has improved during the past several years, further improvement is clearly needed. Expanded testing during an engine development program is one solution.

Much uncertainty exists about the benefits and costs (increases and reductions) attributable to engine monitoring systems. It is clear, however, that the narrow sense of cost savings over the short term should not be the sole criterion on which engine monitoring systems are judged. The potential benefits of anticipated maintenance, improving maintenance crews' understanding of problems as they arise, verifying that maintenance is properly performed, establishing relevant engine test cycles, and the effects of future engine design--all of which we are unable to quantify to date--have substantial value. This is especially so when the U.S. military services are moving to an on-condition maintenance posture as envisioned for the F100 and TF34 engines. Also, the modular design of the engine requires some type of sophisticated fault isolation as the engine matures if on-condition maintenance is to be applied at the engine component level.

The U.S. military continues to investigate and develop turbine engine monitoring systems for engines recently introduced into service and for future engines. The objectives of any new engine monitoring system should include the valuable contribution that

continuous recorded data can make to the engine designer over the long term. Of particular importance to new engine design and new applications of current engines is the correlation between testing and operational duty cycles. Engines with different applications will have quite different mission profiles and each application should be tested to its relevant duty cycles. Such information should help the services in maturing existing engines during component improvement programs, as well as in feedback to future engine design programs, especially now that reliability, durability, and cost issues are apparently on an equal footing with performance. Future aircraft turbine engine life-cycle analyses should benefit immeasurably from the availability of such information and detailed data.

CONCLUSIONS

This paper has presented the results of a study that described a methodology derived from historical data for life-cycle analysis of aircraft turbine engines. The methodology was applied at the engine subsystem and aircraft system levels to demonstrate the insights and information that could be obtained. The methodology enables the weapon-system planner to acquire early visibility of cost magnitudes, proportions, and trends associated with a new engine's life cycle, and to identify "drivers" that increase cost and can lower capability. The procedure followed was to develop a theoretical framework for each phase of the life cycle; collect and analyze data for each phase; develop parametric cost-estimating relationships (CERs) for each phase; use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and examine commercial experience for cost data and operational and maintenance practices.

The methodology was applied at the engine subsystem and aircraft system levels for a military fighter aircraft to demonstrate that decisions about engine performance/schedule/cost must be made at the system level. Commercial considerations were also discussed, as was some limited historical experience on engine monitoring--an approach to obtaining the necessary information and procedures for performance and cost feedback to the operational user, military planner, and engine designer.

The study was prompted by the steadily escalating costs of acquiring and owning turbine engines for both military and commercial users. Most of the causes are readily apparent. Demands for higher overall quality--meaning performance, primarily, for the military--have resulted in larger engines that produce greater thrust, run hotter, are costlier to maintain, and entail higher basic engine prices. Material costs associated with engine price have also risen rapidly in the recent past; over the long term, however, labor costs, primarily in the manufacturing sector, have risen proportionately more so.

The chief problem confronting this study, as it has confronted past researchers, was the lack of disaggregated, homogeneous, longitudinal ownership data that are specific to particular engine types, notably at the base and depot level. The collection of such data will be necessary for perfecting the methodology, which weapon-system planners can then use to calculate the costs and benefits of a proposed engine for a new aircraft in the early stages of planning and selection.

For a new military engine (acquired and owned under conditions similar to those of previous engines constituting the data base) that will have an operational lifespan of 15 years, the findings indicate that:

o   Engine ownership costs are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, can exceed engine acquisition costs. This finding is true for current fighter and transport engines.

o   Depot costs alone can exceed procurement costs.

o   Component improvement programs (CIP) conducted during the operational life of an engine can cost as much as it did to develop the engine to its initial model qualification.

o   If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost. This is true for current supersonic fighter and subsonic transport/bomber engines.

o   Satisfying results, in terms of statistical quality, theoretical behavior, and experience from past programs, were obtained from modeling performance/schedule/cost relationships for the development and production of military engines; mixed but promising results were obtained in modeling ownership costs for military engines.

o   Application of the models derived in this study indicates that there is a continuing trend toward higher ownership costs, measured in both absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the primary reason for this trend. The production cost of the engine (and its parts) is a contributor to depot and base support costs, but so are ownership policies.

o The engine maturation process must be more fully understood if improved analytical results are to be obtained and applied to new engine selection. It takes an engine a long time to mature (commercial experience indicates five to seven years). Consequently, average ownership costs are significantly higher during that period than mature engine steady-state costs in terms of dollars per flying hour, the yardstick most commonly used. It is believed that engine monitoring systems will assist in providing designers with the necessary information in the future.

o Finally, and most importantly, the selection of engine design parameters and the appropriate engine technology level and performance/reliability criteria must be made at the aircraft system level.

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TABLE 1

Classification of Life-Cycle Costs

Cost Element	Acquisition	Ownership	Weapon-System-Related
RDT&E	X		
Flight test	X		
Tooling	X		
Proc. of install engine	X		
CIP		X	
Spare engine		X	
Spare parts (base/depot)		X	
Depot labor		X	
Base labor		X	
ECPs—mod/retro	X	X	
AGE (peculiar/common)	X	X	
Transportation	X	X	
Management	X	X	
Facilities	X	X	
Training	X	X	
Engine attrition			X
Fuel			X

TABLE 2

Synopsis of Aircraft Turbine Engine Developments

Early 1940s (WW II)	Late 1940s	Early 1950s (Korean War)	Late 1950s	Early 1960s	Late 1960s (Vietnam)	Early 1970s
Engine Types						
Turbojet	Turbojet	Turbojet, turboprop/ turboshaft	Turbojet, turboprop/ turboshaft	Turbojet, turboprop/ turboshaft, turbofan	Turbojet turboprop/ turboshaft, turbofan	Turbojet, turboprop/ turboshaft, turbofan
Trends in Engineering Development						
Increased thrust	Augmentation	High pressure ratio, variable stators	Cooled turbine	Supersonic turbofan	High-bypass turbofan (military and commercial)	High thrust/weight
Centrifugal to axial compressor	Two-position nozzle		Mach 3	Multidesign point mission		High component performance
Single-design point mission	Stainless steel, aluminum, conventional steel	Titanium begins to replace aluminum	Small lightweight engines	Superalloy materials	High-temperature turbine	High-temperature materials
Limited use of high-temperature steels; primarily conventional steels	Higher pressure ratio, dual rotor	Sustained supersonic flight	Commercial turbojet	Lightweig't design	Cooling techniques	Cooling techniques
		Small helicopter engines	Subsonic turbofan	Component improvements	3-spool rotor	Composite materials
		Reliability/ durability	Titanium and superalloy material improvements	Commercial turbofan	Compatibility/ integration	
		Moderately higher turbine temperature	Transonic compressor		Increasing sophistication of development	
					Commercial technology and requirements becoming as advanced as military	
Companies						
General Electric Westinghouse	Allison Boeing Curtiss Wright Fairchild General Electric Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney	Allison Boeing Continental Curtiss Wright Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney

TABLE 3

Dates of Development Initiation for the US Aircraft Turbine Engine Data Base

Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s
J30 W	J40 W	J52 PW	J58 PW		TF34 GE
J31 GE	J42 PW	J65 CW	J60 PW		TF39 GE
J33 GE/A	J46 W	J69 C	J85 GE		TF41 A
J34 W	J47 GE	J75 PW	TF30 PW		
J35 GE/A	J48 PW	J79 GE	TF33 PW		
	J57 PW				
	J71 A				
	J73 GE				

NOTE: W = Westinghouse; GE = General Electric; A = Allison; PW = Pratt & Whitney; C = Continental; CW = Curtiss Wright.

TABLE 4

Technical Data for US Military Aircraft Turbine Engines

Engine	Turbine Inlet Temp. ($^\circ$R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft^2)	Specific Fuel Consumption (lb/hr/lb)	Mach No.	Max. Dia. (in.)	Length (in.)	MQT (qtr)
J30	1830	1560	686	1575	1.17	0.9	19.0	94	17
J31	1930	1600	850	1710	1.25	0.9	41.5	72	11
J33	1960	3825	1875	3400	1.22	1.0	50.5	103	19
J34	1895	3250	1200	3400	1.06	1.0	27.0	120	27
J35	2010	4000	2300	3400	1.08	1.0	40.0	168	21
J40	1985	10900	3580	5750	1.08	1.8	41.0	287	45
J42	1825	5000	1729	3640	1.25	1.0	49.5	103	25
J46	1985	6100	1863	6625	1.01	1.8	29.0	192	44
J47	2060	4850	2475	5375	1.10	1.0	37.0	144	26
J48	2030	6250	2040	4880	1.14	1.0	50.0	107	33
J52	2060	8500	2050	12840	0.82	1.8	31.5	150	74
J57	2060	10000	4160	11400	0.80	1.4	41.0	158	41
J58	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	87
J60	2060	3000	460	10360	0.96	1.0	24.0	80	71
J65	2030	7220	2815	8500	0.92	1.8	38.0	127	46
J69	1985	920	333	3400	1.12	1.0	22.0	44	56
J71	2160	9570	4090	11000	0.88	1.5	40.0	195	47
J73	2060	8920	3825	8750	0.92	1.9	37.0	147	49
J75	2060	23500	5950	16724	0.80	2.0	43.0	259	59
J79	2160	15000	3225	18056	0.87	2.0	37.5	208	57
J85	2100	3850	570	10360	1.03	2.0	20.0	109	74
TF30	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	92
TF33	2060	17000	3900	19240	0.52	1.0	53.0	136	71
TF34	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	120
TF39	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	109
TF41	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	107

[a]Deleted for security or proprietary reasons.

TABLE 5

Technology Data for Commercial US Turbine Engines

Engine	Turbine Inlet Temp. (°R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft²)	SFC (lb/hr/lb)	MQT (qtr)	Period of Development Initiation
JT3C	1995	13,500	4234	11,050	0.78	59	Late 1950s
JT4A	1995	15,800	5020	10,200	0.80	59	Late 1950s
JT3D	1995	17,000	4150	11,050	0.52	71	Late 1950s
JT8D	2180	14,000	3160	13,600	0.59	81	Late 1950s
JT12	2000	2,700	465	5,525	0.96	71	Late 1950s
CJ805-3	2100	11,200	2800	11,050	0.83	71	Late 1950s
CJ805-23	2100	16,100	3800	11,050	0.56	77	Late 1950s
CJ610	2060	2,850	399	5,780	0.99	82	Early 1960s
CF700	2100	4,125	725	5,525	0.65	87	Early 1960s
JT9D	(a)	(a)	(a)	(a)	(a)	107	Late 1960s
CF6	(a)	(a)	(a)	(a)	(a)	112	Late 1960s

[a]Deleted for security or proprietary considerations.

TABLE 6

Military Life-Cycle Analysis
(In 1975 dollars)

State-of-Art Trend
$R^2 = .96$
$SE = 6.9$
$F = 92.0 \ (5, 20)$

$$TOA26 = -856.38 + 110.10 \ln TEMP + 11.41 \ln TOTPRS - 26.08 \ln WGT - 16.02 \ln SFCMIL$$
$$(5.8)^a \qquad (3.1) \qquad (5.1) \qquad (2.8)$$
$$+ 18.37 \ln THRMAX$$
$$(2.8)$$

Development Cost ($M)
$R^2 = .96$
$SE = .18$
$F = 55.7 \ (4, 9)$

$$\ln DMQTC = -1.3098 + 0.08538 DEVTIME + 0.49630 \ln THRMAX + 0.04099 \triangle TOA26 + 0.41368 \ln MACH$$
$$(7.6) \qquad (7.1) \qquad (4.9) \qquad (2.3)$$

Component Improvement Cost ($M):
$R^2 = .88$
$SE = .29$
$F = 60.5 \ (3, 22)$

$$\ln CIP = -2.79026 + 0.78862 \ln THRMAX + 0.04312 \triangle TOA26 + 0.00722 OPSPAN$$
$$(9.1) \qquad (5.7) \qquad (2.5)$$

Total Development Cost ($M)
$R^2 = .94$
$SE = .18$
$F = 114.8 \ (4,29)$

$$\ln TDC = 0.97355 + 1.23809 \ln MACH + 0.07345 \ln QTY + 0.40386 \ln THRMAX + 0.00918 \triangle TOA26$$
$$(10.3) \qquad (6.8) \qquad (8.5) \qquad (2.1)$$

1000th Unit Cost ($M)
$R^2 = .95$
$SE = .215$
$F = 63.0 \ (4,13)$

$$\ln KPUSP = -8.2070 + 0.70532 \ln THRMAX + 0.00674 TOA26 + 0.45710 \ln MACH + 0.01804 \triangle TOA26$$
$$(9.2) \qquad (2.8) \qquad (2.6) \qquad (2.4)$$

Cumulative Production Quantity Cost ($M)
$R^2 = .97$
$SE = .22$
$F = 501.7 \ (6, 81)$

$$\ln PRQTYC = -7.8504 + 0.8697 \ln QTY + 0.82204 \ln THRMAX + MFRDUM + 0.01858 \triangle TOA26$$
$$(45.) \qquad (24.) \qquad (6.) \qquad (5.)$$
$$+ .34478 \ln MACH + 0.00277 TOA26$$
$$(4.) \qquad (2.4)$$

Depot Maintenance Cost Per Engine Flying Hour Restored ($/EFHR)
$R^2 = .97$
$SE = .22$
$F = 67.6 \ (4, 7)$

$$\ln DCEFHR = 2.76182 - 0.90604 \ln ATBO + 1.26074 \ln CPUSP + 0.01104 OPSPAN - 0.02245 \triangle TOA26$$
$$(10.2) \qquad (4.2) \qquad (2.2) \qquad (1.9)$$

Base Maintenance Cost Per Engine Flying Hour Consumed ($/EFHC)
$R^2 = .79$
$SE = .26$
$F = 10.0 \ (3,8)$

$$\ln BMCEFHC = 3.50819 - 0.47457 \ln MTBO + 0.01299 OPSPAN + 0.56739 \ln CPUSP$$
$$(4.5) \qquad (2.2) \qquad (1.6)$$

TABLE 7

Engine Monitoring Case Studies

System	Application (Engine/Aircraft)	Time Period
Time-Temperature Recorder	J57/F100D	1967-1969
Engine Health Monitoring System	J85/T-38A	1973-1977
Malfunction Detection Analysis Recording System	TF39/C-5A	1969-Present
In-Flight Engine Condition Monitoring System	TF41/A-7E	1973-Present
Airborne Integrated Data System	Commercial	1969-Present
Engine Usage Monitoring System	British Aircraft	Early 1970s-Present
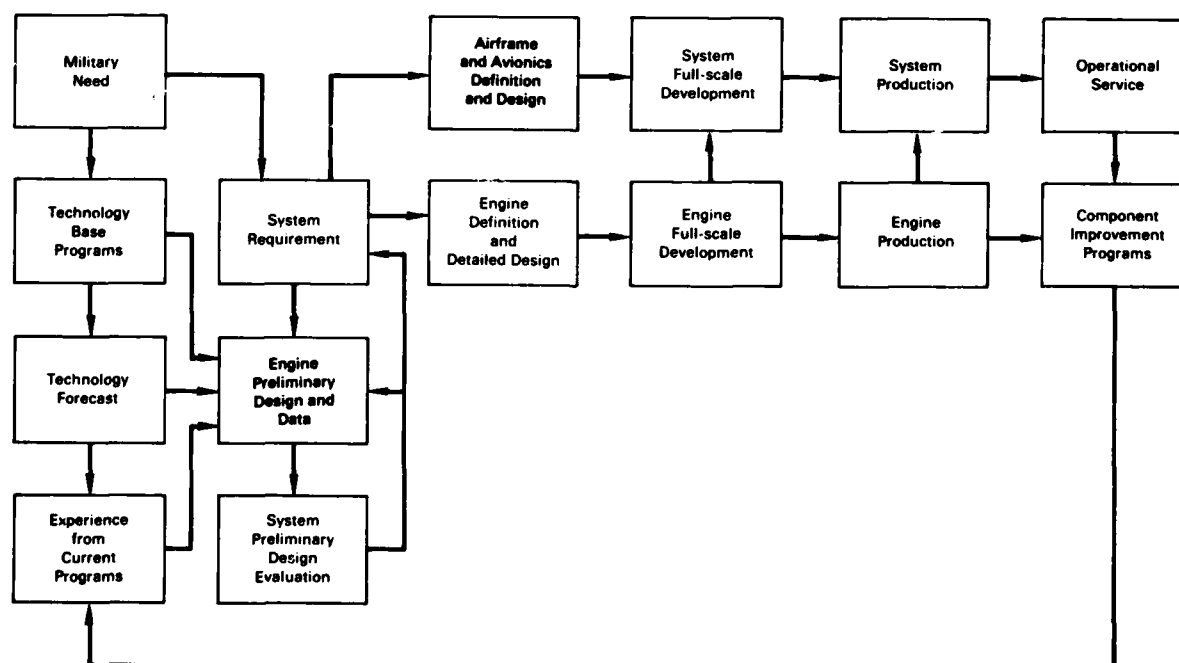
Fig.1   Aircraft turbine engine design and development process
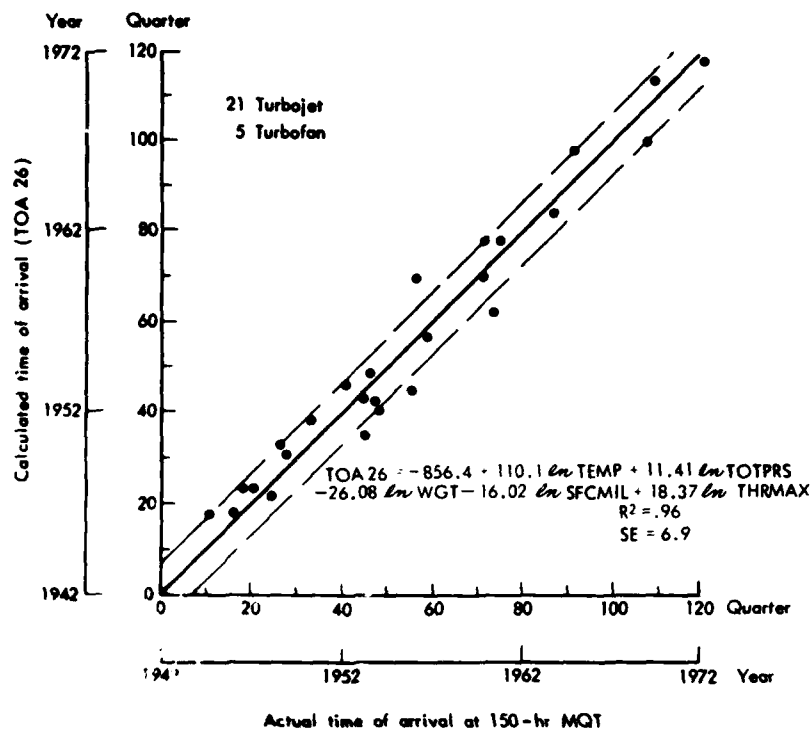
Fig.2 Military turbine engine time of arrival
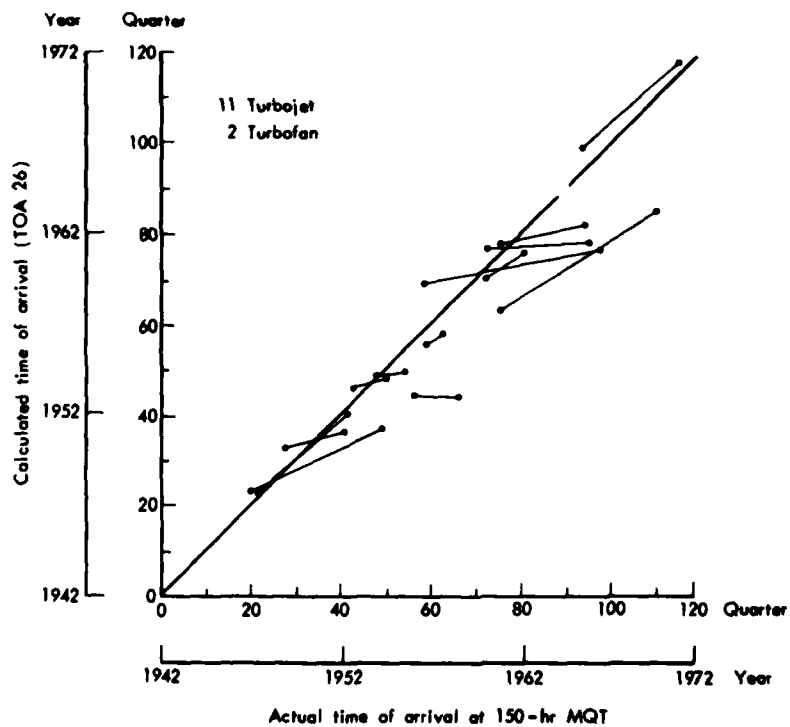

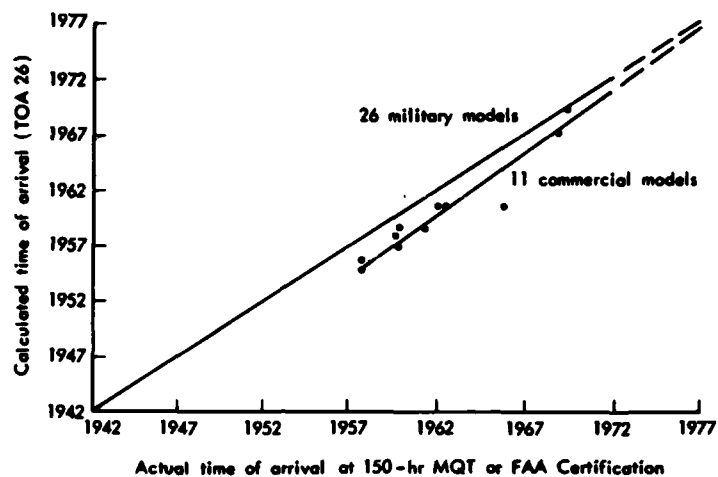Fig.3 Military growth engine time of arrival

Fig.4   Comparison of military and commercial aircraft
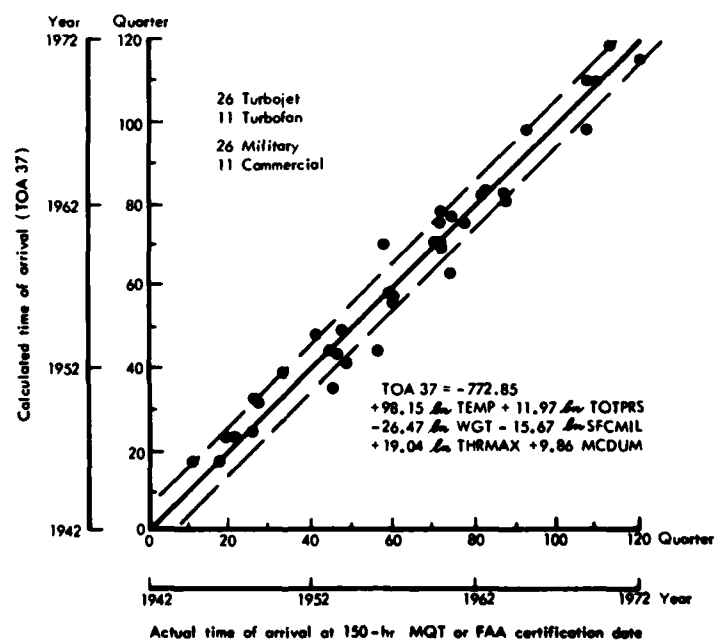turbine engine time of arrival

Fig.5   Military and commercial turbine engine time of arrival

2-22

HYPOTHETICAL PROGRAM: 1975 DOLLARS

5 YEAR DEVELOPMENT (ADVANCED ENGINES)

15 YEAR OPERATIONAL SPAN

6 MILLION ENGINE FLYING HOURS CONSUMED (OPERATIONAL)

5 MILLION ENGINE FLYING HOURS RESTORED (DEPOT REPAIR)

1935 ENGINES

90% LEARNING (PRODUCTION)

750/1200 ATBO/MTBO

NO FUEL OR ATTRITION INCLUDED

Fig.6   A life-cycle cost example (fighter engines: 1950s/1960s/1970s
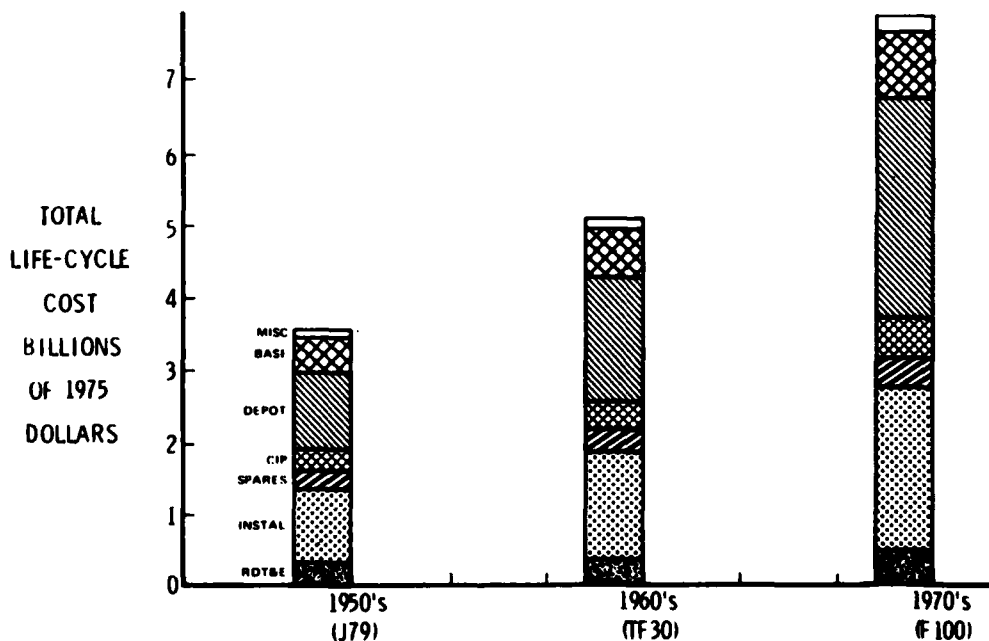(J79) (TF30) (F100))

Fig.7   Life-cycle cost trend example (advanced engines: growth thrust, MACH)
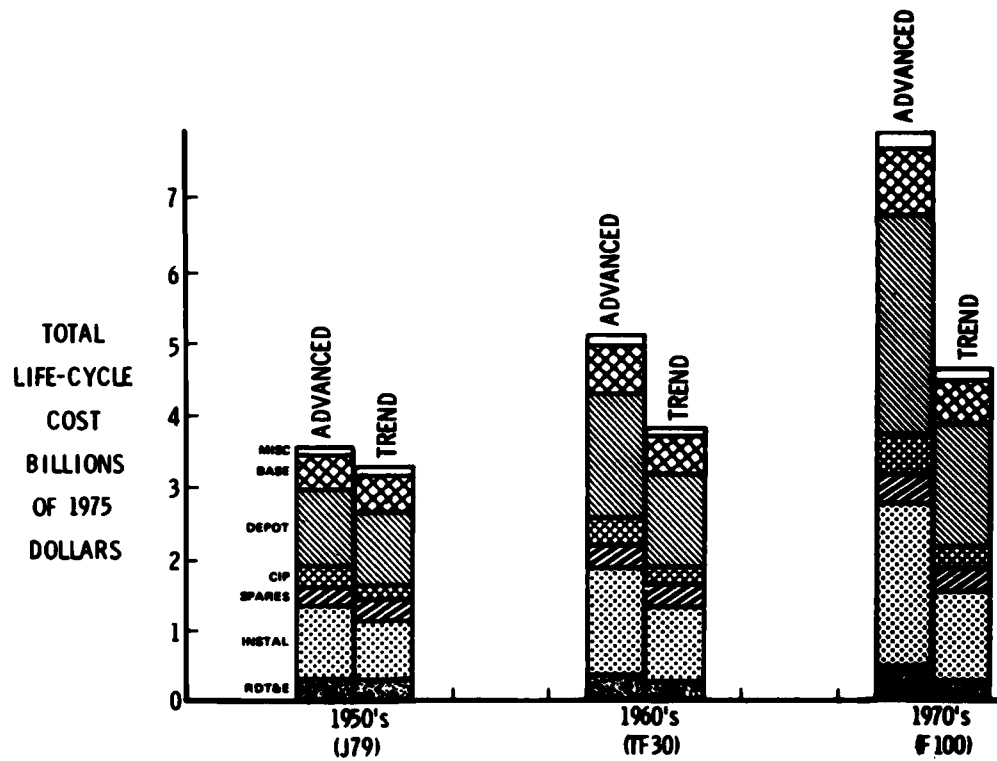
Fig.8   Life-cycle cost trend example (advanced engines: growth thrust, MACH;
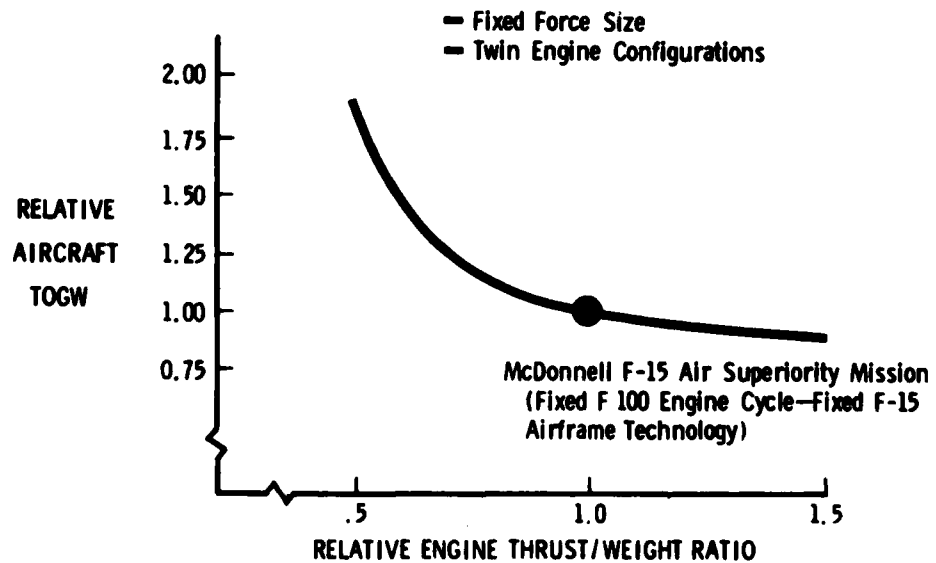TOA trend engines: constant thrust, MACH)

Fig.9   Mission requirement impact on aircraft takeoff – gross weight and
engine thrust/weight tradeoff

ENGINE

- 1975 DOLLARS
- 5 YEAR DEVELOPMENT
- 15 YEAR OPERATIONAL SPAN
- 6 MILLION ENGINE FLYING HOURS CONSUMED (OPERATIONAL)
- 5 MILLION ENGINE FLYING HOURS RESTORED (DEPOT REPAIR)
- 1935 ENGINES PROCURED
- 90% LEARNING (PRODUCTION)
- 750/1200 HRS ATBO/MTBO

FUEL

- F15/F100 — 1250 GAL/FH @ 44¢/GAL WITH FUEL
  CONSUMPTION SCALED TO THRUST
- ATF/F100 — 1100 GAL/FH @ 44¢/GAL WITH 10%
  SFC IMPROVEMENT FOR ADVANCED ENGINE

AIRFRAME

- 1975 DOLLARS
- 729 AIRFRAMES PROCURED
- RDT&E AND PROCUREMENT ONLY
- FIXED AIRFRAME TECHNOLOGY
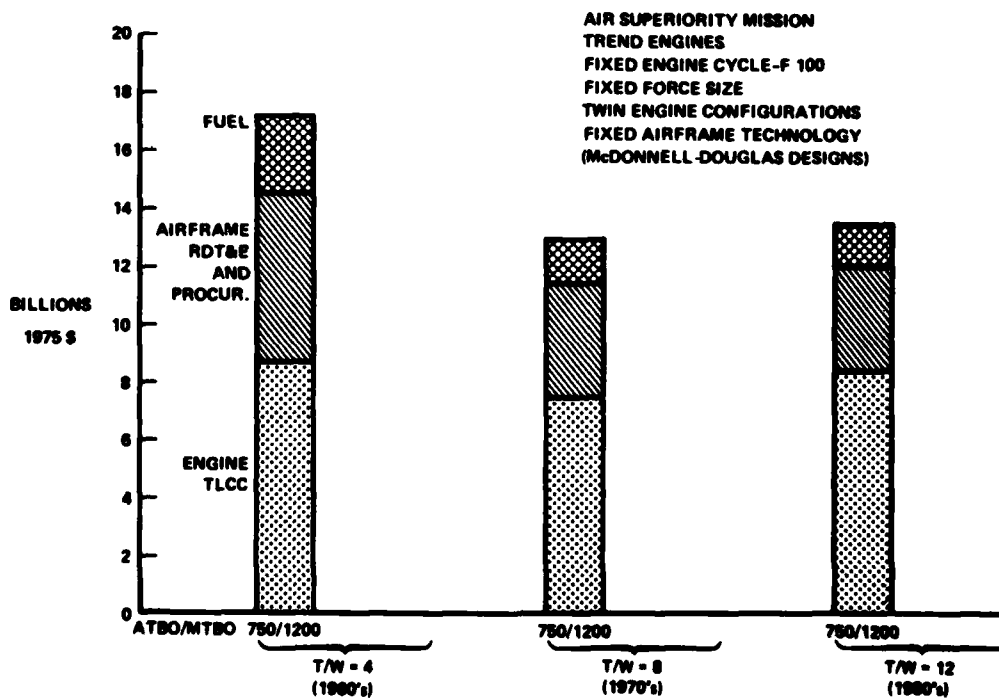
Fig.10   Hypothetical baseline program

Fig.11   System-level cost differences with engine thrust/weight variations
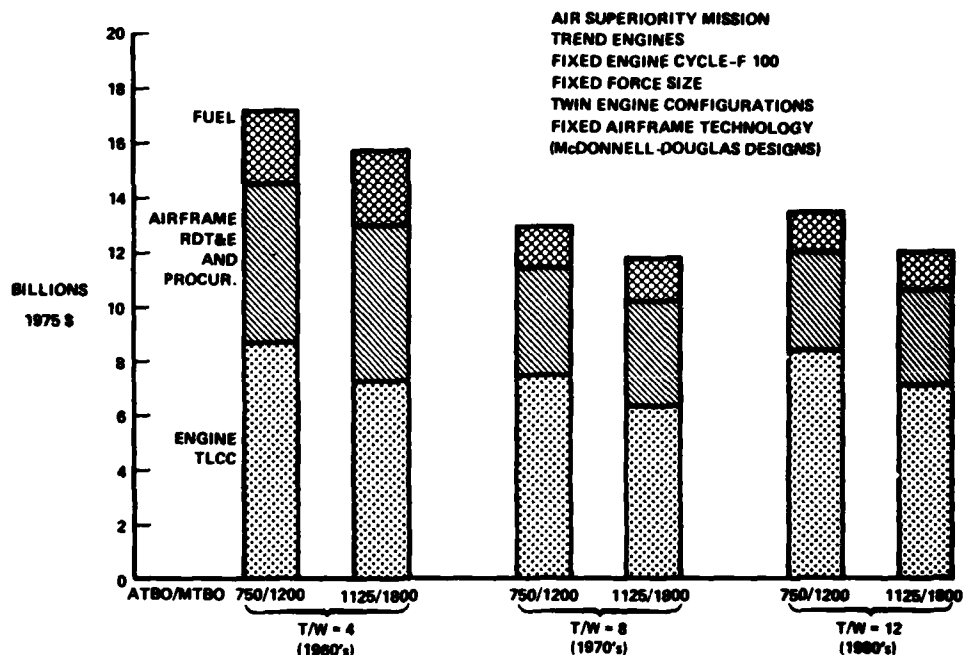
Fig. 12   System-level cost differences with engine thrust/weight
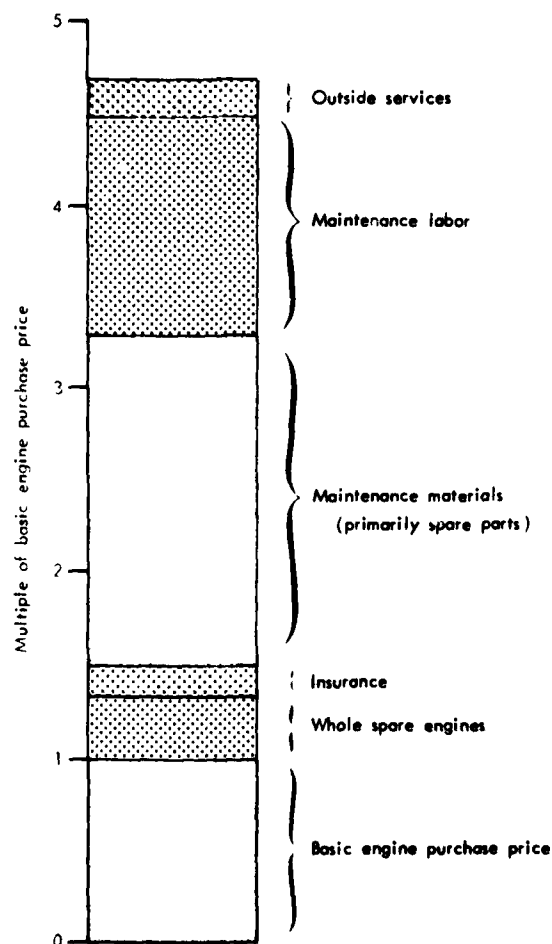and depot repair variations

Fig. 13   Typical 14-year life-cycle costs for first — and second-generation
commercial turbojet and turbofan engines
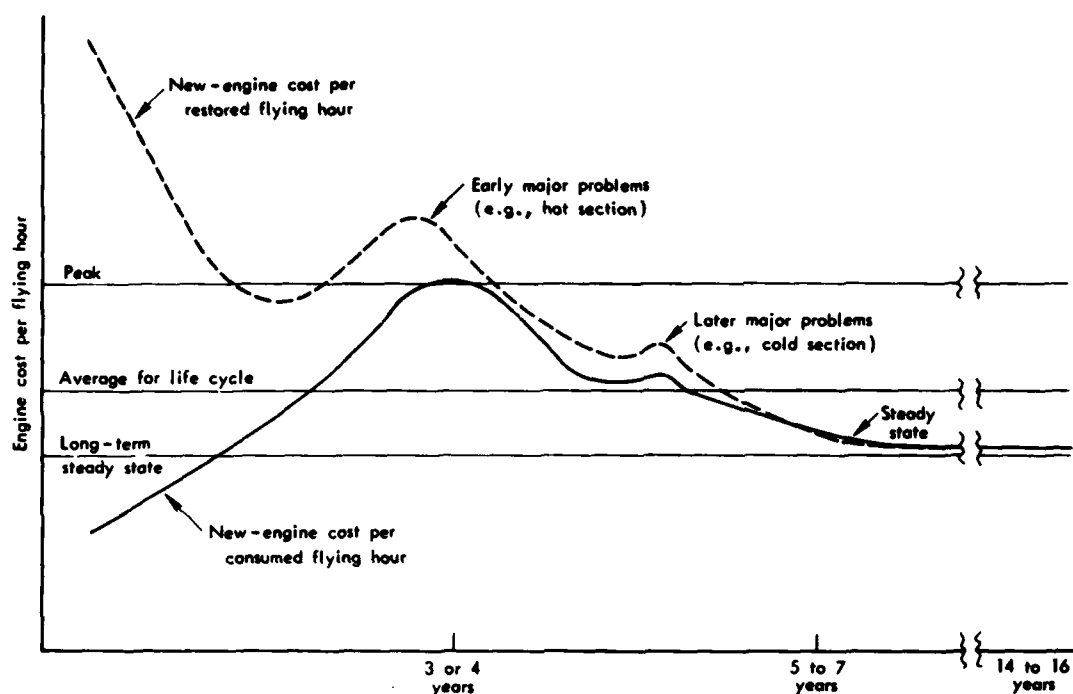
Fig.14   Cost profile for commercial turbine engines

MAINTENANCE ORIENTED

● OPERATIONAL

    ━ AWARE OF ENGINE HEALTH
    ━ AWARE OF ENGINE OVERTEMPERATURES

● MAINTENANCE

  √ ━ LESS MAINTENANCE MANPOWER
  √ ━ LESS TROUBLESHOOTING & TRIM FUEL
  √ ━ LESS ENGINE REMOVALS
  √ ━ LESS PARTS CONSUMPTION
    ━ ANTICIPATE MAINTENANCE (TRENDING)
    ━ IMPROVE CAUSE & EFFECT UNDERSTANDING
    ━ VALIDATE MAINTENANCE ACTION

● MANAGEMENT

  √ ━ MODIFY TBO
    ━ PROVIDE CONFIGURATION CONTROL

DESIGN ORIENTED

    ━ GUIDE CIP
    ━ CORRELATE TEST/DUTY CYCLES
    ━ AID FUTURE ENGINE DESIGN

Fig.15   Summary of engine monitoring systems outcomes
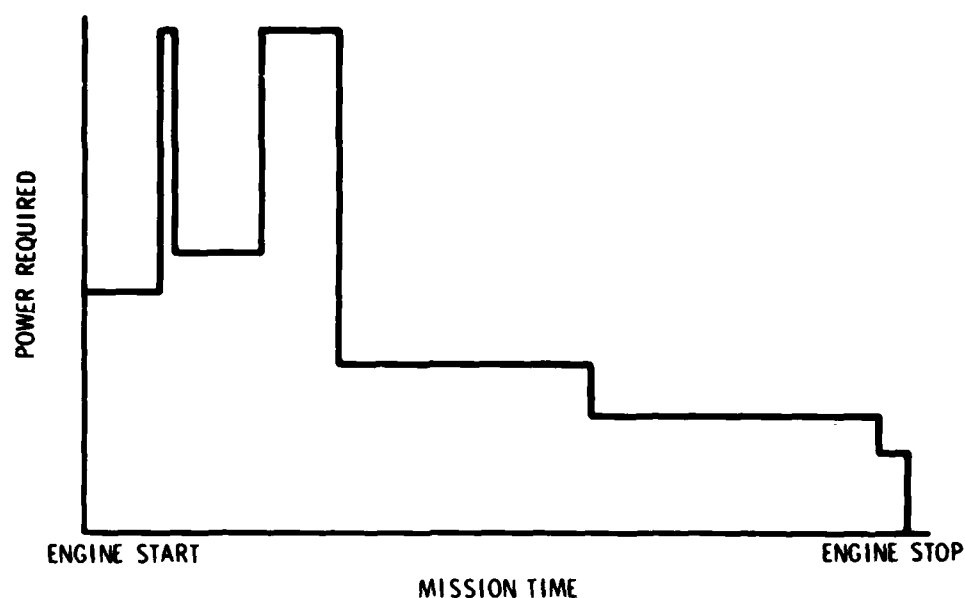
Fig.16   F-14 proposed power required profile

- RFP
- FLIGHT TEST DATA

IMPACT ON ENGINE COMPONENT LIVES

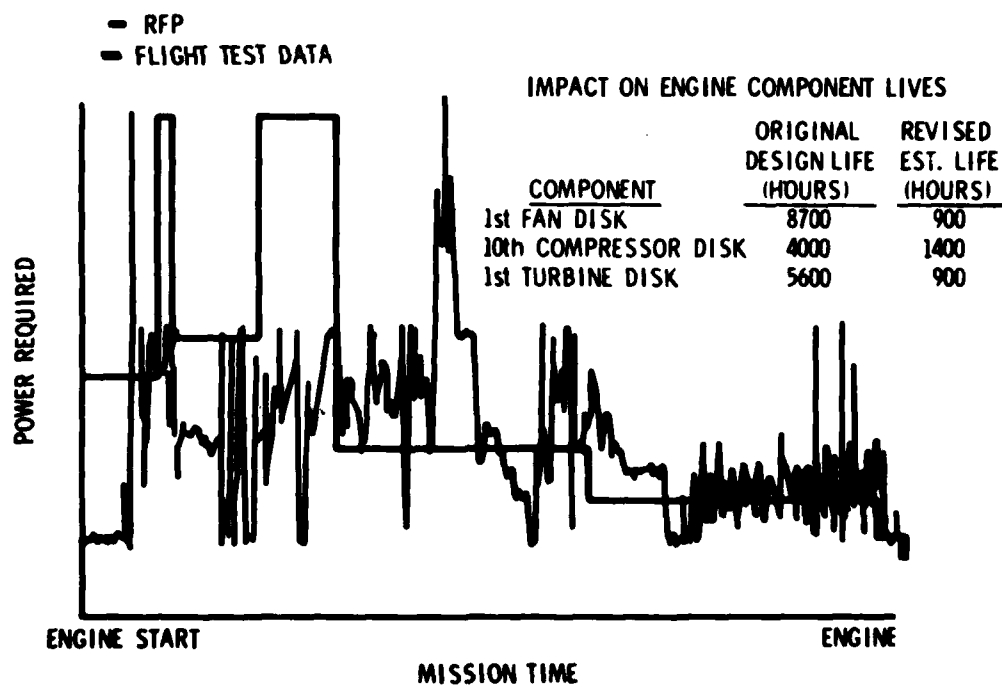| COMPONENT	ORIGINAL DESIGN LIFE (HOURS)	REVISED EST. LIFE (HOURS)
1st FAN DISK	8700	900
10th COMPRESSOR DISK	4000	1400
1st TURBINE DISK	5600	900

Fig.17   F-14 actual power required profile

Source of Figures 16 and 17 is Ref.5

DESIGN TO LIFE CYCLE COSTS

INTERACTION OF ENGINE AND AIRCRAFT

by

E J JONES

United Kingdom   Ministry of Defence

SUMMARY

The distribution of Life Cycle Costs for a typical combat aircraft between airframe, avionics and engine is discussed. The distribution of Life Cycle Cost for the aircraft between development, production, initial support and operation and support is compared with the distribution for the engine. The effect of fleet size and service life upon the Life Cycle Costs are indicated. The large commitment of Life Cycle Costs early in the conceptual and feasibility phase of the programme is indicated. The choice of engine is an example of this early commitment. The relative effect of the choice of single or twin engine installation, of a de-rated engine or the use of an existing engine upon the engine Life Cycle Costs and the interaction with aircraft costs is discussed. The severe operating conditions for the engine of a combat aircraft are reviewed. Reduced support costs are not expected to give a large-fold return on extra engine development investment.

DESIGN TO LIFE CYCLE COSTS

INTERACTION OF ENGINE AND AIRCRAFT

INTRODUCTION

1. The particular aspect of the Design to Life Cycle Costs (DTLCC) which is discussed is the interaction and contribution of the engine to aircraft Life Cycle Costs (LCC). This needs to be explored before an optimum decision and programme for DTLCC for the entire aircraft may be made. There is an implicit assumption that the criterion for deciding the optimum may be defined and agreed; that is perhaps not least of the problems. Design to Cost (DTC) and more recently peacetime Design to Life Cycle Cost (DTLCC) have engendered a great deal of enthusiasm, but the criterion for DTLCC is by no means clear, apart from the obvious desire to have aircraft better in all respects at lower costs. Better reliability is sought but it is not clear whether this is to reduce operating and support costs or to reduce LCC or for the quite different benefits of improved aircraft availability.

LIFE CYCLE COSTS

2. Predictions of LCC are of great value, if not essential, for various trades off of different design features to be assessed, and this may be the greatest importance of DTLCC.

3. For analysis of the Life Cycle Cost of an aircraft it is convenient to consider the main technology sub-systems of Airframe including hydraulic and electro-mechanical equipment, Avionics and Engine. It is also instructive to consider the LCC for the various programme phases of the project, ie

    Development including definition
    Production Acquisition
    In Service Support - Initial and ongoing - and operation.

In the discussion UK terminology - perhaps it is jargon - is used, but the terms are broad and sufficiently general for my argument without the need for detailed definition. All the avionics or engine costs for the flight development programme are ascribed to those sub-systems.

4. For some purposes the distinction is made between the front end investment or non-recurring costs which include development, production and initial support, and the recurring operating and support costs.

5. At an early stage of a programme development and production costs may be predicted with some confidence but there is much less experience and less confidence in the ability to predict operating and support costs. Nevertheless LCC are required and should be considered from the earliest phases to assist formulation of the concept and configuration of the aircraft; indeed for rational decision whether a new design is required or whether an existing design should be adapted or even whether available aircraft should be modified, upgraded or retro-fitted to satisfy the staff target or requirement the prediction of LCC at an early phase is essential.

DISTRIBUTION OF LCC

6. Various distributions of LCC have been put forward. To illustrate the engine contribution to and the interaction with the complete aircraft LCC, a distribution appropriate to a combat aircraft is discussed. Consider a combat aircraft with development of a new engine and avionics system as well as airframe. For such a single seat, twin engine aircraft the peacetime LCC for a modest buy of about 300 aircraft and operation over 15 years might be distributed between airframe and equipment, engines and avionics as indicated in Figure 1. Some items of LCC do obviously fall into these three areas of cost; eg fuel costs but for this indication fuel is included with engine costs, and operating costs which are here shown with the airframe. The airframe and associated sub-systems - hydraulic, electro-mechanical, pneumatic etc amount to about 40%, and the avionics and engine each amount to about 30%.

7. The effect of fleet size and years in service are illustrated in Figure 2. A difference of five years in operations increases or reduces the LCC by about 20%. Doubling the fleet increases the LCC by about two-thirds, but halving the fleet reduces the LCC by about one-third. To a first approximation the effect of annual flying rate and years in service are interchangeable, as the total flying hours are the more significant effect on LCC.

8. The distribution of the datum programme aircraft LCC between development, production and operation and support is in Figure 3. Approximately half the LCC is for operation and support of the fleet over 15 years, whereas development is about 20% and production is less than a third; the investment is less than two-thirds. The distribution of LCC between these phases of the total programme depends upon the size of the fleet, the service peacetime life and the amount of annual flying.

9. The distribution of the engine LCC into development, production, initial support - including uninstalled reserve engines and modules - and operating and support costs - excluding fuel - is indicated in Figure 4. Compared with the distribution for the complete aircraft, Figure 1, the development sector at 40% is twice the proportion for the complete aircraft, but the support sector without fuel but including initial support is substantially lower for the engine than for the complete aircraft. The production sector for the engine is somewhat less than for the complete aircraft, although the initial investment sector-consisting of development, production and Initial Support - for the engine is greater than for the complete aircraft.

DESIGN TO LIFE CYCLE COSTS

10. The opportunity for DTLCC to influence the LCC at each phase of the programme is limited by the proportion of the LCC committed in earlier phases. Figure 5 is familiar and indicates how the commitment of LCC increase quickly in the early concept, feasibility and project definition phases of the programme. The particular importance of Figure 5 is to emphasise the high proportion of LCC which is committed by the end of the conceptual and definition phase of the programme. This is when the main characteristics of the aircraft and weapons systems are decided - the technology, the aircraft size and performance, the avionics fit and the engine size and type. DTLCC techniques, technical and managerial skills are essential to design, develop and manufacture the aircraft system and subsequently equally high skills are needed to maintain, operate and support the aircraft in service.

11. To illustrate the importance of the conceptual phase three aspects with respect to the engine choice and interaction with the aircraft LCC will be considered. Firstly the effect of a single or twin engine installation, secondly the effect of de-rating the engine performance standard as a means to reduce engine support costs, and the probable effect upon engine and aircraft LCC and thirdly the attractive one of designing the aircraft around a suitable existing engine.

SINGLE v TWIN ENGINED AIRCRAFT

12. The decision for a single or twin engine installation is invariably made at the conceptual phase of a project. Such a decision is of significance for the various phases of the LCC.

13. Studies indicate that the aircraft weight and total thrust requirements are relatively unchanged for a single or twin installation of the same technology engine. Thus any difference in engine LCC for the single or twin engine installation is the dominant effect on the aircraft LCC. Compared with the engine LCC for the twin engine installation indicated in Figure 4, the engine LCC for a single engine of the same total thrust is indicated in Figure 6. A comparison of the distribution of LCC between the various phases of the programme for the twin and single engine installations is interesting. Development for the larger single engine is more than for the smaller twin engine. This is offset by the lower production and support costs for the fewer larger single engines. The LCC for the single engine installation in Figure 6 is expressed in terms of the LCC of the twin engine in Figure 4. Development of the single engine is higher by about 20%, but the production and support are about 25% lower; the investment costs are virtually unchanged. Overall the LCC of the single engine is about 8% less than for the twin. Any difference in peacetime loss rates for single and twin engined aircraft have to be included in a comparison for total aircraft LCC.

DE-RATED ENGINES

14. The reliability of engines in operation could be improved and support costs reduced, if engines were de-rated to operate below the design thrust, operating temperature and engine speed. To restore the aircraft performance with the de-rated engines of lower engine thrust to weight ratio, a bigger and heavier engine is needed which drives up the aircraft size and weight, which in consequence needs a still bigger engine. The 'snowball' effect of the lower thrust to weight ratio limits this technique severely. Briefly an engine de-rated 5% would require an aircraft and engine increased in weight and thrust about 10% while an engine de-rated 10% would require an aircraft and engine increased about 25%. Beyond an engine de-rating of 10% it is unlikely that the aircraft performance could be wholly restored.

15. It is convenient to express the de-rated engine cost in terms of the datum engine LCC. De-rating improves the reliability but increases the unit and development costs. The combined effect on the engine LCC is indicated in Figure 7.

The support costs might be up to 20% less depending on the extent of the de-rating. The unit production and development costs would be some 5 to 10% more than for the datum engine depending on the extent of the de-rating. For a 5% de-rating the LCC might be about 3% less than for the datum engine, although the investment would be somewhat increased. For a 10% de-rating no reduction of LCC is predicted.

16. The effect of de-rating the engine upon the aircraft LCC must be considered. The de-rated engines have been sized on the assumption that the aircraft size would be increased to restore the aircraft performance. Thus for a 5% de-rated engine the reduced engine LCC would be just about offset by the higher LCC of the heavier airframe, so that there would be no reduction of the aircraft LCC, although the aircraft investment would be slightly higher. For an engine de-rated by 10% there is no reduction of engine LCC to offset the higher LCC of the heavier airframe, so that the aircraft LCC would be increased by about 5%.

EXISTING ENGINE

17. The use of an existing engine could save up to 90% of the engine development costs (flight development engines would still need to be supplied and supported) and use of a mature engine would reduce the support costs. The engine life cycle cost might therefore be reduced by up to about 40%, and the aircraft life cycle costs by about 10 to 15% if the existing engine characteristics had no adverse effects upon the aircraft design. Generally the use of an existing engine for a new aircraft would cause some compromise of design which would reduce effectiveness or increase LCC.

ENGINE SERVICE BEHAVIOUR

18. Going from the conceptual phase to the Service operating phase, it is interesting to consider the behaviour of the engine in service, the importance of engine lifing studies, and the way in which the results from these studies should eventually reduce engine support costs. When an engine enters service, it has an authorised life – the length of time for which it may operate without a major overhaul. This authorised life is increased as experience of its behaviour is acquired and modifications are introduced. Figure 8 indicates the increase of authorised life with time in Service for three non-modular engines. Actual achieved lives may be expressed as the average flight hours between the return of engines to maintenance unit (depot) or industry for major repair or overhaul. Figure 9 indicates that average achieved life for the same three engines varies with the time in service. These average achieved lives appear to be between 40% and 30% of authorised lives, but there are many factors which affect this reduction. For example a significant number of engines will be returned because of foreign object damage (FOD); some engines will be repaired and refitted to aircraft with only a proportion of authorised life remaining; and many engines returned for repair or reconditioning are at a lower modification state with shorter authorised lives than those current at the repair date. Nevertheless the figure indicates that achieved lives increase during the early years of service flying, and there would be significant reductions in support costs if authorised lives were higher at entry into service and the in-service growth of achieved life could be accelerated. The concepts of modular engines and on condition monitoring are changing the relationship but in principle the effect will continue.

19. The continued demand for performance at low engine weight – which has been seen to be desirable overall – means that engines are generally pushing technology limits. The problem is aggravated by a shortage of reliable data on the ways in which engines are used in actual service.

20. Figure 10 indicates somewhat naively how the aircraft height and speed might be expected to vary during a flight of about 1 hour. The aircraft takes off and climbs to about 18000 ft and then goes through a series of climbs to 30,000 ft plus and dives, followed by descent, approach and landing. The speed builds up to 450 knots during the initial climb, drops during the further climb, goes up to about 600 knots during dives, lands and taxies to a stop.

21. The record of actual events is much more complex, Figure 11. Although the idealised altitude profile was a reasoned approximation to the profile flown, the speed varied very frequently and rapidly during the flight. Figure 12 indicates how the engine is subjected to temperature and speed variation during the same sortie. There are at least twelve rapid changes of over 200°C in turbine gas temperature, while there are continual small changes in low pressure shaft speeds, and a significant number in excess of 50%. These are only examples drawn from one mission. Experience is that there are wide differences between missions. There is also some evidence of a significant increase in the severity of use of the wing man's engine in the same mission. The study and analysis of the use of engines in combat missions is aimed at building up statistical representation of temperature, shaft speed and other variations in flight.

22. This data can then be used as a basis for engine design and qualification specifications and applied to engine testing in the development phase, both bench and flight testing, so that the standard of an engine at entry into service may be enhanced, and the growth of achieved engine life in subsequent service accelerated. It is important to emphasise that both bench testing and flight testing is envisaged. Currently most bench engine test and qualification schedules such as SMET and AMT in US and sortie pattern testing in UK aim to simulate operational conditions. Bench testing in the absence of flight testing is of limited benefit; indeed experimental flight testing itself is of limited benefit. Some problems only arise in real life situations. This is the peactime mission flown by service crews in service conditions. The underlying principle here is that development is essentially a process of identifying, solving, demonstrating and qualifying the solution to problems.

3-5

23. It may be predicted that either an intensive flight development or bench development programme backed by an equally intensively flown 'Lead the Fleet' programme might be expected to accelerate significantly the growth of average achieved engine life in service. The benefit in reduced engine support costs might be 5 to 15 times the cost of such small special development programmes. Much of benefit could come from a reduced buy of reserve engines and modules but this would need an act of faith by those responsible for supply and fleet management and confidence that the predicted potential benefits would be achieved. The balance would come from reduced engine support. Although the return on the extra investment would be satisfactory, the effect on the support costs would be small – about 5% – and the effect on the LCC almost negligible.

BENEFIT OF INCREASED INVESTMENT

24. What benefit might be expected from increased investment in an enhanced engine development programme? Let us speculate, and do so on the distribution of engine LCC indicated in Figure 4. Suppose an extra 5% is expended in development which improves reliability and reduces support costs by 20%. To avoid deterioration of aircraft performance and increased aircraft weight and LCC, the engine weight and performance is maintained at an extra cost of about 1% in production. Then on the cost distribution of Figure 4, the change in engine LCC is indicated in Figure 13. The overall effect expressed in terms of the datum LCC is an increase of 2.2% for front end investment – predominantly development, and a reduction of 7% for support. The net effect is a small reduction of engine LCC of 5% of the datum, and the return of the extra investment is about three-fold.

25. To justify an extra front end investment something like a ten-fold return in reduced support costs would be the target. Such a high return is needed to allow for the uncertainity of front end engine development investment, whereas the benefit of reduced support costs would be realised over the greater part of the service life, and are not expressed in DCF terms. This would require the support costs to be reduced from 35% to 15%, in terms of the datum LCC which would be a reduction of 60%.

26. It will be recalled that a comparatively small fleet of aircraft has been used to discuss engine life cycle costs. It might be argued that a larger fleet would give a much better return on investment for improved reliability. Consider a fleet twice as big, then similar increased costs for development and production and reduced costs for support would be expected to reduce LCC by about 7%. For a ten-fold return on the investment the support costs would have to be reduced by about 40%; which must still be an optimistic expectation!

CONCLUSION

27. My conclusions will not be unexpected.

Firstly advanced technology engines for high performance combat aircraft are costly, their development costs are a high proportion of the total aircraft development costs.

Secondly engine support costs are high and are a high proportion of engine LCC after development. Combat and peacetime training missions impose very severe operating conditions on engines.

Thirdly less advanced or de-rated engines would be expected to have enhanced reliability and to some extent might have reduced engine support costs, but it is unlikely that the aircraft support and LCC would be reduced significantly. If the aircraft performance or military effectiveness are maintained the aircraft LCC are more likely to be increased rather than reduced, although there would be some improvement in availability.

Fourthly it is difficult to envisage large-fold returns for reduction of engine support costs by enhanced front end investment programmes.

Fifthly if it is wished seriously to reduce engine operating and support costs, a "lead the fleet" engine life flight programme needs priority early in service life, so that engine problems sensitive to service use are identified early in the fleet build up and may be rectified.

Sixthly the traditional aims of aeronautical research of improved materials leading to reduced weight and enhanced life and aerodynamic research for better lift and lower drag remain essential if aircraft LCC are not to escalate. Engine usage and lifing studies are equally important; there is no simple panacea for reduced support and LCC.

ACKNOWLEDGEMENTS

AIRCRAFT LIFE CYCLE COST
15 YEAR PEACE TIME OPERATION

FIG. I.

