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Combat Survivability with Advanced Aircraft Propulsion Development

Les Throndson*
Naval Weapons Center, China Lake, California

The increasing need for improved aircraft combat survivability is introduced and the requirement for attention to the propulsion system is presented. Design approaches and technology advances contributing to reduced vulnerability are reviewed. Also discussed is a survivability investigation for future aircraft attached to the Navy-Air Force Advanced Technology Engine Study (ATES). The ATES survivability investigation will evaluate candidate means for reduced propulsion signature and vulnerability in projected combat scenarios—and will assess all weight performance tradeoffs including life cycle cost considerations to identify cost effective survivability approaches.

Introduction

IN the Vietnam War, fixed-wing aircraft losses in combat were more than 2500. Inclusion of helicopters brings the total U.S. air vehicle losses due to hostile action to well over 5000.[1]

In the first 3 days of the 1973 Yom Kippur War, the Israeli Air Force lost 50 aircraft over the Suez Canal and a further 30 over the Golan Heights. At least 30 of these 80 aircraft were shot down by the ZSU-23/4 self-propelled AA gun because the threat from the SA-6 missile forced Israeli aircraft operation down to low altitudes.[2]

Seymour J. Deitchman,[3] Institute for Defense Analyses, concluded the following:

> Tactical aviation stands in danger of pricing itself out of business as it tries to overcome increasingly effective defenses.... New tactics and technology can preserve its usefulness only by challenging existing concepts and trends. Potential aircraft fleet draw-down rates (in a NATO scenario with high aircraft kill potential due to overlapping air defenses, modern surface-to-air missiles, and anti-aircraft guns) can cause rapid reduction in tactical aircraft force size...a much more rapid reduction than we are used to based on World War II, Korea, and Vietnam.

A parametric variation on force-size draw-down characteristics in combat from a Northrop air-to-surface (ATS) study[4] is shown in Fig. 1. The percent force remaining is plotted as a function of days of conflict for various attrition rates. A dramatic effect is shown when departing from the usual attrition rates range of from 0.001 to 0.01 aircraft losses per sortie to potential projected levels of 0.03 or greater losses per sortie.

With high attrition rates, an aircraft fleet can be depleted rapidly and quickly reach a level where it is not a potent combat force. In a NATO environment, the strong possibility exists of an aircraft fleet being decimated before it has done its job. Therefore much larger tactical aircraft fleets must be considered. Improved survivability offers the promise of reducing the number of aircraft required, although individual aircraft may be somewhat more expensive.

One purpose of this article is to introduce the subject of propulsion system survivability: the need, some examples of design methods, and favorable advanced technology. The other major purpose is to describe some ongoing advanced propulsion system survivability studies involving extensive tradeoff studies with potential future tactical aircraft designs (1995 time period). These combat survivability investigations are being done attached to the ATES program, described in the latter part of this article.

Tradeoffs are necessary to evaluate some survivability concepts. Improvements fall into several basic categories: 1) those with no significant penalty (e.g., separated control lines to flight control surfaces or separated engines for reduced vulnerability); 2) advanced design features (e.g., smaller, high thrust engines); and 3) survivability improvements that require tradeoffs to determine the total effect on the vehicle. These tradeoffs examine penalties in weight or performance as to their effect on reduced speed, agility, and mission performance. The cost and loss in capability is then traded against the improved survivability of the aircraft before a decision is made on incorporation of the survivability feature.

Survivability comprises two main areas: susceptibility and vulnerability. Susceptibility is the combination of factors that determine the probability of being detected and then the probability of being hit by a given threat; both of these are dependent upon aircraft signature. Susceptibility also depends on countermeasures, tactics, speed, and maneuverability. Vulnerability is the response of the aircraft given a hit. Vulnerability is reduced by redundancy and damage tolerance. Figure 2 presents some methods for reduction of susceptibility and vulnerability.

In the survivability equation of Fig. 3, the propulsion system has a very strong effect on the aircraft susceptibility factors because of propulsion signatures, and has become an important vulnerability consideration (the probability of being killed if hit, $P_{K/H}$). Vulnerability of the propulsion system is critical in that engine damage can result in 1) loss of thrust, 2) aircraft fire, and 3) unconstrained engine parts endangering the aircraft and its systems.

