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Enhanced Capabilities of Future Fighters as a Result of HiMAT

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This paper focuses on projected requirements of future tactical fighters; and relates the HiMAT and other associated research and development programs intended to enhance these fighters. Specific advanced fighter technologies emerging from the programs are discussed, and the potential combat characteristics that can be obtained are presented. The HiMAT program's unique role as a research test bed for high-risk advanced technologies provides an appropriate and economical method of investigating and flight verifying the potential of future fighter technologies. Two remote piloted research vehicles which are 44% scale versions of a 1990 highly maneuverable fighter design, will demonstrate the viability of such advanced technologies as: aeroelastic tailoring, close-coupled canard, supercritical airfoils, variable camber, advanced composite materials, and integrated propulsion controls. Successful development and air vehicle integration of emerging technologies such as these should provide substantial improvements in supersonic performance, low-speed control, transonic maneuverability, and low-weight, low-cost vehicles capable of superior operation over the broad flight envelope potentially required of future fighters.

Introduction‡

ALTHOUGH today there are no published requirements, new generations of fighter aircraft will certainly be needed by the United States and its allies. This will occur, if for no other reason, to bolster the tactical fighter force as older aircraft are phased out of the active inventory. Studies are being conducted by Government and industry to define requirements for advanced flighters for both air-to-surface and air-to-air tactical roles. The results of these studies indicate that air-to-air fighters will be needed in substantial numbers. Along with the emphasis on numbers will come demand for superior performance.

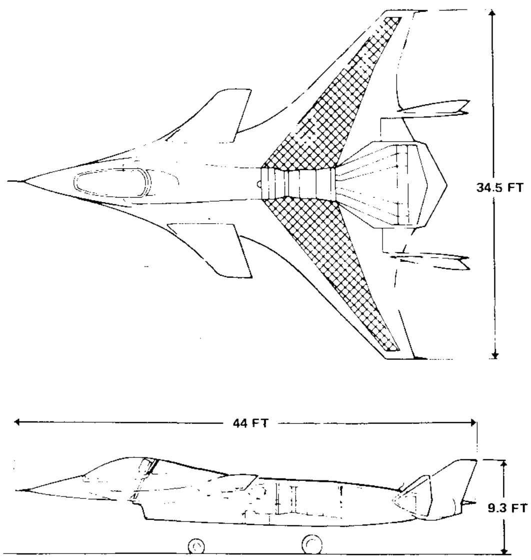
An additional critical factor in future weapon system development and procurement programs will be cost. In planning any program which involves procurement of aircraft in large numbers, low unit cost will be a prime consideration. Thus, the design objectives for future fighters must include low cost along with high performance.

The HiMAT Program

The ability to meet the simultaneous requirements of high aircraft performance, substantial quantities, and low cost will depend to a large extent on technology applications. Rockwell International (Rockwell) has developed a number of potential advanced fighter technologies during recent years under the highly maneuverable aircraft technology (HiMAT) program sponsored by NASA and the Air Force.

The HiMAT program was directed toward accelerated low-cost development and flight demonstration of advanced technologies for significantly increased maneuverability and combat effectiveness in future fighters. The resulting features, as reflected in a baseline advanced fighter design, are shown in Fig. 1. For a 300 n. mile radius, the takeoff gross weight was 17,064 lb.

The HiMAT program includes building two remotely piloted research vehicles (RPRV's) that are scale models of the advanced fighter design. This approach was pursued to attain the program objective of lowest cost for technology demonstration. In sizing the RPRV, it was desired to match the thrust-to-weight ratio and wing loading of the full-scale fighter at combat conditions (Mach 0.9 at 30,000 ft alt) so equivalent maneuvering performance could be demonstrated.



DESCRIPTION	
TOGW	17,064 LB
FUEL	3,941 LB
ENGINE	64.4 P&W74-20 (0.8 BPR)
WING	298 SQ FT 3.85 AR 45° LE SWEEP
T/W	1.43
W/S	57.2 LB/SQ FT

PERFORMANCE	
RADIUS	~ 300 NMI
SPEED	~ 1.6M AT ALT
SUSTAINED TURN	~ 8G AT 0.9M, 30,000 FT
$N_{Z_{MAX}}$	~ 12G

Fig. 1 Fighter basepoint.

