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DESIGN OF ROTORCRAFT POWERPLANTS:- USE OF LIFE CYCLE COSTING AS AN AID TO DESIGN OPTIMISATION

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Abstract

A new powerplant conceived today can be expected to be in service until at least the year 2010. Furthermore, the design concepts and philosophy of the powerplant, which are set in the early project design phase, will remain with the engine for the 20 to 30 year lifetime of that design. Therefore, a knowledge of the relative importance of engine parameters such as fuel consumption, first cost, support costs and development expenditure is of fundamental value at the conceptual design phase.

Life cycle cost is a universal criteria recognised by civil operators of rotorcraft in assessing the relative merits of airframes, engines and systems, and now to an increasing extent the military procurement agencies are also adopting this criteria. This paper analyses the life cycle cost parameters for future powerplants in both military and civil applications to provide a framework of design requirements for the powerplant. In particular it highlights the way in which the design is influenced by changes in cost parameters, for example a substantial rise in fuel costs.

The paper takes a twin engined helicopter in the 8 tonne class as the example for the numerical analysis to represent a medium weight rotorcraft with wide military and civil sales potential.

The analysis covers a range of operational roles, annual utilisations and fleet sizes appropriate to both military and civil operations. The analysis methods are readily adaptable to the powerplants of helicopters of other sizes.

1. Introduction

The design, development and certification of a new helicopter powerplant is a long, complex and expensive process and the fundamental characteristics of that engine, its concept and configuration, will remain basically unchanged throughout the life of the engine type. The total timescale span from initial concept to the end of its service career may be 30 years or even longer so every effort has to be made at the conceptual design stage to select the best balance between potentially conflicting parameter - for example, an extremely high performance objective leads to design complexity and high unit costs, while an objective of achieving the ultimate in low unit cost can lead to substantial penalties on performance and technical specification.

The early conceptual decisions will therefore need to reflect a carefully selected balance between these conflicting parameters. This selection will have to reflect:-

- the immediate technical requirement for the engine.
- longer term technical requirements (e.g. other applications).
- overall commercial and marketing considerations.
- the background and experience of the engine manufacturer.

Each of these four factors will have an influence on one particular parameter, namely the in-service Life Cycle Cost (LCC) of the engine. This paper illustrates how analysis of the LCC parameters for a helicopter powerplant can assist in selecting the basic technical concepts and configuration for a new engine.

2. The Design Scenario

The basic operational and technical requirements for the powerplant will be set at the beginning of the project by the prime customer; these requirements will form a framework within which the designer has to operate in selecting the optimum concept for the powerplant. These fundamental specifications would normally dictate:-

- the power range and power growth requirements.
- the types of operational use envisaged for the engine.
- the basic engine installation requirements and constraints.
- the reliability and life objectives and the required in-service date.

From these will come some fundamental design decisions about the engine - for example whether or not the engine should embody:-

- front or rear output drive.
- a reduction gearbox to provide low speed output.
- an integrated infra-red suppressor system.
- an integrated intake filtration system.

and what standard of fuel consumption is required to achieve the operational performance of the helicopter.

Within the constraints listed above, the designer is free to optimise the shape, form and technical content of the engine to meet the broader objectives outlined in the Introduction.

3. Relevant Engine Parameters

To establish how analysis of the engine L.C.C. can assist in design optimisation, the parameters which will have either a direct or indirect influence on the eventual L.C.C. of the powerplant need to be identified. The following table summarises these parameters and their effect.