Problem

Many lessons pertaining to survivability were painfully learned in the Vietnam War. Effective strides have since been made in survivability research, and design of new aircraft has already been influenced by this research. Redundant, separated, damage-tolerant flight control and hydraulic systems are now the norm. Especially in the areas of fuel systems, the historic killer of aircraft through fires and explosions, effective design techniques have been devised incorporating fuel tank foams, and nitrogen inerting for internal and adjacent dry bay protection.

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*Project Engineer, Systems Survivability Branch. Member AIAA.

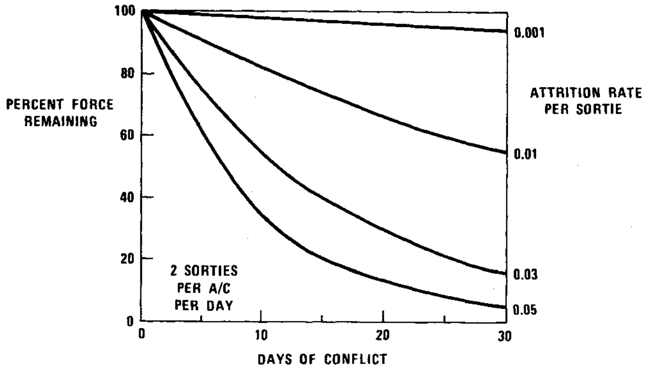


Fig. 1 Force survivability.

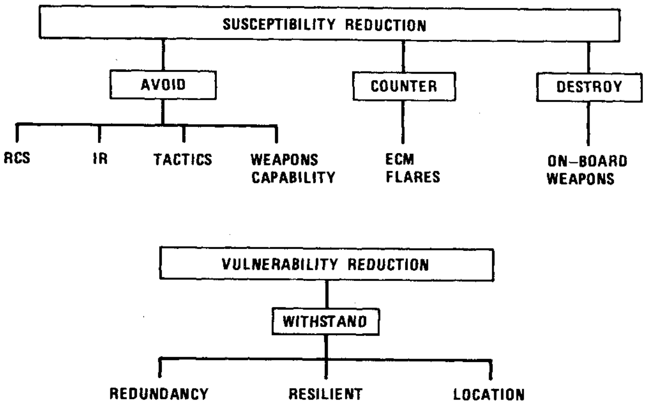


Fig. 2 Survivability methods.

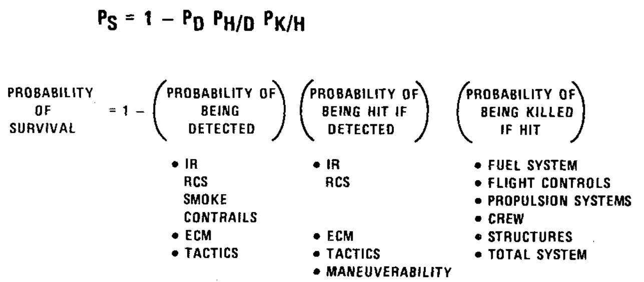


Fig. 3 Survivability equation.

An important area pertaining to both fuel tanks and the engine was demonstrated in Vietnam; this involves engine fuel ingestion with the condition illustrated in Fig. 4. Fuel ingestion into the engine results when a projectile or fragment punctures a tank which interfaces with the engine inlet duct. With ruptures of the tank-inlet duct wall from hydraulic ram pressures in the fuel from projectile impact, substantial fuel amounts can be released into the engine airflow. Fuel ingestion into the engine core in turn results in combined compressor stalls and internal engine explosions, causing thermal distress, mechanical turbomachinery damage, and sometimes engine case ruptures. This phenomenon and the amount of fuel ingestion required for engine kills has been investigated experimentally in full-scale tests at the Ballistic Research Laboratory (BRL), Aberdeen, Md., and at the Naval Weapons Center (NWC), China Lake, Calif. The test setup at NWC using a TF30 engine and A-7 inlet duct is shown in Fig. 5. The NWC high-velocity airflow system, using directed fan air discharged from two TF33 engines, was employed in testing in order to simulate flight ram airflow conditions of 350 knots. Explosions resulting from engine fuel ingestion are shown in Fig. 6. Clearly, an aircraft design where fuel tanks are wrapped around the engine inlet ducts has a survivability disadvantage.

