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EFFECT OF ENGINE TECHNOLOGY ON ADVANCED FIGHTER DESIGN AND COST

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ABSTRACT

The more the development of a new fighter aircraft in Europe is delayed, the more the question, whether an existing or derivative engine is still adequate or if a new engine development is desired, gains in importance.

This paper investigates the effect of possible improvements in engine technology on the design and performance of an advanced fighter of the next generation. The improvements are shown relative to the engine generation existing today. The life cycle cost of engine and aircraft are also considered and an attempt is made to show if a new engine development is cost-effective.

1. INTRODUCTION

For different reasons like rapid increase of development- and production cost, limited budgets available and the possibility to stretch the life of existing fleets, the start of a full scale development of an European advanced air superiority fighter is now delayed for nearly one decade. However, studies, component- and technology development have been going on in several countries. Simultaneously the requirements are growing in order to ensure combat superiority and an advanced, long life design.

Since the in-service target-date is now expected not before the mid Nineties, there would be just enough time for a new engine development, if go-ahead is given soon. A multinational partnership between engine manufacturers would relax potential time-, risk- and cost problems. The existing engines will be somewhat out of date in the mid Nineties; in addition the present European high bypass engine is not optimized for an air superiority fighter. Thus the question arises, if existing engines or their derivatives will be still adequate or whether an engine with advanced technology is mandatory.

This paper investigates the effect of improved relative to existing engine technology on the design and performance of the next fighter generation . Furthermore, the life cycle cost are compared and an attempt is made to show if a new engine development is cost effective.

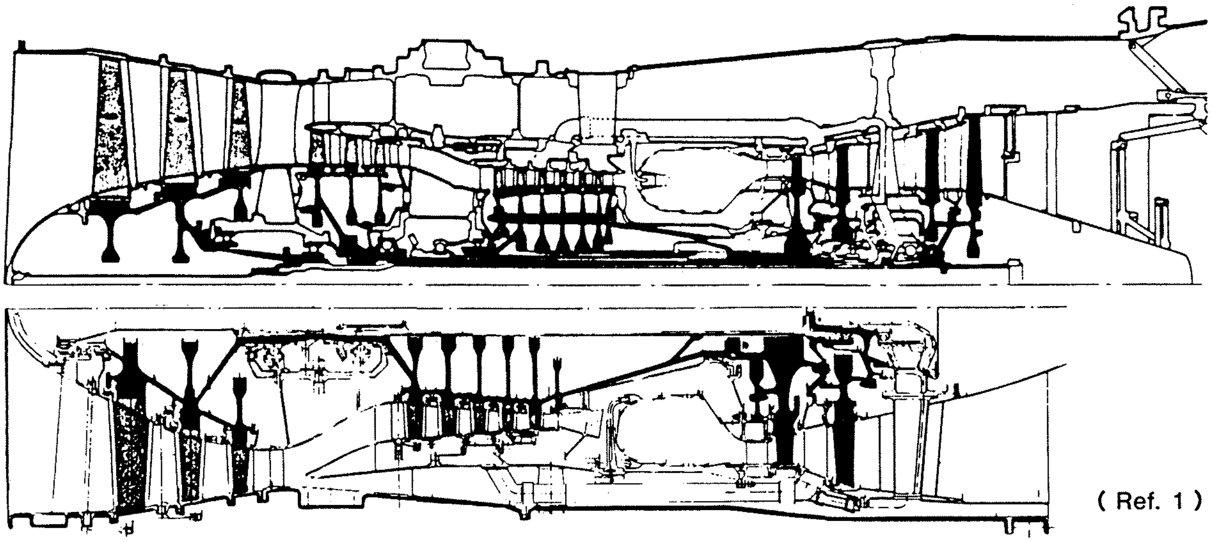
2. ADVANCEMENTS OF THE NEXT FIGHTER ENGINE GENERATION

Besides improving existing engines and offering derivatives all major engine manufacturers consider the development of a totally new engine for the next generation of fighters. It is well understood that an engine development will not pay off, if only performance parameters are slightly increased. Simultaneous improvements such as operational suitability, reliability, maintainability and cost (acquisition and cost of ownership) are indispensable.