Life Cycle Cost Parameters

ENGINE PARAMETER	L.C.C. PARAMETER INFLUENCED	EFFECT ON L.C.C.
CONFIGURATION	UNIT COST	DIRECT
	S.F.C.	INDIRECT VIA CYCLE
PERFORMANCE CYCLE	S.F.C.	DIRECT
	UNIT COST	INDIRECT VIA CONFIGURATION
	DEVELOPMENT COST	INDIRECT VIA TECH. RISK
STRESS LEVELS AND MATERIALS	LIFE & RELIABILITY DEVELOPMENT COST	DIRECT INDIRECT VIA TECH. RISK
TECHNICAL RISK	DEVELOPMENT COST	DIRECT

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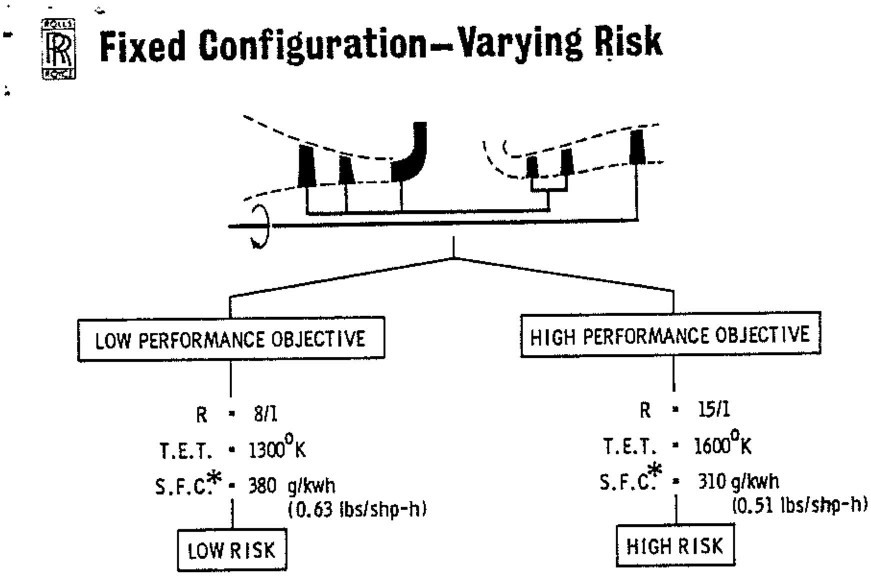
Figure 1

There will be only certain combinations of these engine parameters which can be associated together at any one time by any particular design team.

In particular, there will be only one level of technical risk acceptable for an engine that has to be developed for a specific in-service date.

4. <u>Relationships between Engine Parameters</u>

The relations between engine configuration and engine performance are the most fruitful ones to study since, between them, they dictate a major proportion of the engine Life cycle costs. If we define configuration in terms of the numbers and types of basic turbomachinery components in the engine then, for each particular configuration, there will be a range of performance levels that could be contemplated:-



(*S.F.C. at 60% power) Figure 2

It will be the levels of risk and hence development cost that will vary across the performance spectrum for any fixed configuration. Other parameters, such as unit cost, size and weight will also vary.