AIRFRAME, SYSTEMS OPERATION 40 %

AVIONICS 30 %

OPERATION

FUEL

ENGINE & FUEL 30 %
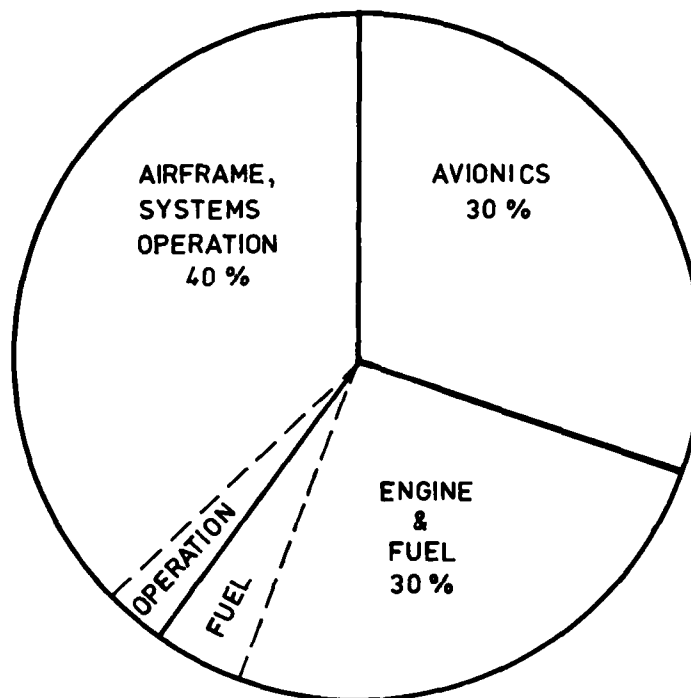
AIRCRAFT LIFE CYCLE COST
EFFECT OF FLEET SIZE AND SERVICE LIFE

FIG. 2

AIRCRAFT LIFE CYCLE COSTS

SERVICE LIFE YEARS

+5 DOUBLE

DATUM

FLEET SIZE

-5

DATUM

HALF

200

150

100

50

AIRCRAFT LIFE CYCLE COST FIG. 3
15 YEAR PEACE TIME OPERATION

DEVELOPMENT 20 %
OPERATION & SUPPORT 50 %
INVESTMENT
PRODUCTION 30 %
INITIAL SUPPORT

ENGINE LIFE CYCLE COST FIG. 4
15 YEAR PEACE TIME OPERATION

DEVELOPMENT 40 %
SUPPORT 37 %
INVESTMENT
PRODUCTION 23 %
INITIAL SUPPORT

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COMMITMENT OF LCC
DURING PROGRAMME

FIG. 5

Feasibilty   P.D.   Full Scale Development   Production ⟶   Operation phase ⟶

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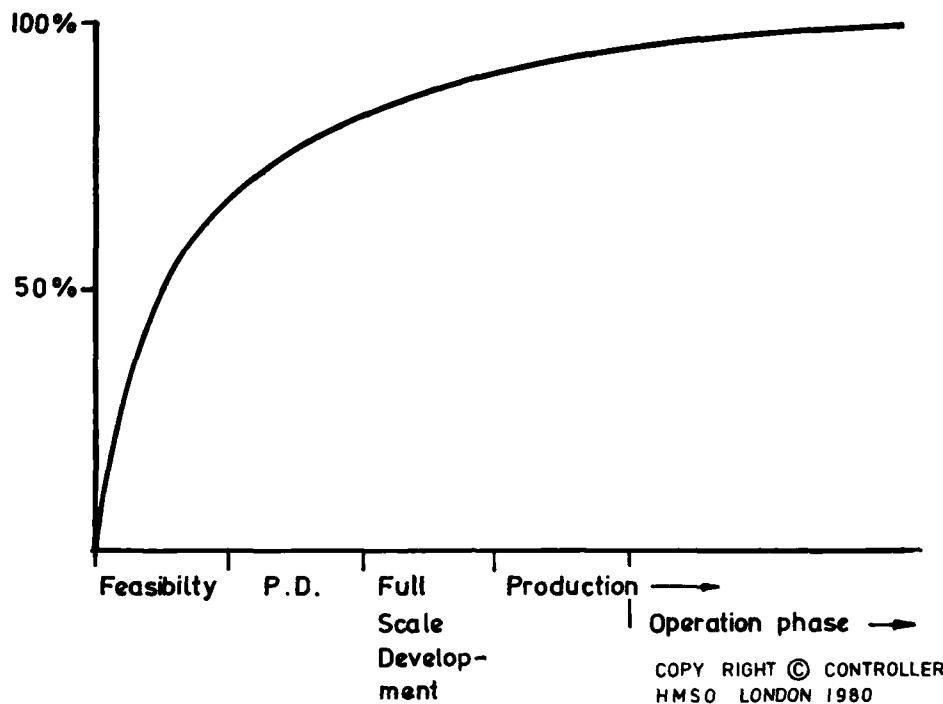
ENGINE   LCC
COMMITMENT OF SINGLE ENGINE WITH TWIN

FIG. 6

SAVING 8%

SINGLE DEVELOPMENT 48%

TWIN DEVELOPMENT 40%

SUPPORT 37%

SUPPORT 27%

PRODUCTION 23%

I S

INITIAL SUPPORT

PRODUCTION 17%

INVESTMENT

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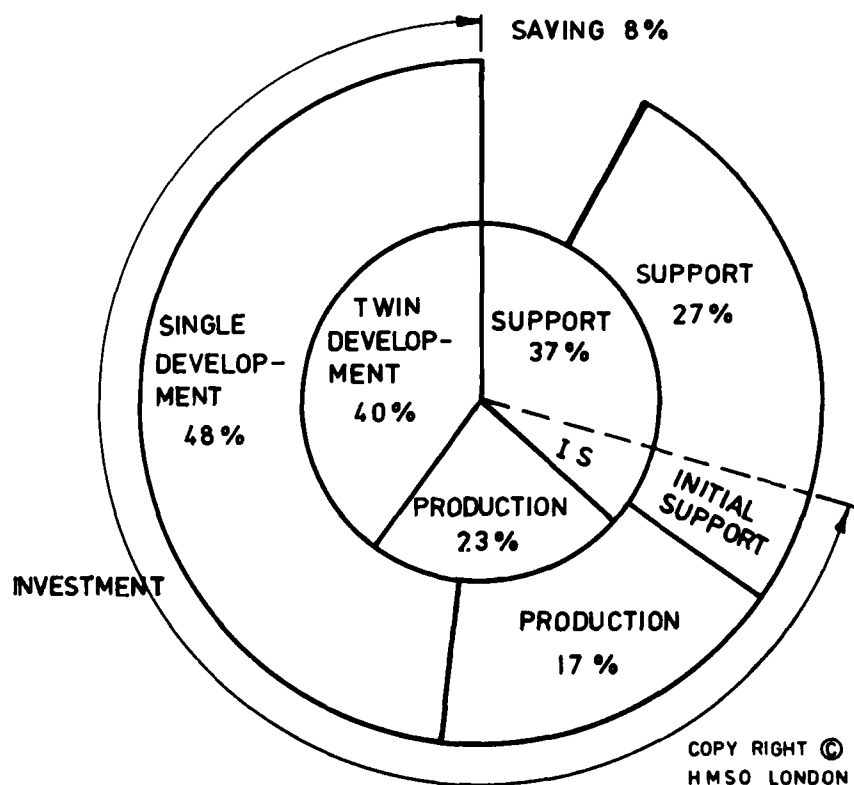
ENGINE LCC   FIG. 7

DE-RATED ENGINE BENIFIT

FIG. 8
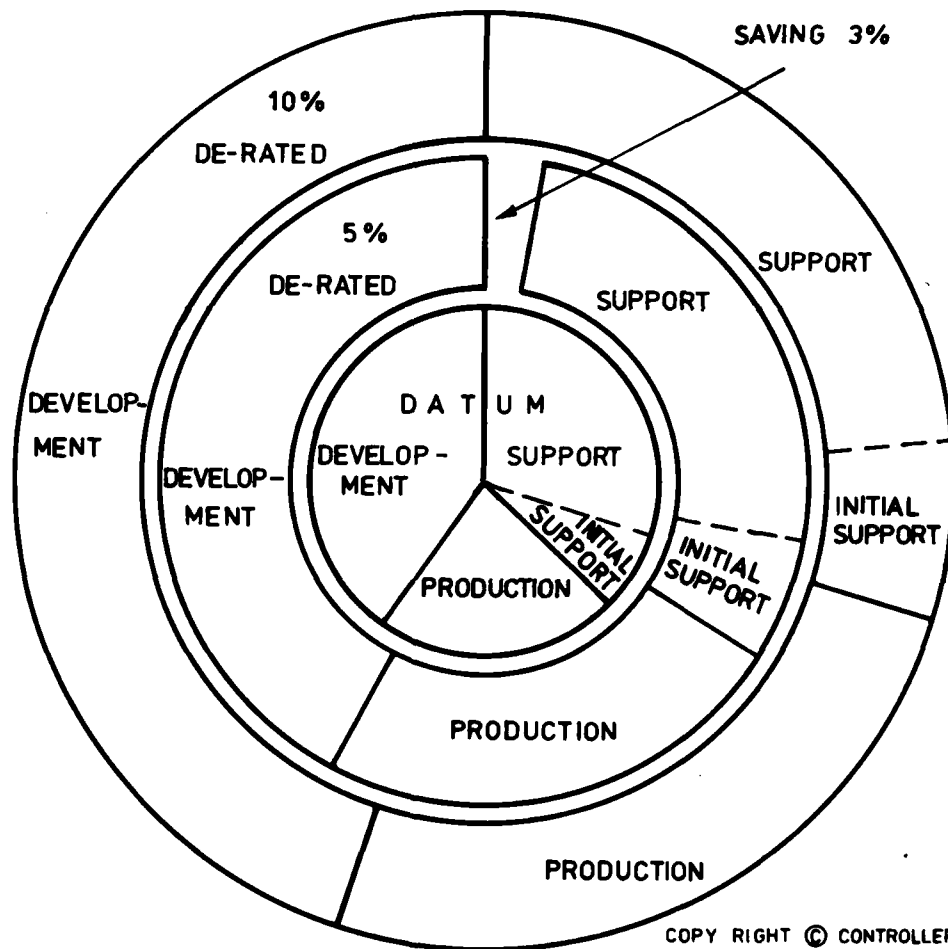
FIG. 9

KEY

● ENGINE A
■ ENGINE B
▲ ENGINE C

TIME BETWEEN
OVERHAULS
* hours

TIME IN SERVICE   years
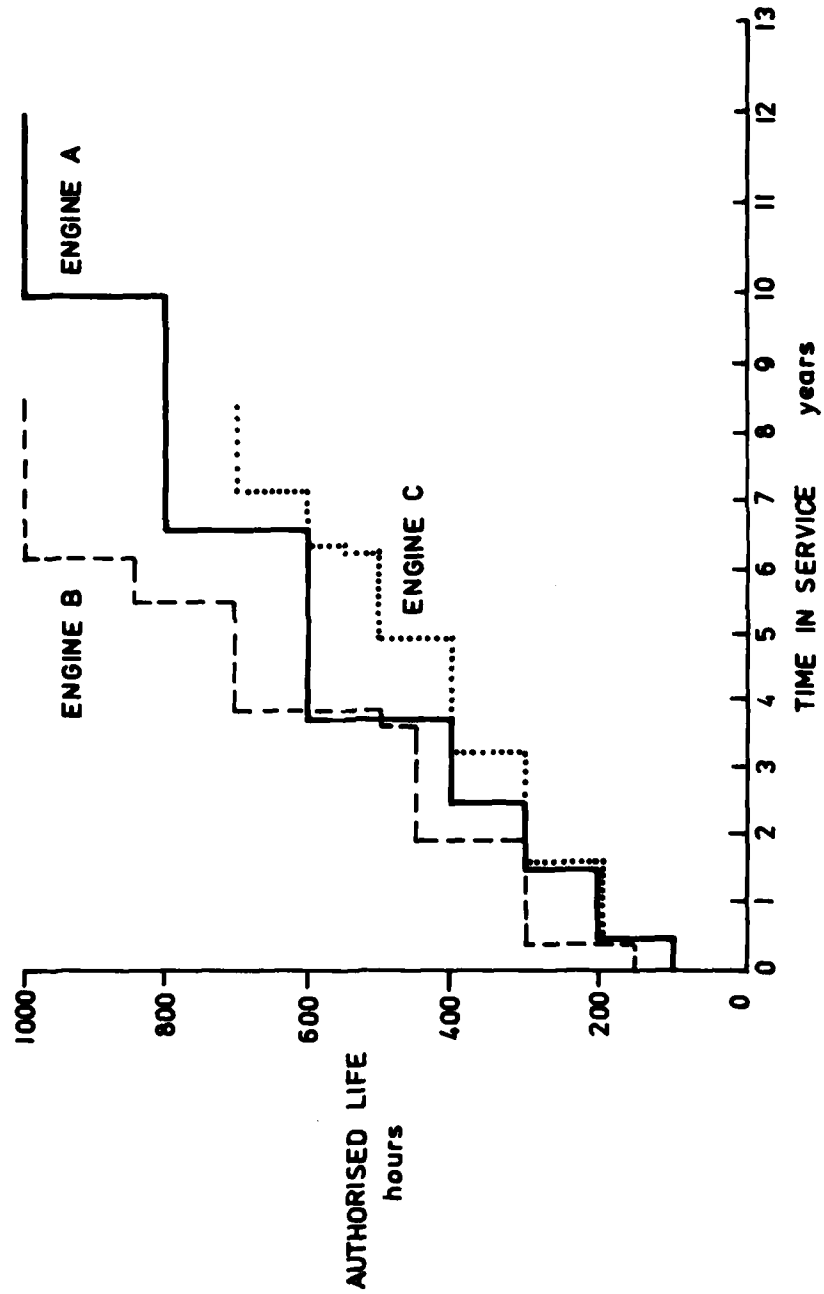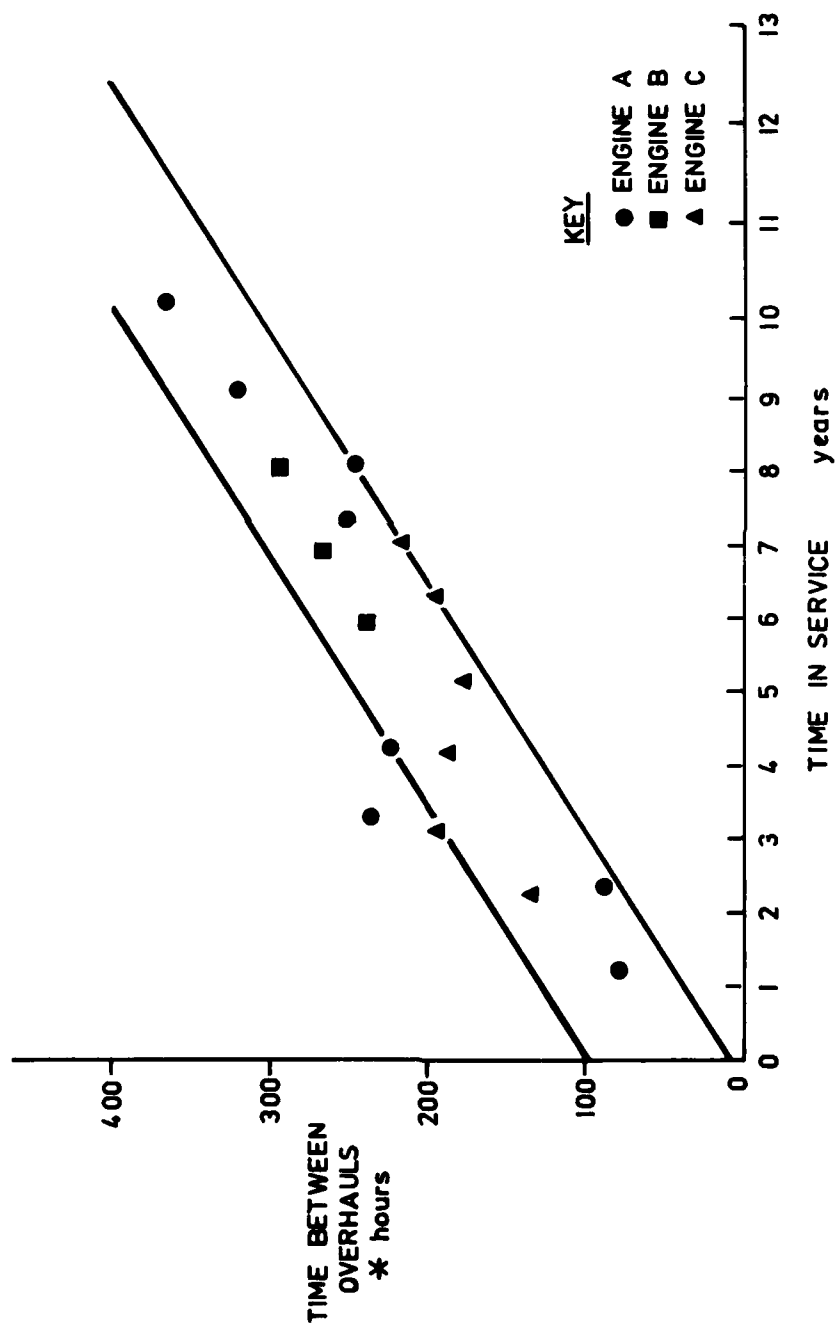
* INCLUDES ENGINES RETURNED FOR ALL REASONS SUCH AS FOREIGN OBJECT DAMAGE.

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3-12

FIG. 10

IDEALISED FLIGHT PROFILE
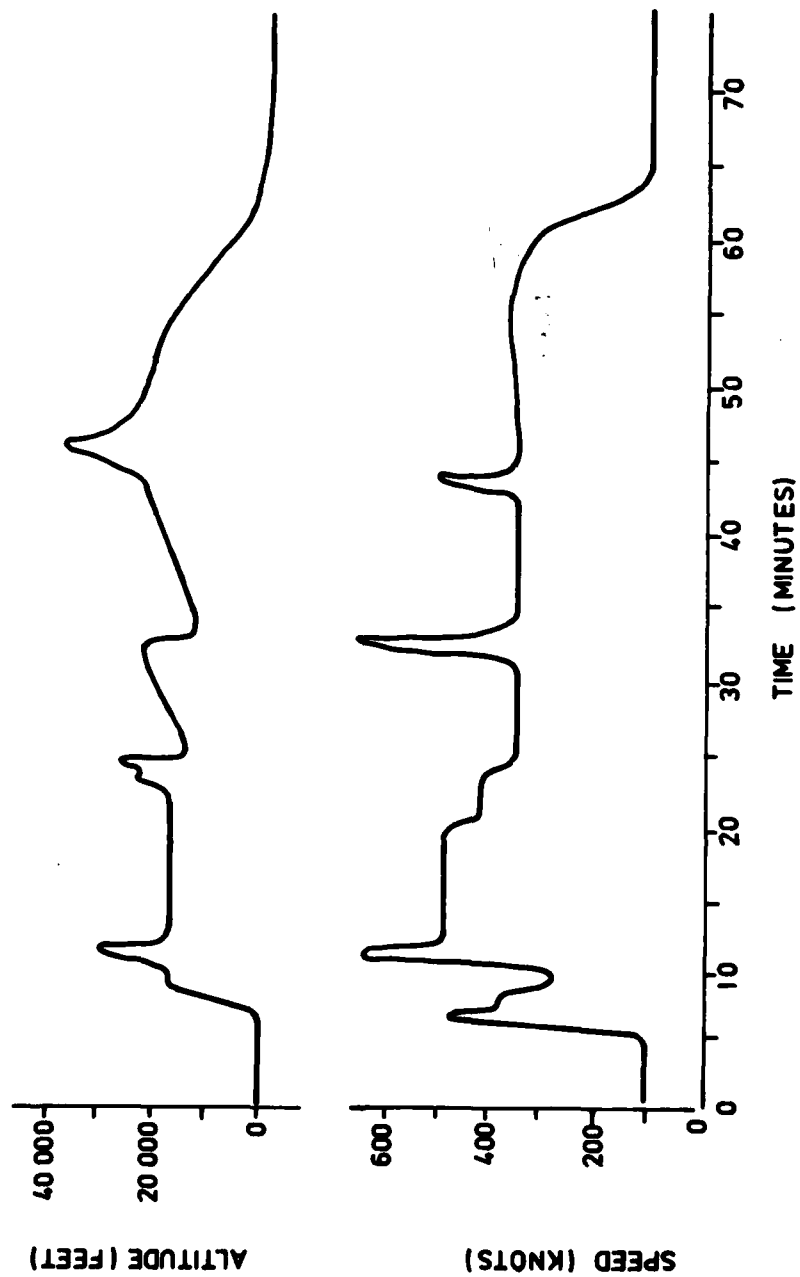
ALTITUDE (FEET)

40 000
20 000
0

SPEED (KNOTS)

600
400
200
0

TIME (MINUTES)

0   10   20   30   40   50   60   70

FIG. II

ACTUAL FLIGHT PROFILE

ALTITUDE (FEET)

40 000

20 000

0

SPEED (KNOTS)

600

400

200

0

0   10   20   30   40   50   60   70

TIME (MINUTES)
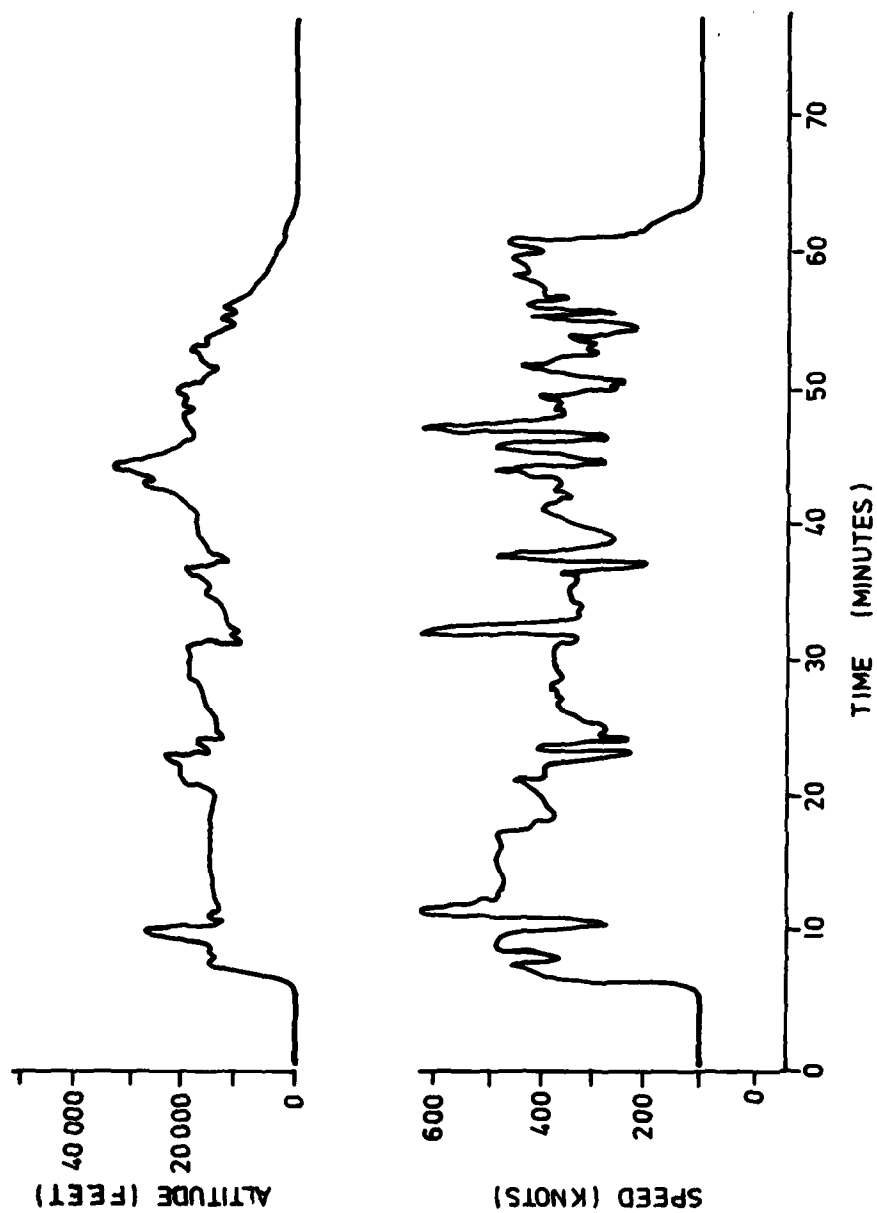
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FIG. 12

TYPICAL ENGINE PARAMETERS FOR AN ACTUAL FLIGHT

TIME (MINUTES)

TURBINE GAS TEMPERATURE (°C)

SPEED OF LOW PRESSURE SHAFT (% OF R.P.M.)
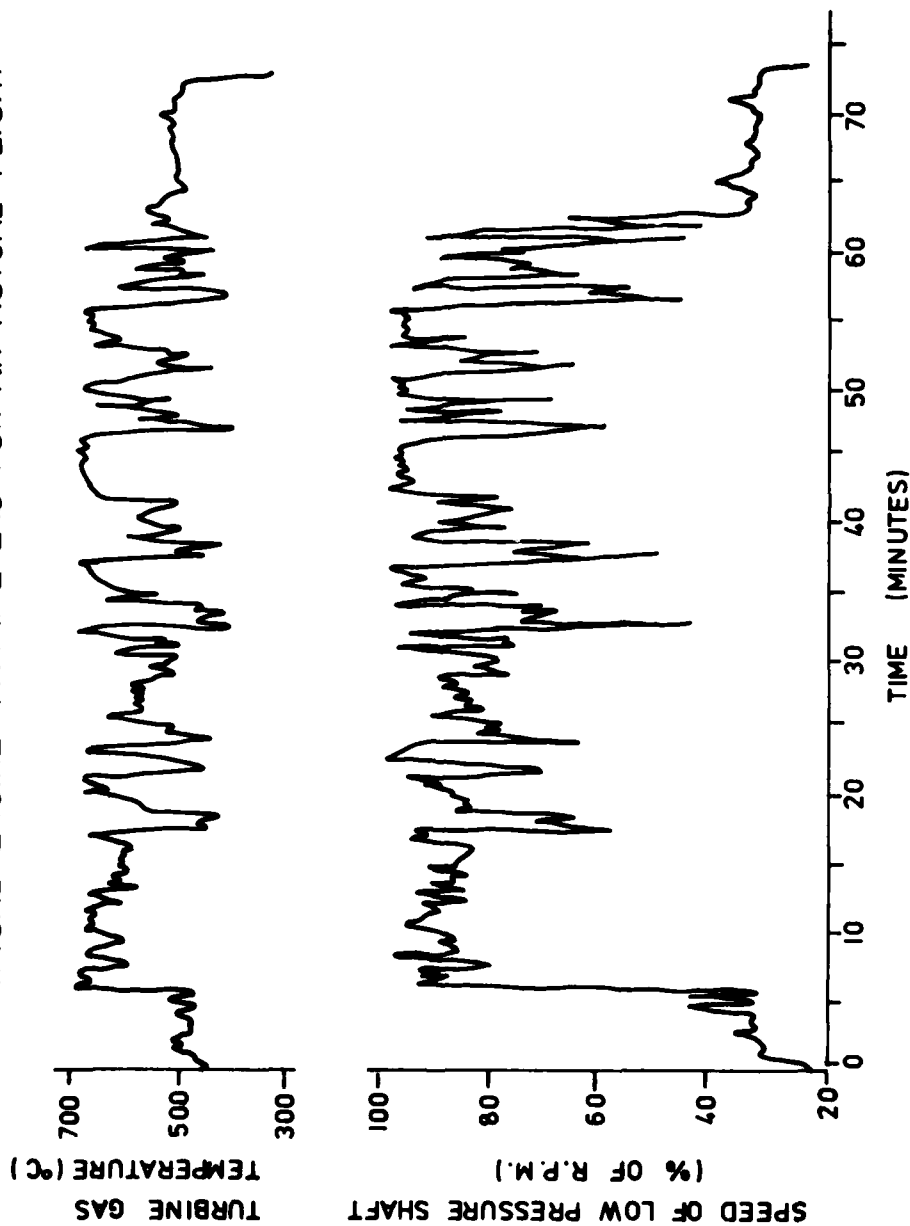
ENGINE LCC   FIG.13
BENEFIT OF ENHANCED DEVELOPMENT
IN TERMS OF DATUM LCC

	DATUM	ENHANCEMENT		
		RATE	EFFECT	
DEVELOPMENT	40	+ 5%	+ 2	
PRODUCTION	23	+<1%	+ 0·2	+ 2·2
SUPPORT	37	− 20%		− 7·4
LCC	100	—		− 5·2

"PROGRESS ON THE U S AIR FORCE APPROACH FOR THE
PRACTICAL MANAGEMENT OF ENGINE LIFE CYCLE COSTS"

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SUMMARY

This paper presents progress of the USAF efforts to more effectively influence the life cycle costs of newly acquired gas turbine power plants. A combination of technical and business practice initiatives have been undertaken or planned across the entire life cycle spectrum, i.e., from first entry with the exploratory development program thru the decision to phase the product out of the active inventory. References are made to earlier papers dealing with the identification and management of life cycle costs, such as, the so called "New Developments Concepts" and the "Engine Structural Integrity Program." This paper addresses the status of those technical and management activities and presents, for the first time, various business concepts and strategies being studied by the U S Air Force which complement the earlier initiatives as they impact engine life cycle costs. The role of the USAF Propulsion System Program Office as the continuing focal point for these life cycle efforts will be discussed. The ideas presented are not new as they have been employed successfully at one time or another on an individual basis in the development and support of military and commercial gas turbine power plants. What is new, is the systems management view of the life cycle process and what can be done practically today vs tomorrow to enhance engine life cycle costs in an integrated fashion.

INTRODUCTION

In their infancy, military gas turbine engines were relatively short-lived creatures that required much nurturing by the user and support organizations. As a result of significant metallurgical advances, a near optimum balance between turbine engine performance and life was achieved during the 50's and through mid-60's; hence, a near optimum life cycle cost (LCC). Dramatic advancement of gas turbine aerothermodynamic technology coupled with more sophisticated, lighter-weight mechanical design practices (with lesser metallurgical advances) once more unbalanced the performance-life scales in the late 60's. As a consequence, the military user and support organizations expressed their dissatisfaction with the high operational and support cost posture in which they found themselves in the early 70's. An Ad Hoc Committee of the Air Force Scientific Advisory Board in 1973 and a General Accounting Office Study in 1974 questioned the technical adequacy and management practices of the turbine engine development process. The Air Force Aeronautical Systems Division (ASD) at Wright-Patterson Air Force Base, Ohio, concluded in 1973 that the Air Force should revise both the technical and management approach to the development process; hence, the birth of the so-called "New Concepts for Engine Development", Reference 1. The "New Concepts" objective was to develop a total life cycle management strategy which would drive engine life cycle costs to the lowest practical limit for each new engine development or new application of an existing engine. The life cycle development process for turbine engines is being revised to provide more durable, reliable, and lower life cycle cost engines to the military services. Greater attention is being given earlier in the life cycle to the cost trades between performance, durability, producibility, and operability/supportability; i.e., during the technology, conceptual and validation phases of the development process. The full-scale development phase has been restructured to provide formal demonstrations of useful engine life limits; operational and logistic characteristics; and validation of the engine life management process to provide economic management rationale for the production hardware acquisition, operational usage, and logistic support phases.

LIFE CYCLE OVERVIEW

Figure 1 defines the life cycle flow process and the major activities occurring in the Laboratory Technology, ASD Acquisition and, User/Support Phases of the general life cycle process. Historically the data generation flow has moved downward and to the right with ineffectual feedback within and between phases of the life cycle. The engine life cycle process has in effect operated open loop with attendant results. In addition, not all essential technologies were addressed in parallel time periods which tended to cascade significant unknown problems into later life cycle phases for their solution. Figure 2 provides a more detailed understanding of the life cycle flow process. The top three horizontal arrows represent relatively high-risk, laboratory-technology developments that are funded on a continuing level of effort which is directed towards engine needs for future weapon systems. The next arrow represents modest-risk,

advanced-engine demonstrators which collect the laboratory technology and apply it towards a specific weapon system need during the System Validation Phase and are funded only as required by specific system needs. The bottom three arrows represent low-risk, full-scale engineering developments of specific engines and their follow-on product support programs which are funded in conjunction with specific weapons. The two middle arrows depict the ASD and User-Support Phases of life cycle activities for the weapon system and the engine. During the Conceptual Phase, trade sensitivity studies are performed between engine performance and engine life cycle cost to achieve best practical balance between development costs, hardware/software acquisition costs, and operational/support costs. The cost drivers are identified and the risk associated with Cost Estimating Relationships (CERs) for these drivers is assessed. High risk technology inputs at this point tend to create high risk CERs which, in turn, identify the need for advanced engine demonstrations during the Validation Phase to drive these risks to a level acceptable for initiation of Full-Scale Development (FSD). The engine FSD is laid out to address/manage the performance, life, and cost risks remaining; to develop a technical data base relative to engine useful performance, life, and logistic characteristics; and to validate the Life Cycle Cost Model (LCCM) developed during the Conceptual and Validation Phases. The technical data base and LCCM are then used to manage the follow-on hardware acquisition and operational support costs decision process. Figure 3 presents another view of the life cycle, i.e., the accumulation of engine operating experience and the conditions under which obtained. We cannot obtain real-world, statistically significant development data without building production engines in significant quantity and deploying them in the operating environment. Thus, the ground developmental activity cannot be expected to identify all of the potential systemic problems associated with a particular engine design. Historically our technical data capture during the shaded area of the chart has been poor; especially for the single-crew, high-performance aircraft which have carried a minimum of engine diagnostic equipment. This data deficiency in the process has tended to prevent the earliest identification of new problems and thereby delayed development and deployment of required solutions. Another not so obvious point to reflect upon is the fact the rate of buildup of engine run time on the early operational engines is quite low and several years will elapse before the high time field engines approach the developmental hours accumulated on the high time development engines. Thus, deficiencies in the developmental testing relative to engine longevity characteristics naturally show up late in operational inventory. For this reason, the USAF has developed and effectively employed the so-called Lead-the-Force Program to keep a few operational engines ahead of the general inventory in terms of running hours to blunt the effect of operational surprises to the extent practical. Figure 4 addresses the life cycle risks associated with erroneous technical or cost information. The technologists frequently work with incomplete "technical capability" objectives relative to downstream technical needs. More often than not the "cost objective" is non-existent. The conceptual planners, by nature, are optimistic without a sound empirical data base. In so doing they fail to recognize the built-in shortfall the developers will of necessity pass on to the producers, users and their logistic supporters. Validation demonstrations which have been conducted prior to full scale development have often failed to identify the technology shortfall as they were not organized to address all aspects of technology uncertainty. By the time the full impact of compounding effects of the direct technical and cost shortfalls are known, the system is irrevocably locked into a significant increase in outyear operating and support costs even though the engine is a "good performer" in most technical aspects. Under these conditions the management of the initial operational-break-in maturity process becomes even more critical. Without prior knowledge that an outyear shortfall is impending, the engine system manager may experience a short period of no problems, followed by a continuing series of minor problems which temporarily impact the operator but does not turn on the logistic support system in a timely manner. Phase lags (lead time) between operator need and support capability can and have caused wildly fluctuating operational support cost which in worst case have gone unstable and caused a breakdown in the supportability of the engine. A final point is the need to develop operational/support indicators and attendent analysis capability which will reliably tell the manager that the economic life of the engine is being approached and phase out of the engine inventory should be initiated if possible.

Figure 5 presents the classical engine maturity characteristic under optimum circumstances which provides clear justification for competent engineering support of the engine throughout its operating life. Each of the three phases have unique problems associated with technical problem identification and development of practical management solutions.

Figure 6 presents a simple picture of the closed cycle management loop which has seldom been used. Throughout the life cycle estimates are made by some manager in the areas of performance, operability, durability, producibility, maintainability and resulting costs. As discussed earlier, these estimates may or may not be recognized for what they are (estimates) and require validation by some appropriate demonstration. The resulting accomplishment may or may not coincide with the estimate; thus, the need for positive feedback analysis to evaluate the appropriate management action to correct any "error" in planning based on the estimated value. Closed cycle management during the various development phases is a practical management tool which must be religiously embraced by the development community. The process has been used successfully to varying degrees for the production phase, especially during the initial production years. Studies of its use are on-going relative to the practicality of embracing closed cycle management for elements of the process during the operational phase.

Another aspect of closing the management loop relates to the entire life cycle management process. It is addressed in the following equation which applies to both technical and cost capability and generally has not been recognized for its simplistic importance in the past:

Useful Engine System Capability = Demonstrated System Engine Capability
$\pm$ System Operator <u>Usage</u>
$\pm$ System <u>Maintenance</u> Actions
$\pm$ System Product <u>Support</u> Actions

The useful engine system operational capability is not that "required by specification" or "designed-to," but, that "demonstrated by analysis and confirming development tests." Implicit in the development demonstrations, however, are system/engine assumptions about future <u>Usage</u>, <u>Maintenance</u>, and <u>Support</u> actions which must be validated and updated on a continuing basis by the engine life manager throughout the engine's operational life. The use of this simple equation is called Closed Loop Life Cycle Management in that the engine manager can close the loop on engine operational and support decisions relative to demonstrated engine capability, to favorably impact outyear system acquisition and support costs from that decision point on.

An analysis of the foregoing overview of the life cycle process has led the Air Force to the following rather simply stated, but yet to be accomplished, life cycle investment strategy:

(1) Make the necessary front end and back end investments, i.e., pre-FSED and post-FSED.

(2) Avoid all unnecessary investments, either by accident or intent.

(3) Maximize the return on prior investments by placing renewed emphasis on derivative developments.

(4) Keep the management loop(s) closed to maximum extent possible throughout the life cycle process.

DEPUTY FOR PROPULSION

The Deputy for Propulsion was established at the Aeronautical Systems Division of the Air Force Systems Command (AFSC) in September 1976. This was done in recognition of the continuing management problems that the Air Force was experiencing with no central engine management authority within any element of the Air Force. The objectives set before the Deputy clearly addressed the need:

"Establish a single Air Force Program Office with Primary Responsibility for Engine Acquisition Including Appropriate Deployment Matters in Association with the Aeronautical System Program Offices, the Air Force Logistics Command (AFLC) and the Operating Commands."

The organization was to have both AFSC and AFLC elements included for direct and continuous interaction throughout the engine life cycle. It was to provide a clear focus for internal Air Force engine business and advocacy, as well as, serve as an effective interface with industry, sister services and other governmental agencies. It was directed to improve the effectiveness of limited engine community resources through matrix management. And finally, it was to provide the vehicle for development and application of unified, disciplined business and technical management practices.

Figure 7 is an organizational chart of the full-spectrum engine program office that was desired.

Approximately 100 program managers under the administrative control of the Deputy, with the support of 250 matrixed functional collocates sit under one roof (Bldg 46 WPAFB, Ohio) to:

(1) Directly manage engine development and acquisition activities for 12 engine models utilized by Air Force and Navy with combined annual contracts of 2 billion dollars.

(2) Provide interface support to the AFLC and Using Commands as necessary for some 50,000 operational engines which require 1.5 billion dollars annually to maintain.

The New Engine Project Office is the ALPHA of the organization, i.e., it interfaces heavily with the DOD Laboratories and DOD/Industry planners and manages the Conceptual and Validation Activities which lead to new or derivative engine starts.

The In-Service Joint Engine Project Office (JEPO) is the OMEGA of the organization, i.e., it interfaces heavily with the AFLC and Using Command and Industry in managing the late production phase activities and the program management transfer to the AFLC after production is complete.

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The F100 and F107 JEPOs are heavily involved in managing the development and early phase of production and deployment for highly complex, politically visible and nationally critical engines which encompass the entire spectrum of interface activities involving multi-national and multi-systems applications.

We believe we are rapidly achieving desired maturing as an effective management instrument for the Air Force and have applied many "lessons learned" to accelerate the process.

INITIATIVES FOR IMPROVING THE PROCESS

The proceeding sections of this paper have addressed generalized initiatives which apply to all elements of the life cycle or to the overall life cycle. The remaining elements of this paper will therefore be directed to specific initiatives within individual life cycle phases to minimize overall life cycle costs.

TECHNOLOGY PHASE:

Greater emphasis should be placed on the examination of performance and operability characteristics, which classically experience premature field deterioration, with the aim of developing technological solutions with reduced deterioration sensitivity. The current NASA "Energy Efficient Engine Program" and the Air Force Aero Propulsion "Bore Entry Cooled Turbine Disc Program" have taken the initial steps in this direction.

Much has been accomplished but significant investments must be made on a continuing annual basis to improve our understanding of the inherent durability of the Gas Generator Technology Engines. This basically falls into two areas of empirical data gathering: (1) Obtain earlier and broader characterization of materials, especially for fatigue and fracture toughness and (2) Subject the technology demonstration engines to significant and realistic numbers of mechanical and thermal fatigue cycles as experienced by operational engines for the various technology classes, i.e., fighter, bomber, transport, etc at the performance level "demonstrated" by the engines. Without such data, engine conceptual designers will naturally lay down a design which is unrealistically imbalanced towards performance.

Manufacturing and Software Technology investments must occur in parallel with the other engine technologies and not be delayed until the FSED or later as has been the case in many past programs.

Hardware-Software Technology cost trades must be examined to direct technological investment decisions in the future. The engine development community must apply lessons learned by the avionics development community as engine controls and diagnostic equipments employ more digital avionics.

CONCEPTUAL PHASE:

Complete LCC Models should be developed for each specific engine as installed in each specific system application under consideration during the conceptual phase. Without such models, necessary cost trades and cost sensitivity analysis cannot be performed to properly influence downstream development investment decisions.

The total engine system must be included in the life cycle trade sensitivity studies to assure identification of all high risk cost drivers, as well as, when and what kind of investments need to be made relative to:

(1) Hardware/Software Design

(2) Manufacturing/Refurbishment

(3) Facilities/Test Equipments and Ranges

(4) Personnel Subsystem

(5) Aerospace Support Equipment

We must completely identify the need for, the scope of and the content of Validation Phase demonstrations consistent with technical/cost risks identified in LCC studies.

VALIDATION PHASE:

A complete complement of all essential engine demonstrations should be conducted in accordance with risks identified in the Conceptual Phase. These demonstrations should use flight-weight, full-scale, flight-configured hardware; operationally configured software; and address all manufacturing technology transfer issues.

The conceptual LCC trades should be validated and the LCC Model updated to reflect revised cost understanding and future investment planning. The technical capability requirements and associated costs reflected in the LCC Model should be frozen as the input baseline towards which the FSED is directed.

We must completely identify the scope and content of all essential FSED program activities consistent with the level of risk remaining in the LCC Model baseline.

FULL SCALE ENGINEERING DEVELOPMENT PHASE:

The FSED program should be conducted consistent with the general guidelines for the "Four Milestone FSED" discussed as a part of the "New Development Concepts" and the "ENGINE STRUCTURAL INTEGRITY PROGRAM" (ENSIP), Reference 2 and 3.

We plan to utilize contractor "Configuration Management" and "Field Test" support to facilitate rapid iteration of the engine system configuration to that which will meet the technical and cost baseline.

We plan to "incentivize" durability, producibility and maintainability demonstrations to assure their completion within the FSED test schedule.

Consideration will be given to use of an "Award Fee" for timely and thorough contractor response to unplanned program changes and/or unforeseen setbacks.

We plan to utilize correction of deficiency (COD) clauses for the update of production line and production assets delivered prior to FSED completion.

We should freeze the operational capability baseline at technical and cost levels demonstrated during FSED, validate/update LCC Model to reflect this capability and manage initial deployment at the demonstrated levels.

We will identify the scope and content of the engineering product support program for the planned operational life of the engine including the Lead-the-Force Program.

We will identify the critical engine technical and cost characteristics to be tracked and the requirements for periodic re-validation of the approved operational baseline characteristics.

We plan to identify peculiar repair, maintenance or overhaul facilities required by AFLC or Using Command consistent with approved operational baseline and LCC Model.

We will develop maturity-growth predictions for all critical field characteristics for the engine which can be tracked with existing Air Force Field Maintenance Management Information Control System (MMICS) and the proposed Air Force Logistic Center Comprehensive Engine Management System (CEMS).

PRODUCTION PHASE:

We need to incentivize the unit-cost "learning curve" developed during the FSED.

We plan to buy an initial-service warranty for each delivered engine (install or spare) analogous to the "commercial-type" warranty.

We must validate and update follow-on spares cost elements of the LCC Model to be consistent with whole engine delivery costs.

We plan to perform continuous sampling and analysis of trends for each engine delivered for all critical engine characteristics identified during FSED.

We should incentivize the periodic re-validation of the "current production engine" to assure that it has retained the approved operational baseline characteristics.

OPERATIONAL USAGE/SUPPORT PHASE:

We should incentivize on a "package basis" the operational inventory maturity-growth path predictions developed during FSED.

We plan to maintain an effective Lead-the-Force program throughout the operational life cycle.

We plan to establish a "K Account" program with the engine Air Logistics Center (ALC) for the timely collection and technical evaluation of all engine parts scrapped during engine maintenance at the ALC. Such accounts are invaluable to assist in the general maturing of the production configuration and the timely development of economic refurbishment/repair procedures for broken and worn parts which otherwise tend to go unrecognized until excessive economic hurt is experienced.

We should plan for and conduct continuous engineering product support throughout the operational life cycle.

We plan to periodically evaluate and demonstrate the operational LCC effectiveness of utilizing late technology transfusions into the operational engine inventory as is being done for the USAF/USN T56 Turbo Prop Engine to dramatically reduce fuel burned.

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During the "mature" portion of the operational phase we plan to develop and implement phase-out indicators which will provide the engine manager clear indication that the engine is entering the pre-specified non-economic wear-out-phase and should be retired if possible.

SUMMARY

One could make a case that engine development is a continuous life cycle process in that "new problems" can be expected to surface throughout the life cycle. One can also make a point that historically the development community has failed to surface problems which could have been found early in the development phases rather than the operational phase. One can also make the point that consistent life cycle management policies/ practices (both technical and business) have not been established and enforced. The eye of the needle that must be threaded over the life cycle has been either ill-defined or not defined at all. Often the thread is too coarse to stuff through the small eye or the manager is so myopic that he can't perform the feat when its possible. Clearly the time has come to correct this gloomy picture. We in the Deputy for Propulsion believe that success in this regard is achievable, i.e., intra-command and inter-service management improvements are possible. In the last seven years much serious attention has been given to the "propulsion problem" and significant progress has been made with more to come. We expect the Deputy for Propulsion will continue to provide a central USAF focus for influencing: (1) the acquisition investment strategy, (2) the life cycle business practices; and (3) the technical understanding to more effectively acquire, operate and support current and future gas turbine propulsion systems. We further believe that such changes can and should occur only in an evolutionary rather than revolutionary manner.

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LABORATORIES   **ASD/YZ**   **USER/AFLC**

* IDEAS

* COMPONENT TECHNOLOGY   * CONCEPTUAL STUDIES   * EFFECTIVE USAGE

* ENGINE TECHNOLOGY   * VALIDATION DEMOS   * EFFECTIVE MAINT

* SOFTWARE TECHNOLOGY   * FULL SCALE   * EFFECTIVE LOGISTICS
                            DEVELOPMENT

* MATERIALS TECHNOLOGY   * PRODUCTION

* MANUFACTURING TECH
                          * PRODUCTION SUPPORT   * PRODUCT SUPPORT
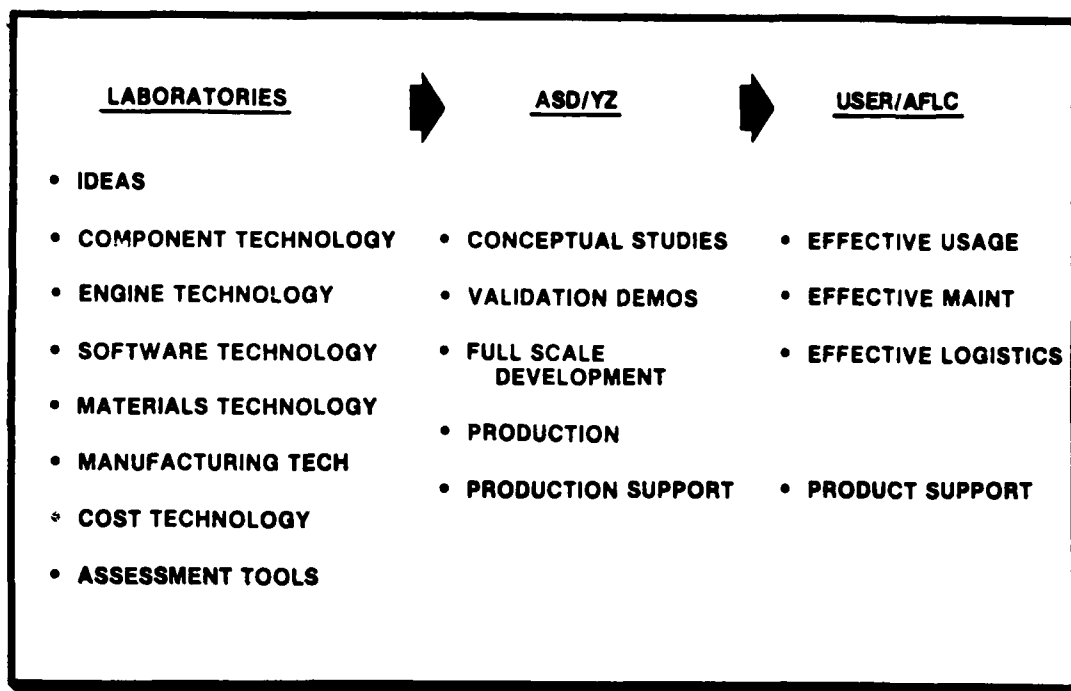* COST TECHNOLOGY

* ASSESSMENT TOOLS
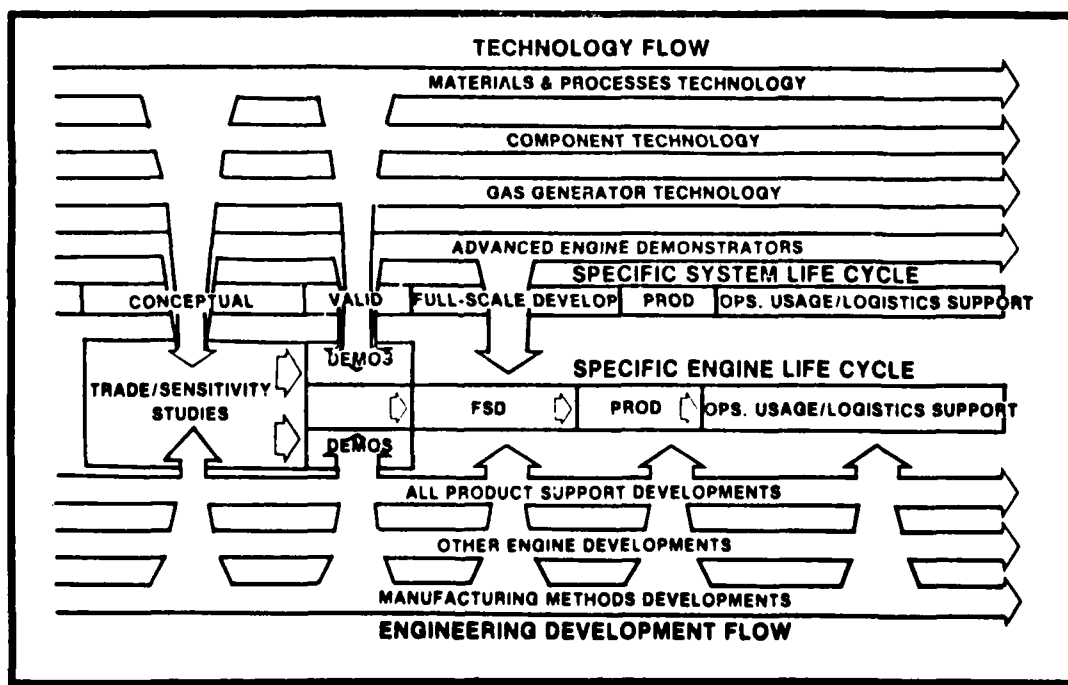
FIG. 1 ENGINE LIFE CYCLE PROCESS

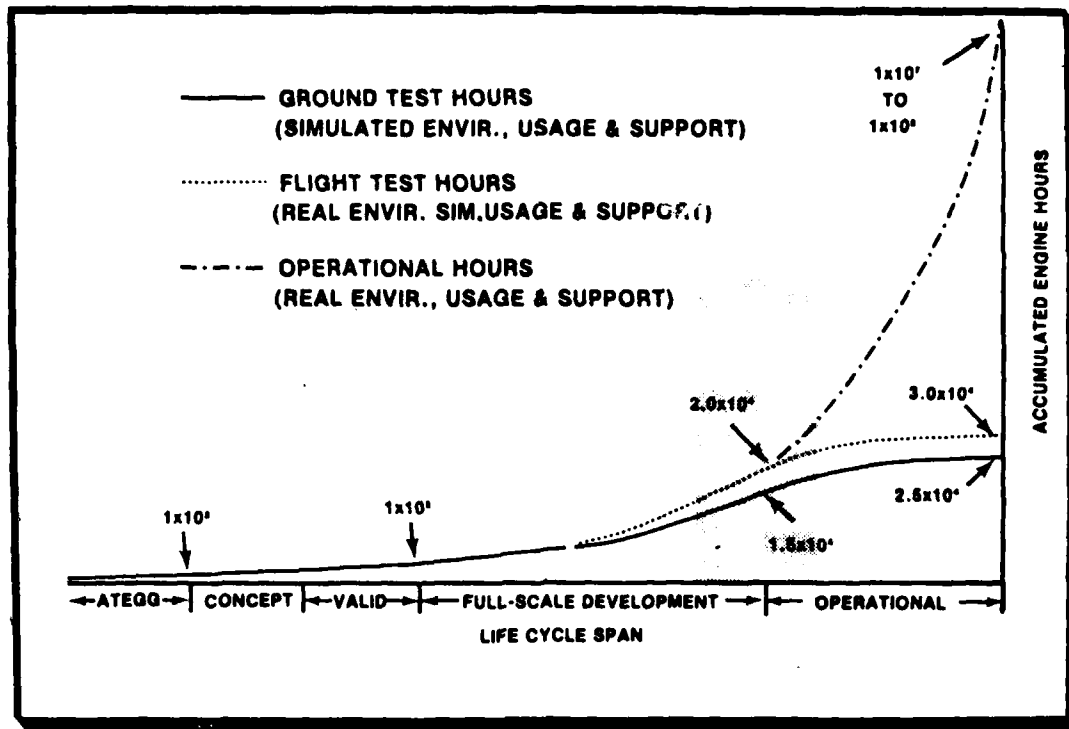FIG 2. ENGINE DEVELOPMENT PROCESS AND RELATED ACTIVITIES
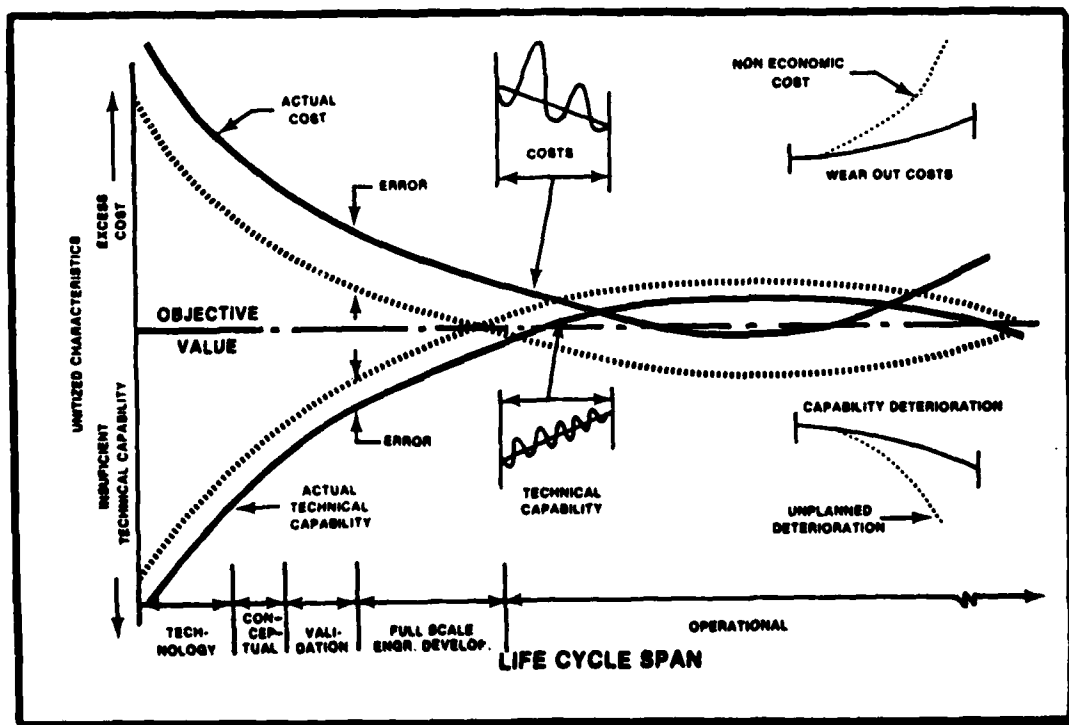
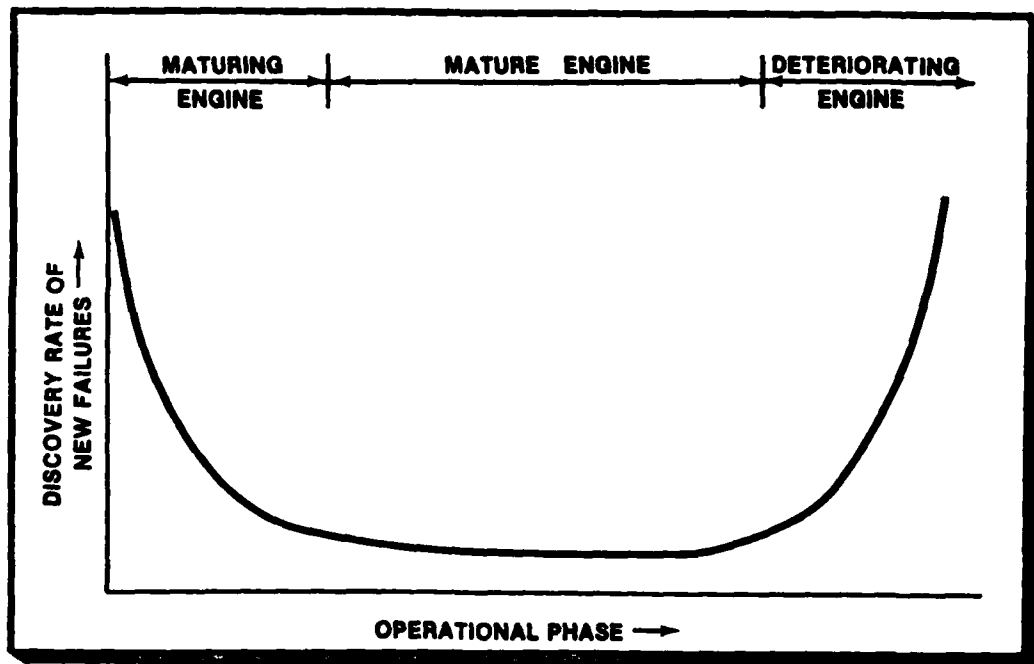FIG 3. ENGINE RUNNING HOURS RELATIONSHIPS

FIG 4. LIFE CYCLE RISKS
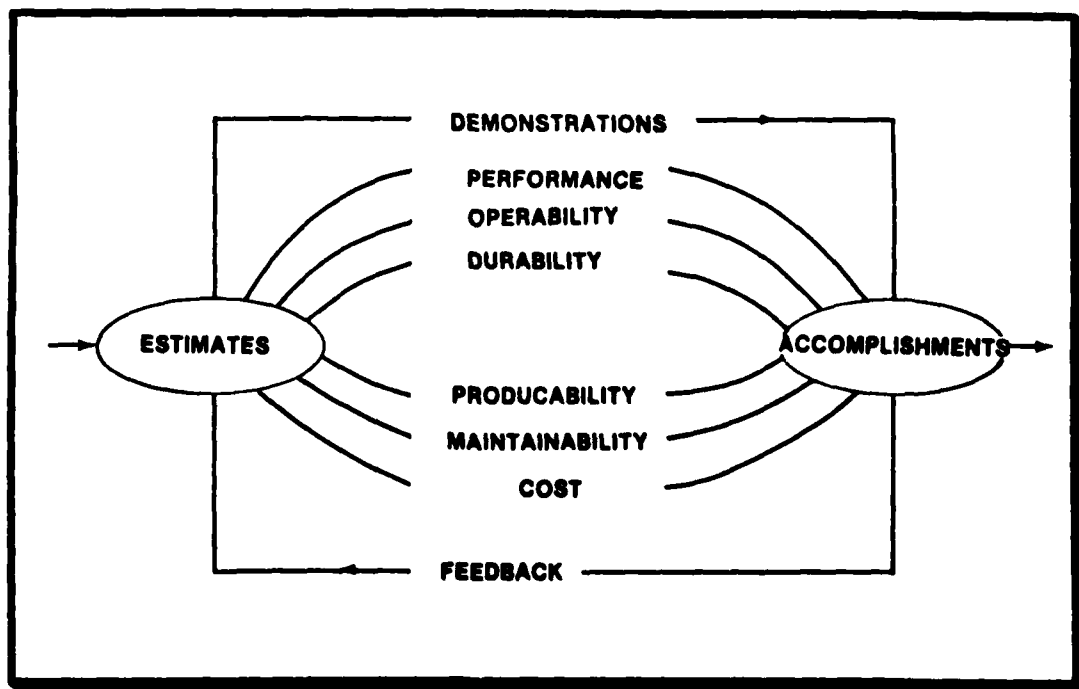
FIG 5. CLASSICAL ENGINE MATURITY CHARACTERISTIC
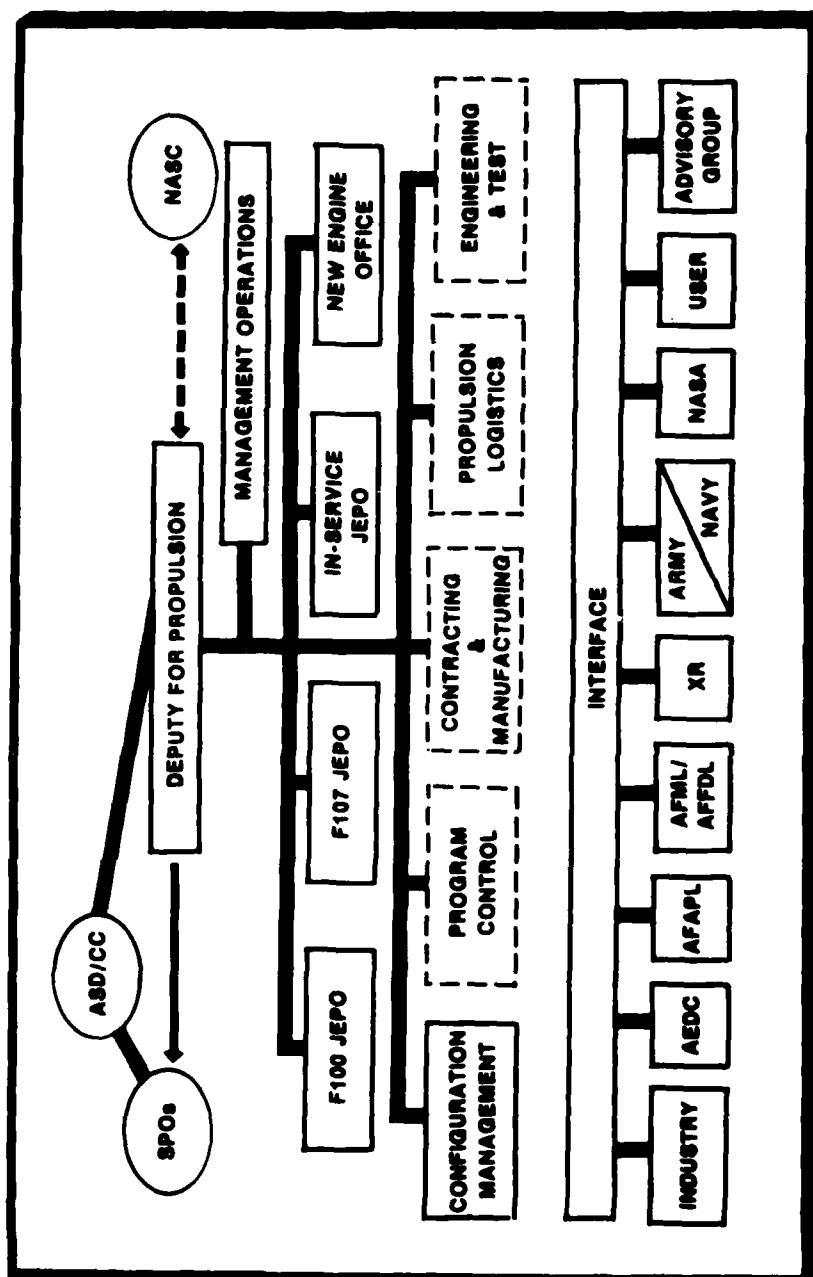

FIG 6. CLOSED CYCLE MANAGEMENT LOOP

FIG.7   ORGANIZATION

PROGRAMMES DE MOTEURS MILITAIRES A OBJECTIFS DE COUT

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RESUME

   Quelques approches y conduisant : analyse de la valeur, études de fiabi-
lité et de maintenabilité, coût direct d'exploitation (part moteur) consi-
déré par les compagnies aériennes, gestion des efforts de progrès
technologiques.

- Moyens de prévision des coûts dont il est souhaitable de disposer à
  chaque phase d'un programme

- Types d'organisation adaptés à de tels programmes

- Actions possibles lorsque les objectifs sont fixés ou révisés postérieu-
  rement à la définition initiale, sans ou avec modification de cette
  définition. Mesures d'économies entraînées par la hausse du prix des
  carburants

- Retour sur le concept de Valeur, taux d'échange.

