Setting Design Goals for Advanced Propulsion Systems

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Significant reduction in the life cycle cost (LCC) of advanced weapon systems can be achieved without sacrificing combat capability by setting design goals for propulsion system "ilities" that are balanced with the traditionally emphasized performance goals. This design philosophy was evaluated as an integral objective of the Advanced Technology Engine Studies (ATES) program under joint U.S. Navy/Air Force cognizance. This paper documents the methodology and results of ATES program conceptual design studies that set balanced cost-effective propulsion system design goals for durability, reliability, maintainability, and operability for several advanced aircraft weapon systems.

Introduction

DURING the past two decades, the life cycle cost of aircraft weapon systems has increased dramatically. This cost escalation, together with funding limitations, makes it difficult for the United States military services to replace aircraft lost through attrition or to introduce new systems. Clearly, the challenge in the design and development of future propulsion systems is to provide for superior performance weapon systems, while at the same time reducing their life cycle cost.

In response to this challenge, the Advanced Technology Engine Studies (ATES) program is a currently ongoing 18-month study effort tasked to identify cost-effective design and development philosophies for advanced propulsion systems and to reflect these philosophies in a long-range propulsion plan. The program is under joint U.S. Navy/Air Force cognizance. Pratt & Whitney Aircraft (P&WA) is a prime contractor in this program for the study of propulsion system requirements for 11 advanced aircraft weapon systems. The P&WA study encompasses a wide range of potential applications, including advanced fighters, subsonic bombers, transports, and subsonic and supersonic V/STOLs. To properly assess the propulsion system impacts upon each aircraft weapon system, P&WA has subcontracted to four major airframe companies: The Boeing Company, Grumman Aerospace Corporation, McDonnell Aircraft Company, and the Vought Corporation.

Aircraft takeoff gross weight (TOGW) typically has been the figure of merit for evaluating previous weapon systems, largely because it is representative of airframe related development, acquisition, and support costs. In this competitive environment, engine manufacturers have placed emphasis on maximizing engine performance to minimize TOGW while placing less emphasis on the engine "ilities." As a result, engine maintenance costs have escalated and have contributed to the elevated life cycle cost of today's weapon systems.

As an integral objective of the ATES program, an advanced design philosophy was applied whereby goals for the engine ilities are established during the conceptual design phase of propulsion system development. Balancing these ilities goals with the traditional engine performance criteria should result in minimum overall weapon system cost of ownership. P&WA developed and applied this conceptual design methodology to identify cost-effective design goals for the engine ilities.

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While the evaluation of all of the many aspects of the engine ilities was beyond the scope of the ATES program, P&WA investigated cost-effective goals for key aspects of the following engine ilities: 1) durability—design life goals for life-limited hot and cold-section parts; 2) reliability—goals for scheduled inspection intervals and engine control redundancy requirements; 3) maintainability—engine design and monitoring features offering potential for reducing maintenance; and 4) operability—stall margin design goals.

Before discussing the methodology employed, it should be noted that weapon system life cycle cost is the primary figure of merit for the ATES program design studies. As shown in Fig. 1, weapon system life cycle cost is the sum of the RDT&E, acquisition, operational, and support costs of the airframe, engines, and avionics. Weapon system LCC is a valuable figure of merit because 1) it accounts for the total cost of a weapon system from program initiation through retirement, and 2) it provides a common denominator for the evaluation of many dissimilar aspects of propulsion system costs for design, development, acquisition, and operation. Life cycle costs projected by P&WA incorporate the costs of weapon systems physically sized and force structured to design combat mission requirements while operating in a peacetime environment.

Methodology

To set design goals for engine ilities that are cost effectively balanced with performance levels, P&WA developed and utilized a methodology that employed design trade studies as depicted on Fig. 2.

Baseline conceptual designs of four advanced engines, representative of the wide range of propulsion system requirements under study, were defined. These included the design of an advanced fighter, bomber, transport, and supersonic V/STOL engine. These baseline designs were

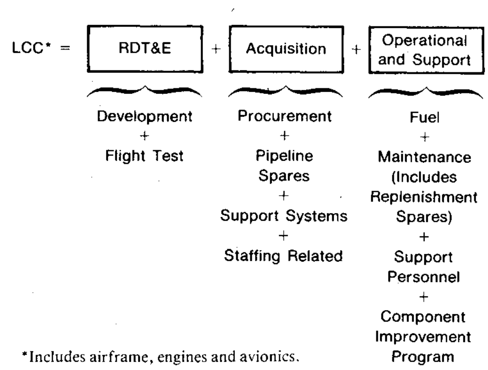

Fig. 1 Life cycle cost is a valuable figure of merit.