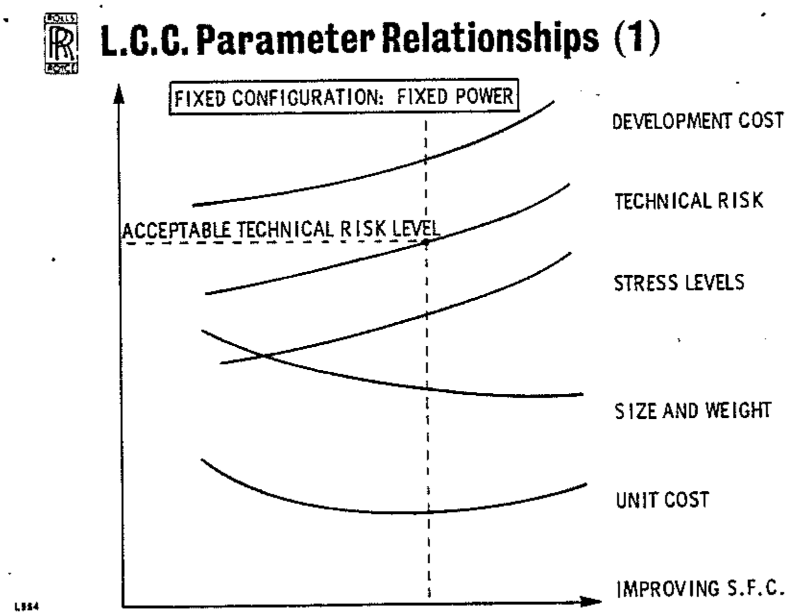


Figure 3

The benefits of improved performance (S.F.C.) are obtained at the cost of increased risk and hence increased development costs, and these two L.C.C. parameters will tend to counterbalance each other. It can be concluded therefore, that for each engine configuration there is a maximum performance level set by the acceptable level of risk, and at this performance level, the LCC of the configuration is likely to be a minimum. This hypothesis will apply for any realistic configuration, each layout having its own appropriate level of performance. Hence, for a range of configurations, the variation of these performance levels can be assessed:-

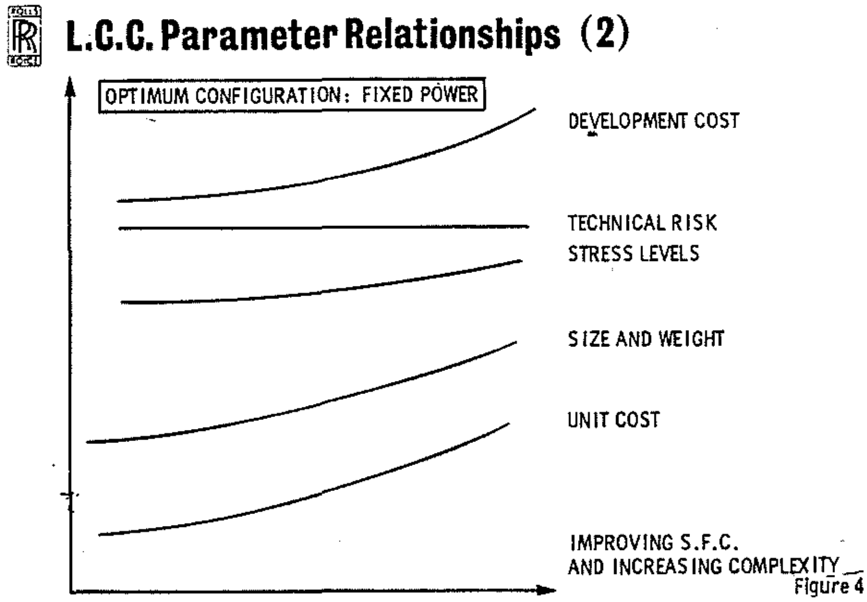


Figure 4

These parameter relationships will not necessarily be smooth or continuous, because the search for high performance could involve heat exchanger engines, for example, if they fall within the acceptable level of risk for the particular project. In addition there will be a minimum technical standard set for the engine by the helicopter which will eliminate some engine options.

This type of analysis can only begin to influence an engine design if it is on a quantitative rather than qualitative basis. The following section is a numerical analysis in which the L.C.C. parameters of a datum engine design are considered and compared with the parameters of other concepts having different levels of complexity, performance, cost etc. This datum engine will be one point on the cost / performance chart; it will not necessarily be the optimum engine from any viewpoint.

5. L.C.C. Analysis For The Datum Engine

The specific numerical example visualises the following datum situation:-

the helicopter:- a new twin engined helicopter is planned in the 8 tonne class in a timescale compatible with the design and development of a new powerplant. The new helicopter is envisaged as having world-wide Sales potential in both military and civil markets and a wide range of operational roles are therefore to be anticipated.

the engine:- the concept and design of the new engine has to be decided based on technical and commercial considerations, using an L.C.C. study as one of the inputs. A datum engine proposal is assumed and variations from this datum are considered in order to establish an optimum design concept and development approach. The datum engine is one which meets the technical and timescale requirements of the helicopter programme.

5.1 Numerical assumptions - engine

Nominal power of engine = 1200 Kw each

Fuel Consumption = 328 g/kW-h at typical cruise condition

Configuration - Front drive from single stage free turbine.

Single spool gas generator -
compressor 2 ax+cf
turbine - 2 stage

Life and reliability standard - datum, as defined in Figure 11.

