Potential Payoffs of Variable Geometry Engines in Fighter Aircraft

P. Czysz,* F. C. Glaser,† and S. A. LaFavor‡
McDonnell Aircraft Company, St. Louis, Mo.

The design and control characteristics of military aircraft engines are generally established to perform a specific design mission. For any such mission, there is one engine type which will produce the thrust levels and mission fuel requirements which minimize aircraft size. No single engine type can, however, optimally perform all missions. Variable geometry can improve engine performance at specific operating conditions. For missions which require significant operation at those operating conditions, variable geometry engines can be superior to fixed geometry designs. Using multitechnology computer techniques, aircraft sizing studies compared two advanced, fixed-geometry augmented engines (a turbojet and a turbofan), and an advanced, variable-geometry turbine, augmented turbojet. Sensitivities in takeoff gross weight are compared for a number of mission and aircraft performance elements. Results of the application of variable geometry engines to the various mission roles are summarized.

Introduction

EVALUATION of potential payoffs must be considered in terms of the over-all system rather than for a single aircraft component. For aircraft designs the payoff is a desirable increment in capability and/or a decreased cost to achieve a required level of capability. For fighter designs, the subject to which this paper is addressed, this decreased cost is a function of the decreased size/weight of an aircraft system to achieve a level of capability with a given level of technology. The real question then is whether, for fighters, the use of variable geometry turbine (VGT) engines in aircraft designs results in reduced size and weight sufficient to justify and offset the development costs required for a successful engine design. A companion question is the versatility of VGT engines as applied to different mission roles. This is especially important since firm mission requirements for future fighters are difficult to define early in the development cycle, and engine development times are long. Therefore, the versatility of engines to meet several mission roles is paramount. These questions were addressed utilizing readily available data and computational tools in a "first cut" look.

Our study shows that there are potential payoffs for the use of variable engines.

VGT Engines Applied to Fighters

The fighter offers an excellent vehicle for evaluating engines as it is required to meet specific performance values at several flight conditions, as well as operate over a wide range of flight conditions. This leads to a complex matrix of sizing requirements for the engine and aircraft. The fighter design iteration is a multifaceted sizing task since the performance requirements are often conflicting in their influence on configuration components. (For instance, subsonic maneuverability favors reduced wing loading, while supersonic performance favors increased thrust to weight and increased wing loading.) Figure 1 illustrates a representative turbofan powered fighter which serves as a baseline for this study. The integration of engines into fighter configurations is generally representative of supersonic aircraft designs and is more complex than for large subsonic aircraft. The "buried" engine installation strongly influences fuselage size, wing location and empennage surface arrangements. Engine size, length and weight are prime factors in the aircraft configuration. The fighter design goal clearly favors the smaller, lighter aircraft, and in most cases the takeoff gross weight becomes an effective measure of merit for evaluation. For a set of performance capabilities such as turn rates, specific excess power, acceleration and maximum Mach number, an aircraft can be scaled to fly any distance, up to the point of design divergence, assuming all major components (including the engine) are varied appropriately in size and the same technology is maintained. The variable geometry engine concept is aimed at providing supersonic performance in augmented operation comparable to a fixed geometry turbojet engine while providing the fuel economy of a fan in intermediate power operation. Do the factors involved in installation of the engine enhance or negate these effects?

Critical Factors for Engine Installation

The critical engine installation factors to consider are engine weight, engine size, inlet losses, and aft-end losses. Each of these has significant effects on the outcome of the problem. Engine weight has two effects. First, the weight of the engine influences the amount of structure, the size of wing, (therefore the size of associated components) and the amount of fuel required. Second, the location of the engine influences the aircraft balance and hence wing and landing gear location. For the fighter aircraft baseline used in this study and a "rubberized" engine (scalable for constant performance), the growth factor weight sensitivity is about 3.5. Engine size is important, also for two reasons. One is length which directly relates to the balance question, the other is engine diameter. For fighters, the engine diameter directly influences the maximum cross section of the fuselage which, in conjunction with wing location for balance, determines supersonic wave drag values. Inlet losses are a most significant factor in installed performance and can have large influence on vehicle size because of "off design" operation. Aft-end losses are also important for the same reasons.

One important additional factor that needs to be recognized is strong interaction between engine cycle and airframe parameters. Tailoring the cycle parameters in con-

Received December 4, 1972; revision received March 12, 1973.
Index catagories: Subsonic and Supersonic Airbreathing Propulsion; Aircraft Performance; Aircraft Powerplant Design and Installation.

*Project Technical Engineer, Multitechnology Computer-Aided Design. Member AIAA.

†Senior Group Engineer, Propulsion Department.

‡Director, Project Technical Engineering.

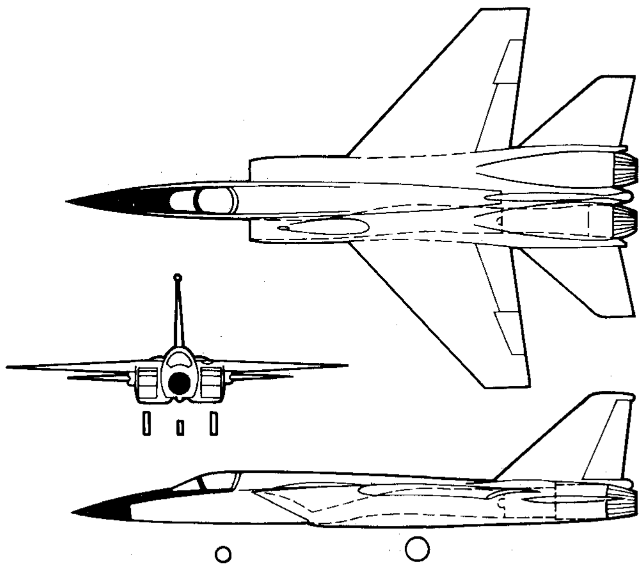


Fig. 1 Baseline configuration.