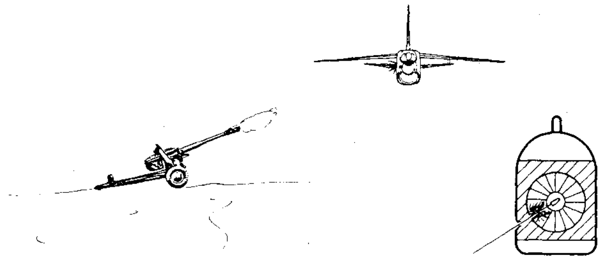


Fig. 4 Engine fuel ingestion from inlet duct puncture.

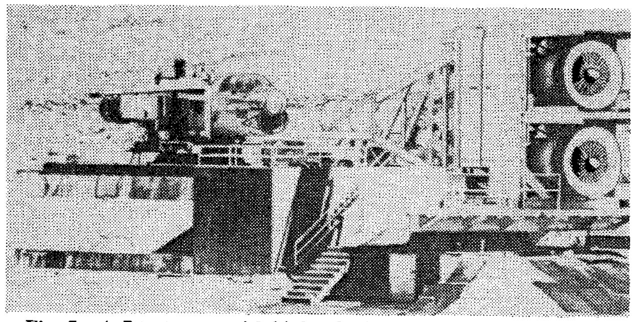


Fig. 5 A-7 test setup with high velocity airflow system at NWC.

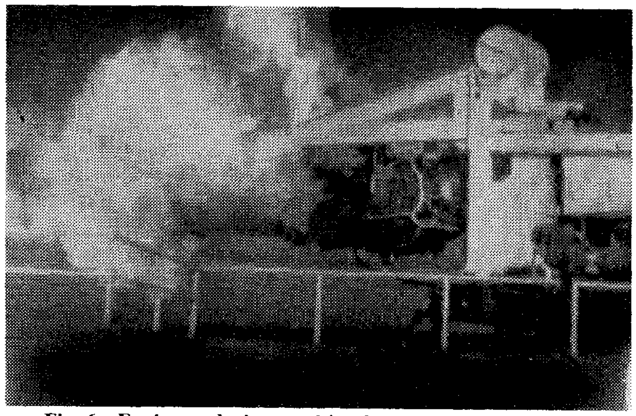


Fig. 6 Engine explosion resulting from inlet fuel ingestion.

Fuel ingestion is a unique form of engine vulnerability and not an engine kill mode that is initially obvious. Fuel ingestion does dramatically point out the need to address the total aircraft, and the vulnerability interactions that can occur between systems and components, resulting in cascading effects.

Engine turbomachinery damage from projectiles or warhead fragments has always been a major concern. If several vanes or blades are knocked loose, damage can cascade from stage to stage, resulting in massive "foreign object damage" (FOD). Besides catastrophic engine failure from massive FOD, thrust loss and severe engine damage can result from combustor puncture (giving high engine "bleed" and resulting engine roll-back, or turbine distress with hot streaks from combustor damage). Combustor puncture is of major concern with turbojets because of torching into the engine compartment, with a resulting aircraft fire probability. In other instances, some engines have had combustor cases that ruptured after being punctured, an example of poor material selection. Also titanium fire, from blades knocked loose and the resulting FOD friction, can result in complete destruction of the engine.

Engine "kills" from combat damage are defined for vulnerability assessment when greater than 50% thrust loss from intermediate power setting occurs (including precautionary shutdowns and fires). Kills are characterized according to time required as a K kill—aircraft loss occurs within 30 seconds after hit; an A kill—loss occurs within 5 min after hit; or a B kill—loss occurs within 30 min after hit.