Table 1 **Fighter engine design baseline and alternative ilities goals**

Design concept	Baseline goals	Alternative goals
Durability		
Hot part design life	½ airfame life	¼ and full airframe life
Cold part design life	Full airframe life	½ and twice airframe life
Reliability		
Schedule inspections	Three per airframe life	Two and four per airframe life
Engine control redundancy	Fully redundant electronics, hydraulics, and fuel	Fully redundant electronics with single channel hydraulics and fuel
Maintainability		
Engine configuration	Fully modular	Limited modularity
Installed engine access	Partial access	Complete access
Engine monitoring system	Integrated with control	Separate engine multiplexer (EMUX)
Flight line engine checks	Electronic centralized display	Electro-mechanical indicators
Hot-section access	Conventional combustor case	Telescoping combustor cases
Borescope inspections	Conventional ports	Rapid access fiber optics
Operability		
Stall margin for low pressure compressor	30%	10, 15, and 20%

Table 2 **Fighter engine duty cycle summary for full airfame life**

Flight hours	4,500
Total hours	7,200
Type I cycles[a]	4,000
Type III cycles[b]	35,000
Partial throttle transients[c]	13,000
Total time at intermediate and above, hours	500
Augmented time, hours	310
Lifetime	
Years	15
EFH/year	300

[a]Engine start-intermediate-shutdown cycle. [b]Engine idle-intermediate-idle cycle. [c]Engine 40-90-40% intermediate cycle.

established about engine size and cycle definitions obtained from ATES program weapon system optimization studies and incorporated a level of technology consistent with mid-1980s availability for full-scale development. The derived designs incorporated baseline design criteria for the engine ilities and projected peacetime duty cycle requirements. The ilities criteria and duty cycle requirements for the advanced fighter engine design are summarized on Tables 1 and 2.

The primary engine design characteristics which influence weapon system LCC were next ascertained from the baseline engine designs. These characteristics include engine thrust and total specific fuel consumption (TSFC) levels, weight, diameter, length, and engine RDT&E, acquisition, operational, and support costs. Generic comparative costing techniques were utilized to derive baseline levels of acquisition

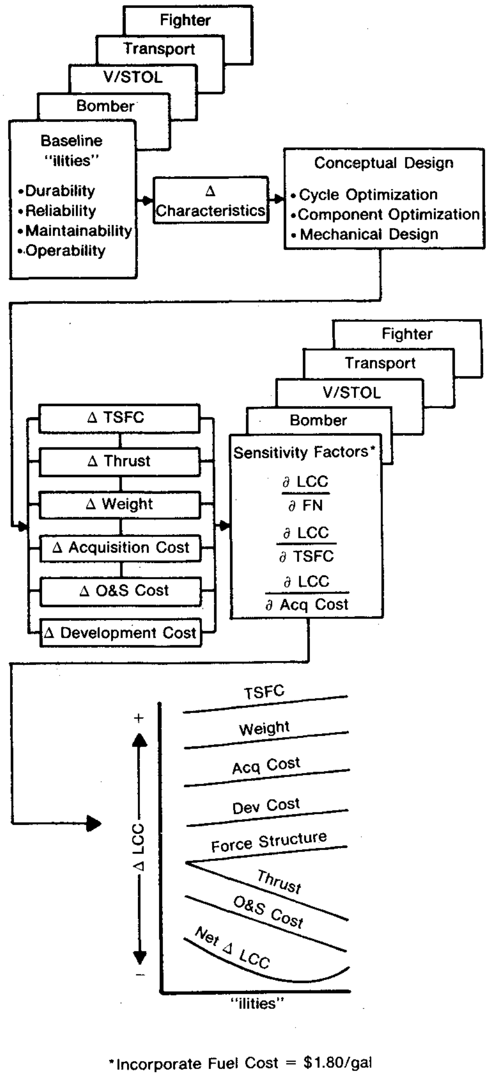

Fig. 2 ATES methodology analyzes the propulsion system impact upon weapon system LCC.

cost while historically derived cost-estimating relationships were utilized to project RDT&E and CIP costs. Detailed cost accounting techniques were used by the P&WA maintenance simulator to project engine maintenance costs. This simulator uses Weibull input for up to 400 engine part removal causes to project engine maintenance cost levels.

With the baseline design defined, the design criteria for the engine ilities were each varied from their baseline level to their alternative goals, which also are summarized for the fighter engine design on Table 1. Figure 2 shows that for each alternative goal, the conceptual design methodology and the previously described cost methodologies were applied to define the impact of the alternative selections upon the primary design characteristics which influence weapon system LCC. These impacts were evaluated with each alternative engine design resized to achieve minimum thrust requirements which allow combat mission requirements to be maintained. Further, required modification to the weapon system force structure to maintain a constant sortie rate capability also was projected for each alternative ilities design goal. Thus, full combat capabilities were maintained for each alternative ilities goal studied.

