Application of Energy Saving Concepts to Fighter/Attack Design

S. A. Powers,* H. H. Driggers,† and T. E. Krieg‡
Vought Corporation, Dallas, Texas

A study of 20 energy saving concepts as applied to an advanced fighter/attack aircraft intended for an initial operational capability (IOC) data of 1995 has been carried out. The results show that the use of surface launched air targeted missiles, advanced engines, conformal external fuel tanks, variable sweep wings, advanced airfoils, relaxed static margin, and the use of advanced structural materials can reduce significantly the fuel consumption of such an aircraft at a modest increase in life cycle costs.

Nomenclature

BCA&M	= best cruise Mach number and altitude
e	= wing span efficiency
M	= Mach number
O&M	= operational and maintenance
SLS	= sea level static conditions
T/C	= wing thickness to chord ratio
$\bar{V}$	= tail volume
Δh_e	= delta energy height, ft

Introduction

THE United States has gradually changed from a petroleum exporting nation to a petroleum importing one. Recent attempts by foreign governments to use oil as a political and economic weapon resulted in minor disruptions of our daily living and served as a reminder that the United States must reduce its dependency on foreign oil in order to prevent the necessity of bowing to such blackmail in the future.

The present paper discusses the results of a study of various energy saving concepts for future Naval aircraft. The goal was to identify those technologies which result in significant savings of fuel when applied to future aircraft employed in roles compatible with present Naval doctrine.

In this study, a baseline aircraft was selected and its performance was quantified. Then, the specific energy saving concepts (ESCs) were defined and their effects on the baseline aircraft quantified. Finally, a number of the ESCs were collectively applied to the baseline aircraft which was resized to meet the exact mission requirements.

Although the study emphasis was on fuel savings, it is necessary for good managers to understand the cost consequences of striving for fuel conservation. Therefore, the life cycle cost (LCC) consequences of each ESC were also determined and reported.

This study was based on the use of three design missions. The Deck Launched Intercept mission (DLI), Fig. 1a, required a fast climb to 40,000 ft and an acceleration to $M=1.6$, followed by a dash and combat at the same speed. The Combat Air Patrol mission (CAP), Fig. 1b, required a 1 h loiter at a moderate distance from the carrier, followed by combat at $M=1.6$. The STRIKE mission, Fig. 1c, was an all subsonic hi-lo-lo-hi mission with a bomb load of 8000 lb. External fuel was carried on all missions. The ranges for these three missions were not specified but were determined by the mission performance of the baseline aircraft. These ranges are shown on Figs. 1a-1c and were then held constant for the remainder of the study. Each aircraft when modified by an ESC was required to meet these ranges.

This study made extensive use of the Vought Aircraft Synthesis Analysis Program (ASAP). (This program is described in some detail in Ref. 1). ASAP was used to estimate the aerodynamic, propulsion, weight, and structural characteristics of the various aircraft, to calculate the performance of each aircraft, and in the process of calculating the performance, to determine the optimum size aircraft.

Included within the ASAP system is the Parametric Aircraft Cost Estimating Routine (PACER). This program computes costs for an aircraft system starting with engineering development and continuing through production. PACER uses aircraft performance parameters as the variables upon which the cost estimating relationships are based.

The operating and support cost portion of the life cycle costs are estimated using the Combat Aircraft Cost of Operation and Maintenance (CACOM) program, which is also contained within the ASAP framework. This program also uses aircraft performance parameters as variables in the cost estimating relationships.

The Baseline Aircraft

A general arrangement drawing of the baseline aircraft is given in Fig. 2. This is a near-term technology aircraft capable of performing Navy all-weather fighter and attack missions. The two scaled F101 DFE engines are fed by separate two-thirds round inlets with central fixed cone compression surfaces. These inlets are located beneath the wing leading edge to allow the aircraft to achieve high angles of attack and/or yaw with minimal degradation of the quality of the captured air.

The slightly swept wings are located at approximately midheight on the fuselage, and are fitted with full-span leading- and trailing-edge flaps. Spoilers and rolling tails are used for lateral control. The wing spoilers also provide lift dumping and speed brake functions when needed for precise flight path control. The low aspect ratio horizontal tails are the all-flying type. Twin vertical tails provide good lateral-directional characteristics in all attitudes and all flight regimes. These vertical tails are canted outboard to minimize wing-tail interference. The 30% chord rudders can also be independently deflected by the digital fly-by-wire control system. Stability augmentation is also provided by this flight control system.

The aircraft is fitted with long-range multifunction radar with look-down, shoot-down capability, supplemented by i.r.

Presented as Paper 83-0092 at the AIAA 21st Aerospace Sciences Meeting, Reno, Nev., Jan. 10-13, 1983; received Feb. 18, 1983; revision received Aug. 18, 1983.