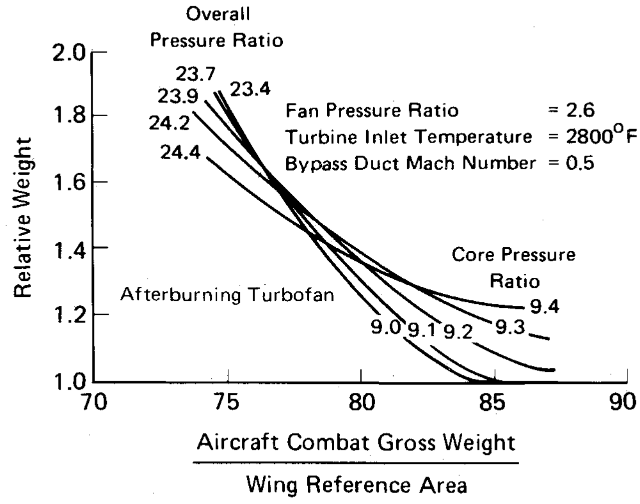


Fig. 2 Engine/airframe design parameters are not independent.

junction with the airframe parameters can significantly reduce the aircraft weight. The thermodynamic cycle of each of the engines considered is fixed, and no attempt was made to determine an optimum configuration for each engine; however, the example presented in Fig. 2 demonstrates the magnitude and character of this fundamental interaction. In the "Exhaust System Interaction Program," AF33615-70-C-1449, the Phase I report showed evidence of a significant reduction in weight with adjustment of the engine cycle variables. We did not include these effects because of the limited scope of the study.

Critical Factors in Aircraft Sizing

Fighter aircraft are sized by the requirements for various mission roles. When the requirements demand a high level of performance in more than one mission role, conflicting sizing requirements arise (i.e., supersonic dash vs transonic maneuverability). The best compromise among these conflicting requirements can be evaluated using sizing relationships based on four performance factors.

Maximum Mach Number—establishes wave drag, cross section area distribution trade-offs, and inlet system size; rarely determines the maximum engine size; emphasizes high wing loading.

Acceleration—dominant engine sizing factor for minimum time to intercept missions; favors high wing loadings.

Maneuverability—specific excess power and turn rate requirements in the transonic and supersonic flight regimes dominate the engine size and wing loading as maneuvering requirements become demanding; emphasizes low wing loadings and minimum high lift induced drag planforms.

Maximum Load Factor—(buffet free) wing loading and planform are altered by this parameter to minimize

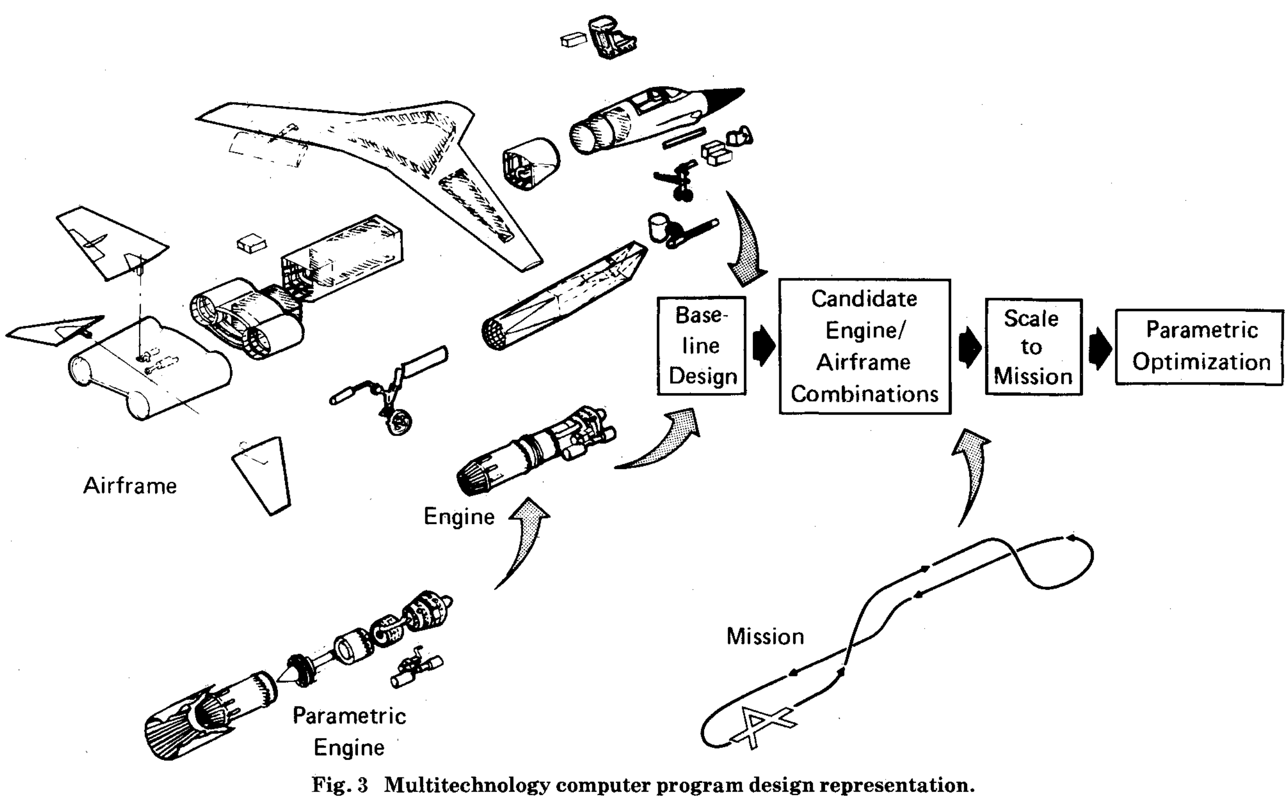
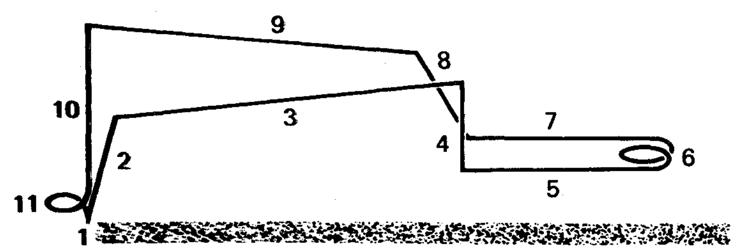
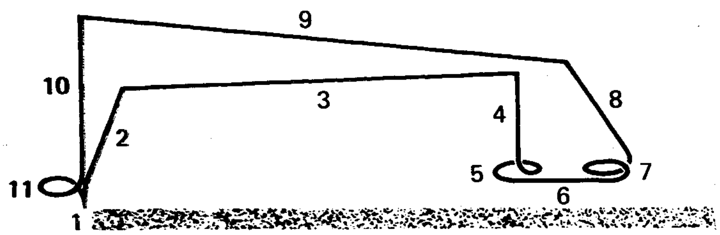