The ATES program weapon system optimization studies defined sensitivity factors for each weapon system which relate changes in the primary engine design characteristics and force structure requirements to their resultant influence on weapon system LCC. The sensitivity factors reflect the total impact on weapon system RDT&E, acquisition, and O&S

costs and hence incorporate the influence of required aircraft/engine size and fuel usage alterations. These sensitivity factors were applied to the defined engine design and force structure impacts at each alternative ilities goal. The resultant weapon system LCC increments were then summed to achieve the total weapon system LCC impact at each alternative goal. Finally, by comparing the LCC impact between the baseline and the alternative goals, cost-effective ilities design goals were identified for each of the four representative advanced engines.

Results

The ATES design trade studies have shown that significant reduction in the cost of ownership may be achieved by an appropriate setting of design goals for the engine ilities which are balanced with traditional performance criteria. While the cost-effective ilities design goals for a representative advanced fighter, bomber, transport, and supersonic V/STOL engine have been identified, the detailed results presented by this paper are limited, for brevity, to those achieved for a representative advanced fighter engine.

Durability

The ATES advanced fighter engine design life trade studies have identified ½ airframe life as the most cost-effective design goal for hot-section components (e.g., turbine airfoils). The weapon system LCC associated with this design goal relative to alternative selections is shown on Fig. 3. At design life selections less than ½ airframe life, the required increase in maintenance man-hours, pipeline and replenishment spares, and force structure overpower the benefits of improved engine performance (from reduced turbine cooling air) for a resultant net penalty to weapon system LCC. Note that the benefits of improved engine performance were accounted for via the weapon system sensitivity factors and include allowed reduction in aircraft/engine size and fuel requirements. At design life selections greater than ½ airframe life, the influence of degraded engine performance (from increased turbine cooling air) was dominant with, again, net penalty to LCC. Hence, ½ airframe life represents the design goal for hot-section design life that is balanced with performance to achieve minimum weapon system LCC.

Full airframe life was identified as the design life goal for cold-section components (e.g., engine disks) that are balanced with performance to achieve minimum weapon system LCC, as shown on Fig. 4. At design life selections less than full airframe life, the required increase in engine maintenance cost overpowers the influence of improved engine thrust/weight and reduced engine acquisition cost (accompanying allowed reduction in disk weight and cost) for a net penalty to weapon system LCC. At design life selections greater than full airframe life, which offer increased component structural design margin, the influence of reduced engine thrust/weight and increased engine acquisition cost is dominant with, again, a net penalty to LCC.

Reliability

The LCC comparisons for the ATES advanced fighter engine reliability concepts studied are summarized on Fig. 5. The trade studies have shown that reducing the number of scheduled inspection intervals (i.e., increasing on-condition maintenance) is cost effective. While fewer scheduled inspections result in increased unscheduled engine removals and associated costs, inspection-related costs are substantially diminished for a net weapon system LCC savings.

ATES reliability LCC studies also have shown that the redundancy for engine hydraulic and fuel units incorporated in the baseline design is not cost effective for the twin-engine advanced fighter studied. Elimination of these redundant units results in LCC savings because the associated reduced weights and costs overpower the enhanced mission reliability offered by the redundancy.

Maintainability

The LCC comparisons for the ATES maintainability concepts studied are summarized on Fig. 6. With the exception of rapid access fiber optics for borescoping, the alternative design maintenance features considered did not show significant savings relative to the concepts employed in the baseline designs.

It should be noted that, while the results of the ATES reliability and maintainability studies provide LCC substantiation for several R&M baseline design selections as well as provide valuable guidance to an improved design for

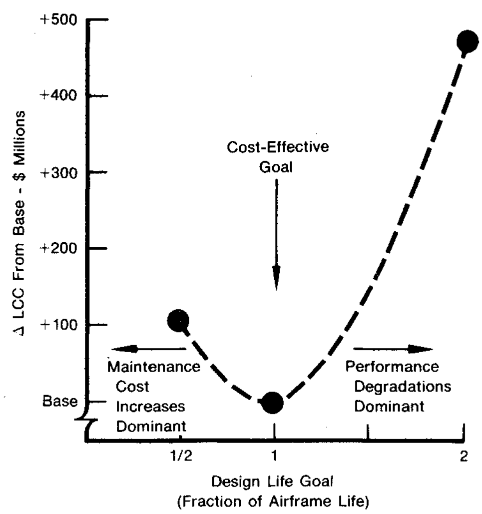

Fig. 4 Advanced fighter engine cold-section design life impact on weapon system LCC.

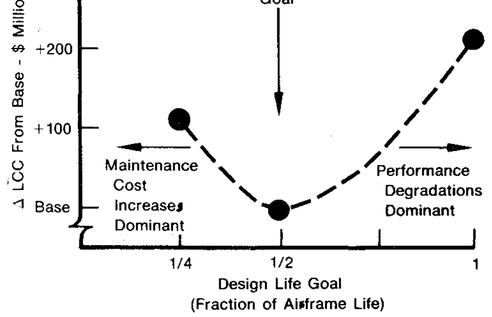

Fig. 3 Advanced fighter engine hot-section design life impact on weapon system LCC.