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Index categories: Aerospace Technology Utilization; Configuration Design.

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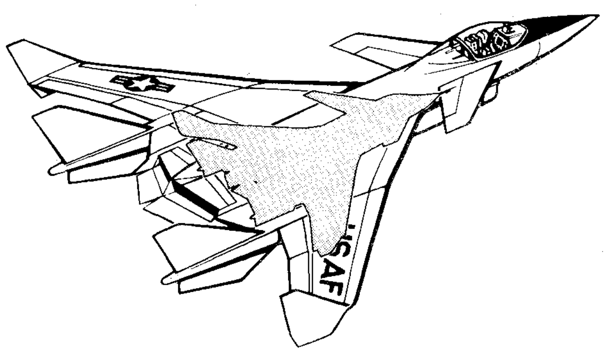
‡Since the time of the original presentation of this paper, HiMAT has very successfully completed three captive flights, and three free flights at NASA's Dryden Flight Research Center, Edwards, Calif.



	FIGHTER CONCEPT	RPRV STANDARD A/B
TOGW, LB	17,064	3,370
W_{FUEL}, LB	3,940	630
FOR 0.9M/30K:		
- W_{COMBAT}, LB	15,094	3,055
- W_C/S, PSF	50.6	52.7
- F_{NE}, LB	12,496	2,516
- T_C/W_C	0.828	0.824
- P_S AT 8g's, FPS	+2	-350*
- N_Z AT P_S = 0, g's	8	6.76*

*8 g at 0.9M/25,000 ft for RPRV

Fig. 2 Comparison of HiMAT fighter and RPRV demonstration vehicle.

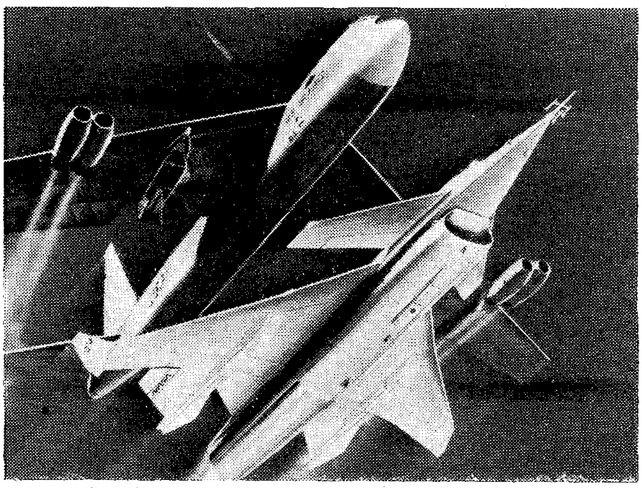


Fig. 3 HiMAT remotely piloted research vehicle.

Within the constraints imposed by the availability of off-the-shelf engines, the best match was a 44% scale factor, using the GE J85-21 afterburning turbojet engine. This resulted in a gross weight of 3370 lb for the RPRV (size comparison of the fighter and RPRV is shown in Fig. 2). Rockwell has completed fabrication of the two RPRV's and delivered them to NASA, where they are in final preparation for the flight test program.[1] Figure 3 is an artist's concept of a launch of the HiMAT RPRV from its B-52 carrier aircraft.[2]

The state of development of HiMAT technologies is such that they could be employed directly in advanced fighter designs. HiMAT derivative aircraft could be designed to meet projected NATO air-to-air fighter requirements for performance, maneuverability, and force size at low unit cost. The features of a representative study design of a counterattack fighter, using HiMAT technologies, are presented in Fig. 4. Takeoff gross weight is in the 10,000–15,000-lb class. A size comparison of the counterattack fighter with the F-15, F-16, and F-5 aircraft is shown in Fig. 5.[1] Size and gross weight have been reduced without sacrifice in performance through technology application. Cost was the driving factor for size reduction, since unit flyaway cost tends to be proportional to vehicle weight. If the small size causes concern, a look at history will provide a different perspective; Fig. 6 shows a comparison of the counterattack fighter with the F-86, one of the finest "dogfighters" ever produced.