Vulnerability of engine components is illustrated in Fig. 7. These results are typical of afterburning turbofan engines and are a composite of engine tests at NWC and BRL. For vulnerability analysis of a given engine, $P_{K/H}$ values are estimated for various projectile and fragment sizes, over a range of impact velocities, and for different viewing angles. Probability of kill estimates employ penetration calculations, empirical data, and recognize engine mechanical design features such as shrouded vs nonshrouded compressor stators. The message in the composite results of Fig. 7 is the relative importance of what component is hit, as to whether an engine kill results. The variation in engine kill $P_{K/H}$ also serves to point out components where attention should be focused for total engine vulnerability reduction.

Notable in Fig. 7 is engine kill vulnerability with accessory hits. Lubrication systems have proven to be especially vulnerable. The same is true for the fuel control and fuel lines. Fuel controls and lines can, however, often be located where they are shielded or protected by more rugged engine or aircraft components. It is estimated that about 30% reduction can be achieved in the total engine system vulnerability with weight investment of only 10-20 lb in the accessories area through designs such as emergency lube provisions and less vulnerable fuel controls. The importance of avoiding control damage to both engines of a twin-engine aircraft by a single hit is obviously critical.

Engine turbomachinery containment is a major consideration, learned from costly experience. Blade containment structure has been added to engines as a result of aircraft losses, losses attributed to fan blades severing fuel lines and producing major fires. Uncontained fan blade vulnerability experience was one of many lessons that influenced F/A-18/F404 engine requirements.

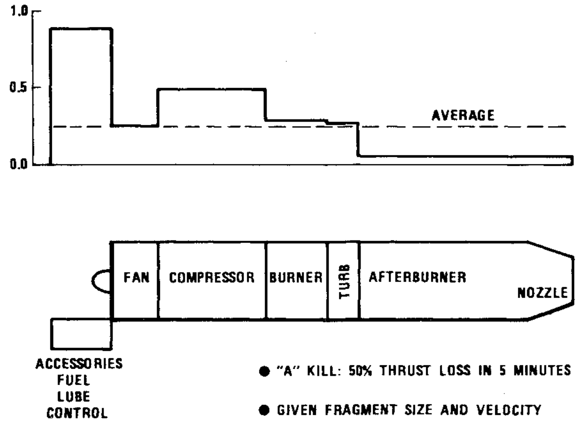


Fig. 7 Engine probable kill characteristics.

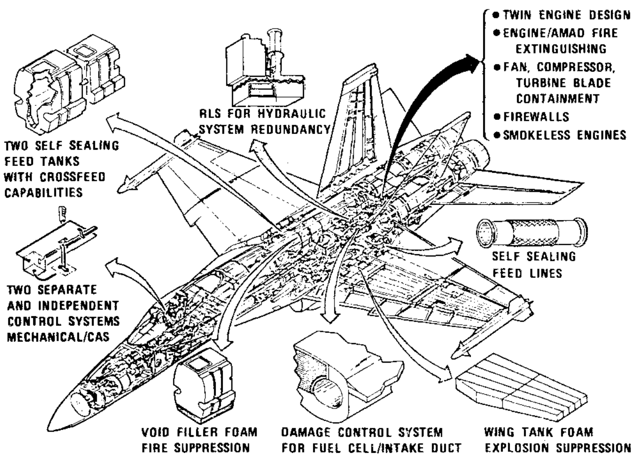


Fig. 8 Survivability through design.

Progress

Figure 8 illustrates some survivability features of the F/A-18 aircraft. Along with its twin-engine design, the blade containment, firewall design, and engine compartment and airframe-mounted accessory drive compartment fire extinguishing are important. Containment and firewalls are necessary to promote true twin-engine survivability. Redundancy, a principle of survivability, is not accomplished if severe combat damage of one engine is likely to result in failure of the other engine. Fuel system and propulsion design features of the F/A-18 are listed in Table 1 and contrasted with systems for the earlier F-4 and A-7 (aircraft which it replaces) and the A-6. The survivability features of the F/A-18 reduce its total vulnerable area (projected area multiplied by P_K) to under half that of the predecessor aircraft. Thus considerable survivability can be designed into an aircraft at little cost in weight or performance. In fact, this is the only way effective survivability can be provided. Add-on fixes generally entail too great a weight or performance penalty.