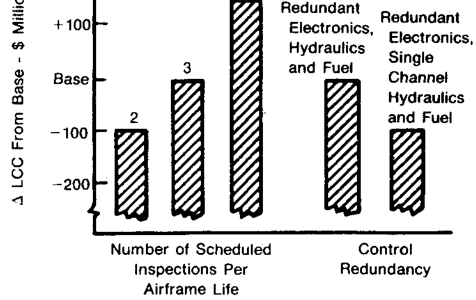

Fig. 5 Advanced fighter engine reliability goal impact on weapon system LCC.

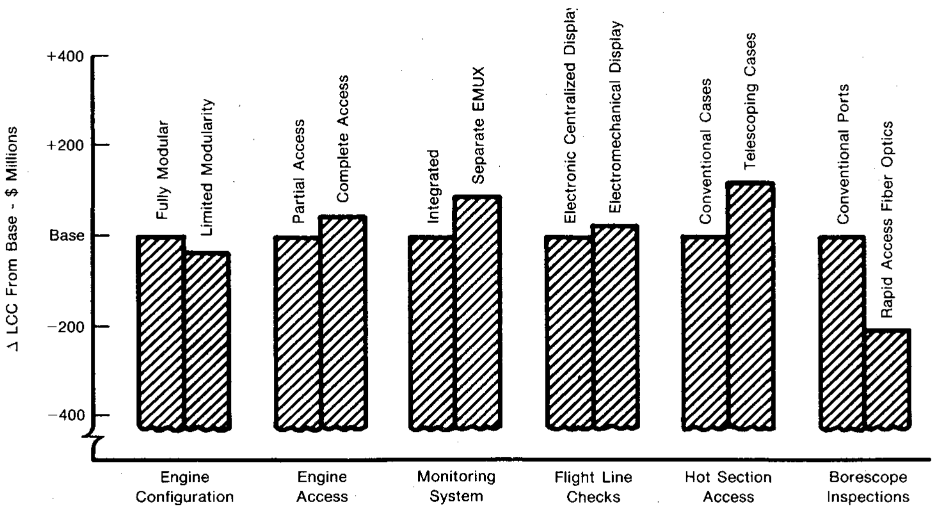

Fig. 6 Advanced fighter engine maintainability concepts impact on weapon system LCC.

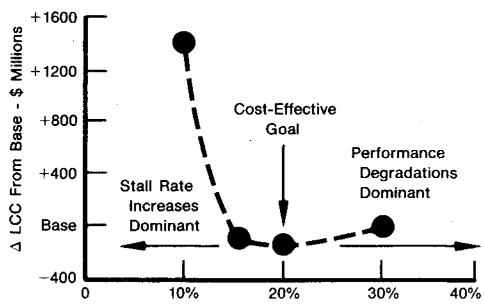

Fig. 7 Advanced fighter engine low pressure compressor stall margin impact on weapon system LCC.

advanced propulsion systems, substantially greater effort is required to more completely define cost-effective design concepts for enhanced R&M. The ATES advanced fighter engine results presented illustrate that propulsion system design and maintenance concepts can be planned and balanced to reduce the cost of ownership of advanced weapon systems.

Operability

The ATES advanced fighter engine operability trade studies have identified 20% stall margin as the design goal for the low-pressure compressor (a predominant source of engine stalls projected for advanced fighter engines) which is balanced with performance to minimize the cost of ownership as shown on Fig. 7. At stall margin selections less than 20%, the increased stall rate and associated increased force structure requirement causes a resultant net weapon system LCC penalty. At stall margin selections greater than 20%, the influence of degraded engine performance resulting from diminished low-pressure compressor efficiency is predominant with a resultant net LCC penalty.

Conclusions

Many weapon system decisions affecting the total life cycle cost of an advanced propulsion system occur during conceptual design studies and prior to the completion of the preliminary design system definition phase. If a design starts out on the wrong foot, it is difficult to fix and usually ends up being "patched" to meet requirements. With the proper setting of design goals for advanced propulsion systems, we all can get started together on the right track earlier and with superior products so necessary to maintain our excellence—for our economic well-being and for our defense posture.

A design philosophy that quantitatively considers design goals for the engine ilities balanced with engine performance criteria can significantly reduce the life cycle cost of advanced weapon systems without sacrificing combat capabilities. Future engine design and development activities should incorporate this design philosophy for advanced propulsion systems. It is recommended that the necessary dialog between the engine, airframe, and government communities be undertaken to further the activities in this arena.

Acknowledgments

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