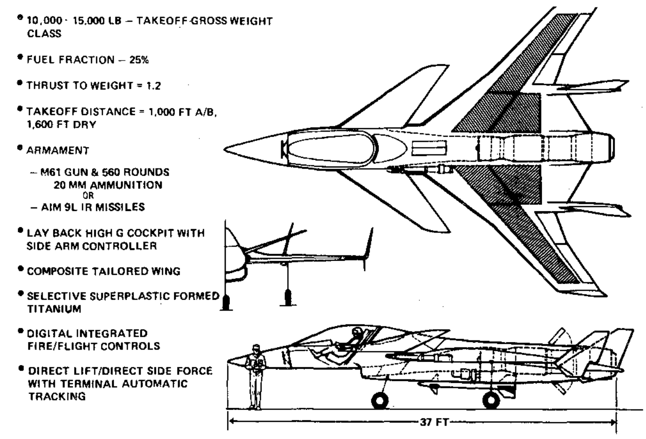


Fig. 4 Counterattack fighter.

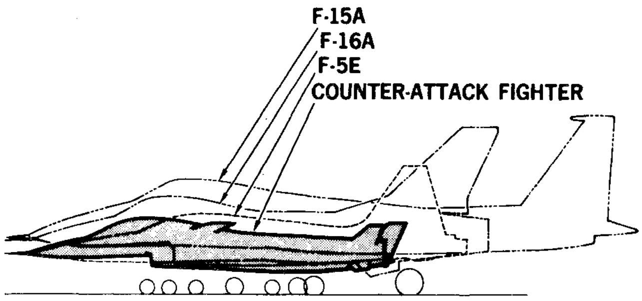


Fig. 5 Air-to-air fighter comparison.

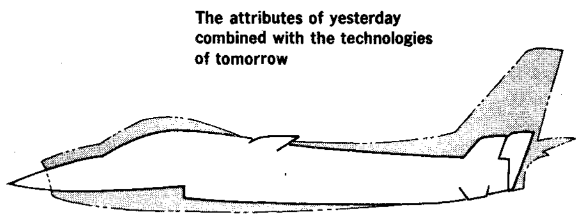


Fig. 6 Size comparison of counterattack fighter and F-86.

The main objective of the HiMAT program was to investigate high-risk interdisciplinary technologies as applied to a high-performance fighter design, at the lowest possible cost and program risk. In the three completed phases of the program, new technologies have been developed and incorporated into the RPRV in the areas of aerodynamics, structures, materials application, propulsion, control systems, and advanced control techniques. The technologies are those which best contribute to exceptional maneuverability and good overall performance at transonic speeds and supersonic speeds up to Mach 1.6. Table 1 shows a list of the HiMAT technologies adapted to the RPRV. From this list, four individual items are selected for further discussion. These are the technologies which have the most impact on concepts for minimizing the cost to meet the required performance. They include the close-coupled canard, active control technology, composite structure, and aeroelastic tailoring, which are represented here by a self-trimming wing with controlled twist.

Table 1 HiMAT fighter technology features

• Close-coupled canard	• Integrated propulsion controls
• Rockwell airfoil	• Digital FBW
• Variable camber wing	• Act-relaxed static stability
• Wingtip fins	• Composite structure
• Cambered fuselage	• Wing controlled twist
• Self-trimming wing	• Stress-limited controls
• Underbody inlet	• Direct lift and side force

Close-Coupled Canard

One of the most important identifying features of HiMAT is the canard, which shows prominently in Fig. 3. The canard was incorporated in the HiMAT design to improve overall lift characteristics and achieve a high maximum-lift capability.