*Senior Staff Engineer, Flight Technologies; currently, Engineering Project Manager, Fairchild Republic Company, Farmingdale, N.Y.
†Engineering Project Manager, Aircraft Development Engineering.
‡Senior Engineer, Engineering Cost Analysis.

detection systems. Tactical aircraft navigation (TACAN), inertial, and advanced tactical positioning systems are provided for navigation. The aircraft normally carries two short-range missiles (Sidewinder-type) and two medium-range missiles (Sparrow-type) in addition to a single internal 20 mm cannon. Four long-range air-to-air missiles of the Phoenix type are carried semisubmerged beneath the fuselage. Four pylon stations are provided for the carriage of external fuel tanks and other weapons.

The dual-wheel nose gear retracts forward and is fitted with an automatic catapult attachment mechanism. The single-wheel main landing gear retracts aft into the fuselage.

The fuselage is constructed principally of aluminum. Access doors and removable panels are constructed of Kevlar or graphite/epoxy composites. Laminated polycarbonate is used for the windshield and canopy. Wings and tails are primarily graphite/epoxy. Titanium is used for actuators, hinges, and attachments. The main landing gear and side braces are designed using 280 ksi steel.

Figure 3 shows the cumulative weight buildup of the baseline aircraft. Note that the fuel and propulsion system comprise 50% of the aircraft weight. Following in order of decreasing weight fraction are body, wings, avionics, alighting gear, engine section, tail, and flight controls. These items comprise 90% of the aircraft weight when combined. Hence, they represent the high leverage items for weight reduction. In order to significantly reduce the weight of the aircraft, technology must concentrate on reducing the weight of these items. The remaining items can offer no significant weight reduction payoffs; however, the cumulative effects of weight reductions in these areas cannot be overlooked.

The baseline aircraft has a maximum Mach number of 2.25 at 36,000 ft, and a ceiling of 60,000 ft. The aircraft is aerodynamically capable of developing load factors in excess of 12 at low levels at combat weight (60% internal fuel). The sea level rate of climb is 48,000 ft/min. The aircraft can accelerate from $M=0.8$ to 1.6 in 120 s at 35,000 ft. The mission radii of the baseline aircraft using two 300 gal external tanks are 124 nm for the DLI mission, 105 nm for the CAP mission, and 525 nm for the STRIKE mission. It has a carrier approach speed of 124 knots with 60% internal fuel. Note that this is 1 knot less than the specified maximum carrier approach speed. This difference represents the limit of the ability of the optimization program to size an aircraft to meet specific design constraints.

In order to minimize the fuel usage, it is necessary to know how the fuel is used. This is shown for the baseline aircraft in Figs. 4-6. Figure 4 shows that 30% of the DLI mission fuel is expended in the climb and acceleration segment. Another 39% of the fuel is expended in supersonic flight. Figure 5 shows that 21% of the fuel used on the CAP mission is expended on the midmission loiter. Another 44% of the fuel is expended in the acceleration and combat portions of the mission. Figure 6 shows that 33% of the STRIKE mission fuel is expended on the high-altitude cruise segments, and another 17% on the low-altitude dash.

From these three figures it can be seen that an energy-efficient aircraft must have low supersonic drag and a propulsion system which minimizes the fuel required for the extended supersonic flight times generated on these missions. In addition, the aircraft and engine also must be efficient in cruise and loiter. The first requirements can be satisfied by using a highly swept low aspect ratio wing and a turbojet engine. The latter requirements can be satisfied by a high aspect ratio straight wing and a high bypass ratio turbofan engine. A familiar dilemma in aircraft design is finding the lowest cost compromise between mutually contradictory requirements.

For purposes of estimating the life cycle costs, the production run was fixed at 1000 aircraft and the lifetime at

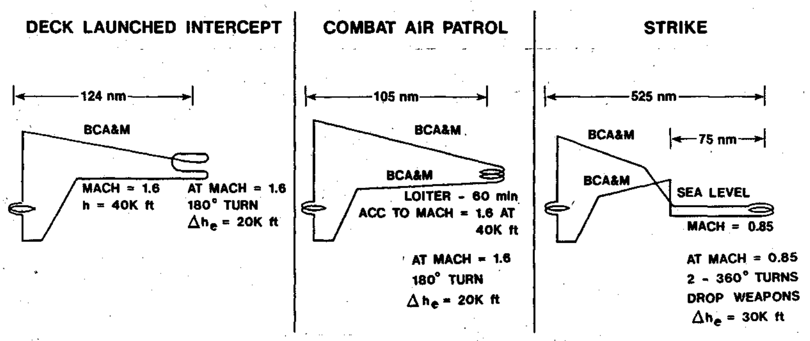
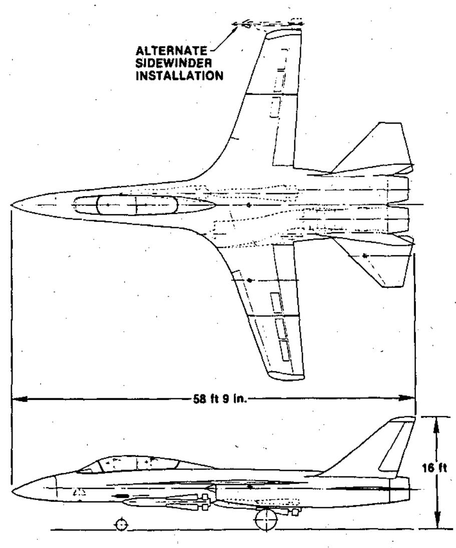


Fig. 1 Mission definitions.

