Monte Carlo Simulation of the Engine Development Process

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A probabilistic model of the engine development process has been formulated for studying the effects of variations in engine design and development program parameters on engine maturity The model allows the consideration of risk at both the engine and component levels to affect developed life, program duration, and program cost The general structure and logic of the model are described, as well as its validation to completed engine programs and its use to evaluate different development philosophies This effort was sponsored by the U S Navy Advanced Technology Engine Studies (ATES) Program

This computer code is a Monte Carlo" simulation of the engine development process, based on the engine part list and the development scenario selected by the user The model covers all phases of development ac tivity – design, fabrication, rig test, engine development testing, and engine verification testing – experienced by the engine manufacturers Design and development risks are considered within the model and are the reason for the Monte Carlo approach to the simulation The model provides the user with the capability to make com parative assessments of different design and development approaches The scope of the model includes only costs undertaken by the engine manufacturer in carrying an engine concept from preliminary design to com pletion of durability verification tests

Introduction

GARRET undertook the simulation of the engine development process to satisfy a requirement of the U S Navy sponsored Advance Technology Engine Studies (ATES) effort The overall objective was to provide a tool by which changes in engine maturity at the conclusion of engine development could be predicted to be the result of variations in the development plan; i e , in the manner in which the design and test efforts would be carried out The other ob jectives established by Garrett were: 1) The model approach would be a simulation, rather than based on parametric equations because greater precision and sensitivity were desired than could be obtained from parametrics; 2) The basis of the simulation would be the engine parts list and the development plan; 3) The uncertainty and risk which are normally a part of the development process would be a dominant feature of the model; and 4) The outcome would include details of the required resources (time material manhours, facilities) to perform the programs so that a comparison could be made with resource usage in actual programs These objectives essentially dictated that the model must be sensitive to the degree of complexity built into the engine, the resource requirements of the development plan and the technical risk designed into each component of the engine The decision to formulate a Monte Carlo simulation was a result of the observation that despite the application of the highest engineering skills, the typical development program encounters some problems delaying the attainment of design and program goals These shortcomings are due to random events that cannot be precisely predicted; i e , it is known that components will fail but not which ones The variability in engineering and management skills are part of these random events

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Approach

The approach to formulating the model (named DEVSIM) was by setting up a chronological event sequence (Fig 1) and an accounting structure for resource usage The Monte Carlo aspects deal with: 1) determining if a problem has occurred, 2) selecting the component responsible for the problem, and 3) relating engine maturity (a function of all component lives) to the development effort Engine problem risk assessment is based on probability distributions for endurance, per formance weight, mechanical integrity and manufacturing cost Good judgement must be used in setting up these distributions Parts are grouped by their sensitivity to each of these kinds of risk The output of a random number generator is applied to the probability distributions to generate a value of whichever parameter is being tested Risk assessments are performed at a large number of points in the simulation as shown in Fig 2 and Table 1

Individual component risk assessments are based on user judgment of the level of design risk in performance and endurance for each part The model assigns varying magnitudes of design effort to flow path parts (identified at three levels of influence on engine performance) and life critical parts (segregated into six combinations of stress field temperature environment and internal cooling) as shown in Table 2 Susceptibility to failure is reduced after each redesign

The user sets up the development plan by specifying the prices for each resource used in the program, selecting the rig and engine tests, defining the hours per test and the minimum cumulative hours for each type of test, and identifying the engines to be committed to each type of test

Component life at the conclusion of development is modeled in two aspects the improvement of life capability through design effort and the reduction of uncertainty about that capability through testing Realistic limits were applied by 1) formulating the life improvement function as a decreasing return to scale 2) assigning different effectiveness in uncertainty reduction to each kind of testing, and 3) assuming varying sensitivity of life improvment to added design effort for each of ten classes of parts Little history is published on the variation of achieved lives relative to design goals Assumption of a normal distribution seemed op timistic A distribution with Weibull characteristics was in