Fig. 3 Multitechnology computer program design representation.



Hi-Lo-Lo-Hi Mission Profile

1. Takeoff, Acceleration to Best Climb Speed
2. Climb, Best Rate of Climb/Fuel Flow
3. Cruise (Outbound), Altitude/Mach Number Specified or Optimum
4. Descent or Climb, Range Credit When Dash Supersonic
5. Dash (Outbound), Specified Mach/Altitude
6. Combat Fuel Allowance
7. Dash (Inbound), Specified Mach/Altitude
8. Climb or Dive, Range Credit When Dash Supersonic
9. Cruise (Inbound), Altitude/Mach Number Specified or Optimum
10. Descent, No Range Credit
11. Landing Loiter Fuel Allowance



Hi-Lo-Hi Mission Profile

Segments 1, 2, 3, 9, 10, 11 Same as H-L-L-H

4. Descent, No Range Credit
5. Combat Loiter Fuel Allowance, Mach Number for Minimum Fuel Flow
6. Acceleration From $M_{Initial}$ to M_{Final}
7. Combat Fuel Allowance
8. Climb to Optimum Cruise, Range Allowance

Fig. 4 Generalized mission descriptions.

nonparabolic induced drag and separated flow effects. Usually dominates the empennage size to provide necessary control at desired flight stability. Combat endurance for aircraft survivability and kill potential favors intermediate power operation.

The study approach to evaluate the potential payoffs of VGT engines should include consideration of all these factors. Any assessment which fails to consider these complexities of determining potential payoff predetermines the results and is of little value. The use of available multitechnology computer techniques provided a direct means of properly addressing the potential payoff trades.

This study was directed toward determining whether there are payoffs for VGT engines rather than searching for an optimum VGT application. These results do provide some direction for future study effort.

Study Approach

In the multitechnology computer approach used, three ingredients are necessary: the engine concept, the aircraft concept, and potential design missions. The multitechnology computer programs contained the design relationships required to size individual aircraft and/or engine components to meet the demands of the mission requirements, and the analytic relationships required to express these size changes in terms of aerodynamics, propulsion, and weights. Through an iterative process these changes converge to a final sized aircraft for the specific mission requirements. A representation of this process in Fig. 3 illustrates how the aircraft baseline appears to the computer. As indicated, the components are sized individually, and are then integrated with matching interfaces into a sized design. If a particular engine is used in the evalua-

Hi-Lo-Lo-Hi Category
Loiter Landing Allowance 20 Min at S.L.

	Dash Mach/Alt	Radius Cruise/Dash (Naut. Mile)	Engine Sizing Points (Fig. 6)	Combat Fuel Allowance
1	2.1/20k	200/30	B, F	3 Min Max AB 0.9/30k
2	0.9/20k	200/50	A, B, G	3 Min Max AB 0.9/30k
3	2.3/50k	200/50	C, F	3 Min Max AB 0.9/30k
4	0.9/10k	200/50	B, G	3 Min Max AB 0.9/30k

Hi-Lo-Hi Category

	Cruise Mach/Radius (Naut. Mile)	Engine Sizing	Combat Fuel Allowance	Loiter Fuel Allowance
5	0.875/500	F	6 Min, Inter., 0.9/30k	5 Min S.L. Landing
6	0.875/200	G	6 Min, Inter., 0.9/30k	{5 Min S.L. Landing {1 Hour 30,000 Combat
7	0.875/500	H	6 Min, Inter., 0.9/30k	2 Min S.L. Landing
8	2.3/200	D	3 Min Max AB 2.3/50k	10 Min S.L. Landing

Fig. 5 Specific study missions.

	Mach	Altitude (ft)	Load Factor	Throttle Setting	Specific Excess Power (SEP) (ft/sec)
A	0.9	20,000	1.0	Max AB	750
B	2.1	20,000	1.0	Max AB	1000
C	2.3	50,000	1.0	Max AB	150
D	2.3	50,000	1.0	Intermediate	150
E	0.9	30,000	1.0	Intermediate	250
F	0.9	30,000	2.5	Intermediate	0
G	0.9	30,000	3.0	Intermediate	0
H	0.9	30,000	3.2	Intermediate	0

Fig. 6 Engine sizing points for study missions.