In general terms the technology of the next generation of engine differs from the existing one by:

- Aero-thermo-dynamics: leading to improved component efficiencies, higher specific mass flows and increased compression ratios per stage (higher rotational/ circumferential/ axial speeds)
- Materials, cooling methods and barrier coatings: enabling a substantial raise of turbine entry temperature to increase specific thrust and improve reheat SFC's
- Mechanical design: reducing complexity i.e. less parts, stages, airfoils with increased rigidity may lower acquisition- and operational cost and will improve the "-ilities".

Fig. 1 indicates the effects of this progress in rough quantities. The 40 % higher thrust to weight and thrust to frontal area ratio either improves aircraft performance for fixed engine physical dimensions or leads to a lighter engine with smaller diameter, thus reducing aircraft weight, size, drag and cost for a given performance level. A future moderate bypass-ratio design combines the good reheat-SFC of the low-bypass engine with the favourable dry-SFC of the high-bypass engine (see Fig. 2). This either enhances mission range and combat time or allows a substantial saving of tank volume, fuel weight and cost.



(Ref. 1)

Advanced Design :

- 40 % Higher Thrust to Weight and Thrust to Frontal Area
- 30 % Higher Thrust to Airflow
- 10 % Higher Airflow to Frontal Area
- Improved Specific Fuel Flows
- Up to 40 % Less Parts

➤➤ About 30 % Reduction in Aquisition Cost per Pound of Thrust

Fig. 1 Next Generation Technology

Data Base

The performance and cost data for the future engine are based on a common MTU and MBB investigation conducted in spring 1983. A certain technological standard as expected to be available in the mid Nineties was assumed.

The main design features are:

- Mixed flow turbo fan with afterburner
- Moderate bypass-ratio 0.5 : 1 at the design point
- 3 stage low pressure compressor with variable inlet guide vanes
- 5 stage high pressure compressor with 2 variable stages
- Total compression ratio 24:1 at the design point
- Annular combustion chamber
- 1 stage cooled high pressure turbine, allowing a maximum stator outlet temperature (SOT) some 250 K higher than existing engines.
- 1 (or 2) stage cooled low pressure turbine
- Fully variable convergent-divergent axisymmetrical nozzle.

The chosen engine cycle parameters result from previous cycle studies conducted together with MTU. The moderate bypass ratio of 0.5 represents a good compromise for a variety of expected fighter war- and peace-time missions. The overall compression ratio of 24:1 at SLS-design point enables good dry SFC without exceeding the thermal structural limit of the last HP-compressor disc.

Fig. 2 shows a comparison of some important performance parameters of this future design relative to existing engines. On the basis of this technology difference the effect on aircraft performance or weight was investigated.

	Alt/Mach/P/S	Existing Engines		Future Engine
Turbine Entry Temperature		1600 – 1650 K		1850 – 1900 K
Thrust to Weight	0/ 0/Max	7.5		9.9
	11/1.8/Max	5.7		7.2
Thrust to Frontal Area	0/ 0/Max	180 kN/m^2		245 kN/m^2
	11/1.8/Max	135 "		180 "
Thrust to Airflow	0/ 0/Max	1.00 – 1.10 kNs/kg		1.27 kNs/kg
	11/1.8/Max	0.9 – 1.0 "		1.04 "
Specific Fuel Consumption rel. to High-Bypass Engine		High-	Low-Bypass	
	0/ 0/Max	100 %	82 %	80 %
	11/1.8/Max	100 %	85 %	85 %
	0/0.6/Cruise	100 %	112 %	102 %
	11/0.9/Cruise	100 %	110 %	100 %

Fig. 2 Comparison of Important Engine Performance Parameters

3. METHOD OF EVALUATION

3.1 General

A predicative assessment of the future relative to the existing engine technology can only be conducted by involving a relevant aircraft design, analyzing the point performance and mission requirements and evaluate the effects on performance or weight in relation to the total required cost.