Table 1 General risk assessment

Item	Wt (lb)	Cost	Mechanical	Performance	Endurance
Design	X	X			
Fabrication					
Rig Test	X	X	X		
Performance				X	
Endurance				X	X
Engine Development Test					
Mechnical			X		
Performance				X	
Endurance				X	X
Altitude				X	
Flight			X	X	X
Operability				X	
Integration					X
Engine Qualification					
PFRT/IFR	X	X			X
MQT/FFR					X
SMET					X
AMT					X

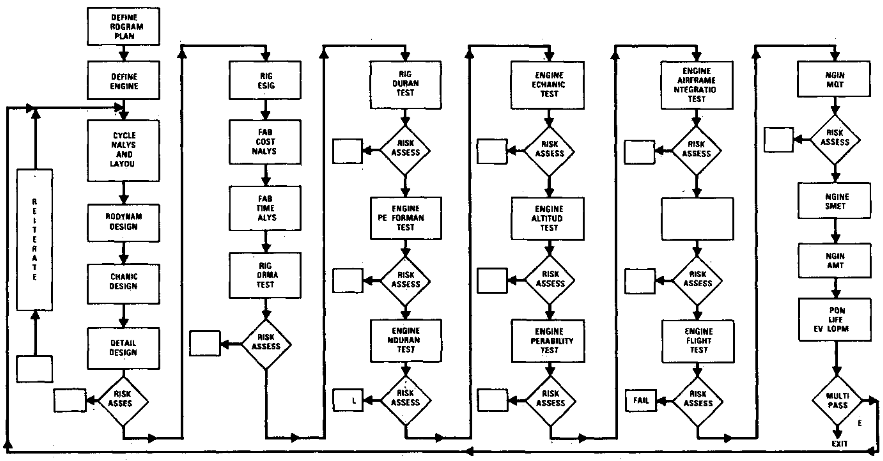

Fig 1 DEVSIM logic sequence for an engine development program

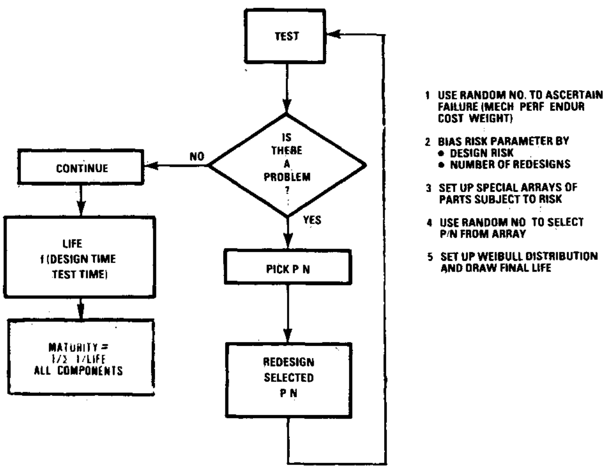

Fig 2 Risk assessment logic

tuitively satisfying (since production part lives behave in that way) and was convenient to use since its parameters are well understood Accordingly, the specific life achieved by each component was assumed to be Weibull distributed, with characteristic life a function of the design effort, and slope a function of the test effort That life is selected from the resulting Weibull distribution with use of a random number generator

One execution of the development program simulation would therefore, have different results than a previous or later execution from the same input data set For this reason the output from a single execution (or pass) of the model cannot be assumed to be a median, average, or representative case, and multiple executions are required to evaluate the full range of possible outcomes To estimate the mean and standard deviation of this range accurately for the development program being evaluated a very large number of passes (≅10,000) are required The benefit of such accuracy when using so many estimates in the input data set, is questionable and would not justify the cost An evaluation of 100 ,300 , and 1000 pass cases showed that 300 passes would be an acceptable compromise between precision and cost

