Effect of Engine Technology on Advanced Fighter Design and Cost

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The longer the development of a new European fighter aircraft is delayed, a central question becomes ever more critical: Is an existing engine still adequate or is it necessary and more cost-effective to develop a new engine? To help answer this question, a detailed study of the configuration, performance requirements, and costs has been conducted. Based on typical aircraft design and performance, the effect of the expected performance and cost of a newly developed engine on either higher aircraft performance or lower aircraft weight and cost was investigated. A completely new engine was found to be not only technically superior, but also less expensive, if 1) the new technology were used to reduce the size of the engine and aircraft and 2) the aircraft performance were held constant. With this "small aircraft approach," the development cost for a new engine can be recovered at the end of the acquisition phase, provided at least 450 aircraft are sold. Considering the total life cycle cost, the break-even point is less than 300 aircraft. For a multinational concept, these results clearly indicate that the development of a new engine is cost effective.

Introduction

VARIOUS factors, including the rapid increase in development and production costs, the limited budgets available, and the possibility of stretching the life of existing fleets, have delayed the start of full-scale development of a European advanced fighter aircraft for nearly a decade. However, component and technology development studies are ongoing in several countries. Simultaneously, the requirements have increased to ensure combat superiority with a long-life design.

Since the in-service target date is now not expected before the mid-1990s, there is just enough time for the development of a new engine, if the go-ahead is given soon. A multinational partnership between the engine manufacturers should relax potential time, risk, and cost problems. The existing engines will be out of date in the mid-1990s; in addition, the present European high-bypass-ratio engine is not optimized for an advanced fighter. Thus, the question arises whether the existing engines or their derivatives will still be adequate or whether an engine with advanced technology is mandatory.

The results of a study investigating the effect of improved engine technology on the design and performance of the next fighter generation is described herein. In addition, the life cycle costs are compared and the cost effectiveness of a new engine development is discussed.

Advancements in the Next Fighter Engine Generation

Besides improving existing engines and offering derivatives of them, all of the major engine manufacturers have been considering the development of a totally new engine for the next generation of fighter aircraft. It is well understood that an engine development will not pay off if only the performance parameters are slightly increased. Simultaneous improvements in such items as operational suitability, reliability, maintainability, and cost (acquisition and maintenance) are indispensable. In general, the technology of the next generation of engines differs from current models in several ways:

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1) Aerothermodynamics: improved component efficiencies, higher specific mass flows, and increased compression ratios per stage (higher rotational/circumferential/axial speeds).

2) Materials, cooling methods, and barrier coatings: a substantial increase in turbine entry temperatures for higher specific thrust and improved reheat specific fuel consumption (sfc).

3) Mechanical design: reduced complexity, i.e., fewer parts, stages, and airfoils with increased rigidity. These may lower acquisition and operational costs and improve the "-ilities."

Figure 1 indicates the effects of technological progress in approximate quantities. The 40% higher thrust-to-weight and thrust-to-frontal-area ratio can be used to either improve aircraft performance for fixed engine physical dimensions or to utilize a lighter/smaller engine, thus reducing the aircraft's 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 favorable dry sfc of the high-bypass-ratio engine (see Table 1). This either enhances the mission range and combat time or allows a substantial saving of tank volume, fuel weight, and cost.

The performance and cost data for the advanced engine are based on a joint Motoren-und Turbinen-Union (MTU) and Messerschmitt-Boelkow-Blohm (MBB) investigation conducted in the spring of 1983. A certain technological standard, expected to be available in the mid-1990s, was assumed. The main design features are:

1) Mixed-flow turbofan with afterburner.

2) Moderate bypass ratio of 0.5:1 at the design point.

3) Three-stage, low-pressure compressor with variable inlet guide vanes.

4) Five-stage, high-pressure compressor with two variable stages.

5) Total compression ratio of 24:1 at the design point.

6) Annular combustion chamber.

7) Single-stage, cooled, high-pressure turbine, allowing a maximum stator outlet temperature (SOT) some 250 K higher than existing engines.

8) Single- or two-stage, cooled, low-pressure turbine.

9) Fully variable convergent-divergent axisymmetric nozzle.