The influence of canards on lift characteristics was studied by Rockwell and NASA aerodynamicists during the initial phases of the HiMAT program. It was found that through careful selection of vertical and longitudinal location of the canard in relation to the wing, lift of the total system could be more than the sum of the isolated wing and isolated canard lifts. The close-coupling effects of the canard have several benefits for achieving high-lift efficiency. The canard-induced downwash on the wing results in a redistribution of loading. The reduction of inboard wing loading more than compensates for the upwash on the outer wing if the wing-canard design is properly integrated, so that (for a given twist and camber) wing flow separation is delayed. At lift coefficients where separation is present, the vortex lift of close-coupled canard systems can result in favorable induction effects which increase the total lift above that of an uncoupled or weakly coupled system. At high angles of attack, the lift of the close-coupled wing-canard is about 25% greater than the wing alone.

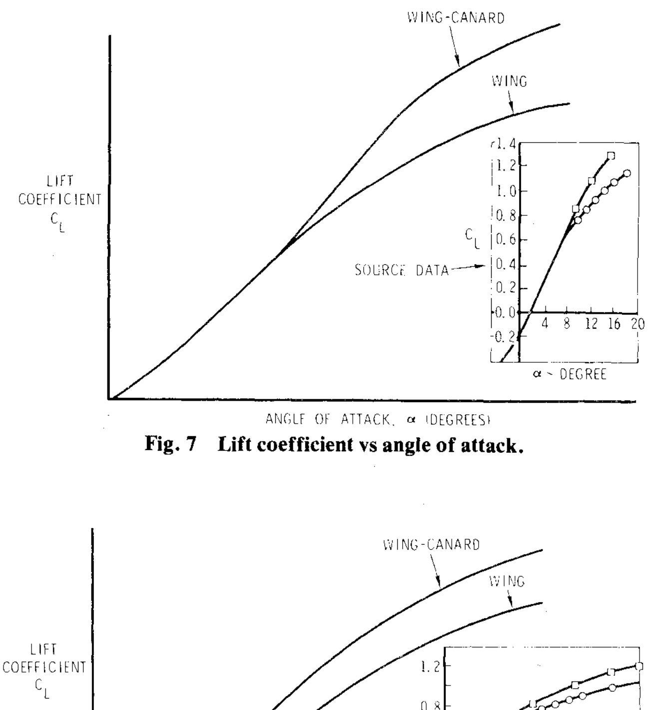


Fig. 7 Lift coefficient vs angle of attack.

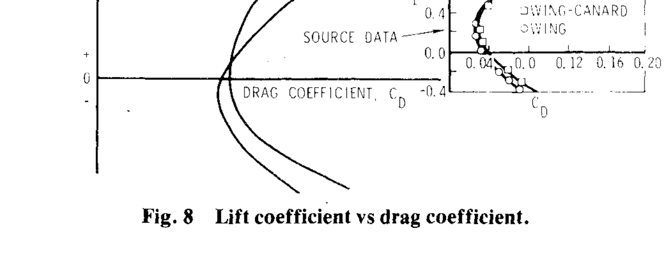


Fig. 8 Lift coefficient vs drag coefficient.

The HiMAT canard application results in improvement in both lift and drag characteristics. At lift coefficients where separation occurs on the wing without canard, the flow for the integrated wing-canard system is still attached. This effect on lift is represented in Fig. 7 which shows lift coefficient vs angle of attack. The corresponding improvement in lift vs drag is shown in Fig. 8. For example, at a lift coefficient of 1.0, the lift-to-drag ratio is 5.0 for the wing alone but greater than 8.0 for the wing-canard combination.

Some of the interactive aspects of the close-coupled canard related to its function as a trimming surface. It is possible that, with a jet flap, the full potential of supercirculation effects can be realized without adverse trim requirements which would be present in a conventional configuration. The capability of direct lift can also be provided, in conjunction with the wing or jet flap. With dihedral incorporated in the canard design, direct side force capability may also be obtained through simultaneous differential canard and rudder deflections.