3.2 Point Performance Requirements

This study is based on typical fighter manoeuvre performance goals such as turn rates, turn radii, specific excess power values in the subsonic range and maximum Machnumber sustaining a 4g turn at the optimum altitude in the supersonic regime.

Max. Sustained Turn Rate	10 kft	➞	Wing Area, Thrust
Sustained Turn Radius	10 kft	➞	Wing Area, Thrust
Max. Attained Turn Rate	10 kft	➞	Wing Area
Spec. Excess Power	Ma:0.7, 3 g, 10 kft	➞	Thrust
Spec. Excess Power	Ma:0.9, 1 g, SL	➞	Thrust
Max. Sustained Machnumber	4 g, Opt. Alt.	➞	Thrust

Fig. 3 Point Performance Requirements

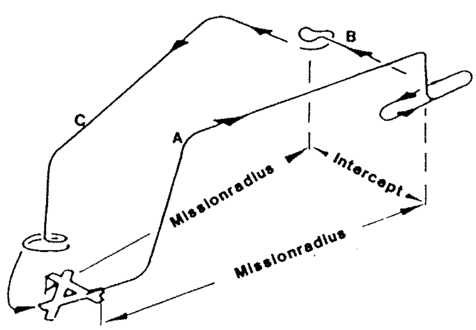
Fig. 3 shows the assumed requirements and indicates by which the wing area or engine size is affected.

3.3 Mission Requirements

Two typical main missions (see Fig 4) were assumed for this study, which essentially define the required internal fuel capacity of the aircraft design:

- **Mission A:** An air superiority mission with internal fuel only, where a high amount of the total fuel is consumed during subsonic cruise and loiter phases.
- **Mission B:** A combination of combat air patrol, flown with external fuel and a subsequent minimum time intercept phase leading to a medium range combat. The internal fuel capacity in this case is defined by the mission legs beginning with the intercept phase.

The two missions obviously differ in the amount of fuel consumed at or close to maximum power setting. In mission A about 30 % of internal fuel is burnt during take off and combat phase with full afterburner, while in mission B about 75 % of the available internal fuel is used up during climb, acceleration, supersonic cruise and combat phase with afterburner.

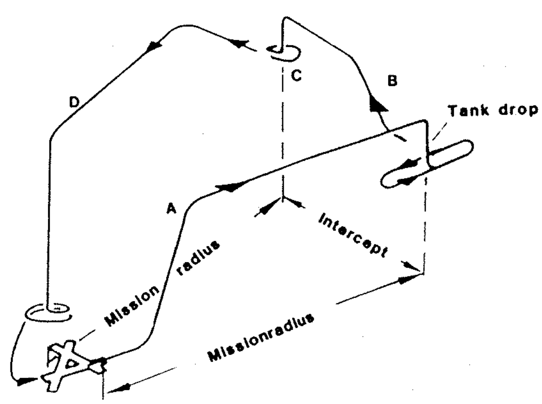


Mission A

A) Take off, economic cruise out and loiter

B) Intercept acceleration and combat (max P/S)

C) Economic cruise back and landing



Mission B

A) Take off, economic cruise out and long time loiter with external fuel

B) Intercept climb, acceleration (max P/S) and supersonic cruise

C) Combat (max P/S)

D) Economic cruise back and landing

Fig. 4 Assumed Missions : A) Air Superiority
B) Combat Air Patrol and Minimum Time Intercept

3.4 Configuration

For this study a single seat, twin-engine delta canard configuration as shown in Fig. 5 was chosen. The design with moderate instability, low wing loading and variable geometry two shock underfuselage inlets is tailored to the specific performance requirements in Fig. 3 and optimized for high angle of attack maneuvres, short take off and landing distances, low drag and good supersonic acceleration. It offers high agility in the short and medium range combat scenario by high thrust to weight ratio and special means like vectoring nozzles.

