A Cost Modeling Approach to Engine Optimization

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Greater emphasis on cost control in all phases of the engine program life cycle has resulted in life cycle cost (LCC) becoming a figure of merit for engine optimization studies This paper discusses a study conducted by Garrett using a cost modeling approach to further refine engine cycles and configurations for an optimum weapon system LCC The cost model is described, and the results of the study are included to illustrate the impact of this type of study on deriving additional savings in total weapon system cost and weight It was concluded from the study that LCC is a sensitive tool for the engine designer for engine optimization in terms of both cycle and configuration selection The sensitivity study began with the baseline design derived from a conventional approach Nine engine parameters were changed, resulting in a 16% improvement in engine thrust/weight ratio and a 10% improvement in fuel consumption Development strategy studies indicated that optimization of the balance of effort between design and testing could benefit engine maturity at initial operational capability (IOC)

Introduction

LIFE cycle cost (LCC) is now recognized as a figure of merit for optimization of engine/airframe combinations Since engine definition precedes airframe definition because of the longer engine development cycle, the engine manu facturer must be familiar with airframe synthesis. In the early 1970's, to facilitate engine and total aircraft LCC studies, Garrett prepared analytical models for sizing and costing the airframe and engine for specific missions In 1978, Garrett formulated a two part model with sizing criteria based in one case on mission parameters, and in another on engine parameters to which airframe size is sensitive The models took into consideration several aspects of engine/airframe application: 1) new engine and airframe (each scalable), 2) existing airframe, new engine (engine scalable), 3) existing airframe and engine (neither scalable), and 4) new airframe, existing engine (airframe scalable) Each application required different assumptions about apportioning aircraft weight fractions to variable and fixed categories

This paper outlines an engine optimization study carried out as part of the Navy Advanced Technology Engine Study (ATES) Program The objective of the study was to determine a set of engine cycle parameters, and then to establish a set of component technologies and a development strategy that would result in the lowest peacetime LCC for six different aircraft fleets For simplicity, one tactical system (using an engine in the middle of the study size range) is discussed Preliminary sizing was based on conventional optimization criteria. The LCC model used is briefly described, and the scenario for the mission is given Finally, the study results are shown in terms of both LCC and aircraft takeoff gross weight (TOGW)

LCC Model

The LCC model is comprised of a manager routine and various subroutines that are called as required These subroutines deal with:

1) Airframe and engine size
2) Airframe LCC
3) Engine development and Component Improvement Program (CIP)
4) Engine production
5) Mission operation
6) Engine maintenance and availability
7) Airframe-engine cost integration
8) Cost discounting and inflation
9) Engine LCC sensitivity (for simultaneous evaluation of baseline and trade cases)

The airframe sizing and costing equations used in the model are sensitivity coefficients provided by the airframe manufacturer (or, in some cases, those developed by Grarrett synthesis studies) For cycle and component trade studies, engine development and CIP costs are estimated using 18 different parametric equations; for the development strategy studies, a Monte Carlo simulation of the engine development process is used This Monte Carlo simulation estimates engine maturity (individual component lives), total cost, and elapsed time at the end of the development program (as a function of design risk and complexity) Fabrication cost is input for each part; the total engine cost is then scaled for engine resizing and passed through a learning curve based on the total production quantity, including calculated spares requirements as a function of engine maturity Mission operation analysis includes calculations of both fuel usage and mission damage events for all segments of each mission. Damage events are compared with those of the design mission so that mission severity effects on component life can be considered Engine maintenance cost and availability are based on individual part Weibull characteristics as altered by their sensitivity to mission damage events and reliability growth Costs are either calculated as, or divided into, annual amounts that can be inflated or discounted, as desired Eleven elements of engine LCC are modified in the LCC sensitivity routine for changes in engine thrust, weight, SFC, diameter, part life, part cost, and part reliability

Mission/Airframe/Engine Definition

The Low Cost Interceptor (LOCI) mission and airframe evaluated in this study were both configured by Grumman Aerospace Corporation The LOCI was conceived as a low cost, lightweight, short range, defensive interceptor that could be purchased in quantities that numerically match those of the opposition Both the engine and airframe are new