Input and Output

The input comprises definition of the resource costs, development plan, overall engine characteristics, and each section, assembly, and major part The data shown in Table 3 are input for each part Setting of design life goals is based on analysis and experience with similar parts This input data set and some of the output data, were designed to be compatible with the Garrett LCC model, FITRCOST [1,2] used for detailed evaluation of engines in aircraft The model was calibrated for a level of engine definition that comprises approximately 250 major part numbers for modern small fighter engines (e g , G E F404) Manufacturing cost at the 250th to 300th engine is input for each part, and is converted to development hardware price levels within the model A 10% cost factor is added for miscellaneous small parts

The output of the model comprises event summaries (Tables 4 to 6), resource usage (Table 7), and a calendar of

Table 2 Component classification for risk assessment

Flow path parts
Blades vanes, combustors
Labyrinth seals
Struts housings
Life critical part categories
Hot cooled rotating, HCR
Hot cooled static HCN
Hot uncooled rotating,HRO
Hot uncooled static HNR
Cold rotating, CRO
Cold static CNR
Mechanical problem drivers
Bearings, seals shafting, and bearing supports

Table 3 Engine part identification input data for simulation model

ID number (section assembly part)
Name
Manufacturing cost in production (Development hardware averages 4 to 5 × cost of 250th engine)
Weight
Flowpath/mechanical classification
Life critical category
Design life goal (β and θ)
Design performance risk
Design life risk
Status (old or new design)

Table 4 Segment of event summary (engine simulation)

Test event No	Test	Run hours	Responsible component	Part No	Test No	Eng No
103	Endr	500	HPT Nozzle	3103	1	4
104	Perf	50	No failure	–	2	4
105	Endr	500	No failure	–	3	4
106	Endr	500	Nozzle flap	5203	1	5
107	Perf	50	No failures	–	2	5
108	Endr	500	No failures	–	3	5
109	Endr	500	No failures	–	1	6
110	PFRT	50	LPT bearing support	4207	1	1
111	PFRT	50	No failures	–	2	1