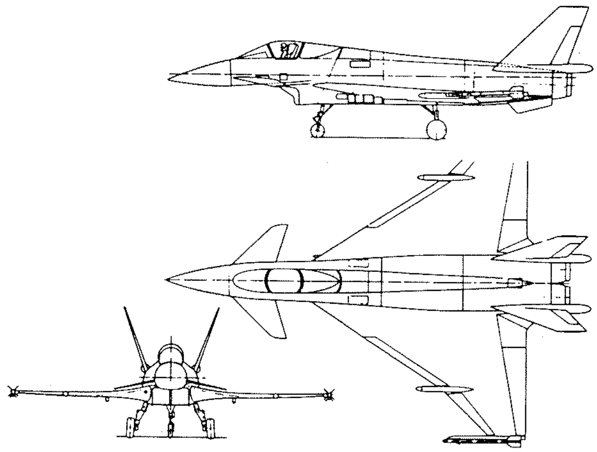


Fig. 5 Baseline Configuration

3.5 Methodics

Simultaneous with the required wing loading and engine size resulting from the point performance goals the fuselage size is in addition to other criteria derived from the amount of fuel necessary to meet either the desired radius of mission A or the desired combat time of mission B.

Two different approaches have been applied leading to two corner point aircraft designs:

- **Step I:** New engines (future technology) installed in a physically unchanged aircraft, i.e. new engines have the same main dimensions as the existing ones, with the consequence of essentially higher engine- and aircraft performance.

- **Step II:** The aircraft is scaled down together with the new engines to keep mission- and maneuvre performance to the same level as for the aircraft with existing engines. Aircraft-, engine- and fuel-weights are thus considerably reduced.

For these two datum designs the acquisition and life cycle cost have been established and compared with an aircraft design equipped with existing engines.

4. RESULTS

4.1 Performance Gain with Fixed Aircraft Size

In the first step the future engine with similar main dimensions as the existing high bypass engine was installed into the unchanged airframe. Fig. 6 shows the changes of point performance, mission A radius and mission B combat time of the aircraft with new engines relative to the one with existing engines. The aircraft performance for the existing high bypass engine is selected as reference. The performance for an existing low bypass engine is additionally shown in order to separate the effect of cycle and technology.

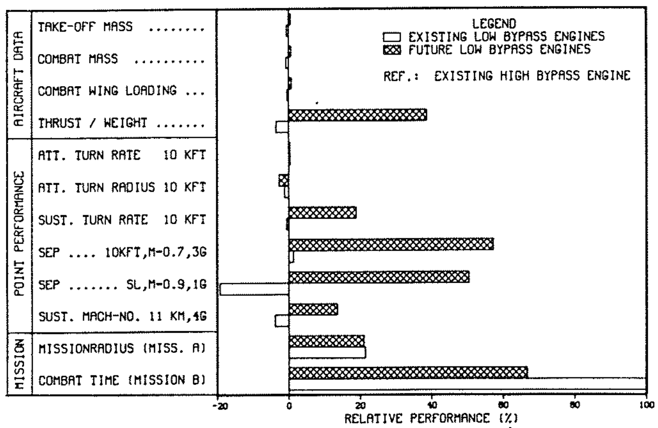


Fig. 6 Aircraft Performance Comparison

Due to the very similar wing loading all aircraft show nearly equal instantaneous turn capability. The thrust dependent performance, which is close together for the existing engines, gains up to 60 % for the future engine. Mission A radius and mission B combat time are strongly dependent on the engine cycle and gain from a future engine mainly from matching the cycle to the postulated missions.

The excessive raising of sustained aircraft performance can not be entirely utilized, since due to the expected avionics- and weapon-technology an increase of conventional maneuverability in the subsonic regime will not substantially increase combat effectivity. Thus the advantages of this solution with regard to combat superiority seem to be marginal.