Unit selling price of engine = £120,000 excluding amortisation

Development and Tooling cost amortisation = £12,000 per engine

5.2 Numercial assumptions - helicopter

Maximum Au Wt	=	8000 kg
Payload and fuel weight	=	3200 kg
Power required to cruise	=	1440 kw
Annual utilisation	=	300 hours/year
Fuel cost	=	£0.15/kg
Life cycle	=	15 years

From these basic numerical assumptions, the engine life cycle costs for one helicopter are assessed in terms of cost attributable to development, acquisition and operation:-

5.3 Development Costs

It is assumed that the selling price of the engine and engine spares includes a supplement aimed at recovering a proportion of the non-recurring costs of engine development and production launch. For purposes of this analysis of the datum engine, this supplement is taken as 10% of the basic selling price.

5.4 Cost of Acquisition

The acquisition costs are those of purchasing the two engines initially installed in the helicopter plus, it is assumed, one spare engine purchased at the same time and of the same technical standard.

5.5 Cost of Operation

Fuel costs:- for the purposes of this analysis, the life cycle fuel costs are evaluated by taking a typical level of aircraft cruise power and the corresponding S.F.C. for the two engines. A more refined analysis can be done for specific sortie patterns and mission profiles but the approximate method used here serves to illustrate the principle.

Maintenance Costs:- these are assumed to be in three categories:-

- the cost of spares used during "in field" maintenance.
    - assumed to be a cost per engine equivalent to 25% of new engine price over the 15 year life cycle.
- the costs of overhauls and module replacements required during the 15 years due to rectify significant engine problems and replace time-expired components and modules. The costs of replacement parts/modules is assumed to be 30% of new engine cost for each of these major "shop visits". The datum engine requires 4 shop visits during its 15 year lifetime.
- labour costs associated with the engine maintenance and overhaul, assuming 0.2 man hours per engine flying hour.

5.6 L.C.C. Estimate for Datum Engine/Helicopter Combination

Costs of acquisition:-

2 engines + initial spare @ £132,000 each = £396,000 per helicopter including £36,000 development cost recovery

Costs of operation:-

Fuel costs:-

300 hours/year operation for 15 years with a fuel consumption of 472 kg/hour -

LCC fuel cost = £318,000 per helicopter

"In-field" maintenance:-

Materials cost:- £66,000 per helicopter

including £600 development cost recovery

Overhaul and Major maintenance:-

Number of engine overhauls during 15 year life cycle of helicopter = 8.4 Assuming each overhaul/major maintenance activity costs 30% of the price of a new engine then Costs incurred are:-

8.4 x 0.3 x £132,000 = £333,000 per helicopter

including £30,000 development cost recovery.

Labour Costs:-

Assuming £15/man hour =

15 x 0.20 x 15 x 300 x 2 = £27,000 per helicopter

Hence, the total cost associated with acquisition and operation of the engines of one helicopter over the 15 year life span is £1,140,000 for the datum engine considered. Figure 5 summarises this data in terms of the relative contribution to overall L.C.C. made by each cost parameter.