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configurations The aircraft is shown in Fig 1, and the design mission is outlined in Table 1 The fleet was defined in the model as 494 aircraft, with 375 of these aircraft having an accumulated flight time of 300 h/yr extending over a 15 year period Fuel cost was set at $1 80 per gallon The engine was designed as a 14,770 lb thrust, afterburning two spool tur bofan scaled to 10,080 lb thrust as the airframe was defined Engine and aircraft characteristics are listed in Table 2 with the baseline LCC estimates shown in Fig 2

Parametric Study Results

Engine cycle optimization began with preparation of aircraft sensitivity factors to engine parameters Grumman supplied Garrett with sensitivities of TOGW and fuel burned in relation to engine weight, diameter, and TSFC (Figs 3 and 4) Off design point models were then developed from which engine output and efficiency were obtained at all mission conditions Several cycle parameters were incrementally changed on an independent basis New engine weights and costs were then estimated, and component lives were adjusted for changes in hot time and Type III and IV cycles The airframe and engine were resized for each parameter change, and the LCC was then recomputed for the entire fleet The cycle parameters evaluated were: 1) fan-pressure ratio (FPR), 2) compressor pressure ratio (CPR), 3) core/bypass and flow pressure balance (at afterburner mixing plane), 4) flat rating point (theta break), and 5) turbine rotor inlet temperature (TRIT)

An example of these study results is shown for fan-pressure-ratio in Fig 5 The cycle parameter study is sum marized in Fig 6 and Table 3 The studies provided the following information

Fan Pressure Ratio (FPR)

Improvements in SFC by decreasing FPR are offset by the necessity of increasing bypass ratio, and thereby the diameter of the engine

Compressor Pressure Ratio (CPR)

The larger compressor size required to supply increased CPR offset the SFC improvements obtained as CPR was increased Although both TOGW and LCC would benefit from a slight reduction in CPR, no change was made to CPR

Core/Bypass Flow Pressure Balance

To maintain augmentor stability, only a ±5% deviation from a flowstream static-pressure ratio of 1 0 could be

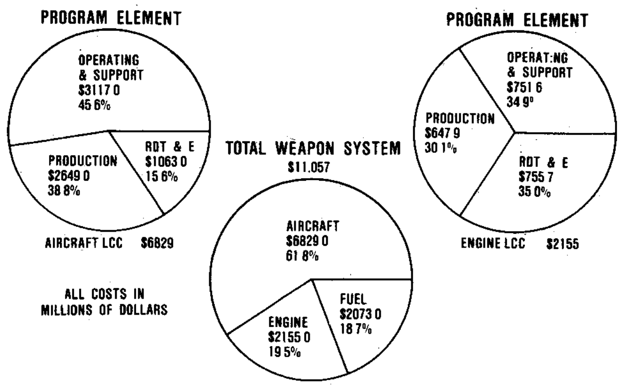

Fig 2 LOCI optimized engine

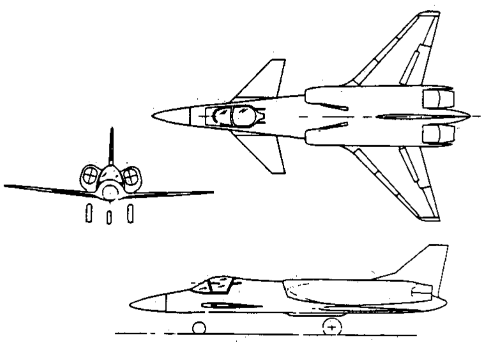

Fig 1 Initial LOCI as configured by Grumman.

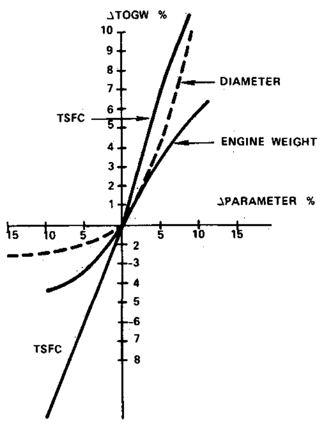

Fig 3 LOCI TOGW sensitivities

Table 1 LOCI selected design mission

1	Warmup takeoff acceleration	8	Land—5% reserve
2	Cruiseout (110 n mi) at Mach 0.9, 1000 ft alt	9	Takeoff and landing distance 1250 ft
3	Combat (1) 8 0g Mach 1 2 sustained 360 deg turns; expend (2) srm	10	Acceleration: Mach 0 85 to 1 5 30 000 ft—70 s max
4	Inbound cruise (20 n mi) at Mach 1 2 1000 ft alt	11	Maneuver at Mach 0 9, 30 000 ft 4 3g
5	Combat (2), 8 0g Mach 1 2 sustained 360 deg turns; expend (2) srm	12	Limit turn capability 8 0g
6	Cruise return (80 n mi) at bcm 1000 ft alt	13	Weapons—4 srm (320 lb)
7	Loiter	14	Gun (optional) 500 rounds —1350 lb

considered This became a trade between SFC and weight, as bypass ratio varied

Flat Rating Point (Theta Break)