In addition the thrust dependent performance exceeds by far the expected air staff targets.

4.2 Aircraft Weights for a Constant Performance Level

In a second step the aircraft with the advanced engine, described in 4.1, was scaled by relevant computer programs with respect to size, weight, drag, fuel etc. including the engine such that the missions are still fullfilled and the maneuvre performances are brought to the same level as for the aircraft with existing engines (high bypass). Unscalable items as weapons, avionics, cabin, a.s.o. were kept constant.

Related to the latter as a datum it can be seen from Fig. 7 that the aircraft masses with the new engine can, dependent on the mission considered, be reduced by up to 20 %, the masses for the fuel and the engine by even 37 %. This leads to an airframe, which is up to 20 % smaller in wing area and wetted surface, 30 % smaller in cross section and 10 % smaller in fuselage length and wing span.

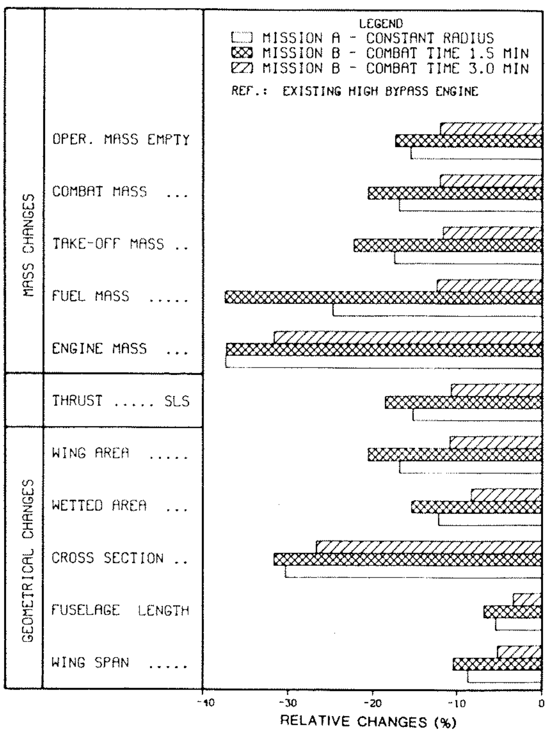


Fig. 7 Aircraft Mass and Size Changes for Constant Requirements

The three designs (bars in Fig. 7) differ mainly by the amount of internal fuel necessary for the mission. For mission A the fuel capacity is sized to keep the given radius constant; for mission B it is sized to achieve a combat time of 1.5 minutes or 3.0 minutes respectively.

The remarkable reduction in masses and dimensions will certainly lead to a less expensive airframe and to a significant fuel saving during peace-time operation.

4.3 Life Cycle Cost Comparison

For the reference aircraft with the current (high bypass) engine and the two corner point designs with the new engine i.e. the "same size aircraft" as shown in Fig. 6 and the "same performance aircraft" as shown in Fig. 7 the life cycle cost (LCC) have been established for the engine (input of MTU) and the airframe. The main elements of the LCC are:

- **Development cost** including flight test, component improvement post FQT and part of production investment.
- **Procurement cost** including part of production investment, acquisition cost of the production units (300 aircraft as part of an assumed trinational programme) with initial spares and initial support, consumable spares, AGE, documentation.
- **Operation and support** for 300 aircraft with 1.156 million flying hours (= 2.312 million engine flying hours) within 20 years, maintenance, material and fuel.

For simplicity only these three main blocks have been plotted into the relative cost comparison in Figures 8 and 9, the operation and support cost (cost of ownership) just splitted in fuel cost and the rest. The fuel cost are based on a peace time mission-mixture. The economic conditions for all cost in this study are January 1983.