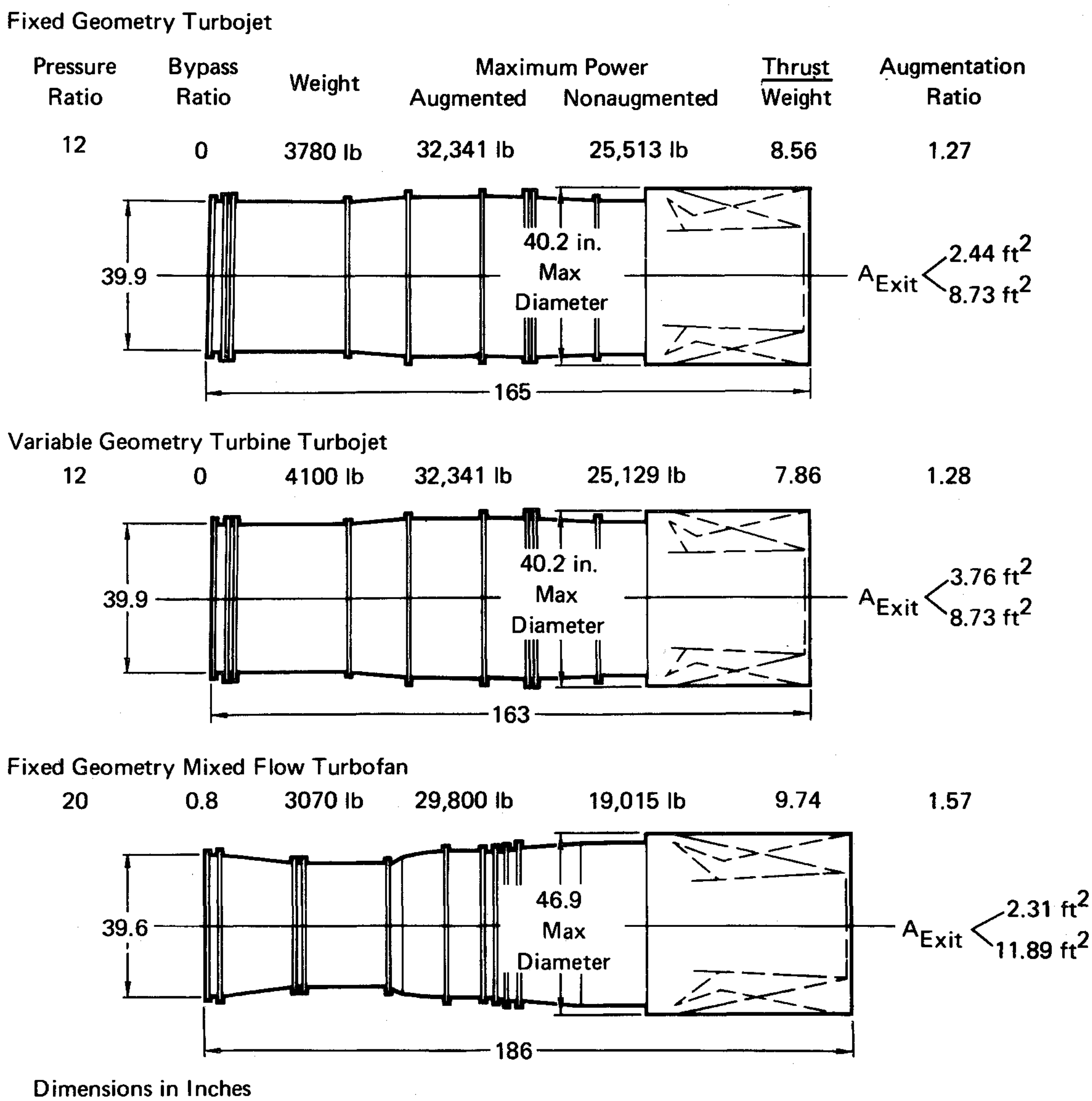


Fig. 7 Study engine characteristics.

tion, as was the case for this study, the engine becomes a single entity scaled according to predetermined growth laws. If a parametric engine program is used, individual engine components are considered as shown in Fig. 3.

Two basic mission categories were employed: a Hi-Lo-Lo-Hi which is a typical interdiction or air superiority type mission; and a Hi-Lo-Hi which is a typical area defense, combat air patrol intercept, or supersonic cruise type mission. These two missions are described in Fig. 4. The various elements of these missions can be adjusted to obtain the desired design mission. The eight specific study missions considered are given in Figs. 5 and 6. These missions were arbitrarily selected to provide a wide variation in mission roles covering the requirements of most fighter types. For each of these missions, a wing loading parametric was used to determine the minimum weight engine/aircraft combination which could meet the mission requirements.

The baseline aircraft was a fuselage integrated, twin engine design with fixed capture area, variable ramp external compression inlets. It was assumed that the study engines would integrate as contemporary engines at a customer connect mounting point within an engine compartment. In the multitechnology sizing program the engine size and weight are scaled according to rules provided by Pratt and Whitney Aircraft.

Propulsion System Description

The size, weight, performance and scaling characteristics of the three study engines were supplied to MCAIR by Pratt and Whitney Aircraft (P&WA). The performance defined by P&WA included the cycle thermodynamics, internal nozzle losses and isolated nozzle external boattail drag. Comparisons of the aircraft size and mission performance obtained with the three candidate engines used in this study required careful and consistent evaluations of component performance and installation losses. MCAIR estimated the inlet and nozzle/aft-end installation losses for each of the study engine designs and included these losses in the installed engine performance data.