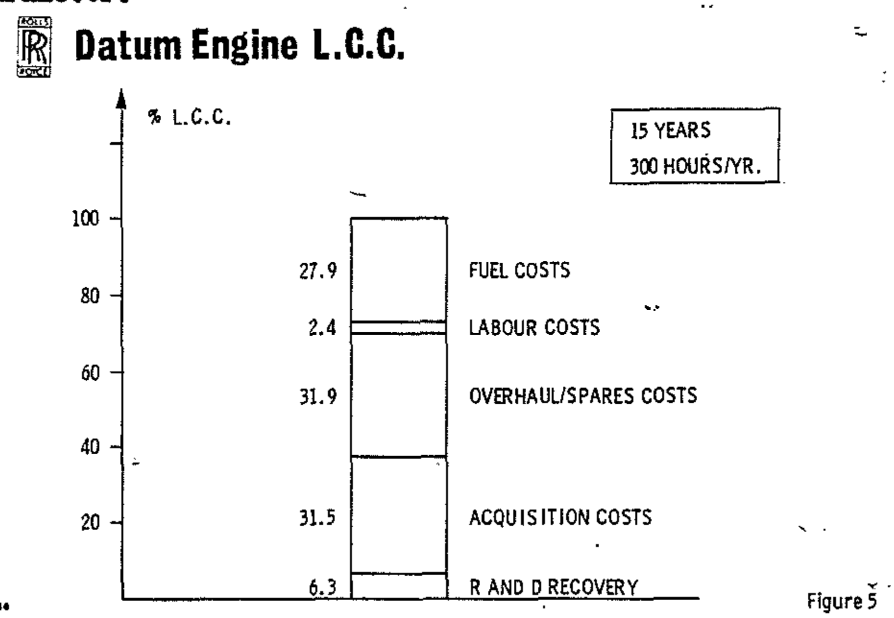


Figure 5

6. <u>Alternatives to the datum engine</u>

The datum engine is one point on the cost performance picture illustrated in Figure 5; by definition it meets the technical requirements of the datum helicopter, but there could be L.C.C. advantages with an engine of higher performance standard.. Sections 6.1 and 6.2 analyse two particular design approaches to a higher performance standard and assess the relative L.C.C trends.

6.1 Conventional engine of higher performance

To assess the L.C.C. effect an alternative design has been analysed which offers a 10% improvement in performance. The characteristics of this alternative engine are shown in Figure 6.

Technical Summary for Alternative Designs

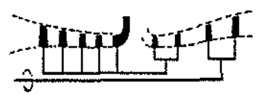
	DATUM ENGINE	HIGH PERFORMANCE ENGINE
CONFIGURATION		
PRESSURE RATIO	12/1	16/1
T.E.T. (°K)	1350	1500
AIR FLOW (Kg/s)	5.2	4.3
POWER (kW)	1200	1200
S.F.C. AT 60% POWER (g/kW.h)	328	295
UNIT COST £	120,000	145,000
R AND D RECOVERY £	12,000	14,000

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Figure 6

Converting these basic characteristics into the L.C.C. parameters gives the results shown in Figure 7, which is a comparison with the datum engine.

L.C.C. Comparison for Two Technical Standards

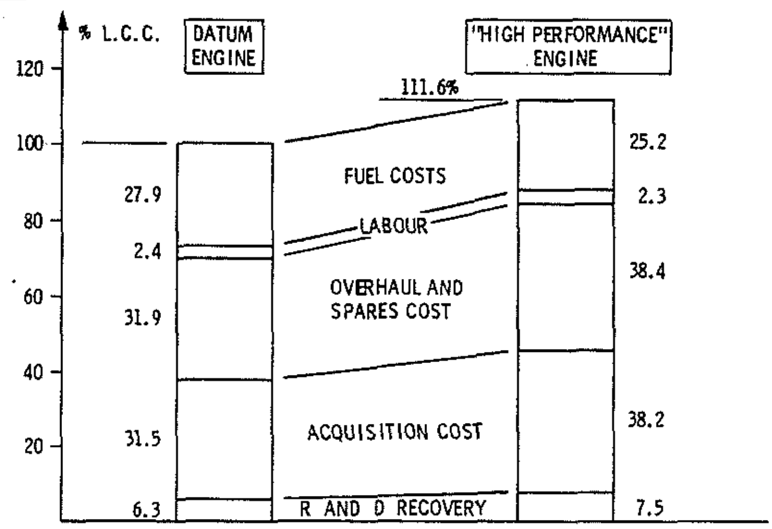


Figure 7

It shows that, despite its improved performance, the L.C.C. costs are estimated to be 12% higher than the datum engine

The extra (production) cost associated with the increased complexity has outweighed the fuel cost savings. Clearly this analysis is sensitive to fuel costs but it requires a five fold increase in fuel price relative to every other L.C.C. parameter before the two engines considered have equal L.C.C.'s. Even if the assumed annual utilisation is doubled from 300 to 600 hours per year, the L.C.C. for the datum engine is still 9% lower than the high performance engine. Again, a very large increase in fuel price is needed (X3.7) to offset this margin. The datum engine still retains an L.C.C. advantage at a high utilisation of 1200 hours/year; clearly the unit cost penalties of the "improved performance" engine are too severe.