Active Control Technology (ACT)

A combination of active flight control and a digital fly-by-wire system was used in the HiMAT design. Incorporation of an active control system allows considerable flexibility in tailoring the design of the basic configuration. With full-time active control to provide stability augmentation, it becomes feasible to use relaxed static stability (RSS) or to design for negative static stability in the subsonic flight regime. RSS is used to allow the designer to assume an approximate airfoil camber shape, including the control surfaces, to minimize induced drag. The favorable effects of minimal induced drag and greatly reduced pitch-control trim drag permit the use of smaller control surfaces and contribute to reduction in wing size. These factors can lead to significant decreases in structure weight and takeoff gross weight for a given payload in an aircraft design optimized for ACT application. No quantitative assessment of the impact of ACT on HiMAT is possible since no HiMAT aircraft was designed without ACT. However, one recent air-to-ground fighter study included tradeoff evaluations of ACT that showed savings of more than 20% of structure weight.

The use of RSS and ACT requires a highly reliable flight control system. Use of a fly-by-wire concept provides this through the ease with which control path redundancy and inherent high reliability can be provided without significant weight penalty. Modes of redundance that can be used include triplex or quadruplex systems, dual redundancy with multipath, selective routing of lines and circuits, etc. However, the demand for signal processing and computation is high in such a system. Digital flight control techniques pay off effectively in this situation because of the inherent capacity of digital systems to handle heavy computation workloads. Thus, the combination of active flight control and digital fly-by-wire becomes a logical and effective integrated design choice.

Composite Structure

The HiMAT design made use of several advanced materials and composite structure applications. This contributed to program objectives of low weight and costs, while providing an opportunity to gain more in-flight experience with the selected materials and structural concepts. Fig. 9 represents a general view of the HiMAT structural concept and a percentage breakdown of materials.[2] There are advanced materials and construction techniques in both primary and secondary structures.

On the basis of extensive trade studies, actual design, and fabrication experience with HiMAT and B-1 aircraft, it has been generally established that graphite/epoxy is the prime candidate material for lifting surface primary structures and

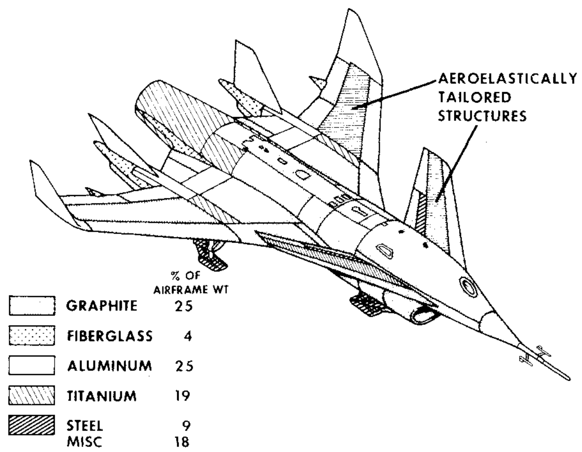


Fig. 9 RPRV implementation of advanced structural technology.

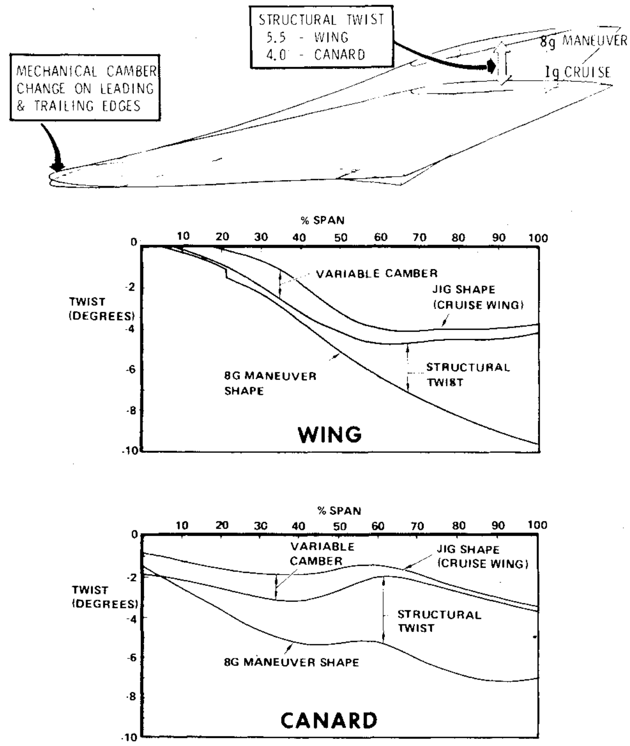


Fig. 10 Aeroelastic tailoring.