	WING	HORIZONTAL	VERTICAL
AREA (ft²)	430	113 (EXPOSED)	58 (EACH)
ASPECT RATIO	6.00	1.92	2.50
SWEEP (deg)	15.0	35.0	35.0
TAPER RATIO	0.4	0.25	0.25
T/C	.055	.050	.050
MAC	9.0	8.6	5.3
$\bar{V}$		0.56	0.09 (TOTAL)

TOGW (lb) - 39,721
INTERNAL FUEL (lb) - 12,537
ENGINE, 65% SCALE GE F-101DFE
SLS THRUST (lb) - 18,850



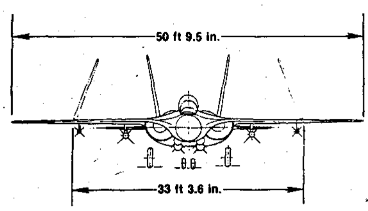


Fig. 2 The baseline aircraft.

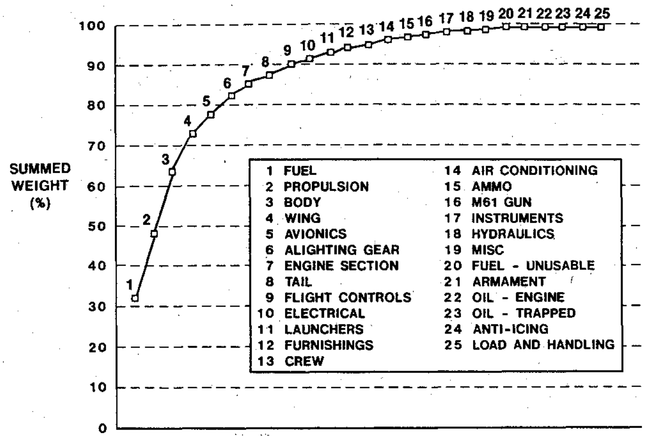


Fig. 3 Baseline aircraft weights.

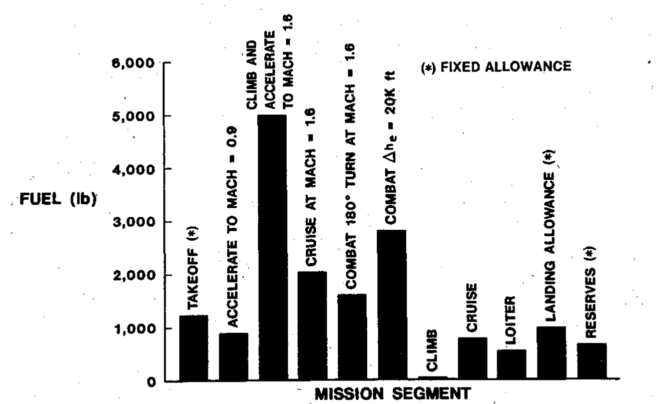


Fig. 4 DLI mission fuel usage.

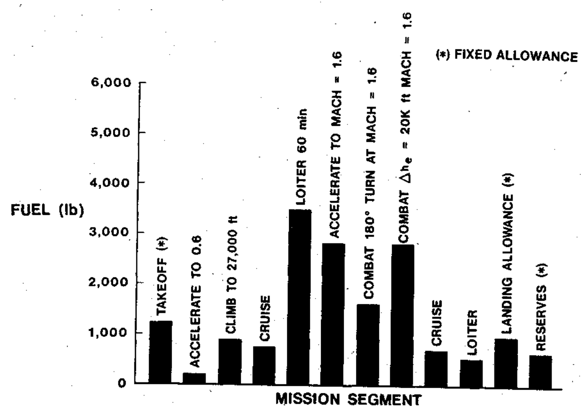


Fig. 5 CAP mission fuel usage.

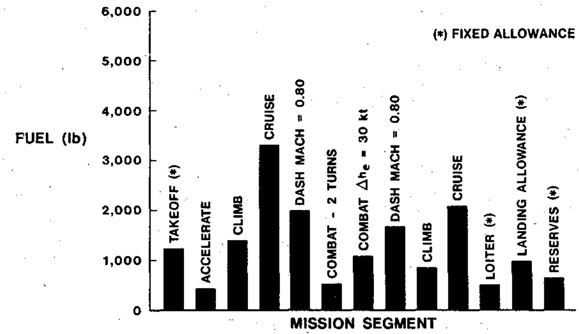


Fig. 6 STRIKE mission fuel usage.

15 yr. Fuel costs were established using the current rate of \$1.18/gal. Each aircraft was assumed to fly 60 h/month.