6.2 Unconventional engines

The "high performance engine" considered in section 6.1 is a logical extrapolation of the datum engine technology:- higher performance from higher pressure ratio and temperatures and hence greater complexity. There is today, increasing interest in heat exchange powerplants as a possible solution to the cost/complexity penalties of conventional engines. If H.E. engines fall within the acceptable level of risk for the particular project then an L.C.C. analysis can be particularly valuable to the design optimisation because of the large number of design variables that exist.

A typical H.E engine proposal has been included in this analysis and its assumed characteristics are summarised in Figure 8.

Technical Summary for H.E. Engine

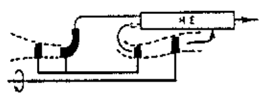
	DATUM ENGINE	H.E. ENGINE
CONFIGURATION		
PRESSURE RATIO	12/1	8/1
T.E.T. (°K)	1350	1550
AIR FLOW (kg/s)	5.2	4.6
POWER (kW)	1200	1200
S.F.C. @ 60% POWER (g/kW-h)	328	230
UNIT COST £	120,000	150,000
R AND D RECOVERY £	12000	18,000

Figure 8

The L.C.C. comparison of such an engine with the datum powerplant is illustrated in Figure 9.

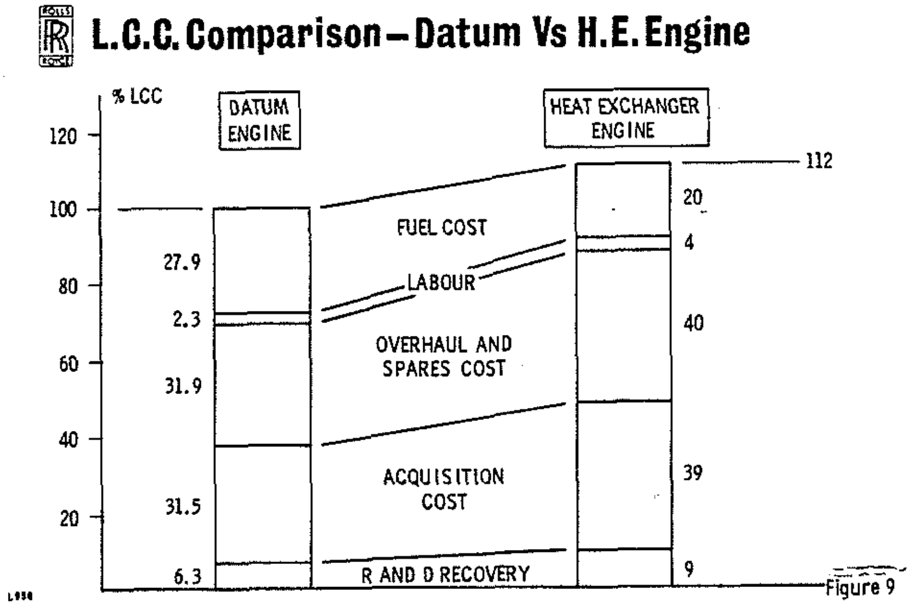


Figure 9

Again, the datum engine retains its cost advantage, despite the 30% lower S.F.C. of the H.E. engine. The comparison is now more sensitive to fuel cost since a 2.4 times increase in fuel relative to other prices results in equal L.C.C.'s. At 600 hours/year utilisation, a relative fuel cost of 1.7 times the datum price results in equal costs. Hence this analysis shows that H.E. engine concepts are a more promising route for the designer to investigate than conventional "high performance, complex engines".