CHAPITRE 1 - INTRODUCTION

1.1. PROGRAMMES DE MOTEURS MILITAIRES A OBJECTIFS DE COUT

Le titre de cet exposé indique qu'il est relatif aux actions à mener dans le cadre et au profit de
programmes de moteurs lorsque des objectifs de coût sont à définir concuremment aux objectifs techniques
et à poursuivre en même temps que ceux-ci, en y accordant la même importance.

Le coût de développement avant qualification est naturellement introduit dans les objectifs internes
et dans les marchés d'étude. Le coût de production, si c'est un objectif interne, le coût d'acquisition si
c'est un objectif contractuel sont aussi associés aux objectifs techniques et, de plus en plus, les coûts
d'utilisation et de maintenance sont considérés dans le cadre d'un coût "au long de la vie".

La délivrance de documents formels sanctionnant la tenue des objectifs techniques est suspendue à la
satisfaction d'épreuves au banc, puis en vol.

Accorder, comme il est dit plus haut, la même importance à la tenue des objectifs de coût conduit à
suspendre la poursuite d'un programme à la démonstration - qui ne peut être que prévisionnelle - de la
tenue de ces objectifs de coût.

Qu'il s'agisse d'une décision interne à un constructeur ou à une coopération ou d'une décision
contractuelle, elle ne peut reposer que sur les éléments d'une convention dont la crédibilité a été
reconnue, sinon établie, par l'ensemble des parties.

La complexité s'accroît avec les coûts d'utilisation et de maintenance qui dépendent non seulement
de l'avion mais aussi des missions à assurer.

On peut prévoir des litiges dans l'établissement et l'interprétation de ces conventions, mais n'en
a-t-on pas rencontré dans l'établissement et l'interprétation des clauses techniques.

Il ne faut pas cacher que ce type de programme paraît à certains très ambitieux.

Le pas à franchir n'est pas aussi grand qu'il paraît, pour autant que certaines approches, examinées
dans la suite, aient été faites et exploitées à cet effet.

1.2. LA PRATIQUE DE L'ANALYSE DE LA VALEUR

Elle a familiarisé les constructeurs avec :

(a) l'identification et la hiérarchisation des besoins exprimés par l'utilisateur ou par ceux qui
    ont mission de les prévoir.

(b) la stricte identification des fonctions à assurer, correctement quantifiées en regard de l'en-
    semble de niveau supérieur (avions potentiels pour le moteur complet).

(c) la prévision des coûts de production, quelquefois d'utilisation, nécessaire pour le choix de la
    solution présentant la meilleure adéquation au problème posé.

Plus l'analyse de la valeur se pratique en amont dans la vie d'un moteur, plus elle a de pouvoir sur la définition et plus il est nécessaire de disposer de moyens de prévision capables de synthétiser, en se basant sur les règles de l'art et leur évolution, ce qui sera défini en détail plus tard.

Pour l'essentiel, les moyens de prévision des coûts de production nécessaires à la conduite de programmes à objectif de coût résultent ou sont un développement de ceux nécessaires à l'analyse de la valeur.

Des exemples de tels moyens sont donnés dans le chapitre 2.

L'analyse de la valeur par ailleurs contribue à l'efficacité de la poursuite des objectifs de coût, lors de la conception initiale ou lors des actions correctives.

1.3. LES ETUDES DE PROGRES TECHNIQUE ET TECHNOLOGIQUE

Ces études par lesquelles les constructeurs de moteur préparent leur avenir sont nombreuses, souvent longues et coûteuses.

Une distinction est faite ici entre le progrès technique qui vise l'amélioration des performances des moteurs par leur conception et le progrès technologique qui porte sur les moyens de rendre ces conceptions possibles ou possibles à un coût admissible :

- matériaux nouveaux ou nouvelles mises en oeuvre,

- réalisation de pièces de forme ou caractéristiques plus élaborées,

- réalisation d'assemblages nouveaux,

- détection de défauts sur pièces en cours de fabrication ou d'utilisation.

S'il a généralement les moyens de détecter ou d'imaginer les multiples études susceptibles de contribuer au progrès technique ou technologique, aucun constructeur ne peut les mener toutes de front. Des choix sont indispensables. Une décision favorable au développement d'une étude ne peut être prise que si à un stade d'exploration impliquant des dépenses limitées, il est possible à la fois d'estimer les améliorations à attendre et les délais et le coût approximatifs jusqu'à mise en application.

Suivant cette voie, des programmes de progrès technique et technologique peuvent être mis sur pied puis menés avec détermination.

Ces programmes comportent néanmoins des incertitudes de réussite et de délai et sauf s'ils sont dans la phase finale précédant la mise en application, ils ne peuvent être directement pris en compte par le programme d'un moteur à objectifs de coût.

Indirectement toutefois ce peut être le cas :
Une appréciation statistique des chances d'aboutissement des programmes en cours peut donner une indication de la contribution à en attendre pour le développement des performances et la décroissance des coûts après qualification d'un programme moteur.

Ceci fait apparaître la dépendance de la rentabilité effective de programmes de moteurs à objectifs de coût de la bonne "gestion" des programmes de progrès technique et technologique.

1.4. LES ETUDES DE FIABILITE ET D'ENDURANCE

Les constructeurs de moteurs ont mis en place, au sein des organisations de conception, des équipes spécialisées dans la prise en considération de la fiabilité. En fait toute la conception d'un moteur contribue à sa fiabilité mais la prévision de celle-ci et de son évolution repose principalement sur :

- les études d'endurance des pièces dans leurs conditions de travail, notamment sous les aspects corrosion, fluage et fatigue oligocyclique,

- les études de pannes (y compris celles du système de régulation) et leurs conséquences.

Ces études contribuent à la hiérarchisation des caractéristiques de définition du moteur et de ses constituants.

Elles doivent par ailleurs déterminer comment la fiabilité varie suivant le cycle de fonctionnement auquel le moteur est soumis, notamment pour assurer que les cycles d'épreuve au banc, puis en vol, couvrent bien l'ensemble des conditions d'emploi prévues.

Elles contribuent bien sûr à la prévision des coûts de maintenance.

Quelques exemples de prévision d'endurance de pièces seront donnés au chapitre 3.

1.5. TRAVAUX DANS LE DOMAINE CIVIL

La prise en considération, par les Compagnies Aériennes et de ce fait par les avionneurs, du Coût Direct d'Opération (DOC), avec sa part inhérente au moteur, constitue une approche des programmes de moteurs militaires à objectifs de coût "au long de la vie".

De nombreuses études ont été menées sur la prévision de coûts d'opération et plus particulièrement des coûts de maintenance et de leur dépendance aux missions.

Certaines ont abouti à des formules faisant usage d'un facteur de sévérité de la mission déduit d'un pourcentage pondéré de réduction de la poussée (détarage), de la dilution et de la durée du vol type. Le chapitre 4 rappelle quelques travaux menés dans le cadre de la SNECMA et du GIFAS (Groupement des Industries Françaises Aéronautiques et Spatiales).

D'autres investigateurs concluent qu'une prévision valable ne peut reposer que sur un programme de simulation très élaboré.

Toutes ces études constituent une base pour considérer le "coût au long de la vie" dans un programme de moteur militaire. A noter toutefois que la dépendance du coût aux missions y revêt une complexité particulière.

1.6. LES ETUDES RELATIVES A LA MAINTENANCE

Dans le domaine militaire, elles ont d'abord visé l'amélioration de la sécurité des vols et de la disponibilité du matériel.

La connaissance, l'analyse des coûts de maintenance et la recherche de leur amélioration ont surtout été développées pour assurer la rentabilité des utilisations civiles (voir chapitre 4).

Il y a cependant beaucoup de points communs entre les efforts pour améliorer la disponibilité du matériel et ceux pour réduire les coûts de maintenance, que ce soit par l'évolution des méthodes et politiques de maintenance ou par la maintenabilité ou capacité des moteurs à admettre des méthodes de maintenance.

Il sera fait mention :

Chapitres 5 et 6 : des conclusions qu'on peut tirer de modèles de simulation de la maintenance d'un parc de moteurs ayant divers niveaux de modularité, pour un moteur non modulaire comme l'ATAR 09 K 50 et pour un moteur de conception modulaire comme le LARZAC.

Chapitre 7 : des méthodes de surveillance de l'état et des conditions de leur application sur un moteur, qui sont une des clés d'évolution de la politique de maintenance vers la réduction de ses coûts.

On trouvera également mention au chapitre 8 de ce que l'expérience acquise sur les problèmes d'introduction directe des caractéristiques de maintenabilité dans la conception d'un moteur conduit à recommander dans une organisation adaptée aux programmes de moteurs à objectifs de coût.

1.7. ACTIONS POSTERIEURES A LA CONCEPTION INITIALE POUR REDUIRE LE "COUT AU LONG DE LA VIE"

Il peut s'agir d'actions menées sur des programmes de moteur n'ayant pas donné lieu initialement à la formalisation d'objectifs de coût ou pour lesquelles de nouveaux objectifs ont dû être fixés.

Dans le premier cas on peut considérer que l'expérience acquise est une approche utile des programmes à objectifs de coût.

Dans les deux cas des actions postérieures peuvent être faites sans ou avec modifications significatives de la définition du moteur.

Dans le chapitre 9 seront mentionnés :

- la réduction des dépenses d'essais (réception et contrôle après réparation) portant notamment sur la consommation de carburant,

- l'introduction de modifications à bilan "au long de la vie" favorable, bien que le prix du moteur et de certaines de ses pièces soit accru,

- l'examen des possibilités de substitution d'autres matériaux à des matériaux de prix et d'approvisionnement aléatoires.

CHAPITRE 2 - PREVISION DES COUTS DE PRODUCTION

2.0. Le coût de production d'un moteur militaire, même s'il n'est qu'un élément du coût "au long de la vie", en reste l'élément principal, quantitativement, au travers du coût d'acquisition et du coût des pièces de rechanges et psychologiquement car, après le développement, le premier engagement financier tangible en dépend.

L'utilisateur ou celui qui achète pour son compte et bien entendu le constructeur se doivent d'acquérir les moyens de le prévoir, ceci dès que s'esquisse une fiche programme, puis aux différents stades de la définition.

2.1. STADE DU PROJET DE FICHE PROGRAMME

Le projet de fiche programme moteur doit exprimer les objectifs techniques et de coût que l'on vise d'associer.

Il convient donc de disposer des moyens de prévision du coût (a) faisant intervenir les seuls paramètres considérés à ce stade (méthode paramétrique) (b) dont l'usage est admis par les parties en présence.

S-4

MASSE DU CONSTITUANT EN FONCTION DU VOLUME CARACTÉRISTIQUE.   Fig 2.1

COUT MASSIQUE RELATIF EN FONCTION DE LA MASSE
DU CONSTITUANT   Fig 2.2

Une voie possible pour l'acheteur potentiel est de confier l'élaboration de telles méthodes paramétriques à un organisme tiers qui les dégage statiquement des données du passé et propose des projections de l'évolution constatée.

Chacun connaît et utilise ou adapte les formules de la Rand Corporation.

Bien entendu le constructeur ne peut se contenter d'avoir une indication de ce que devrait être le coût, compte tenu des objectifs techniques formulés à ce stade, il lui faut prévoir ce que pourrait être ce coût à la lumière des études de faisabilité qu'il a pu mener.

2.2. STADE CHOIX DU CYCLE ET DIMENSIONNEMENT DE LA VEINE

2.2.1. Estimation des masses

Parmi les méthodes utilisables à ce stade un développement particulier est à accorder à celles qui prennent la masse comme intermédiaire.

Après qu'une hypothèse ait été faite sur la poussée et le cycle du moteur (taux de dilution, rapport de pression, température devant turbine), on peut pour un état disponible de la technique déduire la "géométrie de la veine" notamment les diamètres internes et externes à l'entrée et à la sortie de chaque constituant, le nombre d'étages, la corde de leurs aubages.

Il a été montré que la masse des divers constituants pouvait être estimée à partir de cette définition géométrique initiale de la veine.

On utilise un paramètre de corrélation homogène à un volume (produit du carré d'un diamètre moyen par une longueur caractéristique) et en coordonnées bilogarithmiques on obtient des droites du type $m = A (V) \exp \alpha$. (voir deux exemples figure 2.1).

Sauf stipulation contraire, la longueur est la somme des cordes à mi-hauteur des aubes fixes et mobiles et le diamètre est la moyenne arithmétique des diamètres à mi-hauteur de veine, à l'entrée et à la sortie.

NOTA : La masse de certains constituants tels le relais d'accessoires, les équipements et canalisations externes doit être estimée par d'autres méthodes. La possibilité de déduire les masses de celles de tout ou partie des constituants intéressés par la veine est à examiner.

La masse totale du moteur correspondant à une hypothèse sur le cycle est estimée et peut être comparée à celles données par d'autres hypothèses et à l'objectif de masse qui a pu être défini par ailleurs et introduit dans des formules paramétriques.

2.2.2. Indicateurs de coût massique

Le coût par unité de masse d'un moteur est un indicateur souvent considéré et l'on peut étudier son évolution en fonction de divers paramètres d'avancement technologiques "externes" ou "internes" tels que la poussée massique ou le contenu de matériaux coûteux.

Au stade choix de la veine, on procède aux premières prévisions sur la nature et la proportion des matériaux utilisés dans chaque constituant. Ceci permet de définir un facteur du type Maurer pour chaque constituant et son coût de production. La somme étendue au moteur peut alors être comparée au coût objectif.

L'intérêt est qu'au passage on a une définition, qui peut être comparée à d'autres avant d'être retenue, de la masse et du coût de chaque constituant, dont la compatibilité avec les objectifs au niveau moteur est vraisemblable.

En poursuivant l'analyse on peut considérer le coût massique relatif des constituants, c'est-à-dire leur coût massique rapporté à celui du moteur complet.

L'avantage de cet indicateur est qu'il est sans dimension et autorise des comparaisons dans le temps et ... dans l'espace.

La figure 2.2 donne à titre d'exemple, pour un moteur militaire avec réchauffe, l'évolution du coût massique relatif de divers constituants en fonction de la masse du constituant.

On constate des différences entre les coûts massiques relatifs des constituants et dans leur variation.

2.3. STADE PREMIER DIMENSIONNEMENT DES PIECES

Au bureau d'études avant-projet, lors du "preliminary design" le projeteur est amené à faire des choix rapides entre diverses solutions et à les justifier au niveau des coûts sans faire constamment un appel direct aux spécialistes de la production. Un des principaux cas est l'estimation des pièces brutes notamment des pièces de forge classique de différents matériaux.

2.3.1. Pièces brutes de forge classique

On admet que le projeteur est capable d'estimer la forme, le volume vb et la masse mb de la pièce brute préusinée, dont pourrait être tirée la pièce finie de la solution à examiner avec un certain matériau.
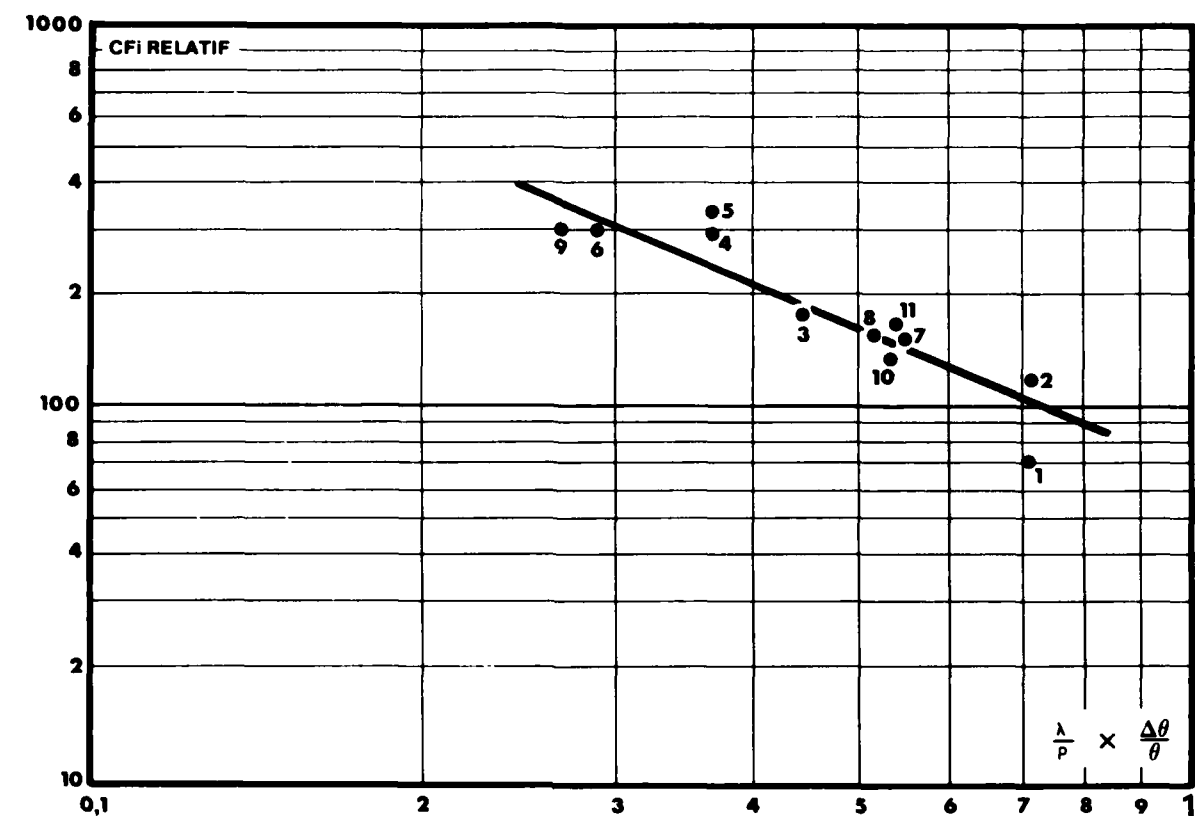
COÛT DE FORGEAGE EN FONCTION DE LA MATIÈRE   Fig 2.3
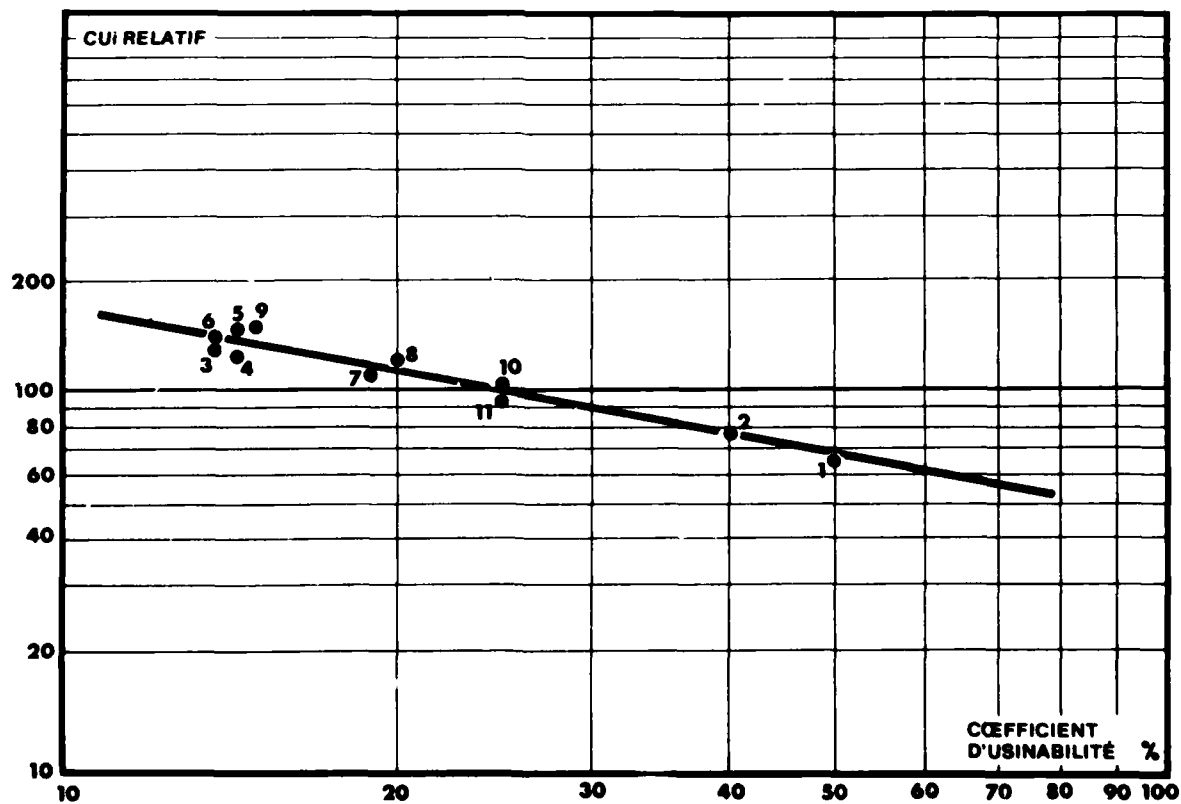
COÛT DE PRÉUSINAGE EN FONCTION DE LA MATIÈRE   Fig 2.4

Il apparaît que le coût Ci d'une pièce de forge classique préusinée dans un matériau i pour lequel une expérience est acquise, est linéaire, pour les morphologies les plus courantes, en fonction de la masse mb que l'alliage soit martensitique, austénitique ou de titane.

Ces abaques peuvent être utilisés directement mais lorsqu'on cherche à substituer à un matériau connu un matériau moins connu, parce qu'il est moins cher, d'approvisionnement moins aléatoire dans le futur ou de caractéristiques mieux adaptées, il est utile de restituer de tels abaques.

Une étude a été menée en décomposant le coût Ci en ses composants, CMi de matière première (billette), CFi de main-d'oeuvre de forge, CUi de préusinage.

Elle fait apparaître que pour :

- CMi, les écarts de prix massique en fonction du diamètre des billettes peuvent être négligés,

- CFi, la connaissance de l'intervalle relatif de température de forgeage ($\Lambda \theta/\theta$) i et de la diffusivité thermique ($\lambda/\rho cp$)i étaient suffisante. (figure 2.3)

- CUi, la connaissance du coefficient d'usinabilité suffisait (figure 2.4).

Sur ces bases les abaques de prévision du coût de la pièce brute de forge classique pour ces matériaux mal connus peuvent être tracés et utilisés.

CHAPITRE 3 - TRAVAUX SUR L'ENDURANCE DES TURBOREACTEURS

Il est tout à fait classique d'associer un bureau de calcul de résistance des matériaux au bureau de dessin pour le dimensionnement des pièces d'un moteur. Autrefois les méthodes de calculs étaient sommaires et conduisaient à l'application de coefficients de sécurité (en fait c'étaient des coefficients d'ignorance résultant de l'expérience plus ou moins fragmentaire de l'homme de l'art). L'augmentation des performances, en particulier de la poussée massique, n'a pu se faire qu'avec des méthodes de calcul de plus en plus sophistiquées, dont certaines (par éléments finis) n'ont été applicables que grâce aux ordinateurs de grande capacité, avec le complément très utile, pour saisir les distributions spatiales, d'investigations telles que la photoélasticimétrie.

En partant des caractéristiques de fatigue et de fluage des matériaux, des contraintes d'origine mécanique et thermique, il est possible de produire par exemple :

- le potentiel en heure d'une aube mobile de turbine dans le domaine de vol (figure 3.1)

- l'endommagement relatif en fonction du détarage et du temps de mission d'une partie chaude (figure 3.2).

Sur la figure 3.3 sont donnés les facteurs multiplicateurs de la durée de vie d'une aube mobile et du distributeur de turbine, de l'arbre de compresseur et de l'aube fan d'un même moteur en fonction du détarage.

La pente apparaît d'autant plus grande que la fatigue prime sur le fluage (pièces froides) et qu'on passe des réfractaires au titane (aube fan).

De tels éléments permettent d'estimer les temps de fonctionnement autorisés par la définition et de chercher une optimisation sur le coût "au long de la vie" entre ces temps et le coût des pièces correspondantes.

CHAPITRE 4 - TRAVAUX SUR LE COUT D'OPERATION DIRECT (DIRECT OPERATION COST, DOC)

C'est sur les effets, sur l'économie de l'avion équipé, de caractéristiques du moteur telles que la masse, la poussée, le prix, la consommation spécifique SFC et les coûts de maintenance que portent ces travaux. Ces effets peuvent être très différents en fonction de l'adaptation initiale avion/moteur.

Lors de l'étude des mérites potentiels d'un moteur projeté, il faut donc faire des hypothèses sur les avions qu'il est destiné à équiper et leurs missions, compte tenu des délais de développement comparés d'un moteur et d'un avion, c'est l'objet d'une supputation.

Dans le cadre du programme CFM 56 par exemple la SNECMA s'est particulièrement intéressée au cas d'un bi-moteur court/moyen courrier.

Une représentation "en tapis" permet de schématiser en deux figures les effets sur le DOC de la consommation spécifique, de la masse et du prix du moteur (rapportés à sa poussée) et des coûts de maintenance (figures 4.1 et 4.2).

Pour estimer les coûts de maintenance en fonction de la mission, notamment du pourcentage de réduction de la poussée utilisée au décollage, en montée et en croisière, on calcule d'abord un détarage équivalent. La formule proposée par la SNECMA et le GIFAS est la suivante :

$$\% D = (0,637 - 0,407 \log t) Dto \quad \text{(terme décollage)}$$
$$+ (0,228 + 0,142 \log t) Dcl \quad \text{(terme montée)}$$
$$+ (0,135 + 0,265 \log t) Dcr \quad \text{(terme croisière)}$$

OO t sont les temps passés dans la phase de vol correspondante.

5-8
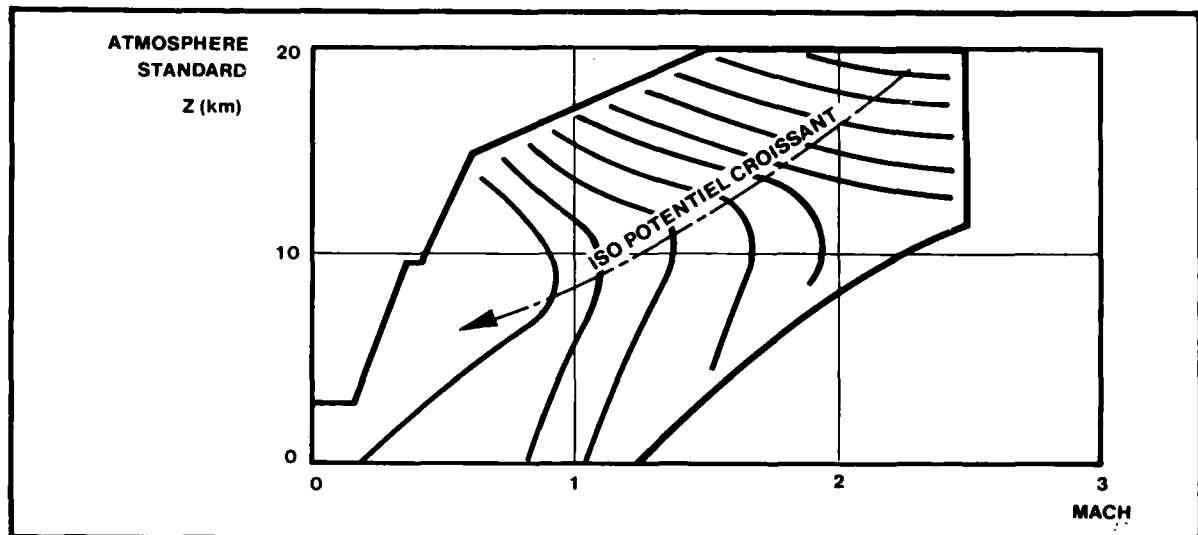
**POTENTIEL D'UNE AUBE MOBILE DE TURBINE
DANS LE DOMAINE DE VOL**

Fig 3.1

Dto   DÉTARAGE AU DÉCOLLAGE EN %

Dcl   DÉTARAGE MONTÉE EN %

Dcr   DÉTARAGE CROISIÈRE EN %

t   DURÉE DE LA MISSION EN HEURES.

$$\text{ENDOMMAGEMENT RELATIF} = \frac{A\,f_1\,(Dto) + B\,f_2\,(Dcl) + \left[1 + a(t-1)\right] \times C\,f_2\,(Dcr)}{t}$$
(PAR HEURE DE MISSION)
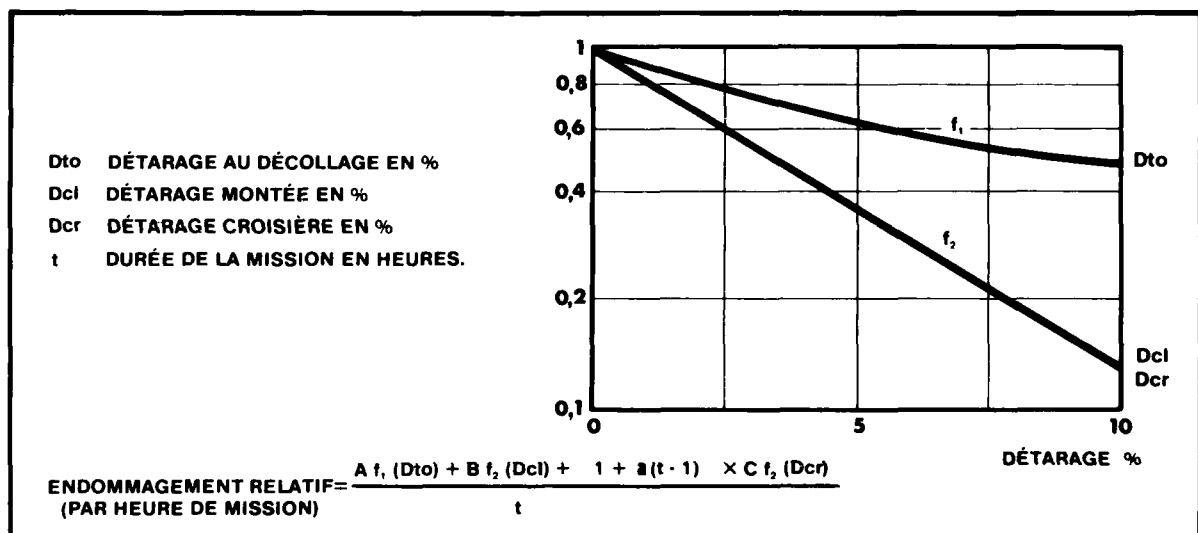
**ÉVOLUTION DE L'ENDOMMAGEMENT D'UNE PARTIE CHAUDE
EN FONCTION DU DÉTARAGE**

Fig 3.2
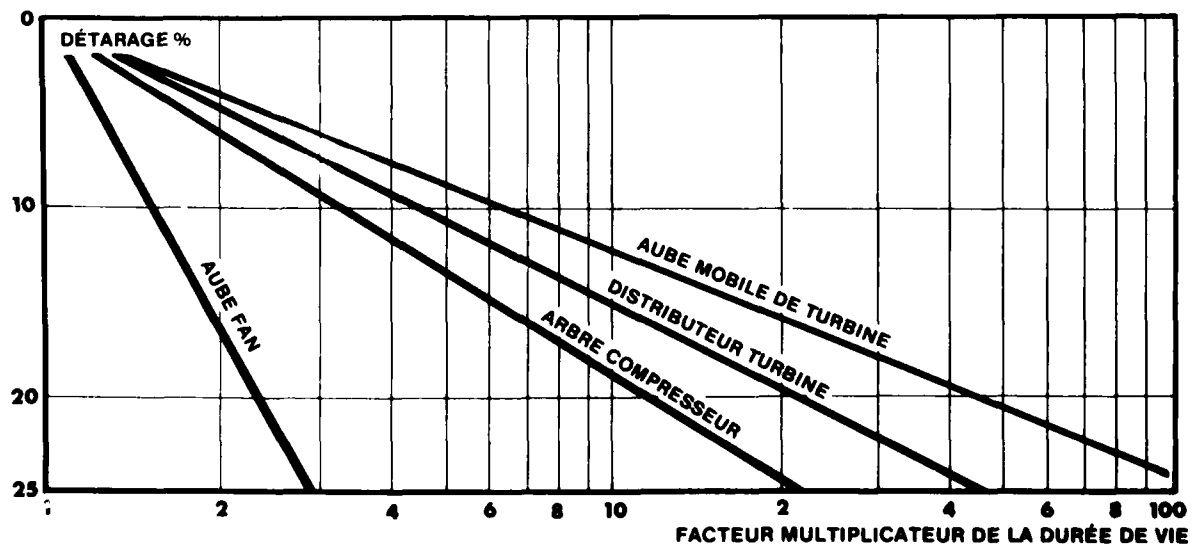
FACTEURS MULTIPLICATEURS EN FONCTION DU DÉTARAGE

Fig 3.3
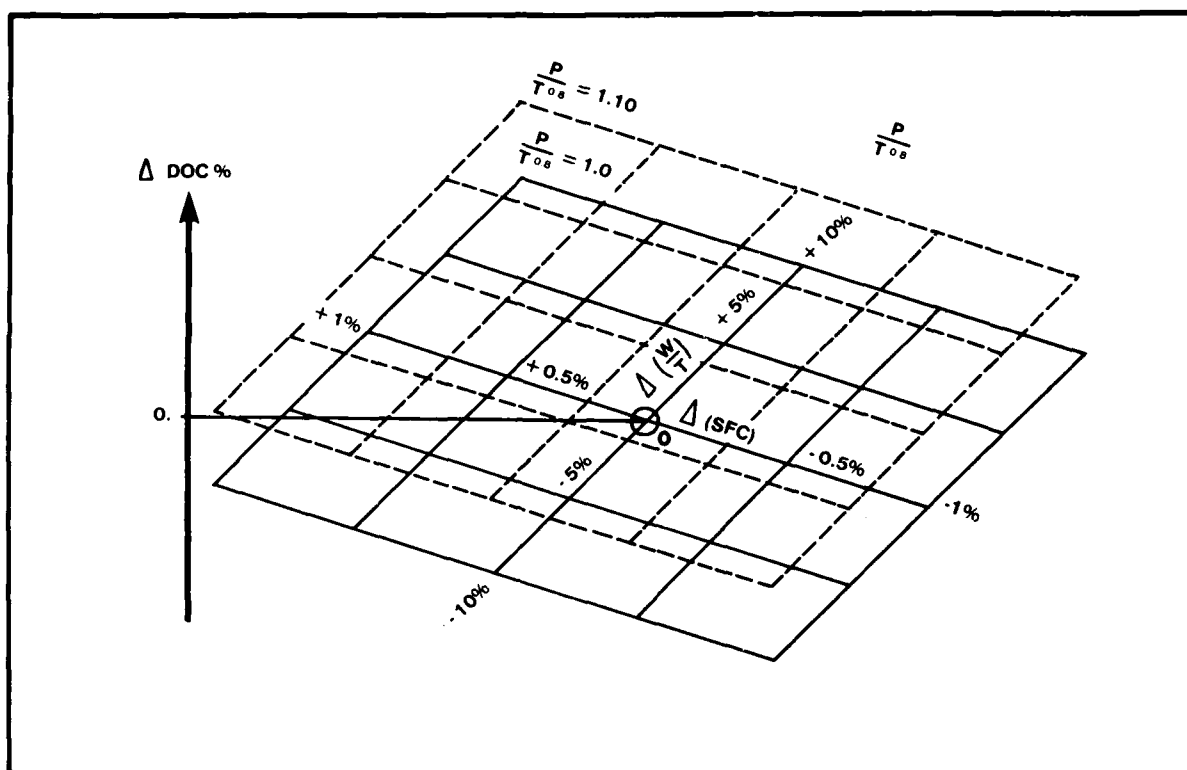
**EFFET SUR LE DOC DE LA CONSOMMATION SPÉCIFIQUE SFC
DE LA MASSE W, DE LA POUSSEE T, ET DU PRIX P.**   Fig 4.1
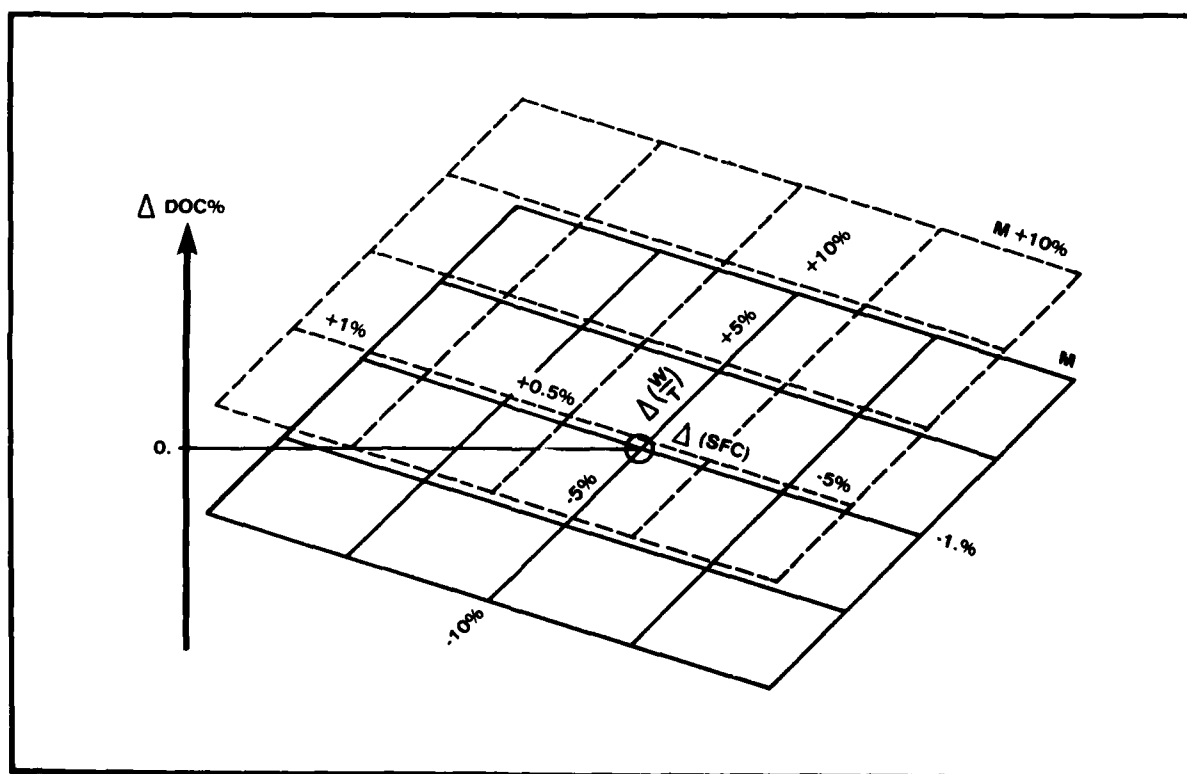
**EFFET SUR LE DOC DE LA CONSOMMATION SPÉCIFIQUE SFC,
DE LA MASSE W, DE LA POUSSÉE T, ET DU COÛT DE MAINTENANCE M.**   Fig 4.2

Il en est déduit un "facteur" de sévérité comprenant :

- un terme lié à la durée du vol :
$$\frac{43 + 1,6\ D}{100 + 4,1\ D}$$

- un terme lié aux cycles :
$$\frac{57 - 1,6\ D}{(100 + 4,1\ D)t}$$

Le coût de maintenance est lui-même le produit par S de la somme de deux termes (en dollars 1978/heures de vol) :

Coût des pièces   : $1,16\ T + 2,8\ (B - 1)$

Heures de main-d'oeuvre : $0,037\ T + 0,1\ B$

où B est le facteur de dilution (by-pass ratio) du moteur, choisi comme indicatif de complexité. Ces formules tiennent compte, en particulier, de l'expérience acquise avec General Electric sur le CF6/50.

En fait, pour revenir aux moteurs militaires, plus que ces formules, valables au stade d'un avant projet) ce sont les analyses qui ont permis de les établir, qui sont utilisables.

CHAPITRE 5 - ETUDE SUR LA MAINTENANCE DU 09 K 50

5.1. PRINCIPES DE LA SIMULATION ET OBJET DE L'ETUDE SUR 09 K 50

5.1.1. Les modèles établis par l'Atelier Industriel de l'Aéronautique de Bordeaux et par la SNECMA font vivre, par semaine ou décade, un parc de moteurs et un parc de sous-ensembles.

Les moteurs sont mis en service suivant un calendrier. Les évènements qui provoquent la mise hors service d'un moteur sont codés : dépose programmée ou accident et incident introduits de manière aléatoire dans le cadre d'hypothèses.

En outre les moteurs ou les sous-ensembles, compte tenu du suivi de leur âge et de leur potentiel restant d'une part et de l'apparition (introduite aléatoirement dans le cadre d'hypothèses) de dommages lors d'une visite, font l'objet ou non d'un retour en usine (RU).

L'activité aérienne, la périodicité des visites (s'il y a lieu) les temps d'immobilisation (suivant les opérations) et de transfert, le potentiel restant perdu au 4ème échelon (Usine de Réparation) ou au 2ème échelon (Atelier de Base) font également l'objet d'hypothèses, ainsi que le mode de recomplètement.

5.1.2. La réparation du moteur 09 K 50 s'effectue, depuis le début de l'année 1977 à l'Atelier Industriel de l'Aéronautique de Bordeaux, selon une méthode nouvelle dite : réparation en SERI (Sous Ensembles à Réparation Individualisée).
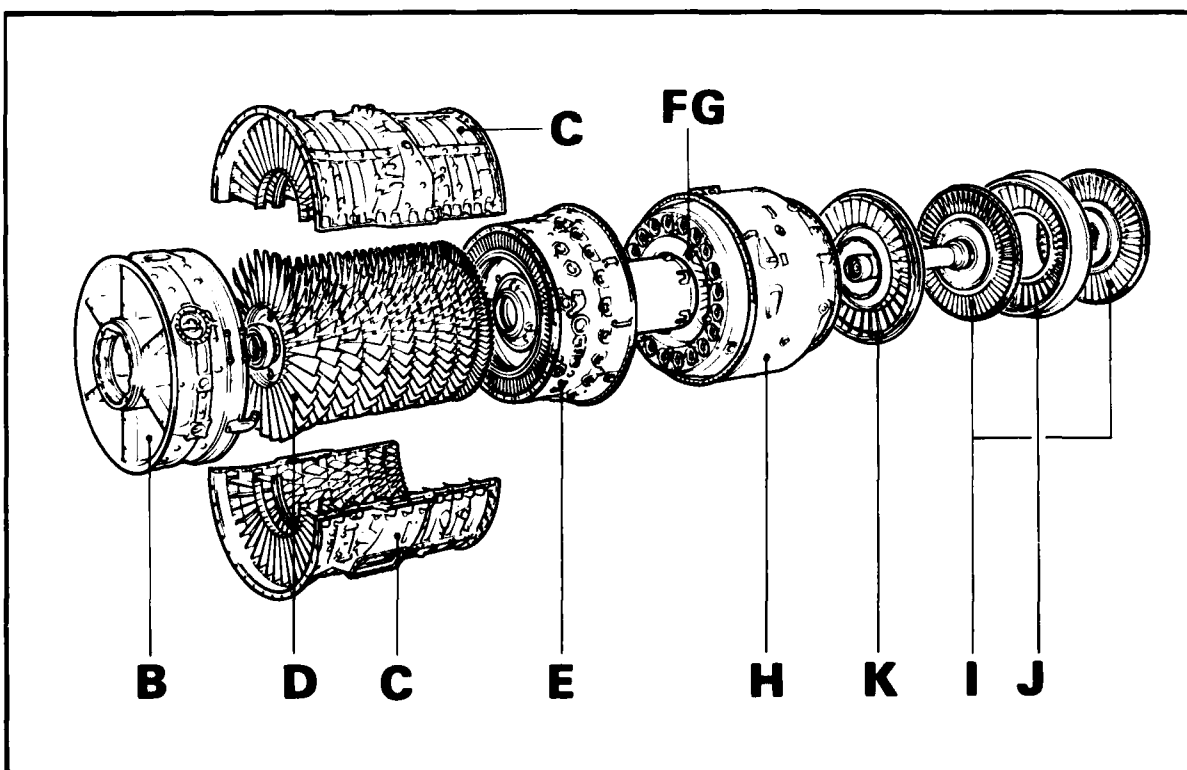
SOUS ENSEMBLES ATAR 9K50   **Fig 5.1**

Cette méthode doit en fait être considérée comme une transition entre la réparation classique ou "traditionnelle" encore utilisée aujourd'hui pour les moteurs militaires et la maintenance modulaire déjà expérimentée dans le domaine civil.

Cette méthode peut s'appliquer à des matériels dont la conception de base n'est pas modulaire.

Les principes essentiels retenus pour cette réparation, à savoir :

- utilisation de limites de fonctionnement propres à chaque SERI

- en usine, un SERI ne subit une réparation que s'il est incidenté ou en limite de fonctionnement

- immobilisation en usine propre à chaque SERI et non tributaire du SERI à réparation longue,

tendent implicitement à faire admettre l'intérêt, au moins sur le plan financier, de cette réparation. Une confirmation par modèle de simulation a été demandée à la SNECMA.

5.2. DEFINITION DU MOTEUR UTILISE DANS LA SIMULATION

Suivant que la réparation est classique au SERI le moteur est composé comme suit : (voir figure 5.1)

Réparation classique	SERI
Un ensemble comprenant :	5 SERI :
Eléments circuit carburant/ divers	SERI A
Carter d'admission	SERI B
Stator compresseur	SERI C
Rotor compresseur	SERI D
Carter central	SERI E

et de 6 Sous-Ensembles

F - Mélangeur intérieur

G - Mélangeur extérieur

H - Carter de chambre

I - Rotor de turbine

J - Carter de turbine/distributeur II

K - Distributeur I

Un moteur qui doit subir une intervention au 4ème échelon rentre au 4ème échelon

Un SERI qui doit subir une intervention au 4ème échelon, nécessite le retour du moteur sur lequel il est monté au 4ème échelon

Un Sous-Ensemble (équivalent à un module) qui doit subir une intervention au 4ème échelon est déposé du moteur sur lequel il est monté en 2ème échelon, un autre S.E est monté en remplacement.

Le moteur reconstitué devient un moteur disponible au 2ème échelon, le S.E rentre seul au 4ème échelon.

5.3. COMPARAISON ENTRE LA REPARATION CLASSIQUE, ET LA REPARATION EN SERI.

5.3.1. Nombre de retours en usine de moteurs.

La réparation en SERI apporte un accroissement de retours en usine de moteur de + 17 %.

Ce pourcentage apparaît lorsque l'ensemble du parc a déjà subi une 1ère réparation en SERI.

5.3.2. Coût Main-d'Oeuvre.

Au 2ème échelon : Le type de réparation n'a pas d'influence sur le coût.

Au 4ème échelon : La réparation en SERI apporte un gain de 30 à 35 %.

La réparation en SERI apporte un gain sur le coût Main-d'Oeuvre global de 20 à 25 %.
(le coût M.O. calculé ici ne prend pas compte :

5-12

- les interventions programmées sur avion,

- l'entretien du canal et des accessoires).

5.3.3. Besoins en volant.

      La réparation en SERI apporte un gain d'environ 14 %.
      (l'étude exclut le canal et les accessoires).

5.3.4. Ces résultats sont basés sur une comparaison entre une réparation classique et une réparation en SERI "optimale".

      Cela signifie que les choix des paramètres retenus sont les "meilleurs" qui ressortent d'études comparatives faites :

- sur le type de recomplètement, c'est-à-dire sur le critère du choix des SERI au moment d'un assemblage moteur,

- sur la valeur du potentiel restant au-delà duquel il n'est pas rentable de laisser un SERI en l'état lorsqu'il se trouve au 4ème échelon (Potentiel perdu ΔLF4),

- sur la valeur du potentiel restant du moteur au-delà duquel il est rentable de rentrer le moteur au 4ème échelon lors d'une intervention au 2ème échelon (Potentiel perdu ΔLF2).

5.4. ETUDE SUR LE CHOIX DU RECOMPLETEMENT

5.4.0. Deux recomplètements ont été étudiés :

- A) FIFO : le choix se fait sur l'ancienneté du SERI dans l'état volant disponible au 4ème échelon (First In First Out).

- B) OPTIMISE : le choix se fait sur une optimisation des potentiels restants sur chaque SERI après interventions.

5.4.1. Nombre de retours en usine de moteurs.

      Le recomplètement "FIFO" apporte en moyenne une augmentation de 15 % du nombre de Retours en Usine.

5.4.2. Coût Main-d'Oeuvre.

      Le coût Main-d'Oeuvre n'est pas influencé par le choix du recomplètement.

      Le coût sensiblement inférieur au 2ème échelon avec le choix "FIFO" est compensé par le coût sensiblement supérieur au 4ème échelon.

5.4.3. Besoins en volants.

      Le recomplètement "optimisé" apporte un gain d'environ 4 %.

5.4.4. Il a été conclu qu'un recomplètement établi à partir d'un optimisation sur les potentiels restant des SERI était un élément favorable.

5.5. ETUDE SUR LES POTENTIELS PERDUS

      Lorsqu'un moteur subit une intervention à l'atelier de la base aérienne (2ème échelon), quel est le potentiel restant au moteur au-dessous duquel il est rentable de le retourner en Usine de Réparation (4ème échelon) ? De même le moteur étant démonté au 4ème échelon, quel est le potentiel restant aux Sous-Ensembles à Réparation Individualisée au dessous duquel il n'est pas rentable de les remonter en les laissant en l'état ?
      Pour le déterminer, les modules permettent de faire le bilan des retours en usine, de la main-d'oeuvre en 2ème et 4ème échelons, des besoins en volant, pour diverses hypothèses de potentiel perdu ΔLF (quelquefois appelés queues de potentiel) et de faire apparaître les valeurs optimales.

      Hypothèses faites (Voir tableau de la page 13)

      au 2ème échelon 30, 50, 100, 200 heures

      au 4ème échelon 200, 300, 360, 400 heures

      Les valeurs optimales retenues pour le potentiel perdu sont 50 heures au 2ème échelon et 360 heures au 4ème échelon.

5.6. CONCLUSION

      La simulation a montré que la réparation par Sous-Ensemble à Réparation Individualisée apporte des gains significatifs sur la maintenance du 09 K 50.
      Le choix des recomplètements doit être optimisé sur les potentiels restant des SERI. L'optimum pour les potentiels perdus se situe à 50 heures au 2ème échelon et à 360 heures au 4ème échelon.
      L'expérience a confirmé les résultats de cette simulation et a montré en outre un gain en consommation de rechanges très important.

Δ LF (h)	Retours en usine	Main d'Oeuvre	Besoins volants	Bilan
2ème échelon 30				
50	mini	mini	mini	optimum
100				
200	+ 15 %	+ 6 %	+ 3 %	
4ème échelon 200	+ 17 %		+ 6 %	
300		faible		
360	mini	influence	mini	optimum
400				

CHAPITRE 6 - ETUDES SUR LA MAINTENANCE DU LARZAC

6.0. Il a été demandé par les Services Officiels d'effectuer une série d'études à l'aide du programme de simulation SNECMA, qui permette de choisir, pour le parc LARZAC, la méthode de maintenance la mieux adaptée à ce moteur; c'est-à-dire celle qui donnera à la fois les coûts minima d'entretien au 2ème et au 4ème échelons, les coûts minima d'acquisition, la meilleure disponibilité du matériel.

Les études effectuées ont consisté :

- à comparer différentes méthodes :

. de maintenance au 2ème échelon,
. de réparation au 4ème échelon.

- à mesurer la sensibilité de certains paramètres.

6.1. MODULARITE TOTALE (Voir figure 6.1.)

Le moteur LARZAC étant de conception modulaire, la première étude entreprise est une simulation d'un parc de moteur en exploitation selon le concept de la modularité totale au 2ème échelon dès la mise en service, à l'exception du prélèvement de quelques échantillons de moteurs complets rentrant au 4ème échelon, et de quelques cas où le moteur complet nécessite une remise en état.

La flotte est composée de 150 avions; il peut s'agir en réalité de plusieurs bases ayant des interactions totales entre elles du point de vue logistique.

La modularité implique :

- des modules disponibles au 2ème échelon : ou modules de volant,

- un choix dans le prélèvement du module de remplacement parmi ces volants.

Les conséquences sur les coûts d'entretien, les coûts d'acquisition, la disponibilité du matériel, de 3 choix de recomplètement ont été comparés :

(1) le module de remplacement est choisi au hasard; c'est "qualitativement" la solution la plus simple,

(2) le module de remplacement est choisi en fonction de son ancienneté dans l'état volant : le plus ancien,

(3) le module de remplacement est choisi en fonction de son potentiel restant vis-à-vis des potentiels restants des autres modules sur moteur.

Ces deux derniers choix nécessitent une gestion du matériel complexe surtout dans le cas où le matériel est en exploitation sur plusieurs bases.

Le résultat de l'étude est, compte tenu des hypothèses retenues sur le potentiel restitué en usine, qu'un recomplètement qui ne serait pas au "hasard" apporte peu d'intérêt.

Cependant, puisqu'un recomplètement optimisé sur le potentiel restant lors d'un échange modulaire apporte peu, il est envisagé d'étudier l'hypothèse d'un désassemblage complet du moteur au 2ème échelon, afin d'étendre les possibilités du choix sur les modules. Cette hypothèse paraît d'autant plus réaliste que les temps de démontage du LARZAC sont faibles.
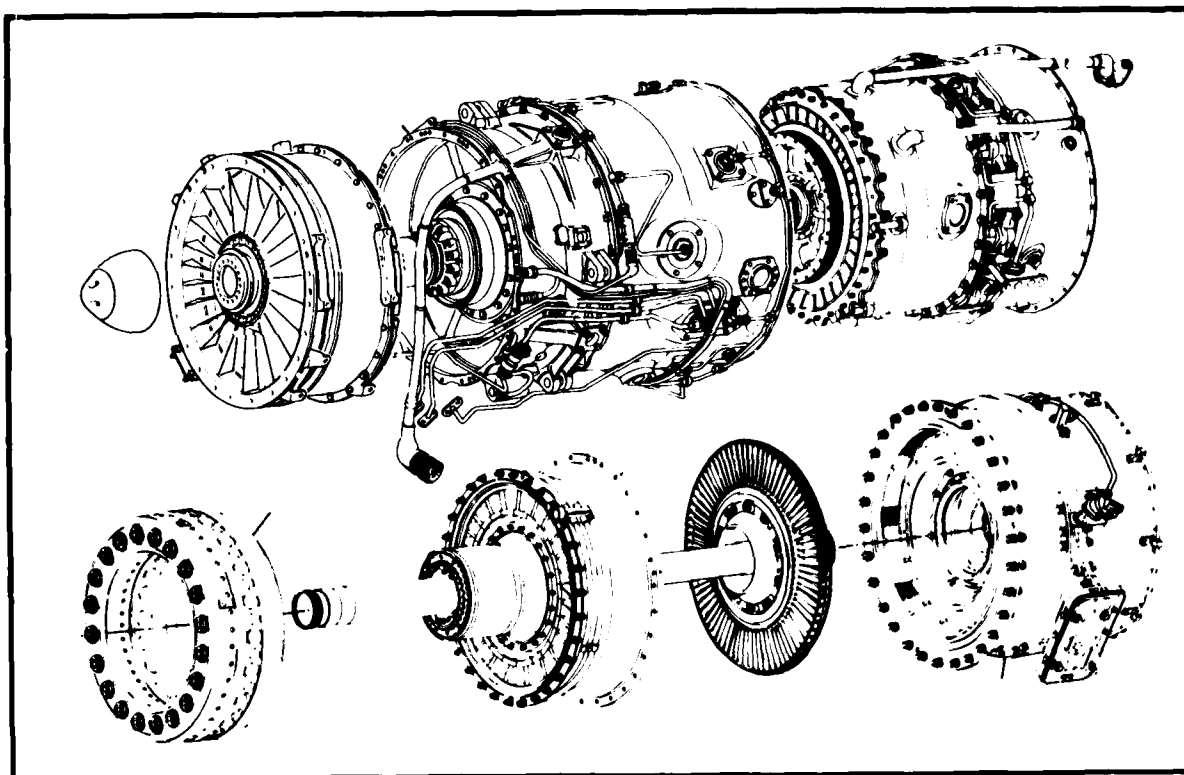
DÉMONTAGE MODULAIRE LARZAC   **Fig 6.1**

Finalement, cette maintenance permet, par rapport aux échanges de modules, une optimisation plus effective qui a pour conséquence une meilleure disponibilité du matériel, des interventions moins nombreuses au niveau du moteur. Mais chaque intervention coûte plus cher. La résultante sur les coûts main-d'oeuvre totaux est un abaissement du coût de 7 % environ. Le coût d'acquisition est fortement majoré : de + 15 %.

6.2. REPARATION TYPE SERI

Les études précédentes reposent sur une modularité totale au 2ème échelon.

La recherche suivante consiste à chiffrer l'opportunité d'une réduction de la modularité au 2ème échelon, et de la reporter au 4ème échelon : il s'agit d'étudier l'intérêt d'une réparation du type à Sous-Ensembles à Réparation Individualisée.

Il a été retenu 6 S.E.R.I.
          et 3 Modules (ou 3 sous-ensembles),

le recomplètement au 4ème échelon se faisant à partir d'une optimisation sur les potentiels restants.

Les résultats montrent, comparativement à la maintenance modulaire au 2ème échelon, un coût d'acquisition beaucoup plus élevé : + 16 % de besoins en volant avec cependant une disponibilité supérieure du matériel, des déposes moteurs pour interventions sur les S.E.R.I. ou les modules moins nombreuses et mieux réparties dans le temps.

Le coût total main-d'oeuvre est sensiblement le même.

En conséquence, la méthode de maintenance S.E.R.I. n'a pas été retenue.

La conclusion tirée des études sur la maintenance est :

La maintenance à retenir pour le LARZAC est la maintenance modulaire avec échange des modules au 2ème échelon et recomplètement des moteurs au hasard.

On étudie ensuite l'influence que peuvent avoir certains paramètres sur cette maintenance.

A savoir :

- la taille de la flotte,

- la valeur du potentiel perdu au 2ème échelon,

- le temps de transit et de réparation.

6.3. INFLUENCE DE LA TAILLE DE LA FLOTTE :

L'hypothèse retenue jusqu'alors de 150 avions sur une base est une simplification.

En réalité, il y aura 2 bases avec 60 avions chacune, et 30 avions "détachés".

S'il n'y a pas d'interaction entre les deux bases, si l'éloignement amène à des transits excessifs par exemple, les besoins en volant pourraient se trouver majorés, d'où la demande de comparer les besoins en volant pour :

- un parc de 150 avions,

- un parc de 60 avions.

La 2ème exploitation conduit à un supplément des besoins de + 8 % environ.

Il s'agit donc d'un paramètre important sur le coût d'acquisition.

6.4. INFLUENCE DE LA QUEUE DE POTENTIEL "PERDU" : ΔLF2

L'hypothèse retenue pour les études précédentes est :

ΔLF2 = 100 h sur tous les modules,
sauf ΔLF2 = 260 h sur le carter de sortie.

Nous avons repris l'étude avec :

ΔLF2 = 200 h sur tous les modules,
sauf ΔLF2 = 260 h sur le carter de sortie.

Les résultats montrent qu'un ΔLF2 plus élevé conduit à plus de modules révisés pour limite de fonctionnement, à moins de déposes moteurs, à un meilleur étalement de ces déposes dans le temps.

Les besoins en volant ne sont pas modifiés. Le coût d'entretien total est légèrement plus élevé = + 3 %.

Un Δ LF individualisé par module est à rechercher pour le LARZAC.

6.5. INFLUENCE DES TEMPS DE TRANSIT ET DES TEMPS D'ACCESSIBILITE ET DE REPARATION :

L'hypothèse retenue pour les études précédentes comme temps de transit est de : 2 mois aller + retour.

Nous avons repris l'étude avec :

- durée du transit aller + retour : 1 mois
                                     5 mois

Les résultats montrent que l'influence du temps de transit est très importante sur le coût d'acquisition. Cette influence cependant est pondérée par la valeur relative des temps de réparation par rapport au transit.

Une dernière étude est faite avec des temps d'accessibilité aux modules majorés de + 6j et des temps de réparation des modules majorés de + 18j.

L'influence de ces majorations sur les besoins en volant est de même importance que des majorations identiques des temps de transit.

CHAPITRE 7 - PROCEDES ET METHODES DE SURVEILLANCE

Pour tout constructeur, disposer des meilleurs procédés de surveillance applicables sur moteur, autorisant la politique de maintenance la plus efficace et la moins coûteuse est l'objet d'efforts constants.

Ce qui suit résume un travail de synthèse établi fin 1978 des travaux faits par la SNECMA portant sur :

- la surveillance du circuit d'huile :

. analyse spectrométrique

. analyse des particules

- l'analyse vibratoire

- la gammagraphie

- l'endoscopie et ses variantes

- la surveillance des circuits électriques et électroniques.

7.1. ANALYSE SPECTROMETRIQUE DES HUILES

7.1.1. Deux solutions sont applicables.

- Spectrophotométrie d'absorption atomique où l'échantillon mis en solution sous forme d'un fin brouillard est introduit dans une flamme, laquelle est sur le parcours d'un rayonnement dont on mesure l'absorption pour la longueur d'onde caractéristique de l'élément à déceler.

- Spectrométrie d'émission où un arc électrique est établi entre une électrode fixe et une électrode tournante baignant dans l'échantillon d'huile. Les atomes contenus dans l'huile sont excités et émettent des raies spectrales, séparées par un réseau, dont les longueurs d'onde sont caractéristiques de la nature des éléments et l'intensité en rapport avec les concentrations.

    Les avantages et les inconvénients des deux méthodes sont :

- Spectrophotomètre d'absorption atomique

    . Seuil de détection très bas (entre 1/10 et 1/100 de ppm).

    . Excellente reproductibilité.

    . Il nécessite la dilution des échantillons d'huile (dans le méthylisobutil-cétone par exemple).

    . Pour un échantillon, il faut effectuer autant de mesures que d'éléments recherchés.

    . Capacité d'analyses d'environ 40/jours.

- Spectrométrie d'émission

    . Seuil de détection moyen (entre 0,3 et 0.5 ppm).

    . Reproductibilité moyenne

    . Ne nécessite pas la dilution des échantillons

    . Tous les éléments recherchés sont analysés simultanément

    . Ne nécessite pas un personnel très qualifié

    . Capacité d'analyses de 100 à 150/jours.

    La SNECMA et de nombreux utilisateurs dont l'Armée de l'Air Française et la Marine ont choisi la spectrométrie d'émission plus facile de mise en oeuvre. La spectrophotométrie a un temps d'analyse beaucoup plus long, mais, plus précise, elle a cependant été choisie par certains clients.

    On obtient une concentration qu'il faut relier à la vitesse d'usure.

7.1.2. Interprétation des mesures de concentration.

    En fait la vitesse d'usure recherchée n'est qu'un des facteurs dont dépend la concentration. Il y a eu outre le volume d'huile dans le circuit, la consommation d'huile, le temps de fonctionnement et la fréquence des compléments de plein.

    La vitesse d'usure est donnée par :

$$m = \frac{C1 \left(1 + \frac{qT}{2Vo} \ \frac{n-1}{n} \right) - Co \left(1 - \frac{qT}{2Vo} \ \frac{n+1}{n} \right)}{\frac{n}{q} \ \log \frac{1}{1 - \frac{qT}{Von}}} \quad \text{en mg/h}$$

ou Co et C1 sont les concentrations mesurées en début et fin de période en mg/litre.

    q   la consommation d'huile en l/h

    T   le temps de fonctionnement moteur en heures

    Vo   le volume d'huile après plein en litres

    n   le nombre de pleins dans la période

    Dans l'application de cette méthode, les seuils d'intervention sont fixés en vitesse de pollution. Le suivi de ce paramètre constitue donc un moyen de surveillance précis du circuit, il traduit notamment l'urgence d'intervention. En contre-partie, elle exige une procédure de suivi sévère.