SUMMARY FOR LOCI ENGINE SIMULATION

SCHEDULE OF MAJOR EVENTS

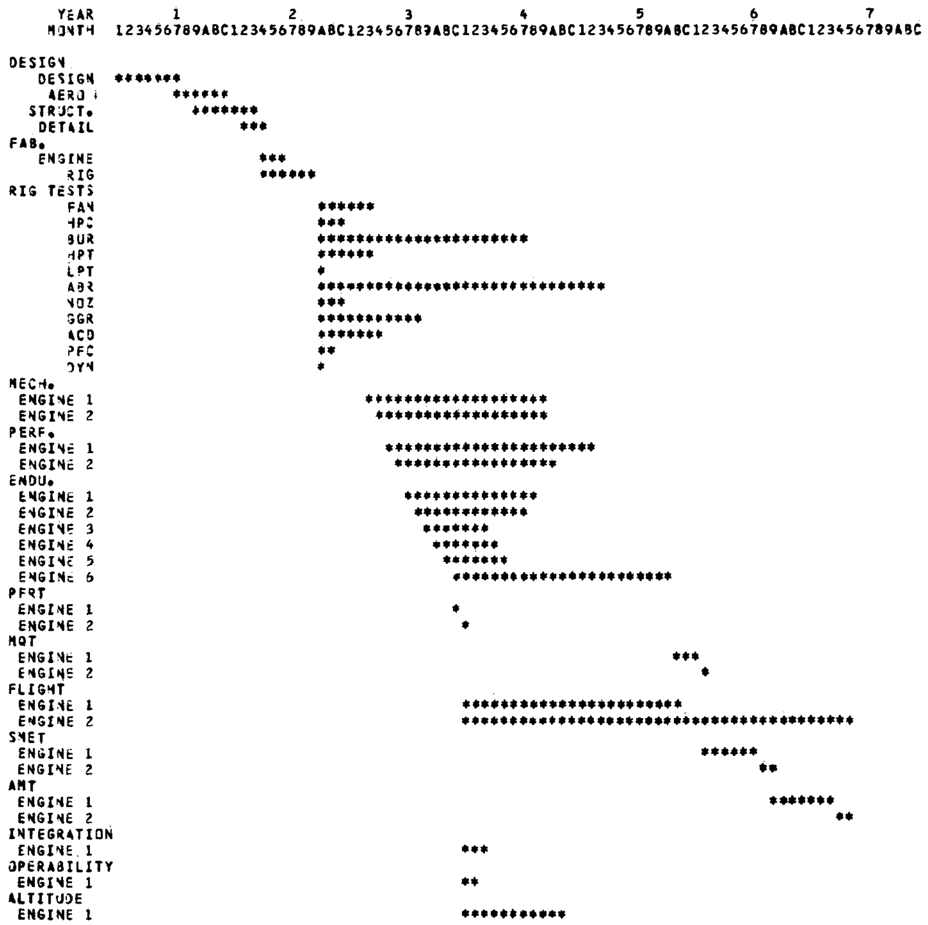

Fig 3 Calendar of major event predictions by DEVSIM

Table 5 Frequency summary of component problems

Part No	Part name	No of component redesigns
313	HPT nozzle	6
523	Nozzle flap	5
523	LPT blades	4
427	LPT bearing support	3
5210	Augmentor liner	3
237	Impeller	3
527	Flame holder	2
233	HP front bearing	2
323	HPT blades	2
255	Inner fan duct	2
416	Bearing support	2
525	Actuators	2
425	LPT stub shaft	1
111	Forward fan bearing	1
118	AFT fan curvic bearing	1
211	AFT fan bearing labyrinth seal	1
227	Gears and bearings	1
321	Curvic coupling	1
426	LPT bearing	1
326	Aft HPT curvic	1

Table 6 Summary by task of component redesigns

Task	Type of risk	No of redesigns
Design	Weight	2
	Cost	1
Rig test	Performance	18
	Endurance	4
	Weight	1
	Cost	1
Engine development testing	Mechanical	8
	Performance	1
	Endurance	6
	Weight	0
	Cost	0
Validation testing	PFRT	0
	MQT	1
	SMET	1
	AMT	0

Table 7 Resource usage predicted by DEVSIM

	Labor instr hours	Computer hours	Facility hours	Energy usage Fuel gal	Energy usage Air lb	Project hours	Engineering support hours	Hardware cost	Total cost
Design									
Preliminary	2600 0	91 0	0 0	0 0	0 0	3400 0	0 0	0 0	32
Aerodynamic	134814 5	1388 2	0 0	0 0	0 0	33703 6	26962 9	0 0	10 05
Structural	144865 5	1491 7	0 0	0 0	0 0	36216 4	14486 5	0 0	10 08