Besides good design methods, improved survivability can also be provided at no penalty with advanced technology. An attractive propulsion survivability feature is the improved engine design of the F404 compared to previous engines, such as the J79. For engines of approximately the same thrust, the size reduction (three-quarter the length and 11% smaller diameter) is notable, as illustrated by the engine drawing comparison of Fig. 9. Even more remarkable is the one-third

Table 1 Fuel and propulsion system

	F/A-18	F-4J	A-7E	A-6E
Fuel system				
Fuel tanks isolated from engines	Yes	No	Yes	No
Inlet duct/fuel tank hydraulic ram damage control	Yes	No	No	...
Self-sealing feed tanks "get home" fuel	Yes	No	Yes	Yes
Self-sealing engine fuel feed lines	Yes	No	Yes	No
Fuel transfer lines inside tanks	Yes	No	Partial	Partial
Split system with crossover capability	Yes	No	No	No
Survivable external fuel tank	Yes	No	No	No
External void filler foam	Yes	No	No	No
Internal foam	Yes	No	Sump tank only	No
Propulsion				
Twin-engine reliability	Yes	Yes	No	Yes
Firewalls between engine, AMAD, and APU	Yes	...	...	No
Fire detection and extinguishing system	Yes	No	No	No
Engine blade containment for fan, compressor, and turbine sections	Yes	No	No	No

fewer parts of the F404 and 10 compression stages instead of 17, which reduce the possibility of turbomachinery damage and cascading damage effects. The turbofan bypass air of the F404 also lowers the likelihood of torching into the engine compartment with combustor punctures. Even less complex turbomachinery is planned for next-generation engines as depicted in Fig. 10, with the trend to increased thrust to weight and reduced parts expected to continue.

In the total propulsion system concept area, great attention is being paid to inlet and exhaust nozzle design and location for reduced radar cross section (RCS) and infrared (IR) signature. Figure 11 is a sketch of a top-mounted inlet aircraft. This inlet approach offers the potential of both lowered susceptibility, and vulnerability, by reducing the engine fuel ingestion danger. The interface area between the inlet duct and fuel tanks is expected to decrease. The tanks that are located ahead or near the inlet duct are deeper, and therefore less likely to sustain projectile exit ruptures. In the past, inlet design was directed by performance and weight considerations; now both RCS and vulnerability should also be considered in the tradeoff selection.

Likewise, in engine design where performance and weight predominate, there is opportunity to assess signature considerations early in the preliminary engine cycle selection. By reasonable increases in bypass ratio, significant reduction in mixed exhaust gas temperature can be obtained. This is important, especially with the projected turbine temperature growth of advanced engines. While exhaust plume IR emissions may be significantly reduced with engine BPR, the impact of greater airflow must also be assessed. This will cover lower installed engine performance, higher aircraft drag, larger inlets and nozzles—and therefore increased RCS. At the same time, subsonic cruise fuel consumption may be lowered. Thus complete tradeoffs must be conducted in examining some survivability improvement areas.

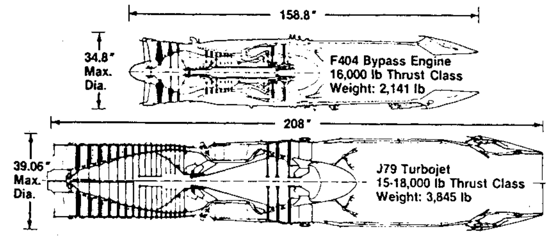
Another major reduced observables approach to IR suppression is nozzle design, and with the additional goal of vertical/short takeoff and landing (V/STOL), and improved maneuver capability, much attention is being directed to two-dimensional or nonaxisymmetric exhaust nozzles. At NWC, a plan to investigate ejector nozzles based on new nozzle concepts is being initiated.

Full-authority digital electronic fuel controls are expected to reduce vulnerability, not only from size reduction and redundancy gains, but also by thrust retention under damage conditions. Analytic modeling of combat-damaged engines is being conducted at NWC with one goal being the selection of appropriate control parameters that maximize thrust inherently for combat damage conditions. Computer modeling and testing of penetrator-damaged turbine engines is a major survivability program and is being aggressively pursued to determine design means, materials, and controls to lessen engine vulnerability.