    Une collaboration entre la SNECMA et l'Armée de l'Air Française a permis de vérifier expérimentalement sur les moteurs ATAR, la validité de la méthode. Elle est actuellement largement utilisée sur les matériels militaires et civils et est introduite dans les Manuels de Maintenance.

7.1.3. Possibilités d'amélioration des diagnostics.

Malgré la présence de plusieurs symptômes (ou en l'absence d'autres symptômes), il peut être difficile de localiser l'avarie. Certains moyens permettraient d'améliorer la situation :

- Répartition judicieuse des matières en fonction des différents modules à distinguer ou utilisation de revêtement spécifique à un module : ainsi, la nature de la pollution suffit à en trouver l'origine.

- Implantation de système efficace de captation des particules sur les retours d'huile de chaque module : il suffit ainsi de remonter en amont pour localiser la source.

- Utilisation des traceurs :

  Une étude menée sur ATAR 101 avait consisté en l'utilisation de divers revêtements au niveau des portées de roulement sur chaque ensemble afin de distinguer sans ambiguité l'origine d'une usure. L'argentage, le cuivrage, le chromage et le cobaltage ont été parmi les revêtements essayés.

7.2. ANALYSE DES PARTICULES

7.2.1. Recueil des particules.

Le but de cette analyse est d'examiner les particules de grandes dimensions (supérieures à ~ 50 microns), et qui sont souvent les symptômes d'avaries tels que écaillage des roulements ou arrachements de métal par rotation des bagues des roulements.

A l'origine, les filtres avaient été placés dans les circuits d'huile pour protéger les gicleurs et garantir une certaine pureté de l'huile de lubrification mais, très vite, on s'est aperçu de l'intérêt évident qu'il y avait à surveiller les limailles au point que l'on a ajouté des filtres spéciaux et des barreaux magnétiques, dans les retours d'huile, pour détecter la présence des limailles.

Un dispositif spécial baptisé "piège à particules" a été développé à la SNECMA.

Il est à visite rapide (verrouillage baïonnette) et comporte un barreau magnétique pour capter les limailles magnétiques et un filtre fin (< 50 microns) pour capter les limailles non magnétiques. Il est à self obturation pour éviter les écoulements d'huile lors des inspections. Son efficacité est voisine de 100 % et il permet un examen très rapide et efficace.

7.2.2. Examen des particules.

Les particules non magnétiques sont identifiées généralement par attaque chimique à l'aide de réactifs spécifiques à chaque base d'alliage.

Ensuite, les particules magnétiques (qui sont les plus fréquentes et surtout les plus importantes pour le diagnostic) sont enrobées dans une résine. L'ensemble est poli, puis attaqué chimiquement pour mettre en évidence la structure des alliages composant les particules.

Un examen au microscope métallographique permet donc de trouver à quels types d'alliage on a affaire. On distingue essentiellement : acier ordinaire, acier à roulement, acier cémenté, acier inox.

Pour obtenir la nuance exacte de l'alliage, une analyse complémentaire peut être effectuée par spectrographie, dans une cellule spéciale.

La limaille est fixée dans un support conducteur en graphite fritté et exposée à un bombardement d'ions d'un gaz ionisé. La particule ainsi bombardée génère une lumière comprenant les longueurs d'onde des métaux présents dans la limaille. Cette lumière est envoyée dans un spectromètre donnant les proportions des différents métaux et, par conséquent, l'alliage. On peut, en particulier, distinguer deux alliages de la même famille. Les limailles analysées à l'aide de cette cellule ne sont pas détruites, ce qui permet de procéder à des contre-expertises. Cette cellule peut s'adapter à tout spectromètre, en particulier, à celui capable d'analyser l'huile et les limailles.

7.2.3. Diagnostic.

En fonction de l'importance des différents facteurs relevés, la décision de déposer ou non le moteur est à prendre. Un guide a été établi à cet effet.

L'ensemble des éléments relatifs à l'analyse d'un type de limailles et à l'avarie correspondante est regroupé dans une fiche. La collection de ces fiches constitue le guide de recherche des pannes "limailles". Un tel guide permet, à l'aide de moyens très limités (binoculaire) de faire des analyses grossières sur place et d'avoir une idée de l'intervention nécessaire sur le moteur, sans attendre le résultat de l'analyse du laboratoire. Ce point est particulièrement important lorsque les inspections des filtres sont faites la nuit, alors que les laboratoires fonctionnent le jour; ceci peut permettre de décider de remplacer un moteur dans la nuit plutôt que de courir le risque d'une avarie en exploitation.

7.3. ANALYSE VIBRATOIRE

L'analyse vibratoire est opérationnelle et mise en application sur l'ensemble du parc ATAR 09C et sur le parc ATAR 09 K 50 afin de recueillir les éléments statistiques indispensables.

- Enregistrement vibratoire.

Le signal vibratoire global peut être enregistré sur bande magnétique à l'aide d'une chaîne représentée schématiquement sur la figure 7.1.
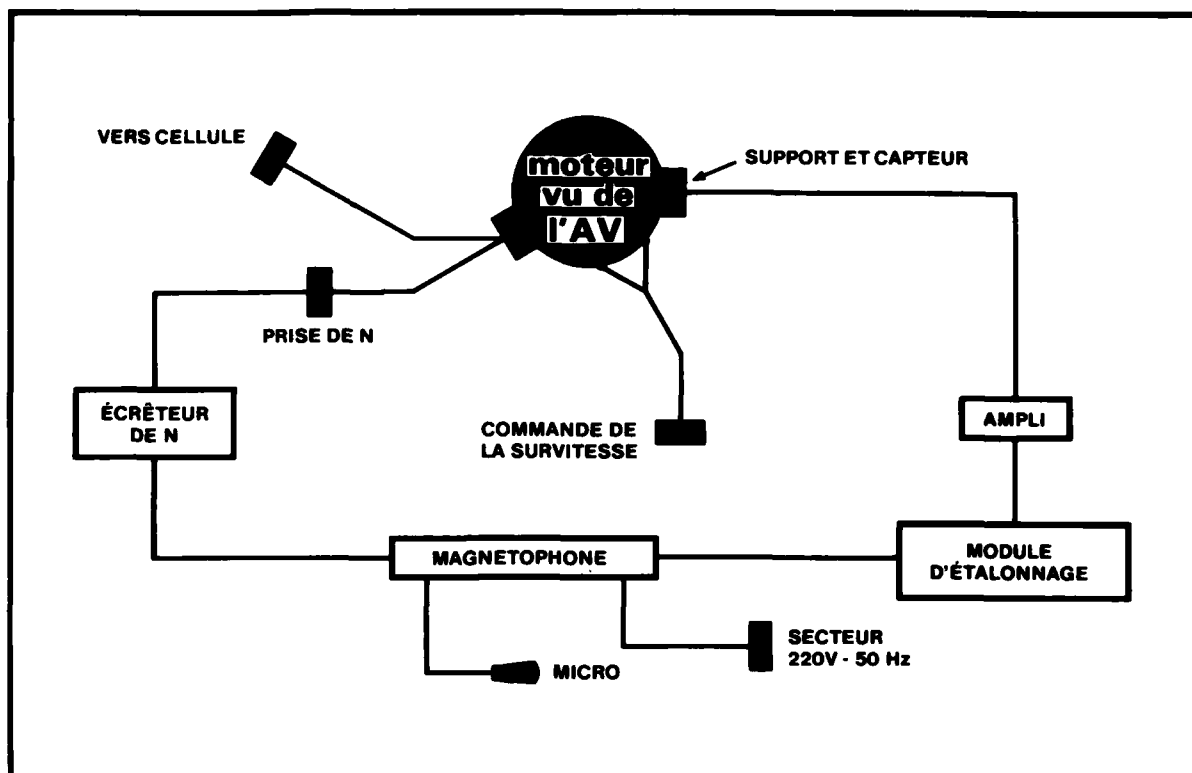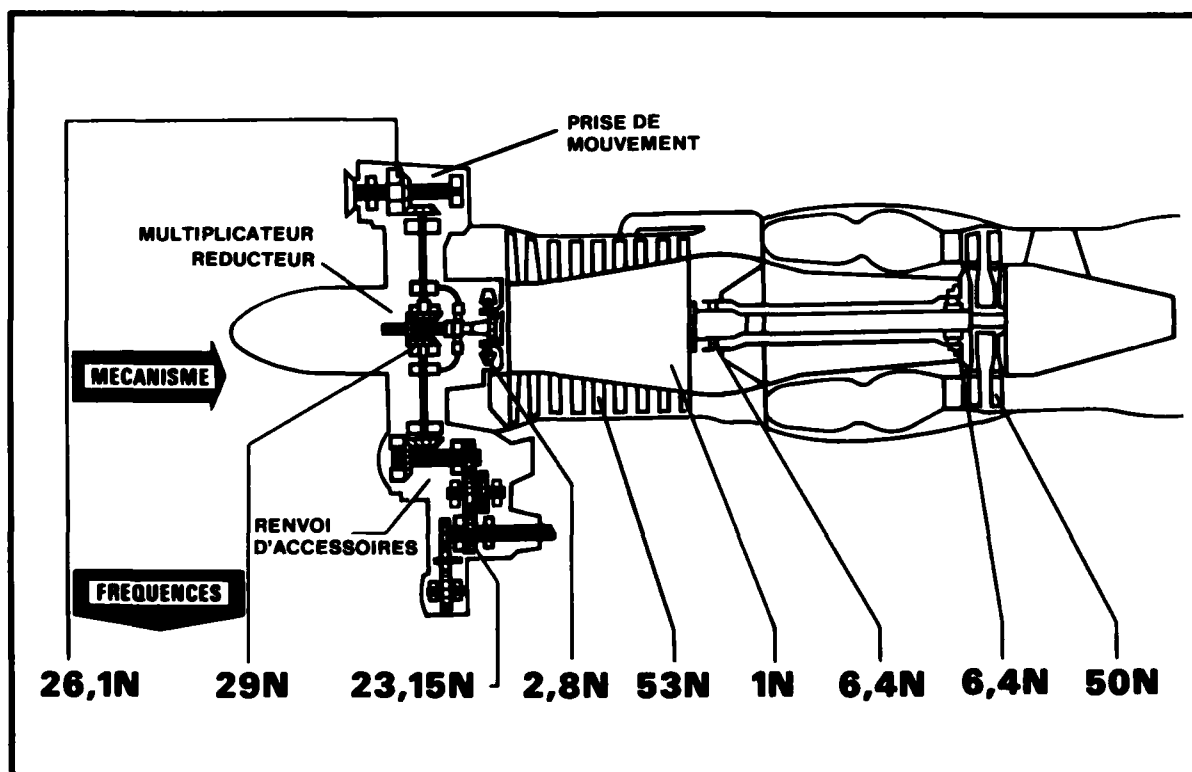
5-18

SCHÉMA DE PRINCIPE DE LA CHAINE D'ENREGISTREMENT - ATAR 9C

Fig 7.1

FRÉQUENCES CARACTÉRISTIQUES ATAR 9C

Fig 7.2

L'enregistrement s'effectue sur moteur avionné ou au banc de point fixe.

L'analyse vibratoire permet de retrouver, à partir du signal enregistré sur bande magnétique, chaque composante correspondant à un organe déterminé. Plusieurs types de processus analytiques de dépouillement peuvent être utilisés, par point, automatiques, par filtre de poursuite.

7.3.1. Dépouillement par filtre de poursuite.

La SNECMA a étudié et réalisé un filtre de poursuite à 12 voies. Cet appareil permet de réaliser un tracking du signal vibratoire global. En l'associant à une série de tables traçantes, on obtient le tracé de l'évolution des intensités vibratoires de 12 ordres pré-sélectionnés en fonction du régime. En repassant plusieurs fois la bande magnétique, on peut ainsi obtenir les tracés sur tous ordres pré-déterminés de 1 à 99. Cette méthode peut constituer un complément au dépouillement automatique car elle permet en particulier, de rechercher les ordres correspondant à des intensités vibratoires très faibles.

Les grandeurs considérées pour ces analyses sont les suivantes :

- la vitesse efficace pour la surveillance des éléments pour lesquels la fréquence de vibration est moyenne,

- l'accélération pour la surveillance d'organes pour lesquels la fréquence de vibration est élevée et mettent en jeu de faibles énergies cinétiques.

7.3.2. Diagnostic.

Deux études parallèles ont été menées.

- Le suivi du signal "hors tout" (basses fréquences).

Il permet la surveillance du balourd de l'ensemble mobile compresseur-turbine qui constitue l'origine essentielle des vibrations perceptibles par les pilotes.

Cette méthode peut être appliquée sans enregistrement à partir d'un indicateur de vibrations. Ce dispositif a été mis au point pour ATAR 09C et équipe les cabines de point fixe ATAR 09 K 50.

- Le suivi en large bande par analyse vibratoire.

L'étude a été menée de façon statistique. Grâce à la collaboration de l'Armée de l'Air et au développement des performances des capteurs à cristal piézo-électriques, les enregistrements vibratoires ont été réalisés sur un grand nombre de réacteurs. Des tableaus ont alors pu être constitués pour chaque ordre (Fig. 7.2.), ce qui a permis d'en déduire des moyennes. A partir des valeurs situées nettement en dehors des moyennes, des corrélations entre les niveaux ou l'aspect des spectres vibratoires et les constatations au démontage des moteurs ont pu être entreprises progressivement. La vérification de ces corrélations a été axée sur les recherches suivantes.

- présence d'avarie lorsqu'un symptôme vibratoire anormal était décelé,

- absence d'avarie en l'absence de symptômes.

Au fur et à mesure de l'avancement de l'étude et de l'acquisition des éléments de corrélation, un guide de signature de panne a été élaboré.

L'analyse vibratoire, qui permet de détecter l'apparition d'anomalies sans démontages, est susceptible, d'une part, de renforcer la sécurité, d'autre part, d'alléger la maintenance.

Son application, limitée précédemment à la chaine cinématique, avait permis de retirer du service certains renvois de commande; aujourd'hui appliquée au moteur complet, elle évite l'emploi de moteurs douteux.

Dans l'optique de la maintenance, l'application systématique de ce contrôle permet, d'ores et déjà, d' supprimer certaines opérations de maintenance programmées.

7.4. GAMMAGRAPHIE

7.4.1. Principes.

Il consiste donc à placer la pièce à examiner entre la source de rayonnements et le film.

Les sources utilisées en gammagraphie sont des isotopes artificiels. Suivant les pays, les isotopes disponibles peuvent être différents. En France on utilise essentiellement l'Iridium 192.

Il faut noter que le rayonnement issu de la source émet sur un angle de 360° qui permet donc d'effectuer un contrôle panoramique en un seul tir.

Ceci est particulièrement intéressant sur des carters de moteur, qui sont des pièces de révolution et on peut donc, en un seul tir, contrôler toute une virole circulaire. Le rayonnement qui ne rencontre pas de film est donc inutilisé.

7.4.2. Utilisation.

L'outillage nécessaire en gammagraphie est relativement simple. (voir figure 7.3.)

5-20
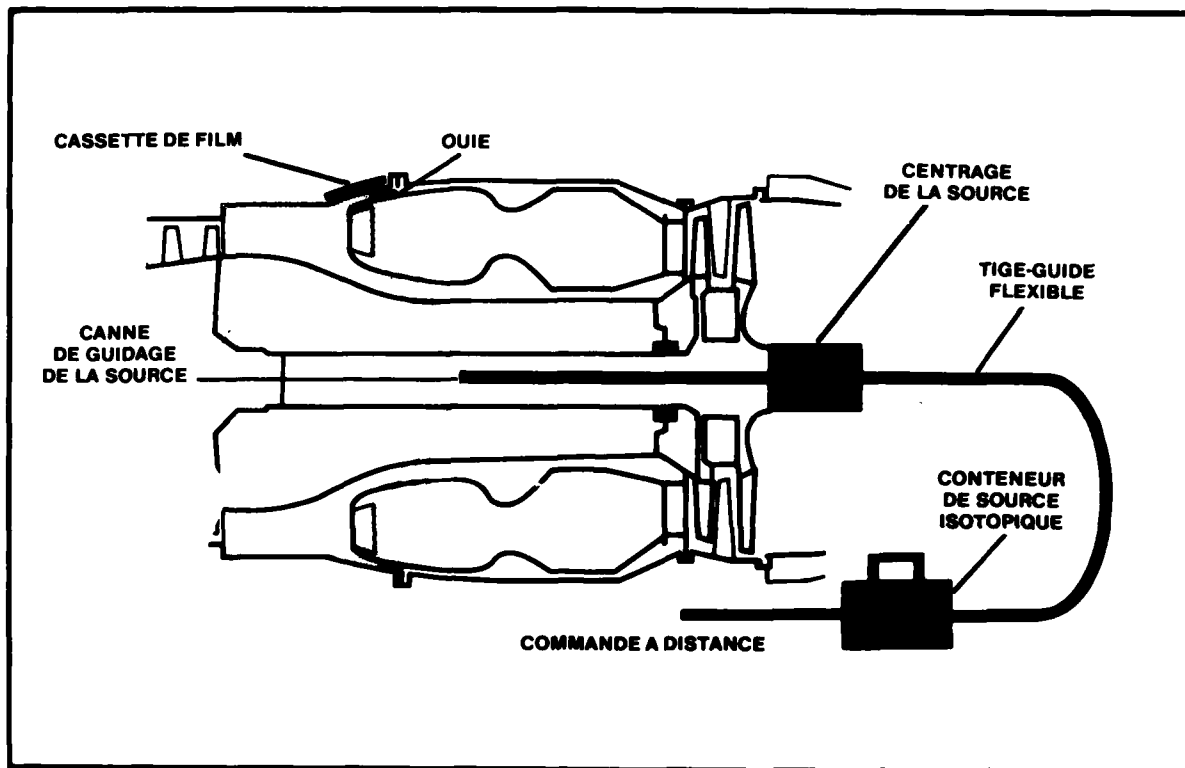
GAMMAGRAPHIE · CONTROLE DE LA CHAMBRE DE COMBUSTION. **Fig 7.3**

(a) outillage spécifique au moteur : il se limite à un outillage de centrage de la canne porte source.

(b) outillage standard :

- canne : la source pénètre dans sa position de contrôle par une canne creuse fermée à une extrémité - son diamètre est de 12 à 14 mm,

- conteneur de source avec source : le conteneur sert au stockage et au transport de la source. Il est généralement en Uranium appauvri, matériau très dense et qui apporte donc une excellente protection pendant les phases de son utilisation,

- télécommande : lorsque la source transite du conteneur vers l'intérieur du moteur (dans un conduit flexible entre le conteneur et la canne) il faut éviter d'approcher de la source qui émet alors le maximum de radiations puisqu'il n'y a aucune absorption autour d'elle. L'opérateur utilise donc une télécommande qui lui permet de provoquer ce transfert avec un recul suffisant (environ 15 mètres).

A la SNECMA, tous les moteurs nouveaux en étude sont l'objet de campagnes de tir systématiques pour déterminer toutes les possibilités de contrôle en gammagraphie et pour améliorer l'adaptation du moteur avant que le dessin de la Série ne soit figé.

7.5. ENDOSCOPIE

7.5.1. Domaine d'application.

Les applications de l'endoscopie découlent du mode de contrôle visuel qu'elle réalise et qui fait percevoir les défauts suivants :

- impact dû au passage d'un corps étranger,

- déformation,

- criques,

- traces de frottement ou d'usure,

- déplacement,

- colorations, pouvant traduire une surchauffe.
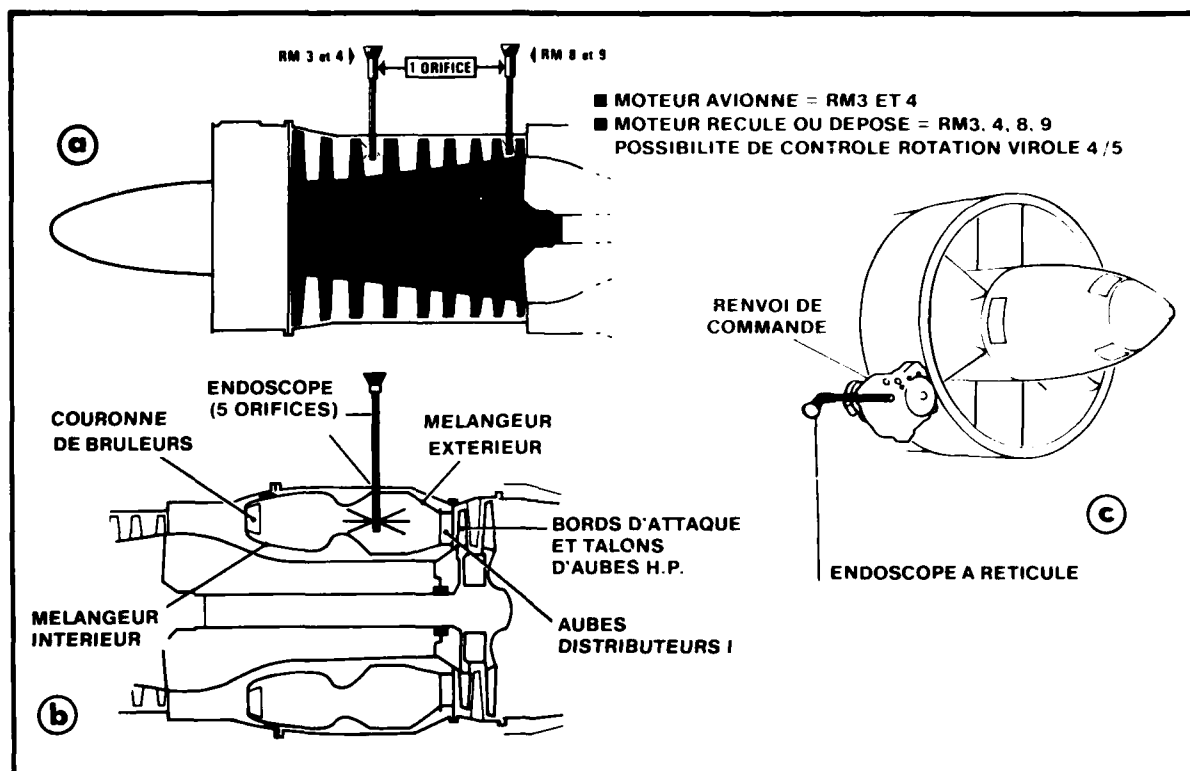
CONTROLES ENDOSCOPIQUES SUR ATAR 9K50 Fig 7.4

Or, sur un turboréacteur, il est particulièrement intéressant de visualiser les éléments qui sont, soit exposés à des dégradations de type aléatoire (aubages de compresseur), soit soumis à des ensembles mécaniques et thermiques sévères de contraintes (parties chaudes). Le domaine d'application préférentiel de l'endoscopie sera donc la veine d'air, c'est-à-dire :

- aubages mobiles du ou des compresseur (s) (figure 7.4. a)

- chambre de combustion (figure 7.4. b)

- aubages mobiles de turbine.

Ainsi, sur tous les nouveaux turboréacteurs, on trouve des passages endoscopiques donnant accès à ces parties du moteur par introduction radiale d'un endoscope au-travers des carters.

Par ailleurs, on a développé des applications spéciales de l'endoscopie telles que :

- endoscopie à réticule, pour le contrôle quantitatif d'usure de cannelures internes dans des arbres ou des pignons (figure 7.4. c),

- endoscopie de ressuage, pour réaliser le contrôle des criques non visibles à l'oeil nu dans des conditions d'accès limitées à celles de l'endoscopie classique,

- vidéo-scopie, qui consiste à remplacer l'oeil humain par une chaîne de télévision en circuit fermé.

7.5.2. Conditions d'adaptation du matériel endoscopique et du moteur.

Il faut que le matériel endoscopique soit adapté à la machine et vice versa. Il faut que les orifices d'accès tiennent compte des performances du matériel. L'expérience a montré que la réalisation d'une adaptation optimale passe impérativement par la satisfaction des conditions suivantes :

(a) une bonne répartition des orifices d'accès, le long de la veine d'air et au niveau des parties chaudes et périphériquement pour les parties qu'on ne peut faire défiler devant l'endoscope. Une bonne répartition est celle qui permet d'avoir uniquement recours à des endoscopes rigides.

(b) un dimensionnement approprié des orifices. Pour cela il faut d'abord bien connaître la nature des défauts à visualiser et leur distance. L'élément prépondérant dans le diamètre de l'orifice est la profondeur de champ. Pour guider les bureaux d'études de conception, des recommandations générales sur l'endoscopie ont été incluses dans le Manuel du Dessinateur.

(c) une définition appropriée des endoscopes. Le motoriste ne doit pas se contenter d'offrir des orifices endoscopiques à son client. Il doit lui préciser la nature du suivi en maintenance et lui recommander le matériel le mieux approprié. Le constructeur est conduit à proposer des "kits" endoscopiques dans lesquels l'utilisateur trouve le matériel nécessaire et suffisant pour le contrôle de son moteur.

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7.5.3. Vidéo-scopie, magnétoscopie, photo-endoscopie.

L'endoscopie pour le contrôle des aubages mobiles de compresseur a permis de diminuer les coûts d'entretien du moteur puisque le gain de main-d'oeuvre par rapport à un démontage et à un contrôle visuel est supérieur à 50 heures dans le cas de l'ATAR 09 K 50.
Mais en contrepartie ce contrôle s'est avéré fastidieux et fatigant pour les opérateurs. En effet, l'examen des quatre roues mobiles de l'ATAR 09 K 50, par couronnes successives, représente près d'un millier d'images.

Une chaîne de télévision en circuit fermé remplace l'oeil de l'opérateur en renvoyant l'image sur un récepteur de télévision.

Les images fournies par la chaîne de vidéo-scopie peuvent être aisément enregistrées sur magnétoscope pour garder en mémoire un contrôle.

Inversement, on peut enregistrer préalablement des défauts types sur bande vidéo et les comparer aux images du contrôle direct. La chaîne de vidéo-scopie a été prévue à cet effet avec deux voies d'entrée vidéo sur le moniteur pour un examen successif des images données par la caméra et par le magnétoscope.

Tout comme on peut monter une caméra de télévision sur l'occulaire de l'endoscope, on peut également y adapter un appareil photo.

La photographie à travers l'endoscope facilite le suivi de certains défauts qui affectent une pièce interne du moteur accessible à l'endoscope, lorsque l'on veut suivre l'évolution de ces défauts avec le vieillissement de la machine.

7.5.4. Endoscopie U.V.

L'idée est de créer un dispositif capable, dans les conditions d'accès qui sont celles de l'endoscopie, de réaliser les deux fonctions suivantes :

- une fonction de nettoyage et d'injection de produit de ressuage sur une zone douteuse,

- une fonction de visualisation du ressuage, pour statuer sur l'existence ou l'absence des criques.

7.6. APTITUDE A LA MAINTENANCE AVEC SURVEILLANCE.

Cette aptitude à la maintenance avec surveillance a été un des objectifs de définition du moteur M53. La figure 7.5. résume ses caractéristiques, cependant que la figure 7.6. montre le découpage modulaire du même moteur.
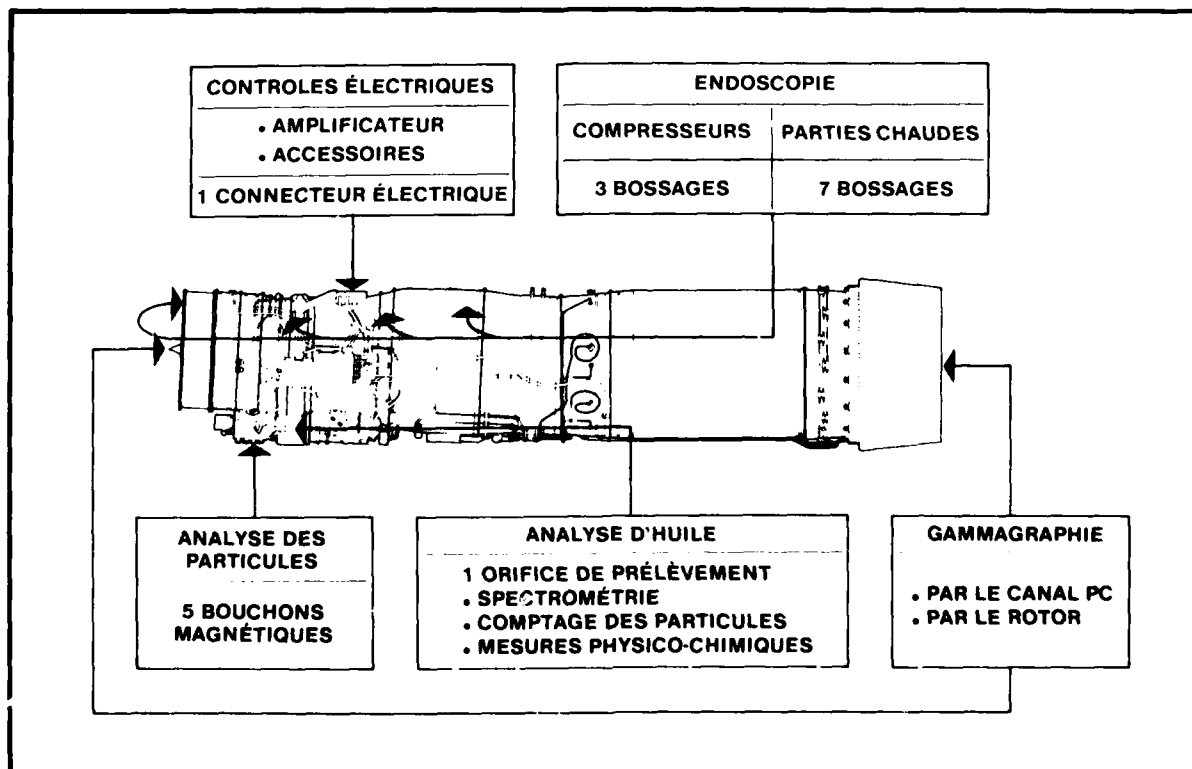
**APTITUDE A LA MAINTENANCE SELON L'ETAT
METHODES DE CONTROLE (M53)**

Fig 7.5

1 - COMPRESSEUR BP
2 - CARTER PRINCIPAL EQUIPÉ
3 - COMPRESSEUR HP
4 - CHAMBRE DE COMBUSTION
5 - DISTRIBUTEUR DE TURBINE
6 - TURBINE
7 - CARTER D'ECHAPPEMENT
8 - DIFFUSEUR
9 - CANAL PC
10 - TUYÈRE
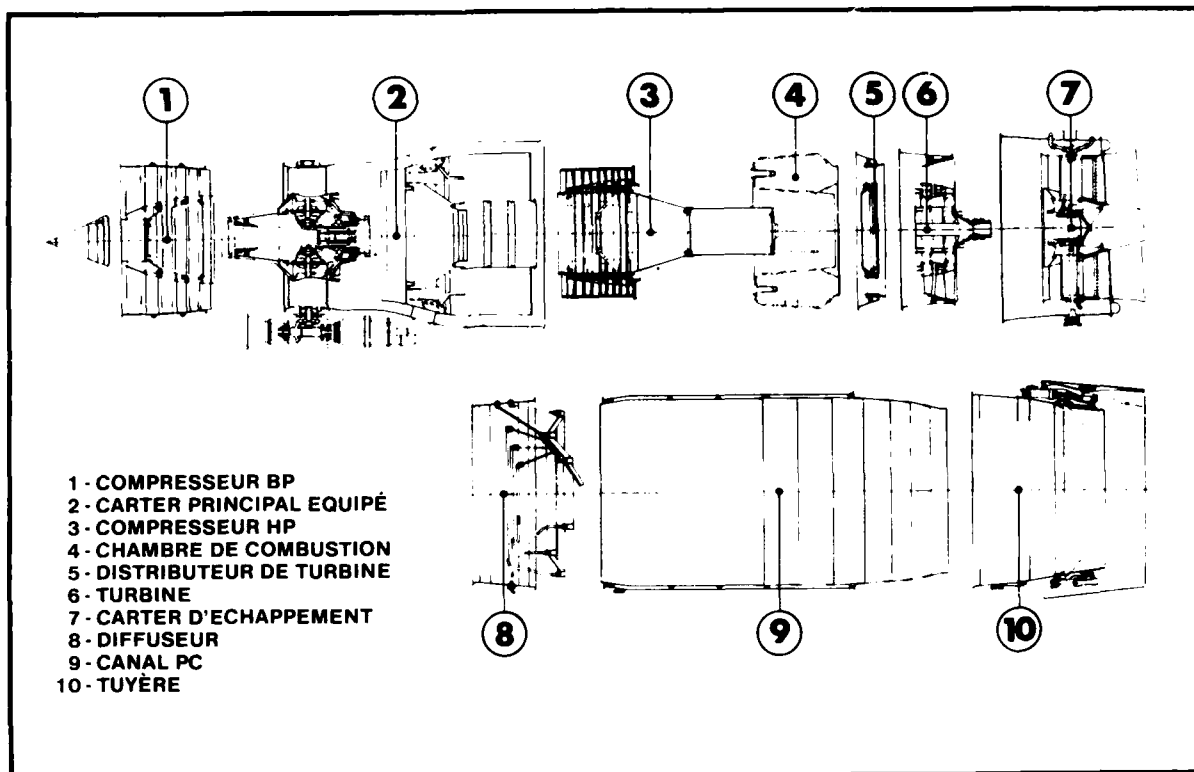
DEMONTAGE MODULAIRE (M53)   **Fig 7.6**

CHAPITRE 8 - TYPES D'ORGANISATION ADAPTES A DE TELS PROGRAMMES

8.1. OBJET

C'est principalement de l'organisation chez le constructeur de moteurs qu'il est question. Quelques commentaires sont faits sur les rapports avec les Services Officiels et les Coopérants éventuels.

Le problème est à considérer dès la recherche et le choix de ce que devrait et pourrait être le moteur pour lequel un programme est envisagé, qu'il s'agisse d'un moteur entièrement nouveau ou d'un nouveau développement d'un moteur existant. En général sont concernées chez le constructeur la plupart des fonctions technico-commerciale, financière, technique, production, logistique/maintenance et qualité et il est nécessaire que les rôles soient définis à toutes les phases.

8.2. STRUCTURES ET PROCEDURES

L'usage s'est établi chez les constructeurs de mettre une structure de coordination, pour chaque programme, pour la synthèse des informations et la préparation sinon la prise des décisions. Il peut y avoir divers degrés dans l'intégration à cette structure de moyens propres. Cela peut aller jusqu'à l'"îlot" du type de celui créé par la SNIAS pour l'hélicoptère Ecureuil où toutes les disciplines sont rassemblées dans un lieu et sous une autorité communs, bien que conservant un lien fonctionnel avec les unités dont elles sont détachées.

Dans cet îlot la circulation des informations, la prise des décisions relatives au programme se font de manière classique et aisée et pour autant qu'on ait regroupé des hommes de talent la réussite est spectaculaire.

Il n'est pas toujours possible ni souhaitable d'aller jusque là, au moins pour un programme majeur de moteur militaire.

La masse de moyens qu'il faut utiliser aux plans techniques, préparation de la production et de la maintenance par exemple doit dépasser un seuil critique au moment de leur utilisation.

Les problèmes de coordination ne sont pas seulement au niveau du programme moteur mais aussi au niveau de la répartition de ces moyens entre les programmes.

Un équilibre efficace entre continuité et répartition des actions et des pouvoirs est à trouver dans des procédures définissant : qui fait quoi, quand et comment, les décisions aux différents degrés et les instances d'arbitrage éventuel.

La prise en considération d'objectifs (coûts compris) au long de la vie du moteur ne peut que renforcer la nécessité d'efforts de mise au point d'une organisation adaptée.

8.3. COMPOSITION TYPE D'UNE FICHE PROGRAMME MOTEUR.

Avant de décrire un exemple d'organisation sur le déroulement d'un programme de développement il convient de rappeler une composition type de fiche programme :

- Indication de la mission et du domaine de vol

- Jeu d'objectifs avec latitudes d'adaptation possibles :

  . Poussée au décollage, en montée, en croisière,

  . Consommation spécifique en montée et en croisière,

  . Masse,

  . Coût et délai de développement jusqu'à homologation,

  . Coût de production pour une hypothèse de série et de cadence,

  . Consommation de rechanges valorisée,

  . Caractéristiques de modularité et maintenabilité.

- Eléments de pondération entre les objectifs ci-dessus et exigences contractuelles prévues ou exprimées.

8.4. TRAVAUX PREPARATOIRES AU DEROULEMENT D'UN PROGRAMME.

8.4.1. Au sein de la fonction technico-commerciale.

- Une exploitation permanente des informations recueillies auprès des avionneurs, et des Etats-majors sur leurs besoins futurs, leurs préoccupations, leurs objectifs de coût est menée.

- Une exploitation permanente est également faite des coûts d'exploitation ou d'utilisation des divers moteurs et de leur évolution, notamment ceux concernant la maintenance et les rechanges (taux de consommation et valeurs pour les différentes pièces) sachant qu'il s'agit d'un élément important du choix des utilisateurs à qui on proposera le nouveau matériel.

- Des méthodes sont élaborées pour estimer l'impact des variations des différentes caractéristiques techniques et économiques d'un moteur sur les avions existants ou probables en fonction de leur "mission".

- Il est tenu compte de l'évolution connue et prévisible des coûts de production des moteurs.

De ces données de base, est dégagée une esquisse de fiche programme.

8.4.2. Au sein de la fonction technique.

Une exploitation permanente est faite :

- des différents cycles envisageables, de ce qui en résulte sur les performances et caractéristiques d'un moteur et de ce qu'ils requièrent au niveau des composants,

- des possibilités et délais d'aboutissements des travaux sur l'amélioration des composants et sur les procédés de fabrication,

- des études statistiques de caractéristiques des moteurs et de leurs composants (en fonction de paramètres accessibles au stade de l'avant-projet) des coûts et délais de développement, ainsi que des coûts de production,

- des mises en mémoire et programmes de calcul informatiques permettant d'utiliser et combiner les diverses données acquises.

De ces données de base, il est dégagé des avant-projets sommaires permettant de concrétiser certains développements exploratoires et de jalonner les possibilités de réponse aux fiches programmes.

8.4.3. Au sein de la fonction maintenance/logistique.

Une exploitation permanente est faite, en liaison avec la fonction Qualité :

- des informations recueillies sur le comportement en exploitation et en maintenance des moteurs, en fonction des caractéristiques de ceux-ci et de leurs conditions d'utilisation,

- des possibilités et délais d'aboutissement des travaux sur la maintenabilité, la réparabilité, la surveillance de l'apparition des défauts.

De ces données sont dégagées :

- l'évolution de la politique de maintenance,

- les méthodes de prévision des coûts de maintenance,

- les caractéristiques exigibles à la conception des moteurs.

8.4.4. Au sein de la *fonction prévision des coûts*.

Dans cet exemple le Responsable de la prévision des coûts anime l'exploitation permanente des informations relatives aux coûts de production et à leur dépendance des principales caractéristiques des moteurs et de leurs constituants.

8.5. MISE AU POINT DE LA FICHE PROGRAMME INITIALE ET PRESENTATION D'UN AVANT-PROJET ADAPTE.

A ce stade, ne doit figurer dans cette fiche programme que ce qui est strictement nécessaire avec, si possible, un ordre de priorité dans les objectifs ou mieux, les poids relatifs à leur accorder.

Au reçu d'une esquisse de fiche programme, la Fonction Technique examine la possibilité d'y répondre par un avant-projet adapté et, si besoin est, propose à la Fonction Technico Commerciale les retouches qui permettraient une meilleure réponse, au vu des éléments dont elle dispose.

Dès ce stade il est, si nécessaire, distingué sur chaque poste de la fiche programme moteur ce qui est objectif à viser de ce qui est exigence à satisfaire impérativement (en général ce à quoi on s'engagera auprès des tiers).

Dès qu'un accord est atteint entre les deux parties, la Fonction Technique prépare et présente l'avant-projet adapté.

La création du programme correspondant est alors proposée à l'accord de la Direction Générale.

8.6. CONCEPTION INITIALE POUR DEMONSTRATION

8.6.1. Sur les bases précédemment définies, le Responsable de Programme désigné (ci-après R.P.) demande au Responsable Technique désigné (ci-après R.T.) *de proposer un programme de développement avec identification des tâches. Des estimations des délais et de la répartition des dépenses entre ces tâches sont faites.*

Il demande, par ailleurs, au Responsable de la Prévision des Coûts (R.C.) de définir une première répartition de l'objectif de coûts de production entre les "constituants" du moteur, conforme au découpage prévu de la définition par dessins.

Il demande également au Responsable de la Maintenance (ci-après R.M.) d'exprimer pour chacun des constituants les caractéristiques de maintenance voulues.

8.6.2. *Le R.T. avec la participation des spécialistes de diverses fonctions veille à ce que l'élaboration de dessins soit faite en visant les objectifs retenus; le R.C. fait procéder au chiffrage des coûts et indiquer les écarts par rapport aux exigences et aux objectifs.*

8.6.3. Au vu de ces écarts le R.T. définit le programme complémentaire et le calendrier des actions sur chaque "constituant" qui permettra d'atteindre les exigences et les objectifs et le soumet à l'accord du R.P.

Si, après avoir recueilli l'avis du R.C., le R.P. ne peut donner son accord à la poursuite des travaux, il demandera de nouvelles instructions de la Direction Générale et des Services Officiels s'ils sont concernés.

8.6.4. Si le R.P. a donné son accord, sur la base de la fiche programme initiale ou modifiée par D.G., le R.T. fait poursuivre les dessins de détail, la réalisation des pièces, le montage et les essais du moteur de démonstration et de ses composants, s'il y a lieu, il engage les actions du programme complémentaire, enfin il présente une synthèse des résultats.

8.6.5. La Fonction Technico Commerciale recueille l'avis des clients connus ou potentiels sur le projet et procède éventuellement à un ajustement des objectifs.

Il est demandé au R.T. de présenter au R.P., *pour accord, une mise à jour du programme de développement en vue de l'homologation.*

8.7. DEFINITION POUR HOMOLOGATION ET PRODUCTION EN SERIE

Lorsque jeux d'objectifs et programme pour homologation ont été retenus selon des spécifications détaillées, le R.T. lance l'établissement des dessins pour lequel il est procédé comme en 6.2.

Toutefois, à ce stade, le chiffrage peut faire partie intégrante du circuit d'approbation et donner lieu à une signature du responsable de la production.

Cette signature exprime, outre la faisabilité, la conformité aux exigences de coût et s'il n'en est pas ainsi, la dérogation doit être obtenue au niveau du R.P. si besoin est, de la Direction Générale après présentation d'un programme d'études et validations complémentaires et d'introduction des modifications correspondantes en début de série, tenant compte des mises en place d'outillage.

8.8. RESUME DES ATTRIBUTIONS SUIVANT CETTE PROCEDURE

Il appartient donc à la Fonction Programme, sur la base des informations exploitées, d'élaborer, faire approuver, à l'origine comme lors des évolutions qui apparaîtraient nécessaires, faire respecter un jeu cohérent d'objectifs et d'exigences.

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Il appartient à la Fonction Technique :

- par son Responsable des Avant-Projets de proposer, sur la base des connaissances exploitées, un avant-projet propre à satisfaire les objectifs et exigences,

- par son Responsable Technique pour le programme de développer, pour un coût et dans un délai donnés, jusqu'à homologation, un moteur conforme non seulement aux objectifs techniques mais aussi à ceux de coût prévisionnel, notamment de coût de production et de maintenance.

Il appartient à la Fonction Maintenance Logistique de :

- élaborer et diffuser les outils et méthodes de prévision des coûts de maintenance,

- s'assurer de l'applicabilité au moteur des méthodes de surveillance de maintenance et de réparation préalablement définies.

Il appartient au Responsable de la Prévision des Coûts de :

- s'assurer de la constitution et de l'utilisation correctes d'outils et méthodes de prévision des coûts,

- d'assurer l'aboutissement des actions permettant de disposer de technologies compétitives,

- contribuer à la définition de l'objectif de coût de production et de fixer sa répartition,

- faire examiner et chiffrer les dessins,

- tenir à jour les écarts entre les chiffrages et les coûts objectifs par "composant" et pour le moteur.

Il appartient à la Fonction Production de s'assurer de la participation des spécialistes de la production à l'élaboration de la définition et aux aménagements de celle-ci en vue de réduire le coût.

8.9. PROGRAMME EN COOPERATION

La nécessité d'une structure et de procédures de coordination pour le programme considéré est encore plus nette. Logiquement la responsabilité du développement, de la production et de la maintenance devrait incomber au même partenaire pour un constituant donné. La répartition des objectifs de coût entre les tâches et les partenaires et leur ajustement peuvent poser des problèmes délicats.

8.10. RAPPORTS AVEC LES SERVICES OFFICIELS

Que ce soit pour l'élaboration et la négociation d'une fiche programme contractuelle ou pour le suivi et les prises de décisions aux étapes clés du programme, il est souhaitable qu'une organisation de coordination de chaque programme existe également au sein des Services Officiels.

Le dialogue avec les constructeurs est facilité si certains éléments ou principes de base de la prévision des coûts sont établis de concert, sous l'égide des Services Officiels.

CHAPITRE 9 - ACTIONS POSTERIEURES A LA CONCEPTION INITIALE

9.0. De telles actions peuvent être engagées avec des objectifs nouvellement définis soit à la suite de l'apparition de valeurs élevées sur un poste de dépenses, soit à la suite d'une modification des conditions extérieures : hausse des prix ou risques de pénurie de carburants ou matières premières. Il est tenu compte des résultats obtenus dans les prévisions ultérieures.

9.1. DEPENSES D'ESSAI DES MOTEURS :

Elles s'imputent au coût d'acquisition pour les essais de réception et au coût de réparation (donc de maintenance) pour les essais de contrôle en sortie de 4ème échelon.

Elles dépendent d'un cahier des charges dont la modification est traitée comme une modification de la définition.

Elles comprennent une part temps d'occupation des bancs d'essais, une part de main-d'oeuvre qui est en première analyse proportionnelle à la première, et une part consommation de carburant.

Une action sur ces dépenses est menée périodiquement.

La dernière en date sur les essais de réception d'un des moteurs ATAR a permis encore une réduction de 25 % sur les deux postes par une action sur le cahier des charges.

Généralement les essais de contrôle en fin de réparation suivent une évolution parallèle.

9.2. INTRODUCTION DE MODIFICATIONS A BILAN "AU LONG DE LA VIE" FAVORABLE

La procédure d'approbation des modifications des moteurs par les Services Officiels français retient depuis longtemps comme élément de décision la présentation d'un bilan "au long de la vie" favorable, notamment quand il y a accroissement du coût d'acquisition.

C'est ainsi que les seules décisions prises en 1975 et 1976 sur les moteurs ATAR (pièces communes) représentaient un gain "au long de la vie" représentant la valeur de plus de 30 moteurs, bien que l'accroissement du coût d'acquisition correspondant soit d'environ 1 %.

9.3. ETUDES D'ECONOMIES SUR MATERIAUX :

Il est apparu au cours des années récentes que l'approvisionnement de certains matériaux pouvait devenir aléatoire et que, bien entendu, leur coût augmentait d'une façon difficilement prévisible.

Ceci pouvait peser, notamment à travers les dépenses de pièces de rechange, sur le coût "au long de la vie".

Il a, de ce fait, été déclenché des études de réduction de la consommation de matériaux tels que le Cobalt, tant par le choix d'alliages à teneur en Cobalt moindre ou nulle, que par la réduction de la "mise au mille" sur les pièces pour lesquelles la substitution n'était pas possible ou lointaine.

Dans le premier cas surtout ceci exige une reprise de la conception longue et coûteuse :

- choix et caractérisation du nouveau matériau,

- études des pièces,

- essais partiels,

- pièces et essais de validation,

- complément d'outillage.

Suivant le moteur considéré, le coût de l'introduction en série peut être compris entre 1 et 3 fois le coût d'acquisition d'un moteur, le délai étant en moyenne, en l'absence de prise de risque, un peu inférieur à quatre ans.

CHAPITRE 10 - RETOUR SUR LE CONCEPT DE VALEUR

10.1. CONCEPT DE VALEUR

Comment se situent "Design To Cost", "Design To Life Cycle Cost", "Direct Operating Cost" par rapport au concept de Valeur ? Pour permettre de tels rapprochements il est utile de préciser le sens retenu ici pour la Valeur dans l'expression Analyse de la Valeur.

Il est admis que la Valeur croisse lorsqu'augmente l'adéquation au besoin réel ou la satisfaction des fonctions à assurer et lorsque s'amenuise l'appel aux ressources que l'on souhaite ménager.

Le cas le plus simple est celui d'un besoin élémentaire ou d'une fonction unique dont la satisfaction peut être repérée dans une échelle unique, d'une part et d'une ressource unique où la dépense est mesurable d'autre part. On appelle Valeur le rapport satisfaction/dépense et on peut en faire une représentation graphique (figure 10.1). Au point A figure une solution A dont la Valeur est la pente de la droite OA. La Valeur d'une solution B est supérieure à celle de la solution A si B est au-dessus de la droite OA. La valeur des solutions B_1, B_2, B_3 est dite supérieure à celle de la solution A, bien que la satisfaction soit moindre pour B_2 et la dépense plus grande pour B_3.

En fait, il y a rarement unicité de fonction et de ressource. Si le dénominateur peut aisément être traité comme une somme de dépenses dans une unité appropriée, le numérateur doit être la synthèse de plusieurs critères dont la composition dépend de l'utilisation, voire même de l'utilisateur qui peut attribuer des coefficients à chacune des notes données pour les différents critères. Vectoriellement il situe son axe de jugement par rapport aux axes sur lesquels chacun des critères est repéré.

Il est rarement fait usage de telles considérations dans la pratique mais elles constituent néanmoins un guide d'analyse.

10.2. UTILISATION COMMERCIALE :

Pour un avion commercial de mission déterminée on peut assimiler sa Valeur à l'inverse du DOC rapporté au produit (km x passager). On peut alors établir des taux d'échanges entre caractéristiques en recherchant,pour chacune d'elles, l'écart ayant le même effet sur la Valeur.

Quand il s'agit d'un moteur monté sur un avion, la composition des critères devient délicate mais l'attribution de coefficients est équivalente à la hiérarchisation des objectifs techniques d'une fiche programme. On peut avoir recours aux taux d'échanges, c'est-à-dire aux écarts sur chaque caractéristique du moteur qui donnent le même effet sur le DOC de l'avion.

Lorsqu'il y a variation de la mission, on peut considérer un facteur de sévérité conventionnel dans le chiffrage du numérateur de la valeur.

10.3. UTILISATION MILITAIRE :

Sauf le cas des transports militaires, qui peuvent s'assimiler aux utilisations civiles, le cas des moteurs pour avions de combat est très complexe, car des critères comme la pilotabilité dans le domaine de vol sont difficiles à chiffrer.
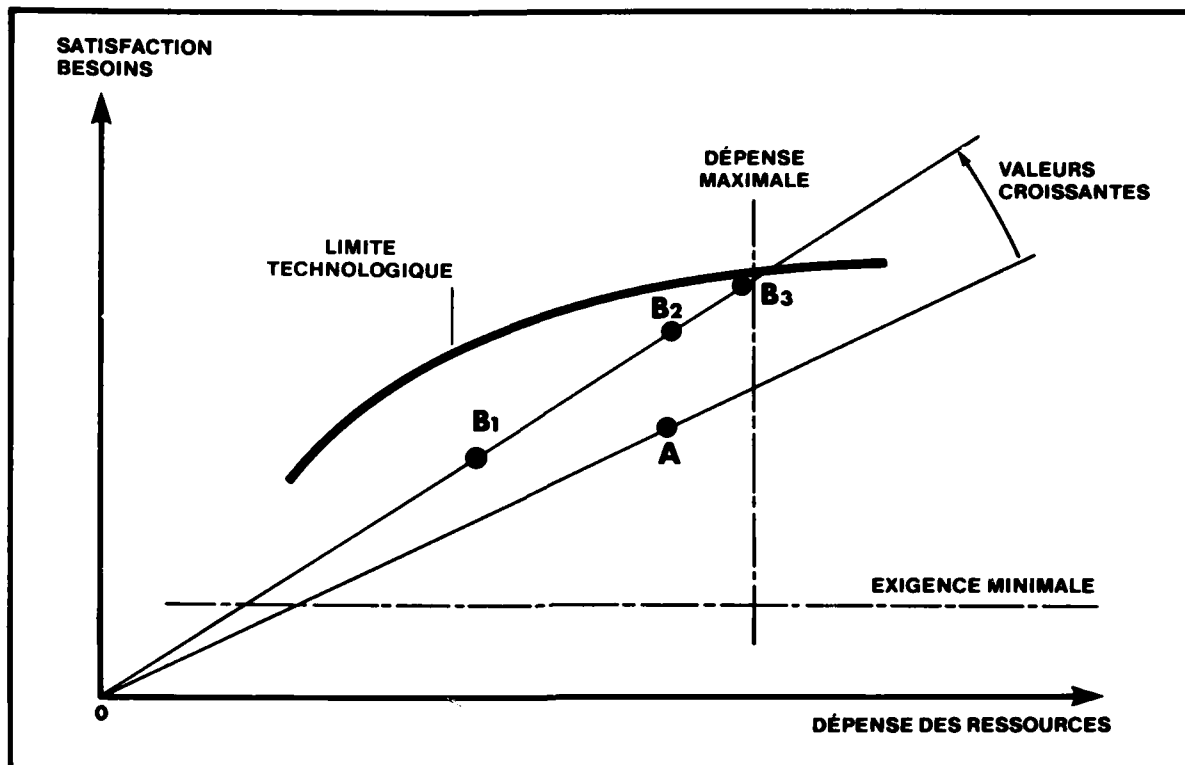
GRAPHIQUE DE VALEUR   **Fig 10.1**

Là encore le problème n'est pas de simple curiosité intellectuelle car ne conviendrait-il pas, pour mieux situer la capacité d'un moteur à satisfaire les besoins, d'attribuer des coefficients aux différentes régions (notamment frontières) du domaine de vol ?

10.4. FORMULES PARAMETRIQUES :

Les formules de la Rand par exemple donnent des valeurs du coût d'acquisition en fonction des caractéristiques "externes" du moteur, elles peuvent être considérées comme donnant une mesure conventionnelle du numérateur de la valeur ou de l'ordonnée du graphique.

10.5. PROGRES TECHNOLOGIQUE ET VALEUR :

Il y a deux façons de considérer leurs rapports.

On peut, comme dans certaines des formules de la Rand évoquées plus haut, situer les caractéristiques "externes" du moteur par le retard ou l'avance par rapport à une évolution historique.

On peut aussi pour un constructeur donné représenter la limite technologique accessible à un moment donné par une branche de courbe marquant qu'à son voisinage toute augmentation des "performances" ne peut se faire qu'à un coût élevé.

CHAPITRE 11 - CONCLUSIONS

Il apparaît que la pratique du DTLCC ou conception pour un coût "au long de la vie", sur un programme moteur, est facilitée par :

- la connaissance et l'analyse des différents postes de ce coût,

- la disposition de moyens de prévision des coûts utilisables lors des choix et décisions, c'est-à-dire partant de données accessibles et dont la crédibilité est suffisante au moment de ces choix et décisions,

- une organisation par procédures et/ou structures adaptées tant pour le programme moteur que pour les actions préparatoires telles que progrès techniques et technologiques,

- l'expérimentation sur des cas plus accessibles où l'on poursuit de nouveaux objectifs postérieurement à la conception initiale.

Pour la préparation de cet exposé, l'auteur a trouvé une aide précieuse auprès de la Direction Technique des Constructions Aéronautiques et auprès de la Société Nationale d'Etude et de Construction de Moteurs d'Aviation.

Logistics Forecasting for Achieving Low Life Cycle Costs

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SUMMARY

Engines currently under development and some that are now entering military service have been designed under the discipline of Design to minimum Life Cycle Cost (LCC). A major contributor to the achievement of lower LCC has been the adoption of the On Condition Maintenance concept (OCM). OCM provides the potential for reduced LCC by fully utilizing potential parts life and reducing maintenance frequency. Traditional concepts of engine maintenance, which have been based on fixed frequency inspections/overhauls, have required comparatively unsophisticated forecasting to provide adequate logistics support. With the advent of OCM on the other hand, logistics requirements are heavily influenced by wearout characteristics and usage severity. In such cases more sophisticated forecasting methods are required which realistically represent the dynamics of the logistics system inherent in such a maintenance philosophy. If efficient logistics management is to be attained, such forecasting tools should also provide the capability to perform trade-off studies on the cost effectiveness of alternative maintenance or logistics systems. The use of modelling methods which are proving practical in forecasting and trade-off analyses and therefore in establishing an optimum logistics and support environment is explored. Methods discussed include the consideration of wearout characteristics where components exhibit an age-related replacement rate, and also replacement of components which may have a specified maximum life in terms of operating cycles or mission severity. The use of engine history recorders and parts tracking systems and their impact on achieving optimum LCC is also discussed.

INTRODUCTION

Efficient management of the Operation and Support (O&S) phase of an engine life cycle is important if the minimum life cycle cost is to be attained. Since the introduction of design to life cycle cost as a major design discipline much has been done to reduce O&S costs both in the form of: (a) engine design eg. improved maintainability, reliability, durability, etc., (b) the engine development; eg. increased severity and realism, simulated mission endurance testing (SMET), better definition of usage cycles and (c) Maintenance Concepts; eg On Condition Maintenance (OCM), Engine Health Monitoring System, Engine Diagnostic Systems. While the greatest impact on the O&S phase costs will be effected on engines that were designed and developed for maintenance and support under the OCM Concept, it has been demonstrated that this concept can also be applied to older engines. This lecture will address specifically the use of logistics management tools in supporting engines under an OCM concept. General Electric experience in this area originated in the support of the commercial section of our business but has been actively applied to our military products. The newer military engine lines, i.e. the F404, F101 and T700 have been designed under the design-to-LCC philosophy since their conceptual phase and will/are being maintained on an OCM basis. The TF34-100 engine whose design was initiated in 1967 preceded the requirements of DOD directive 5000.28. However, extensive durability testing (SMET and AMT testing) augmented by a modest component improvement program has continued and the engine has proven to be readily adaptable to the OCM concept. Whereas the minimum potential O&S costs of an engine entering service are established by its inherent design characteristics, it is possible that additional design modifications will be necessary to bring this potential to the desired level. It is the job of the logistics manager to ensure that this minimum potential level is achieved, and where subsequent modifications are required to improve this potential, that the necessary changes are made in the most advantageous manner.

Managing the logistics support of an engine requires extensive, detailed and long range planning in several areas e.g. manpower, facilities, parts, training and test equipment. Furthermore, this planning must have the capability of dealing with dynamic conditions such as changes in fleet size, utilization, deployment concept and resource availability, the major tool needed for such planning is a forecasting system. A viable forecasting system that can consider variability in engine characteristics, operation requirements and logistics resources will provide the logistics manager with the opportunity to optimize his O&S costs while meeting operational requirements. At General Electric, we have worked on such models for several years now and have developed considerable experience both in their design and use. The complexity of these models has varied considerably, as has the cost of running them and analyzing the resultant output, particularly, the model structure and degree of discrimination has reflected the availability and credibility of the data base. The data base needed to support such models can be divided into three broad categories, i.e. those pertaining to (a) the logistics system, (b) the design characteristics of the engine and (c) the deployment and operational use of the engine.

Category (a) concerns such logistics system parameters as repair times, replenishment, lead times, turnaround times and repair levels. In the case of turnaround and pipe-line times, arbitrary standards which are insensitive to the type equipment or geographical location are sometimes specified by the operator. As the sensitivity of many O&S costs to such parameters is very high, data from actual experience should be used in preference to these arbitrary standards. Data, such as repair times, are generally available from military data systems.

Where no data exists such documents as the Logistics Support Analyses (LSA) will provide rational estimates. Category (b) relates to engine characteristics, such as engine reliability, durability and maintainability, expressed in such terms as mean time between failure (MTBF), wearout characteristics (expressed in terms of the Weibull distribution), maximum operating life (in terms of cycles, mission hours or time at temperature) and times to repair (in terms of maintenance man hours). Category (c) concerns the number of bases, geographical location, utilization and mission severity.

Where operational experience exists, much of this data may be derived from existing military data systems. However, it is GE's experience that the validity of such data can be enhanced by the use of Field Service Representatives' reports. Historically the available data has always been based on engine flight hours and record keeping below the engine level has been erratic. A significant improvement in such data relative to OCM concepts has been the adoption of Engine Time Temperature (ETTR) recorders and of Parts Tracking Systems. Such a system is being developed by the USAF under CEMS, the Comprehensive Engine Management System. Currently two engines are subject to such systems, F100 and the TF34-100. The systems for these two engines are similar, that for the F100 being operated and managed by OC-ALC and that for the TF34-100 by General Electric at AEG Lynn. Both will eventually be incorporated into the single AF managed CEMS system with the Central Data Base located at Oklahoma City ALC and Engine Management responsibility located at San Antonio ALC. Under the CEMS System, engine exposure in terms of low cycle fatigue, thermal cycles and time at temperature is being measured and recorded for each engine. In this discussion the engine history recorders will be referred to as an Engine Time Temperature Recorder (ETTR), and will relate specifically to the methods used on the TF34-100 engine. For other General Electric engines similar systems are incorporated into the F404, T700-700 and T700-401 and is also proposed for the F101/DFE. What follows is a description of a forecasting system that GE feels will be instrumental in developing the full potential of an OCM system and realize the low operation and support costs inherent in the design of the TF34-100. While tailored to this specific engine the concepts and methodology involved will be applicable to any OCM engine maintained under an OCM concept.

The total system may be considered as comprising two parts:

(a) A Parts Life Tracking System (PLTS) comprising a Parts Tracking System (PTS) and an ETTR System and (b) A Logistics Forecasting Model (LFM). The Logistics Forecasting Model is comprised of a series of sub models, the Shop Visit Rate Simulation Model, LCF Optimization Model and Parts Demand/Status Model.

Before describing the elements of the above system, it is pertinent to discuss what is understood by OCM. This is often construed as a means of eliminating the need to replace parts on a Maximum Operating Time (MOT) basis. Where OCM techniques such as borescoping, radiography, oil analysis and vibration analysis can detect incipient failure modes, or where the secondary effects of a specific failure mode do not cause an economic, safety or operational capability burden, the MOT concept can be eliminated. However, particularly in the case of turbo-machinery components, failure modes associated with such characteristics as low cycle fatigue (LCF) thermal fatigue and stress rupture are not always detectable by OCM methods and the secondary effects of such failures are quite often unacceptable. For these components, it is necessary to establish and observe a life limitation, generally expressed in terms of LCF cycles, equivalent full thermal cycles (EFTC), time at or above a sertain operating temperature or time at or above a specific power setting. In the case of the engine upon which this paper is based, the latter is synonymous with time at maximum power and is designated TA. . To fully utilize the potential of such parts and to prevent their use beyond the specified age limits, it is necessary to keep track of each part's operating exposure and location. This is a significant task in an engine fleet that may number in the thousands and operate for 20 years or more.