Detail	323154 0	0 0	0 0	0 0	0 0	80788 5	32315 4	0 0	21 81
Rig	27400 0	99 0	0 0	0 0	0 0	13700 0	1550 0	0 0	2 35
Total	632834 0	3070 0	0 0	0 0	0 0	167808 5	79244 8	0 0	44 61
Fabrication									
Engine	18725 0	0 0	0 0	0 0	0 0	18725 0	0 0	129 7	131 54
Rig	3000 0	0 0	0 0	0 0	0 0	3000 0	0 0	10 2	10 50
Tooling	7137 5	0 0	0 0	0 0	0 0	1427 5	0 0	14 2	14 64
Total	28862 5	0 0	0 0	0 0	0 0	23152 5	0 0	154 1	156 38
Development									
Rig	43920 0	176 0	33758 5	105613 2	68000000 0	19537 5	1550 0	12 0	17 68
Engine	173690 0	656 0	58636 0	30908965 4	9360000 0	44805 0	16320 0	28 0	79 20
Altitude	15000 0	60 0	810 0	1692096 6	4320000 0	3690 0	3000 0	2 8	8 75
Flight	11160 0	18 0	450 0	2538145 0	0 0	4860 0	900 0	8 3	13 07
Total	243770 0	910 0	93654 5	35244820 2	81680000 0	72892 5	21770 0	51 1	118 70
Qualification									
PFRT	2540 0	40 0	535 0	282016 1	0 0	830 0	100 0	9	1 46
MQT	7410 0	60 0	2407 5	1269072 5	0 0	2070 0	450 0	1 4	3 50
SMET	36280 0	80 0	14980 0	7896451 0	0 0	6060 0	2800 0	1 8	14 11
AMT	41080 0	80 0	17120 0	9024515 4	0 0	6660 0	3200 0	1 8	15 83
Integration	2286 0	60 0	642 0	338419 3	0 0	1575 0	120 0	1 4	2 02
Operability	3450 0	60 0	642 0	338419 3	0 0	1575 0	120 0	1 4	2 08
Total	93046 0	380 0	36326 5	19148893 7	0 0	18770 0	6790 0	8 7	38 99
Program Total	998512 5	3980 0	129981 0	54393714 0	81680000 0	282623 5	107804 9	213 9	358 68