The chosen engine cycle parameters result from previous joint studies conducted by MBB and MTU.[2,5,6] The moderate bypass ratio of 0.5 represents a good compromise for a variety of expected fighter war- and peacetime missions. The overall compression ratio of 24:1 at Sea Level Static (SLS) design point enables good dry sfc without exceeding the thermal structural limit of the last high-pressure compressor disk.

Table 1 compares some of the important performance parameters of this advanced design to those of existing engines. On the basis of these technological differences, the effect on aircraft performance and/or weight was investigated.

Method of Evaluation

An assessment of advanced relative to existing engine technology can be conducted only by using a representative aircraft design, analyzing the point performance and mission requirements, and evaluating the effects on performance or weight in relation to the total required cost.

Point Performance Requirements

This study is based on the typical goals for fighter maneuver performance, such as turn rates, turn radii, specific excess power values in the subsonic range, and maximum Mach number sustaining a 4 g turn at the optimum altitude in the supersonic regime. Table 2 shows the assumed requirements and indicates which affects the wing area or engine size.

Mission Requirements

Two typical primary missions (see Fig. 2) were assumed for this study, essentially defining the required internal fuel capacity of the aircraft design as:

1) Mission A—An air superiority mission with internal fuel only, where a high amount of the total fuel is consumed during the subsonic cruise and loiter phases.

2) 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 encounter. The internal fuel capacity in this case is defined by the mission legs beginning with the intercept phase.

These two missions obviously differ in the amount of fuel consumed at or close to the maximum power setting. In mission A, about 30% of internal fuel is burned during the takeoff and combat phases with a full afterburner; in mission B, about 75% of the available internal fuel is used during climb, acceleration, supersonic cruise, and combat with an afterburner.

Configuration

For this study, a single-seat, twin-engine delta canard configuration was chosen. See Fig. 3. The design with moderate instability, low wing loading, and variable-geometry two-shock underfuselage inlets is tailored to the specific performance requirements listed in Table 2 and optimized for high-angle-of-attack maneuvers, short takeoff and landing distances, low drag, and good supersonic acceleration. It offers high agility in the short- and medium-range combat scenario with a high thrust-to-weight ratio and special features such as vectoring nozzles.

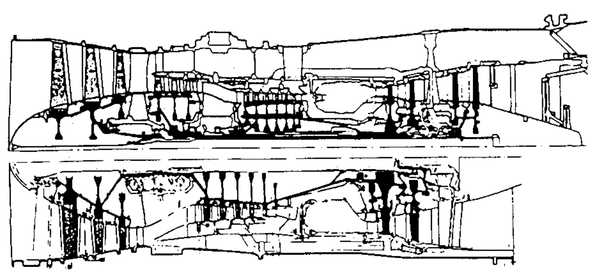
Methodology

The required wing loading and engine size resulting from the point performance goals are worked out at the same time as the fuselage size which is 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 (advanced technology) installed in a physically unchanged aircraft, i.e., new engines having the same main dimensions as the existing ones, with the consequence of essentially higher engine and aircraft performance.

Step II: The aircraft is scaled together with the new engines to keep mission and maneuver performance at the same level as that of aircraft with the existing engines. Aircraft, engine, and fuel weights are thus considerably reduced.

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



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 Acquisition Cost per Pound of Thrust

Fig. 1 Next generation of a technologically advanced fighter aircraft engine (from Ref. 1).

Table 1 Comparison of important engine performance parameters

Parameter	Existing engines	Advanced engines
Turbine entry temperature, K	1600-1650	1850-1900
Thrust-to-weight ratio		
0/0/max[a]	7.5	9.9
11/1.8/max	5.7	7.2
Thrust-to-frontal-area ratio, kPa		
0/0/max	180	245
11/1.8/max	135	180
Thrust-to-airflow ratio, kN·s/kg		
0/0/max	1.00-1.10	1.27
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

[a]Alt/Mach no./P/S.