Looking to the engine LCC in Fig. 8 first, column B shows minor development cost for the existing engine (adaptation for the new fighter) about 35 % acquisition cost 15 % for maintenance/material and 49 % fuel cost, if the total LCC are 100 % (reference).

Relative to the reference the LCC of the future engine of the same physical size (column A) increase to 113 % mainly caused by the development cost which are now essential. The other cost elements do not differ much from column B. The procurement costs of the future engine are even smaller due to its lower complexity.

The scaled future engine (same aircraft performance) in column C needs still a high amount of development, however, the procurement cost, mainly because of the smaller engine size and its simpler design are reduced to a level, such that acquisition cost including development are already less than for the existing engine. Some further gain is achieved from the maintenance/-material cost part and essential improvement can be seen from the reduced fuel cost, altogether adding up to only 87 % LCC relative to the existing engine.

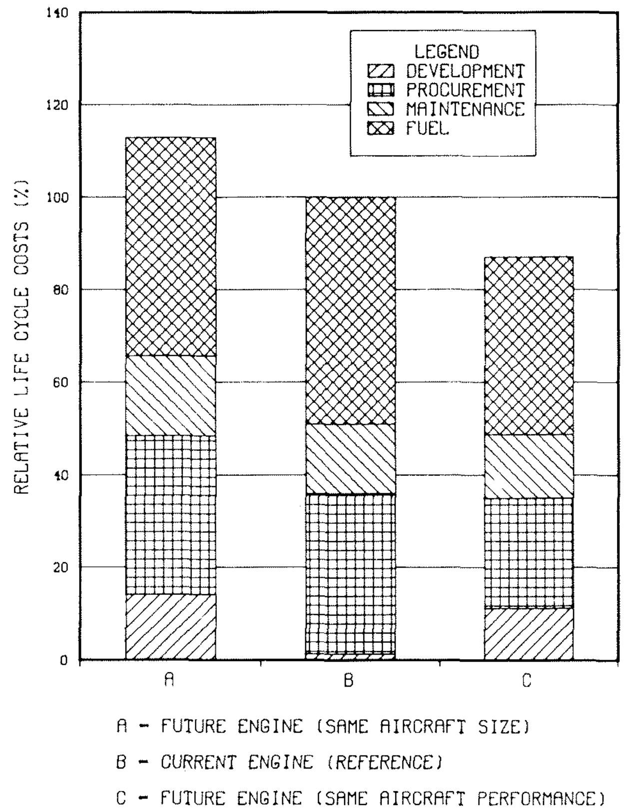


Fig. 8 Engine Life Cycle Costs

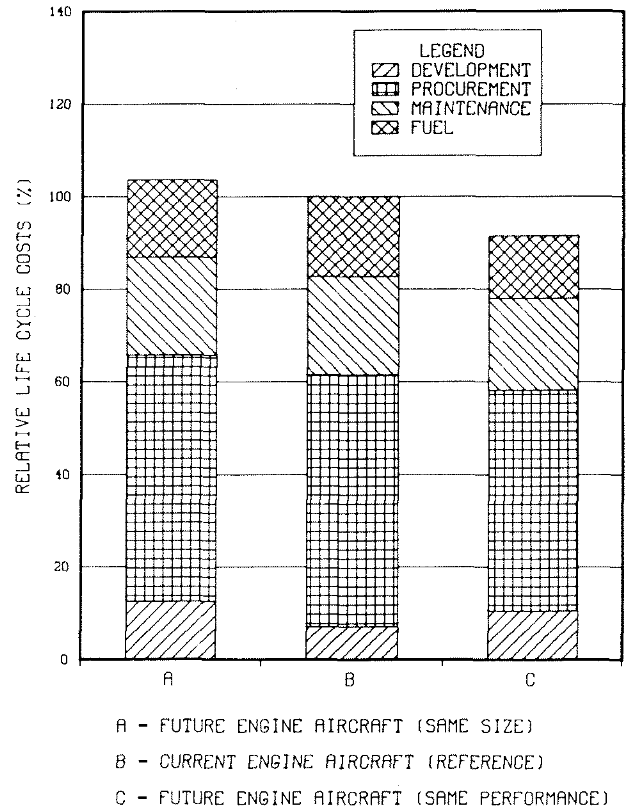


Fig. 9 Aircraft Life Cycle Costs

Considering the total aircraft LCC in Fig. 9 (airframe plus engine), the picture looks quite similar except that the fractions within the LCC are split up differently. The procurement is the major part (about 50 %), maintenance/material approximately 20 % and fuel roughly 15 % of the total. Relative to the reference aircraft with the existing engine (column B) the aircraft with the new engine of the same size and higher performance (A) is 3.5 % more expensive during its life cycle. The LCC for the aircraft scaled down to the same performance level as the reference (B) are only 91.6 %. Again, although the development cost for this aircraft are higher (for the new engine development), the amount of money necessary up to acquisition is less than for the reference aircraft. As can be seen from the figure maintenance contributes to a certain amount and fuel consumption essentially to the cost savings of the scaled aircraft (C).

Summarizing the message of Fig. 9 is:
The development cost for a new engine for a given aircraft performance level are more than compensated by the lower procurement cost. In addition the cost of ownership are essentially lower resulting in a life cycle cost saving of more than 8 %.

4.4 Break-even Point and Sensitivity