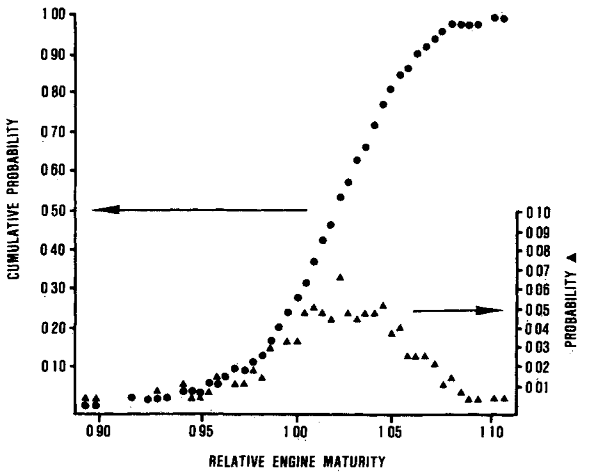

Fig 4 Simulated probability distribution of engine maturity

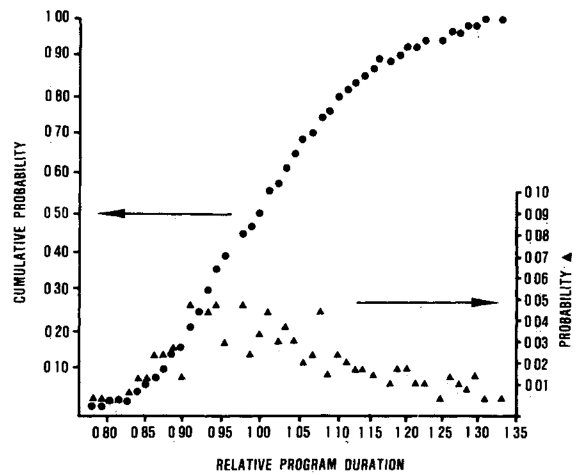

Fig 6 Simulated probability distribution of engine development program duration

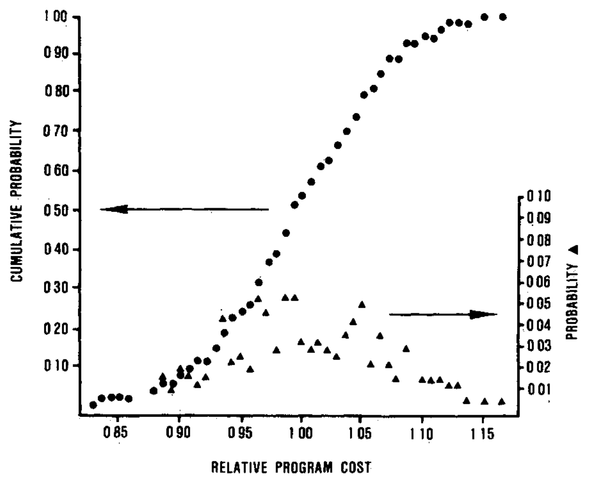

Fig 5 Simulated probability distribution of engine development cost

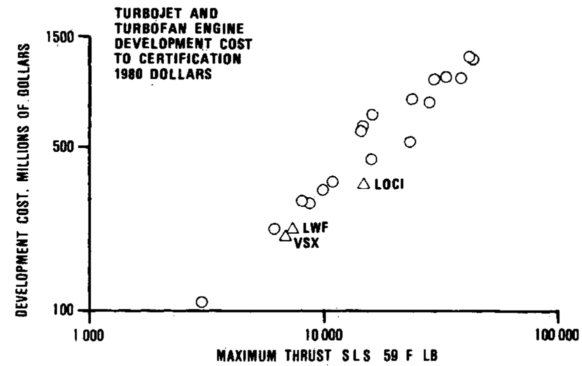

Fig 7 Comparison of ATES development simulations with industry data

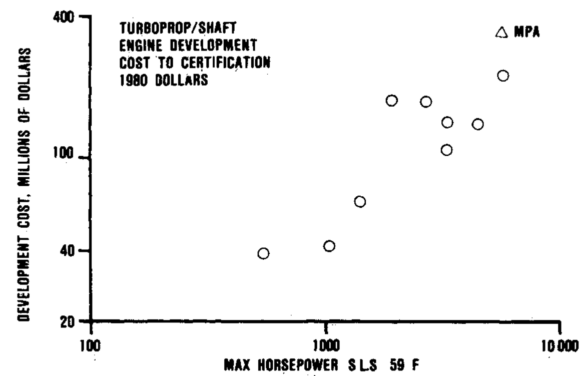

Fig 8 Comparison of ATES development simulations with industry data

Table 8 5700hp turboprop (MPA) engine (with prop gear box) development cost estimates

	Simulation	Parametric model 1	Parametric model 2
Design manhours	840 600	437,000	818 700
Computer hours	5800	12 090	
Laboratory labor h	136 400	503 200	50 100
Test facility hours	67 400	79 600	24 800
Fuel gallons x 10^{-6}	3 89	2 77	–
Conditioned air lb x 10^{-6}	26 1	224 2	–
Tooling, 1980 \$x10^{-6}	21 2	2 9	16 6
Hardware fabrication 1980 \$x10^{-6}	236 8	291 2	150 0
Project engineering hours	302 341	455 300	560 100
Program duration months	80	60	60
Engine test hours	14 060	–	–
Program cost 1980\$x^{-6}	339	370	295
Industry trendline at 5700 shp = \$368M (1980\$)			

Table 9 Simulation of three approaches to developing an engine

	All new 70% engine	Existing engine 30% down scale	Existing engine 30% derate
Development (including CIP)	0.32	0 19	0 08
Manufacturing	0 32	0 32	0 39
Fuel	0 20	0 21	0 29
Maintenance	0 16	0 16	0 16
Airframe effects	0 00	0 04	0 31
Relative LCC	1 00	0 92	1 23