Changes in the flat rating point were made to balance the cruise performance and maximum thrust at the engine sizing condition The cost savings achieved from decreasing core size were offset by component efficiency reductions, as the operating point moved further away from optimum for each component

Turbine Rotor Inlet Temperature (TRIT)

The SFC and size improvements that resulted from increases in TRIT were offset by greater cost and shorter life; however, an increase in TRIT was found to be optimum for LCC This particular trade will be strongly affected by rapidly evolving materials and new fabrication processing technologies

These figures show that LCC optimization results in a slightly different cycle than with TOGW optimization Note that the TOGW was further optimized (reduced 7 5%) as a result of these studies, as shown in Table 3 The airframe manufacturer confirmed the LCC optimized engine characteristics that improved system TOGW and LCC (Table 2 and Fig 2, respectively)

Once the cycle was established, sensitivity to engine design parameters, component efficiency, and life were also evaluated The design parameters varied were as follows:

LP Spool Speed (N_1)

N_1 optimization is essentially a trade between fan and LP turbine efficiencies (which have opposite trends with changes in speed) and various component lives which also have opposite trends for speed changes An N_1 reduction of up to 15% was found desirable, as shown in Fig 7

HP Spool Speed (N_2)

N_2 optimization, like N_1, is essentially a trade between compressor and HP turbine efficiencies and lives An N_2 reduction of 3% was selected, as shown in Fig 8

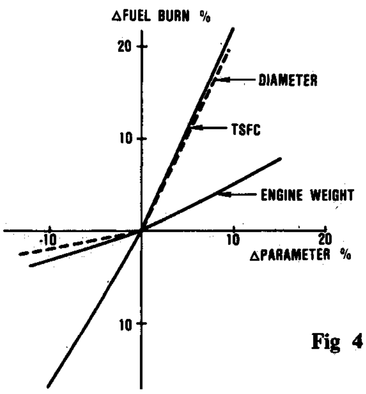

Fig 4 Fuel burn sensitivity results

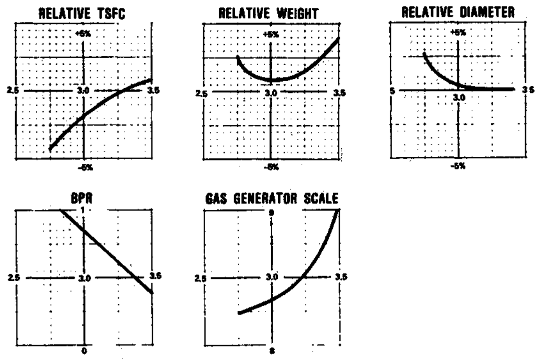

Fig 5 Engine characteristics as a function of FPR

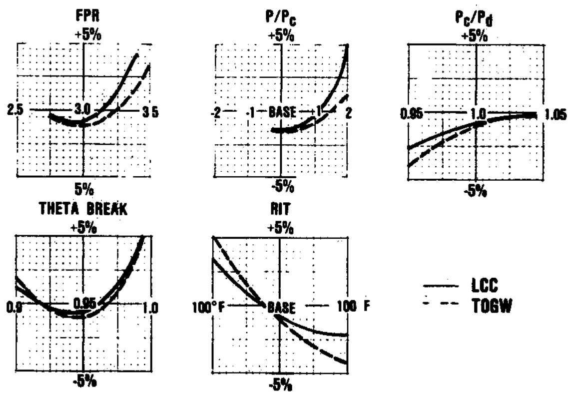

Fig 6 Summary of LCC optimization of LOCI engine parameters

Table 2 Aircraft/propulsion characteristics (TFE Model 1133 turbofan engines, scalable)

