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INFLUENCE OF VARIABLE TURBINE GEOMETRY ON ENGINE INSTALLATION LOSSES AND CYCLE SELECTION

Robert J. May, Jr., et al

Pratt and Whitney Aircraft
East Hartford, Connecticut

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ROBERT J. MAY JR., CAPTAIN, USAF
W. F. ZAVATKAY

PRATT & WHITNEY AIRCRAFT DIVISION
UNITED AIRCRAFT CORPORATION

TECHNICAL REPORT AFAPL-TR-73-18

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FOREWORD

This report was prepared in the Performance Branch (TBA), Turbine Engine Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Project 3066, "Gas Turbine Technology" and Task 30661108, "Turbine Engine Integration Analysis Procedures."

This report was co-authored by Capt. Robert J. May, Jr. of the Performance Branch and Mr. William F. Zavatkay of Pratt & Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Connecticut. The work was accomplished between April 1971 and November 1972. It was presented by Capt. May at the JANNAF/AIAA/SAE 8th Propulsion Joint Specialist Conference in New Orleans, 27 November - 1 December 1972.

This report was submitted by the authors March 1973.

This Technical Report has been reviewed and is approved.

Ernest C. Simpson, Director
Turbine Engine Division
Air Force Aero Propulsion Laboratory

ABSTRACT

The trend in military aircraft is toward increasing thrust loading for improved maneuverability coupled with a requirement for extended subsonic cruise range at low power settings. Conventional turbine engines designed to meet these requirements must operate over large ranges of airflow between maximum power and cruise. As a result, the inlets and nozzles designed for these engines cannot perform efficiently with the low airflow rates typical of subsonic cruise operation. Variable turbine geometry, however, offers a promising approach for obtaining both high thrust loading and efficient cruise performance by permitting large amounts of thrust modulation at constant airflow rates. As an example, the performance of a turbojet engine, which provides efficient high thrust maneuvering and supersonic operation, can be improved by variable turbine geometry to the point where it is competitive with a fixed-turbine-geometry turbofan engine in the low-thrust subsonic cruise regime. A major effort leading to the development of the technology required to produce practical variable-turbine-geometry engines should be pursued if the performance requirements of future military engines are to be met.

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INTRODUCTION

Over the past twenty years, which cover the development of the F-86 airplane through the development of the F-15 airplane, aircraft thrust loading has been increased by a factor of three in response to the requirement for increased maneuvering capability. Concurrently, however, increasing emphasis has been placed on obtaining extended subsonic cruise range. Consequently, the engines for recent military aircraft have been required to provide extremely high thrust levels while still being capable of operating with low fuel consumption rates at very low power settings for subsonic cruise.

The propulsion system most often proposed for this type of mission is an afterburning turbofan engine. On the basis of uninstalled engine performance, this appears to be an excellent choice. The afterburner provides the required maneuvering thrust while the inherently high propulsive efficiency of the fan provides good performance at low power settings. Unfortunately, however, this engine cycle operates over a wide range of airflow rates between cruise and maximum power conditions. When the engine is installed in an airplane the inlet and nozzle must be designed to accommodate the maximum required airflow rates, resulting in high inlet spillage drag and high aft-end drag during operation at low power settings. As the trend toward increasing disparity between the maximum thrust and the cruise thrust continues, the achievement of an acceptable level of overall performance will become more difficult.

Since the installation losses are primarily related to the change in airflow with thrust, one possible solution is to develop an engine cycle that will provide a range of thrust levels with a constant airflow rate. This can be achieved through the use of variable turbine geometry.

To illustrate the effectiveness of this design approach, both the uninstalled and the installed engine performance characteristics have been estimated for a typical variable-turbine-geometry turbojet engine and the results have been compared with similar estimates for a fixed-turbine-geometry turbojet engine and a fixed-turbine-geometry turbofan engine with comparable capabilities. The design characteristics of these engines are summarized in Table I.