Table 2 Point performance requirements

Requirement	Affected area
Max sustained turn rate, 10 kft	Wing, thrust
Sustained turn radius, 10 kft	Wing, thrust
Max attained turn rate, 10 kft	Wing
Specific excess power, Mach 0.7, 3 g, 10 kft	Thrust
Specific excess power, Mach 0.9, 1 g, sea level	Thrust
Max sustained Mach number, 4 g, optimum altitude	Thrust

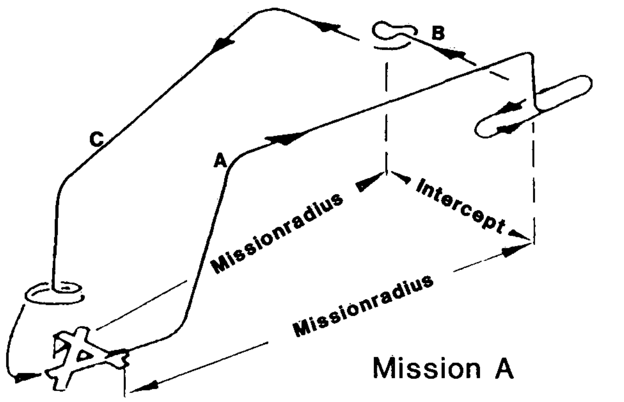


Fig. 2a Assumed air superiority mission: A) takeoff, economic cruise out, and loiter; B) intercept acceleration and combat (max P/S); C) economic cruise back and landing.

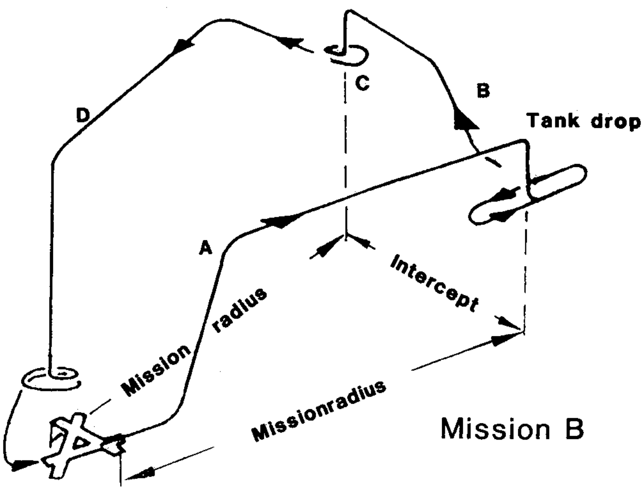


Fig. 2b Assumed combat air patrol and minimum time intercept mission: A) takeoff, economic cruise out, and long-time loiter with external fuel; B) intercept climb, acceleration (max P/S), and supersonic cruise; C) combat [max (P/S), D] economic cruise back and landing.

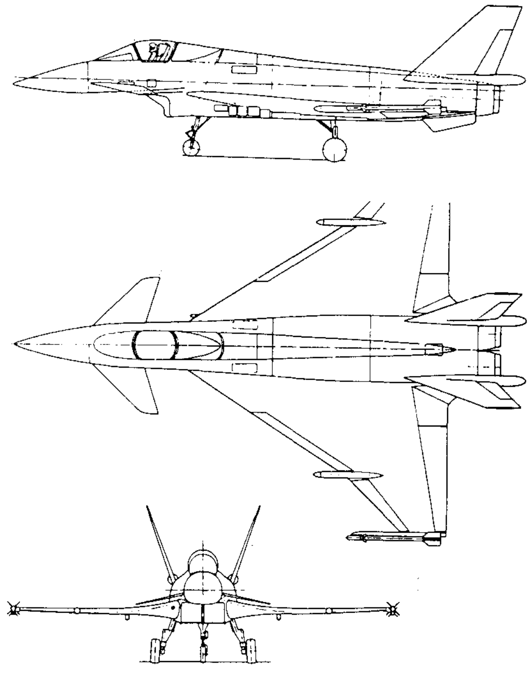


Fig. 3 Baseline configuration.

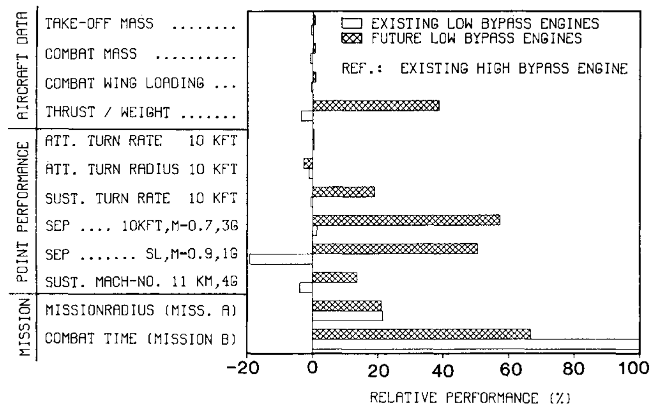


Fig. 4 Aircraft performance comparison.