PARTS LIFE TRACKING SYSTEM (PLTS)

The concept of accounting for the location and age of various parts within an engine is readily understood. The identification of all designated parts must be accomplished during initial engine build-up and a file or record created. In addition to data on parts assembled into production engines, data must be collected, filed and maintained on all spare parts introduced into the system. For this purpose a Central Data Base (CDB) consisting of two sections must be established. The first is a parts master file which encompasses all designated parts entered into the system either as spares or as part of an engine. The second is the engine master file section which contains a record of the engine data and the data for all the designated parts in that engine. Both sections of the Central Data Base are updated each time the status of a part or engine changes. This is achieved by recording the daily status of each engine and the removal/replacement of any designated part. Most commercial operators have done so with a reasonable degree of success for many years, the military has a similar system requiring manual reporting and record keeping; however, its success has been limited - with good reason. The military labor force is less experienced and somewhat transient, parts tracking has not until now provided any obvious relief or improved efficiency at the operator level, thus providing little incentive for meticulous parts record keeping. With the advent of OCM engines into the Air Force inventory, the need for an improved and more comprehensive data collection system was recognized. For several years, the Air Force Logistics Command (AFLC) has been working on a Comprehensive Engine Management System (CEMS) which would establish such a data system to encompass the maintenance information, inventory accountability and technical information required by engine managers within AFLC and major commands. As part of Increment 1 of the CEMS project, General Electric was selected to develop the central data base and institute such a system for the TF34-100. Figure 1 is a schematic of the information flow associated with the PLTS.

The PLTS requires data originating from two sources (a) the mechanic responsible for changing parts and (b) the periodic reading and recording of the ETTR box display. Figure 2 is an illustration of the ETTR display. The data required of the mechanic is the engine Serial Number, part Serial Number, location of part, date and the information displayed on the face of the ETTR recorder.
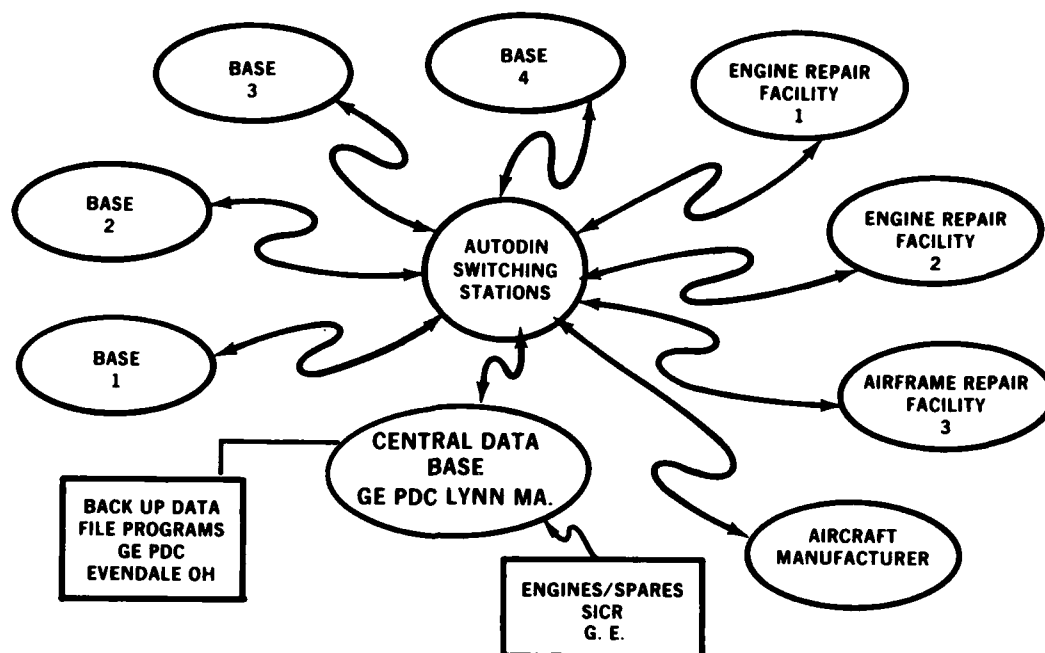
Figure 1. Parts Life Tracking System Data Flow
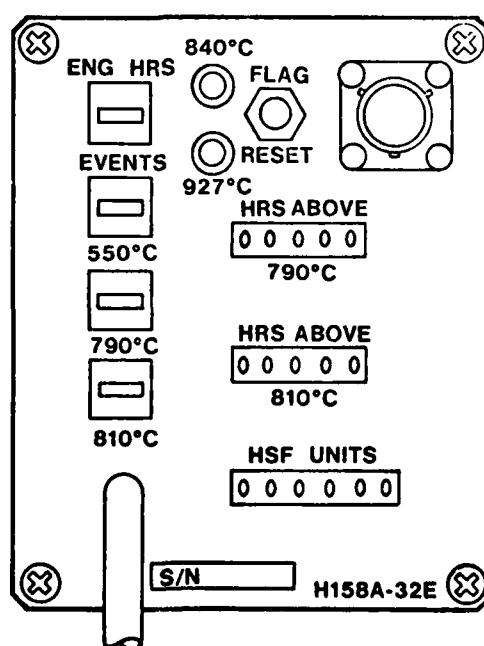
Figure 2. Engine Time Temp Recorder Display

ENGINE TIME TEMPERATURE RECORDER SYSTEM

The input to the Engine Time Temperature Recorder is taken from the signal to the aircraft cockpit Inter-Turbine Temperature Indicator. The source of this signal is the inter-turbine thermocouple harness. The output of the ETTR is displayed on the face of the unit and is a count of events and times as follows:

Engine Time Temperature Recorder Display

Engine Operating Time (EOT)
Events 550° (C) (E550)
Events 790° (C) (E790)
Events 810° (C) (E810)
840° (C) Flag
927° (C) Flag
927° (C) Flag
Flag Reset
Hours above 790° (C) Indicator
Hours above 810° (C) Indicator
HSF Units

The definitions of those used by GE as logistics forecasting parameters and a description of their use is included in the section on ETTR Data Definition and Analysis on Page 8. With this information, the system can track the location of all identified parts, their total operating time in terms of cycles or time at temperature, and time remaining to their respective life limits.

PART IDENTIFICATION AND DATA INPUT LOCATIONS

The TF34-100 engine has 79 parts which are tracked in the PLTS. In the early phases of the program, 120 parts were tracked; but experience showed that this number was not necessary and it was subsequently reduced. The partial list of these parts shown in Table 1 is extracted from the TF34-100 Maintenance Manual T.O. 2J-TF34-6. These part life limits are under continuous revision; the table reflects a combination of analytical and actual engine test experience. As time progresses, we expect the limits to increase as verification test data replace generally conservative analytical life assessments. In establishing the list of parts to be tracked, it is better to err on the side of too many parts rather than on too few in the initial phases. Whereas the elimination of parts from the system is simple, considerable effort can be involved in backfilling data into the system at a later date should the need arise to add additional components.

Criteria used to identify parts to be tracked should include such characteristics as:

● Parts having known life limitations (MOT's that fall within the life expectancy of the engine)
  eg. Compressor Disks
      Turbine Blades
● Parts known to be subject to wear-out characteristics eg. Turbine Nozzles
                                                            Augmentor Liners
                                                            Augmentor Nozzle Components
● Major assemblies/modules incorporating any of the above items.

TABLE 1

PARTS LIST-LIFE LIMITS

Name	Part Number	Engine Operating Hours	Total Cycles	K Factor
Bearing, Ball, No. 1	5023T48P01	6000		
	5023T48P02	6000		
Bearing, Ball, No. 2	5024T40P01	6000		
Shaft, Fan Front	6017T63P04		25950	0.540
Disk, Fan	6020T62G03	1050*	3100*	0.407
	6020T62G04		35000	0.407
	5920T88G01	1500*	35000	0.407
Blade, Fan	3901T93G01		38000	0.463
	6018T30P02		38000	0.463
Spool, Stage 3-8 Compressor	6020T63P01		9755	0.389
	6036T75P01		100000	0.500
Disk, Stage 9 Compressor	6016T43P03		31000	0.310
Spool, Stage 10-14 Compressor	6020T65P01		15000	0.341
	6037T83P02		18500	0.356
Shaft, HPT Rotor	6017T00P03		18000	0.018
Plate, Stage 1 Forward Cooling	4027T15P02		99999	1.000
Disk, Stage 1 HPT	6031T89P01		9600	0.009
Blade Set, Stage 1 HPT	6016T20G05		6800	1.000
	6016T20G07		6800	1.00

*Disk limit requires depot inspection of disk at these time intervals before it can continue in service.

ENGINE MASTER FILE

The core of the PLTS is the engine master file. This file contains the permanent engine data and all data associated with parts subject to tracking. Build-up of this file is initiated with the release of hardware to the engine assembly area. The system used during engine manufacture, designed by General Electric, is known as the Selected Item Configuration Record - SICR. As parts are accumulated prior to assembly, all pertinent data are input to a central computerized data bank by the Production Engine Quality Control Section. As released to the shop for assembly, a list of all parts assigned to a specific engine exists and is on file in the Central Data Bank. As the engine is assembled, parts data are once more input to the system. All actions involving the changing of parts up to final shipping inspection are covered by this system.

As each entry is made, it is reviewed for completeness, the audit routines immediately reveal any duplications, erroneous part numbers, or improper serial numbers. Once the engine has been accepted and is ready to ship, the complete engine file is then transferred on a direct computer-to-computer exchange from the SICR System to the PLTS System, thus creating the engine master file in the Central Data Base in Lynn. The data contained in the SICR System are retained for record purposes.

SPARE PARTS DATA

Designated spare parts that are manufactured or procured from vendors and included in the inventory at GE Lynn are also entered into the SICR System and are transferred to the PLTS System when shipped to the Air Force. In the case of designated spare parts that have been built into a higher level assembly, the higher level assembly data are also recorded. Once entered into the PLTS System, a part identification is retained, even if it is subsequently condemned or removed from the Air Force inventory.

As the PLTS System audits each data entry, it will identify any part that is recorded as being installed elsewhere, that has been condemned or removed from the inventory, or whose life usage is not consistent with the last recorded entry.

INITALIZATION OF BASE LEVEL ENGINE FILE

Engine and parts data are not transmitted from the CDB until an engine is accepted by an operating base or the spare part is installed on an engine. When an engine is accepted into a base inventory, either as an installed engine on a delivered aircraft or as a spare engine being prepared for installation, the data in the engine master file are transmitted to initialize the file at the owning base.

Figure 3 is an illustration of the data flow between the CDB, the Base Communication Center and the Engine Documentation. A similar information flow occurs when a part is drawn from base supply for installation into an engine.
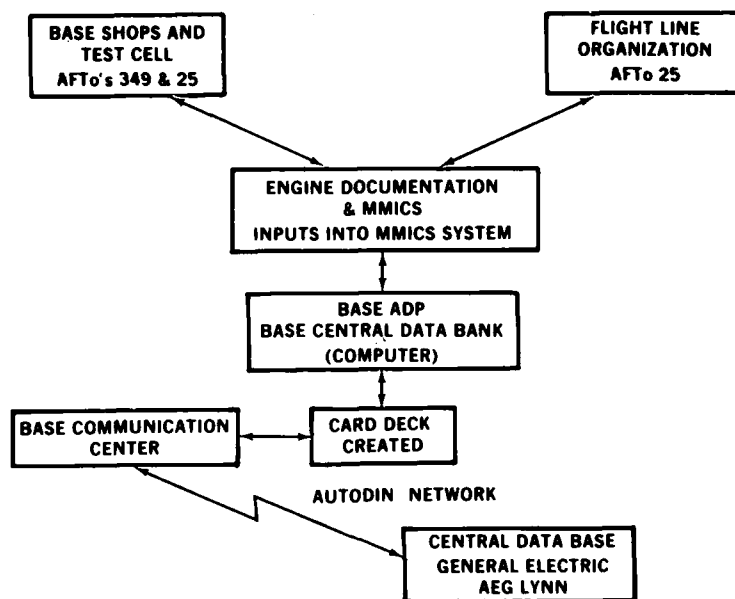
Figure 3. Data Flow Within the TF34-100 PLTS

DATA TRANSACTIONS AT OPERATING LOCATIONS

Initial Installation

Apart from recording any changes in engine parts incurred during manufacturing test or acceptance flight, the aircraft manufacturer provides the necessary input data needed to identify the ETTR recorders installed on each aircraft and their initial readings.

Depot Data Transactions

The depot facility is the main location at which parts are removed, reworked, returned to service or to spares stock, or condemned. Furthermore, there is extensive interchange of parts between engines and major assemblies. This is where the auditing routines built into the PLTS System are most effective. As well as maintaining records on all parts incorporated into engines at delivery, the PLTS maintains records on all designated spare parts subject to tracking.

When an engine or assembly is shipped from a base for repair/rework, a hard copy of the engine master file, generated by the Base Engine Documentation Section, accompanies the engine/assembly. This provides the basis for planned replacement of any life-limited parts. As the engine is repaired, part change data are transmitted to the CDB, audited and the master file in the CDB updated. Similar action is taken for assemblies or components returned from the field for repair.

If the hard copy information is lost or damaged or if teardown reveals any discrepancies in the data, a copy of the engine master file stored in the CDB may be transmitted at the request of the repair facility.

The same process is followed with major assemblies or designated components; however, the assembly data are not transmitted to the base and entered into the MMICS System until the assembly is withdrawn from base supply for installation in an engine.

Once the repair cycle is completed and all part changes and TCTO compliances recorded and transmitted to CDB, the engine/part may be prepared for shipment. All documentation normally transferred with an engine, eg. AFTO 95, is included in the shipment. The CDB records will list the location of the engine as Alameda NARF until notified by message that the shipment has been received at its destination. At this time, the engine file at the receiving base is initialized by the transmittal of the master file and uploaded into the base level MMICS System.

Base Level

At the base level, the Air Force has integrated the necessary data collection into the Maintenance Management Information Control System (MMICS) by means of Automated Components Tracking System (ACTS). The engine data file is initialized at the Base level by transmitting a copy of the engine master file from the CDB to the Base Computer whenever an engine is accepted into the base inventory. Similarly, parts and engine assembly data are also transmitted upon notification of the receipt of parts into base inventory. Figure 3 also represents the data flow for initialization of engine file and parts change data. Maintenance action data and ETTR recordings are input to the system by means of two record cards: the AFTO 25, Engine Time Accumulated Record, by which ETTR records are maintained, and AFTO 349, Maintenance Collection Record, which is used to record part removals and installations.

Readings of each ETTR are taken after the last flight of the day. The ETTR is airframe mounted in one of the avionics bays and is readily accessible, providing line of sight reading capability. ETTR boxes stay with the airframe and a record of their installation history is maintained in the PLTS System. No manual computation to adjust for the ETTR reading at engine removal or installation is required as the PLTS logic considers such factors. The ETTR box itself is tracked in the PLTS, and all ETTR remove and replace actions are recorded as for an engine or part.

The AFTO 349 and AFTO 25 forms are processed by the Engine Documentation Section which reviews them and prepares the data for input to the base MMIC System and data processing. At this point, the base level engine file is updated, and a set of cards is prepared for input to the AUTODIN network for transmission to the Central Data Base. On receipt of the data at the CDB, the information is audited for errors or anomalies. If none are revealed, the system updates the Engine Master File and the Spare Parts Master File. If anomalies are detected, the received data are placed in a suspense file until the anomalies are resolved. This is facilitated by the two-way transmittal of data over the AUTODIN network, but in most cases the real problem solving is accomplished verbally over the telephone. Rapid response by those responsible for maintaining the Central Data Base has been instrumental in maintaining a low error rate and in establishing an excellent working relationship with the base or repair facility personnel. Once anomalies are resolved, the information in the suspense file is corrected and the update of the master file accomplished.

The PLTS relies on accurate and consistent reporting at the base level. Without the wholehearted endorsement and cooperation at this level, the system will not operate efficiently. Air Force personnel (mechanics, engine records, data processing and communications) are to be commended for the excellent coverage they are providing on this program. The TF34-100 system has experienced an extremely high level of accuracy and timeliness, none of which could have been achieved without total teamwork.

PLTS DATA AUDIT AND EDIT

Input errors are an ever-present problem that must be dealt with on any large-scale computerized data system. The TF34-100 PLTS has many error/edit routines designed into the computer system both at the base level and the Central Data Base.

The CDB computer edit routines are designed to check the majority of all incoming data transmittals for duplications, unknowns or other anomalies. Where an error, such as a duplicate serial number is detected, the entry of the relevant data transmission set is suspended and an error message is issued. CDB personnel review all error messages for the required action. If the subject data are from an operating base, a message is transmitted requesting corrective action. The data set under question is meanwhile held until corrected information is supplied. The same procedure is used for data originating from other sources, such as a repair facility.

In addition to the daily edit/error routines and procedures, the accuracy of the PLTS is checked periodically by a "Reconciliation" routine. This is a "one for one" comparative review of the base level data files and the CDB files. Reconciliation is accomplished at a prescribed time after a base level system becomes operational (approximately 6 months) and periodically thereafter.

In reconciliations, every data element transaction over the review period is compared between the two files as well as the current status. This is done on a direct computer-to-computer basis. To date, three such reconciliations have been accomplished with an accuracy level in each case in excess of 98%.

THE NEED FOR COMPLETE ENGINE FLEET AND SPARES STOCK COVERAGE

In areas where the same engine model or models having identical parts are operated, it is important that all the engines and designated spares be subjected to the tracking system prior to shipping. The TF34 engine is a case in point. There are two models, the TF34-100 used by the USAF in the A10 aircraft, and the TF34-400 used by the USN in the S3A aircraft. There is 100% commonality of the parts subject to the parts tracking system on these engines, and there is one repair site for both engines. As the TF34-400/S3A does not presently have an ETTR system and is not included in the PLTS, it is important that common parts that have been used on the TF34-400 are not introduced into TF34-100 engines. The PLTS has this capability and has already revealed some instances prior to engine shipment from the depot. In addition to the case of common parts in different models/applications, there is the use of common parts in different models/applications, and the use of a single engine model by different users. The TF34-100/A10 will be operated by the Air National Guard and possible other operators, as well as the regular Air Force units, so the same level of discipline in record-keeping will be required from these operators. As currently operated by contract, we have in this system the facility to track all designated parts throughout the US Air Force System whether they be incorporated into installed or spare engines, as new or used serviceable spare parts, or as condemned parts. Also readily available is a parts status in terms of estimated life consumed or life remaining on all installed and shelf-stock parts.

ETTR DATA DEFINITION AND ANALYSIS

The engine operating characteristics measured in the PLTS System and recorded on the ETTR are relatively simple when compared to those developed to support an Engine Health Monitoring Program or designed to record mission profiles and relative severity. Such programs have measured and analyzed a wide range of engine parameters with multiple sensors and sophisticated data recording and processing equipment. In the case of the Engine Health Monitoring Programs, the aim has been to provide diagnostic and health trending capability as a means of determining when maintenance is necessary. Such a system would be complementary to an ETTR or have the ETTR function incorporated. Those programs involved in recording mission profiles and relation severity have been utilized in many cases for setting the necessary requirements for such things as accelerated mission tests, simulated mission endurance testing and specification requirements.

Though basically a simple system relying on only one engine input signal, the TF34-100 ETTR System on a fleet-wide basis has given us the opportunity to evaluate the variability of engine operating conditions. This evaluation has shown that, apart from engine-to-engine variations, there are measurable differences between the different operating bases. The resultant understanding of these measures is invaluable in realistically simulating fleet operation for the purposes of logistic forecasting and for the formulation of "no build" or "opportunistic maintenance" plans.

The parameters recorded by the ETTR System were listed previously. The following defines each of these parameters and describes the observed characteristics as related to the TF34-100/A10 fleet and their role in logistics forecasting. The input to the ETTR system is derived from the aircraft turbine temperature indicating system and requires no additional engine mounted sensors or transducers.

Operating Parameter Analysis

The ETTR parameters used in logistics analysis are:

Events at 550°C	E550
Events at 790°C	E790
Events at 810°C	E810
Time at or above 790°C	T790
Time at or above 810°C	T810
Engine Operating Hours	EOT

In addition, the times and frequencies are expressed as ratios compared to engine operating time identified by the suffix R. eg. E550R, which means the ratio of events 550 per hour of operation; T810R, which means the ratio of time above 810°C. Table 2 is an illustration of one of the output formats based on ETTR data, showing the events times and ratios for individual engines at a specific base. This data is one of the basic input files used in the forecasting model.

While all of these measures are a function of engine operating flight time, the relationship to component MOT will vary between types of failure mode, location of component within the engine and the severity of the mission(s) flown by a specific engine. In the case of the TF34-100 engine the life of components subject to LCF limitations is calculated as the basis of events at E550 and E790. The component LCF life in cycles (LC_i) is defined as $LC_i = E550 + K_i E790$, where K_i is defined for each component. Of the 79 parts tracked by the system, 28 are subject to LCF limitations and have separately defined values of K_i.

2 of 2

END
DATE
FILMED
10-80
DTIC

MICROCOPY RESOLUTION TEST CHART

TABLE 2

PARAMETER RATIO SUMMARY

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                              ** PARAMETER RATIO SUMMARY **

REQUESTED                    NOUN                         REQUESTED                    NUMBER OF
CI NUMBER                                                 LOCATION                      ENGINES

TF34100                  TF34-100                          BASE B                         179

*******************************************************************************************************************

          ENG-SN             EVENTS                TIME AT TEMP
          ------    ----------------------------   ------------
                    EOT     550     790     810     790     810     E550/EOT   E790/EOT   E810/EOT   T790/EOT   T810/EOT