Need

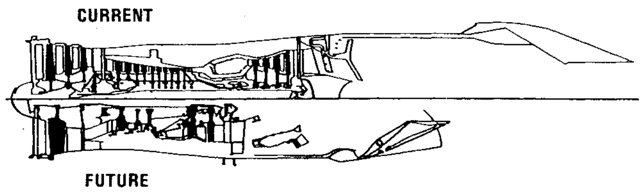
The potential for improved propulsion system survivability exists, and the need is great chiefly because of the projected capability of advanced air-to-air missiles, surface-to-air missiles (SAM's) and anti-aircraft guns. Besides facing advanced threats arrayed in depth, propulsion systems are expected to be more dominant in sharing vehicle volume requirements and providing signature sources in future vehicles because of higher sustained supersonic speeds and maneuvering requirements.

V/STOL aircraft will present especially unique propulsion survivability problems. From two to four engines with large fans are expected for some types of subsonic V/STOL aircraft, as illustrated in Fig. 12. For vehicles with supersonic capability, the V/STOL B aircraft sketches of Fig. 13 portray some of the different propulsion lift approaches. These aircraft are equipped with afterburning engines with vectoring nozzles and, in addition, employ lift augmentation devices.



THE F404 HAS:
- THE SAME THRUST
- 1/2 THE WEIGHT
- 3/4 THE LENGTH
- 11% SMALLER DIAMETER
- 650°F COOLER SKIN AT TURBINE CASING
- NO NEED FOR SECONDARY AIRFLOW SYSTEM
- TWICE THE PRESSURE RATIO
- 14% LESS AIRFLOW
- 8 FEWER TURBOMACHINERY STAGES
- 1/3 LESS PARTS
- ANNULAR vs CANNULAR (10) COMBUSTOR

Fig. 9 Reduction in size and complexity with modern engines.



- INCREASED THRUST-TO-WEIGHT
- LOWER COST
- FEWER PARTS, SIMPLER

Fig. 10 Next-generation engine.

- TOTAL CONSIDERATIONS, USING INLET DESIGN AS AN EXAMPLE
  - PERFORMANCE, PRESSURE RECOVERY, ANGLE OF ATTACK CAPABILITY
  - RCS, INLET LOCATION, DUCT BENDS, ABSORBER AREA
  - VULNERABILITY, FUEL INGESTION

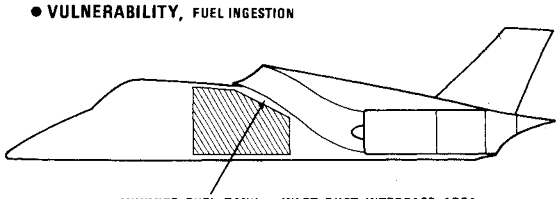
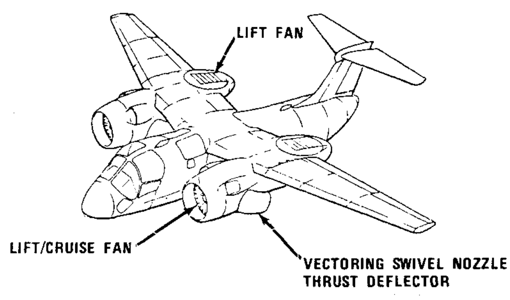


Fig. 11 Propulsion system integration.



TYPICAL V/STOL MULTIMISSION AIRCRAFT
UTILIZING VECTORING SWIVEL NOZZLES

Fig. 12 Type A V/STOL aircraft.

It is apparent that V/STOL entails a propulsion system dominating the aircraft with large propulsion components distributed throughout the vehicle. Engine bleed reaction control systems also contribute to the problem. V/STOL aircraft are especially interesting from a survivability standpoint because the capability of a combat-damaged aircraft to make a vertical or STOL landing with combat damage must be assessed and adds a new dimension in designing for low vulnerability. The classic controversy of single-engine vs twin-engine aircraft will be continued even more vigorously in the V/STOL area. If single-engine fighter-attack aircraft become

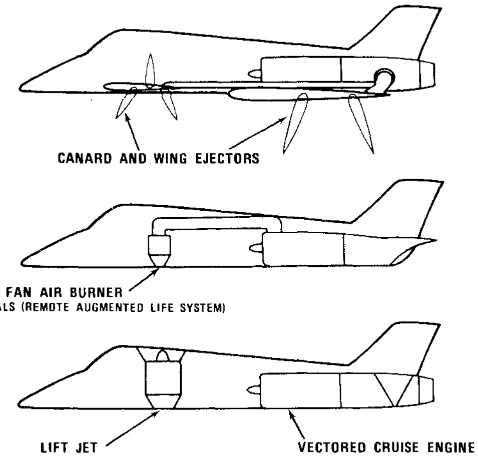


Fig. 13 Supersonic V/STOL propulsion.