Propulsion characteristics	Baseline (2)	Optimized engine (2A)
Uninstalled intermediate thrust lb	7,246	8,648
Augmented thrust, lb	12 104	14,772
Engine weight lb	1,400	1 473
F_N/weight lb	8 65	10 3
Installation		
Normal shock inlets	0 86 contraction ratio	
High pressure bleed	0 3 lb/s/eng	
Power extraction	50 HP/eng	
Nozzle interference drag for closely spaced nozzles		
Thrust reversers—clamshell—55% intermediate thrust		
Weight—15% engine weight		

Aircraft characteristics	Baseline	Optimized engine
Aircraft TOGW, lb	18,438	17 472
SLS Scaled max thrust lbf	10,650	10,080
Takeoff wing loading psf	86	86
Takeoff thrust/weight	1 154	1 154
Liftoff speed, knots	144 5	144 5
Touchdown speed knots	124 5	125 5
No of aircraft	494	494
Fuel cost at $1 80/gal ($ billion)	2 276	2 073
Total LCC ($ billion)	11 951	11 057

Table 3 Summary of engine parameter optimization

Variable	Initial cycle	Optimized cycle	ΔTOGW %	ΔLCC %
FPR	3 12	3 0	−0 2	−0.8
P/P_c	7 75	7 75	0	0
P_c/P_d	1 036	0 95	−3 5	−2 4
θ_b	0 924	0 95	−0 6	−0 3
RIT_{max} F	2500	2600	−3 2	−1 5
Total			−7.5	−5 0

HP Turbine Cooling Flow

HP turbine cooling flow variation is a trade between performance and life The divergence between TOGW and LCC optimization is great, as shown by Fig. 9 A cooling flow reduction of 15 to 20% was shown to be cost effective

HP Turbine Annular Area Optimization

Turbine annular area optimization is a trade between ef ficiency and life that results from changes in blade aspect ratio and weight. In this case, the trade was balanced (Fig 10), and no change in annular area was necessary

HP Turbine Mean Radius

Turbine mean radius optimization is also a trade between efficiency and life resulting from changes in blade aspect ratio and weight Figure 11 shows that a 5 to 7% increase in HP turbine mean radius would be beneficial

The design parameter study is summarized in Table 4 As can be seen, LCC optimization results in further improvement of TOGW

Component Technology Study Results

Prior to the component trade studies, sensitivities of component efficiency and life were prepared (Figs 12 14) The following advanced component technologies of varied risk levels were selected for evaluation, and the benefits obtained from them are summarized in Table 5

Hollow Bladed Titanium Fan

A built up SPF/DB construction blade was compared to the baseline forged and machined blade. A 40% fan rotor weight reduction was projected with no manufacturing, cost, performance, or durability penalty incurred Without penalties, the LCC benefits would justify the developmental expense

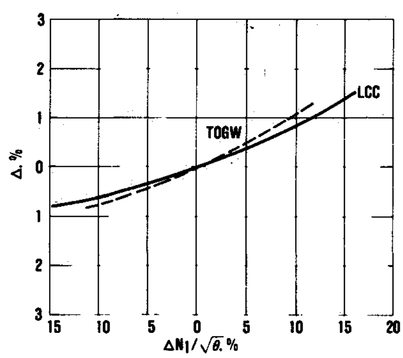

Fig 7 LP spool optimization study (cost and weight)

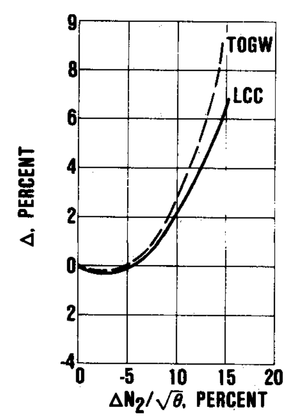

Fig 8 Results of HP spool speed optimization

Table 4 Design optimization

Item	TOGW %	LCC, %
Fan design speed	−0 8	−0 7
Compressor design speed	0	0
HP turbine cooling flow	−2 2	−1 2
HP turbine mean radius	−2 6	−0 2
HP turbine annular area	0	0
Total	−5 6	−2 1