TABLE I

DESIGN PARAMETERS FOR THREE TYPICAL ENGINE CYCLES FOR ADVANCED MILITARY AIRCRAFT

	Turbojet		Turbofan
	Variable Turbine Geometry	Fixed Turbine Geometry	Fixed Turbine Geometry
Compression Ratio	12	12	20
Bypass Ratio	0	0	0.8
Turbine Stator Inlet Temp (°F)	3000	3000	3000

The turbojet engine cycle was chosen because this type of cycle generally provides good performance at high thrust levels and at supersonic conditions but has poor performance at low-thrust subsonic cruise conditions. As a result, the disparity between the performance capabilities at the two operating conditions of interest is large, making the turbojet an excellent candidate for performance improvement through the incorporation of variable turbine geometry.

The afterburning turbofan engine was chosen for comparison with the turbojet engine because the turbofan is frequently selected for diverse missions with both subsonic and supersonic mission segments and high maneuverability requirements. The bypass ratio selected for this study represents a compromise between subsonic cruise and maximum power thrust specific fuel consumption.

In the analysis of these cycles, it will be shown that variable turbine geometry in a turbojet engine will improve the subsonic installed engine cruise performance to the point where it is competitive with the turbofan engine while retaining the good supersonic high-thrust performance that is characteristic of turbojet engines. Although this analysis does not represent a true cycle selection study, it does indicate that variable turbine geometry can have a profound influence on the results of future cycle selection studies for advanced aircraft.

SECTION II

UNINSTALLED ENGINE PERFORMANCE CHARACTERISTICS

The operating characteristics of typical fixed- and variable-turbine-geometry turbojet engines are shown in Figure 1. For the fixed-turbine-geometry engine, the initial decrease in thrust is achieved by reducing the level of augmentation, resulting in no change in the airflow, pressure ratio, or turbine stator inlet temperature. Additional decreases in thrust require a reduction in the turbine stator inlet temperature. This reduction reduces the work extraction rate of the turbine which, in turn, reduces the compressor speed and pressure ratio and. therefore, the engine airflow. The behavior of the fixed-turbine-geometry turbofan engine is similar except that the higher augmentation ratio results in constant turbine stator inlet temperature, airflow, and pressure ratio conditions further into the part-power regime.

The behavior of the variable-turbine-geometry engine is distinctly different, particularly in the unaugmented part-power regime. In this regime, the turbine stator inlet temperature can be reduced while the turbine geometry is varied to maintain the turbine work extraction rate at its design level. With the turbine work extraction rate maintained, the airflow and pressure ratio can also be maintained at their design levels.

Variable turbine geometry also provides an improvement in the maximum power regime at transonic combat conditions. At these flight conditions, the engine with fixed turbine geometry cannot be operated at its design turbine stator inlet temperature without exceeding the flow capacity of the compressor. With variable turbine geometry, however, additional thrust can be produced because the work extraction rate of the turbine can be held constant to maintain the compressor at its design point while the turbine stator inlet temperature is increased to its design level.