Analysis of Energy Saving Concepts

The energy saving concepts considered in this study are:

1) Organic Composites Structures
2) Metal Matrix Structures
3) Advanced Metallic Structures
4) Advanced Engines
5) Sizing for Minimum Fuel Usage
6) Advanced High-Lift Systems
7) Variable Camber Wings
8) Variable Sweep Wings
9) Advanced Avionics
10) Blended Wing body
11) Energy Management of Combat
12) Surface Launched Air Targeted Missiles (SLATM)
13) Single-Engine Loiter
14) Single Crew
15) Conformal Fuel Tanks
16) Advanced Power Generation
17) Digital Flight Planner
18) Relaxed Static Margin
19) Advanced Airfoils
20) Winglets

The influences of these ESC's on drag, weight, costs, maintenance, etc., of the baseline aircraft were estimated, and the performance of the modified aircraft on the three missions was determined. The mission ranges were held constant at the baseline aircraft values, and the change in fuel required to fly the mission with the various ESC's was then determined. In order to rank the various ESC's and to develop life cycle costs, the aircraft fleet was assumed to fly the DLI, CAP, and STRIKE missions in a 15:20:65 ratio. The fuel used on the three missions was then weighted by the above ratio to determine a representative overall fuel usage.

The individual ESC's are discussed below. The influence of each, how each influence was estimated, and the basic result of each are briefly covered. More details are included in Ref. 2.

The first three ESC's concern the materials used to construct the airframe. Maximum possible use was made of each of these three structural materials separately in order to reduce the aircraft weight to the lowest possible level. This type of usage resulted in some surprising fuel and cost usage figures, and resulted in an additional analysis that will be discussed later.

1. Organic Composites

These materials allow the modern aircraft designer to produce very light and very stiff structures at the cost of a labor intensive manufacturing process. The baseline aircraft used approximately the same level of composites as originally proposed for the F-18. The wings and tail of the baseline aircraft are made principally of composites; the fuselage, landing gear, and engines are primarily metal.

By making maximum use of organic composites the takeoff gross weight (TOGW) of the aircraft can be reduced by 1311 lb. This weight reduction results in a fuel savings of 119 million gal over the life of the air fleet. However, the LCC is increased by \$752 million. This increase is due to increased engineering costs, increased costs of materials, and increased production costs. Note that these increases are relative to the costs required for an aircraft which already used a significant amount of advanced structural materials. These increases are not counterbalanced by a significant reduction in operations and support (O&S) costs (principally fuel costs). Thus the baseline level of composite material usage is about optimum for cost.

2. Metal Matrix Structures

These materials are of interest for the same reasons as the organic composites. Maximum use of metal matrix structures results in a total weight savings of 518 lb which, in turn, results in a fuel savings of 38 million gal of fuel, and a LCC increase of $746 million.

3. Advanced Metallic Structures

Considering the two technologies listed above, advanced metallics appeared to offer a means of reducing the structural weight of the aircraft. However, by building a majority of the wings and tails from advanced metallic structures a weight increase occurs. This is due to the near-optimum structure of the baseline aircraft. Increased use of advanced metallic structures in the fuselage also results in an increase in weight. The result is an increase in TOGW of 285 lb, an increase of 21 million gal in the fuel used, and an increase of $2075 million in LCC.

4. Advanced Engines

A Pratt & Whitney Aircraft parametric advanced engine computer program was used to develop a series of engines for this aircraft and mission mix. These advanced engines incorporated technology improvements which resulted in a significant thrust/weight ratio improvement over current engines. The rated thrust level, the burner outlet temperature, and the bypass ratio were varied to optimize the key cycle parameters. The selected advanced engine resulted in a TOGW savings of 2854 lb, 1796 lb of which was fuel. The total fuel savings was found to be 479 million gal, and the LCC savings was $584 million.

5. Sizing for Minimum Fuel Consumption

For those cases where the aircraft size is not yet established, the sizing process can be used to determine the minimum fuel usage aircraft. If the engine size is allowed to vary along with the aircraft size, the minimum fuel usage aircraft will almost always be the minimum gross weight aircraft. In those cases where the minimum gross weight aircraft is not the minimum fuel aircraft, the differences are likely to be small. Later in the design development process, when fixed size engines are being used, the minimum fuel aircraft may be significantly different from the minimum weight aircraft. For this study, the size of the aircraft was fixed and the minimum weight aircraft was also the minimum fuel aircraft when resized.

6. Advanced High-Lift Systems

Advanced high-lift systems are needed on Navy aircraft due to the demanding nature of the carrier takeoff and landing processes. High-lift systems allow a good match between the engine and airframe at cruise, and yet permit the aircraft to take off and land aboard the carrier at reasonable speeds. However, it is not possible to save fuel by this means on an aircraft of fixed size which already meets the minimum approach speed requirement. Additional highlift capability in this case merely reduces the approach speed below the specified maximum approach speed. In this study the baseline aircraft approach speed was 1 knot less than the 125-knot criterion due to roundoff errors in the sizing program. The resized aircraft was fitted with an advanced all-mechanical high-lift system to hold the carrier approach speed to the specified 125 knots.