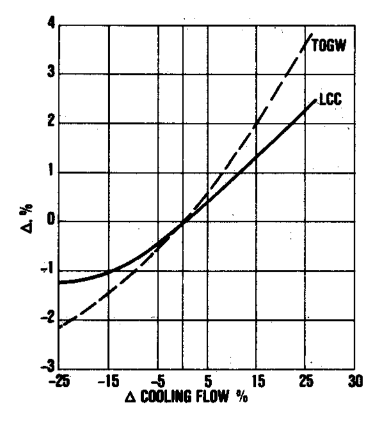

Fig. 9 HP turbine cooling flow optimization results

Table 5 Results of component technology optimization

Item	ΔTOGW %	ΔLCC %
Fan		
Hollow titanium blade	−0 6	−0 4
Composite front frame	−0 2	−0 3
Compressor		
TiAl	−0 1	−0.1
Burner		
Filmed cooled counterflow	0	0
HPT		
Active clearance control	−1 6	−1 1
Modulated cooling flow	−3 6	−2 1
LPT		
Active clearance control	−0 4	0

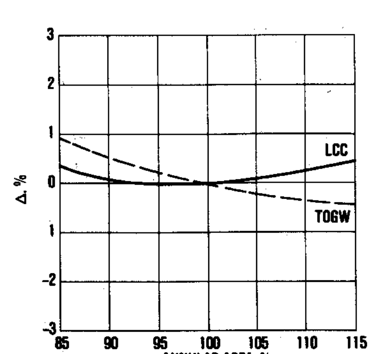

Fig 10 HP turbine annular area optimization results

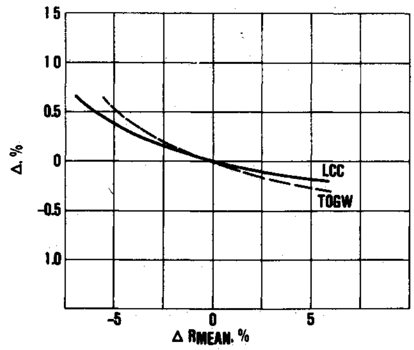

Fig 11 HP turbine mean radius variation results

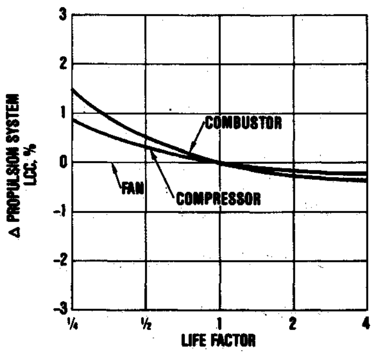

Fig 12 Sensitivity of LCC to increased life of combustor burner.

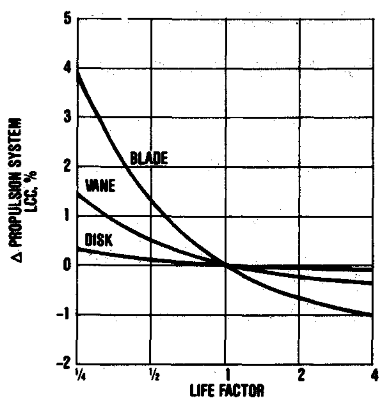

Fig 13 Sensitivity of LCC to increased life of HP turbine.

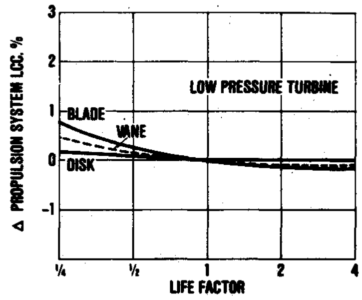

Fig 14 Sensitivity of LCC to increased life of LP turbine

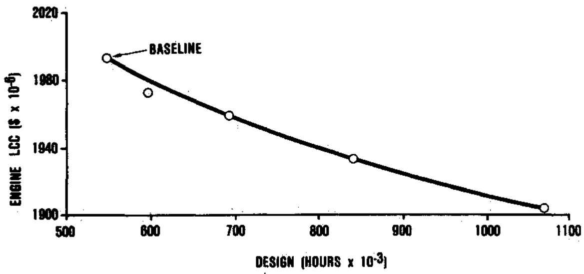

Fig 15 LCC benefits of design effort using a development simulation model

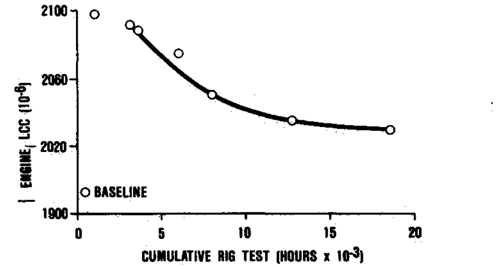

Fig 16 LCC benefits of extended rig endurance testing using a development simulation model