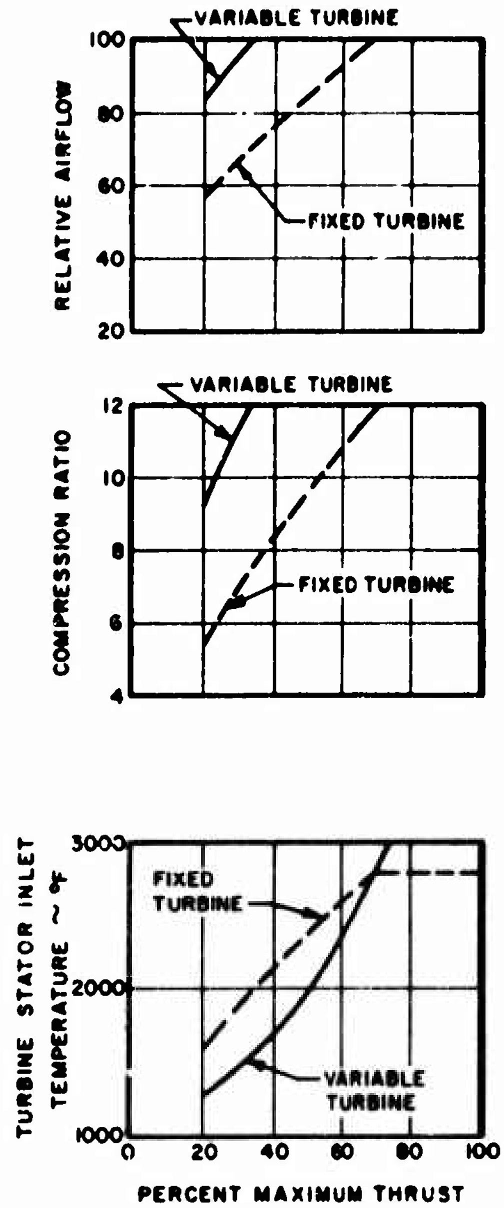

Figure 1. General Operating Characteristics for Variable-and Fixed-Turbine Geometry Engine Cycles

These effects result in an improvement in the performance of the uninstalled variable-turbine-geometry turbojet engine relative to that of the fixed-turbine-geometry turbojet engine, as shown in Figure 2. The improvement is substantial, particularly in the partpower regime typical of subsonic cruise. It is not sufficient, however, to permit the turbojet engine to compete with the turbofan engine. It is only after the installation effects are included that the variable-turbine-geometry turbojet engine becomes truly competitive as discussed in Section III.

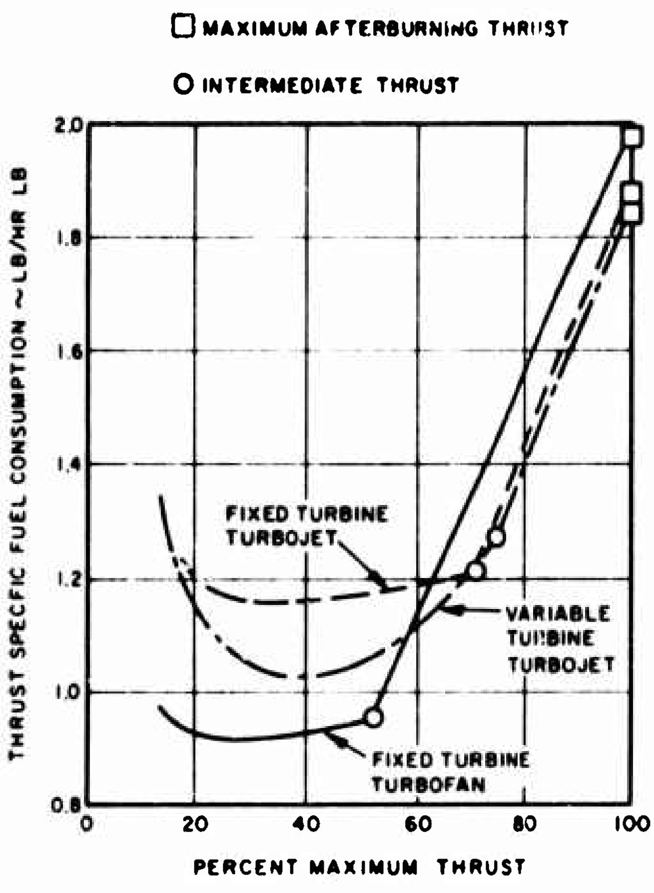

Figure 2. Estimated Uninstalled Engine Performance for Study Engines at 30,000 Feet During Mach 0.9 Flight

SECTION III

INSTALLED ENGINE PERFORMANCE CHARACTERISTICS

General Trends

Variable-turbine geometry offers the potential for substantial improvement in the installation losses at typical subsonic cruise conditions. As shown in Figure 3, when the fixed-turbine-geometry engine is operated at low power conditions, the inlet capture area is too large for the engine airflow demand because it must be sized for maximum airflow conditions. As a result, substantial flow must be spilled incurring large amounts of spillage drag. Further, the reduction in engine airflow requires closing the nozzle throat and exit areas, resulting in increased aft-end drag.