7. Variable Camber Wing

Variable camber wings allow the designer to maintain the maximum wing efficiency in every flight regime. This means a reduction in induced drag at the expense of some increase in weight and mechanical complexity. In this study, variable camber was used to maintain a constant value of the wing span efficiency factor, e, out to fairly large lift coefficients. The result was a decrease in TOGW of 106 lb, of which 66 lb was fuel. However, due to the increased complexity of the variable camber system, the life cycle costs increased by $559 million. The total fuel savings was only 18 million gal.

8. Variable Sweep Wing

Variable sweep wings allow an aircraft to have both the good lowspeed handling characteristics associated with straight wings and the low supersonic drag associated with highly swept wings. This is achieved at the cost of an increase in weight and complexity due to the wing sweep mechanisms. When the drag reduction, and weight and complexity increases were factored into the analysis, the variable sweep wing reduced the TOGW by 517 lb and the fuel usage by 329 million gal. The life cycle costs increased by $148 million.

9. Advanced Avionics

An electronic technology projection method was applied to the 1982 technology baseline avionic suite to determine the equivalent 1990 suite required to meet a 1995 IOC. The result was a reduction in avionic suite weight of 892 lb. This yielded a savings of 1598 lb in TOGW, a fuel savings of 118 million gal, and a decrease in life cycle costs of $456 million.

10. Blended Body

Blending the wing and body together can reduce the supersonic wave drag and the wing-body and wing-tail interference drag. On the present aircraft it was estimated that blending of the wing and body would reduce the minimum drag coefficient by 5 counts (0.0005), increase the wing span efficiency by 2%, and reduce the supersonic drag by 27 counts. The structural weight decreased due to the blending of the wing and body structure. The net result is a decrease in TOGW of 1126 lb and a fuel saving of 302 million gal. The life cycle costs were reduced by $128 million. These savings are principally a result of the reduction in supersonic drag, and illustrate the sensitivity of this aircraft to supersonic drag.

11. Energy Management of Air-to-Air Combat

It is possible to develop a computer and sensor system that can track an opponent through all maneuvers and solve the equations governing the motion of the two aircraft so that real-time optimal solutions can be obtained. These solutions would provide the least time or least fuel flight path required to gain firing position with respect to the opponent. The information could be provided to the pilot in the form of a helmet mounted heads-up display, thus permitting the pilot to fly the fight with his eyes out of the cockpit. A detailed study of such a system was beyond the scope of this study. However, using actual combat flying experience of military aviators it was estimated that some 10% of the combat fuel could be saved in this manner. Factoring this into the analysis resulted in a TOGW reduction of 364 lb and a fuel savings of 84 million gal. Life cycle costs decreased by $233 million.

12. Surface Launched Air Targeted Missiles

By replacing the long-range air-to-air missiles carried on the aircraft for the CAP and DLI missions by surface launched air targeted missiles the weight, drag, and complexity of the aircraft can be reduced. The aircraft then acts as an aerial forward observer, calling for the ship to launch the long-range missiles against incoming targets when necessary. The aircraft is responsible for tracking and targeting the attackers, and therefore must have data links with both the ship and the missiles.

The removal of the four long-range air-to-air missiles and the attendant avionics, and the addition of data link capabilities resulted in a net weight reduction of 7965 lb and a fuel savings of 469 million gal. The life cycle cost was reduced by $1137 million. The aircraft does retain its capability for carrying 8000 lb of weapons on the STRIKE mission.

It should be noted here that the costs of the missiles and their support were not included in this study of the aircraft. A study of the total aircraft-missile-fleet defense system is beyond the purview of this paper. Such a study is needed to determine the best overall solution for the fleet defense mission.

13. Single-Engine Loiter

A twin-engine aircraft can usually save fuel by loitering on one engine if inlet blocker doors are added to reduce the drag of the dead engine. Such doors for the baseline aircraft were estimated to weigh a total of 150 lb. The base drag coefficient of the dead engine was estimated to be 0.0018. Analysis showed that the only mission segment that benefited from single-engine operation was the sea level loiter prior to landing. Under such conditions the TOGW increased by 239 lb and 36 million gal of fuel were saved. The life cycle costs increased by $89 million.

14. Single Crew

With suitable automation a single pilot can perform all flight and weapon delivery functions. The aircraft must have advanced displays and avionics to reduce the pilot workload. These, of course, increase the cost and weight. Counterbalancing these increases is the weight reduction possible due to the removal of the second crew station and the associated life cycle cost decrement due to reduced manning levels. The cockpit of the baseline aircraft was reconfigured to allow single-pilot operation. The fuselage remained the same length to avoid a supersonic drag increase. The result was a TOGW savings of 1191 lb and a fuel savings of 125 million gal. Life cycle costs decreased by $1254 million.