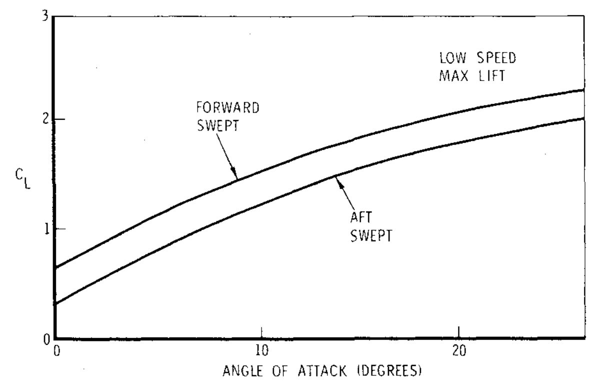


Fig. 11 Lift comparison, forward swept wing vs aft swept wing.

secondary structures. Primary structures include the wing and empennage. Secondary structures include flaps, slats, rudders, and elevons.[3]

Control and lifting surfaces generally are designed, at least in part, by torsional stiffness requirements to resist wrap-up and torsional/bending stiffness requirements for flutter. The significant weight savings attainable by application of graphite/epoxy vs aluminum or other metallic structures for stiffness-governed designs have been well documented, and savings of 25-40% are generally obtained from these applications.

Composites offer a potential for savings in cost and weight. In the fabrication of secondary-structure components for HiMAT, that included canard flaps, wing leading edges, engine inlet duct, tail body fairings, ailerons, and elevons, it was demonstrated that efficiently designed composite secondary structures result in piece-part count reductions, fewer manufacturing operations, cost savings of 10-25% and weight savings noted earlier.

In addition to the composite materials and structural applications, HiMAT also made use of superplastic forming and diffusion bonding (SPF/DB) of metallic materials. This process permits the designer to use more efficient structural forms and simultaneously reduce part count in a given structure. This results in significant weight and cost reductions over conventional design and fabrication methods. In HiMAT, wing secondary spars are fabricated from SPF/DB titanium.

Analytical comparisons of SPF/DB fabrication with conventional forming, machining, and fastening practices in certain airframe components showed potential savings of 30-40% in weight and up to 50% in cost. Dollar savings result from using less metal and reduced fabrication cost.

Aeroelastic Tailoring

The HiMAT design incorporates aeroelastic tailoring in the wing and canard-lifting surfaces. The design objective was to minimize drag due to lift over a wide range of lift coefficients, but particularly at the design 8 *g* maneuver condition, while still retaining low drag values for cruise. This was accomplished by controlling the wing and canard aeroelastic characteristics through structural tailoring, in such a manner that deformation due to application of lifting loads would result in a desired variation in twist from the root out to the tip, and an efficient spanwise load distribution. The required twist distribution for the desired load distribution is shown in Fig. 10. Not all of the twist is provided by aeroelastic tailoring; a portion of it is built into the jig-shape and an increment is also provided by the mechanical leading edge variable camber feature.[4]

Composite materials were used to achieve the aeroelastic tailoring process in HiMAT. These consisted of graphite-epoxy advanced composites in the wing and canard covers. The desired tailoring was accomplished by selecting ply thicknesses and filament orientation, with the use of specialized computer programs, to provide the correct material strength and stiffness characteristics.

The second HiMAT RPRV has been subjected to an 8 *g* maneuver load test in the structures laboratory, which showed good correlation between the predicted design twist distributions and the measured values. It also demonstrated the suitability and effectiveness of the analytical design tools used in the aeroelastic tailoring process.

The technology developed in the HiMAT program can be applied to any lifting surface to provide controlled structural strength and aeroelastic properties.