Composite Front Frame

A hybrid Kevlar/carbon fiber material used for the case is expected to provide a 20% weight reduction and a 25% cost reduction when compared to use of a cast titanium case Again, with no penalties, the LCC benefit justified the projected developmental cost

Titanium Aluminide (TiAl) Impeller

A dual-alloy hollow impeller was projected to offer a 20% weight reduction, a 100% life increase, and a 20% increase in manufacturing cost The benefits exceeded the cost penalties, and, therefore, would justify development

Film-Cooled Counterflow Burner

The enhanced cooling effect achieved with this type design will double burner life, but with a 50% increase in manufacturing cost However, the net benefits were sufficient to justify development

Active Clearance Control

Directing fan air over the HP and LP turbine shroud peripheries will reduce metal temperature and diameter, and is expected to reduce blade running clearance by 60% for the HP and LP turbines This will cause a weight penalty of 5 lb, and an engine manufacturing cost penalty of 0.5% for each turbine The net benefit would make development desirable for the HP turbine. No net benefit was achieved for the LP turbine.

Modulated HP Turbine Cooling Flow

Varying HP turbine cooling flow with changes in engine power setting would add 1 5% to engine manufacturing cost, and an additional 5 lb to engine weight However, this would also allow a 50% reduction in cooling flow at the cruise condition without incurring significant life penalty The LCC benefit was the greatest of any of the technologies studied

For each technology, changes in performance, weight, manufacturing costs, and life were applied to the sensitivities derived from perturbing the models The overall effect was a significant 4% improvement in LCC Combining these results with the results of the cycle studies showed an even more significant improvement in LCC of over 11% These benefits were obtained from a preliminary study using only a few of the possible improvements to the engine design

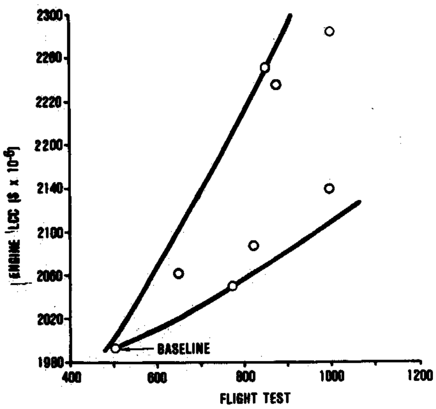

Fig 17 LCC results of extra flight testing using a development simulation model.

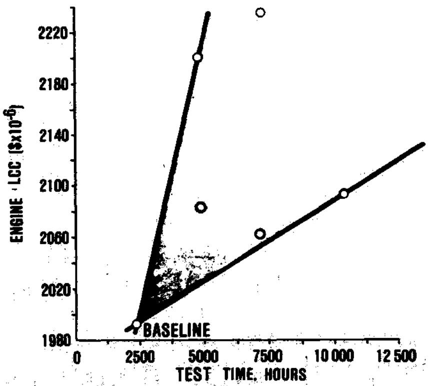

Fig. 18 LCC results of extra AMT testing using a development simulation model.

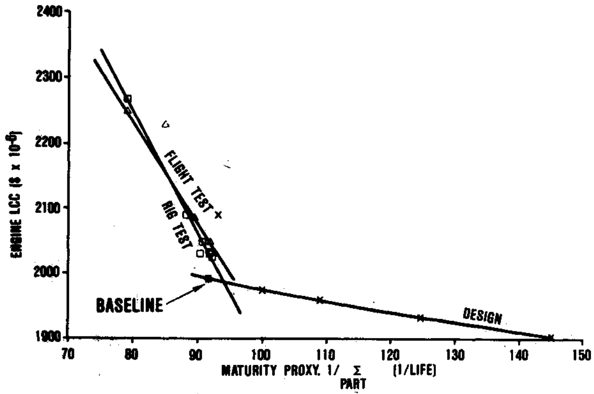

Fig 19 Overall benefits of various development strategies using a development simulation model

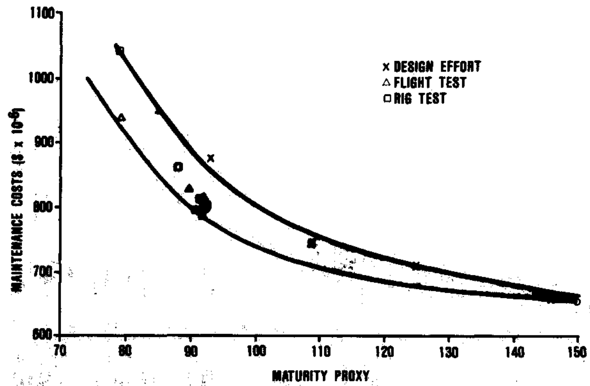

Fig. 20 Overall benefits of various development strategies using a development simulation model.