7. Other Considerations

7.1 Unit Production Costs

The cost of engines and spares affects, directly or indirectly, over 60% of the engine L.C.C. in the analysis made above. It is assumed that each design concept studied embodies design features and manufacturing techniques that will produce the lowest unit cost for that engine, compatible with the required production rates and quantities for the programme. However, if increased expenditure on tooling, for example, produces lower unit costs then such expenditure can reduce L.C.C.'s. For the datum engine, the designer can afford to double the total development and tooling amortisation per engine, provided a unit cost reduction of at least 10% is obtained from the improved production methods.

7.2 Alternative Development Strategies

Nearly 35% of the datum engine L.C.C. is attributable to maintenance and overhaul costs and the cost of spares and replacements is the major part of that 35%. An improvement in the Mean Achieved Life (MAL) of the engines in service, particularly in the early years, can make a significant reduction in maintenance and overhaul costs. Hence it is relevant to assess the possible L.C.C. benefits of supplementing the basic development programme with a "maturity programme" aimed at increasing the MAL especially in the early years.

The datum engine was defined as one that meets the timescale requirements of the initial application, and the timing and content of the development programme were set accordingly. The programme content aimed at meeting the certification requirements and developing sufficient engine maturity to give a realistic Entry into Service (E.I.S) life and reliability standard. This standard is assumed to give a 500 hour M.A.L. for the first batch of service engines. Thereafter, the MAL of subsequent batches of engines is assumed to increase progressively with time and service experience, towards 2500 hours after 15 years as the result of normal life extension and reliability improvement work.

To have maximum benefit a maturity programme needs to be completed before E.I.S., this implies either starting engine development earlier or slipping the E.I.S. date. The latter is clearly not acceptable and the former is usually impractical when engine development timescales are as long or longer than those for helicopters. The Maturity Programme assessed here assumes that no extension of timescale is feasible and that the maturity programme runs through the early years of service. The technical standard of the first production engines does not benefit, but progressively increasing benefits are felt in subsequent years.

Figure 10 shows the timing and relative costs assumed for the development and maturity programmes.

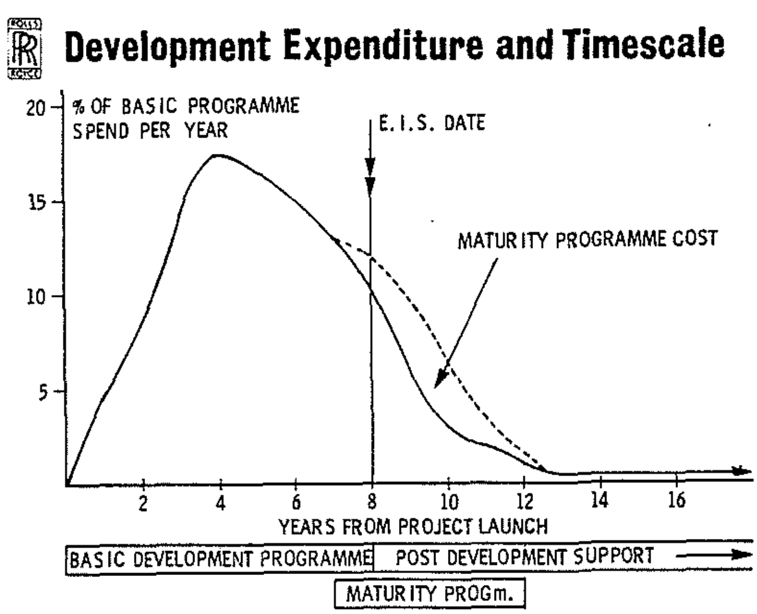


Figure 10

Figure 11 shows the estimated impact of the additional maturity programme on the service life and reliability.