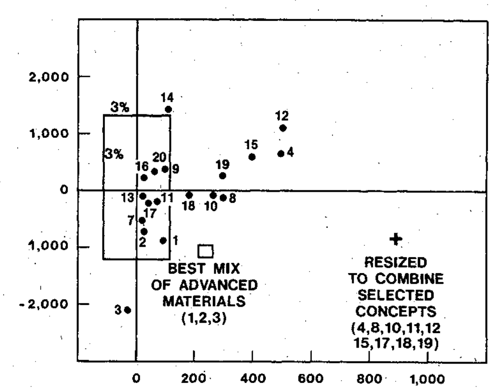


Fig. 7 LCC savings vs fuel savings.

15. Conformal External Tanks

The total drag of an aircraft plus external tanks can be reduced significantly by using conformal tanks. For the baseline aircraft it was estimated that the conformal tank set weighed 186 lb more than the conventional tank set but had only 70% of the drag. Analysis showed a decrease in TOGW of 1361 lb, a fuel savings of 374 million gal, and a life cycle costs reduction of $604 million.

16. Advanced Power Generation Methods

New and more efficient methods of generating electric and hydraulic power are projected to reduce the weight of onboard power generation equipment. This includes multiplexing power distribution systems and very high pressure hydraulics. It was estimated that a total of 224 lb could be saved by these means. The analysis then showed that the TOGW decreased by 404 lb and the fuel required by 31 million gal. The life cycle costs decreased by $249 million.

17. Digital Flight Planners

The term digital flight planner is used here to mean a computer-based system which can be used to determine the best cruise condition for the aircraft given its present load and the local atmospheric conditions. Based on airline experience with similar systems it was estimated that 5% of the subsonic cruise fuel could be saved by this means. Thus the TOGW was reduced by 246 lb, and saved 53 million gal of fuel. The life cycle costs increased by $259 million due to the increased avionic equipment required. It was noted that the digital flight planner and the energy management of air-to-air combat both use similar hardware. If these two functions were combined into one function they would form a usable ESC.

18. Relaxed Static Margin

The trim drag of a stable aircraft can be reduced by decreasing the static margin. The minimum trim drag usually occurs when the aircraft is 3-5% unstable. By fitting an aircraft with a high-authority autostabilization system the aircraft can be allowed to operate in this unstable region. In addition it may be possible to reduce the size of the horizontal tail. From the analysis of supersonic and subsonic wind tunnel data for aircraft of similar configurations it was estimated that a 5% shift in static margin resulted in a span efficiency increase of 0.025, a drag coefficient decrease of 0.0004, and a weight decrease of 68 lb (due to a change in horizontal tail size). These changes resulted in a decrease in TOGW of 908 lb, a savings of 198 million gal of fuel, and $164 million in life cycle costs.

19. Advanced Airfoils

In the 1990/2000 era the equivalent skin friction coefficient for lifting surfaces is expected to reach the laminar flow limit.

	WING	HORIZONTAL	VERTICAL
AREA (ft^2)	431	87 (EXPOSED)	58 (EACH)
ASPECT RATIO	6.0	1.92	2.50
SWEEP (deg)	15/60	35.00	35.00
TAPER RATIO	0.4	0.25	0.25
T/C	0.055	0.050	0.050
MAC	9.0	7.5	5.3
$\bar{V}$		0.428	0.090

TOGW (lb) - 36,980
INTERNAL FUEL (lb) - 11,576
ENGINE - P&W ATES ENGINE
SLS THRUST (lb) - 19,317

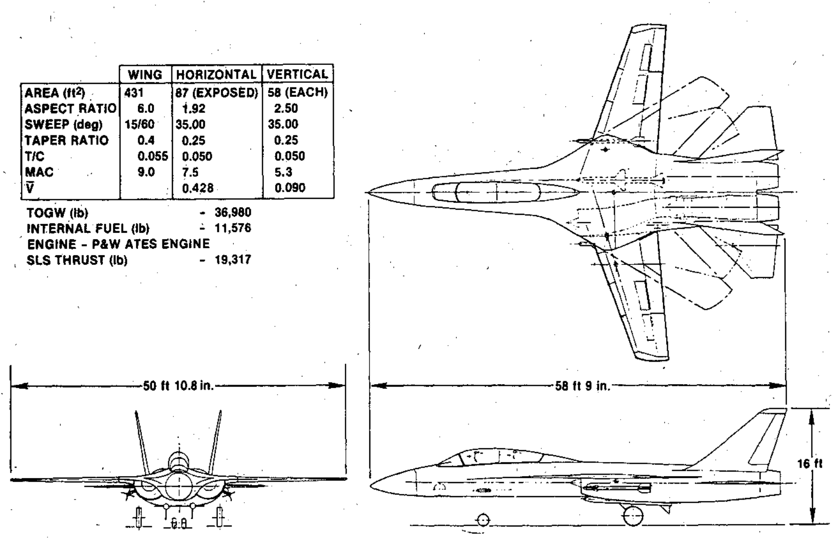


Fig. 8 The energy efficient aircraft.