Development Strategy Study Results

A Monte Carlo model was formulated to simulate the engine development process, and was then combined with the LCC model The combined model was used to evaluate several fundamentally different approaches for comparison with the conventional method: 1) increased design effort on all major parts, 2) increased rig-test effort (more rig endurance tests), 3) increased flight-test effort, and 4) increased accelerated mission testing (AMT)

The rationale behind each of these approaches was:

1) Extensive design efforts will allow life limiting design deficiencies to be found and remedied

2) Rig endurance testing is considerably less expensive than full-scale engine testing, although less credibility exists in determining component durability in the flight environment.

3) Flight testing is an effective means of uncovering durability and operability problems in an engine However, this approach is also the most costly, since aircraft operating costs are greater than test cell operating costs.

4) AMT is thought to be the most cost-effective means of determining durability problems.

A determination obviously is necessary to establish whether the cost effectiveness of any of these four approaches outweighs that of the conventional approach Each of these factors was separately modeled as an addition to the normal development effort The results are shown in Figs 15-18 The unusual results recorded for flight and AMT testing were due, in part, to the high cost of such testing, and also to the fact that the simulation model causes the failures incurred in additional testing to increase the uncertainty regarding the life of the failed part Thereby, the likelihood of lower life and higher maintenance cost is increased This situation will be remedied in the next design evolution of the model The modeling results suggest that efforts to accelerate the maturity

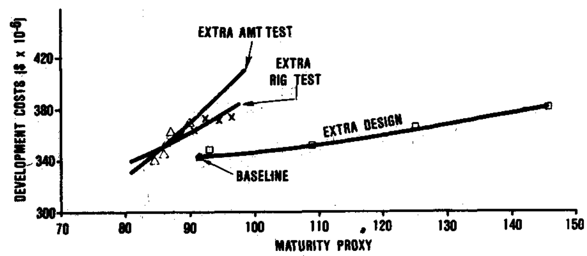

Fig. 21 Development costs for obtaining maturity using a development simulation model.

growth in an engine development program are cost effective, and Garrett will continue these studies

An output of the development simulation model is com ponent durability, which is input to the maintenance section of the LCC model for generation of removal events For analysis of modeling results, engine maturity at IOC was simulated by a maturity proxy

$$\text{Maturity Proxy} = 1/\Sigma[1/\text{Life}] \qquad (1)$$

(Note: in the above equation, Σ applies to all parts) The development strategy studies were then reexamined to see how cost and benefit related to maturity

Figure 19 shows the results restated in terms of the effect of maturity on net LCC benefit for the individual strategies and two cases of combined strategy The marked difference in slope between the design and test strategies is probably due more to the geometric relationship between failure rate and cost than to any difference in effectiveness j owever, it was decided to separate the net LCC into its two components, the cost of development and the benefit to maintenance cost for obtaining greater maturity Figure 20 shows the influence of maturity on maintenance cost, and appears to be very similar to the net LCC benefit The cost of obtaining this maturity is shown in Fig 21 The higher development costs required to achieve the same level of maturity with testing when com pared to design effort suggests that as more accurate design techniques become available, it might be possible to obtain the desired maturity at lower development cost through substitution of design effort for some test effort This aspect will also be studied more thoroughly in future work with this model

Conclusions

LCC analysis is an effective tool for optimization of aircraft designs, if for no other reason than the beneficial aspect of additional study Obviously, early collaboration between the engine and airframe designers hastens this process There is no doubt that the development of more sophisticated modeling techniques will greatly improve these efforts As modeling techniques are improved, and the uncertainties about using simulations (especially probabilistic simulations) are dispelled in the minds of designers and program planners, the entire development process will be enhanced

Acknowledgments

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