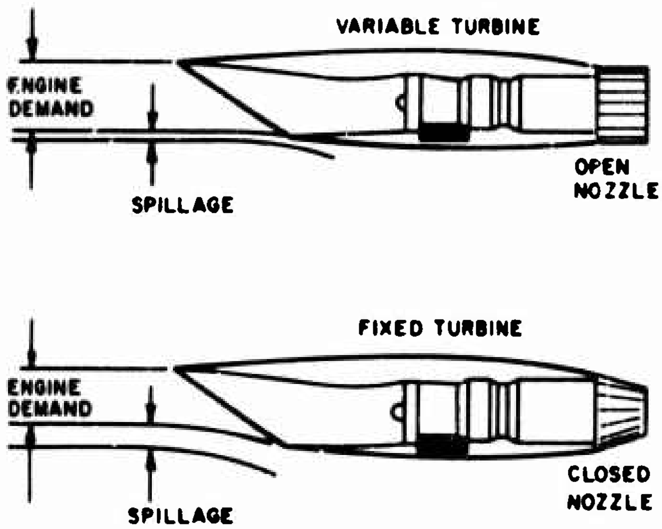

Figure 3. Fixed-and Variable-Turbine Geometry Engines at 30,000 Feet and Mach 0.9 Showing Basic Loss Mechanisms

In contrast, the variable-turbine-geometry engine operates at essentially constant airflow, resulting in low spillage drag as well as reduced aft-end drag. The aft-end drag is lower because the nozzle operates in a more open position. This is a consequence of maintaining the turbine work extraction rate at its design level while the turbine stator inlet temperature is decreased.

Inlet Drag Characteristics

Quantitative estimates of the performance of a typical two-dimensional horizontal-ramp, Mach 2.7 inlet were made for each of the three engine cycles to assess the effects of variable turbine geometry on inlet performance. This type of inlet is typically used for tactical fighters with high maneuverability requirements.

The pressure recovery and drag trends of the selected inlet are shown if Figures 4 and 5. The pressure recovery is a function of the shock system losses and the subsonic diffuser efficiency. The drag coefficient accounts for external spillage drag, bypass drag, boundary-layer control bleed drag, and secondary flow drag. External spillage drag includes both the additive drag and the effects of the forward cowl geometry. Bypass drag represents the loss of the momentum of the excess captured air that is bypassed to maintain the position of the normal shock. Boundary-layer control bleed is used to promote efficient diffusion and uniform flow to the engine. Drag results from the loss of the momentum of the boundary-layer air which is exhausted from the inlet. Secondary flow drag accounts for the loss of momentum resulting from using some of the air captured by the inlet for cooling or other purposes not directly involving the engine cycle.

To facilitate analysis, the total inlet drag was divided into a reference drag component that is independent of power setting and the remaining throttle-dependent component. This division is particularly useful when airplane model testing is to be used to determine the airplane drag characteristics experimentally since it provides a standard point within the operating range of the inlet at each flight Mach number for performance comparisons and for inclusion in the airplane drag polar. Any drag change incurred by operating the inlet off this standard point is then calculated as throttle-dependent drag. For these studies, the reference drag has been defined as the inlet drag occurring at maximum airflow conditions for each flight condition. The same relative variation in maximum airflow rate with Mach number has been scheduled for each engine, with the result that all three engines have the same maximum-power