          205027   1049.7   854    4689    3511   181.92  118.58     .813:1    4.466:1    3.344:1     .173:1     .112:1
          205030   1015.5   710    3453    3010   152.31  113.64     .699:1    3.400:1    2.964:1     .149:1     .111:1
          205035   1100.4   838    5226    4424   202.99  147.16     .761:1    4.749:1    4.020:1     .184:1     .133:1
          205042   1058.1   800    4101    3549   207.36  145.98     .756:1    3.875:1    3.354:1     .195:1     .137:1
          205071    965.5   808    4260    3858   196.81  158.66     .836:1    4.412:1    3.995:1     .203:1     .164:1
          205074    577.6   414    2290    2071   117.01   94.05     .716:1    3.964:1    3.585:1     .202:1     .162:1
          205099    693.3   588    3728    2910    94.92   77.79     .848:1    5.377:1    4.197:1     .136:1     .112:1
          205111   1119.9   893    5108    3374   173.42  108.37     .797:1    4.561:1    3.012:1     .154:1     .096:1
          205112   1068.0   932    4124    3599   211.01  169.22     .872:1    3.861:1    3.369:1     .197:1     .158:1
          205113    807.4   584    2808    2466   129.61  103.41     .723:1    3.477:1    3.054:1     .160:1     .128:1
          205126    957.4   776    4491    3984   150.78  122.52     .810:1    4.690:1    4.161:1     .157:1     .127:1
          205135   1144.5   914    5379    4756   207.44  168.13     .798:1    4.699:1    4.155:1     .181:1     .146:1
          205136    626.6   566    2588    1625    93.20   44.70     .903:1    4.130:1    2.593:1     .148:1     .071:1
          205141    945.8   699    3286    2958   137.11  117.34     .739:1    3.474:1    3.127:1     .144:1     .124:1
          205143    977.5   749    4809    2740   168.02   71.38     .766:1    4.919:1    2.803:1     .171:1     .073:1
          205145    423.2   374    2130    1805    75.10   60.74     .883:1    5.033:1    4.265:1     .177:1     .143:1
          205148    874.9   586    3293    1150   128.59   29.57     .669:1    3.763:1    1.314:1     .146:1     .033:1
          205151    667.9   537    3197    2756   135.15  103.53     .804:1    4.786:1    4.126:1     .202:1     .155:1
          205155    753.8   761    3678    2933   128.17   88.17    1.009:1    4.879:1    3.890:1     .170:1     .116:1
          205156    985.1  1797    4553    3631   164.22  119.06    1.824:1    4.621:1    3.685:1     .166:1     .120:1
          205169    535.9   422    2104    1958   104.12   85.16     .787:1    3.926:1    3.653:1     .194:1     .158:1
          205175    153.5   160     796     263    19.80    7.03    1.042:1    5.185:1    1.713:1     .128:1     .045:1
          205178    764.8   622    3248    2760   114.21   92.51     .813:1    4.246:1    3.608:1     .149:1     .120:1
          205183   1047.3   789    5252    4631   218.04  172.34     .753:1    5.014:1    4.421:1     .208:1     .164:1
          205185    531.5   443    2198    1486    90.06   49.62     .833:1    4.135:1    2.795:1     .169:1     .093:1
          205186    719.5   631    4500    3077   124.58   94.77     .876:1    6.254:1    4.276:1     .173:1     .131:1
          205187    826.3   710    4329    3399   141.20   98.78     .859:1    5.239:1    4.113:1     .170:1     .119:1
          205189    573.1   500    2708    2330    81.85   62.16     .872:1    4.725:1    4.065:1     .142:1     .108:1
          205201    776.1   622    3477     305   117.30   10.24     .801:1    4.480:1     .392:1     .151:1     .013:1
          205202    661.7   575    2718      45   121.80     .73     .868:1    4.107:1     .068:1     .184:1     .001:1
          205203    885.7   825    5007    4433   158.39  125.90     .931:1    5.653:1    5.005:1     .178:1     .142:1
          205204    989.5   719    3793    3383   204.98  162.20     .726:1    3.833:1    3.418:1     .207:1     .163:1
          205205    593.0   672    4999      74   106.12    1.19    1.133:1    8.430:1     .124:1     .178:1     .002:1
          205206    646.4   507    2419    1294   115.10   63.74     .784:1    3.742:1    2.001:1     .178:1     .098:1
          205207    488.3   438    2473    2186    95.18   70.64     .896:1    5.064:1    4.476:1     .194:1     .144:1
          205209    504.3   447    2509     818    93.55   41.31     .886:1    4.975:1    1.622:1     .185:1     .081:1
```

ENGINE OPERATING TIME (EOT)

The ETTR starts accumulating time whenever engine Inter-Turbine Temperature (ITT) exceeds 550°C and stops when the ITT falls below 250°C. The time thus recorded is defined as Engine Operating Time. A typical distribution of EOT/month is shown in Figure 4.

% Fleet
25
20
15
10
5
10
20
30
40
50
60
70
80
Monthly Engine Operating Time
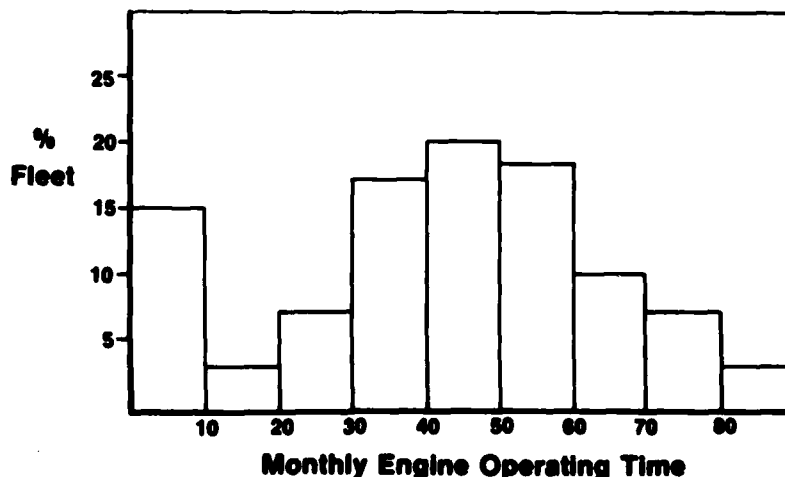
Figure 4. Monthly EOT
TF34-100 Monthly Utilization Histogram

EVENTS 550°C (E550)

This parameter is used for forecasting as a constituent of the LCF measure. The counter is triggered as the ITT passes through 550°C. The ratio E550/EOT is designated E550R and is the inverse of the EOT/mission. Figure 5 is a histogram of E550R for the total A10 engine fleet with ages above 300 hours. This ratio is used in computing the LCF life expended for those components having an MOT expressed in LCF terms. The variability of this ratio is larger amongst low time engines but tends to stabilize with a comparatively low variability as EOT increases.
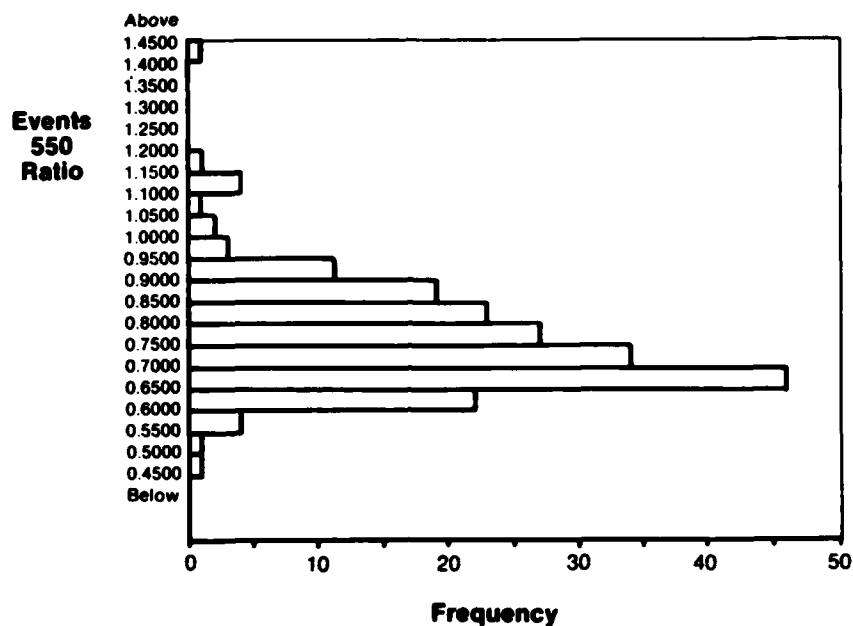
Figure 5. Histogram Events 550 Ratio

Figure 6 a crossplot of E550R vs EOT for each engine in the A10 fleet illustrates this effect. In modelling logistics requirements, the mean value of E550R is used in computing LCF usage.

Engine Operating Time (EOT)
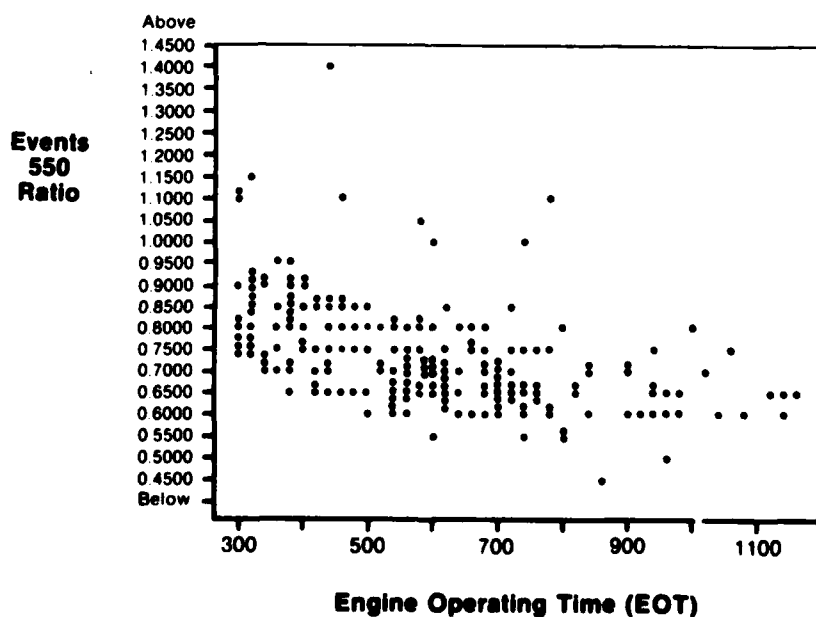
EVENTS 790°C (E790)

Both E790 and E790R show the largest variability of the measures. An E790 is recorded each time ITT passes above 790°C and is a measure of throttle transients within the normal engine operating range. The measure is used in conjunction with E550 to establish LCF usage as described previously. Though of wider variability than the E550 measure, the variability does narrow with age. Figures 7 and 8 are a histogram of E790R and a crossplot of E790R vs EOT respectively. The distribution shows much more variability than E550R. The mean value of the distribution of E790R is used in the logistics forecasting model.
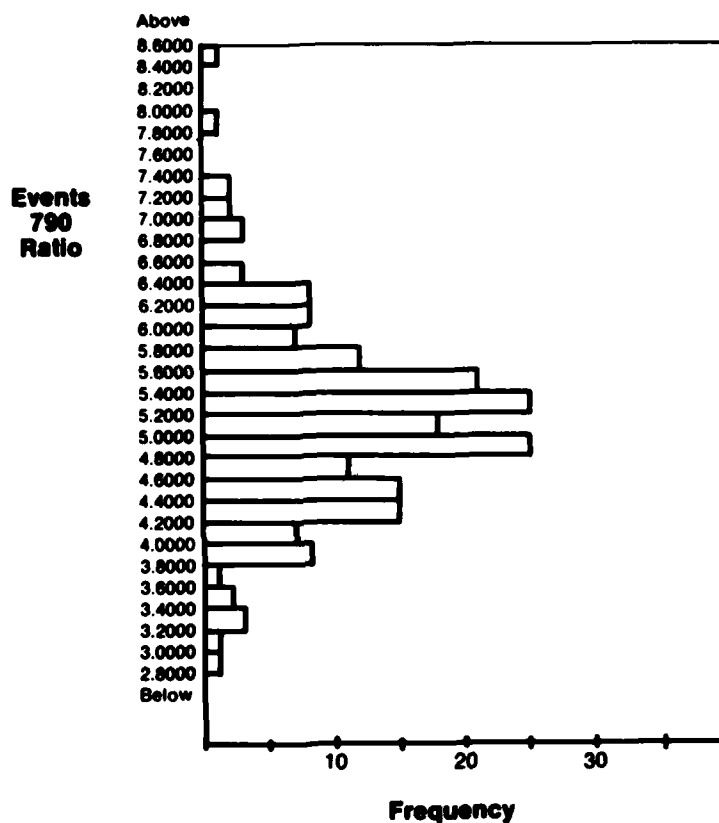
Figure 7. Histogram of E790R
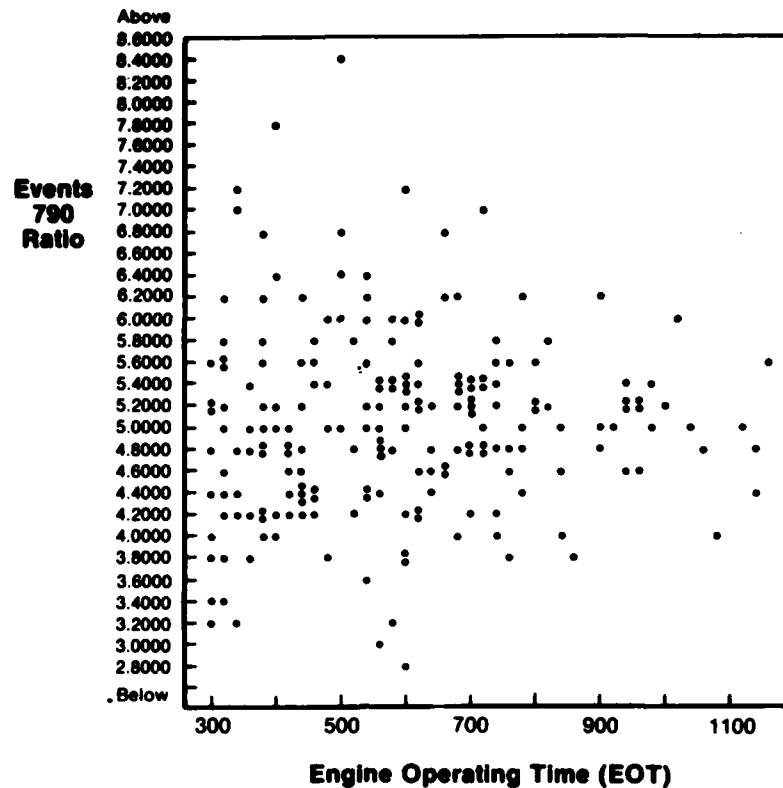
Figure 8. Crossplot E790R vs EOT

TIME AT 810°C (T810)

At operating temperatures above an Inter-Turbine Temperature (ITT) of 810°C hot parts life usage becomes significant. For this reason, the ETTR is set to record all time spent with the ITT at or above 810°C. The TF34-100 control system is timed to provide 100% fan speed at or below 825°C. On engines which have a high performance margin, it is not unusual for 100% fan speed to be achieved below 810°C. Such engines may accumulate several hundred hours before operating at or above 810°C. The variability in the T810R results in a correspondingly large range in EOT at which the allowable MOT at or above 810°C is reached. The data obtained from the ETTR therefore provide us with the tool to measure and incorporate this variability into our logistics forecasting model. Figure 9 is a histogram of T810R and illustrates the large variability experienced.
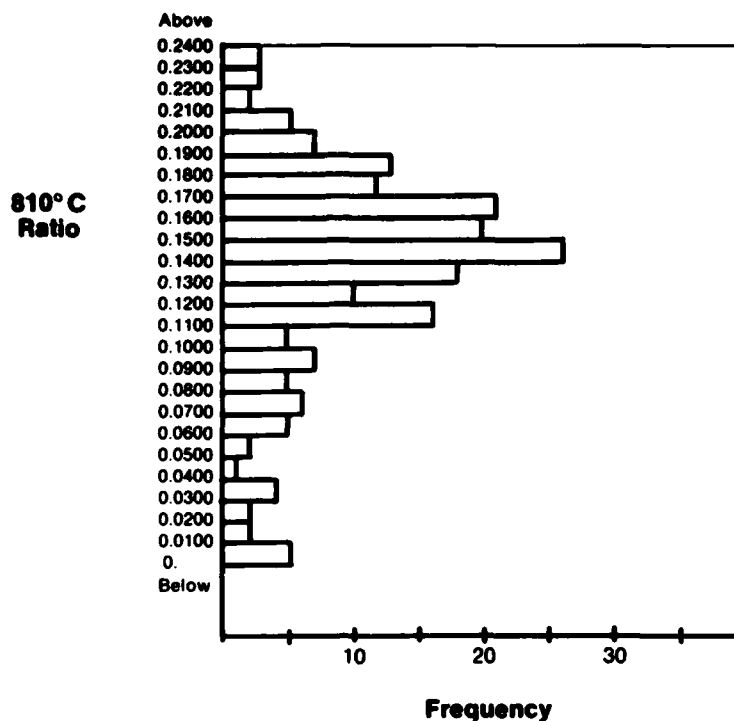
Figure 9. Histogram T810R

In Figure 10, where T810R is plotted against EOT for the TF34-100 engine fleet, the MOT line AB, equivalent to 180 hours at T810°C is superimposed as is the MOT line CB, equivalent to the cyclic life limitation. The distribution of the EOT at which engines reach the MOT boundary line CB is converted into an input to the logistics model. In determining the time at which engines will reach either of these limits, analysis on the change of T810 versus EOT is also accomplished using data from the ETTR. The rate of increase of T810R with EOT is represented by the line DB. The slope of this line was established by analyzing consecutive ETTR readings for a sample of engines. The use of these data permits the forecasting of engine removals due to T810 limitations with a high degree of confidence. It should be noted that if no fleet wide ETTR System were available, a max operating time based on EFH would have to be adopted, probably in the order of 600 EOT, however, the use of ETTR has resulted in an average MOT of 1000 EOT and a subsequent decrease in engine visits to the shop and parts usage cost.

6-14
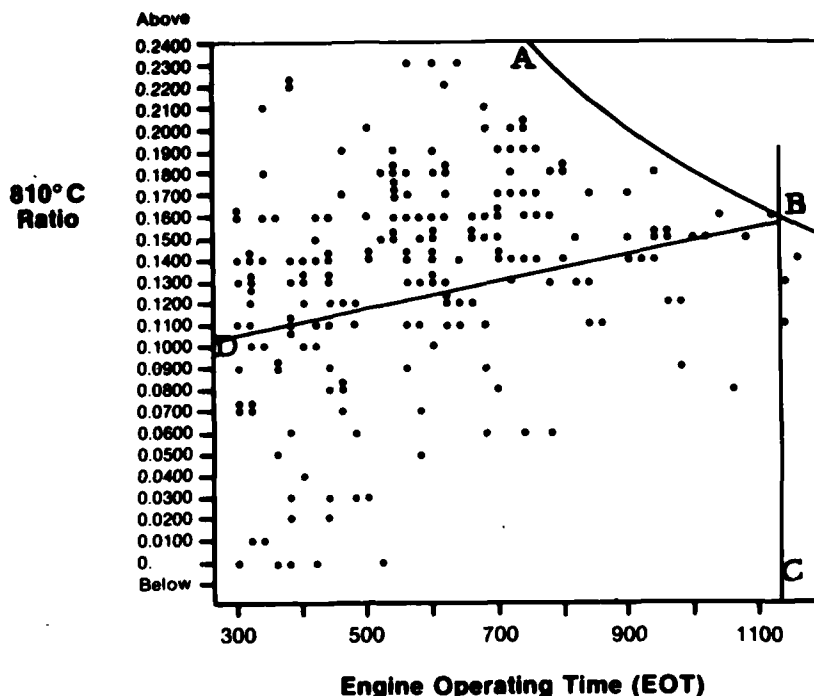
Figure 10. Crossplot T810R vs EOT

LOGISTICS FORECASTING MODELS

The overall logistics forecasting model is based on a model that simulates the operation of a fleet of engines and generates a Shop Visit Rate (SVR) forecast, and which differentiates between the expected causes for the shop visit. In the current use of the model ten different SVR causes are designated, however, the model does have the capacity for additional designations should they be required. Output from this model is used to generate a parts demand forecast. This is accomplished using a model that relates the SVR cause to a replacement parts list and compares expected demand to known parts assests and order position. The parts list per event is based on recorded usage for typical events and MOT limitations. The parts list derived covers what are considered to be logistically significant items, that is to say high cost, long lead time those having expected age dependent wearout characteristics, plus any others that can be identified as relating to the cause of the shop visit or the age of a part at such a shop visit, currently this list comprises approximately 200 items.

For the purposes of forecasting the requirements of the rest of the engine parts list, reliance is placed on utilizing demand history data available in the military logistics data system such as the United States Air Force Recoverable Consumption Item Requirements System (DO41) and Economic Order Quantity (EOQ) Requirement Computation (DO62 System). Historic demand data from these two systems is smoothed and trended and future demand forecast based on expected fleet utilization. This in conjunction with the output from the Parts Requirements Model provides the basis for a complete engine parts list forecast. Another model used in support of the SVR model to optimize the ground rules for changing out parts that are approaching their MOT when exposed due to other corrective maintenance, such ground rules are often termed "Opportunistic" or "No Build" maintenance plans.

Shop Visit Rate (SVR) Model

The Shop Visit Rate model consists of simulation of a fleet of engines operating under specified condition for a prescribed period of time. The logic of the model has deliberately been simplified by including only the major causes of maintenance, thus the excessive computational costs frequently associated with simulation models are avoided. Using the simple simulation approach, it is quickly and easily possible to measure the effects of changes in reliability, maintenance policy or provisioning policy, and attain the objective of minimizing shop visit rate and logistics cost. The simulation logic has been translated into a Fortran computer program and may be run either in Batch or Timesharing mode. The following is a generalized description of how the simulation program is constructed and how our model has been developed to match the OCM concept currently being used to maintain the TF34-100 engine.

Our basic philosophy has been to simulate only those events for which we have credible data and a good understanding of the failure characteristics.

The program for the SVR model can be considered, basically as consisting of three separate phases, which we have called the A, B, and C phases.

The A Phase is the first portion of the program and consists of program initialization, setting counters to zero, reading input, setting up flight schedules, and generating the time to first maintenance event on each initially installed engine.

The B Phase is the time-dependent portion of the program, where the random and wearout events are simulated and scheduled maintenance on individual components and engines is generated based on simulated operating time. As each maintenance event is completed, the program sets up the time for the next maintenance event on the item, either using computer generated random numbers for setting up unscheduled maintenance events or by adding a fixed increment of time in the case of scheduled events. The program has an option to print details of individual events as they are generated by the random process which is useful during initial runs to ensure the program is functioning as the user intends. Time is advanced by incrementing to the time of next maintenance on any engine of the fleet.

The C Phase is the program output portion, where the results generated in the B Phase are printed in summary form (Table 3), giving monthly maintenance events by type. A summary is also given of the status of each engine in the program at the end of each simulated month, indicating whether it is installed, in maintenance or a Ready For Issue (RFI) spare. The simulation program is applicable to most engine programs involving three maintenance levels. Our development work was performed using TF34 engine as an example of a typical application. In other applications, the user's needs will necessitate some tailoring of the program to meet the requirements of his proposed maintenance concept.

TYPICAL SIMULATION

The program simulates the operation of the engine portion of an aircraft fleet and the required maintenance activities and spares necessary to support this operation for a number of years. In the following description, the aircraft is a two-engined type, each engine having equal probability of random failure, or other maintenance events resulting from wearout or life limitations.

The engines are scheduled for certain maintenance events and inspections during their operating life, namely borescope inspection and performance checks with associated fallout based on wearout, and replacement of life expired parts. Unscheduled engine removal and replacement of line replaceable units (LRU) are considered random events. The maintenance actions simulated result in removal of the engine from the operating aircraft and processing through a simulated maintenance shop. The turnaround/repair time itself is a variable related to the type of maintenance event. When this time has expired, the engines are returned to the supply of RFI spares for future use. Engines are selected for use as spares on the basis of the earliest engine to emerge from maintenance.

In the event that no spare engine is available, the logic places the aircraft out-of-action until the first available spare arrives, and accumulates the downtime which results. In this mode the model can be used to estimate the impact of aircraft availability of changes in any of the model variables.

Unscheduled Maintenance Events

The engine random maintenance event function is assumed to follow an exponential distribution.

Engine unscheduled maintenance time is generated according to the following function:

Maintenance Event Time $= -(MTBUME * \ln (X))$

Where

X is a random number between 0 and 1

MTBUME is the mean time between unscheduled maintenance events on the engine.

The function generates removals randomly and at a constant rate as a function of the accumulated flight hours. Provision can be made for reliability growth, based on growth projections for the particular engine model being simulated. This growth provision can be modified, or removed according to the needs of the user.

Age Related Parts Replacement

One problem in forecasting for the On Condition Maintenance concept is the consideration of parts that exhibit a higher probability of failure or need of replacement as they age. Fortunately this condition can be readily modelled using the Weibull distribution.

$$P_f = 1 - e^{-(T/\theta)^B}$$

Where P_f is the cumulation probability of failure at time t.

t is the engine time

θ is the Weibull scale parameter characteristic life

B is the Weibull shape parameter (slope)

Age related parts replacements may occur as a result of scheduled inspections (e.g. borescope), exposure at some other corrective maintenance action or due to failure or performance degradation that initiates the need for corrective maintenance.

In the simulation, fallout at scheduled inspections is based on the conditional probability of the part or engine performance having degraded below acceptable limits since last inspection. This probability is compared to a computer generated random number X (between 0 and 1), and the engine is considered to have failed if the value of X is less than this probability.

For events expected to occur at other than scheduled inspections, the time at which the event is expected to occur is established using the same distribution and a random number generator.

REPLACEMENT OF LIFE LIMITED PARTS

Life limited part replacements are assumed by the program to follow a distribution defined by analysis of the ETTR data (in most cases normal or log normal). Replacement age of a part on a specific engine is randomly selected from within this distribution, the limits being assumed to be ± 3 standard deviations from the mean. The part age may be expressed in terms of hours or cycles in which case conversion is made to hours using a ratio of cycles to hours established by prior measurement. The simulation replaces the time-expired part with a zero-time part, when the number of hours accumulated reaches the established limit.

Derivation of Maintenance Events on Typical Engine

Figure 11 shows the flow of a typical engine through the system. It represents an engine which at the start of simulation has already accumulated 796 hours with 336 hours since the nozzle stator was replaced (block (1)). The program computes the time to next maintenance for the four types of maintenance event (block (2)) and by subtraction how many more hours remain to the time these events are due (Block (3)). The clock chooses the least of the times in Block (3) and reduces all event times by that amount (Block (4)). In this case the Borescope Inspection and Performance Check are due together; the latter is done first. The failure probability is calculated using the Weibull Characteristics (Block (5)), and a random number between 0 and 1 generated by the computer. If the number is < .25 (Block (6)) the engine failed the test (Block (7)); the time remaining on the buckets is checked (Block 8)); this time is compared to the "No-Build" or Opportunistic Maintenance Time (Block (9)); if greater than the "No Build", performance is corrected by a shroud replacement (Block (10)); if less than the "No Build", the buckets are changed (Blocks (11) and (12)). Returning to Block (6) – if the number is >.25, the engine passed the performance check (Block (13). When this happens the borescope inspection of the hot section is made (Block 14) using Weibull characteristics. In similar fashion to the performance failure, failure of the hot section occurs if the computer generated random number is less than the Weibull failure probability (Blocks 16 through 18). Success results in Blocks 19 and 20.

Typically input requirements from the Shop Visit rate model are:

By Base:

Aircraft utilization/month
Engine/Aircraft age and usage data at start of forecasting period (reference Table 2)
Engine configuration
Delivery schedule for new aircraft and engine

Distribution parameter for engine operating ratios (LCF, TAMP)
Preventative maintenance inspection interval (borescope, etc.)

Mean time between maintenance actions

Turnaround times by type event.

Table 3 is a typical tabular output from the model while Figure 12 is a graphical representation showing total SVR broken down by the most significant causes.

Age At Next Maintenance

TAMP Time = 1050
Borescope = 920
Perf. Chk = 920
Random = 980

Read EOT, TAMP Time, Nozzle Time

EOT = 796
TAMP (Bucket)
Time (EOT) = 796
Nozzle Time = 336
Performance Time = 796

Sets Time To Next Maintenance Event, By Type Maint. On Engine

Borescope Insp. = 124 (920-796)
Performance Check = 124
TAMP = 254 (= 1050 − 796)
Random = 184 (= 980 − 796)

Advances Clock Time To Next Event (= Borescope/ Perf. Check)

Time Left to TAMP = 130
Time Left to Random = 60
Time Left to Boresc. = 0
Time Left to Perf. = 0

Perf. Weibull θ = 1000 B = 4

Check Performance — Use Weibull Distribution

$$P_F = 1 - e^{\left[-\left(\frac{796}{1000}\right)^4 + \left(\frac{580}{1000}\right)^4\right]}$$
= .25
Choose Random Number 0-1

Engine Failed Performance Check

Random Number > .25 — No / Yes

Engine Passed Check O.K.

Check Time To Tamp (Bucket) Change (130 Hours)

Nozzle θ = 2000 B = 3

Do Borescope Inspection — Use Weibull Distribution

$$P_F = 1 - e^{-\left(\frac{336}{2000}\right)^3} = .005$$
Choose Random Number 0-1

Time < No Build — No / Yes

Send to Shop Change Shrouds

Perform Tamp

Random Number >.005 — No / Yes

Engine Failed Borescope Inspection

Engine Passed Check O.K.

Set Engine Out Of Action While Tamp Done

Send To Shop Change Nozzles

Set Time For Next Maintenance Event

Set Engine Out Of Action While Nozzles Changed

Figure 11. Typical Engine Flow Through Simulation Model

The SVR model is run separately for each operating base to accommodate the different utilization rates and maintenance concepts that may exist. Data from each base is then compiled by the program to provide a composite fleet SVR forecast and input to the parts requirement model.

Figure 12 is a typical shop visit rate forecast for the TF34-100 fleet. Four basic causes for shop visits are identified in this plot. Further detailed breakout is available in tabular form as required. The four basic causes shown in Figure 12 are:

1. Removals resulting from an MOT limitation in terms of time at maximum power (TAMP).

2. Removals because the engine failed to meet performance criteria.

3. Removals at a scheduled borescope inspection due to wearout characteristics of the first stage turbine nozzle.

4. All other causes.

Legend
1. MOT (TAMP)
2. Performance Deterioration (Weibull)
3. 1st Stage Turbine Nozzle
4. Random Causes

Shop Visit Rates (Per 1000 HRS)

Years
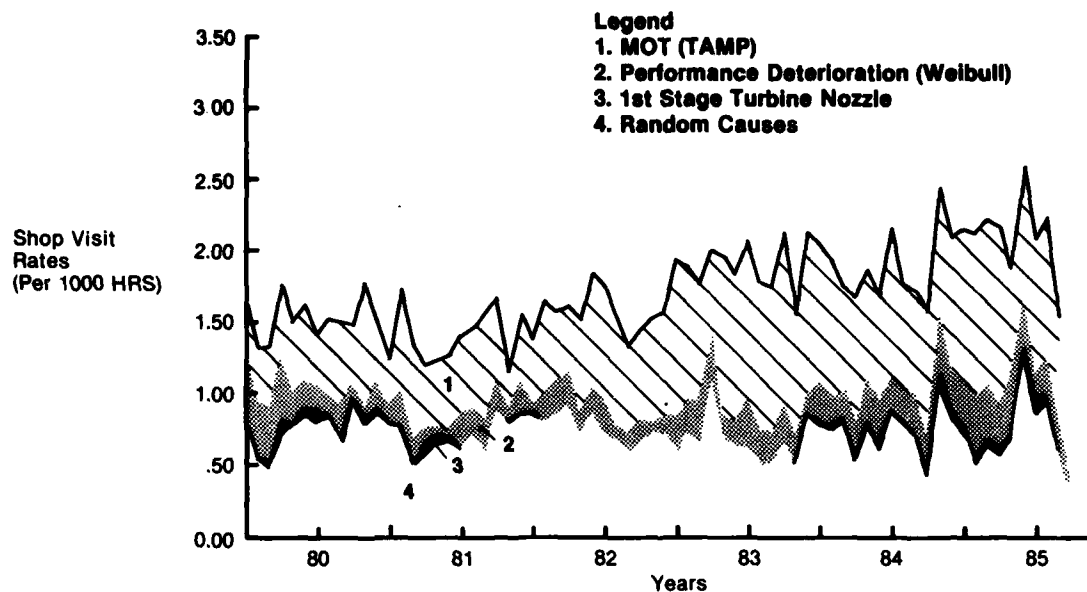
Figure 12. Shop Visit Rate Forecast – Total Fleet

TABLE 3

·SHOP VISIT RATE FORECAST BY CAUSE

MTH	ENGINE STATUS (MONTH END) INST	RFI	SHOP	LRU	MIN UER	MAJ UER	MAINTENANCE ACTIONS BY MONTH SHOP RSI	TAMP	SHOP VISIT	TAMPS 1ST	2ND	3RD	4TH	BSCPE N/F	PERF FAIL	PRF/ TAMP	MAJ/ TAMP	T810 EXCD	RSI/ TAMP	MIN/ TAMP	HR/MO (K'S)	SVR (/KHR)
1	120	20	4	7	2	2	0	0	4	0	0	0	0	20	0	0	0	0	0	0	4.80	0.833
2	120	16	8	11	5	0	1	4	10	4	0	0	0	14	3	3	0	1	0	0	4.80	2.083
3	120	19	5	9	3	0	0	1	4	1	0	0	0	21	1	1	0	0	0	0	4.80	0.833
4	120	22	4	12	2	0	2	2	6	2	0	0	0	18	2	2	0	0	0	0	4.80	1.250
5	120	23	4	12	5	0	1	0	6	0	0	0	0	20	0	0	0	0	0	0	4.80	1.250
6	126	16	6	10	5	0	0	3	8	3	0	0	0	16	3	3	0	0	0	0	5.04	1.587
7	132	19	4	15	1	0	0	3	4	3	0	0	0	22	2	2	1	0	0	0	5.28	0.758
8	132	24	5	10	4	0	0	2	6	2	0	0	0	14	2	2	0	0	0	0	5.28	1.136
9	138	13	10	15	8	0	0	4	12	4	0	0	0	29	4	4	0	0	0	0	5.52	2.174
10	144	14	9	21	6	0	1	6	13	6	0	0	0	14	4	4	0	1	1	0	5.76	2.257
11	144	21	8	6	7	0	2	3	12	3	0	0	0	13	3	3	0	0	0	0	5.76	2.083
12	144	19	11	11	6	0	1	8	15	8	0	0	0	19	5	5	0	2	1	0	5.76	2.604
13	144	19	10	17	9	0	0	10	19	10	0	0	0	10	5	5	0	4	1	0	5.76	3.299
14	144	24	5	9	3	0	1	4	8	4	0	0	0	17	1	1	0	2	1	0	5.76	1.389
15	144	22	7	13	3	0	0	11	14	11	0	0	0	34	8	8	0	2	1	0	5.76	2.431
16	144	16	13	17	8	0	0	9	17	9	0	0	0	10	5	5	0	2	2	0	5.76	2.951
17	144	16	13	10	6	0	0	10	16	10	0	0	0	22	6	6	1	2	1	0	5.76	2.778
18	144	19	10	14	8	0	0	7	15	6	1	0	0	11	6	6	0	1	0	0	5.76	2.604
19	144	26	3	12	2	0	0	3	5	3	0	0	0	14	3	3	0	0	0	0	5.76	0.868
20	144	20	9	15	7	0	0	8	15	8	0	0	0	22	4	4	0	4	0	0	5.76	2.604
21	144	16	13	14	5	1	0	11	17	11	0	0	0	26	7	7	0	2	2	0	5.76	2.951
22	144	22	7	12	4	0	0	6	10	6	0	0	0	22	1	1	0	5	0	0	5.76	1.736
23	144	20	9	13	3	0	0	5	8	5	0	0	0	22	2	2	1	2	0	0	5.76	1.389
24	144	26	3	9	2	1	0	1	4	1	0	0	0	18	0	0	0	1	0	0	5.76	0.694
25	144	25	4	7	1	0	0	3	4	3	0	0	0	23	0	0	0	2	1	0	5.76	0.694
26	144	18	11	12	8	0	0	6	14	6	0	0	0	19	2	2	0	3	1	0	5.76	2.431
27	144	25	4	23	3	0	1	3	7	3	0	0	0	21	2	2	0	1	0	0	5.76	1.215
28	144	19	10	11	4	2	0	5	11	5	0	0	0	21	3	3	0	1	1	0	5.76	1.910
29	144	24	5	14	2	0	0	3	5	3	0	0	0	27	1	1	0	0	2	0	5.76	0.868
30	144	24	5	17	9	0	0	1	6	1	0	0	0	13	0	0	0	0	1	0	5.76	0.868

OPPORTUNISTIC MAINTENANCE MODEL

Parts subject to cyclic or operating time limits can be major drivers of shop visit rates (SVR) and maintenance cost. In most engines the specified cyclic lives will be different for each component, however it is not practical to run all these components to their maximum operating times (MOT's) because unacceptably high shop visit rates would occur if the engine was pulled into the shop to replace a part only when it finally reached its MOT limit. Current practice has been to establish an "Opportunistic Maintenance" plan in which components are replaced at the same shop visit, if a specified amount of their life has already been consumed. The trade-off in loss of useful part life is more than offset by reduced labor costs and lower shop visit rates, if the opportunistic maintenance plan is properly established. For a more detailed dissertation on this subject and a description of a model developed for use on the F100 engine, the reader is referred to the work of J.L. Madden of the Directorate of Management Sciences, Headquarters Air Force Logistics Command, USAF. (references 2 and 3). As part of the logistics forecasting effort, a model has been established incorporating the logic required to set up an opportunistic maintenance plan. The objective of the program is to establish the life remaining interval necessary to minimize shop visit rate and/or overall maintenance cost. The program takes the form of a limited simulation and retains in memory the accumulated time or cycles on a specified number of life limited items on a large fleet of operational engines. Only those parts having specified lives less than the expected duration of the operational life of the engine life cycle are considered. On the engines studied, the number of parts with lives smaller than the expected program life is quite manageable, so this has not been a massive computation problem. Exposure in terms of the limited parameters is accumulated on each of the parts until a life limit is reached, at which time the engine is removed to the shop. When this occurs, the part is replaced and the life remaining on all the other parts is examined. They are replaced if their life is less than are assumed opportunistic maintenance interval. Labor time will include total disassembly time for the "primary" part replacement, including time to remove from the aircraft and any check-out running after replacement. For the "secondary" parts the labor time will be the additional time necessary to replace the other items, once the engine is disassembled to the primary item.

Costs and shop visits are accumulated on a monthly basis over the total duration of the program. The optimum opportunistic maintenance plans for both cost and SVR are established by running further iterations.

Figure 13 is a graphical presentation of a typical optimization study. In this case five MOT items are considered. One item is limited in terms of time at temperature and the other four have different maximum lives specified in terms of LCF cycles. The program was iterated for various opportunistic maintenance intervals and the resultant 15 year maintenance costs and shop visit rate associated with these parts estimated. It will be observed that for OM intervals between 500 and 1000 hours there is very little change in maintenance cost, however, the shop visit rate is reduced by over 50%. Beyond 1000 hours there is a rapid increase in cost for a very small improvement in SVR. Mean values of the 5 component MOT's in terms of engine hours were 1125, 2560, 3100, 3000 and 2600 respectively.
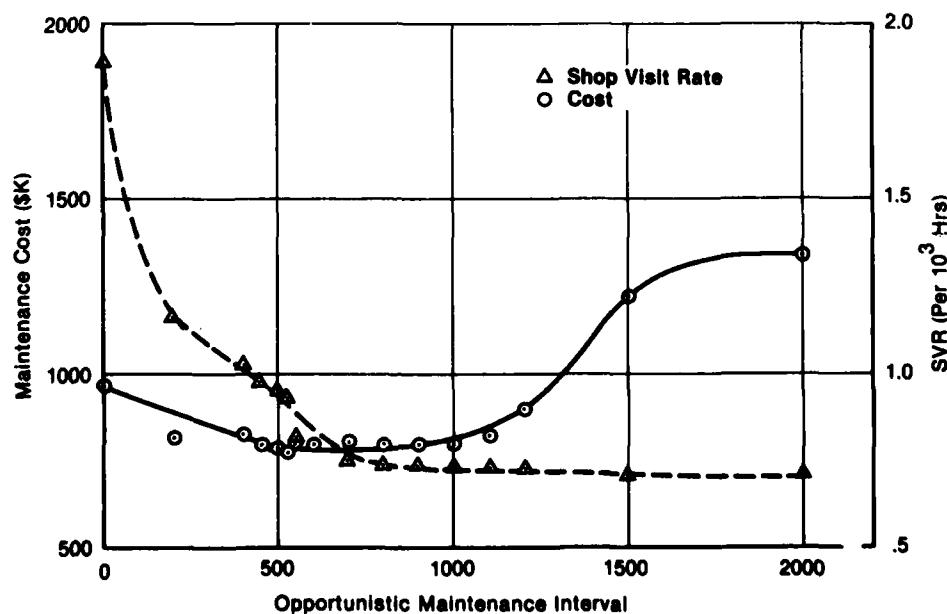
Figure 13. Opportunistic Maintenance Interval Optimization Study

PARTS REQUIREMENT MODEL

This model takes the output from the SVR model and matches it to a parts list per event file to compute total parts requirements by interval over the forecast period. In addition, the program computes pipeline and safety stock level requirements to meet the expected demand for selected components. The program has the option to take input on asset positions and lead times for each part and provide an expected reorder and zero stock points. Further routines are currently being added to this program to convert the expected demand quantities into a format which can interface directly with customer logistics management systems such as the USAF DO62 and DO41 or the USN CSSR system.

USE OF THE FORECASTING SYSTEM

The SVR Forecasting model can be used as the basis for several logistics planning requirements. In its basic form which provides a listing of monthly shop visits by cause, it can be used as a basis for establishing the requirements for:

> Workshop capacity
>
> Facilities
>
> Tooling and Test Equipment
>
> Manpower
>
> Overall Maintenance Support Costs

Typical of the output used to assess the requirements for such resources as workshop capacity and manpower is the graphical presentation shown in Figure 14 and 15. These figures show respectively the expected shop visit rate and the shop loading in total and for certain specific causes by month. As can be observed, some of the causes are cyclic in nature being the result in this case of a wearout characteristics in one component and an MOT limitation in another. The SVR category No. 3 is the result of a wearout characteristic, in this case the first stage turbine nozzle that results in an engine's removal at a preventative maintenance inspection. This is a component that has been subject to a Component Improvement Program and on removal is replaced with an improved design. Thus shop visits due to this component do not start becoming significant again for another four years. The model recognizes the concept in this case of replacing the initial design whenever the engine is removed for other causes such as category No. 1. This category is caused by the first stage turbine buckets which have a life limitation in terms of time at maximum power (TAMP), as described in the discussion on the ETTR system. The resultant distribution in engine operating hours at which this TAMP limit occurs coupled with the engine age distribution smoothes the peak shop loading but the cyclic effect can still be seen as the SVR for this category peaks in the second year, at the end of the fourth, and again at the end of the sixth year.
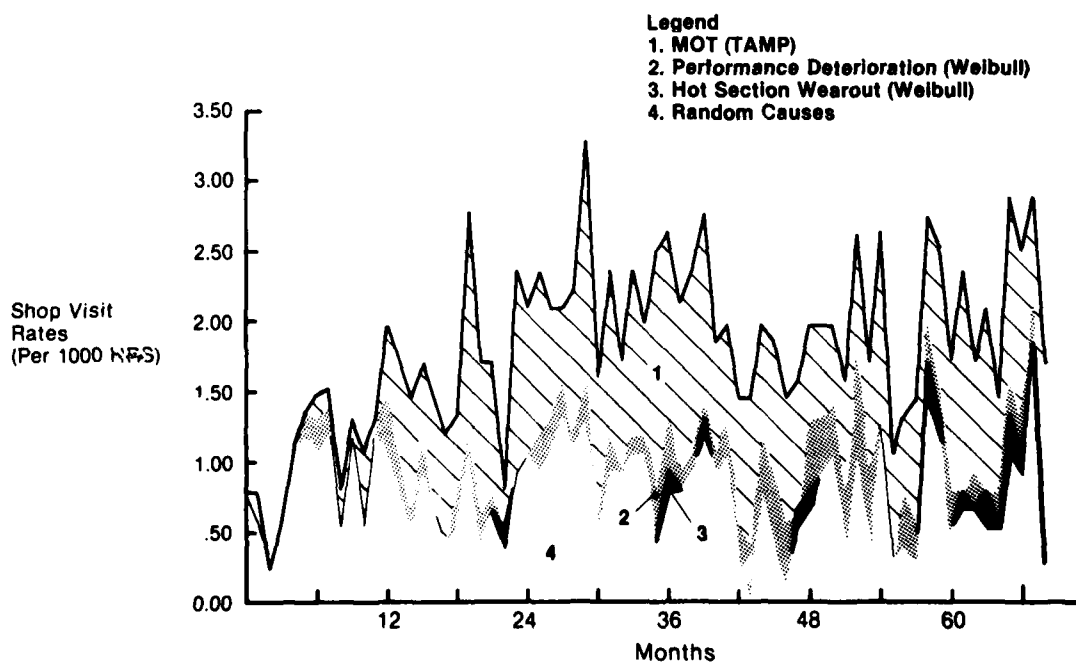
Figure 14. Shop Visit Rate Forecast for Base B.
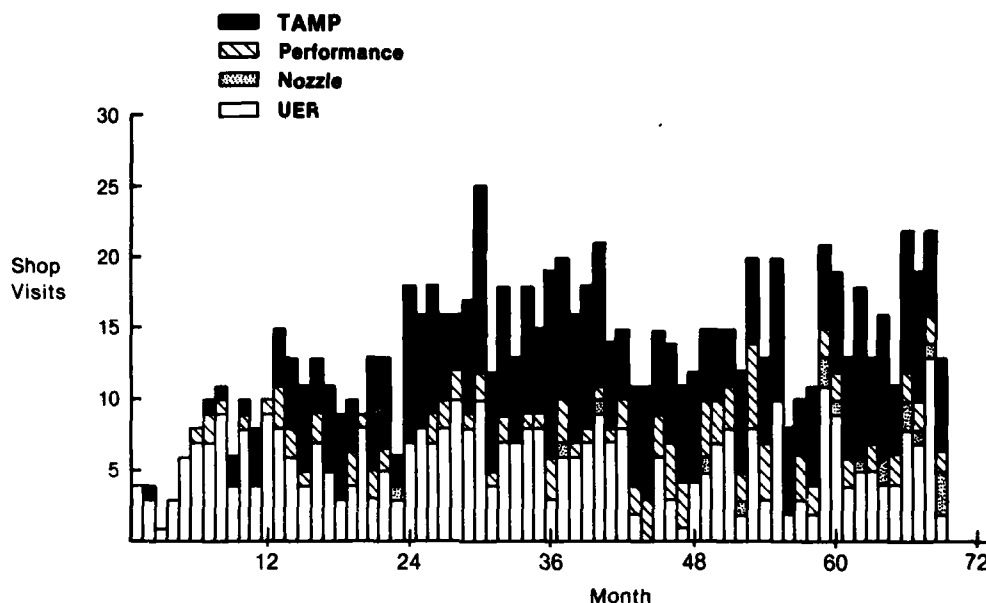
Figure 15. Shop Visit Forecast - Events Per Month

The component responsible for the TAMP removals (Category 1) was included in a study into the cost effectiveness of the ETTR system. If no ETTR were available the component life would of necessity be established in terms of engine flight hours. As can be seen from Figure 8 that life in terms of time at temperature would cover a very wide range of EFH. If the life were to be established analytically, it would be done in terms of conservative assumptions relative to mission, severity, or if having the resource to instrument a sample fleet, a similar distribution to that shown in Figure 9 would be measured. On this basis, we estimated that the MOT would be established at approximately 60% of the mean life achieved using the ETTR system. The impact is shown in Figure 16. This represents the total shop visits caused by MOT limits on the subject component over five years at one base. The number of total visits is more than doubled and the cost impact is in the order of $20 million.
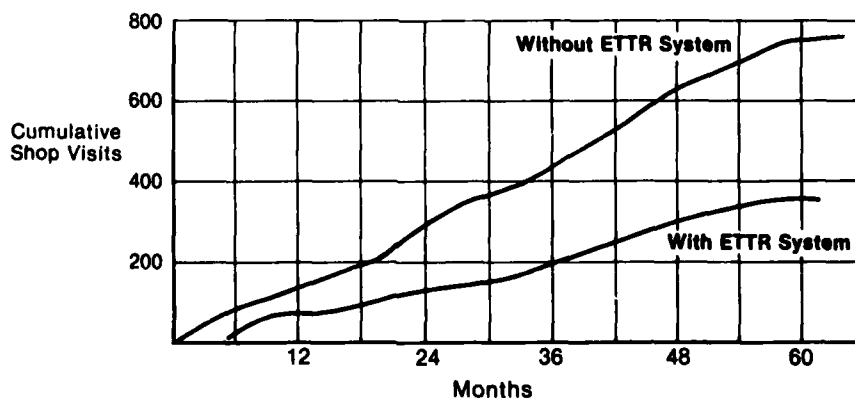
Figure 16. Impact of ETTR System on Total Shop Visits
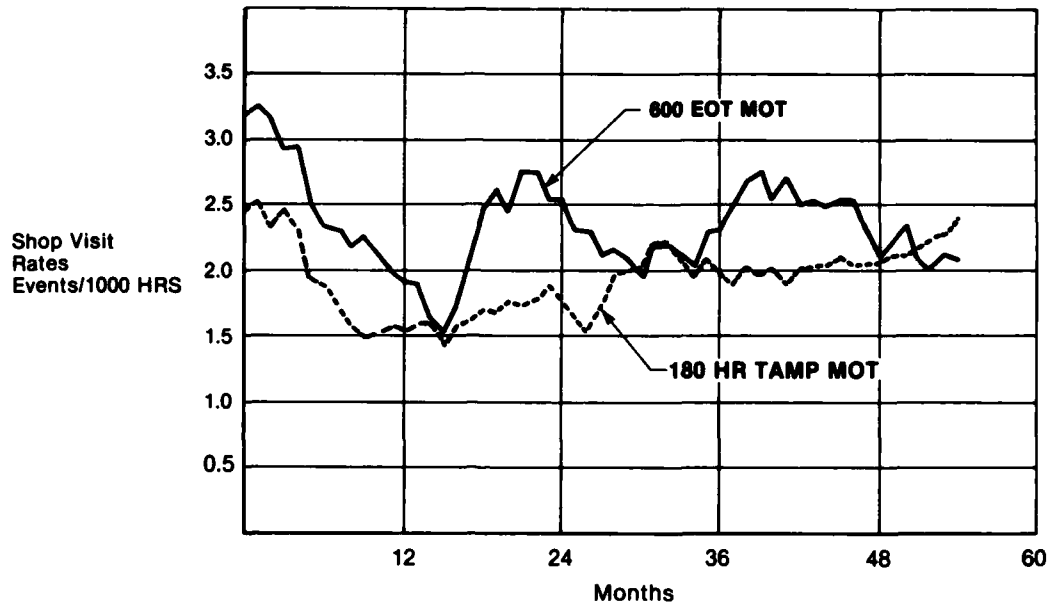
Figure 17. Shop Visit Rate Effect of ETTR System

The significance is not only in the cost but also in the impact on SVR, the reduced MOT and its definition in terms of engine flight hours results in far higher peaks in the SVR during the first four years of the forecast period although the impact on SVR is modified somewhat by the effect of the Opportunistic Maintenance Plan. This is illustrated in Figure 17 where the SVR is plotted for the two cases.

1. With an ETTR system, and MOT specified in terms of time at maximum power, Opportunistic Maintenance Plan 150 hours at intermediate maintenance, 300 hours at depot.

2. No ETTR system, MOT specified in terms of engine flight hours. Opportunistic Maintenance Plan 150 hours at Intermediate, 300 hours at depot.

The first six months of the forecast period reflects the current status, the fleet is currently experiencing the first cycle of MOT removals due to TAMP, two factors act to smooth the periodic surge, one is the engine age distribution due to the fleet build-up period while the second is due to the definition of the MOT in terms of TAMP. This results in quite a wide range of EOT's at which TAMP occurs. In the case illustrated the TAMP MOT cyclic peak is virtually eliminated after the second cycle which occurs at about month 40 of the forecast.

On the other hand, when the MOT is in terms of EOT the cycles are more pronounced (a) because there is no smoothing due to the effect of TAMP ratio and (b) because the cyclic frequency is less than 60% of that in case 1, three cycles are identifiable approximately 20 months apart. At the average assumed utilization of 30 hours/month this cyclic frequency coincides with the 600 hour MOT.

The SVR model has also been used to study the cost effectiveness of proposed changes in engine design, maintenance plan and the extension of maximum operating times. Typical of the latter was a study relative to increasing the MOT of the component described in the last example. Preliminary field operation and factory endurance hours had indicated that an increase in allowable time at max power was possible, however such an increase would be dependent on the continuation of the test and development program. Figure 18 illustrates the impact on SVR where line (1) represents the baseline case and line (3) extended TAMP. It will be noted that there is very little impact. The reason for this may be explained by referring back to Figure 11, which describes the modelling simulation. Block (7) identifies a performance check when the probability of failing the check is described by the Weibull relationship. Correction of performance degradation results in the changeout of the TAMP limited parts if within the opportunistic maintenance plan limits. In the case studied a 180 hour TAMP limitation precludes many of the removals that might otherwise result from performance deterioration. On the other-hand if the TAMP limit is extended to 200 hours the performance deterioration will predominate using removals prior to reaching 200 TAMP hours and thus negating the benefits of a reduced SVR that could have resulted from the increased TAMP limit. Line (2) represents the impact on SVR if the effects of performance degradation are eliminated.
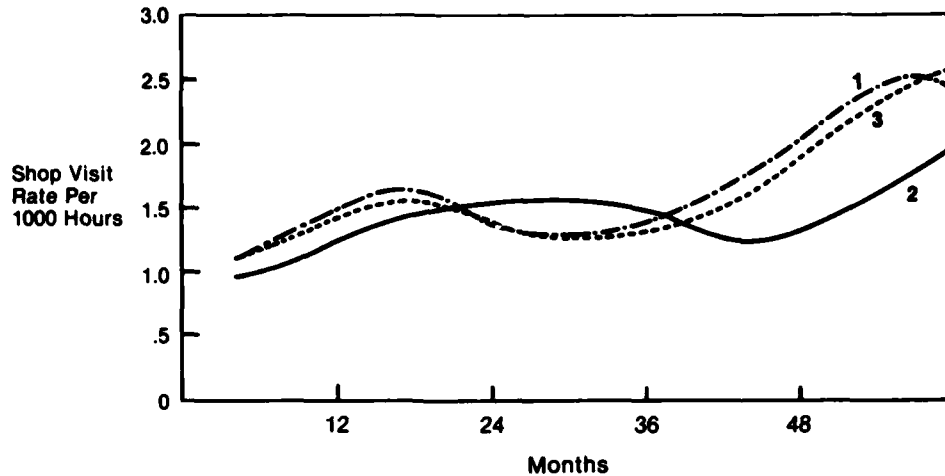
Figure 18. SVR Sensitivity to TAMP Intervals
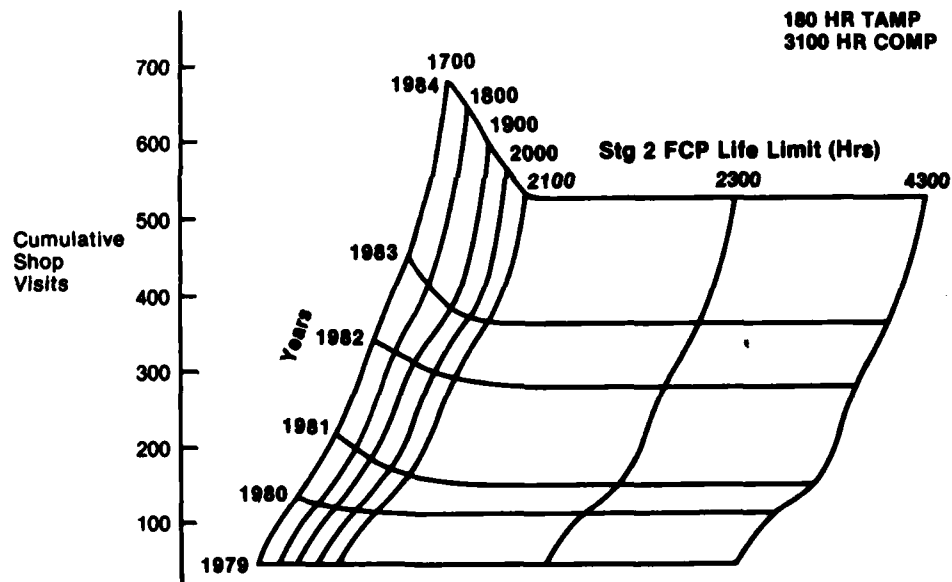
Figure 19. Stage 2 Forward Cooling Plate Life Optimization

The opportunistic maintenance model may also be used for purposes other than establishing opportunistic maintenance policies. In several cases it has been used to evaluate the cost effectiveness of proposed ECP programs to increase component LCF lives. In the study illustrated in Figure 19 continued endurance testing had shown that a part in the HP turbine rotor had a mean MOT in terms of engine operating hours of 1700 hours. This was low relative to associated components. Various design changes were possible each of which could provide some degree of increased life. The model was used to determine the life needed to provide the maximum decrease in SVR. In many cases the MOT of component within a module or major assembly will vary considerably resulting, even with the optimum opportunistic maintenance plan in considerable waste of available part life. Selecting a desirable goal for the improved life capability can be assisted by the use of this model. In the case illustrated, the opportunistic maintenance model was used to forecast the total shop visits that would be generated over a five year period for various values of the component MOT. The results are shown in Figure 19 where cumulative shop visits requiring replacement of the subject part are shown plotted against year and average part life in terms of operating hours. In this case, it can be seen that there is no reduction in savings related to the shop visit rate for a component MOT greater than 2100 hours. Above the component age of 2100 hours the MOT's of other parts will become the primary driver of the shop visit rate. However the lives of other parts begin to drive the need for shop visits and the associated usage of parts subject to the opportunistic Maintenance Plan.

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FORECASTING TOOLS DIRECTLY AVAILABLE FOR THE PLTS/ETTR SYSTEM

Certain forecasting aids to logistics management are available directly from the PLTS/ETTR Systems. Typical of these are the Engine Status Report and 20% Life Remaining Report.

Engine Status Reports

Whenever an engine is inducted for major repair decisions must be made as to whether to charge out MOT parts which still have life remaining as described in the section in opportunistic maintenance. It is necessary therefore that the repair facility has an accurate listing of the total exposure to operating house, low cycle fatigue cycles, time at temperature or whatever other parameters by which a component's MOT is specified generated automatically by the PLTS whenever a third engine is inducted into a repair facility.

Life Remaining Report

Typical of reports generated on a periodic basis as part of the PLTS Program is the "Twenty Percent Life Remaining Report". This lists by item designation, the information necessary to locate all parts, in the fleet or in storage, having less than 20% of their designated MOT remaining.

Table 4 is part of such a listing. In this case the example identifies two parts in engine Serial Number 205183 that are within 20% of their MOT. The report identifies the aircraft in which the engine is installed and the base at which it is located. In the case of both components, the part and serial number of the Next Higher Assembly (NHA) is noted. The first item referenced to is the Fan Disc, the MOT limit is in terms of LCF cycles as designated by the Time Limit Code C. The limit of 3100 cycles and the current life used is 2927 cycles leaving 5.58% of life remaining. The second item is the first stage high pressure turbine bucket - in this case there are three MOT limits, code C, the LCF limit of 8000 cycles, code V, which is hours at or above 790°C and code E which is at or above 810°C which equates to time spent at maximum power. The limiting exposure here is in terms of time at 810°C, 172 of the limit of 180 hours has been consumed and 4.44% of the life remains.

Table 5 is from the same report but identifies a part being held as a spare. In this case it is a set of turbine buckets that are part of a spare rotor assembly identified by the NHA part number.

The life used is computed from the ETTR data which is also issued in report form as shown in Table 2.

In this table the engine referred to in Table 4 is identified. The data in terms of E550 and E790 is used in conjunction with the K factors as shown in Table 1 to compute the cycles used. T790 and T810 are used directly from the ETTR files.

This and other reports are generated periodically for various operations. The Central Data Base is generally responsible for supplying reports to the using commands, Logistics Command and operating bases while base documentation/MMICS operations provide reports for base maintenance management planning and forecasting.

TABLE 4.

*** TWENTY PERCENT LIFE REMAINING ***

AS OF DATE 24 JAN 80   DATE 04 FEB 80 TIME 0954

REQUESTING ORGANIZATION-

REQUESTED CI NUMBER TP 54100	ENGINE TMS0000S/N IF0054100 205183	AIRCRAFT MDS000TAIL NO. AU10A 76-0520	POSITION 1	LOCATION BASE B

ITEM CII	NOUN	ITEM P/N000S/N	NHA P/N000S/N	ITEM INST DATE	STATUS	LIMIT	TLC	USED	REMAINING	PERCENT REMAINING
TP 54220	DISC FAN	002010200J GA100/0200	00J1TV5002 GAL007020	7725	INSTALL	3100	C	2927	173	5.58
TP 54005	BLADE SET STG 1 HPT	0010120005 GA100/J200	00J110WW1 GA100/J200	7725	INSTALL	8000 450 180	C V E	6001 219 172	1959 231 8	24.40 51.33 4.44

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TABLE 5.

*** TWENTY PERCENT LIFE REMAINING ***

AS OF DATE 24 JAN 80   DATE 04 FEB 80 TIME 0954

REQUESTING ORGANIZATION-

REQUESTED CI NUMBER TF34000	ENGINE TMS****S/N GALOU3I500	AIRCRAFT MDS***TAIL NO.	POSITION	LOCATION BASE B

....

ITEM CII	NOUN	ITEM P/N***S/N	NHA P/N***S/N	ITEM INST DATE	STATUS	LIMIT	TLC	USED	REMAINING	PERCENT REMAINING
TF34005	BLADE SET STG 1 HPT	0010T20005 GAT0065000	6031T8VPU1 GAT0065000	77244	SPARE	8000 450 180	C V E	5223 191 160	2777 259 20	34.71 57.55 11.11

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1. On-Condition Maintenance Review of Military Engine, Donald H. Story, SAE Technical Paper 791102, December 3-6, 1979.

2. Opportunistic Maintenance Policies for Economic Replacement of Internal Life-Limited Components in Modular Aircraft Engines, John L. Madden, SAE Technical Paper 791101, December 3-6, 1979.

3. Opportunistic Maintenance Engine Simulation Model: OMENS II, John L. Madden, et al, AFLC XRS 79-137-1 AD/A 072 516, June 1979.

THE APPLICATION OF DESIGN TO COST AT ROLLS-ROYCE

by

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1.   INTRODUCTION

The Rolls-Royce Aero Division is composed of factories situated on a variety of sites and includes three main groups, each of which has full sales, design manufacture and product support capability. While all sites accept the basic philosophy of Design to Cost, the practical application has evolved in accordance with local experience and the working methods of the individual areas and this paper specifically deals with the Bristol Group whose workforce is approximately 18,000 strong and whose main factories are at Bristol and Coventry. The paper is significantly the work of two authors having overall responsibility for the cost control function, one within the Engineering Department and the other within the manufacturing areas. The views expressed are those of the authors and should not be interpreted as necessarily representing offical Company policy.

The fact that Design to Cost has only lately become a worthy subject for papers and seminars is a sympton of the inheritance of most nations who were early in the development of industrialised society. In those early days the desirability of what the inventors and engineers had to offer in the way of solutions to age old problems was such that designing and making were pursued as subjects separate from their cost consequences on the basis that if desirability and availability were catered for, customers who would pay the costs could always be found. It was the classic seller's market which inevitably results when widely desirable commodities are available from few sources. It was in these early days that most manufacturing companies evolved the normal structure in which Engineering, Manufacturing, Commerce and Finance are each made as autonomous as possible, usually having their own directors responsible only to the head man. This is no doubt the best structure to address a market place where the customer is concerned only to get what he wants when he wants it but it can respond only with difficulty when he also has a maximum price beyond which he genuinely cannot go.

Between 1939 and 1945 the British aero engine industry multiplied its capacity by 75 times and no doubt a similar situation applied in other countries. At the end of this period the turbine engine looked likely to completely displace piston engines for nearly all civil and military applications and thus it was inevitable that the 'cost plus' environment was continued by the placing of Government contracts, often of a research nature, with the dual purpose of developing gas turbine technology and cushioning the industry during a period when it had to find a new peace-time role and the capacity to match it. While thirty years have passed since the start of this period aircraft projects have a life span nearly as long as this and so the full realisation of the cost consequences of the inherited working methods has only become widely apparent in the last decade. This is particularly true of the operating costs of modern engines which are now such as to convince anyone that a radical approach to life cycle costs is essential, particularly for military equipment where there has been a tendency to pursue all technological developments in terms of ever more sophisticated performance.

During this same period the less industrialised countries have significantly reduced our relative wealth by learning to make for themselves many of the manufactured goods for which they were previously dependent on our industries, while we have been unable to keep ahead because of the increasingly effective restrictions of reducing resource availability and other environmental pressures. Thus the full realisation that cost is as important to our customers as technical performance or delivery is quite recent and rapid response is particularly difficult because most industrial companies are structured to respond to technical, delivery, commercial or accounting problems but not to cost which is a consequence of the way in which all four interact with each other. The introduction of a radically new discipline is, furthermore, paced by the timescale of projects themselves and by the difficulties of achieving a major cultural change in large multi-disciplined organisations.

This paper describes the work done in the Bristol Group of Rolls-Royce Aero Division during the last five years and shows how our Product Cost Control system (of which Design to Cost is a part) grew from the disappointing Value Engineering experience of the 1960's and the encouraging results of the approach which subsequently evolved. The major financial benefits which it is now showing are quoted.

The important aspects of the background which influenced the Rolls-Royce approach are described and conclusions drawn regarding the origins of unnecessary cost and the problems to be overcome in avoiding them. The detailed objectives in setting up the Design to Cost procedure are stated and the reasons explained.

A new type of department has been created to face the princi~~~ ~~ ~~~ that true control of costs requires new interactive links between th~ ~~ ~ disciplines at all levels. The paper describes the way in wh ~ roup fits into the existing organisation to ensure that effective cost ~~~~ becomes part of the established routine.

Comments are made on the nature of cost and its fundamental difference from the other parameters which the Designer has traditionally managed.

The Seminar specifically addresses itself to Designing to Cost <u>and</u> Life Cycle Cost. It is certain that the cost of ownership of most high technology equipment greatly exceeds the already too high aquisition costs but this must not be allowed to mislead the designer into believing that these are separate subjects. The gathering of basic data, from the field, the overhaul base, from within our own factories and the processing necessary to make it digestible to a designer are worthy of a paper in their own right and no doubt others will deal with these aspects. In the meantime it is worth noting the extent to which life cycle costs are driven by component costs (Fig.1). Provided that the designer can be given a quantified understanding of the cost effects of the differential spares consumption rates of the major components he can handle the major aspects of LCC without difficulty. The Rolls-Royce system is structured this way.

Conclusions likely to apply to any commercial manufacturing company are suggested and comments made regarding the future responsibility of engineers in determining the financial success of the companies for which they work. Complementary roles for management and financial accountants to support the new responsibilities of the engineers are also indicated, as is the much greater involvement of everyone in the true nature of their company's business. It is believed that all these things, however daunting or strange they may initially appear to our over-specialised workforce, will in the end turn out to be wholly good for the Company, its individual members in all the disciplines and, perhaps most importantly, for the customer.

The Rolls-Royce experience in evolving and applying a formal Design to Cost discipline is described in chronological order of the main events which have occurred during the last five years with brief reference to the period before that.

2. <u>VALUE ENGINEERING</u>

The first significant aspect of cost control for the purposes of this paper concerns the emergence of Value Engineering as a meaningful activity. Although it originated in the 1950's, like most new subjects, it was at least a decade before its pioneers had developed and evolved the basic principles and procedures and had published them together with factual information on the results of their application. The potential of the Value Engineering approach as a means of identifying ways of reducing the cost of components then soon became apparent to the specialists involved, although unfortunately little thought was given by the senior management of most companies to its proper application. In most cases Value Engineering was wrongly presumed to be a quick and ready-made solution to all cost problems and was consequently not given a fair chance. Certainly this was true at Rolls-Royce. The Company Training College provided Value Engineering courses at which the basic attitudes and thought processes of disciplined Value Analysis were taught and practical case studies used to demonstrate the potential cost benefits. Over the years these courses were attended by the majority of designers, detailers and production engineers. A Value Engineering Department was also established within the Design Office staffed by engineers transferred from the Manufacturing areas. Copies of all newly issued design schemes were routed to this department who examined them from the manufacturing viewpoint and sent their recommendations back to the Design Office. Initially results were encouraging in terms of the sums of money being reported as savings. After a while, however, it was realised that only a very small proportion of the recommendations were ever implemented and eventually the department was disbanded for this reason.

At this time the total manufacturing activity of the Bristol Group consisted of the combined resources of what had been two separate companies and consequently it was not always evident at the design stage where production manufacture for a given component would finally be placed. Another very significant aspect of this period was that the manufacturing engineers who formed the Value Engineers Department, having spent their lives a long way downstream of the Design Office, considered that they were making the earliest possible impact by obtaining copies of the design schemes at their time of issue. To the designer, however, scheme issue was the end of the line, not the bginning. Thus, the value engineers were giving advice too late as far as the designers were concerned. Furthermore, the advice necessarily lacked an absolutely vital ingredient. It did not and could not carry any real commitment in the sense that the eventual manufacturing methods and costs would later be determined by the production engineers who worked in the production shops, who had executive control over the plant and processes and who also had quality and programme requirements to meet.

The Value Engineering Department failed. It was not, however, a failure of Value Engineering as a discipline nor was it a failure of the value engineers involved. It was a management failure. Good people were given an important task to do but were set up organisationally in a way which could not have succeeded. Advice was being given too late by the wrong people. Fig.2

What had not been recognised by management was the futility, particularly in the 'cost plus' climate which then prevailed, of installing a group to whom cost was the only consideration alongside an organisation which was structured only to recognise and respond to levels of technical and timescale priority and expecting the group to make a significant impact on costs. We know this experience to have been common in many companies and at Rolls-Royce it has coloured all our subsequent thinking about cost control and the importance of carefully planned implementation.

3.   MANUFACTURING, DESIGN LIAISON

In the early 1970's a major rationalisation of the Production Manufacturing Department was initiated. Product Centres were established, each with sole responsibility for the supply of specific types of component. For example: Product Centre 3 is responsible for the shafts for all engine types; Product Centre 4 is responsible for all compressor blades; and so on. Each centre is self-supporting in terms of planning, estimating, purchasing, sub-contracting and quality. The advantages of an organisation of this type include specialisation, improved capital plant planning and, significantly for the subject of this paper, positive identification during the design phase of the Manager, and the team, who will have supply responsibility for each component during production phase of the programme.

A new attack on cost, designed specifically to avoid the mistakes of the Value Engineering experience was then launched. Liaison engineers with similar backgrounds to the value engineers were located in the Design Office (while remaining on the Production payroll) charged with ensuring that designers were given manufacturing advice while they are designing, not after, and that the advice came from the man who was going to plan and make in production.

Great emphasis was placed on the role of the liaison engineers as link men who were specifically not there to advise designers but to arrange timely and direct contact with the production engineers from the appropriate Product Centres. What the Design Liaison Group offered to designers was a service which could provide advice at the right time and with commitment. Commitment could only come from the production engineer of the Product Centre with sole responsibility for production manufacture.

The effort was first directed at the RB401, a small two spool fan engine which had just been launched into the main Design Office. The market situation for this engine was clearly understood to be very dependent on low cost, so that the Design Team was receptive to cost advice, especially since the advice was now coming from the production engineers who would have responsibility for manufacture. The new liaison activity succeeded in linking designers and production engineers without significant interruption or delay to either. During this period the objective was to minimise labour and material content, although no specific cost target was being aimed for. At appropriate intervals the cost of the engine was estimated, and by the time the design was ready to instruct manufacture of the first bench engines, its cost was some 35% lower in terms of $/lb thrust than a similar engine previously designed by substantially the same design team. There was no significant impact on the design time cycle and no compromise at all to the technical standards of the engine. The price paid in terms of additional manpower was insignificant. (Fig. 3)

After the failure of the Value Engineering activity this first result of the Design Liaison approach seemed very satisfactory. However, at this point the Technical Director suggested that a lower cost might be obtained and specified on arbitrary cost target which required a further 15% reduction. This was the first time a specific cost target had been set for Designers and it stimulated the team to such good effect that the target was reached within a few weeks. This clearly demonstrated the need for specific cost targets. They tell people when to stop.

(A paper dealing more specifically with the engine in question 'Low Cost Design Techniques and their Application to the Design of the Rolls-Royce RB401' was given at the Seminar on 'Engine Design and Life Cycle Cost' at the Naval Air Development Centre, Warminster, Pennsylvania, 17th to 19th May, 1978.)

In parallel with the above activity the liaison engineers became very involved in campaigns to reduce the cost of several engines already in production. Cost reduction in this sense means eliminating unnecessary cost from the components of an established design and so is quite specifically not a question of design to cost. The experience is nevertheless quoted here because the detailed examination of some 2,000 detail drawings by teams of designers, detail draughtsmen and production engineers gave a very thorough understanding of the origins

of unnecessary cost. It was discovered that only 20% of unnecessary cost could be avoided by Production Engineering changes alone, 30% required some change to the detail drawings and 50% to the design schemes. Fig.4. This strongly supported the belief that the real impact on cost must be made during the design phase. It is an example of Pareto's observation. When 10% of the project time-scale has elapsed, 90% of the cost level has already been determined. Fig.5.

Another important fact which became clear during the cost reduction exercise is the paramount need for Design, Detail, Development and Production Engineers to work as a team, in parallel and not as is often customary in series, if the most cost effective designs and manufacturing methods are to emerge.

This Design Liaison experience gave a clear picture of the potential and generated a resolve by top management to ensure that costs were managed as effectively as thrust, weight or S.F.C. and as far as possible by the same sort of means. However, it was recognised that since the cost of the product was outside the direct control of Commercial, Engineering, Manufacturing or Accounting Departments alone, a carefully concerted approach by all four disciplines would be essential. The implications of this requirement deserve a lot of thought since all other working practices are likely to be based on this fundamental division to four which in most companies occurs at director level. Specifically the requirements of effective cost management are likely to cut across or be in opposition to many of the established procedures, attitudes and responsibilities within each of the four areas.

After several months of discussion between the directorial areas and with other companies, it was decided that a department would be formed with the task of advising designers on cost in a manner analogous to the role of the Stress Office on stress or the Weights Department on weight. The new department would, however, be composed of members seconded from the four directorial areas remaining on their original payrolls and responsible, as were the design liaison engineers, for 'linking out' with their line areas in order to ensure the essential element of commitment. The department would be headed by an ex-designer.

The decision to form such a department was the start of the Product Cost Control discipline at Bristol.

4.   PRODUCT COST CONTROL

4.1   The Objective

The objective in introducing Product Cost Control was to manage cost as far as possible in the same way as the Engine Development Programme or Manufacturing Production Programme. This objective was defined as 'Professional Management of Costs as a Line Routine.'

- "Professional" in the sense that all the data and the decisions that are put into the discipline come from the areas and the individuals who will be responsible for carrying out that particular part of the operation 'on the day'

    (While this may appear to be stating the obvious it must be remembered that costs cut across many established disciplines and advice without commitment is as abundant as it is useless. Everyone likes giving advice to others but no one can commit anything which will be outside his direct control on the day. Thus, a Designer may need advice from a Purchaser on material, a Planning Engineer on the manufacturing process, tools and plant, a Shop Supervisor on shop performance, an Inspector on inspection techniques and equipment, a product support specialist on maintainability, a commercial specialist on life cycle effects and warranties and an Accountant on cost based decision making.)

- "Management" in the sense that at each stage of the work flow, from design through detail drawing, development, planning, making, sales and product support, monitoring data must be reported which will indicate at the earliest possible moment variance from the component target cost and the areas where action may be needed.

- "Costs" in the simple sense as far as possible unconfounded by sub-divisions to direct, indirect, standard or any of the many esoteric cost categories used in financial accounting.

- "As a line routine," meaning that the cost control discipline is built into office paperwork in such a way that a group of management auditors could establish the detailed workings of the control by an examination of the paperwork and its route from the Design Office to Despatch. Cost Control like Programme Control should be independent of personalities and fashions.

    Clearly Product Cost Control is not only Design to Cost but Make to the Design Cost. (Fig.6).

4.2 Design Cost Control Group

As previously mentioned the principal organisational feature of the Cost Control system is the group whose task it is 'to advise designers on cost like the Weights Department does on weight.' This is the Design Cost Control Group (D.C.C.G.). Accepting that cost cannot be controlled other than by the joint action of Commercial, Engineering and Manufacturing interests, this department is staffed by people seconded from Commercial and Manufacturing and headed up by a senior designer. Interestingly this group is the only one in the Company whose interests are not limited to one of the four major disciplines.

The Departmental Head was given the same status in the Engineering Department as the Chief Designer of any project, responsible, as they are, directly to the Director of Design. His entire staff, apart from office administration, belong either to Commercial or Manufacturing. Secondment means that while the day to day work is controlled by the man to whom they are seconded they remain on the payroll of the areas which second them and must be used in a manner satisfactory to the seconders. As far as we know this structure is unique. (Fig.7).

The psychology of this group is such that the major disciplines are constrained to try and agree amongst themselves at working level and this is undoubtedly a major factor in eliminating unnecessary cost. It must be stressed that the re-sponsibility of the Manufacturing and Commercial members of the D.C.C.G. is to link out with the line areas within Manufacturing, Business Planning and Accounts to involve those people who have executive control of the many functions which can affect and are affected by cost. The D.C.C.G. is a small group, currently seven people.

4.3 Procedure

Figure 8 shows how the Product Cost Control procedure impacts on the normal work sequence in a manner which achieves the objectives of 4.1. The diagram reads from left to right and represents the succession of departments through which the work flows.

- The Marketing specialists determine the type, size, programme and price of a potential new engine and if this looks attractive pass this data to Business Planning. (NOTE: Price in this context is that judged to give some sort of optimum balance between margin over cost and maximum market penetration for the aircraft).

- Business Planning Department take this data and add their contribution on launch costs, spares, warrantee costs return on capital, cost of inventory etc., and deduce the maximum factory cost per engine compatible with good business. If this does not look attractive it is referred back to Marketing for discussion and resolution. If it does look attractive the maximum accept-able factory cost is passed to the Design Cost Control Group as their target.

    The D.C.C.G. assesses the new engine by:-

- Predicting the probable design features, particularly those which will have a major impact on cost, of the eventual production standard engine.

- Estimating the progress of manufacturing technology, both towards the avail-ability to Production of new types of process and toward achieving the higher material utilisation and higher metal removal rates that may be available by the time the full production rate is established.

- An examination of similar components and processes in existence to identify areas where cost reduction might be achieved within the project's timescale.

This assessment is done separately for each of the sixty or seventy major components which together constitute some 90% of the total cost. The remaining 10% consists of the usual large number of minor components and a single figure for this group is set such that it represents only a small reduction over current actual costs for similar components, say 10% less. The targets are expressed in standard hours of labour content and material price. Exceptionally, targets may be set in a more arbitrary manner, for example no component is given a target of over 200 standard hours simply because this would almost certainly imply a long lead time which has many disadvantages apart from high cost.

If the total exceeds the target cost it is referred back to Business Planning for resolution, who in turn may also involve Marketing. If the costs are below the Business Planning target cost then the D.C.C.G. assessment figures become the targets and are issued to the Design Team and (via the Manufacturing members of the D.C.C.G.) to the Production Engineering managers in the appropriate Production Product Centres.

At this stage the designers have specific cost targets for particular parts before they start to draw in the same way that they have stress and weight targets. They also know through the D.C.C.G. who are the Production Engineers and Purchasing specialists with whom they should deal and these people also have the same cost targets in front of them.

The essentially iterative process of design then takes place with the designer drawing and redrawing in consultation with stress, weight, production engineers and other specialists in order to reach the best balance of conflicting interests. The Commercial and Production members of the D.C.C.G. provide a liaison service between the designer and any specialists outside the Engineering Department in order to obtain advice with commitment.

When the design cycle is complete the Designer and Production Engineer know whether they have achieved their targets or not and if not, why not. If the cost target has been achieved the D.C.C.G. requires the signature of the appropriate production engineer on a new piece of control paperwork, the P.E.P.1 (Fig.9) as his statement of, and commitment to, the cost level. Since the production costs are of necessity to be realised several years after the initial design phase, the Production Engineers are encouraged to anticipate future manufacturing and engineering developments provided they state on the P.E.P.1 form any specific actions which must be carried out before the production commitment can be met.

If the target has not been, and cannot be, achieved, the reasons as agreed by the Designer and the appropriate Production Engineer are registered on the P.E.P.1. The D.C.C.G. may give a raised target if it has some margin, otherwise they in turn report back to Business Planning that the total factory cost cannot be achieved. Business Planning may then accept the higher total factory cost or refer to Marketing for resolution.

Eventually the costs associated with the scheme are resolved and the P.E.P.1 is signed by the appropriate Production Engineer. This signature is only given against a target achieveable by Production, the targets being raised above the original figure by D.C.C.G. if necessary. In this way the variance is registered against the D.C.C.G. so that manufacturing is not monitored against an unachievable target. If the project still looks attractive the next phase is launched. This involves the preparation of detail drawings and a set of management Cost Action Plans.

The Cost Action Plans (C.A.P.) are a major factor in the cost management of the project. They are in general sheets of a standard format, one for each major component (Fig.10) compiled and co-ordinated by the D.C.C.G. from data gathered from whichever area is involved in taking action necessary to secure a component cost target. They are published as a set to Senior Management who use them as the principal tool for controlling the project costs.

Each Cost Action Plan normally carries as its basic data:-

- The actions that must be taken if the target is to be achieved.

- The cost effect of each action.

- The timescales for completion of each action.

- The area and individual responsible for each action.

The C.A.P.'s are monitored constantly by the D.C.C.G. and are updated and re-issued as required. It is important to note that actions may be required in any or all of the major disciplines, also that although the cost effect of individual actions may be small, the total may be significant. Small cost increments must be treated like small weight increments.

At Rolls-Royce the detail component drawings which are sent to Manufacturing are produced in the Engineering Department Detail Office which is separate from the main design area. It is a Design Office responsibility to ensure that the data issued with the scheme drawings includes such manufacturing data in their possession as may guide the detail draughtsmen towards preserving the target costs. This always includes the appropriate P.E.P.1. The D.C.C.G. production engineer assigned to the project ensures that close contact is maintained between the detail draughtsmen and the appropriate Production Product Centre as detailing proceeds. Difficulties in maintaining the target levels during this process are dealt with by the team approach already described with the D.C.C.G. co-ordinating the activity.

The formal issue of detail drawings to Production constitutes the limit of the Engineering Department's activity and prime responsibility for maintaining the cost levels thereafter must rest with the Manufacturing areas. This formal transfer of responsibility from Engineering to Manufacturing is recorded by a second signing of the P.E.P.1 by the same Production Engineer who signed at the scheme stage. This may be done when the detail drawings are issued or, if judged prudent, when the complete manufacturing process has been established. In any case the

costs are 'at risk' until the P.E.P.1 carries the two signatures, which means that production processes must be determined as soon as possible even though production manufacture may not be scheduled for two years or more. All such 'at risk' situations are shown in the Cost Action Plans.

During the designing and detailing cycles production engineers build up data folders against each part and it is these which form the basic planning outline against which the final sets of production operation sheets are produced. Synthetic time data against the individual operations form the final time estimate generated by Manufacturing prior to actual manufacture and it is these which normally support the production engineer's second signature.

Although the emphasis is initially on direct labour and material costs all the fundamental cost parameters which are under the control of Manufacturing such as batch size, setting time, scrap rate, shop performance, and lead time are considered at the appropriate time. The possibility of any such factor being untypical is thus identified as early as possible and necessary action detailed in the Cost Action Plans.

5. DEVELOPMENT PROGRAMME

Where separate development manufacturing facilities exist the availability of production processes at the start of the development programme gives the opportunity for minimising duplication of effort and tooling. Those components expected to be relatively design-stable are ordered directly on Production from the start with the rest being transferred from Development item by item as their design also stabilises. The decision to classify a component as design-stable and place supply responsibility on Production is a Project Management decision made conjointly by Engineering and Manufacturing.

Those design schemes and detail drawings which need to be changed in the light of development running experience are subject to the same cost control disciplines as are used during the initial design phase. Any re-design can be treated as an opportunity for reducing cost.

6. PRODUCTION MANUFACTURE

For the purposes of business planning our production costs are conventionally taken to be those of the 250th unit with learner allowances based on our own previous experience. The actual times and material prices have traditionally been monitored against this 250th standard but the increased pressures to achieve the D.C.C.G. cost targets make it necessary to incorporate the learner effect in the shop performance monitors in such a way as to indicate progress down the planned learner curve and thus help to secure maximum involvement of the workforce and their immediate supervision in achieving this vital aspect of cost control.

As with all the various upstream stages, failure to achieve the cost targets on the shop floor must lead to corrective action in whatever area or areas can best find a solution whether this requires changes to method, material, the engineering drawings or all three. Some changes to our shop performance monitor are now planned in order to ensure that the performance factors indicate where corrective action is required rather than simply the variance.

Throughout the complete flow of work from drawing board to the shop floor the D.C.C.G. co-ordinates and reports the Project's production cost situation. The co-ordinated set of component Cost Action Plans drawn together by this small department which shares Engineering, Manufacturing and Commercial interests forms the basic management tool for controlling costs throughout the life of a project. It enables Senior Management to exert control at the most effective stage, the front end, by bringing help to those actions which are faltering and being in a position to take advantage of those which are succeeding. By their involvement Senior Management can manage, and, be seen to manage costs.

The above procedure meets the objectives of Professional Management of Costs as a Line Routine. The data and decisions come only from those who have authority, management is achieved by the open publication of the cost data and action plans and the line routine aspect is assured by the utilisation of the two new pieces of paperwork (P.E.P.'s and C.A.P.'s).