The three engine designs include two fixed turbine geometry designs (augmented mixed flow turbofan and an augmented turbojet), and an augmented turbojet with variable area turbine stators. These engines described in Fig. 7 were all designed to operate at speeds up to Mach 2.5 and with maximum turbine inlet temperatures up to 3000°F. Definition and evaluation of variable geometry turbofan engines was beyond the scope of this preliminary investigation.

The airflow and throttle schedules used to establish the augmented thrust of the mixed flow turbofan engine were defined to best match the requirements of a typical air

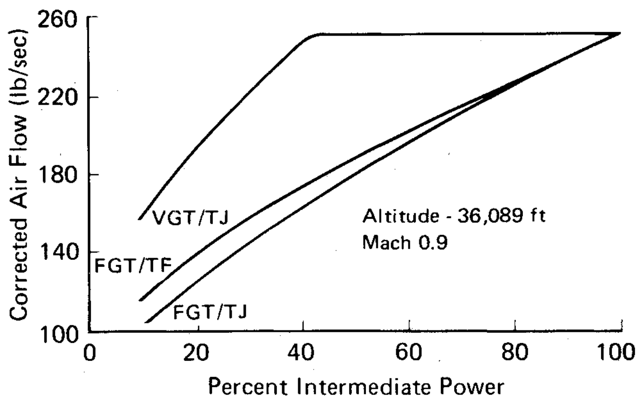


Fig. 8 Reduced power engine airflow characteristics.

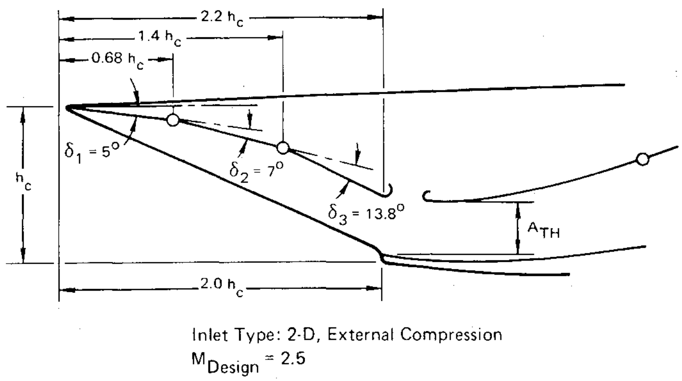


Fig. 9 Inlet design used for study evaluations.

superiority fighter mission. The turbojet engine design variables and schedules were then defined to match the thrust and airflow lapse characteristics of the turbofan. As the result, the ratios of maximum power thrust and airflow to the sea level static values are identical for all three engines over their operating speed range.

The key factor of the variable geometry turbojet design was operation at reduced power without the attendant decay in engine corrected speed and airflow of fixed geometry designs. To accomplish this, P&WA incorporated a turbine design in which the geometric stator flow area could be varied by about 50% (30 to 40% in effective flow area). As shown in Fig. 8, this large variation in turbine stator flow area permits operation to about 40% of intermediate power thrust with constant engine airflow, while both fixed geometry engines exhibit airflow decay at all reduced power settings.

A fixed capture area external compression inlet was used to conduct these studies. This inlet, defined in Fig. 9, is designed to operate at speeds up to Mach 2.5. The mass flow ratio of this inlet was determined using a predetermined ramp angle schedule, full side plate geometry, and estimated boundary layer bleed flow rates.

Propulsion System Installation Losses

Propulsion system installation losses include degraded engine cycle performance resulting from inlet total pressure losses, inlet drag forces, and nozzle/aft-end drag forces. Engine cycle performance was estimated by P&WA using the inlet total pressure recovery characteristics defined in Mil-Spec E5008C. This data was used without further correction by MCAIR.

Inlet/engine airflow matching must be accomplished to determine the inlet capture area required to provide the engine with its required airflow at all operating conditions. Airflow allowances equal to 6% of the engine airflow were incorporated to provide for engine tolerance, inlet leakage, cooling and the airflow required for an environmental control system. Scheduling all the engines to exhibit identical airflow lapse characteristics results in the required inlet capture area being equal for all three engines. For the 250 lb/sec sea-level static airflow of the reference engine, the required inlet capture area is equal to 7.7 ft^2. Airflow captured by the inlet, in excess of that required for the engine and allowances, must be bypassed with a resultant drag penalty. Total inlet drag includes the sum of additive, bleed, bypass and allowance airflow drags. The relationship of inlet airflow and related drag elements is illustrated in Fig. 10. At reduced power settings, i.e., operating at thrust levels less than intermediate, the engine airflow demand is reduced; inlet drag increases as a result of operating at a reduced mass flow ratio. Figure 11 illustrates the substantial reduction in inlet drag achieved by utilizing the variable engine geometry to delay the reduced power airflow decay in relation to the fixed geometry engines.