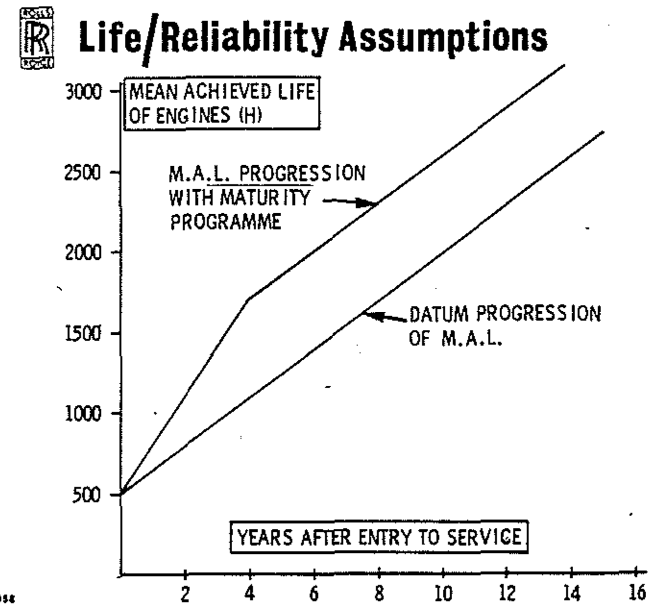


Figure 11

On completion of the formal maturity programme, the MAL of the engine continues to improve at a similar rate to the datum programme as a result of normal life development activity. In addition it is anticipated there will be a saving in maintenance man hours for the more mature engine.

The impact of the maturity programme on the requirements for engine/ module overhaul is quite signficant over the 15 year life cycle. The datum engine L.C.C. is reduced by approx. 5% with the assumed maturity programme (see Figure 12).

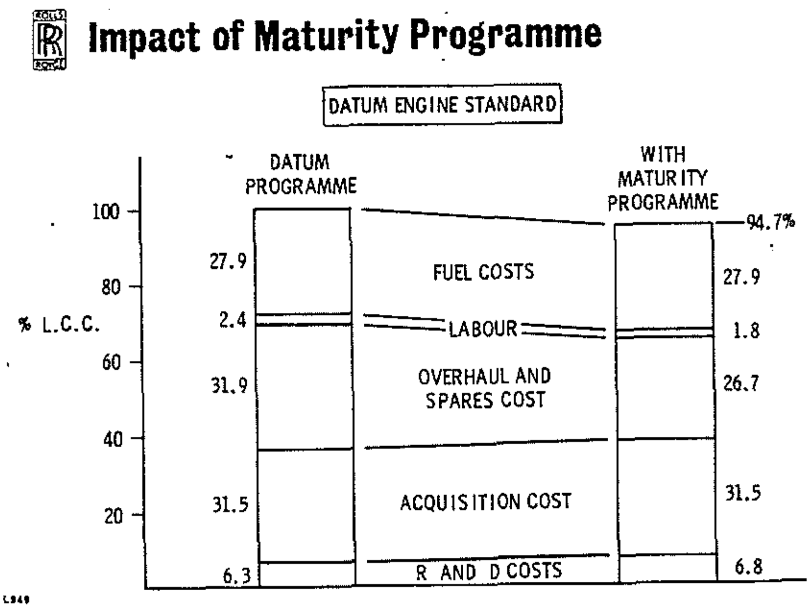


Figure 12

At higher annual utilisations the savings are greater, and they are also greater for engine concepts that incur high overhaul and spares costs e.g. the H.E engine. In addition there will be a number of other benefits from the maturity programme in terms of improved safety and operational readiness, reduced spares inventory and lower requirements for in-service modifications.

8. Conclusions

The numerical analysis presented in this paper shows how L.C.C. analysis can assist at the conceptual design stage, in particular in the selection of engine configuration.

The key is deciding what level of technical risk is acceptable since this draws a dividing line between technical features which may or may not be included in design studies. Having made that decision then alternative designs which meet or exceed the technical requirements can be studied. For the assumptions made in this paper, the technical conclusion is that engine L.C.C is significantly higher for engine concepts that achieve improved performance at the expense of increased production, R&D, and maintenance costs. This trend will be counterbalanced under certain circumstances by payload/range benefits to the helicopter with the higher performance engines. The L.C.C analysis can clearly be extended to the engine/airframe combination to assess this effect.

The paper also illustrates the potential benefits of maturity programmes. These benefits are still worthwhile when the total development timescale cannot be extended to the ideal of completing the maturity programme before entry into service.

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