Because the Value Engineering failure had been caused by insufficient consideration of its detailed integration with established routines a great deal of trouble was taken to think through the details of Product Cost Control and to set down and publish the policies and procedures. Over forty presentations were given to managers in all areas of the Company and also to representatives of appropriate Trades Unions. This seems to have been well worth while both in terms of communication and involvement and in ensuring that everyone's interests had been considered.

7.   RESULTS

The complete time cycle from go-ahead to established production manufacture may take five or six years and we have not yet completed such a cycle strictly to the discipline described. Results to date, however, are very encouraging bearing in mind that the opportunity for avoiding costs are a maximum in the early part of a project (Fig.4).

7.1   The RB432

The first opportunity to apply the Product Cost Control discipline formally occurred on a new engine project developed from the RB401. The RB432 is a 19,000 lb. thrust, two spool fan engine and was scaled up from the RB401 as far as possible in order to read across the low cost features. The judgement to launch it into the main Design Office was based on a Project Office general arrangement drawing, a formal specification of design requirements and a corresponding cost estimate generated in the Commercial Department. After much discussion with designers, production engineers and material buyers the D.C.C.G. generated a set of target costs for the seventy major items in the manner already described. These target costs related to the Marketing Department optimum price in a way which made the project commercially attractive and were based on what the D.C.C.G. judged to be achievable within the project timescale in terms of engine defini- tion and manufacturing methods development. They represented a reduction of 30% below both the Commercial Department estimate and a prediction based on engine parameters and historic costs of other engines. No extraordinarily difficult targets were set with the exception of the intermediate casing where the project estimate suggested a work content of over 600 standard hours. For the reasons already explained this was arbitrarily set at 200 standard hours.

Two major briefing sessions were held by the Production Director supported by senior members of the Engineering and Commercial Departments at which all the senior members of the Product Centres were given the market background, main design features, details of the target costs, how they had been set and the way in which they related to the market price with a sensible profit margin. Following the briefing sessions the D.C.C.G. was set the task of obtaining the agreement of the Product Centres and Designers that the routes identified by the D.C.C.G. necessary to meet the target costs, were compatible with the RB432 technical requirements and Production Programme timescales.

Many changes were subsequently made to the design as a result of this joint activity, co-ordinated by the D.C.C.G., towards the specified cost targets. A new general arrangement (G.A.) was produced after a further four months and P.E.P.'s were issued by the D.C.C.G. to all Product Centres in order to get their formal estimate of the costs of their parts. These P.E.P.'s were returned signed by the Production Engineering Managers with the material price and labour hour estimates which resulted from their outline processes. Where special plant, tooling or material form were necessary to meet the targets, this was stated. The sum of these component costs was within the total target for the engine.

Among the design changes which took place during this first formal attempt to design to a specified cost were a reduction in the number of blades, a re- duction in the use of expensive alloys such as titnaium and waspaloy and much closer relationship between the shapes of components and their manufacturing processes. The intermediate casing labour content was reduced from 600 standard hours to 270 standard hours by the actions resulting from the imposition of the arbitrary 200 standard hours maximum. Still not on target but a very encouraging step.

These changes were introduced as part of the normal process of design with- out delaying programme timescale or reducing the technical standard of the engine and with no unacceptable demand on production engineers' time. The fact that target negotiations with the Product Centres were completed within eight weeks was, in itself, an indication of the success of the carefully planned introduction of Product Cost Control into the line management of the site. Hitherto production engineers and product centre managers would not have been involved with a project until it reached production release. At this stage the opportunity to influence the programme and recover disadvantageous situations generated during the development phase are minimal, although all too often in the past production have borne the brunt of blame for production cost problems. On the RB432 well over 100 production managers and engineers had been involved in up-front planning of the business involved in making the decisions against which they will subsequently be monitored. This development has great signifi- cance for the future status of engineering in production.

Achievement of the specified cost target and the resultant project profitability were largely responsible for the signing of the formal project launch which followed soon after. The impact on cost of the disciplined approach to targets by the joint action of Designers and Production Engineers had been crucial. Had the Product Cost Control discipline not been used a formal launch would have been unlikely.

7.2 Other Applications

For Rolls-Royce Design to Cost is now part of the routine. Product Cost Control is now operating on a new mark of military engine. Targets are issued and negotiated and the combined design/production engineering activity is in progress.

7.3 Accessories and Control Systems

These essential parts, which are almost always purchased from very specialised sub-contractors, can account for 10% - 15% of the factory cost of a civil engine and up to 25% in the case of a reheated military engine. These percentages are so significant that any cost reduction programme, or new engine being subject to cost control must include this group of components. In the case of existing engines where contractual relationship already exists between the sub-contractor and the Company, two difficult problems immediately become apparent. Firstly, a desire by both sides to share the cost reduction cake before it has been baked, may positively prevent engineers from both sides coming together. Secondly, the sub-contractor may, understandably, feel that the only result of cost reduction is to reduce his price and factory workload. This introspective and inhibiting commercial response was eventually overcome by extending the open management concept, already being adopted internally, to our major sub-contractors. Their senior managers and managers are shown the part their component prices play in our business plans and marketing assessments, particularly the sensitivity of the business to cost changes.

Accessory cost make-up and the opportunity for cost reduction have a number of differences when compared with the basic engine and to date we have found that the potential for cost reduction is lower. Reasons for this include the fact that controls are largely a collection of different parts whilst much of an engine cost is concentrated in multiples such as blades. There is seldom the opportunity to eliminate or reduce the amount of expensive material used, frequently a major area of cost reduction on engines. Conversely production acceptance testing can constitute a significant part of a control system's price. The importance of specification and test schedule are obvious particularly in ensuring the requirements are real, and not simply transferred from a previous specification without consideration.

The major U.K. suppliers have been very responsive to this activity and joint teams have been set up with Rolls-Royce on military and civil projects with significant results already achieved. Specific targets 30% below existing prices were recently set for the Fuel Control Systems of a military reheated engine. This resulted in formal proposals identifying realistic routes to achieve reductions of between 35 and 50%.

The cost targets are like those for the main engine components, generated by the Design Cost Control Group, in this case working with experts from the Control Systems Performance Department and the appropriate purchasing specialists. In general the total accessory package target cost is taken firstly as a percentage of the main engine target cost and the resulting total broken down to the major items plus the rest.

The specification for each accessory is then set down in terms of the essential functions that it has to perform, rather than in terms which tell the supplier how he must achieve them. The target price is added to the technical specification and the Purchasing Department is then responsible for making contact with potential suppliers. In principle it is a question of negotiating a specification with the Purchasing Department in place of a scheme or detail drawing with the production engineers. The P.E.P.1 document is used in order to record the commitment of the Purchasing Department to buy a given accessory for a given price.

It is worth reminding oneself that aero engines are themselves aircraft accessories. What works for us can also work for our accessory suppliers.

7.4 The Present Situation

We have moved a long way from the days of the Value Engineering Department, through a phase of joint but informal co-operation of designers and production engineers to one where specific cost targets derived from market requirements have been formally accepted and achieved by a joint Production and Design

Engineering activity as an extension to the established working routine. In so doing we have realised very substantial cost benefits with virtually no effect on the timescale or on the technical specification and the Cost Action Plans promise to solve the problems of ensuring that these forecast cost levels are realised in the shops. Many problems, mostly of understanding and communication have been solved during this process but as with most human situations the solution to one problem always reveals others and this is certainly true of the cost situation.

However, since problems for the workforce are opportunities for Management today's problems represent tommorrow's improvements.

There are three major areas which offer special opportunities for future improvements, which we have classified as:-

- Total Engineering

- Functional Estimating

- Engineer's Cost Data.

7.5   Total Engineering

As with most engineering companies our engineering activity is split into two functions. Those who engineer what is to be made and those who engineer the way it is to be made. The two groups are responsible to the Technical and the Manufacturing Directors respectively. We have convinced ourselves, however, that if cost is to be minimised it must be made a design requirement so that it can be traded with the other factors like weight and stress in the early days of the project. Thus, the definition of each part and the method by which it is made, must be engineerd conjointly. We have coined the phrase 'Total Engineering' to represent the ideal we should aim at in terms of blending the two branches. The size of this task is indicated by the fact that one group of engineers has always operated upstream of the development programme, when there is maximum scope for innovation and change and the other has been confined almost exclusively downstream of the development programme, when there is little of either. Their backgrounds and attitudes are consequently very different and their marriage must, therefore, be arranged with care.

7.6   Estimating

It is a characteristic of the aero engine business that we become almost totally committed financially long before there is any hard evidence of how much things will eventually cost. The success of our business, therefore, cannot be better than the quality of our financial estimates.

Traditionally our cost estimating especially in the early days of a project, has been heavily dependent on past experience and a small number of people in the commercial area have become expert at predicting future costs in this way. However, having made radical changes to the cost behaviour of the two engineering departments we have had to change our attitude to estimating.

In the last two years we have arrived at eighteen different categories of estimate each useful for its own purpose. There are six step changes in the quality of the engine definition each one occurring at a different point in the flow of work down the line from marketing to production:-

- No drawings

- Project G.A.

- Design Schemes

- Detail Drawings

- Manufacturing Operation Sheets

- Actual Manufacturing Times

For any given definition there is also the extent to which an estimate should anticipate future changes either to definition or manufacturing methods or performance. We use three classifications to cover:-

- Current definition

- Agreed changes planned but not yet incorporated

- Other changes being considered for incorporation.

We now see the estimating function as a very much broader activity in which the engineering and manufacturing areas predict the expected evolution of the engine definition and its manufacturing processes, with the Business Planning Department supplying the commercial and financial input. Estimates formed in this way result in a much wider understanding and business awareness amongst those people who will eventually incur the costs and they carry a degree of commitment that is not otherwise possible. These estimates are more professional.

7.7   Cost Data

When designing and making to a specific cost level alternative designs and processes have to be generated and the most effective chosen. Thus, design to cost requires engineers to make cost based decisions as a normal part of their routine. As all accountants know, the cost data required for decision making is different from that required for financial accounting and pricing and whereas all companies will have the latter, few if any have the former. The financial accountant is concerned with cost recovery whereas the designer and production engineer are concerned with minimising cost generation. The two tasks are very different and both are essential.

Cost based decisions are properly made using marginal or incremental costs, that is those costs which would be generated or avoided as a direct result of the decision. Thus, no fixed cost should be included in the data to be used for making a decision since by virtue of the fact that they are fixed they cannot effect or be affected by the decision. Nearly all cost data readily available in most manufacturing companies however contain fixed or overhead elements and thus can lead to wrong decisions on the drawing board and in the development programme. A few examples may illustrate this very important matter:-

-    If one Product Centre is obliged to install expensive capital plant for a particular project and if this is included in an average fixed cost for that Product Centre the designer may well conclude that he should avoid designs which would be made there because the cost rate appears higher than other Product Centres. Thus he may avoid designing sheet metal fabrications in favour of castings, say. The apparent savings are illusory, however, since the expensive plant is still there and still has to be paid for. Ideally it should be given more work not less.

-    Designers are often concerned to achieve a particular shape without being especially concerned how that shape is achieved. For example, it may be of no technical consequence whether a component's shape is forged or machined from solid. If, however, the Company does not have its own forging facility the designer in specifying a forging has made a decision to buy rather than make the desired shape. Once again management accountants are well aware of the difficulties of making correct make or buy decisions. All management accounting text books deal with the subject of make or buy decision-making and some deal with nothing else. Many companies' available accounting data favours buying, but this is not to say that it is in fact cheaper to buy but rather that the associated direct costs are less. Whether the associated increase in overhead costs outweighs this or not is what constitutes the basic difficulty of the make or buy decision.

-    In attempting to design to a cost target of, say, fifty standard hours plus £800 material a solution may be found which gives seventy standard hours plus £400 material. In deciding the cost of the extra twenty standard hours work in-house it is important not to multiply the time by the average hourly rate as again this will contain fixed elements. It is similar to the make or buy decision, incremental costs must be used.

-    Alternatively in the above example a solution may be found which gives fifty standard hours plus £1,000 material but a shorter manufacturing lead time. Thus, the financial value of shorter lead time has to be balanced against the extra cost of the material. This certainly needs advice from the management accountant.

Our experience of the last few years has enabled us to see clearly the interaction between the financial accounting conventions and the design features of our engines and as more and more people become personally involved in the use of cost data in their daily tasks its unsuitability for their purpose becomes more apparent. It is vital that this situation does not lead the engineers to conclude that the financial accountants are wrong. They are not wrong, their purpose and therefore their cost data are different from his. For most engineers the problem is that there are no cost data which have been generated for his purpose, and he must first learn something of management accounting and then work with management accountants to get what he needs.

6.8   The Future

The experience of Design to Cost has shown itself to be not only practical and financially rewarding but to be the source of many subsidiary benefits, all of which stem from the increased involvement in and understanding of costs by engineers, of engineering by accountants and by everyone in the real nature and purpose of our business. We see the changing attitudes to the estimating function and the eventual recognition of the cost data needed by engineers for their decision-making and its relationship with financial accounting data as leading to a much wider and responsible role for engineers as the principal managers of the generation of cost. After all, when the engineers have decided what is to be made and how, 90% of the financial affairs of the Company are determined. It is the engineers, therefore, who must accept the major responsibility for the financial performance of commercial manufacturing companies. If they can define and make the goods which the customer requires, while ensuring that the minimum costs are generated in the process, the established financial accounting of cost recovery and pricing will ensure that we supply what the customer wants when he wants it at a price he can afford and be seen to be doing so.

That will be more rewarding and satisfying for everyone.

AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD LS. 107

Life Cycle Cost ~ Make-Up

Fuel 20%

Repair Labour 15%

Miscellaneous 3%

Spare Parts, Modules and Engines 37%

Installed Engines 25%

PARTS COST 2/3rds TOTAL LIFE CYCLE COST
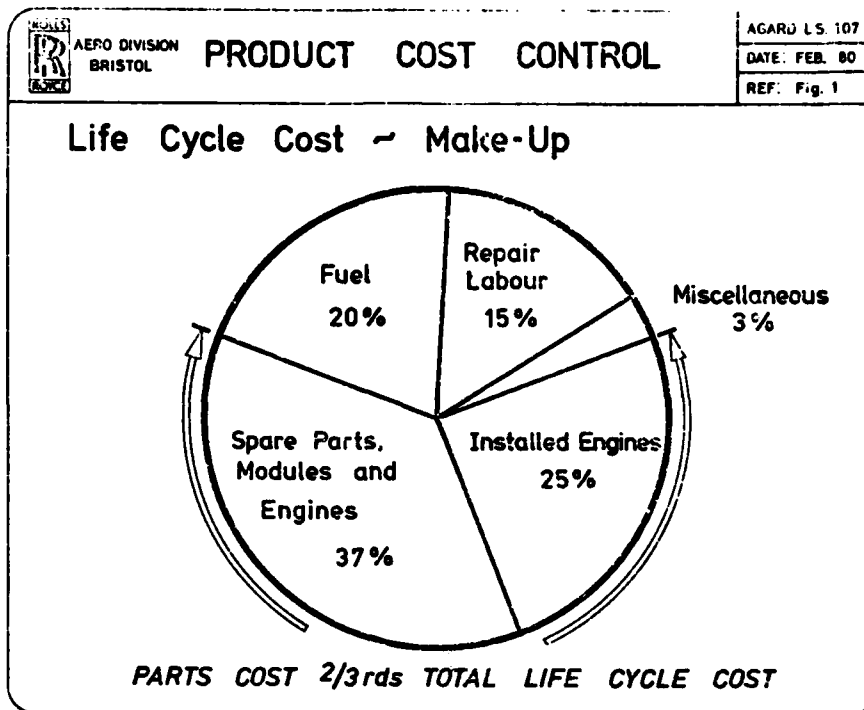
This shows the L.C.C. designer his first priority

AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD LS. 107 DATE: FEB. '80 REF: Fig. 2

Value Engineering In The 1960's

Design → Manufacture
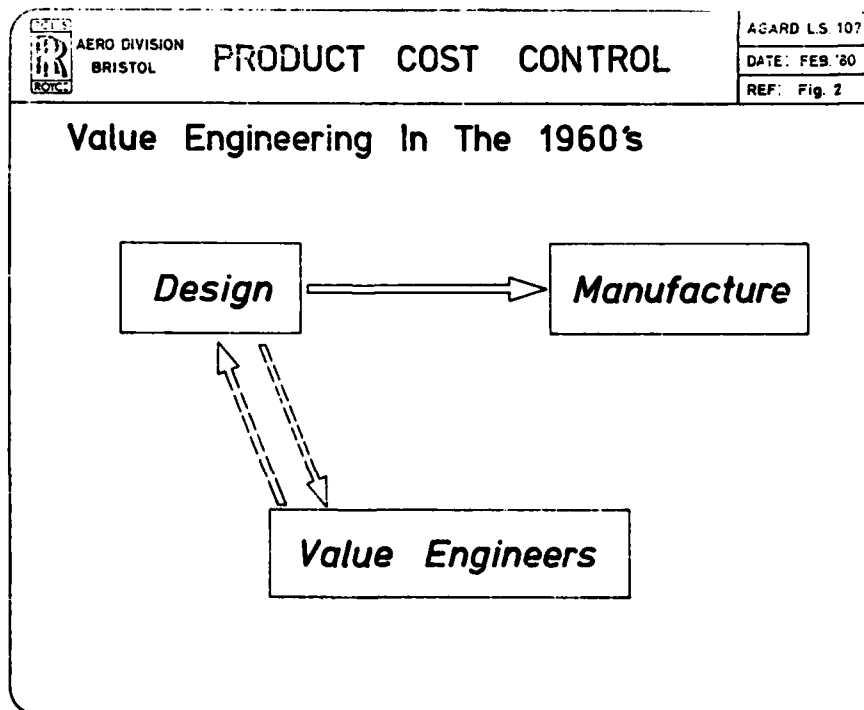
Value Engineers

Value Engineers in the 1960's were placed outside the line activity. Work was thus able to proceed without them, and did.

	AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD L.S. 107
			DATE: FEB. '80
			REF: Fig. 3

RB401 Factory Cost Progression

New "DESIGN LIAISON" Procedures Introduced
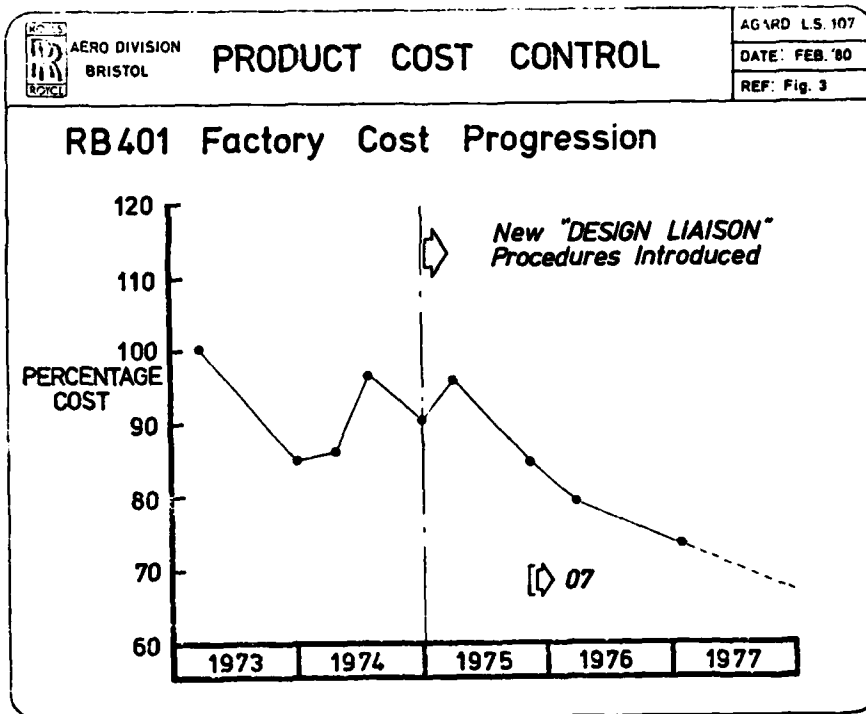
This shows the impact of the "Design Liaison" activity inserted in the middle of a designing cycle

	AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD L.S. 107
			DATE: FEB. '80
			REF: Fig. 4

Sources Of Unnecessary Cost

Design Schemes_____50%

Detail Drawings_____30%

Production Engineering_____ 20%
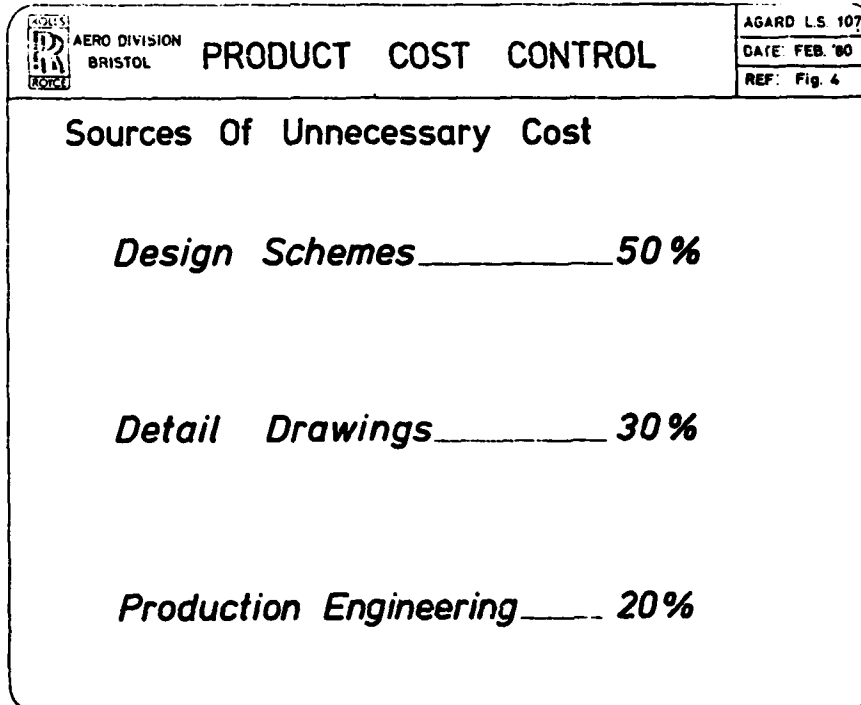
Analysis of over 2,000 detail drawings by Cost Reduction Teams for new and well established projects has shown that the removal of avoidable costs requires action in Design, Detail and Production Engineering areas roughly in the above ratios. This strongly supports the argument that cost control must start when the Design starts.

AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD L.S. 107
		DATE: FEB. '80
		REF: Fig. 5

Cost Trading Opportunity

By the time 10% of the project timescale has elapsed 90% of the costs are irrevocably committed.

AERO DIVISION BRISTOL	PRODUCT COST CONTROL	AGARD L.S. 107
		DATE: FEB. '80
		REF: Fig. 6

D.T.C. In The Organisation

PRODUCT COST CONTROL ~ PCC

_____

(Design and make to cost)

_____

PCC = DTC + MTC
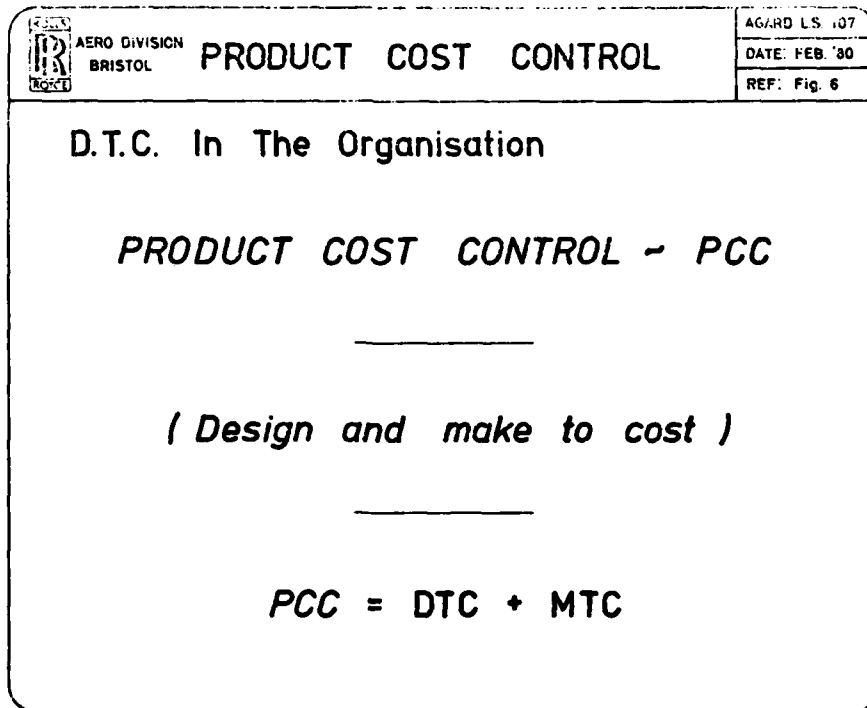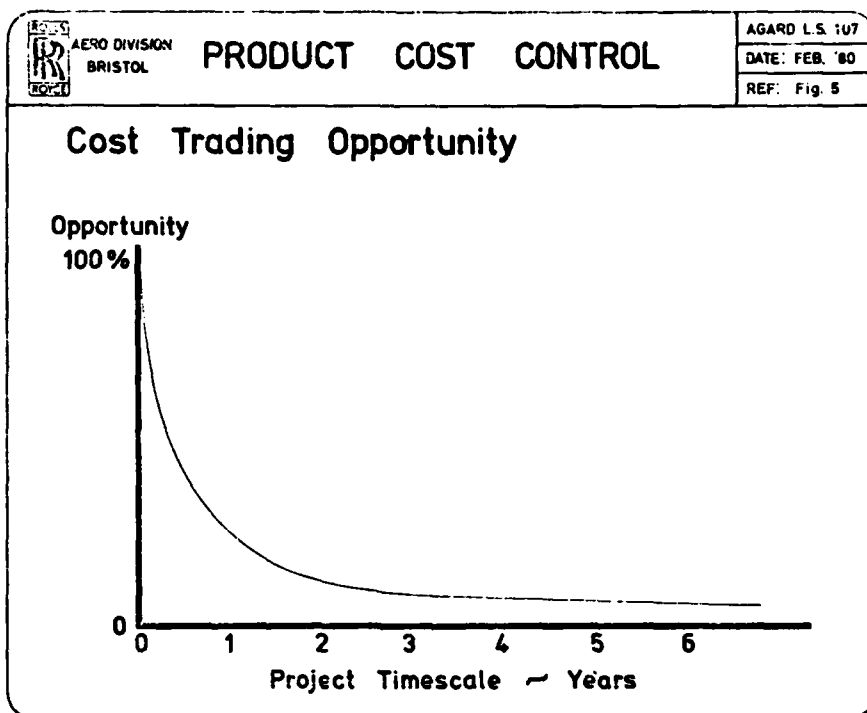
The Rolls-Royce Bristol Product Cost Control procedure controls cost both during the design phase and during subsequent production manufacture.

Product Cost Control consists of Design to Cost plus Make to the design Cost.

PRODUCT COST CONTROL

AERO DIVISION BRISTOL — ROLLS ROYCE

AGARD L.S. 107
DATE: FEB. '80
REF: Fig. 7

The Design Cost Control Group

SENIOR DESIGNER
All aspects of engineering content of costs.
Directly responsible to Director of Design.

Business Planning	Prod. Engineering	Purchasing	Quality	Admin.
Cost Price Spares Warranties Profit plans Life cycle costs.	Processes S.H. Content Matl. Utilisation Plant Tooling	Matl. price Matl. Utilisation B.O.F.	Cost of Inspection Inspection Techniques Acceptance Standards.	Book-Keeper

NOTE:- With the exception of the admin. man the entire team is seconded from the appropriate Production and Commercial Departments.

Simplified organisation of the Design Cost Control Group. This is the only department in the Company whose task is not limited to one of the Directorial disciplines.

PRODUCT COST CONTROL

AERO DIVISION BRISTOL — ROLLS ROYCE

AGARD L.S. 107
DATE: FEB. '80
REF: Fig. 8

P.C.C. ~ The Line Routine

Customers

Contract Price

Marketing → Business Planning → Design Cost Control Group → Design & Prod Planning → Detail → Prod Planning → Make → Sell

| Type Size Price Programme | Factory Cost | Cost Targets | Targets Achieved (PEP 1) | P.E. Signature | Monitor Against PEP 1 | Monitor Method & times against PEP 1 | Profit |

8 TO 20 YEARS

This slide shows the line sequence of work flow from Marketing to Sales and the position of Design Cost Control Group in the line.

The management data available at each stage and the feedback loops which operate when this data is unsatisfactory are indicated.

PRODUCT COST CONTROL

AERO DIVISION BRISTOL

AGARD LS.107	
DATE: FEB '80	
REF: Fig. 9	

A Typical P.E.P. 1

Engine Type	Description	Supply Resp	Rat Code	Date
RB401	SINGLE PIECE H.P. COMPRESSOR ROTOR	PRODUCT CENTRE 3	C	23/7/78

Scheme or Drawing No.	Information to be used for Estimate
CJT 7019/2	1. GENERAL SURFACE FINISH AND TOLERANCES SIMILAR TO JJ5093/8.

Purpose

COMPARISON OF SCHEME COST AGAINST £4,500 TARGET

2. FOR METHOD OF DATUMING SEE DCCG/MCR/587
3. ASSUME MACHINING TRIALS (RCF: JW/DP/849) SUCCESSFUL

Requested by AH Robbins	Programme Reqt. 30 SETS PER MONTH

Factory Cost

STANDARD HOURS   98

TOTAL SETTING TIME   137 HRS.

Material	Spec.	NS RR 2983
	Form	FORGING
	Cost	£2.50 (QUOTE)

Capital Plant Reqt.

EXISTING O.K.

Remarks

O.P. SHOULD NOT BE TAKEN AS GREATER THAN ·6 UNTIL TRIALS ARE COMPLETE. THEREAFTER TARGET O.P. ·8

SCRAP RATE 5% (ROUGH GUESS)

Tooling   NORMAL

Approved by D.G. REIDALL PEM (PC3)	Date 19/8/78

This is an example of the P.E.P.1 document. It is one of the two new pieces of executive paperwork that the P.C.C. discipline has required.

It records the share of cost responsibility and commitment between Engineering and Production. It has put DTC 'in the line.'

PRODUCT COST CONTROL

AERO DIVISION BRISTOL

AGARD LS.107	
DATE: FEB '80	
REF: Fig 10	

A Typical C.A.P.

ENGINE 432-05	COMPONENT COST ACTION PLAN					REFERENCE N° CCAP 432/21	

MODULE FAN DISC	COMPONENT FAN DISC	DRAWING N°	ISSUE 2	DATE OCT '79	SUPPLY RESPONSIBILITY PRODUCT CENTRE	

TARGET FACTORY COST ECONOMIC CONDITIONS AT MID '79	PURCHASES £3,000	STH 30	TOTAL £3,750	CMT CONTROL YES/NO	C2

ACTIVITY	RESPONSIBILITY	VALUE	COMPLETION DATE					APPROVAL	
			1980	1981	1982	1983	1984	TECHNICAL	FINANCIAL
1. MINIMISE PRE-ULTRASONIC MACHINING	PRODUCT LABORATORY	2 STH		▼				RAB	GMR
2. TEST SPECIFICATION	STRESS OFFICE		▼					NAB	—
3 MINIMISE BILLET SIZE	DESIGN PROD. ENG PURCHASING	2 STH −£200 MTL			▼			TWR	—
4. MECHANICAL DEBURR	PROD ENG	4 STH				▼		RWS	VJA
5. HIGH SPEED BROACH						▼			

DESIGN COST CONTROL GROUP	COMPONENT REF N° (PROJ GA) 3	P.E.P N° 432/3/2	ISSUED BY:	DATE: 6-11-79

This is an example of a Compont C.A.P. The sum of these documents for those components which need Management Action constitutes the basic Management tool for controlling cost generation.

EVALUATING AND SELECTING
THE PREFERRED AIR-BREATHING WEAPON SYSTEM

by

FRANK A. WATTS

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Requirements and Strategy Planning
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ABSTRACT

Aerospace contractors are continuously attempting to detect new military requirements emanating from changing international threats. In clarifying the requirements and defining a weapon system, contractors are led down multiple paths, depending upon whether they are influenced more by the military technology agencies, the operating commands, the headquarters general staff, or the civilian secretaries.

In arriving at the preferred military system, contractors have established a reputation that is generally accepted by military organizations. Too often, however, these weapon systems fail to pass the budgetary approval process because of inadequate cost analysis. This paper discusses life-cycle costs of three strategic forces, each having equal effectiveness, with the objective of isolating the preferred air-breathing component. Terms are defined, cost elements are reviewed, and an example is described in which various strategic forces containing advanced aircraft are compared and the preferred choice is dependent upon whether least cost is measured by short-term, long-term, or immediate budgetary considerations.

INTRODUCTION

Other papers in this lecture series have described how the analysis of aircraft turbine engines and their costs can aid military program managers in making better policy decisions concerning the management and control of existing weapon systems. In addition, these cost analyses have significantly improved the ability to forecast acquisition and operating costs of new and advanced weapon systems powered by turbine engines. This improvement in cost estimating can be seen in absolute budgetary terms and also in the technology-versus-cost trade studies during the initial planning and approval stage.

This paper discusses cost analysis from a more global point of view by reviewing a typical analysis that examines the effect and interaction of an air-breathing weapon system in an overall force mix. This study determines whether the effectiveness of a force is increased by the introduction of a new or modified weapon system when compared with alternative systems. Conventionally, the relative effectiveness of a proposed system is measured in comparison with current and alternative systems, in each case assuming that the total force cost is held constant. Conversely, the relative costs are measured when effectiveness is held constant. In addition to the primary usage, this analysis will also assist long-range planners by providing a point of reference when considering the development of new engines or the improvement of those already in the inventory.

The procedure discussed in the following paragraphs is applicable whenever qualitative or quantitative changes are being considered in a force mix. This particular paper dwells on a strategic force in which new land-based missiles and new air-breathing systems are being reviewed as possible candidates for improving effectiveness. Simultaneously, existing systems are considered for major modification, while other systems are assumed to have outlived their usefulness and have been phased out. Although typical study results are shown here this paper emphasizes life-cycle-cost analysis leaving any discussion of the effectiveness analysis to another classified presentation. Examples are shown for the strategic area, but the same principles are valid for the examination of tactical forces.

A REPRESENTATIVE PROBLEM

Figure 1 is an example of the defense budget trend in the United States in constant 1980 dollars and shows in real terms how one element of the budget, that dealing with strategic forces, has experienced a significant reduction between 1950 and 1980. Depending upon the method of analysis, a similar curve, or a series of similar curves, could be generated to show the decline in force effectiveness of the U.S. strategic forces in comparison with those of the Soviets. Such a series of curves would contain different assumptions on a wide range of parameters, including U.S. alert rates, the number of Soviet reentry vehicles per missile, the accuracy of their reentry vehicles, or the condition of our command, control, and communication assets after a first strike. However, despite assumptions used in comparing U.S. and Soviet forces, there is a general agreement that the currently planned U.S. strategic forces may not support their main objectives. What are these objectives?

When planning alternative strategic forces in the United States, the traditionally stated goals have been—

a. To deter nuclear attack on the United States and its allies

b. If deterence fails, to terminate the conflict on terms as favorable as possible

The first goal is self-explanatory.

The second goal is more dynamic one in terms of analysis. It requires, after taking into account the losses expected from a Soviet first strike, that the remaining U.S. strategic forces (however depleted) shall be seen to be structured in such a way that no advantage could be gained by the Soviets continuing the conflict. In achieving the first goal, relative capability is often measured and expressed in terms of quantity of weapons, warheads, or potential number of targets destroyed. When analyzing requirements for achieving the second goal, the units of measure are similar after taking into account additional issues, particularly survivability during a preemptive strike and endurance during protracted periods of nuclear hostilities.

Measuring and comparing strategic capabilities, either before or after a suprise attack, form a complicated exercise that requires detailed analysis and the use of force exchange models. This aspect of the analysis will not be discussed in this paper. It has been generally accepted that the United States has maintained an adequate deterrence for many years; however, with the Soviet deployment of their latest generation of strategic missiles in the next decade, there is a belief that the U.S. forces are inadequate to meet the second goal stated previously. The problem is associated specifically with the survivability of land-based ICBM's and bombers under a suprise strike by the Soviets. For discussion purposes, the aim is to determine from several force modernization options the preferred force that would correct this specific weakness. In this instance the objective of the analysis is to achieve nuclear parity by 1990 with the least cost and the least disruption to the defense budget in terms of annual funding. Parity is defined here in terms of equivalent weapons available after a nuclear exchange. The manner in which cost is measured is the primary concern of this paper.

STRUCTURING THE STUDY

What is the current U.S. strategic force that needs to be modernized? Essentially it has three elements: offensive, defensive, and command and control. This paper discusses the offensive element only. The offensive strategic triad consists of land-based intercontinental ballistic missiles (ICBM), sea-launched ballistic missiles (SLBM), and a force of bombers. As shown in figure 2, it is assumed that the current force, which will be called the reference force, does not yet include the multiple-aimpoint MX ICBM.

In this particular study, the weakness of the reference force is taken to be its lack of retainability or "enduring survivability" after a first strike on the United States. After examining performance characteristics of various systems including target coverage (payload, range, accuracy) survivability, command flexibility, system reconstitution, and weapon penetration, a series of alternative forces was generated. The effectiveness of these forces was analyzed by a set of U.S.S.R./U.S. force exchange calculations in which the Soviets, when striking first, employed tactics designed to meet their objective of maximizing their postexchange net advantage. The United States, on the other hand, employed tactics to deny Soviet attainment of those objectives. The study was structured so that after a nuclear exchange both parties retained equal strength in terms of equivalent weapons. An assumption inherent in this study was that the new U.S. strategic systems should achieve this operational capability by 1990.

BUDGET CATEGORIES

When proposing the introduction of a new weapon system into the strategic forces, it is not enough to express costs in simple terms such as development cost, flyaway cost, or annual operational cost. A new system is much more likely to be considered if its costs are presented in terms similar to those used by the budget planners within the Department of Defense.

The DOD budget is portrayed in several ways. One is shown in table 1, a format in which the Army, Navy, and Air Force have their individual budgets shown separately and in total. Budget authority values shown in table 1 are those amounts the DOD submits to Congress each year for approval and represent the funds each service may obligate for specific activities over the coming years. Table 2 shows the budget authority displayed in terms of major expense categories such as RDT&E, procurement, and military construction regardless of which service is involved. For the purpose of planning a new program it is normal to portray its cost in terms of program element, as shown in table 3. For example, those military services involved in strategic programs have their direct RDT&E, production, operations, and military construction costs combined in one budget code; that is, the Air Force's bombers and ICBM's and the Navy's sea-launched ballistic missiles are contained in one budgetary planning classification, program 1, strategic forces. Program 2, general-purpose forces, contains those combat forces associated with conventional land, sea, and air warfare primarily of a tactical nature. Program 3, intelligence and communications, includes resources related primarily to centrally directed DOD communications and intelligence. Program 4, airlift and sealift, consists of those transport organizations supplied basically by the Air Force and Navy. Program 5, guard and reserve forces, is self explanatory. Program 6, research and development, contains all RDT&E activities not related to systems approved for deployment. Program 7, central supply and maintenance, covers among other things the central depot maintenance activities not organic to another program element above. Program 8, training, medical, and other general personnel activities, and Program 9, administrative and associated activities, contain training, medical, and headquarters costs as their titles imply.

When planning to modernize the strategic forces, it is normal to consider costs in program 1 terms. However, it is often necessary to depart from the rigid budget system to ensure inclusion of all relevant costs. For example, by definition, a program that is funded for development but not approved for production would have its development cost in program 6 by each fiscal year. Once approved for production, the remaining development funds yet to be requested would be transferred to program 1 by convention. Similarly, a program once deployed would have its direct operating costs in Program 1, but certain of its indirect operating costs by definition would be in programs 7 and 8. Thus, to ensure that a contractor is not proposing new programs with undeclared costs, it is necessary when discussing program 1, strategic forces, to make the additional correction of taking the related direct and indirect costs expected to be found in programs 6, 7, and 8 and including them in program 1.

Figure 3 shows how costs are related to time, recognizing that strategic offensive costs contain a mix of Air Force and Navy services, a mix of direct and indirect costs, and a mix of programs 1, 6, 7, and 8, and that all costs are expressed in terms of budget authority and not outlays. The ordinate is in billions (10^9) of 1980 dollars; the abscissa is in fiscal years from 1980 to 2000. Each system has its RDT&E, acquisition, and operational costs shown versus time. The first example represents a typical program in which all costs need to be funded during the time period of the study. The second example shows the B-52 fleet in which modifications are under way to install cruise missiles and associated avionics. In this instance operational costs of the B-52 are the dominant issue. If the KC-135 tankers are included, the cost of operating the B-52 fleet becomes significant. The third example shows a new cruise missile carrier in which prototypes have been flown and tested and hence, within the study period, a smaller RDT&E funding is portrayed. The fourth case shows a new bomber. The fifth example is the Minuteman intercontinental ballistic missile which, in relation to air-breathing systems, has relatively low operational costs. Modifications planned for the Minuteman over the study period are small. The sixth example shows the new MX intercontinental ballistic missile.

From figure 3 it can be seen that the interplay of RDT&E, acquisition, and operational costs between all systems has to be taken into account for a contractor to propose an advanced system for the strategic force with the requirements that (1) it contributes to the aim of obtaining parity by 1990 and (2) it is the least costly and the least disruptive to the budget in combination with existing forces. In addition, when proposing a new airplane, the time to develop and deploy the system to its full operational capability (in this study 1990) has a strong influence on whether available or advanced engine technology will be incorporated into its design.

SYSTEM COST ESTIMATE

Introducing a new system into the force requires an estimate of its cost. The MX ICBM is a typical example. Such a system, having been in the conceptual and preliminary design stage for the last 10 years, has had many different missile air-vehicle designs, different types of basing proposed (pools, trenches, vertical silos, horizontal shelters, etc.), and different modes of operation concerning security or verification from Soviet overflights. The cost-estimating equations developed during the last 10 years have also undergone significant changes in style, format, and confidence. In the case of the MX, a well-defined estimate might take the form shown in table 4 for a force of 400 missiles with further expansion as shown in table 5 for RDT&E and acquisition and in table 6 for operations. Table 7 shows a cost summary for a force of 160 bombers. Costs would be transposed into fiscal year funding (authority) as shown in table 8 for the MX, for example, taking into account the necessary time lags.

The term "time lags" in this context refers to the years between a firm proposal being made and the subsequent fully operational capability of that force. For a fleet of 10 nuclear submarines this period can be 20 years. For 200 land-based ICBM's, the overall time lag can be 12 years, and for 200 airplanes it can be 11 years. The time will be longer if a proposed system requires additional feasibility studies or exploratory development or if a new system is still only in the mind of a contractor but not yet accepted by the appropriate military service. In an emergency, of course, certain programs can be accelerated, but emergencies are rare. No matter how much a contrac ˒r believes his proposal should receive special privileges, it is realistic to allow for normal time lags.

Where does all this time go? As an example, a new, dual-purpose bomber might require a minimum of 1 year for DOD to formulate its requirements, another year to obtain design studies from several contractors, 1 year for Congress to authorize funds, 4 years to develop and test, 2 years to deliver and train a squadron before an initial operational capability (IOC) is achieved, and 2 more years to deliver another 200 airplanes. Naturally, further time would be required if major modifications were required in the air vehicle's design, or if budget constraints were imposed.

FORCE COST ESTIMATES

Approximately fifty individual forces were costed initially to eliminate the more expensive options. Table 9 displays the force options finally considered in this study. The reference force (i.e., a notional force thought to be inadequate) is to be modified as shown in alternative A, B, or C. Alternative A has as its objective the least change to the existing reference force. It phases down the Minuteman III and adds a force of 300 MX ICBM's and a fleet of 216 STOL cruise missile carriers. To maintain survivability, an

additional 5,730 multiple-aimpoint dispersal fields are required for this force. Alternatives B and C make no attempt to continue with systems approaching obsolescence. Alternative B phases down all existing ICMB's and bombers while adding a force of 400 MX's and, at the same time, introduces 160 new dual-purpose bombers requiring 4,233 dispersal bases. The dual mission referred to here is first as a standoff cruise missile carrier and second as a penetrator. Alternative C also phases down existing ICBM's and bombers. In exchange, it adds a force of 370 MX's and 190 STOL cruise missile carriers having 4,910 multiple-aimpoint dispersal bases. In all cases, the SLBM's remain a constant force.

After detailed costing of each of the candidate systems is completed and with the knowledge that all three of the alternative force options produce parity with the Soviets by 1990, the costs of the alternatives are compared. The elements of RDT&E, investment, and operations are time phased to allow for the time lags described previously. Costs are expressed in fiscal year 1980 dollars as congressional budget authority by year. The typical output of such an analysis is shown in figure 4.

For the sake of brevity, only alternative B is shown. Each weapon system is listed in the first column showing its RDT&E, investment, and operational cost. The headings at the top of figure 4 show each fiscal year and a 20-year total. The values in the matrix are in millions of FY 1980 dollars. The table shows existing ICBM's and bombers being slowly phased out by 1990. At the same time the new systems, the MX and the dual-purpose bomber, are phased into the force according to their individual schedules and funding patterns. The summations for each year at the bottom of the table show the annual funding requests that require approval by Congress for offensive strategic forces. The cumulative total, the cost shown in the bottom right-hand corner of the table is the total life-cycle cost of this particular option over 20 years. Table 10 summarizes the cumulative totals of the reference force and each of the three alternatives. Given that all three alternatives achieve parity by 1990, then the preferred choice is alternative C, which has the lowest overall cost. However, not everyone considers comparisons of cost in this simplified way and hence the value of time needs to be introduced.

THE PROBLEM OF TIME

In table 10, alternatives B and C show a cost savings over alternative A. By examining the distribution of the costs, one can detect that substantial part of the savings of alternatives B and C is in reductions in operational costs between 1990 and 2000. This is portrayed in table 11. No analysis that extends so far into the future can be certain that such operational cost savings will indeed be accrued; hence it is the convention when discussing the effect of time to use some mechanism to discount those future costs that contribute to the belief that one system costs less than another. Discounting techniques used in the commercial world to optimize cash flows are well established. Although it is agreed that the Department of Defense does not have the same cash-flows or revenues as a commercial industry, the problems and uncertainties of time inherent in both activities are similar. Hence, an attempt is often made to modify a cost analysis of military systems by discounting all future cash streams on the premise that no public investment should be undertaken without explicitly considering the alternative use of the funds that it absorbs or displaces. When cash flows are discounted, inflation within the discount rate is included only if the cash flows themselves are inflated. Here, by definition, all costs are in 1980 dollars so a discount rate can be applied directly. However, it is theoretically inapplicable to use normal discounting procedures here since, to be correct, cash flows should be expressed in "outlays," not obligational authorities, as defined earlier. To simplify the calculations in this example, a nominal 10% value has been selected to illustrate the point. Table 12 shows the effect discounting has on the comparison. Previously, alternative C was the preferred choice in undiscounted terms, as shown in table 10. With discounting, alternative C is still the preferred choice but by a considerably narrower margin.

Although it is true that discounting provides a procedure for measuring the time value of money, it does not provide a practical solution to the immediate problem of selecting the preferred alternative of obtaining parity by 1990.

NEAR-TERM BUDGET CONSIDERATIONS

While isolating the preferred force option from a small list of three alternatives, some statement should be made on the effect these options have on the budget in the immediate future. One option might be to select the system that achieves parity by 1990 but costs the least through 1985. Table 13 shows the costs between 1980 and 1985, indicating that the preferred choice is alternative B -- the new b mber and MX option -- not alternative C. Although not arrived at by discounting, per se, in effect by considering this shortened time period the decision could be said to have been based upon a discount rate of 0% over the first 5 years and an infinite discount rate over the remaining 15 years. However, a more likely outcome would be one in which the Department of Defense recognized that force modernization is essential, necessitating a growth in the strategic budget. There are many ways to describe real growth but for the purpose of this paper, since all three alternatives achieve parity by 1990, it might be that the preferred choice is that which can be contained within a 10% budget growth between 1980 and 1983 and with a fixed no-growth budget after 1983.

Figure 5 shows that none of the alternatives can achieve the goal of remaining within a fixed budget constraint of 10% over the next few years. Given that this constraint is real, then one could change one's judgement value and approve the option that achieved parity first. In this case, alternative B achieves parity by 1993 while alternative C slides into 1994.

In summary, the decision can be taken from the options shown in table 14. The least cost over 20 years is alternative C, either undiscounted or discounted. It calls for the introduction of 370 MX missiles and 190 STOL cruise missile carriers. The cruise missile carrier would have an initial operating capability of 1984 and a full operational capability of 1989. This implies either an off-the-shelf engine with minor scaling or the immediate start of a new engine having 1980 technology. If minimizing the cost through 1985 is the selection criterion, alternative B is preferred. This is a force that would eventually include 400 MX's and 160 new bombers. If the initial operational capability is to be 1985 and 1987 for the MX and bomber, respectively, then once again 1980 engine technology is required. However, if a fixed funding constraint of 10% growth to 1983 is placed on the strategic budget and parity by 1993 is acceptable, then alternative B, the new-bomber option, is once again preferred. With the additional 3-year grace, it might be possible for the new bomber to contain later technology, particularly in the engine. In addition, one would have the time to trade alternative engine cycles and designs against the cost of dispersal bases where the cost advantage of substituting STOL versus quantity and length of runways could be considered.
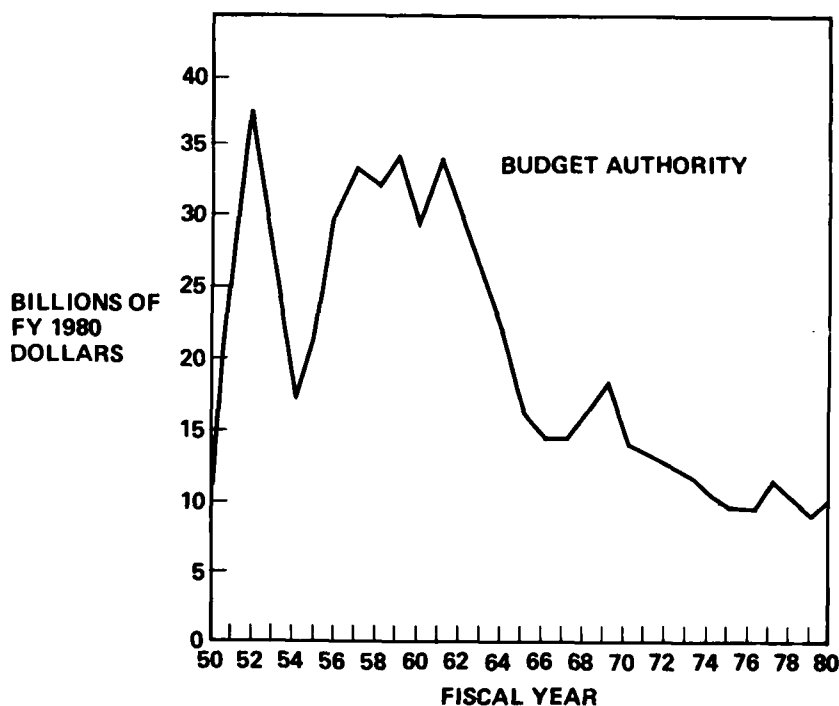
Figure 1. Strategic Forces Budget Trend

- Titan
- Minuteman II/III
- Polaris
- Poseidon
- Trident
- FB-111A
- B-52 D/G/H
- KC-135

Figure 2. Existing Strategic Offensive Force

	FY 1978	FY 1979	FY 1980
Army	28.9	31.6	34.0
Navy	39.6	41.5	44.0
Air Force	33.1	35.4	39.0
Defense agencies/OSD	4.2	4.6	5.3
Defense-wide	10.6	12.6	13.2
Total	116.5	125.7	135.5

Table 1. Department of Defense Financial Summary by Component—Budget Authority—
Current Dollars (Billions)

	FY 1978	FY 1979	FY 1980
Military personnel	27.2	28.7	30.3
Retired pay	9.2	10.3	11.5
Operation and maintenance	34.9	38.1	40.9
Procurement	30.3	31.5	35.4
RDT&E	11.5	12.8	13.6
Military construction	1.9	2.6	2.2
Family housing	1.4	1.7	1.6
Revolving and management funds	0.2	0.1	—
Total	116.5	125.7	135.5

Table 2. Department of Defense Financial Summary by Appropriation—Budget Authority—
Current Dollars (Billions)

Program		FY 1978	FY 1979	FY 1980
1	Strategic forces	9.1	8.6	10.8
2	General-purpose forces	42.5	47.6	50.0
3	Intelligence and communications	7.9	8.1	9.1
4	Airlift and sealift	1.6	1.8	1.9
5	Guard and reserve forces	6.9	7.0	7.1
6	Research and development	10.1	11.1	11.8
7	Central supply and maintenance	11.9	12.9	13.8
8	Training, medical, other general personnel activities	23.9	25.8	27.9
9	Administrative and associated activities	2.2	2.3	2.6
10	Support of other nations	0.3	0.4	0.6
	Total	116.5	125.7	135.5

Table 3. Department of Defense Financial Summary by Program—Budget Authority—
Current Dollars (Billions)

Figure 3. Typical Funding Profiles

9-8

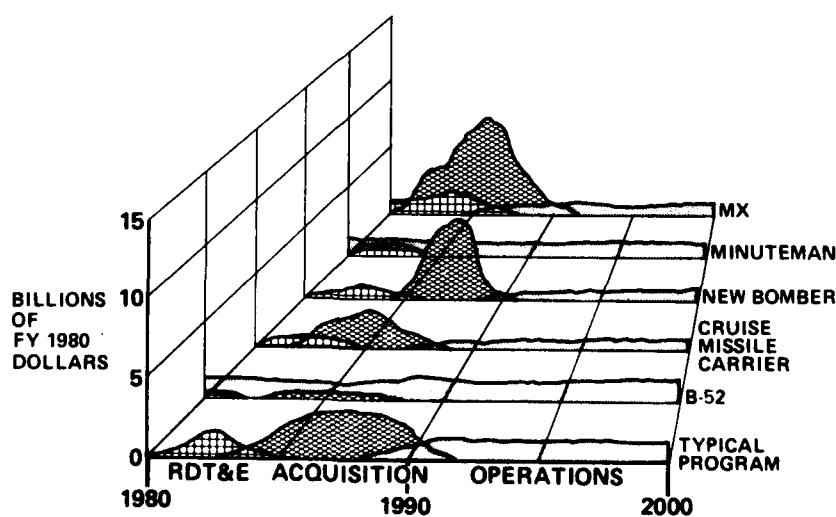|	Millions of FY 80 Dollars
● RDT&E	
• Missile	4,820
• Basing	2,180
	7,000
● Investment	
• Missile	8,904
• Missile spares	1,780
• Countermeasures	744
• Vehicles	3,138
• C^3	825
• Ground equipment	1,511
• Physical security	1,120
• Miscellaneous support equipment	333
• Training	327
• Data, ECP, general support	1,094
• Government costs	1,032
• ALCC	74
• Shelter	10,388
• Other facilities	727
• Roads and railways	5,100
	37,097
● Annual operations and support	
• Recurring investment	501
• Pay and allowances	254
• BOS/medical	15
• Personnel support	10
• "Pipeline" support	23
	803

Table 4. MX Cost Summary—400 Missiles—RDT&E, Investment, and Operations

	Millions of FY 80 dollars
● **RDT&E**	
● Missile	4,536
● Basing	2,052
● Nonrecurring missile	284
● Nonrecurring basing	128
	7,000
● **Investment**	
● Missile	8,904
● Missile spares	1,780
● Comprehensive countermeasures	744
● Vehicles:	
● Transporter emplacer-launcher	2,408
● Transporter launcher shield	596
● Mobile launch command and control	53
● Cover-remover vehicle	80
● Cover-remover support vehicle	1
● Command, control, and communications	825
● Ground power	718
● Physical security	1,120
● Mechanical equipment	793
● Maintenance support equipment	150
● Depot support equipment	109
● Transportation and handling equipment	74
● Training	327
● Aging surveillance assets, date, engineering change orders, and general support	1,094
● Other Government costs	1,032
● Air-launch command and control facilities and land	74
● Shelter	9,738
● Shelter door	650
● Other facilities	727
● Roads and railways	5,100
	37,097

Table 5. MX RDT&E and Investment—400 Missiles

	Millions of FY 80 Dollars	
● Recurring investment and miscellaneous logistics		501
• SE, common (REPL) and spares	8	
• Maintenance, base (material only)	31	
• Maintenance, depot (labor and material)	108	
• Modification, class IV and spares	27	
• Replenishment spares	52	
• Operations missile test and analysis	266	
• Vehicular equipment	9	
● Pay and allowances		254
• Military, PPE and BOS/RPM	242	
• Civilian, PPE and BOS/RPM	12	
● BOS/RPM, nonpay support of primary mission		5
• PPE man-years	4	
• BOS/RPM man-years	1	
● Medical (MFP VIII) support of mission		10
• Officers, PPE and BOS/RPM	3	
• Airmen, PPE and BOS/RPM	7	
● Personnel support		10
• PCS–officers	3	
• PCS–airmen	7	
● "Pipeline" support		23
• Acquisition–officers (nonaircrew)	4	
• Acquisition–airmen	5	
• Training–officers (nonrated)	1	
• Training–airmen (maintenance)	13	
Total annual cost estimate		803

Table 6. MX Annual Operations and Support Costs—400 Missiles

	Millions of FY 80 dollars
● RDT&E	
● Airframe	$ 1,582
● Engines	950
● Avionics	139
● Flight test	454
	$ 3,125
● Investment	
● Unit equipment (UE)	
• Airframe	$ 8,332
• Engine	868
• Avionics	1,596
● Command support	1,079
● Advanced attrition bay	1,080
● Initial spares	972
● Support equipment	324
● Training equipment	216
● Technical publications and data	107
	$14,574
● Annual operations and support	
● Recurring investment	$ 206
● Pay and allowance	121
● BOS/medical	7
● Personnel support	4
● "Pipeline" support	17
	$ 355

Table 7. Dual-Purpose Bomber Cost Summary—160 UE—RDT&E, Investment, and Operations

	80	81	82	83	84	85	86	87	88	89	90		99	Total
MX-MPS														
R&D	700	840	1,050	1,260	1,540	1,050	350	210						7,000
Investment		527	2,821	2,957	4,895	5,679	6,911	6,442	3,094	2,275	750			37,097
Operations and support					20	100	301	502	602	703	803	03	803	10,261
Total	700	1,367	3,871	4,217	6,455	6,829	7,562	7,154	3,696	2,978	1,553	03	803	54,358

Table 8. MX Budget Authority in Millions of 1980 Dollars—400 Missiles

	Reference force	Alternative A	Alternative B	Alternative C
Poseidon	448	448	448	448
Trident	312	312	312	312
Titan	54	54		
Minuteman II	450	450		
Minuteman III	391			
MX-MPS		300	400	370
B-52 D/H (penetrator)	173	173		
B-52G (standoff)	169	44		
ALCM (B-52G)	3,000	520		
FB-111	66	66		
AMST-CMC		216		190
ALCM (AMST-CMC)		4,865		4,455
Dual-purpose bomber			160	
ALCM (standoff)			2,912	
Penetrator payloads			36	
Dispersal fields		5,730	4,233	4,910

Table 9. Strategic-Force Structure Alternatives—Alternatives A, B, and C Achieve Parity by 1990

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	20 YR TOTAL
SLBM'S																
POLARIS																
OPS+SUPT	469	469	469	376	329	141	0	0	0	0	0	0	0	0	0	2254
TOTAL	469	469	469	376	329	141	0	0	0	0	0	0	0	0	0	2254
POSEIDON																
INVEST	47	42	33	28	0	0	0	0	0	0	0	0	0	0	0	150
OPS+SUPT	1343	1343	1343	1343	1343	1213	1213	1213	1213	1213	1213	1213	1213	1213	1213	24915
TOTAL	1390	1385	1377	1371	1343	1213	1213	1213	1213	1213	1213	1213	1213	1213	1213	25065
D5-MISL																
R-AND-D	0	200	500	500	1000	500	500	0	0	0	0	0	0	0	0	3200
INVEST	0	0	0	0	489	698	1029	922	619	121	0	0	0	0	0	3877
TOTAL	0	200	500	500	1489	1198	1529	922	619	121	0	0	0	0	0	7077
C4-MISL																
R-AND-D	19	10	10	10	0	0	0	0	0	0	0	0	0	0	0	49
INVEST	883	830	791	702	0	0	0	0	0	0	0	0	0	0	0	3206
TOTAL	902	840	801	712	0	0	0	0	0	0	0	0	0	0	0	3255
TRI-SUB																
R-AND-D	91	62	26	26	0	0	0	0	0	0	0	0	0	0	0	204
INVEST	1936	1913	1893	1253	424	0	0	0	0	0	0	0	0	0	0	7619
OPS+SUPT	44	88	176	220	308	352	396	440	484	528	572	572	572	572	572	8756
TOTAL	2071	2063	2095	1499	932	352	396	440	484	528	572	572	572	572	572	16579
FBMS-SUP																
OPS+SUPT	231	231	231	231	231	231	231	231	222	194	166	139	111	83	55	2846
SLBM'S TOTAL	5063	5189	5472	4688	4324	3135	3369	2806	2538	2056	1952	1924	1896	1868	1841	57075
ICBM'S																
TITAN																
R-AND-D	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5
INVEST	11	32	20	13	0	0	0	0	0	0	0	0	0	0	0	76
OPS+SUPT	119	119	119	119	119	99	79	60	40	20	0	0	0	0	0	893
TOTAL	134	152	139	132	119	99	79	60	40	20	0	0	0	0	0	974
MM-II																
OPS+SUPT	243	243	243	243	243	202	162	121	81	40	0	0	0	0	0	1822
TOTAL	243	243	243	243	243	202	162	121	81	40	0	0	0	0	0	1822
M-IIISA																
R-AND-D	33	30	23	16	7	6	0	0	0	0	0	0	0	0	0	115
INVEST	117	135	91	46	0	0	0	0	0	0	0	0	0	0	0	389
OPS+SUPT	297	297	297	297	297	247	198	148	99	50	0	0	0	0	0	2227
TOTAL	447	462	411	359	304	253	198	148	99	50	0	0	0	0	0	2731
MX-MPS																
R-AND-D	700	840	1050	1260	1540	1050	350	210	0	0	0	0	0	0	0	7000
INVEST	0	527	2821	2957	4895	5679	6911	6442	3094	2275	750	746	0	0	0	37097
OPS+SUPT	0	0	0	0	20	100	301	502	602	703	803	803	803	803	803	10261
TOTAL	700	1367	3871	4217	6455	6829	7562	7154	3696	2977	1553	1550	803	803	803	54357
ICBM'S TOTAL	1524	2224	4644	4951	7121	7384	8001	7484	3916	3088	1553	1550	803	803	803	59885
AIR-BTHR																
FB-111A																
OPS+SUPT	154	154	154	154	154	154	154	116	77	39	0	0	0	0	0	1310
TOTAL	154	154	154	154	154	154	154	116	77	39	0	0	0	0	0	1310
B-52D/H																
INVEST	94	157	220	220	170	170	57	0	0	0	0	0	0	0	0	1090
OPS+SUPT	693	693	693	693	693	693	693	521	349	172	0	0	0	0	0	5893
TOTAL	787	850	913	913	863	863	750	521	349	172	0	0	0	0	0	6982
B-52G																
OPS+SUPT	722	640	589	342	171	85	13	0	0	0	0	0	0	0	0	2562
TOTAL	722	640	589	342	171	85	13	0	0	0	0	0	0	0	0	2562
B52GCNC																
R-AND-D	79	44	0	0	0	0	0	0	0	0	0	0	0	0	0	123
INVEST	4	50	84	52	44	33	0	0	0	0	0	0	0	0	0	249
OPS+SUPT	0	4	56	85	128	171	188	188	85	43	0	0	0	0	0	948
TOTAL	83	99	140	137	174	204	188	188	85	43	0	0	0	0	0	1340
KC-135																
R-AND-D	12	53	29	7	3	3	0	0	0	0	0	0	0	0	0	108
INVEST	78	48	205	29	0	0	0	0	0	0	0	0	0	0	0	380
OPS+SUPT	1298	1298	1298	1298	1298	1298	1298	973	650	325	0	0	0	0	0	11031
TOTAL	1388	1419	1532	1333	1301	1301	1298	973	650	325	0	0	0	0	0	11518
SRAM-A																
OPS+SUPT	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	433
TOTAL	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	433
ALCM-B																
R-AND-D	342	100	36	0	0	0	0	0	0	0	0	0	0	0	0	478
INVEST	231	607	820	585	488	430	390	230	0	0	0	0	0	0	0	3780
OPS+SUPT	0	2	14	37	57	75	92	109	119	119	119	119	119	119	119	1809
TOTAL	573	709	870	622	544	504	482	339	119	119	119	119	119	119	119	6067
NEW-BMBR																
R-AND-D	0	400	600	1000	500	500	125	0	0	0	0	0	0	0	0	3125
INVEST	0	0	0	0	0	206	3373	4570	4882	774	385	383	0	0	0	14574
OPS+SUPT	0	0	0	0	0	0	2	67	178	311	355	355	355	355	355	4109
TOTAL	0	400	600	1000	500	706	3500	4636	5059	1087	740	738	355	355	355	21809
SIOP-FLB																
BF4233	0	354	506	607	708	810	1012	658	253	152	0	0	0	0	0	5060
TOTAL	0	354	506	607	708	810	1012	658	253	152	0	0	0	0	0	5060
AIR-BTHR TOTAL	3728	4647	5326	5131	4437	4649	7417	7452	6613	1958	881	879	495	495	495	57082
FINAL TOTAL	10316	12060	15462	14770	15882	15168	18787	17742	13068	7102	4386	4352	3195	3167	3139	174042

Figure 4. Alternative B Cost Summary—Present Force Plus Introduction of MX and Dual-Purpose Bomber—Millions of 1980 Dollars

	Reference force	Alternative		
		A	B	C
SLBM	57	57	57	57
ICBM	12	54	60	57
Aircraft	66	79	57	52
	—	—	—	—
Total	135	190	174	166

Table 10. Life-Cycle Cost of Strategic Options—1981 Through 2000—Billions of 1980 Dollars

	Reference force	Alternative		
		A	B	C
SLBM	18	18	18	18
ICBM	6	10	10	9
Aircraft	30	26	6	5
Total	54	54	34	32

Table 11. Operational Costs of Strategic Options—1990 to 2000—Billion of 1980 Dollars

	Reference force	Alternative		
		A	B	C
SLBM	31	31	31	31
ICBM	6	30	33	32
Aircraft	31	41	34	33
Total	68	102	98	96

Table 12. Life-Cycle Cost of Strategic Options—1990 to 2000—
Billions of 1980 Discounted Dollars

	Reference Force	Alternative		
		A	B	C
SLBM	28	28	28	28
ICBM	4	28	28	28
Aircraft	23	35	28	34
Total	55	91	84	90

Table 13. Life-Cycle Cost of Strategic Options—1980 to 1985—Billions of 1980 Dollars
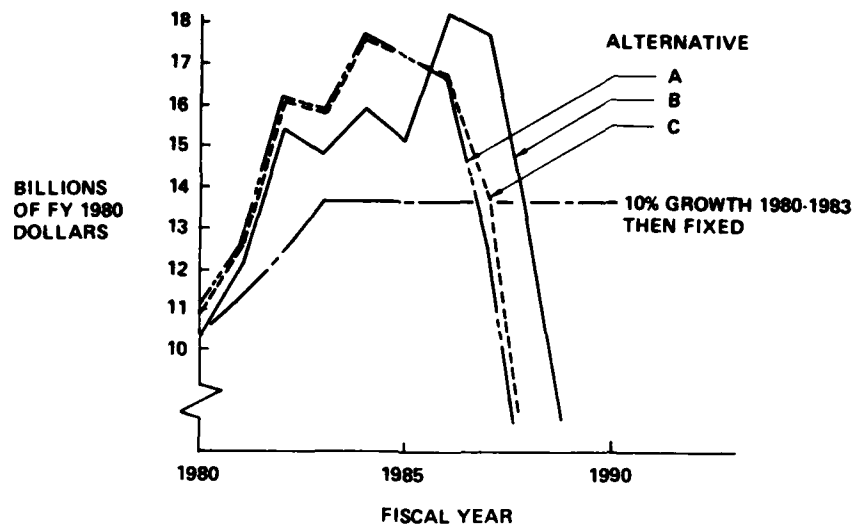
Figure 5. Annual Budget Authorities Versus Budget Constraint

Criterion	Procedure	Alternatives		
		A	B	C
Least cost (billions of dollars)	Undiscounted dollars	190	174	(166)
	Discounted dollars	102	98	(96)
	1980 to 1985	91	(84)	90
Parity date	10% budget growth to 1983	1994	(1993)	1994

Table 14. Summary

AGARD Lecture Series No. -107

Methodology for Design-to-Cost of Aero Engines

This Bibliography with Abstracts has been prepared to support
AGARD Lecture Series no. 107 by the Scientific and Technical Information
Branch of the U.S. National Aeronautics and Space Administration,
Washington, D.C., in consultation with the Lecture Series Director,
Mr. Robert W. Ackerman.

The bibliography consists of 91 citations.

range - for cruise missiles are discussed. Low detection is enhanced by low-altitude flight, where a cruise missile can take advantage of the decreased horizon range, terrain masking, and background clutter. This low-altitude-flight results in a high-wing-loading vehicle and the need for an effective terrain-following/avoidance system. An advanced engine with improved TSFC over current small engines is considered for advanced cruise missiles along with high-density fuels, such as carbon slurry, which reduce vehicle size. Prelaunch survivability, penetration survivability, carriageability, cost, and reliability are discussed as features driving the measure-of-merit (MOM).
AIAA PAPER 79-1817   79/08/00   79A47897

UTTL: New versus existing engines for new helicopter systems - A life cycle cost view
A/WALKER, G. I.   PAA: A/(General Electric Co .   AIAA.
Aircraft Engine Business Group, Lynn, Mass.)   AIAA.
SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA 6 p.
The use of life cycle cost analysis as a tool for decision making in system selection with respect to new helicopter system development and acquisition is examined. The tradeoff in choosing an existing engine or a completely new engine as a power plant for a new helicopter is studied. Emphasis is given to the analysis of derivative twin versus new twin engines using parameters for disk loading, rotor solidity ratio, rotor tip speed, and equivalent flat plate areas.
AIAA PAPER 79-1316   79/06/00   79A47348

UTTL: An analysis of operational procedures and design modifications for aircraft fuel conservation
A/AGGARWAL, R.;   B/DUSHMAN, A.;   C/CALISE, A. J.
PAA: B/(Dynamics Research Corp., Wilmington, Mass.);
C/(Drexel University, Philadelphia, Pa.) In:
Atmospheric Flight Mechanics Conference for Future Space Systems, Boulder, Colo., August 6-8, 1979.
Collection of Technical Papers. (A79-45302 19-01) New York, American Institute of Aeronautics and Astronautics, Inc., 1979. p. 232-242.
This paper is taken from a two year study conducted to determine the effectiveness of fuel conservation measures as applied to Air Force bomber/transport type aircraft. The impact of various potential design and operational procedure improvements are quantified. A major contribution of this study is the approach taken to generate the effect of design changes on fuel consumption and direct operating cost (DOC).

UTTL: Aircraft engine developments centre on improved performance, higher efficiency
A/SENS, W. H.   PAA: A/(United Technologies Corp., Commercial Products Div., East Hartford, Conn.)   ICAO Bulletin, vol. 34, Apr. 1979, p. 18-23.
Improvements that can be made to reduce the fuel consumption of current engines are reviewed as well as for new production versions of current engines. In addition, the potential fuel savings with advanced turbofan engines are discussed. Four ways to improve fuel consumption are covered: improvement in component performance, improved maintenance procedures that reduce the amount of engine performance deterioration with operational use, improvement in the power plant cycle, and by designing the engine to be less sensitive to factors causing performance deterioration. Modification to current engines can improve fuel consumption by 5%. It is concluded that the advanced turbofan configuration has the potential of providing a 20% reduction in fuel burned relative to today's designs for a high bypass ratio turbofan for 1990.   79/04/00   79A50207

UTTL: Derivative engines for the 1980s will help limit acquisition and maintenance costs
A/WORSHAM, J. E.   PAA: A/(General Electric Co.,
Commercial Engine Div., Cincinnati, Ohio)   ICAO Bulletin, vol. 34, Apr. 1979, p. 14-17.
It is noted that the projected increase in commercial aviation will lead to greater demand for new aircraft and thus new engines. The industry is shown to be emphasizing derivative engines. Attention is given to the advantages of such development such as rapid maturity of the design resulting in a reduced shop visit rate, and reduced acquisition costs. As an example the CFM56 engine, suitable for re-engineering narrow body aircraft such as the B-707, DC-8, and DC-9, utilizes the core of a high performance engine previously developed for the U.S. Government. It is concluded that meeting costs continues to be a major challenge for the airlines, the aircraft companies, and the engine manufacturers.   79/04/00   79A50206

UTTL: A perspective on the requirements and design for advanced cruise missiles
A/NICOLAI, L. M.   PAA: A/(U.S. Defense Advanced Research Projects Agency, Arlington, Va.; USAF, Washington, D.C.)   American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting, New York, N.Y., Aug. 20-22, 1979, 7 p.
Conflicting requirements - low detection and long

more accurate assessment of capital costs than does the conventional direct operating cost method, which considers only capital costs due to depreciation. The application of payback period analysis to design improvements in the JT8D turbofan engine is presented.
AIAA PAPER 79-1235   79/06/00   79A39817

UTTL: What small turbine engine does the small helicopter need, or The road to hell is paved with good intentions
A/COHEN, E. E.   PAA: A/(Hughes Helicopters, Culver City, Calif.)   AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA 7 p.
It is argued that today's small turbine engines do not meet the requirements of small helicopters as well as does the turbocharged piston engine. It is suggested that in developing advanced turbine engines for small helicopters, engine weight (unless it reduces the weight of the fuel system plus fuel) should be subordinate to other design considerations such as reduced fuel consumption, improved altitude performance, improved environmental acceptability, and increased engine reliability and maintainability. The specific fuel requirements of small turbine and piston engines are compared; growth trends in demand for small rotorcraft are presented.
AIAA PAPER 79-1314   79/06/00   79A39032

UTTL: Damage tolerant design - An approach to reducing the life cycle cost of gas turbine engine disks
A/MEECE, C. E.; B/SPAETH, C. E.   PAA: B/(United Technologies Corp., Pratt and Whitney Aircraft Group, West Palm Beach, Fla.)   AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA   6 p. USAF-supported research.
The rupture of a disk in a gas turbine engine, although it is a rare occurrence, invariably requires engine shutdown and frequently results in extensive damage to the engine. For this reason disks are designed to be the most reliable parts in the rotating structure. This emphasis on reliability coupled with typical variations in material properties, engine operating characteristics, and manufacturing tolerances has resulted in the retirement of most disks from service before their total useful lives are depleted. Current disk lives are established so that at the end of the calculated lifetime one disk in one thousand will develop a very small crack at the limiting location. The life prediction method employs classical damage summation techniques to deal with mission complexities and identifies for the disk

Sensitivity plots of fuel and DOC savings as a function of the design parameters are generated for each aircraft type. These plots are based on actual mission trajectory data as opposed to 'typical' mission trajectory profiles.
AIAA 79-1656   79/00/00   79A45328

UTTL: Causes of high pressure compressor deterioration in service
A/RICHARDSON, J. H.; B/SALLEE, G. P.; C/SMAKULA, F. K.   PAA: C/(United Technologies Corp., Pratt and Whitney Aircraft Group, East Hartford, Conn.)   CORP: Pratt and Whitney Aircraft Group, East Hartford, Conn.   AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA   8 p.
The high mechanical reliability and low deterioration rate of the JT9D high-pressure compressor results in long utilization without exceeding engine operational limits. The increasing cost and decreasing supply of fuel have focused attention on the fuel burned implications of such high time use without refurbishment. The paper presents the results of JT9D high pressure compressor studies. The mechanical deterioration of the JT9D high-pressure compressor gaspath parts versus increasing service usage, documented from inspection of service parts, is presented and discussed including changes in airfoil roughness, blade length, airfoil contour and outer air seal trench characteristics. An estimate of the performance loss versus usage is related to each type of damage. The combined estimated high-pressure compressor performance loss for all mechanisms determined from part inspection is compared to historical engine test data to establish the validity of the predicted loss levels. The effect of cold section refurbishment on engine fuel consumption recovery and the results of an optimization study to determine the appropriate interval for high pressure compressor refurbishment are also reported.
AIAA PAPER 79-1234   79/06/00   79A40483

UTTL: Payback period - An engineering cost/benefit method
A/WEBB, D. E.   PAA: A/(United Technologies Corp., Pratt and Whitney Aircraft Group, East Hartford, Conn.)   AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA 7 p.
An aircraft engine cost/benefit analysis method which uses the payback period (ratio of investment to before-tax annual cash savings) as the basic parameter is described. The payback period method provides a

population a life at which disks must be removed to ensure safe operation.
AIAA PAPER 79-1189   79/06/00   79A38976

UTTL: The selection of materials technologies for full-scale development
A/ARONSTAMM, G. A.   PAA: A/(United Technologies Corp., Pratt and Whitney Aircraft Group, East Hartford, Conn.)   CORP: Pratt and Whitney Aircraft Group, East Hartford, Conn.   AIAA, SAE, and ASME, Joint Propulsion Conference, 15th, Las Vegas, Nev., June 18-20, 1979. AIAA   8 p. NASA-sponsored research.
Candidate material technologies offering the largest application payoff for the least development costs and the least risk should be selected for full-scale development funding. A cost/benefit methodology is developed to rate candidate material and process opportunities for future aircraft engine applications. A development cost estimate and risk analysis is compared with the economic benefit to establish a ranking of the candidate advanced technologies. Also included are examples of this methodology as applied to high-strength HIP turbine disks, advanced oxide dispersion strengthened burner liners, and ceramic first-stage high-pressure turbine vanes.
AIAA PAPER 79-1152   79/06/00   79A38962

UTTL: Trade-off studies with an interactive engine/airframe life-cycle-cost model
A/COMEY, D. H.; B/CULY, D. G.; C/CASSIDY, J. E.   PAA: C/(AiResearch Manufacturing Company of Arizona, Phoenix, Ariz.; Rockwell International Corp., Pittsburgh, Pa.)   Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978.   10 p.
The purpose of this paper is to show the importance of interactive connections between the engine and airframe sections of an aircraft life-cycle-cost model in performing trade-off studies. A model is defined that can accept engine descriptions at the part level, and aircraft mission descriptions for each segment. An important feature of the model is airframe and engine resizing as a result of changes in mission and engine design parameters. Three different trade-off studies are shown to illustrate the versatility of this type of model. The effects of not resizing the airplane and engine are also shown.
SAE PAPER 781033   78/11/00   79A25905

UTTL: Life cycle cost in preliminary engine design
A/VERNON, J.   PAA: A/(United Technologies Corp., Pratt and Whitney Aircraft Group, West Palm Beach, Fla.)   Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978.   7 p.
The life cycle cost (LCC) effects of the F100-PW-100 engine design life and duty cycle on the F-15 weapon system LCC are analyzed. The analysis reveals that (1) the preliminary design phase presents the first and most profitable opportunity to maximize the cost effectiveness of life-limited engine parts; (2) the weapon system life cycle and engine duty cycle must be accurately determined early in the engine design and continually updated in order to fully benefit from trade studies involving part life, cost, weight, and LCC; (3) the ratio of total engine operating hours to engine flight hours is far greater than generally thought; (4) small weight increases in life-limited parts often provide considerable LCC savings; (5) the trade between engine weight and manufacturing cost is a variable which depends on the actual part life and the engine life cycle; and (6) designing major parts for full engine life pays off in reduced weapon system LCC.
SAE PAPER 781032   78/11/00   79A25904

UTTL: Turbine engine cost reduction using Life Cycle Cost techniques
A/CURRY, C. E.; B/EARLE, R. V.; C/PEDERSEN, G. H.   PAA: C/(General Motors Corp., Detroit Diesel Allison Div., Indianapolis, Ind.)   Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978.   9 p.
This paper describes the technical approach and development of methodologies used to conduct design trade studies from a Life Cycle Cost standpoint. A discussion of computer program capability is followed by a general discussion of several engine design trade studies. The potential for influencing engine design using a Life Cycle Cost methodology is emphasized.
SAE PAPER 781031   78/11/00   79A25903

UTTL: Applying design-to-life cycle cost methods during engine advanced development
A/APEL, J. R.; B/WILTSE, D. E.   PAA: B/(Teledyne CAE, Toledo, Ohio)   Society of Automotive Engineers, Aerospace Meeting, San Diego, Calif., Nov. 27-30, 1978.   10 p.
In order to make better decisions during advanced development of turbine engines, life cycle cost (LCC) methodologies must adequately reflect the impact of engine design decisions on the total system LCC. Two

applications of Teledyne CAE's APSICOST Methodology are presented herein. These demonstrate the integrated nature of turbine engine LCC analyses with total aircraft system LCC. It is recommended that a joint airframe/propulsion/government effort be undertaken to standardize methods for reflecting aircraft system LCC impacts in turbine engine advanced development activities.
SAE PAPER 781030   78/11/00   79A25902

UTTL: Requirements and constraints in the development and qualification of gas turbine engines for the Navy