Results

Performance Gain with Fixed Aircraft Size

In the first step, the advanced engine with dimensions similar to those of existing high-bypass-ratio engines was installed on an unchanged airframe. Figure 4 shows the changes in the point performance, mission A radius, and mission B combat time of the aircraft with the new engines relative to the one with existing ones. The aircraft performance for the existing high-bypass-ratio engine is selected as reference. The performance for an existing low-bypass-ratio engine is also shown in order to separate the effect of the engine cycle and the differences in technology.

Due to similar wing loadings, all of the aircraft show nearly equal instantaneous turn capability. The thrust-dependent performance, which is similar for the existing engines, increases up to 60% for the advanced engine. The mission A radius and mission B combat time are strongly dependent on the engine cycle and increase with an advanced engine mainly because of the matching of cycle to mission.

However, the increase in sustained aircraft performance cannot be entirely utilized. Due to the expected avionics and weapons technology, an increase in conventional maneuverability in the subsonic regime will not substantially increase combat effectiveness. Thus, the advantages of this solution with regard to combat superiority seem to be material.[3,4] In addition, the thrust-dependent performance by far exceeds the targets expected by military planners.

Aircraft Weights for a Constant Performance Level

In a second step, the aircraft with the advanced engine, described in the previous subsection, was scaled with respect to size, weight, drag, fuel, etc., including the engine such that the missions are still fullfilled and the maneuver performance is brought to the same level as that of the aircraft with existing engines (high bypass). Unscalable items, such as weapons, avionics, cabin, etc., were kept constant.

Taking the aircraft with the high-bypass-ratio engine as a reference, it can be seen from Fig. 5 that the aircraft mass with the new engine can, dependent on the mission considered, be reduced by up to 20% and the mass of the fuel and the engine by 37%. This leads to an airframe that 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.

The three designs shown in Fig. 5 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 or 3.0 min.

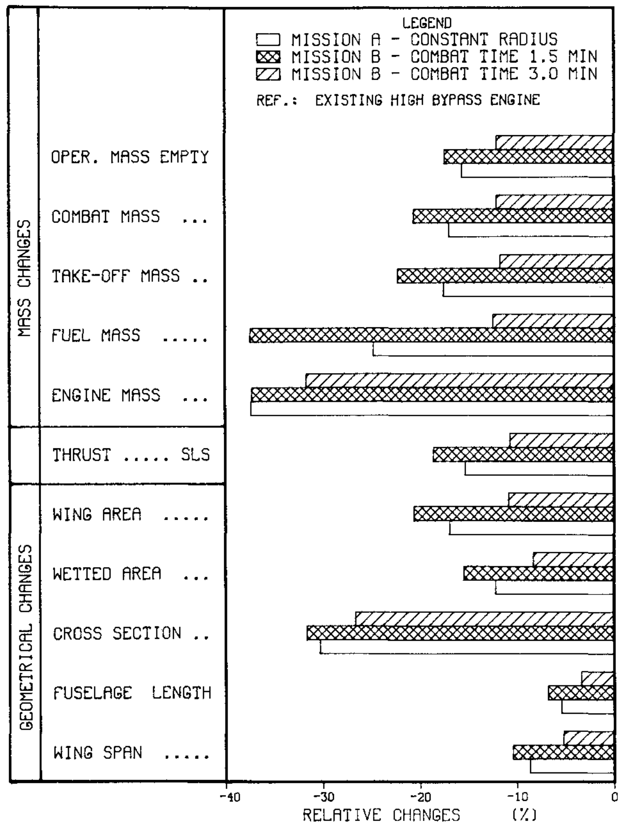


Fig. 5 Aircraft mass and size changes for constant requirements.