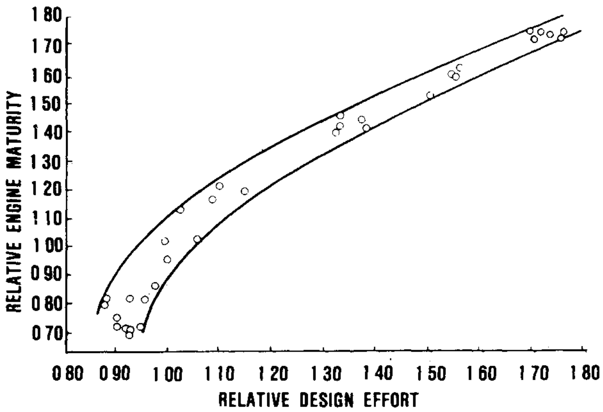

Fig. 9 Simulated influence of design effort on engine maturity

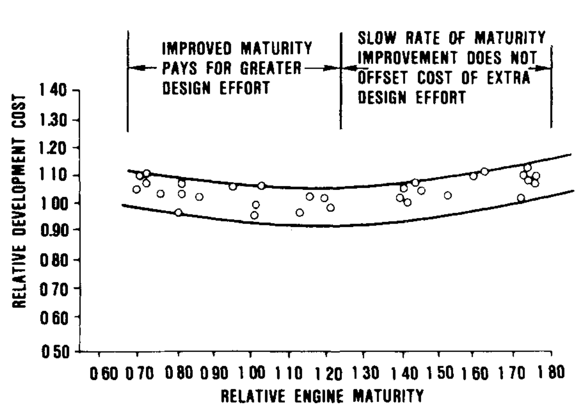

Fig 10 Simulated development cost to obtain engine maturity

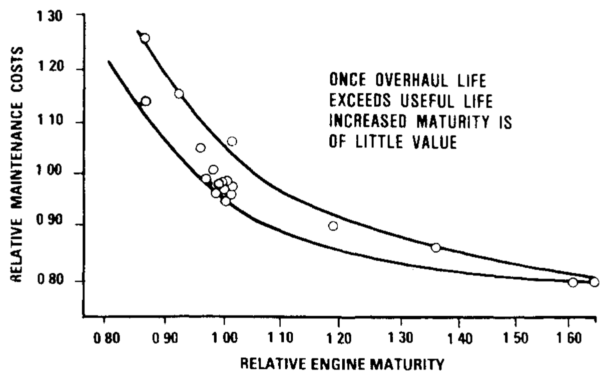

Fig 11 Simulated benefit of engine maturity in reducing main tenance cost

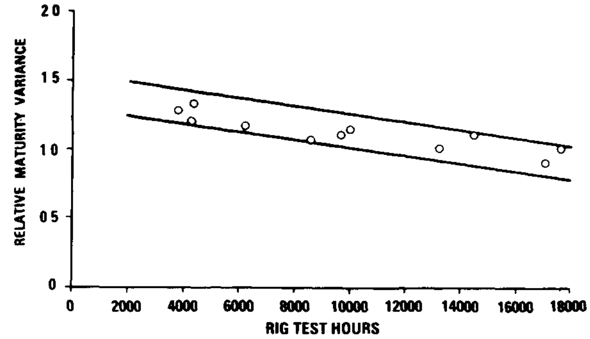

Fig 12 Simulated effect of rig endurance testing on uncertainty about engine maturity at certification/qualification

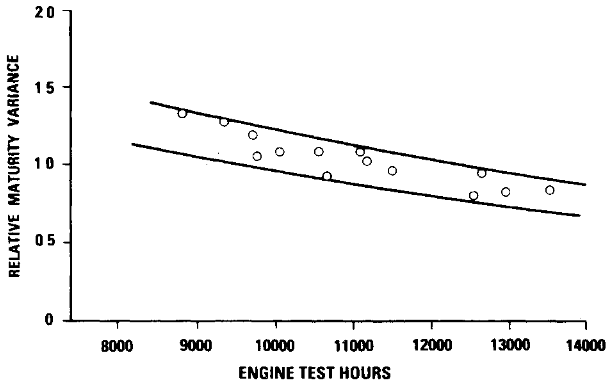

Fig 13 Simulated effect of engine endurance testing on uncertainty about engine maturity at certification/qualification

events (Fig 3) For multipass executions crossplots of maturity, total costs, and duration are provided as well as probability density and distribution functions (Figs 4 to 6) The single pass results are provided in multipass cases for the lowest, median and highest cost passes