A/DELL. M. E.; B/MEAD. M. D.   PAA: A/(U.S. Naval Air Propulsion Test Center. Trenton. N.J.);   B/(U.S. Naval Air Systems Command. Washington. D.C.)   Society of Automotive Engineers. Aerospace Meeting. San Diego. Calif.. Nov. 27-30. 1978. 11 p.
An improved approach to the development and qualification of aircraft turbine engines has been developed by the Navy. The approach places emphasis on durability testing throughout the engine development program. This testing is intended to assure that structural requirements have been achieved upon the introduction of new engines into service. The approach utilizes three different types of durability tests each of which is intended to address a separate aspect of the overall durability problem.
SAE PAPER 780994   78/11/00   79A25879

UTTL: Planning the development and qualification process for the next generation of high technology aircraft engines
A/HUDSON. S. M.; B/MCINTIRE. W. L.   PAA: B/(General Motors Corp.. Detroit Diesel Allison Div.. Detroit. Mich.)   Society of Automotive Engineers. Aerospace Meeting. San Diego. Calif.. Nov. 27-30. 1978. 14 p.
The concurrent requirements to maximize performance and minimize cost and program risk provide a great challenge for the weapon-system planner and the propulsion-system manager. The propulsion-system development process consists of the definition of requirements. the selection of the appropriate technology. the design and fabrication of the configuration. the verification of characteristics. and the resolution of problems identified during the verification phase. The development process must be structured to be consistent with the current procurement policies and be responsive to requirements of timing and funding constraints. This paper addresses the development process for the high-technology aircraft engine in the light of recent military engine experience and the current policies

and constraints.
SAE PAPER 780992   78/11/00   79A25878

UTTL: Manufacture of ring rolled components for gas turbine engines
A/HANSEN. W.; B/HUUSKONEN. N. T.   PAA: A/(General Electric Co.. Lynn. Mass.);   B/(General Electric Co. Cincinnati. Ohio)   Society for the Advancement of Material and Process Engineering. National Symposium and Exhibition. 23rd. Anaheim. Calif.. May 2-4. 1978. Paper. 12 p.
The precision ring rolling process (patented in Dec. 1976) is a new and cost effective alternative for manufacturing precision rings for gas turbine engines. The paper describes this process. noting several characteristics and capabilities as for example. that the contour can be maintained within .002 of an inch. the rings are expanded to a diametrical tolerance of + or - .010 inch and grain size is controlled by proper selection of annealing temperatures. Figures showing cost benefits for several production shapes are presented. indicating that the major cost savings are related to material utilization. Some specific nickel base alloys for which the process is used are mentioned.   78/05/00   79A20884

UTTL: Progress on the ENSIP approach to improved structural integrity in gas turbine engines - An overview
A/TIFFANY. C. F.; B/COWIE. W. D.   PAA: B/(USAF. Systems Command. Wright-Patterson AFB. Ohio)   American Society of Mechanical Engineers. Winter Annual Meeting. San Francisco. Calif.. Dec. 10-15. 1978. 12 p.
The paper describes the turbine engine structural integrity program (ENSIP). defined as 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. increasing service readiness. and reducing life cycle costs through substantially reducing the occurrence of structural durability problems during service operations. ENSIP was applied in the F-101 engine development program. Topics discussed include damage tolerance. durability. ground and flight verification test policy and guidelines. and engine life management policy.
ASME PAPER 78-WA/GT-13   78/12/00   79A19800

UTTL: Advanced turbine powerplants for future helicopter systems
A/PELUSO, P. P., JR. PAA: A/(Avco Corp., Avco Lycoming Div., Stratford, Conn.) In: International Helicopter Forum, 12th, Bueckeburg, West Germany, May 8, 9, 1978. Proceedings. (A79-16227 04-01) Bueckeburg, West Germany, Heeresflieger-Waffenschule, 1978. 12 p.
Significant advancements have been made since the mid-1960s by Avco Lycoming in small turbine engine design through component technology programs specifically addressed to the 5-10 pound per second airflow size. This paper reviews the development background, design criteria, performance objectives, and program status for two distinct engine configurations: the LTS 101 turboshaft engine and ATDE (Advanced Technology Demonstrator Engine). The ATDE engine represents configuration tradeoff studies biased in favor of exceptional performance, while the design of the 101 engine family has evolved from tradeoff studies emphasizing simplicity and minimum cost of ownership. 78/00/00 79A16228

UTTL: The F/A-18 challenge - Readiness and low total cost
A/MITCHELL, C. M.; B/CAPELLUPO, J. P.; C/MCGEE, R. L. PAA: A/(U.S. Naval Air Systems Command, Washington, D.C.); C/(McDonnell Douglas Corp., St. Louis, Mo.) In: Annual Reliability and Maintainability Symposium, Los Angeles, Calif., January 17-19, 1978. Proceedings. (A79-15351 04-38) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 412-416.
The F/A-18 'Hornet' strike fighter represents the next generation aircraft to be introduced into the Navy inventory. This paper summarizes some of the reliability and maintainability activities of the program with attention given to Hornet design and program decisions, the stores management set, the inertial navigation set, the HUD ground power switching, the radar, and the engines. The integrated test plan for the Hornet is described along with the operational mission environment and demonstration testing. 78/00/00 79A15402

UTTL: Promises of cost savings motivate innovative techniques
A/MAYFIELD, J. Aviation Week and Space Technology, vol. 109, Nov. 20, 1978, p. 44-46, 51, 53, 55.
The production of commercial and military jet engines is discussed noting direct hot isostatic pressing of preforms for JT8D-17 first-stage turbine disks, the gatorization isothermal process, and the powder

UTTL: 800 shaft horsepower advanced technology demonstrator engine
A/ELLIOTT, G. A.; B/FURGURSON, R. G. PAA: B/(U.S. Army, Applied Technology Laboratory, Fort Eustis, Va.) In: American Helicopter Society, Annual National Forum, 34th, Washington, D.C., May 15-17, 1978. Proceedings. (A79-18126 05-01) Washington, D.C., American Helicopter Society, 1978. 10 p.
The broad objectives of the Advanced Technology Demonstrator Engine (ATDE) program are to determine the achievable level of performance of turboshaft engines in the 800-hp category designed for use in the Army environment. Key engine performance and design characteristics established at the start include the following: (1) specific fuel consumption at 480 shaft hp no greater than 0.55 lb/hr-hp, (2) minimum of 600 shaft hp at 4000 ft, 95 F operating conditions, (3) free shaft engine, (4) front drive concentric with engine centerline, (5) integral inlet particle separator, and (6) 220 lb as maximum engine dry weight. The basic design concepts proposed by the two competitors are shown. The scope of analyses with regard to reliability and maintainability, ballistic vulnerability, and engine costs and tradeoffs is discussed. A test schedule is outlined.
AHS 78-47 78/00/00 79A18170

UTTL: Important criteria for the definition and design of future helicopter powerplants
A/GROENEWALD, H. PAA: A/(Motoren- und Turbinen-Union Muenchen GmbH, Munich, West Germany) In: International Helicopter Forum, 12th, Bueckeburg, West Germany, May 8, 9, 1978. Proceedings. (A79-16227 04-01) Bueckeburg, West Germany, Heeresflieger-Waffenschule, 1978. 34 p. In German.
The paper discusses weight/performance tradeoffs in the development of powerplants for future military helicopters, with reference to the influence of a number of design and cost factors. Particular consideration is given to relationships between weight and cycles of operation; specific fuel consumption as a function of initial powerplant weight; the effects of one- and two-engine designs; typical characteristics of unscheduled engine removal rate; and factors in the selection of multiengine helicopters. Definitions of turbine powerplant performance ratings are presented and recent helicopter engine design advances are outlined.
78/00/00 79A16236

the use of missiles, drones, and remotely piloted vehicles (RPV's). Propulsion system cost accounts for a significant portion of the total system cost. The development of low cost propulsion systems becomes in this connection a crucial factor for the feasibility of such applications. An investigation was conducted with the objective to design such a low-cost propulsion system. The studies led to the preliminary design of a short life turbojet engine applicable to subsonic missions. The gas generator portion of this engine is also applicable for use in a turbofan engine. Component efficiencies were traded off for designs which could be fabricated using low cost manufacturing processes. Attention is given to compressor design, combustor design, turbine design, mechanical design features, aspects of material and fabrication process selection, and a manufacturing and cost analysis.
ASME PAPER 78-GT-202   78/04/00   79A10822

UTTL: Evolution of the turboprop for high speed air transportation
A/HOLBROOK, G. E.; B/ROSEN, G.   PAA: A/(General Motors Corp., Detroit Diesel Allison Div., Indianapolis, Ind.); B/(United Technologies Corp.. Hamilton Standard Div., West Hartford, Conn.) American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978. 14 p.
The paper reviews the historical development of the turboprop, with special emphasis on technology development and advanced turboprop projections. The status and ultimate potential of an advanced turbine engine and propeller-fan propulsion system are described. Also discussed are prop-fan efficiency, prop-fan noise and fuselage attenuation, maintenance costs, and public acceptance. It is concluded that the turboprop, with the prop-fan concept, can achieve higher propulsive efficiencies with significant improvements in cost, mission effectiveness, and flight speed.
ASME PAPER 78-GT-201   78/04/00   79A10821

UTTL: Making turbofan engines more energy efficient
A/HEMSWORTH, M. C.; B/ZIPKIN, N. A.   PAA: B/(General Electric Co., Cincinnati, Ohio)   American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978.   13 p.
A review of transport aircraft gas turbine engine development and evolution during the past two decades is presented in terms of energy consumption. The

metallurgy extrusion process. Attention is given to automated physical vapor deposition coatings, automated hole drilling by electron beams, and an automated laser welding machine, and the laser marking of parts for traceability. Brief mention is also made of: high-speed machining with cermet and cubic boron nitride inserts, high-energy reaction forming, inertia bonding, plasma arcwelding, induction welding, and vacuum heat treating.   78/11/20   79A14299

UTTL: Control system requirements for aircraft gas turbine engines
A/RIHA, B.   Zpravodaj VZLU, no. 3, 1978, p. 129-133. In Czech.
The paper presents a brief review of control system requirements for gas turbine engines from the point of view of development specifications. The main obstacles associated with satisfying such requirements are discussed. Attention is also given to the possibility of objective quality evaluations of such control systems on the basis of combined engineering and cost criteria.   78/00/00   79A12530

UTTL: Near-net-shape engine methods emerge
A/KOLCUM, E. H.   Aviation Week and Space Technology, vol. 109, Oct. 30, 1978, p. 42-46.
The paper discusses the emergence of aircraft engine parts fabrication techniques by which a significant fraction, sometimes as much as 75%, of the input weight is saved. Powder metallurgy techniques that reduce machining losses are the hot isostatic pressing (HIP) process and the HIP-plus-hot-die forging process. An advanced powder-metal superalloy, AF115, for turbine disks is being developed which, like Rene 95, is nickel-based and is designed to operate at temperatures 200 F higher than Rene 95. Other advanced-technology programs being studied are discussed, including direct numerical control, computerized electron-beam welding, net-shape rolled rings, laser machining and joining, and inertia welding.   78/10/30   79A11449

UTTL: The application of low cost manufacturing technology to a turbine gas generator
A/DUE, H. F.; B/BUCHANAN, E.   PAA: A/(Teledyne CAE, Toledo, Ohio); B/(USAF, Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio)   American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978.   9 p.
Low system cost is one of the primary criteria for most future unmanned mission applications involving

UTTL: Prospects for commercial commonality in military transports

A/BARBER, E. A.; B/MARHEFKA, R. J.; C/BLATTNER, D. G. PAA: C/(Boeing Aerospace Co., Seattle, Wash.)
American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Conference. Los Angeles, Calif., Aug. 21-23, 1978. 21 p.

A description is presented of work conducted in connection with the Innovative Aircraft Design Study (IADS-77) which was concerned with an examination of the prospects for commercial commonality in military transports. IADS-77 is an extension of a previous study, Innovative Aircraft Design Study. Task II. IADS-Task II was oriented toward studying the size effects of logistic transports. The viability of commercial commonality was also investigated with the express purpose of assessing the feasibility of the C-XX concept as proposed by the Military Airlift Command. The IADS-77 objectives included evaluating the validity of commercial commonality as related to aircraft design, determining the impact of technology on commercial commonality, evaluating the applicability of transport design to alternative military missions, and evaluating the military use of a minimum-size outsize design.
AIAA PAPER 78-1467   78/08/00   78A49784

UTTL: Aircraft fuel economy - The propulsion system contribution

A/HARVEY, R. A.; B/MORRIS, R. E.; C/PALFREEMAN, B. J. PAA: C/(Pratt and Whitney Aircraft of Canada, Ltd., Longueuil, Canada) In: Canadian Symposium on Energy Conserving Transport Aircraft, Ottawa, Canada, October 3, 4, 1977, Proceedings. (A78-31301 12-05) Ottawa, Canadian Aeronautics and Space Institute, 1978. p. 8-1 to 8-20.

Results are presented of some engine performance and design studies intended to determine the potential improvements in fuel efficiency that can be made over a 10 year period by advances in engine technology. The study is confined to 'small' gas turbine engines of the type used for executive and commuter aircraft, i.e., turboprops up to 2500 SHP and turbofans up to 6000 lb thrust. Using projections of technology improvements, equivalent 1987 production engines were synthesized; this showed that a 15.1% reduction in cruise specific fuel consumption could be expected for this class of engine over the next 10 years. Two pairs of aircraft were designed - turboprop and turbofan powered using 1977 and 1987 engines but constant 1977 airframe technology. Reduction in specific fuel consumption and specific weight results in reduction in aircraft weight for the same mission with further

Interaction and effects of cycle pressure ratio, firing temperature, bypass ratio, and component efficiencies on installed fuel consumption are reviewed. The possibilities for further substantial improvement in energy efficiency with improved operating economics and with improved environmental characteristics are identified and evaluated. Parametric data are presented showing trade-offs in the areas of efficiency and economics. Environmental considerations are also discussed. The balance of these factors in a cost-effective advanced turbofan is discussed. In conclusion, projections are made for the capability of an advanced turbofan engine compared with the goals established by NASA for their Energy Efficient Engine Program. The characteristics of this more efficient, cost-effective power plant, that can be operational in the late 1980's are shown in relationship to current turbofan engines.
ASME PAPER 78-GT-198   78/04/00   79A10818

UTTL: Advanced turbofan engines for low fuel consumption

A/SENS, W.   PAA: A/(United Technologies Corp., Commercial Products Div., East Hartford, Conn.)
American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, London, England, Apr. 9-13, 1978. 12 p.

A projection of jet fuel usage by the free world commercial fleet shows that the fuel used by new advanced turbofan engines developed from technology advances anticipated in the next six to eight years would become significant toward the end of this century assuming that the advanced turbofans start entering the fleet by approximately 1990. During the time period 1980 to the year 2000 approximately 90 percent of the total will be burned by engines in existence today, or new engines based on existing design technology. Only about 10 percent would be used by advanced turbofan engines designed in the mideighties or later. Means of improving the fuel consumption of current engines by as much as 5 percent are identified and attention is given to an advanced turbofan configuration which has the potential of providing a reduction in fuel consumption of 20 percent.
ASME PAPER 78-GT-192   78/04/00   79A10816

reduction in fuel flow, from 17% for the larger
turbofan engine to 21% for the larger turboprop.
78/00/00 78A31309

UTTL: Determining the reliability requirements of
aircraft engine control systems during design stage
A/SVOBODA. M. (Konference na thema Regulace
Leteckych Proudovych Motoru, Velesin, Czechoslovakia.
June 1-3 1976.) Zpravodaj VZLU, no. 4, 1977. p.
193-201. In Czech.
The requirements on reliability of aircraft engine
control systems are expressed through the reliability
characteristics of the repair parts. The requirements
are derived from acceptable safety levels and the
criterion of attaining optimal cost effectiveness of
the designed system. 77/00/00 78A29590

UTTL: Analysis of complex decisionmaking processes
A/MILL. J. D.; B/OLLILA, R. G. PAA: B/(Battelle
Columbus Laboratories, Columbus, Ohio) CORP:
Battelle Columbus Labs., Ohio. IEEE Transactions on
Systems, Man, and Cybernetics, vol. SMC-8, Mar. 1978.
p. 193-204.
The analysis of corporate decisionmaking processes
related to major system developments is unusually
difficult because of the number of decisionmakers
involved in the process and the long development
cycle. A method for analyzing such decision processes
is developed and illustrated through its application
to the analysis of the commercial jet engine
development process. The method uses interaction
matrices as the key tool for structuring the problem,
recording data, and analyzing the data to establish
the rank order of the major factors affecting
development decisions. In the example, the use of
interaction matrices permitted analysts to collect and
analyze approximately 50 factors that influenced
decisions during the four phases of the development
cycle, and to determine the key influencers of
decisions at each development phase. The results of
this study indicate that the cost of new technology
installed on an aircraft is the prime concern of the
engine manufacturer. 78/03/00 78A28806

UTTL: JT8D-209 - The first refan
A/WILSON. M.; B/MORSE, B.; C/HEMLOCK, W. PAA:
C/(United Technologies Corp.; Pratt and Whitney
Aircraft Group, East Hartford, Conn.) Flight
International, vol. 113, Feb. 18, 1978, p. 428-430.
The Pratt & Whitney JT8D-209 refan is evaluated, and
compared with new generation commercial jet engines in

terms of thrust and cost parameters. Attention is
given to the DC-9-80 aircraft and its suitability for
retro-fitting with the JT8D-209. When noise
regulations and fuel economy considerations eventually
force the first generation by-pass engines out of the
air, the lower development, maintenance, and
acquisition costs, and higher thrust (18,500 lbs.) of
the JT8D-209, as compared with completely new engines,
should prove an attractive alternative for commercial
aviation. 78/02/18 78A24765

UTTL: Approaches to improving aircraft efficiency
A/SLIVINSKY, C. J. PAA: A/(Rockwell International
Corp., General Aviation Div., Bethany, Okla.)
American Institute of Aeronautics and Astronautics,
Annual Meeting and Technical Display, 14th,
Washington, D.C., Feb. 7-9, 1978. 4 p.
Investigations have been conducted concerning the
approaches which can be used to increase the cost
effectiveness of general aviation type aircraft. It
was found that the utilization of larger propellers
turning more slowly develops the highest thrust per
horsepower ratio. The employment of such propellers in
connection with aerodynamic and material improvements
being developed will permit aircraft to go faster and
carry more payload while flying at higher altitudes
for longer periods of time. Turboprop engines have
demonstrated both a lighter weight per horsepower and
a higher degree of reliability than higher powered
piston engines. Configurations which use two turboprop
engines driving a single propeller and tied together
by a combined gear box offer twin engine reliability
and could obtain aircraft efficiency well beyond those
presently available.
AIAA PAPER 78-305 78/02/00 78A24007

UTTL: The improvement of various engine installation
components in a subsonic transport aircraft
A/DEVRIESE, J. PAA: A/(SNECMA, Paris, France)
(Congres International Aeronautique, 13th, Paris,
France, June 2, 3, 1977.) L'Aeronautique et
l'Astronautique, no. 66, 1977, p. 33-40. In French.
Attention is given to energy losses via the thermal,
aerodynamic, and propulsion characteristics of
aircraft engines. Suggestions are made for the
modification of several engine components in order to
conserve fuel, including (1) the development of new
materials for turbine blades, (2) increased turbine
entry temperature, (3) improved compressor efficiency,
(4) active control of turbine clearances, and (5) a
possible heat exchanger between gases and compressor
delivery air. Various economic considerations

cost variations encountered in modifying turbine inlet temperature need to be lessened. Finally, to determine effectiveness of the selected design, the engine duty cycle, simulations for usage definition, and the impact of mission and environmental changes on the life of components are studied.
AIAA PAPER 77-953   77/07/00   77A41989

UTTL: Engine design decisions impact aircraft life cycle costs
A/WAGNER, W. Q.   PAA: A/(Teledyne CAE, Toledo, Ohio)
American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977. AIAA 9 p.
This paper discusses the concept of design to life cycle cost (DTLC) as applied to propulsion subsystems of military aircraft. It describes the resources necessary for DTLC effort during various engine life cycles, emphasizing the need for engine-oriented LCC models. Two examples of DTLC applications are cited: a deployed engine component study and a concept phase selection task. These results highlight the need for both early attention and 'front-end-loading' to reduce propulsion - subsystem-affected elements of aircraft life cycle cost (LCC).
AIAA PAPER 77-916   77/07/00   77A41986

UTTL: Aero engine development costing
A/FITZGERALD, R. M.   PAA: A/(Rolls-Royce /1971/, Ltd., Derby, England)   In: Methods of cost prediction; Proceedings of the Symposium, London, England, March 9, 1977. (A77-40007 18-83) London, Royal Aeronautical Society, 1977. 19 p.
The costing of an aircraft engine development program is discussed. Resources which might be used by hypothetical programs for a new 20,000 lb thrust fan engine or for a derivative of an existing proven engine capable of satisfying a need for an additional 4000 lb of thrust are given. The reconciliation of innovation and risk is considered. A typical engine development program is outlined, and the cost distribution of a hypothetical program is estimated.
77/00/00   77A40010

UTTL: Engine life considerations in the preliminary design of a tactical weapon system
A/ECKARD, G. J.;   B/KYLE, S. G.   PAA: B/(Boeing Co., Seattle, Wash.)   American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July

regarding such modifications are briefly discussed.
77/00/00   78A15022

UTTL: System evaluation of aircraft-derivative gas turbines for naval ship propulsion applications
A/KUO, S. C.;   B/HORTON, T. L. O.   PAA: B/(United Technologies Research Center, East Hartford, Conn.)
In: Intersociety Energy Conversion Engineering Conference, 12th, Washington, D.C., August 28-September 2, 1977, Proceedings. Volume 1. (A77-48701 23-44) La Grange Park, Ill., American Nuclear Society, Inc., 1977, p. 187-193.
Navy-supported research.
A projection has been made for the typical specific weights which can be expected for naval ship propulsion systems utilizing large aircraft-derivative open-cycle engines in the early 1990's. The expected performance, size, and weight characteristics for these engines were identified and integrated with the expected future characteristics for the remaining conventional propulsion system components to estimate the total propulsion system specific weight. Several propulsion system arrangements were considered and the most promising were used to predict the payload/endurance relationship for the selected naval ship types considered.   77/00/00   77A48718

UTTL: Advanced design procedure for aircraft engine selection
A/ESCHWEILER, J.;   B/GLASER, F. C.;   C/MARTENS, R. E.   PAA: C/(McDonnell Aircraft Co., St. Louis, Mo.)
American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 13th, Orlando, Fla., July 11-13, 1977. AIAA 10 p.
A systematic and economical program for engine and airframe selection for advanced fighter aircraft is discussed, with attention given to the interactions between performance requirements, life cycle cost, and effectiveness. During initial concept formulation, performance and cost are used as criteria in design development, and a computer-based technique is employed to select engine variables (airflow schedule parameters, overall pressure ratio, and turbine inlet temperature) which meet performance and cost specifications while also minimizing gross takeoff weight. Life cycle cost, including development, investment and maintenance costs, is also analyzed, and a second computer program is used to determine the most cost-effective design. The available techniques for assessing engine production cost yield sufficiently accurate estimates; however, long-range

UTTL: Life Cycle Cost as a propulsion system design consideration
A/CURRY, C. E.   PAA: A/(General Motors Corp., Detroit Diesel Allison Div., Indianapolis, Ind.)   American Society of Mechanical Engineers, Gas Turbine Conference and Products Show, Philadelphia, Pa., Mar. 27-31, 1977, 7 p.
This paper deals with applying Life Cycle Cost (LCC) and Design to Cost (DTC) principles to aircraft engine programs. The dynamic driving elements of LCC are identified with an example of direct application to a deterministic computer model. This model was used as the principal tool to project operating and support costs for the XT701 turboshaft engine in conjunction with the U.S. Army Heavy Lift Helicopter Development that featured a specific DTC-related award fee in the contract. The overall methodology of LCC and DTC supported by the math model earned a Superior evaluation with an unprecedented 100 percent award fee for this kind of application. The customer audit, in support of the performance award, supports the conclusion that computer models can be used to enhance the LCC aspects of propulsion system development programs.
ASME PAPER 77-GT-99   77/03/00   77A28609

UTTL: Development of materials used in gas turbine engines - R and D guide lines and proposals for a priority scheme
A/ESSLINGER, P.; B/HUFF, H.   PAA: B/(Motoren- und Turbinen-Union Munchen GmbH, Munich, West Germany)   (Zeitschrift fur Werkstofftechnik, vol. 7, May 1976, p. 167-177.) Revue Internationale des Hautes Temperatures et des Refractaires, vol. 13, no. 3, 1976, p. 172-180. Translation.
(For abstract see issue 16, p. 2433, Accession no. A76-34574)   76/00/00   77A22166

UTTL: Propulsion system requirements for expendable low cost turbine engines for missile application
A/WILSON, F.; B/LEHNHARDT, D. S.   PAA: A/(U.S. Naval Air Systems Command, Washington, D.C.); B/(Teledyne CAE, Toledo, Ohio)   In: International Symposium on Air Breathing Engines, 3rd, Munich, West Germany, March 7-12, 1976. Proceedings. (A77-17226 05-07) Cologne, Deutsche Gesellschaft fuer Luft- und Raumfahrt, 1976, p. 759-780.
This paper identifies and discusses some particular requirements for an expendable low cost turbine propulsion system for missile application. The basic requirements that must be considered are low cost, high reliability, safety, minimum maintenance, no

11-13, 1977, AIAA, 11 p.
Six independent variables which included engine and airframe design parameters and mission or operational variables were parametrically analyzed to identify seven candidate weapon systems for a selected set of tactical mission requirements. These systems were examined as point designs to determine an optimum design region-of-interest on the basis of weight, system cost and engine life. The engine life analysis was based upon time near maximum turbine inlet temperature, with resulting values considered to be acceptable for conceptual and preliminary design sensitivity trades. An objective, that of identifying quantitative figures-of-merit that might be more comprehensive than those that have been used traditionally, was not achieved. However, some qualitative conclusions suggest that engine life considerations should be taken into account in preliminary design analyses and, therefore, that analytical capabilities which would allow this, should be pursued.
AIAA PAPER 77-955   77/07/00   77A38612

UTTL: Engines - Towards lower costs
A/HOOPER, J. A.   PAA: A/(Rolls-Royce /1971/, Ltd., Derby, England)   In: Seeds for success in civil aircraft design in the next two decades; Proceedings of the Spring Convention, London, England, May 19, 20, 1976. (A77-29651 12-01) London, Royal Aeronautical Society, 1976, 21 p.; Discussion, p. H.1-H.7.
The paper reviews the cost situation of aircraft engine in fairly broad terms and attempts to indicate areas and means whereby cost savings might possibly be effected in the future. The discussion covers major cost components and the cash flow situation; elements of major cost components, interactions and cost reduction possibilities; and design organization for low cost. A new computer method called COMPAS is described which is intended to produce data for decision making over a wide range of relevant disciplines with a view toward selecting the correct engine. The effect of technology level on cost is assessed. Aircraft engine development and fabrication are recognized to be a high-technology high-risk industry in which the interactions between conflicting requirements of performance, development, manufacture, and production and running costs are manifold and complex.   76/00/00   77A29663

pre-launch preparation and storability. This type of engine is clearly different from engines for man-carrying and/or reusable drone applications. As such, a new set of specifications must be generated for design, test and manufacturing/producibility practices.   76/00/00   77A17263

UTTL: Turbine engine cycle selection procedures
A/FREDERICK, J.; B/SUTTON, R.; C/MARTENS, R.   PAA: A/(USAF, Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio); B/(Boeing Aerospace Co., Seattle, Wash.); C/(McDonnell Aircraft Co., St. Louis, Mo.)   In: International Symposium on Air Breathing Engines, 3rd, Munich, West Germany, March 7-12, 1976, Proceedings. (A77-17226 05-07) Cologne, Deutsche Gesellschaft fuer Luft- und Raumfahrt, 1976, p. 629-663.
A multivariable design method is described whereby subsystems can be properly selected, advanced engine cycles can be examined adequately as they evolve, and insight as to technology leverages and direction for developments can be provided in a timely and cost-effective manner. A systematic procedure for fighter engine and airframe design selection is developed and demonstrated. Three aircraft roles, encompassing sixteen missions, are defined. Tradeoff studies regarding the size and design characteristics of both the engine and the airframe can be successfully achieved.   76/00/00   77A17257

UTTL: A new development concept for gas turbine engine optimize life cycle costs
A/COWIE, W. D.; B/ABELL, E. E.; C/HORN, E. W.   PAA: A/(USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio)   In: International Symposium on Air Breathing Engines, 3rd, Munich, West Germany, March 7-12, 1976, Proceedings. (A77-17226 05-07) Cologne, Deutsche Gesellschaft fuer Luft- und Raumfahrt, 1976, p. 27-38.
The life cycle development and management process for turbine engines is being revised to provide more durable, reliable, and lower life cycle cost engines to the military services. Greater attention is being given earlier in the life cycle to the cost trades between performance, producibility, and operability/supportability: i.e., during the technology, conceptual and validation phases of the development process. The full-scale development phase has been restructured to emphasize structural durability and to provide formal demonstrations of useful engine life limits; operational and logistic characteristics; and validation of the engine life management process to provide economic management

rationale for the production hardware acquisition, operational usage, and logistic support phases.   76/00/00   77A17228

UTTL: Life cycle cost impact on design considerations for civil transport aircraft propulsion systems
A/SWAN, W. C.; B/BOUWER, D. W.; C/TOLLE, F. F.   PAA: A/(Boeing Co., Seattle, Wash.)   In: International Symposium on Air Breathing Engines, 3rd, Munich, West Germany, March 7-12, 1976, Proceedings. (A77-17226 05-07) Cologne, Deutsche Gesellschaft fuer Luft- und Raumfahrt, 1976, p. 11-26.
This paper reviews recent history on both narrow and wide body transport aircraft with respect to cost of ownership of the propulsion systems. A careful analysis of design decisions made and the resulting cost impact in service are reviewed in an effort to define certain lessons learned. Suggestions for design consideration for future long- and short-haul transport and cargo aircraft are outlined to support low life cycle cost at a minimum penalty in propulsion performance   76/00/00   77A17227

UTTL: International Symposium on Air Breathing Engines, 3rd, Munich, West Germany, March 7-12, 1976, Proceedings
A/HENNECKE, D. K.; B/WINTERFELD, G.   Symposium sponsored by the U.S. Army, U.S. Air Force, U.S. Navy, Bundesministerium der Verteidigung, DFVLR, et al. Cologne, Deutsche (DGLR-Fachbuch, Volume 6), 1976. 964 p. (DGLR-Fachbuch, Volume 6), 1976. 964 p. $41.25.
The present collection of papers is concerned with economics and operational aspects, progress in engine and component design and assessment, and advanced powerplant concepts for air breathing flight propulsion systems. Papers presented in the field of combustor development promise new knowledge derived from theoretical and experimental studies which should help lead the way to a better combustion chamber flow analysis and improved fuel injection systems. Featured topics include matching problems and SST engines, variable geometry for high-performance aircraft engines, high-temperature turbine problems, and the hypermixing-ejector concept applied to greatly shortened mixing chambers for rocket ejector ramjet composite engines. A review of supersonic combustion ramjet (scramjet) engine development in the United States is included. Individual items are announced in this issue   76/00/00   77A17226

UTTL: Future trends in transport aircraft propulsion
A/SENS. W. H. PAA: A/(United Technologies Corp.. Pratt and Whitney Aircraft Group, East Hartford, Conn.) In: The future of aeronautical transportation: Proceedings of the Princeton University Conference, Princeton, N.J., November 10, 11, 1975. (A76-45776 23-03) Princeton, N.J., Princeton University, 1976, p. 10-1 to 10-27.
Twenty one charts on possible future trends in transport aircraft propulsion technology are presented. Attention is paid to future engine requirements, airline economics, engine related costs, subsonic transport fuel consumption, potential turbofan fuel consumption, advanced technology long range quadjet fuel use trends, fan efficiency improvement, technology advancements in fan blade design, compressor efficiency improvement, turbine airfoil alloys, coatings on turbine airfoils, progress in compressor airfoil reduction, lower aspect ratio blading, fabrication technology for lower cost, digital electronic engine control, a variable stream control engine (VSCE-502B), and the VSCE relative to the first generation SST turbojet. 76/00/00
76A45784

UTTL: Engine life cycle cost
A/SININGER. W. B. PAA: A/(General Electric Co., Aircraft Engine Group, Evendale, Ohio) American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 12th, Palo Alto, Calif., July 26-29, 1976. AIAA 11 p.
This paper discusses the results from a study of engine subsystem life cycle cost (LCC) and engine contribution to various type aircraft systems LCC. The development and acquisition phases of LCC are considered with emphasis on operating and support (O & S) elements. The study objectives were to determine the major opportunities for reducing LCC and to provide baseline data for improved forecasting of new engine LCC. The relative values of LCC elements for two contrasting engine types are discussed, and the effects of recent abnormal fuel price increases are explored. The system LCC and engine contributions are presented for a fighter, a helicopter, and a transport, and summary data are included for all aircraft types studied. Analysis of the data indicates that fuel and maintenance (labor and material) are the only significant targets for engine O & S cost reduction. Maintenance and fuel are also the significant targets for system O & S cost reduction, even for helicopters, where crew costs overshadow fuel cost.
AIAA PAPER 76-754 76/07/00 76A38249

UTTL: Design-to-cost methodology
A/SANDLER. G. H.; B/RACHOWITZ. B. I. PAA: B/(Grumman Aerospace Corp., Bethpage, N.Y.) Society of Allied Weight Engineers, Annual Conference, 35th, Philadelphia, Pa., May 24-26, 1976. 23 p.
In the prevailing cost conscious atmosphere, it is extremely important for all sectors of the Aerospace Industry to develop methods that will permit an understanding of the factors which affect costs in all the phases of a program's life cycle. A design-to-cost methodology developed at Grumman for establishing design-to-cost/life cycle cost goals is discussed. The tools developed to permit the design engineer to trade cost and performance during the design process are described. Examples of trades within and between subsystems are included, along with the management tools for specifying design-to-cost requirements and tracking design-to-cost targets. Practical examples of applications on programs and management training are given
SAWE PAPER 1138 76/05/00 77A12199

UTTL: Future trends in aero gas turbine design. I - Conventional engines
A/DENNING. R. M.; B/MILLER. S. C.; C/WRIGHT. G. H.
PAA: C/(Rolls-Royce /1971/, Ltd., Aero Div., Derby, England) Aeronautical Journal, vol. 80, Aug. 1976. p. 343-349.
Single-stage turbofan engines of high bypass ratio are compared and classified as the preferred design for aircraft cruising at high subsonic Mach numbers. Specific fuel consumption is singled out as the most important criterion, in view of current fuel price trends, and attention is given to weight, noise, and exhaust pollution. The turbine engines are grouped in three thrust size categories: (1) large engines powering large aircraft including wide-body craft, and delivering 40,000 lb thrust and over 189 kN; (2) intermediate engines delivering 15,000 to 30,000 lb thrust, or 65 to 135 kN; (3) small engines, including helicopter propulsion engines, delivering about 10,000 lb thrust and below 45 kN. Space parts and maintenance costs, specific thrust, endurance, overall pressure ratio, and turbine entry temperature are also considered as criteria for comparisons. 76/08/00
76A47847

An economico-mathematical model based on relative criteria of cost effectiveness is used to provide an optimal scheme for the production of aircraft engines. The model, which incorporates the finishing stage and the beginning of mass production, would greatly decrease production time, lead to somewhat increased production costs, decrease prices in the long run after short term increases due to increased production costs, and increase service life. 73/00/00 76A20142

UTTL: Design and development for maximum reliability and minimum maintenance costs
A/GRIGG, R. E. PAA: A/(Hawker Siddeley Aviation, Ltd., Hatfield, Herts., England) In: Symposium on the Changing Balance of Design Requirements and How Designers are Reacting to It, London, England, February 26, 1975, Proceedings. (A76-15401 04-01) London, Royal Aeronautical Society, 1975. 20 p.
The paper examines some design aspects which must be considered when the design criteria are maximum reliability and minimum maintenance costs for modern subsonic transport aircraft. Structure design and development to improve reliability and reduce costs and weight should progress parallel with requirements to improve safety levels and structural endurance. Main lines to follow would be to simplify load paths to avoid diffusion problems which are difficult to analyze, minimize the number of stress concentration areas by reducing cutouts and joints, and working to generally lower allowable stress levels. The design aim as far as system design is concerned is to enable the aircraft to complete its scheduled flight after a single failure has occurred without requiring any immediate crew action. New technology should only be used where a significant improvement is forseen that will bring real benefits, not problems. Later types of fire detection systems, such as pneumatic loops, would be more reliable and less costly than the double electronic redundant system and would have delay rates at least as good. Continuous monitor built-in test equipment has the advantage that faults are detected and displayed under actual operating conditions. 75/00/00 76A15402

UTTL: Engine life cycle cost considerations during the validation phase
A/GIBSON, J. D. S.; B/COLLINS, D. E.; C/CONLEY, C. A. PAA: C/(USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio) American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 11th, Anaheim, '

UTTL: Apsicost - Model and method for turbine engine design to life cycle cost
A/WAGNER, W. Q.; B/PHEATT, C. B. PAA: B/(Teledyne CAE, Toledo, Ohio) American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 12th, Palo Alto, Calif., July 26-29, 1976. AIAA 7 p.
An engineering method has been developed to facilitate designing propulsion turbine engines to achieve life cycle cost objectives. The approach includes a computerized model, which structures the contribution of each engine design discipline. The analytical technique consists of establishing a baseline life cycle cost, derived from aircraft mission, performance and deployment definition. Design iterations are then evaluated for cost-benefit impact with respect to the baseline. A hypothetical aircraft and engine program is evaluated to illustrate the course of an analysis which encompasses the conventional and aircraft related costs of propulsion engine ownership. AIAA PAPER 76-750 76/07/00 76A38247

UTTL: Cost effective designs - The challenge posed to the metallurgist and structural engineer
A/WEIBLEN, W. A. PAA: A/(United Technologies Corp., Pratt and Whitney Aircraft Div., East Hartford, Conn.) In: Structures, Structural Dynamics, and Materials Conference, 17th, King of Prussia, Pa., May 5-7, 1976. Proceedings. (A76-30004 13-39) New York, American Institute of Aeronautics and Astronautics, Inc., 1976. p. 577-584.
The paper discusses the significance of cost effectiveness for the technical specialist, examining factors limiting cost effectiveness and studying the desired interrelationships and flow of economical and technical communications between the technical specialist and groups such as management, design assurance, and the design engineer. Some areas of development demonstrating a positive impact on cost effectiveness in aircraft gas turbine technology are indicated, including fracture mechanics, computer-aided design, directional solidification, fine-grained alloys, hot isostatic pressing, isothermal forging, gatorizing, and holography. 76/00/00 76A30061

UTTL: Optimal relations between the final design stage and the initial mass production of aircraft engines
A/GAZIZOV, R. M. In: Aspects of economics and production management in mechanical engineering. (A76-20138 07-83) Kazan, Kazanskii Aviatsionnyi Institut, 1973. p. 17-20. In Russian.

Calif., Sept. 29-Oct. 1, 1975. AIAA 11 p.
The current status of aircraft engine life cycle cost
methods in the context of Department of Defense
development and acquisition programs is reviewed.
Important validation phase life cycle costing
activities are discussed, and some cost prediction and
model development programs are outlined. Related
government-industry interface activities in the
validation phase are discussed.
AIAA PAPER 75-1289   75/09/00   76A10279

UTTL: A parametric determination of transport aircraft
price
A/ANDERSON, J. L.   PAA: A/(NASA. Ames Research
Center, Moffett Field, Calif.)   Society of Allied
Weight Engineers, Annual Conference, 34th, Seattle,
Wash., May 5-7, 1975.   35 p.
Cost per unit weight and other airframe and engine
cost relations are given. Power equations representing
these relations are presented for six airplane groups:
general aircraft, turboprop transports, small jet
transports, conventional jet transports, wide-body
transports, supersonic transports, and for
reciprocating, turboshaft, and turbothrust engines.
Market prices calculated for a number of aircraft by
use of the equations together with the aircraft
characteristics are in reasonably good agreement with
actual prices. Such price analyses are of value in the
assessment of new aircraft devices and designs and
potential research and development programs.
SAWE PAPER 1071   75/05/00   75A47501

UTTL: The challenge of weight and balance control and
design-to-cost for YC-14 prototype development
A/HUTTON, J. G.   PAA: A/(Boeing Aerospace Co.,
Seattle, Wash.)   Society of Allied Weight Engineers,
Annual Conference, 34th, Seattle, Wash., May 5-7,
1975.   16 p.
Development of the Boeing YC-14 STOL aircraft to meet
program goals of airlift capability of a 27,000 lb
payload in and out of a 2000 ft. undeveloped field
and a 400 nmi radius of operation is discussed. Design
characteristics of the aircraft, including engine
placement, flight control system, and empennage are
given. The design-to-cost approach in each of the
major components of the YC-14 prototype (propulsion
system, wing, empennage, and fuselage) is detailed,
and the design work package team concept for rapid
dissemination of accurate information early in the
design process, is discussed. Problems of planning for
weight and balance control are considered.
SAWE PAPER 1056   75/05/00   75A47491

UTTL: Logistics management of F100 engine through
operational introduction
A/CALLEN, R. L.; B/BAHAN, T. E.; C/JOHNSON, E. A.,
JR.   PAA: A/(United Technologies Corp., Pratt and
Whitney Aircraft Div., West Palm Beach, Fla.);
C/(USAF, Aeronautical Systems Div., Wright-Patterson
AFB, Ohio)   American Institute of Aeronautics and
Astronautics and Society of Automotive Engineers,
Propulsion Conference, 11th, Anaheim, Calif., Sept
29-Oct. 1, 1975. AIAA   8 p.
The F100 represents a significant advance in terms of
improved thrust-to-weight ratio that is so important
to a fighter application. Attention is given to the
engine development status at the time of the flight
test, the flight test plan, procedures and tools used
to plan and control the program, the organization for
complete support of the aircraft engine system, and
the procedures used to implement the program.
Questions of F-16 support as related to life cycle
cost are examined and the objectives of the component
improvement program are discussed.
AIAA PAPER 75-1291   75/09/00   75A45679

UTTL: Engine life cycle cost modeling in the
conceptual phase
A/CURRY, C. E.   PAA: A/(General Motors Corp., Detroit
Diesel Allison Div., Indianapolis, Ind.)   American
Institute of Aeronautics and Astronautics and Society
of Automotive Engineers, Propulsion Conference, 11th,
Anaheim, Calif., Sept. 29-Oct. 1, 1975. AIAA   8 p.
DOD requirements are considered and a typical
functional system flow is shown. Once the systems
requirement is established, design teams develop a
concept to answer the stated operational need. This
concept generally includes a mission analysis,
performance characteristics, and a schedule interface.
A program example is presented, taking into account a
turboshaft engine, which powers the Army Heavy Lift
Helicopter. The example illustrates the depth of
information that must be considered and made available
to the designer early in the concept phase of the
product life cycle.
AIAA PAPER 75-1288   75/09/00   75A45678

UTTL: Engine life cycle cost - A laboratory view
A/PANELLA, R. F.   PAA: A/(USAF, Aero Propulsion
Laboratory, Wright-Patterson AFB, Ohio)   American
Institute of Aeronautics and Astronautics and Society
of Automotive Engineers, Propulsion Conference, 11th,
Anaheim, Calif., Sept. 29-Oct. 1, 1975. AIAA   4 p.
The engine related cost throughout the life cycle of
the aircraft weapon system is addressed. The cost

UTTL: A brief look at engine installations for future naval aircraft
A/GAERTNER, R. M. PAA: A/(U.S. Naval Air Systems Command, Washington, D.C.) Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, San Diego, Calif., Oct. 1-3, 1974. 11 p.
This paper discusses various engine installations in naval aircraft, looking especially at their costs of maintenance. Fuel systems, fuel control systems, and several engine accessories are discussed for present and future engines. It is concluded that simple, reliable equipment is necessary to keep aircraft in the air instead of in maintenance areas on the ground.
SAE PAPER 740881   74/10/00   75A16924

UTTL: Teledyne aims at low-cost engines
A/YAFFEE, M. L.   Aviation Week and Space Technology, vol. 101, Nov. 11, 1974, p. 55, 57, 58.
The Teledyne CAE/Navy J402-CA-400 turbojet, selected as the cruise engine for the McDonnell Douglas Harpoon anti-ship missile, has been designed for high reliability at low cost. It is an expendable engine that uses low-cost castings generally in the as-cast condition. Materials and manufacturing methods were dictated by the need for low cost and five-year storage life in a marine environment. Regardless of launching mode, the Harpoon is designed to fly at sea level at a cruise speed of Mach 0.85. The missile is boosted to cruise speed by a solid propellant rocket motor in the case of a surface or subsurface launch. The J402 turbojet is programmed to start after the missile is boosted to cruise speed.   74/11/11   75A12722

UTTL: Reliability and maintainability of aircraft jet engines. II
A/MIHAIL, A.   PAA: A/(Centre de Documentation de l'Armement, Bureau Veritas, Paris, France)   AFCIQ, Bulletin, vol. 10, Sept. 1974, p. 12-19. In French.
The present work discusses some of the economic considerations, in terms of both time and cost, of approaches to continuous jet engine condition monitoring. A manual approach consists in having the crew itself make rough calculations of the deviation of engine condition from a standard on the basis of in-flight readings. This system is simple and has the advantage of being conducted in real time. Its disadvantages lie in that it is not exactly continuous, is difficult for a two-man crew, and requires additional ability of the crew members to interpret the results. An operational approach

associated with each phase (development, acquisition and operational) of the engine life cycle is investigated from a laboratory viewpoint. In the development phase, a significant part of the engine related cost is for hardware; and factors driving hardware cost are identified. Acquisition cost can be a major portion of life cycle cost, and techniques for estimating and controlling engine acquisition costs are explored. The cost associated with the operating and support phase is examined, and certain elements influencing this cost are identified.
AIAA PAPER 75-1287   75/09/00   75A45677

UTTL: Powerplants for wide-bodied aircraft - What we bought and what we got
A/GOODWINE, J. K.   PAA: A/(United Air Lines, Inc., San Francisco, Calif.)   American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Propulsion Conference, 11th, Anaheim, Calif., Sept. 29-Oct. 1, 1975. AIAA 6 p.
The wide-bodied aircraft era, with a new generation of high-bypass ratio propulsion engines, arrived in the early 70's full of promise of ever lower engine operating costs. Now, several years and billions of passenger miles later, we can look back at what we obtained relative to what we thought we bought. This paper reviews the factors which determine engine operating costs: i.e., performance margin, durability, dispatch reliability, and ease of maintenance, and compares one airline's actual experience with their expectations.
AIAA PAPER 75-1204   75/09/00   75A45628

UTTL: Engine maintenance cost reduction through improved component design and development
A/CRAVENS, C. T.; B/FLICKINGER, R. W.; C/MURPHY, R. M.   PAA: C/(Boeing Co., Seattle, Wash.)   Society of Automotive Engineers, Air Transportation Meeting, Hartford, Conn., May 6-8, 1975. 8 p.
High maintenance costs of the three 40,000 lb. thrust class aircraft engines manufactured by Pratt and Whitney, General Electric, and Rolls-Royce are discussed. Primary emphasis is on existing engine problems which contribute to high shop visit rate. Maintenance cost in terms of monetary value is not discussed. It is concluded that increased emphasis on total life cycle durability is necessary by the engine manufacturers. It is recommended that a higher level of priority be given durability in design and analysis, pre-production proof-of-design testing, and engine program management.
SAE PAPER 750621   75/05/00   75A40525

consists in recording of data for ground processing by computer. This permits more exact evaluation but not in real time. It is also more costly. 74/09/00
75A12125

UTTL: An inexpensive jet engine, dream or reality
A/FAURY, MR. PAA: A/(Societe d'Innovation et de Developpement en Aerothermodynamique, Toulouse, France) L'Aeronautique et l'Astronautique, no. 47, 1974, p. 82-84. In French.
Discussion of the development of an expendable, short-lived jet engine of utmost design simplicity and suitable for mass production by processes of moderate tooling requirements, intended for the propulsion of remotely piloted vehicles for ground or sea attack, reconnaissance, illumination, decoy, interference, and target practice missions. A brief description of the French TRI 60 jet engine is presented. 74/00/00
75A11724

UTTL: Engine systems ownership cost reduction - aircraft propulsion subsystems integration (APSI)
A/WAGNER, W.; B/GABRYS, A.   CORP: Teledyne CAE, Toledo, Ohio.   AFAPL
AD-A030788 TCAE-1467-VOL-2 AFAPL-TR-75-100-VOL-2
75/08/00 77N76899

UTTL: Proceedings of OSD Aircraft Engine Design and Life Cycle Cost Seminar
A/DIENEMANN, P. F.; B/BIRKLER, J.; C/PRESSMAN, A.
CORP: Naval Air Development Center, Warminster, Pa.
Proc. held at Warminster, Pa., 19-21 Nov. 1975
AD-A030548 75/11/00 77N75472

UTTL: Relating technology to acquisition costs.
Aircraft turbine engines
A/NELSON, J. R.; B/TIMSON, F. S.   CORP: RAND Corp., Santa Monica, Calif.
AD-780636 R-1288-PR   74/03/00   75N76248

UTTL: Ti/Al design/cost trade-off analysis
A/HOLOWACH, J.; B/REDDEN, T. K.   CORP: General Electric Co., Cincinnati, Ohio.   CSS: (Aircraft Engine Group.)
A new class of alloys based on intermetallic compounds in the titanium aluminum system has shown the potential for application in the temperature range of 1000-1700 F. This program was undertaken to investigate the type of application and payoff that

would result. Two titanium aluminum alloys were looked at, the Ti3Al (alpha two) and TiAl (gama). The use of TiAl was restricted to static components, whereas Ti3Al was limited to dynamic components. The dynamic application selected was a compressor and turbine blade. The static application was a mixing duct and exhaust duct liner. Cost of the selected titanium aluminides components was compared with the current cost of the nickel-base-superalloy components. The results show a cost increase for all the components. A detailed structural analysis of the four components shows the substitution would lead to longer life components. This substitution would result in not only a weight reduction in the engines, but a reduced fuel load and structure weight for a similar mission with the same bomb load, avionics, and other fixed equipment. An estimated $41.6 million dollars cost saving would result based on 240 aircraft for 20 years.
AD-A064693 R78AEG534 AFAPL-TR-78-74   78/10/00
79N22283

UTTL: Low cost expendable engine
A/HUBEN, C. A.; B/METSKER, B. L.   CORP: Williams Research Corp., Walled Lake, Mich.   AFAPL
A low cost expendable turbojet engine in the 200 pound thrust class was fabricated and tested. The design, manufacturing, and inspection concepts of the program resulted in the achievement of a projected engine cost of $2883 each in lots of 1000 engines in terms of 1975 economics. Problems solved during the compressor rig testing and engine tune-up testing are discussed. The results of the engine demonstration testing both at sea level static conditions and under a simulated Mn 0.7 condition are presented.
AD-A062864 AFAPL-TR-78-33   78/03/00   79N20125

UTTL: Study of the turbine engine industry
A/GRISSMER, D. W.; B/KIM, K. H.   CORP: Mathtech, Inc., Bethesda, Md.
This report provides a summary and analysis of original data from seven major US aircraft engine manufacturers over a time period 1960-75. Analysis of large and small engine production, surge capacity, costs, productivity, and industry structure was made and compared with historical trends and the use of econometric models. Emphasis was placed on the lead times, shortages, and roles of subcontractors. component availability, and materials.
AD-A055895 REPT-7050-DG-KK-78-FR-1-DOD   78/01/31
78N32103

UTTL: Technical evaluation report on the 49th(B) Propulsion and Energetics Specialists Meeting on Power Plant Reliability
A/SALLEE. G. P. PAA: A/(Pratt and Whitney Aircraft Group, East Hartford, Conn.) CORP: Advisory Group for Aerospace Research and Development. Paris (France). Meeting held at The Hague, 31 Mar. - 1 Apr. 1977
The following observations reflect the tone of the meeting and the major results: (1) Engine reliability is not satisfactory in either commercial or military services. In particular the newer commercial engines are not living up to operators expectations. (2) It seems that civil and military authorities are considering the promulgation of more stringent requirements and standards concerning the development, certification/qualification and acquisition of future engines with respect to the reliability requirements that must be met. (3) Manufacturers are designing for improved maintainability and employing improved testing techniques to expose problems early. Further progress is contingent on the availability of engineering data on actual engine usage in military service. Detailed part failure data is needed to determine the causes for part failure with respect to usage and the relationships that exist between the various modes of failure. (4) The economic impact of military engine unreliability has not been discussed. The cost consequences of premature engine removals, aborts, part failures, etc., are needed to establish the role of engine reliability in engine life cycle cost. (5) The growth of engine health monitoring in the commercial airlines and the increased experimentation of such approaches in the military are indicative of the serious consequences of poor engine reliability. The future growth/potential for such techniques is impressive.
AGARD-AR-110 ISBN-92-835-0207-8 AD-A048081 77/11/00 78N14048

UTTL: An identification and characterization of cost models/techniques used by Air Force Logistics Command to estimate jet engine operation and support costs
A/DAVIDSON. G. H.; B/GRIFFITHS. R. E. CORP: Air Force Inst. of Tech., Wright-Patterson AFB, Ohio.
CSS: (School of Systems and Logistics.)
The Life Cycle Cost (LCC) for jet engines includes the cost of design and development, test and evaluation, production, operation and support, and where applicable, disposal. Although only a small portion of the total LCC is incurred prior to production, the decisions made up to that point determine most of the total engine LCC. It is during this early design phase

UTTL: Study of a compromise between the complexity of a rocket engine and its cost
A/CHEVALIER.J. F. CORP: Societe Nationale d'Etudes et de Construction de Moteurs d'Aviation. Moissy-Cramayel (France). In AGARD Fighter Aircraft Design 8 p (SEE N78-30099 21-05)
The cost of an aircraft is often related to takeoff weight or the complexity of the engine. The performance of the engine can reduce the weight of the aircraft and also the cost of the entire aircraft. These two aspects are discussed in detail. Aircraft weight and costs were calculated and the following missions were analyzed: (1) low altitude penetration: (2) tactical support; (3) aerial superiority; and (4) interception. 78/06/00 78N30112

UTTL: Life cost management, methodology, and case studies
A/BERARD. A. H. CORP: Defense Systems Management School. Fort Belvoir, Va.
This study project examines the management policies that have initiated O and S costing methodology. Costing progress made on O and S cost control and the guidelines prepared by LMI are summarized to provide the reader with an overview of the guidelines content and a preview of CAIG O and S costing methodology guidelines. The RAND report on LCC analysis for aircraft turbine engines provides analysis methods that allows performance to be assessed with the present technology and determines cost and schedule risks. Further, commercial operational and maintenance practices are reviewed for military applicability. Three case studies representative of LCC management techniques are discussed in detail showing the impact of logistics alternatives, reliability by design, and maintainability features that contribute towards reduced O and S costs and lower LCC. The cases were selected from a LCC Seminar held on 29 Sept. 1977. The Army's Black Hawk program, Navy's F-18 program, and the Air Force's ARC-164 program are the three case studies selected. Important lessons learned on all three c the case studies should serve as models for other programs to follow that are concerned with LCC procurement. The results of the case studies provide positive indications that LCC management does work and can provide affordable systems.
AD-A052388 77/10/00 78N24999

that there is insufficient operational information on the new engine to permit prediction of costs incurred during the operation and support phase of LCC. Estimation of LCC is further hindered by the absence of knowledge about techniques which could be used during engine design. This research involved a systematic investigation of the models and techniques used by the Air Force Logistics Command to estimate jet engine operation and support cost. These models and techniques are used in the areas of requirements determination for recoverable spares, engine overhaul, and total annual support-cost estimates for recoverable items. They are characterized to allow a determination as to their applicability for use during engine design.
AD-A044083 AFIT-LSSR-01-77A 77/06/00 78N12095

UTTL: An investigation of the relationship of section production costs to total production costs of gas turbine engines
A/GREENE, J. K.; B/STARK, A. E. CORP: Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. CSS: (School of Systems and Logistics.)
The Air Force Aero Propulsion Laboratory is currently exploring techniques which may be used to estimate the production costs of gas turbine engines in the conceptual and validation phases of system acquisition. This study served as a part of that on-going exploration and was designed to investigate the relationship of engine section production costs to total production costs of gas turbine engines. The results of this research include the following findings: (1) correlation analysis provides an effective technique for determining those relationships; (2) among engine sections, costs of the high pressure turbine and compressor sections demonstrated the highest consistent correlations with total engine production cost; (3) regression analysis using the costs of high pressure turbine and compressor sections appears to hold promise for estimating total engine production cost; (4) a modification of the industrial engineering approach in which a cost estimate of the high pressure turbine section would be 'built up', and used, in turn, to estimate production costs of the complete engine also appears to hold promise; and (5) engine cost data presently collected and retained within the Air Force appear inadequate for estimating studies utilizing the production costs of engine parts, assemblies, and sections.
AD-A044172 AFIT-LSSR-34-77A 77/06/00 78N12091

UTTL: Aircraft engine design and development through lessons learned
A/KOFF, B. L. CORP: General Electric Co., Cincinnati, Ohio. CSS: (Aircraft Engine Group.) In AGARD Power Plant Reliability 11 p (SEE N77-33181 24-07)
Aircraft engine design was examined in terms of performance and reliability. Durability, maintenance, weight, initial cost and timing were also considered. It is stated that design and development are derivatives of a 'lessons learned' approach. Since materials, modern analytical and experimental techniques have progressed, so has our ability to design and develop modern aircraft. 77/08/00 77N33190

UTTL: Reliability versus cost in operating wide body jet engines
A/DEMARTEAU, S. K. W. J. CORP: KLM Royal Dutch Airlines, Amsterdam (Netherlands). In AGARD Power Plant Reliability 7 p (SEE N77-33181 24-07)
The high degree of reliability required by scheduled international airline operational and maintenance characteristics is discussed. Standards must be met in order to offer a safe but also commercially and economically justified product. A specific cost/reliability level was investigated for the General Electric CF6 engine. Reliability was found to be influenced by inherent design deficiencies, operation environment and maintenance policy. Cost consequences were dependent on airline operation, the way an airline is organized, the scale of operation and airline standards.
77/08/00 77N33186

UTTL: Power plant reliability CORP: Advisory Group for Aeronautical Research and Development, Paris (France). Presented at the 49th Meeting of the AGARD Propulsion and Energetics Panel, The Hague, 31 Mar. - 1 Apr. 1977
AGARD-CP-215 ISBN-92-835-0198-5 AD-A045678 77/08/00 77N33181

UTTL: A methodology for estimating jet engine costs early in weapon system acquisition
A/YANKE, M. A. CORP: Air Force Contract Management Div., Kirtland AFB, N. Mex.
The Department of Defense (DOD) is deeply concerned about developing accurate initial estimates for weapon system production costs. An area of particular interest is providing estimates of future production

UTTL: Advanced supersonic propulsion system technology study, phase 2
A/ALLAN, R. D.   CORP: General Electric Co.,
Cincinnati, Ohio.   CSS: (Aircraft Engine Group.)
Variable cycle engines were identified, based on the
mixed-flow low-bypass-ratio augmented turbofan cycle,
which has shown excellent range capability in the AST
airplane. The best mixed-flow augmented turbofan
engine was selected based on range in the AST Baseline
Airplane. Selected variable cycle engine features were
added to this best conventional baseline engine, and
the Dual-Cycle VCE and Double-Bypass VCE were defined.
The conventional mixed-flow turbofan and the
Double-Bypass VCE were on the subjects of engine
preliminary design studies to determine mechanical
feasibility, confirm weight and dimensional estimates.
a-, identify the necessary technology considered not
yet available. Critical engine components were studied
and incorporated into the variable cycle engine
design.
NASA-CR-134913 R75AEG508   75/12/00   76N14129

UTTL: Engine health monitoring in a civil airline
A/WALLER, P.; B/WHITE, E. R.   CORP: British Airways,
Middlesex (England).   In AGARD Diagnostics and
Engine Condition Monitoring 14 p (SEE N75-31083
22-07)
The operational effects of prematurely failed engines
are reviewed with estimated economic effects. The
estimated return from an engine health monitoring
system is considered in relationship to the cost of
implementing and running it, and it is shown that a
positive financial return is only likely if the basic
data acquisition and analysis equipments are readily
available for other purposes. The theoretical and
experienced benefits are compared, and the limitations
imposed by operating such a system in a competitive
commercial environment are discussed, including the
effects of stringent control over financial and
personnel resources. The results achieved so far are
critically examined in terms of the equipment design
specifications and actual performance, and also the
mathematical processes employed in reducing the data.
Some of the deficiencies in these processes are
discussed, with proposals for their improvement. The
characteristics of the RB211 engines for BAED's next
aircraft, the TriStar, as relevant to engine health
monitoring, are examined in relationship to the
recording system to be fitted, which includes a small
but powerful computer with an input/output device for
communicating with the flight crew.   75/06/00
75N31106

costs for jet engines. Current parametric models used
by the Air Force identify engine cost as a function of
output variables. Other DOD agencies consider relating
input variables as well as output variables to
production costs. This study was designed to find a
better way to estimate engine production costs. The
results of this research include the following
findings: (1) current Air Force cost-estimating models
are operationally ineffective; (2) raw
materials-related variables are highly correlated with
cost and should be considered in developing future
cost-estimation models; (3) statistical validation of
cost models should incorporate confidence interval
testing at a specified alpha level for each
prediction; and (4) the use of confidence intervals is
the correct statistical approach for developing cost
estimates which may be used in decision making.
AD-A033667   76/08/01   77N25001

UTTL: Phase 2 of feasibility study of initial aircraft
propulsion subsystem integration cost model, part 2
A/DRAKE, J. W.; B/REDA, M. R.; C/ALLEN, J. J., JR.
CORP: Purdue Univ., Lafayette, Ind.   CSS: (School of
Aeronautics, Astronautics and Engineering.)
This report describes two methods of estimating the
production costs of jet engines not yet built: (1) by
building up the costs of the 'cost driving' parts in a
traditional Industrial Engineering fashion; and (2) by
using regression techniques to estimate either entire
engine costs (RAND approach) or parts of engines. The
report concludes that both methods are feasible though
the former has a greater theoretical accuracy.
Potential problems of accounting for changes in
performance and schedule may well give the second
method the edge in practical application on the bases
of cost, speed and speed of implementation.
AD-A021083 REPT-75-2-PT-2 AFAPL-TR-75-88-PT-2
75/10/00   76N29237

UTTL: Heavy lift helicopter engine development program
design to cost. 2nd period award fee evaluation report
A/FABER, C. W.   CORP: Army Aviation Systems Command,
St. Louis, Mo.
During development of a 8079 shaft horsepower gas
turbine engine, the contractor performed an extensive
design to cost effort under an award fee provision.
This report summarizes the government's evaluation of
this effort and includes a description of the
contractor's design to cost policy and procedures.
AD-A016120 USAAVSCOM-TR-75-41   75/08/00   76N18135

UTTL: Diagnostics and engine condition monitoring
A/FUHS, A. E.   CORP: Naval Postgraduate School,
Monterey, Calif.   CSS: (Dept. of Aeronautics.)   In
AGARD Diagnostics and Engine Condition Monitoring 18
p (SEE N75-31083 22-07)
Diagnostics and aircraft engine condition monitoring
by computer are examined. Data cover computer costs,
electronic reliability, prediction of impending engine
malfunctions, engine control, and other instruments
and data needed for computer operation.   75/06/00
75N31084

UTTL: Joint generalized least squares applied to cost
estimation for fighter aircraft
A/OBRIEN, P. W.   CORP: Air Force Inst. of Tech.,
Wright-Patterson AFB, Ohio.   CSS: (School of
Engineering.)
Joint Generalized Least Squares is an extension of
least squares techniques which decreases statistical
uncertainty in derived regression equations.   The
technique is applied to historical costs for
airframes, avionics, and engines in fighter aircraft.
A comparison is made of parametric cost estimating
relationships derived using ordinary and Joint
Generalized Least Squares to demonstrate reductions in
statistical uncertainty.
AD-A003354 GSA/SM/74D-7   74/12/00   75N21275

UTTL: Problems in managing the development of aircraft
engines   CORP: Comptroller General of the United
States, Washington, D.C.
The method traditionally followed by the military in
developing and acquiring aircraft engines is evaluated
in terms of its cost effectiveness. Evidence is
presented that aircraft engines require further
development of capability, performance and endurance
beyond that needed to pass the model qualification
test. The budgeting and financing of the component
improvement program is detailed. Revisions of the
presently used methods are proposed.
B-179166   74/05/23   75N17226

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14. Abstract

This Lecture Series No.107 is sponsored by the Propulsion and Energetics.Panel of AGARD
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All of the NATO nations are faced with a major concern for the growing cost of defence and
the need to ensure that cost and performance are optimized. The requirements and related
costs of weapon systems have come under close examination. The entire life cycle of a
weapon system and its subsystems must be examined. The cost of design and development
must now include not only the cost of production but also deployment, training, operational
use, and support. The use of new technology and new management techniques are essential
to obtaining the most for the available money.

The purpose of this Lecture Series is to examine the latest methodologies of cost/performance
comparison and trade-offs for aircraft engines. Information will include data collection,
analysis, modelling and estimating all development and operations costs. Also addressed will
be contractual provisions and the costs related to incentives for performance and reliability.
The latest applications in both government and industry will be covered, with examples and
experiences from the military and civilian sectors.

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