The Next Step

The technologies demonstrated in the HiMAT program offer significant improvement in the low-cost fighter technology base and form the basis for other major advances in high-performance aircraft design. Forward swept wing (FSW) is one of these concepts.

The aerodynamic benefits of FSW have been recognized for a number of years and verified through analytical studies and experimental research. These include higher maximum

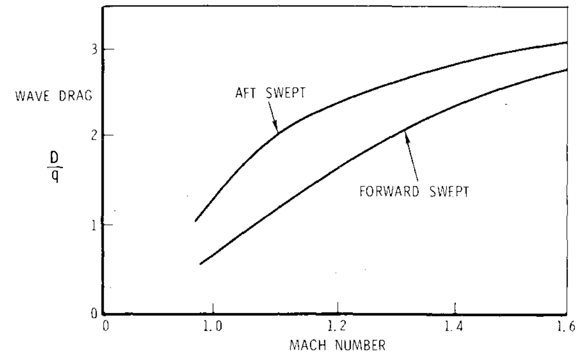


Fig. 12 Wave drag comparison, forward swept wing vs aft swept wing.

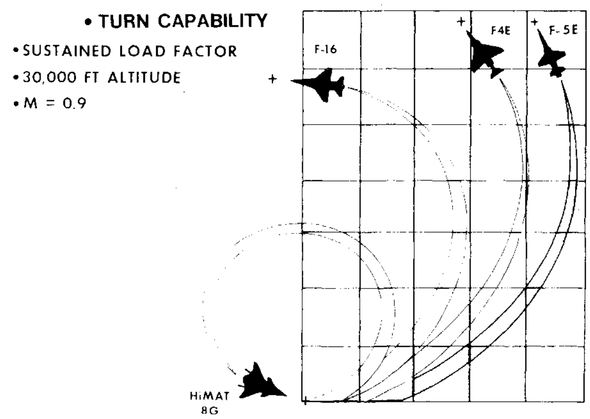


Fig. 13 Maneuverability.

operational lift relative to the aft swept wing (ASW) counterpart (Fig. 11), lower supersonic drag (Fig. 12), improved flutter characteristics, and a capability for fuselage shaping which permits better distribution of internal volume. The main deterrent to the development of practical FSW configurations in the past has been an inherent tendency toward wing divergence, which could only be overcome by means of an extremely rugged structural design. The weight penalties associated with the required structural strength, using conventional materials, were unacceptable from a performance/payload standpoint. Since initiation of the HiMAT program, accomplishments in three important areas provide effective solutions to the divergence problem, as follows:

1) Composite structures: The use of advanced composite materials in composite-structure designs provides the necessary stiffness and structural tailoring to compensate for the divergence phenomenon.

2) Aeroelastic tailoring: With the selection and control of composite-material-ply thicknesses and filament orientation, the stiffness characteristics of lifting surfaces can be tailored to prevent the onset of divergence. Studies conducted to date indicate that the combined effects of composite-structure design and aeroelastic tailoring make it possible to eliminate the divergence problem without weight penalties.

3) Active control technology (ACT): Wing bending moment relief and possible active divergence/flutter suppression, with minimum trim change, can be provided through maximum use of an active flight control system.

Study results indicate that an advanced composite, high-forward-swept wing can be designed to be divergence-free with no weight penalty. In addition, with equivalent technology and optimization, the FSW design will have a gross weight at takeoff approximately 29% less than that of an ASW comparator aircraft. This has a direct impact on system acquisition and operational costs.

The performance improvements available through the favorable effects of FSW design further extend the benefits of the advanced technologies from HiMAT to a spectrum of future high-performance aircraft. These improvements may be taken in the areas of increased speed/maneuverability performance, reductions in aircraft size for specified jobs, associated cost reductions, or varying tradeoffs between the different design areas.

Cost Trades

Cost vs Performance

Aircraft costs have always tended to increase as performance capabilities increase. This dictates that no better performance be provided in the design than is required to do the job specified in the design criteria. Excess performance is not cost effective.