Nozzle/aft-end drag results from reduced static pressure on the aft fuselage or nozzle boattail surfaces. Such reduced pressures result from overexpansion or separation of the local flow. MCAIR used an analytical procedure of examining the local body slope of the aft fuselage and

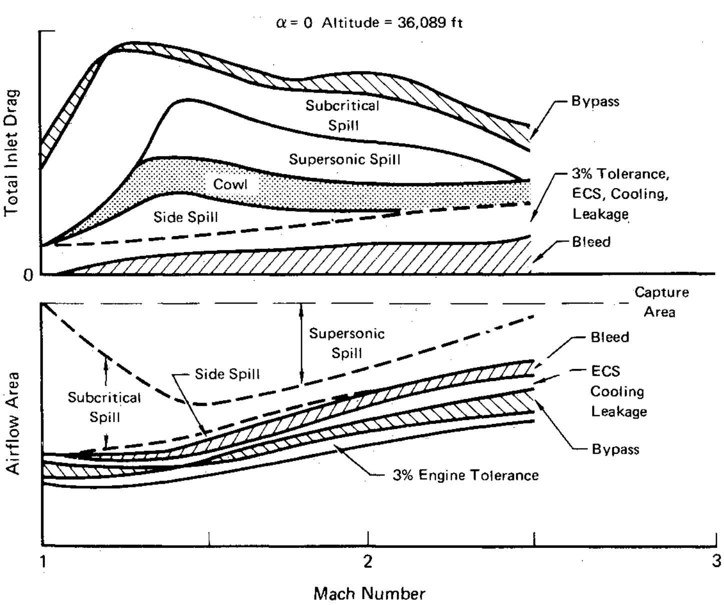


Fig. 10 Inlet/engine airflow matching considerations.

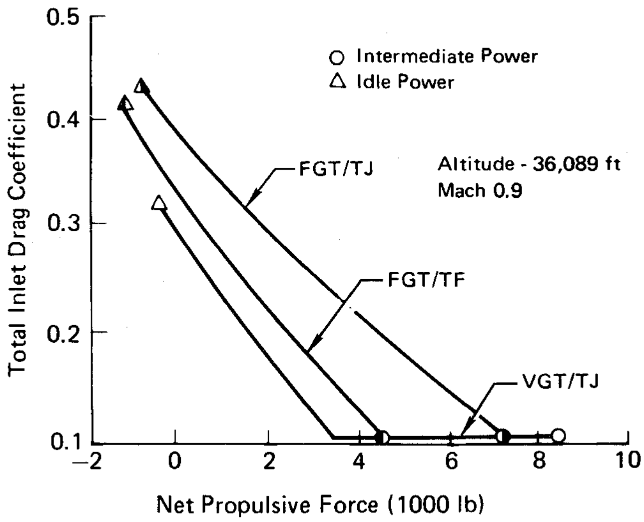


Fig. 11 Inlet drag comparison at reduced engine power.

nozzle boattail contours to predict regions of flow separation. This procedure consists of examining overlayed aircraft cross sections, beginning at the maximum fuselage cross section, to identify the regions on the fuselage where the local slope exceeds that at which flow separation occurs. A typical example of such overlayed cross sections and the indicated regions of local flow separation is illustrated in Fig. 12. The drag in the regions of flow separation was estimated using an axisymmetric separated flow pressure coefficient.

In our bookkeeping system, the external aerodynamic drag includes the forces on the aft fuselage and nozzle at its maximum exit area position. With varying flight speed, altitude and power setting, the nozzle exit area is varied to maximize engine thrust. As a result, the aft projected area of the nozzle boattail continuously changes throughout the flight envelope. It is necessary then to estimate the variations in nozzle boattail drag as functions of both flight speed and power setting. These throttle dependent drags include the MCAIR separation drag estimates in the predicted regions of airframe induced separation and the P&WA isolated boattail drag estimates in the regions free of separation.

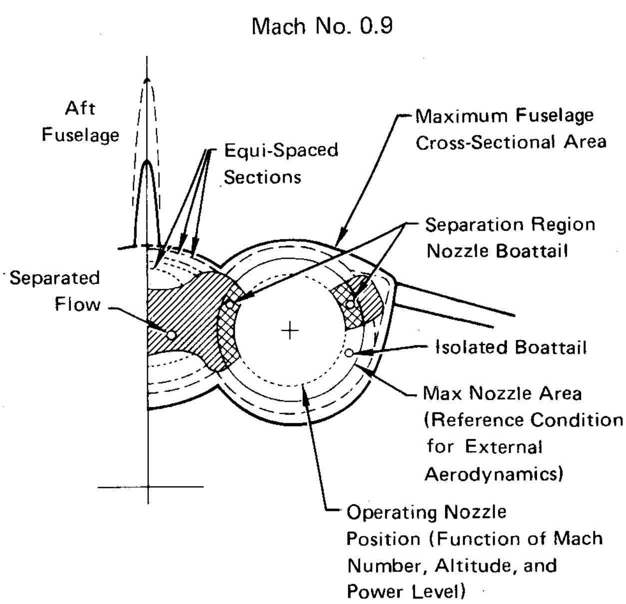


Fig. 12 Local body slope nozzle/aft-end drag analysis model.

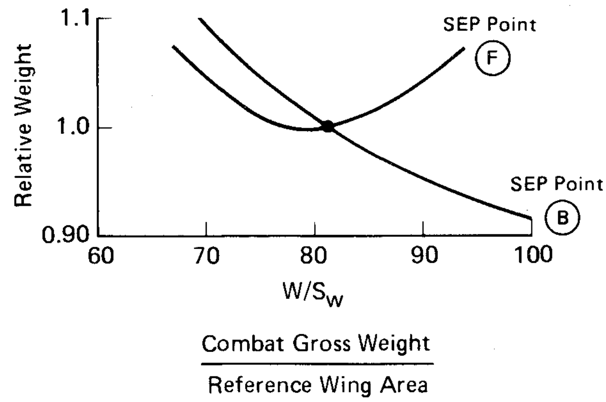


Fig. 13 Sizing relationships for two specific excess power points exhibit different sensitivities.