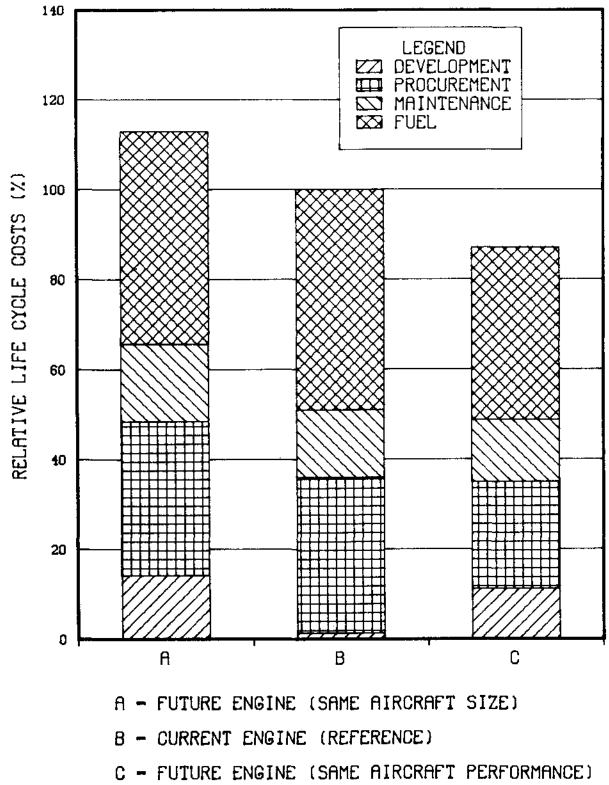


Fig. 6 Engine life cycle costs.

The large reduction in weights and dimensions will certainly lead to a less expensive airframe and to significant fuel savings during peacetime operation.

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. 4 and the "same performance aircraft" as shown in Fig. 5, the life cycle cost (LCC) has been established for the engine and airframe. The main elements of the LCC are:

1) Development cost, including flight test, component improvement post Formal Qualification Test (FQT), and part of the production investment.

2) Procurement cost, including part of the production investment, acquisition cost of the production units (300 aircraft as part of an assumed trinational program) with initial spare engines and support, consumable spare engines aircraft ground equipment (AGE), documentation, etc.

3) Operation and support for 300 aircraft with 1.156×10^6 flying hours ($= 2.312 \times 10^6$ engine flying hours) within 20 years, maintenance, material, and fuel.

For simplicity, only these three main blocks are presented in the relative cost comparison of Figs. 6 and 7, with the operation and support cost (cost of ownership) split into fuel cost and maintenance. The fuel costs are based on a peacetime mission mixture. The economic base for all costs reported in this study is January 1983.

The engine LCC comparison presented in Fig. 6 shows minor development cost for the existing engine (column B), about 35% acquisition cost, 15% for maintenance/material, and 49% fuel cost for a total of 100% (reference). Relative to the reference, the LCC of the advanced engine of the same physical size (column A) increases to 113%, caused mainly by the required development costs. The other cost elements do not differ significantly from column B. The procurement costs of the advanced engine are even smaller, due to its greater simplicity.

The scaled advanced engine (same aircraft performance) in colum C also requires large development costs. However, the procurement cost, mainly because of the smaller engine size and its simpler design is reduced such that the acquisition cost including development is less than for the existing engine. Some further gain is achieved from the maintenance/material cost. The main improvement is obtained from the reduced fuel cost. The overall LCC is 87% relative to the existing engine.

Considering the total aircraft LCC in Fig. 7 (airframe plus engine), the results look quite similar, except that the fractions within the LCC are different. The procurement cost predominates (about 50%), with the maintenance/material and fuel comprising approximately 20 and 15% of the total, respectively. Relative to the reference aircraft with the existing engine (column B), the aircraft with a new engine of the same size and higher performance (column 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 (column B) is only 91.6%. Again, although the development costs for this aircraft are higher (for the new engine development), the costs prior to the operational phase are less than for the reference aircraft.

In summary, the results presented in Fig. 7 show that the development costs for a new engine for a given aircraft performance level are more than compensated for by the lower procurement cost. In addition, the costs of ownership are lower, resulting in a life cycle cost saving of more than 8%.

Break-Even Point and Sensitivity

Since the procurement cost savings of the scaled aircraft C depend on the number of the acquired units, the economic efficiency of the new engine development can be expressed by the number of aircraft necessary to achieve a cost equal to the reference aircraft B with the available engine. This break-even point is shown in Fig. 8 (solid line). At the start of the user phase (acquisition including development), it is at 450 aircraft. Considering the LCC for 20 years operation, the break-even point is achieved with only 270 aircraft.