The HiMAT advanced fighter concept was designed with a limit load factor of 12 *g* and the ability to sustain 8 *g* at Mach

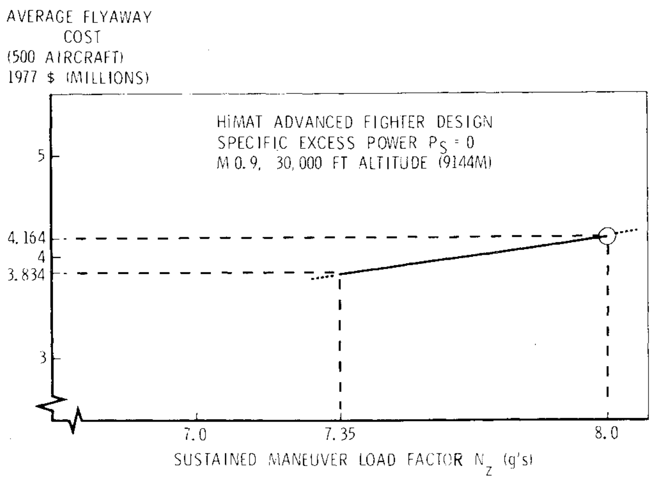


Fig. 14 Cost-maneuverability trade-off.

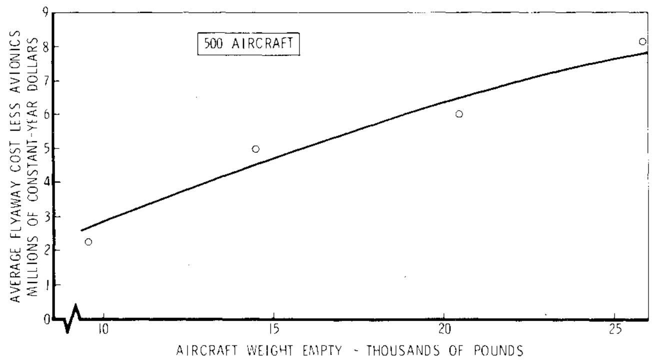


Fig. 15 Aircraft unit cost vs empty weight.

0.9 at 30,000 ft alt and zero specific excess power. Maximum design Mach number was *M* 1.6, with research maneuvering requirements specified in terms of time vs Mach number and maneuvering condition at 40,000 ft alt. The specification of maneuverability requirements was based primarily on the fact that HiMAT is a research vehicle; however, the load-factor values reflect analyses of the effects of maneuverability on combat effectiveness and of the expected physiological limits of human crewmembers. Figure 13 shows the impact of the sustained 8 *g* maneuvering capability of HiMAT in comparison with other current fighter aircraft. Figure 14 shows representative cost trades for maneuverability relative to the HiMAT basepoint.

Cost vs Air Vehicle Size

Aside from the maneuverability criteria which provided the main thrust of the HiMAT program, many of the technologies used have a favorable impact on aircraft physical size and weight. The payoff in weight savings, discussed throughout this paper, directly affects cost. From the standpoint of application of HiMAT technologies, cost avoidance ranks with the most important benefits. For the purpose of providing air-combat fighters to meet the projected requirements of NATO's air defense structure, low unit cost is an essential criterion.

The relationship between aircraft size and cost is illustrated in Fig. 15, which shows a representative variation in unit flyaway cost as a function of aircraft empty weight.

Summary

This treatise has examined two aspects of the outlook for tactical fighter forces, a projected requirement and technological resources, that can be applied in meeting the requirement. It is evident that NATO will have a future need for a large number of air-to-air fighters. The aircraft to fill the role must also be inexpensive, in terms of unit cost and operational costs. These dictate a relatively small vehicle. Technologies developed in the HiMAT program and recent developments such as FSW's make it possible to provide small high-performance aircraft at low cost.

The various HiMAT technologies, which will be flight verified in the remotely-piloted research vehicles, represent needed solutions to problems in aerodynamics, propulsion, structures, materials, and control systems. The benefits are improvements in supersonic performance, improved low-speed control and transonic maneuverability, aircraft weight reduction, manufacturing processes, and cost reduction. These benefits are probable requirements of many future aircraft designs.

Acknowledgment

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