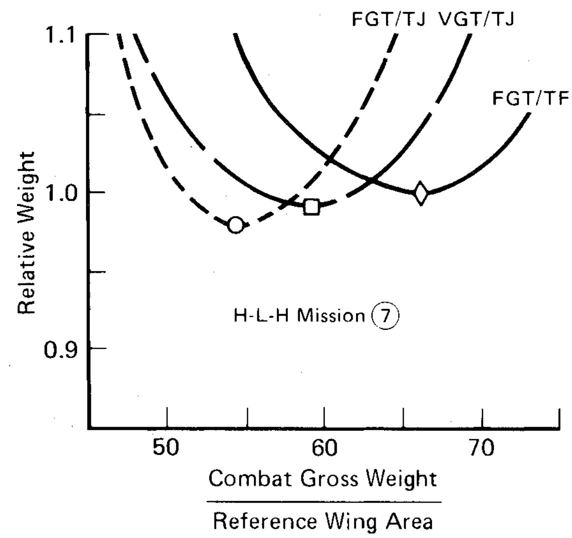


Fig. 14 Mission sensitivity for subsonic high G maneuvering SEP points.

Results

If the VGT/TJ is to result in a lower aircraft weight than obtained with the fixed geometry engines, the weight increment between engines (Fig. 7) installed in the aircraft must be offset by fuel savings. The eight study missions listed in Fig. 5 were used for evaluation. Each of the engines was sized along with the airframe to achieve the performance and mission radius of the study mission for a constant wing loading at combat weight. Combat weight is defined as TOGW minus one-half the internal fuel. This

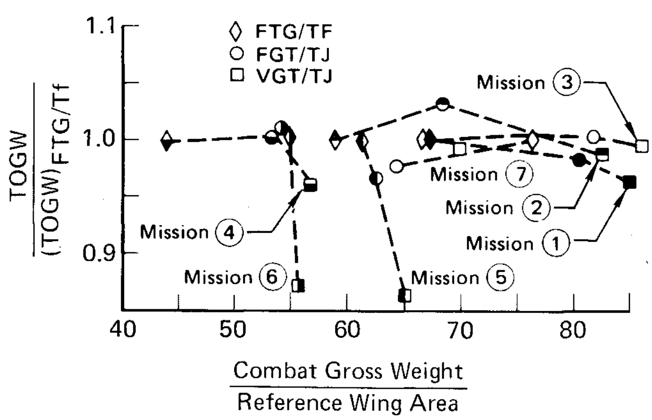


Fig. 15 VGT/TJ impacts favorably on the aircraft size to achieve a desired mission.

FGT/TF	FGT/TJ	VGT/TJ	
0	−3.7	−5.5	Base Mission (1)
0	+1.1	−3.3	Cruise Δ 200 Naut. Mile
0	−7.8	−11.0	Dash Δ 50 Naut. Mile
0	−4.6	−6.9	Combat Time Δ 5 Min
0	−3.3	−4.2	Engine Size Δ 110% Dia
0	−4.0	−5.9	Aft End Drag Δ 150% Base
0	−7.1	−10.3	Engine Sizing Points, B. G
+5	0	−3.7	Engine T/W T/W = 8.56
0	−5%	−7%	Inlet Drag Δ 50% Base

Fig. 16 VGT/TJ has desirable sensitivities to design and mission changes for Mission 1.

airframe/engine/fuel sizing was done at a series of wing loadings for each engine/airframe combination in order to determine the best wing loading, i.e., the wing loading at which the TOGW was a minimum. Each of the Specific Excess Power (SEP) points exhibits a different sensitivity between weight and wing loading. Figure 13 shows this relationship for the two engine sizing points used in Mission 1 (Fig. 5). There is only one wing loading at which both requirements can be satisfied. If more sizing points had been specified to be simultaneously satisfied, then additional independent variables (such as wing sweep angle, aspect ratio, taper ratio, camber, and thickness) must be permitted to vary, and a search technique must be employed to identify the parameter combinations providing high payoff. The characteristics shown in Fig. 13 are representative of a subsonic high g, intermediate power, engine sizing point (Fig. 6), and a supersonic, 1 g, maximum A/B power engine sizing point (Fig. 6).

An intermediate power sizing point is considered important for combat endurance. MCAIR flight simulator results indicate a high performance aircraft may combat at intermediate power from 50-65% of the time.

Because of the differences in installed engine performance characteristics, each airframe/engine integration

	Base Mission 6	Combat Loiter Δ 2 Hours
FGT/TF	0	0
FGT/TJ	−3.0	−3.3
VGT/TJ	−12.0	−14.0

Note: Percent change in TOGW with respect to FGT/TF

Fig. 17 VGT/TJ displays favorable combat endurance trades for Mission 6.

Mission 1

Total Fuel Relative Weight	FGT/TF	FGT/TJ	VGT/TJ
	1.0	1.03	0.97
Takeoff Fuel	6.4%	8.8%	8.6%
Climb Fuel	7.0	7.5	7.3
Descent Fuel	10.4	10.0	12.4
Cruise Fuel	18.2	24.0	21.9
Dash Fuel	36.8	28.6	28.2
Combat Fuel	14.1	11.1	11.2
Landing Allowance	7.1	10.0	10.4
Total Fuel	100%	100%	100%

Mission 1, with 50 Nautical Mile Dash

Total Fuel Relative Weight	FGT/TF	FGT/TJ	VGT/TJ
	1.0	0.94	0.89
Takeoff Fuel	5.6%	8.0%	7.6%
Climb Fuel	6.0	6.5	6.4
Descent Fuel	8.4	8.1	9.9
Cruise Fuel	14.9	21.0	19.1
Dash Fuel	47.6	38.2	38.1
Combat Fuel	11.8	9.9	10.0
Landing Allowance	5.7	8.3	8.9
Total Fuel	100%	100%	100%