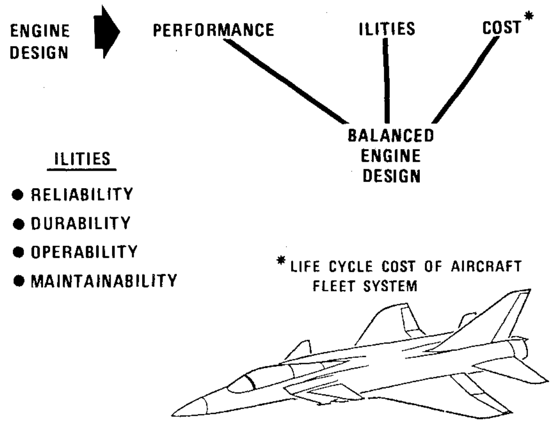


Fig. 14 ATES balanced engine design.

predominant in V/STOL, then rigorous engineering design for survivability will become a greater necessity with loss of twin-engine propulsion redundancy.

ATES/MACE Program

Since experience and study have demonstrated that survivability gains can best be accomplished by early attention in the initial engine and aircraft design (as opposed to relatively heavy add-on fixes), survivability is now being closely examined in advanced conceptual engine and propulsion designs. In a comprehensive program, propulsion system combat survivability is being addressed under contract in the current major advanced engine effort—the Navy/Air Force Advanced Technology Engine Study (ATES). The ATES program is an important broad advanced engine study in that it addresses 1) multiple application core engine (MACE) utilization, 2) balanced engine design, 3) improved technology development methods, and a 4) long-range propulsion plan.

The Air Force and Navy are funding five engine manufacturers in the ATES program, most supported by three to four airframers, in a total $8.3 million contract to conduct studies covering MACE core sizing, engine conceptual designs, broad advanced aircraft applications, and LCC. Influence of durability, reliability, maintainability, and operability goals on LCC will be evaluated in depth. Most of the engine manufacturers, supported by airframers, will be involved in conceptual design of from 5 to 10 vehicle propulsion systems.

The ATES program will compare MACE engines with unique engines (designed only for a specific application). Cost savings and performance penalties for MACE engines will be determined in the study. Based on the results, a long-range propulsion plan will be established. Another very important aspect of ATES is to examine cost, performance, and "ility" tradeoffs to provide balanced engine designs as indicated in Fig. 14. Survivability in the ATES program is being addressed under special contracts.

For the survivability study portion, a competitive Request for Proposals was held in November 1980. It was decided not to perform survivability studies on all the vehicles covered in ATES, but to do in-depth survivability analyses, emphasizing the complete advanced propulsion system, for a few representative Navy and Air Force tactical aircraft types.

Starting with the defined baseline propulsion system, the vehicles will "fly" against a variety of air-to-air threats, SAM's, and AA guns in a campaign scenario specifying the missions, threat densities, and conflict duration. Since results will be threat sensitive, scenarios have been carefully selected for broad coverage such that both IR guided and radar guided threats will be faced. Some scenarios will cover air-to-ground missions—and other scenarios will investigate air-to-air engagements. With a baseline vehicle fleet survivability and *force-effectiveness* (targets destroyed) established, a sensitivity analysis will be conducted.

The sensitivity analysis will be conducted with signature and vulnerability levels arbitrarily varied to parametrically determine the change in probability of survival (P_S) with RCS, IR, and vulnerable area (A_V), where A_V is defined as projected area times the probability of kill ($A_V = A_P P_{K/H}$).

The sensitivity study will also show the reduced signature levels and vulnerability levels which must be reached for *significant* survivability (P_S) gain.