Validation

As the model formulation evolved, rules of thumb were used to set various calibration points so that the output looked realistic using an ATES engine as a test case When development reached a point where the model was believed ready for validation, a new engine case was set up describing a completed Garrett engine development program for the 3500 lb thrust TFE731 2 turbofan engine This program en countered a few (but not a large number) problems relative to other Garrett engine programs and was believed by many to be a typical development program It was therefore assumed to be a typical program and several DEVSIM calibration points were adjusted so that the results for the median program of a 300 pass execution coincided closely with the actual results of the TFE731 2 program

The model has at the time of this writing been executed for nine different engines (as well as a large number of variations of specific engines for sensitivity analysis) with airflow ranging from 1 lb/s to 250 lb/s The results compared well with industry data (Figs 7 and 8) for engine development and with the output of several different parametric models One such comparison is illustrated with more detail in Table 8

Evaluation of Development Strategies

As an example of DEVSIM's capability to evaluate development strategy, three issues are examined in the model: 1) Is the relative level of design effort in current practice optimal? 2) Is the use of rigs for additional endurance testing more cost effective than engine testing for reducing the un certainty regarding engine durability? 3) For a new ap plication requiring 30% less power is scaling or derating of an already developed engine more LCC effective than developing a new engine?

The model was iterated with several levels of uniformly applied design effort some less than as well as more than that with which the model was calibrated The results are shown in Figs 9 and 10, and suggest that from a development cost standpoint the current practice in design is close to optimum in improving maturity although up to 20% ad ditional design effort could reduce engine failures enough during development to offset the cost of the extra design activity The effect of engine maturity on maintenance cost was modeled by use of the Garrett LCC model, FITRCOST, and is shown in Fig 11 It can be seen that since maintenance cost decreases with increasing engine maturity the optimal level of design effort, from the standpoint of total LCC would be approximately 50% greater than current practice if all assumptions in the simulation were accurate

DEVSIM was separately executed with minimum hours for rig endurance testing set at levels up to six times normal, and with the minimum hours for engine endurance testing set at levels up to twice normal The results (Figs 12 and 13) show that for the range of rig testing normally used a 10% im provement in engine maturity requires a 135% increase in rig endurance testing, while the same improvement can be ob tained by only a 15% increase in engine testing; i e rig testing is 11% as effective as engine testing From the simulation the cost of an hour of rig testing is 12% of the cost of engine endurance testing; so the use of additional rig endurance testing to extend engine maturity appears to be equally as cost effective as engine endurance Therefore, other con siderations can dominate the decision on whether or not to do endurance testing in rigs

To evaluate scaling and derating vs all new development the DEVSIM simulation model and the FITRCOST LCC model were coupled together and executed for three cases: 1) a new fighter engine design at a thrust level 70% of an already developed engine design; 2) a fighter engine design that was a 70% scale of the already developed engine; 3) a fighter engine that was a 30% derate of the already developed engine The engine quantities and flying hours of the larger and smaller programs were identical, although the missions were assumed sufficiently different to cause the derated engine to be requalified for the new duty cycle The LCC breakdown of the three development alternatives is shown in Table 9 It can be seen that the lower development cost (inital and CIP) of scaling a proven design would offset the slightly higher fuel cost of a cycle not fully optimized and that the cost penalty from the larger engine size, in fuel, airframe costs, and in engine manufacture more than offsets the savings in development cost and improved durability from derating an existing engine Although the results of the simulation in dicate that scaling is the preferred approach the small dif ference between the scaled and new engine cases could disappear with more detailed analysis

Acknowledgement

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References

[1]Comey D H Culy D G , and Cassidy J E , Trade off Studies with an Interactive Engine/Airframe Life Cycle Cost Model, SAE Paper 78 1033 Nov 1978

[2]Culy, D G and Gunness R C A Cost Modeling Approach to Engine Optimization AIAA Paper 82 1185 June 1982