Fig. 18 Comparison mission segment fuel fractions.

achieves minimum weight at a different wing loading. This point is illustrated in Fig. 14. The relative weight trends are shown for the three study engines with Mission 7 which is a Hi-Lo-Hi type with only subsonic maneuvering points for engine sizing. The indication that the FGT/TF has the highest wing loading is characteristic of this particular aircraft/mission combination. We shall see in our next case, Mission 1, that when a supersonic sizing point is added, the FGT/TF always has the lowest wing loading. Fig. 15 compares the minimum weight points and the best wing loadings for Mission 1-7 defined in Fig. 5. Again the relative weight is defined with this figure. 1) For the same mission, each engine cycle exhibits a unique value of wing loading at which minimum TOGW is achieved. 2) For each engine/airframe combination, the differing mission requirements result in a unique wing loading for the minimum weight point. 3) Although the benefits of the variable geometry turbine vary considerably from mission to mission, in no case was the VGT/TJ a significant disadvantage, in spite of a 1000 lb weight penalty for this engine over the fixed geometry turbofan.

This last fact points out the potential payoff growth for the variable geometry turbine engine as its thrust to weight ratio improves and as more is learned to advantageously employ its inherent operating advantages. Although aircraft weight savings up to 14% are indicated, it is more important to stress the versatility of the VGT/TJ in accommodating a wide range of mission requirements without incurring an aircraft weight penalty, despite the fact that its thrust to weight ratio is 19% less than the fixed geometry turbofan.

The sensitivity of the aircraft weight to changes in mission requirements and engine design and installation characteristics was also investigated. These sensitivities for Missions 1 and 6 are presented in Figs. 16 and 17, respectively. Again the adaptability of the VGT/TJ can be illustrated. For each increment investigated, the change in TOGW is less for the VGT/TJ than for the other two engines considered. If, in fact, the thrust to weight ratio of the VGT/TJ were increased to equal that of the FGT/TJ, then an additional 4% payoff in terms of TOGW appears possible. From Figs. 16 and 17 it would appear that for long loiter times and for transonic high g maneuverability utilizing intermediate power for combat persistence, the VGT/TJ has its best advantage. Also, for long supersonic dash missions the payoffs for the VGT/TJ approach those achieved for the subsonic flight conditions. These three areas are very important to the tactical interdiction, air superiority, and interceptor type aircraft. The variable geometry turbine engine can provide potential payoffs in the key areas for maintaining weapon superiority while holding aircraft size and cost to economical values.

Figure 18 illustrates how significant the fuel flow reduction is in offsetting the 1000 lb weight penalty of the VGT/TJ when considering supersonic dash mission requirements. The reference fuel quantities for Mission 1 and Mission 1 with a 50 naut mile dash are about 16,000 lb and 23,000 lb respectively.

Conclusions and Recommendations

The study performed to date at MCAIR has illustrated that effective integration of variable cycle engines into fighter aircraft designs will be an extremely complex activity, and that defining the potential payoffs is a very complicated process. At the outset, it was hoped that a brief survey of mission roles would reveal one or more significant advantages for variable geometry turbine engine applications. Instead, all three engines we examined were good engines. We found areas of significant payoff as well as standoffs and areas of small advantage.

The study performed leaves no doubt that the variable geometry turbine engine offers a great deal of potential payoff for fighter aircraft over a wide range of mission roles. Consider these results.

1) An aircraft with VGT designed for combat maneuvering and high loiter capability is significantly lighter (14%) than one designed using a turbofan.

2) An aircraft with VGT designed for combat has a high combat/loiter trade as compared to an aircraft with a turbofan.

3) An aircraft with VGT designed for combat and supersonic dash is slightly lighter than an aircraft designed with a turbofan.

4) An aircraft with VGT designed for combat plus supersonic cruise at intermediate power is much lighter than one using a turbofan, and shows promise for converging to a design with a realistic weight. This would be a major breakthrough in fighter design and some Air Force experts contend this would revolutionize air combat tactics.

It is worthy of note that the study shows that when the aircraft and engine size are permitted to be optimized, the VGT design is consistently superior (in terms of lower TOGW) to the fixed turbojet and is at least equal to the turbofan engine. This occurs despite the 1000 lb reference engine weight decrement favoring the turbofan.

To put weight reduction in proper perspective, consider the F-4 Phantom. In the 45,000 lb class aircraft, a 10% reduction in weight if related to an increase of specific excess power would yield an increase of over 250 fps at flight conditions significant to combat. Hence an aircraft designed nearly two decades ago would be competitive with current aircraft requirements today. The impact of these engines on future aircraft design is equal to or more significant than such developments as supercritical wing technology, control configured vehicle active control technology, and composite materials applications.

The limitations of this study should be emphasized. We used data and design approaches available to us which did not reflect the specific capabilities that may be realized by more complete integration of engine and aircraft controls. The engines were arbitrary selections having identical nozzle schedules, controls and lapse rates. Nor did the study involve interaction of engine cycle variables with airframe configuration parameters, which past work on the Air Force contracted Exhaust System Interaction Program indicated to be significant in effectively integrating engine and airframe. We have only scratched the surface and have over simplified the problem for expediency.

There is no question that this is an area of engine technology development that can be exploited by future advanced aircraft and that the technology development should be begun and pursued to provide early future options for air vehicle systems. Development studies by engine and airframe technologies as a "team" effort expanding on the goals of the study described in this paper is considered essential to establishing engine definition, and additional in-depth efforts should be initiated by the Air Force to accomplish these studies.