Next, survivability concepts will be developed in the following areas:

1) Inlet designs for reduced RCS.

2) Nozzle modifications for reduced IR signature and reduced RCS.

3) Engine cycle variations for reduced IR, RCS, and A_V.

4) Engine configuration and mechanical design for reduced vulnerability.

RCS, IR, and A_V levels will be estimated for the survivability concepts; then the gain in P_S will be estimated from the previous survivability sensitivity study. The improvements will be determined using the parametric variation in P_S with signature and vulnerable area reduction. Thus the survivability approaches will be screened and only selected approaches chosen for definition. For the selected inlet, engine, and nozzle concepts, the propulsion weight, performance, dimensions, and engine costs will be evaluated. The concepts will then be integrated into the vehicles.

Then, ATES vehicle-engine sensitivity factors developed in the *basic* ATES balanced engine design and weapons system LCC study will be applied to the survivability exercise. ATES sensitivity factors will be used to assess changes in vehicle takeoff gross weight (TOGW) and mission performance. After this, the baseline vehicles modified in size and performance for individual concepts will be tested against the mission threats in the campaign scenario. Thus the overall P_S effectiveness of individual inlet, engine, and nozzle concepts will be established.

In a like manner, the altered aircraft costs will be established. Using changes in engine costs, specific fuel consumption, and weight, the resultant total effect on vehicle development, acquisition, and operating costs will be determined with ATES basic study sensitivity factors. With improvement in survivability, the aircraft fleet size to maintain a given force effectiveness in the scenario conflict duration will be reduced. This, in combination with altered aircraft costs, results in a new weapon system LCC. High-payoff concepts will thus be identified from an extensive, complete, tradeoff study of survivability improvements and costs as illustrated in Fig. 15.

It must be noted that designing for effective, built-in, passive survivability in advanced propulsion systems and vehicles is not expected to obviate the need for electronic

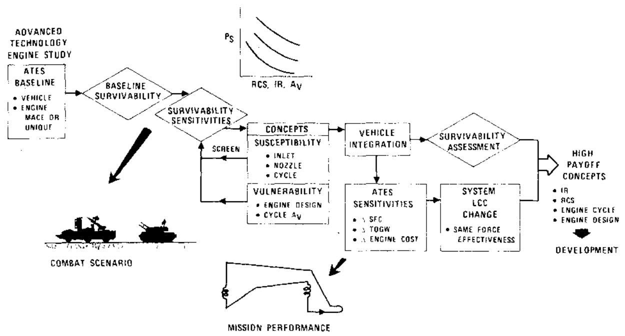


Fig. 15 Propulsion survivability payoffs evaluation.

countermeasures and special aircraft tactics. With survivability improved, especially in the area of susceptibility, the power requirements for jammers and deceptive devices can be reduced. Therefore the cost, weight, volume, and reliability and *maintenance penalties* to be paid for carrying this "add-on" active radiating equipment can be reduced.

Concluding Remarks

Improved propulsion system survivability with insignificant penalty is available through good design practice, e.g., configurations that avoid fuel ingestion. Reduced vulnerability also is becoming available through smaller, advanced engines with fewer turbomachinery stages—and significant gains should be available with attention to the engine accessories.

Contracted studies, attached to the ATES program, with advanced aircraft combat scenario simulations against projected threats are being conducted to investigate means for IR suppression, inlet/nozzle radar cross-section reduction, and advanced engine vulnerable area reduction. The studies will also assess any corresponding weight, size, or performance changes in terms of the resulting vehicle TOGW, mission performance, acquisition expense, and training costs. Conclusions on the overall effectiveness of various survivability approaches will be made from LCC analysis of advanced aircraft fleets, with and without survivability improvement.

Acknowledgments

Survivability has become an important part of advanced engine and vehicle development owing to James L. Byers, Manager, Development Systems, Plans and Programs Branch, NAVAIR-536, who developed the ATES Program; Dale Atkinson, Manager, Combat Survivability Branch, AIR-5184, who formulated the Navy plan for aircraft survivability; and Bob Hume, Triservice Joint Technology Coordinating Group for Aircraft Survivability, who provided JTCG support.

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