Table 1 Fuel, costs, and weights summary

Concept	Fuel used, million gal	LCC, $m	TOGW, lb	Δfuel, million gal	ΔLCC, $m	ΔTOGW, lb
Baseline	4427	39940	39721			
1) Organic composites structures	4308	42335	38410	−119	2395	−1311
2) Metal matrix structures	4389	42329	39203	−38	2389	−518
3) Advanced metallics structure	4448	43658	40006	21	3718	285
4) Advanced engines	3948	39356	36867	−479	−584	−2854
5) Sizing for minimum fuel usage	NA	NA	NA	NA	NA	NA
6) Advanced high lift systems	NA	NA	NA	NA	NA	NA
7) Variable camber wings	4409	40499	39615	−18	559	−106
8) Variable sweep wings	4098	41731	39204	−329	1791	−517
9) Advanced avionics	4309	41127	38123	−118	1187	−1598
10) Blended wing-body	4125	41711	38595	−302	1771	−1126
11) Energy management of combat	4343	40173	39357	−84	233	−364
12) Surface launched air targeted missiles	3958	40446	31756	−496	506	−7965
13) Single-engine loiter	4392	41672	39960	−36	1732	239
14) Single crew	4303	40329	38530	−125	389	−1191
15) Conformal fuel tanks	4053	40979	38360	−374	1039	−1361
16) Advanced power generation	4397	41334	39317	−31	1394	−404
17) Digital flight planner	4375	40199	39475	−53	259	−246
18) Relaxed static margin	4229	40104	38813	−198	164	−908
19) Advanced airfoils	4170	39646	38552	−257	−294	−1169
20) Winglets	4325	39546	39454	−102	−394	−267
20) Winglets	4325	39546	39454	−102	−394	−267
21) Best mix structure	4162	41006	36853	−265	1066	−2868
22) Resized aircraft	3563	40967	36980	−864	1027	−2741

This represents a value of 0.0012 for the baseline aircraft in contrast to a conventional conservative estimate of 0.0026. It was also estimated that wing efficiency factor could be maintained at the 0.82 level up to reasonably large angles of attack. Introducing these changes into the analysis, the TOGW decreased by 1169 lb and the fuel required by 257 million gal. The life cycle costs decreased by $294 million.

20. Winglets

The effects of winglets on transport aircraft are well known. The application to highly maneuverable fighter/attack aircraft is less well documented. References 3 and 4 were used to define winglets suitable for this aircraft. These winglets were estimated to add approximately three drag counts to the aircraft minimum drag subsonically, six counts transonically, and two counts in the Mach 2.0 region. Winglets also caused a 12% increase in span efficiency factor up through $M=1.5$. Using these values in the analysis the TOGW decreased 267 lb, the fuel required decreased by 202 million gal, and the life cycle costs decreased by $394 million.

The results from the first three ESC's could be interpreted to mean that advanced materials offer no advantages; a conclusion clearly at variance with present experience. This is a result both of the choice of the technology level in the baseline aircraft and the maximization of the use of each advanced structural material alone. The baseline aircraft used advanced structural materials to about the same level as originally proposed for the F-18. Thus, significant weight and cost savings had already been accomplished.

The maximum use of the individual structural ESC's did not achieve the sought for reductions in weight and costs because of problems associated with minimum gage panels, the strength of highly stressed parts, and secondary structures.

In order to demonstrate the synergism capability of advanced structural materials, an additional aircraft was developed. This aircraft used all the various advanced structural materials in a manner designed to reduce the aircraft weight and parts count to a minimum. This required a more detailed look at the structure that was previously done. However, the results now show that the "best mix" structural concept saves 2868 lb of TOGW and 265 million gal of fuel. However, there was an increase in life cycle costs of $1066 million. The message should now be clear—large amounts of advanced materials can achieve additional weight reductions in future aircraft, but at some expense.

Recommended ESC's

The results from this study are summarized in Table 1. The total fuel savings per average mission, the life cycle costs savings, and the TOGW savings are given.

Figure 7 plots the life cycle costs as a function of the fuel saved over the life of the program. Note that negative deltas from Table 1 are plotted here as positive savings. The box around the origin of the plot represents 3% of the LCC and fuel usage of the baseline aircraft. This provides a sense of scale for the various amounts of savings to be discussed. Those ESC's falling within this box were deemed to be not significant and were therefore not used in the final resized aircraft.

The upper right quadrant of this figure represents savings of both fuel and costs; obviously a desirable situation. The lower left quadrant represents increases in both fuel use and life cycle costs; clearly an undesirable situation. The lower right quadrant represents saving of fuel at an increase in life cycle costs. For some program this may be acceptable. The upper left quadrant represents a savings in life-cycle costs at the expense of an increase in fuel usage. This also may be acceptable in some circumstances.