Since the procurement cost savings of the scaled aircraft C strictly depend on the number of the acquired units the economic efficiency of the new engine development can be expressed by the number of aircraft which are necessary to achieve equal cost as for the reference aircraft B with the available engine. This break-even point is shown in Fig. 10 (solid line). At the start of the users phase (acquisition including development) it is at 450 aircraft. Considering LCC for 20 years operation, the break-even is already achieved with 270 aircraft.

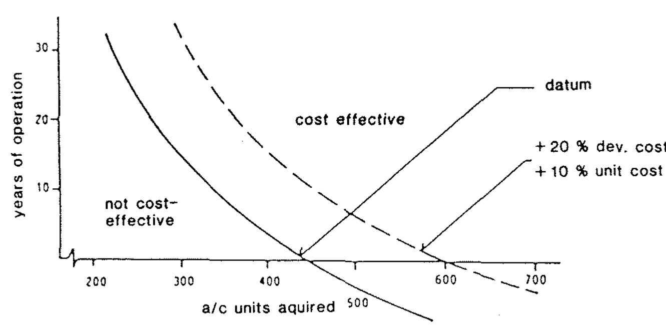


Fig. 10 Cost Effectiveness of an Engine Development

In order to obtain an idea of the sensitivity of the break-even point to changes in the assumed cost, a calculation was done with 20 % higher development and 10 % higher production unit cost of the engine. The dotted line in Fig. 10 shows the result. The break-even points shift to 600 aircraft considering acquisition (+ development) only or 360 aircraft respectively counting LCC over 20 years operation.

5. SUMMARY

A detailed configuration-, performance- and cost analysis has been conducted for a European next generation air superiority fighter with the aim of quantifying the technical- and cost-effectiveness of using either an existing or a newly developed advanced engine.

With the assumptions described in the report concerning the technology level and cost data of the advanced engine, the time scale and the expected missions, the result of the study is as follows:

A new engine is not only technically superior but also leads to a less expensive programme, if the progress of the new technology is used to reduce the size of engines and aircraft relative to a design with an existing engine. The thrust dependent conventional aircraft performance should be kept at the required level and not be excessively increased since this, according to our studies [3] cannot further improve combat effectiveness in the subsonic regime with the new generation of avionics and weapons.

With the "small aircraft approach" the development cost for the new engine can be recovered already at the end of the acquisition phase, provided at least 450 aircraft will be procured. Considering the total life cycle cost the break-even point is less than 300 aircraft.

These numbers may be marginal for a national programme, for a multinational concept however, they clearly indicate that a new engine development is cost effective.

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