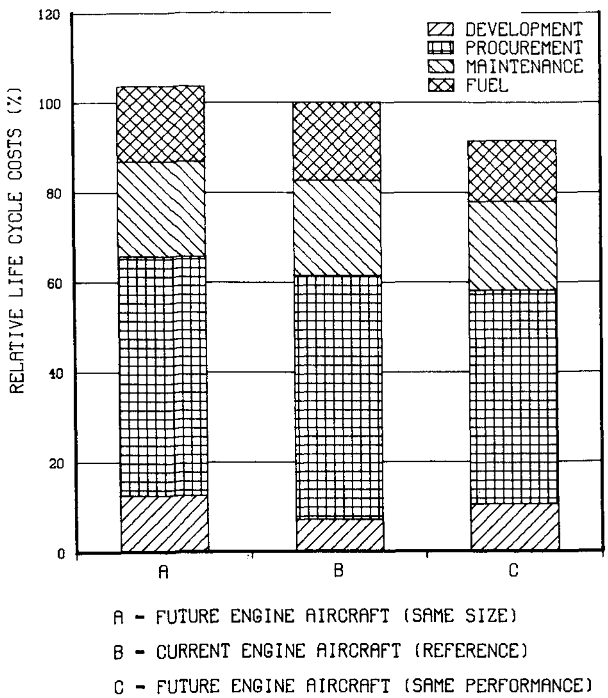


Fig. 7 Aircraft life cycle costs.

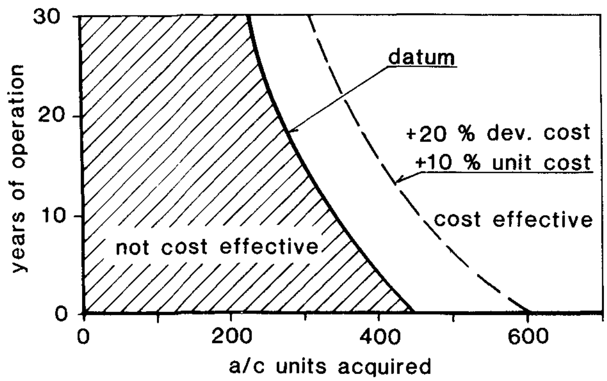


Fig. 8 Cost effectiveness of an engine development.

In order to obtain an idea of the sensitivity of the break-even point to changes in the assumed cost, a calculation was made with 20% higher development and 10% higher production unit cost of the engine. The dotted line in Fig. 8 shows the result. The break-even points shift to 600 aircraft considering only acquisition and development or 360 aircraft counting LCC over 20 years operation.

Summary

A detailed configuration, performance, and cost analysis has been conducted for a European next-generation advanced fighter aircraft 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 concerning the technological level and cost data of the advanced engine, time scale, and 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 program, if new technology is used to reduce the size of the engine 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, according to our studies,[3] this 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 at the end of the acquisition phase, provided at least 450 aircraft are procured. Considering the total life cycle cost, the break-even point is less than 300 aircraft. This number of aircraft may be marginal for a national program; but, for a multinational concept, they clearly indicate that development of a new engine is cost effective.

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References

[1]Grieb, H. and Tracksdorf, P., "Entwicklungstendenzen bei Strahltriebwerken fuer zukuenftige Kampfflugzeuge," DGLR, Rept. 82-072, 1982.

[2]"Triebwerke mit und ohne Nachbrenner fuer den Phantom-Nachfolger," MTU, Technischer Bericht 83/029 (unpublished).

[3]Herbst, W.B., "Design for Air Combat," Paper presented at AGARD FPM Conference, Florence, Italy, Oct. 1981.

[4]Herbst, W.B., "Supermaneuverability," DGLR, Rept. 83-106, 1983.

[5]Biehl, W. and Herrmann, O., "Einige Aspekte zur Auslegung der Triebwerksanlage von kuenftigen Kampfflugzeugen," DGLR, Rept. 82-071, 1982.

[6]Herrmann, O. and Reich, D., "Eignung nachbrennerlosen Antriebs fuer zukuenftige Jagdflugzeuge," DGLR, Rept. 83-097, 1983.