Using the analyses discussed above the following energy saving concepts were chosen for incorporation into the final resized aircraft: advanced engines, variable sweep wings, blended wing and body configurations, surface launched air targeted missiles (SLATM), conformal external tanks, relaxed static margin, advanced airfoils, advanced high-lift systems, digital flight planner/energy management of air-to-air combat, and best mix of structural materials.

Advanced engines result in the largest fuel savings of any of the ESC's. The study engines used here reflect an emphasis on the development of lighter, cheaper, and more efficient engines.

Variable sweep wings are required to meet the conflicting demands of high aerodynamic efficiency at both subsonic and supersonic speeds. A change in the amount of supersonic flight required could significantly effect the payoff due to variable sweep.

Table 2 Comparison of aircraft

Item	Resized	Baseline
TOGW, lb	36,980	39,721
Wing area, ft^2	431	430
Wing sweep, deg	15/60	15
Aspect ratio	6	6
Rated thrust SLS, lb	19,317	18,850
Airframe weight, lb	12,389	13,565
Internal fuel, lb	11,567	12,537
Total useful load, lb	13,537	14,508
Life cycle costs, $m	40,967	39,940

Blended wing-body configurations should be used because of the beneficial effect on the aircraft supersonic drag. Secondary improvements are possible subsonically. With the growth of the use of composite materials for primary structure the desirability of maintaining straight lines on the aircraft external surfaces has diminished. Therefore, the blended wing-body concept should be applied wherever possible.

The use of SLATM's will significantly reduce the cost, size, and weight of the aircraft component of the fleet defense system. However, a study of the total fleet protection problem needs to be done before it can be stated with certainty that this concept is the most cost-effective solution to the overall problem.

Conformal external fuel tanks should be used because of the drag reduction inherent in such a system. These tanks should be integrated into the aircraft design at the outset.

Relaxed static margin should be used to decrease the trim drag to the lowest possible levels. With the advent of fly-by-wire control systems relaxed static margin flight can be implemented easily.

Advanced airfoils should be used because of the decrease in wing profile drag. Secondary benefits occur in the transonic region where advanced airfoils can be used to delay the drag rise. In addition, advanced airfoils interact beneficially with advanced high-lift systems.

Advanced high-lift systems must be used because of the nature of carrier landings. Mechanical high-lift systems are more desirable than powered systems due to lower maintenance requirements. In addition, blown systems compete with other requirements for engine bleed air and complicate the aircraft systems.

Digital flight planner/energy management of air-to-air combat combined provide an opportunity to reduce fuel usage by proper management of resources. Since modern aircraft are using onboard computers in increasing numbers, this ESC would cost little in terms of hardware to implement.

The best mix of structural materials should be used to reduce the structural weight of the aircraft. With the growth of the use of these materials the cost of materials and fabrication is decreasing constantly.

The Resized Aircraft

The multiple energy saving concepts described above were added to the baseline aircraft, and the sizing process was repeated. The STRIKE mission set the internal fuel requirement since it was the most demanding. This sizing process varied wing area and engine scale factor. The $M=0.85$ dash in the STRIKE mission set the value of the engine scale factor at 0.7. The interaction of this engine scale factor and the minimum approach speed constraint set the final wing area at essentially the same value as the baseline aircraft. However, with the improved structure, engines, and variable sweep wings the combined technologies aircraft is considerably lighter than the original (37,000 vs 39,700 lb). The principal characteristics of the two aircraft are compared in Table 2. The redesigned aircraft will use only 79% of the fuel required by the baseline aircraft, on the basis of a fleet of 1000 aircraft operating for 15 yr. This is accomplished at a 2.6% increase in life cycle costs. A general arrangement drawing of the resized aircraft is given in Fig. 8. Note that the variable sweep wings are the most distinctive difference between this new energy-efficient aircraft and the original version.

Concluding Remarks

This study has investigated the effects of 20 energy saving concepts on the fuel usage and life cycle costs of an advanced fighter/attack aircraft. This study showed that significant fuel savings result if surface launched air targeted missiles, variable sweep wings, advanced airfoils, relaxed static margin, conformal external fuel tanks, and the best mix of advanced structural materials are used in the design from the outset. There is a relatively small cost increase associated with building such a fuel-efficient aircraft.

Acknowledgment

This work was carried out under Contract N622691-81C-0534 from the Naval Air Development Center.

References

[1] Roch, A.J. and Ladner, F. K., "The Impact of Effectiveness Considerations on Design Synthesis," ASME Paper 760935, 1976.

[2] Powers, S.A., Driggers, H.H., and Krieg, T.E., "Advanced Fighter/Attack Aircraft Energy Saving Concepts Investigation," NADC Report 81099-60, in publication.

[3] Ishitsu, K.K., et al., "Aerodynamic Design and Analysis of Winglets for Military Aircraft," AFFDL-TR-76-6, Feb. 1976.

[4] Flechner, S.G. and Jacobs, P. F., "Experimental Results of Winglets on First, Second and Third Generation Jet Transports," NASA TM 7264.