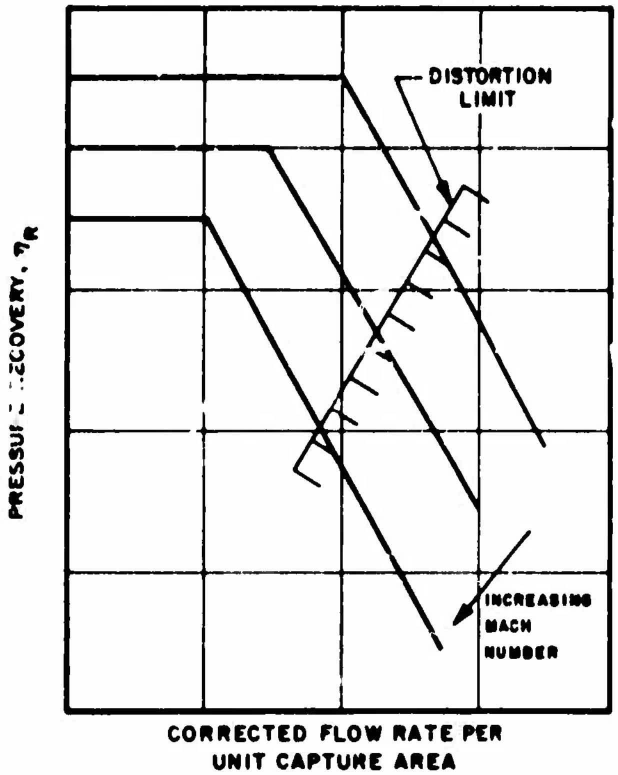

Figure 4. Pressure Recovery Trends for Typical Tactical Fighter Inlet

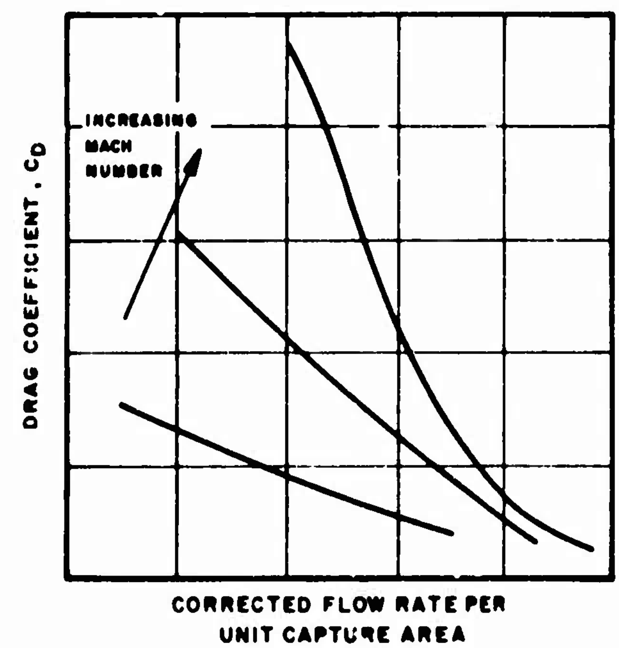

Figure 5. Drag Coefficient Trends for Typical Tactical Fighter Inlet

drag coefficient at any given flight condition. Consequently, the throttle-dependent drag coefficient is an accurate representation of the differences in the total inlet drag coefficients among the three systems.

Representative throttle-dependent drag coefficients for each of the three engine cycles are shown in Figure 6 for a typical subsonic cruise condition. As shown, the capability of the variable-turbine-geometry turbojet engine to maintain near-maximum airflow at cruise conditions results in substantially less throttle-dependent drag at this condition for this engine than for the two fixed-turbine-geometry engines.

Aft-End Characteristics

A variable convergent-divergent nozzle was selected for these studies. In this type of nozzle the throat area is varied to provide the desired engine matching. The nozzle exit area is also varied to obtain the maximum thrust minus external drag for the exhaust system. This type of nozzle is typical of that which has evolved from various nozzle design and performance studies and represents a realistic trade between nozzle weight and performance. Increasing the nozzle flap length would reduce the internal wall divergence as well as the external boattail angle, both of which would increase the performance, but a greater flap length would also impose an excessive weight penalty. A close-spaced twin-engine installation such as shown in Figure 7 was assumed. As shown, twin vertical stabilizers are mounted on the engine centerlines with horizontal stabilizers mounted adjacent to the engine centerlines.

The internal nozzle performance and the aft-end external drag were calculated separately since the internal exhaust nozzle area ratio and internal flap divergence angle govern internal performance while the external drag is closely interwoven with the airframe drag. The nomenclature used in this study is shown in Figure 8.

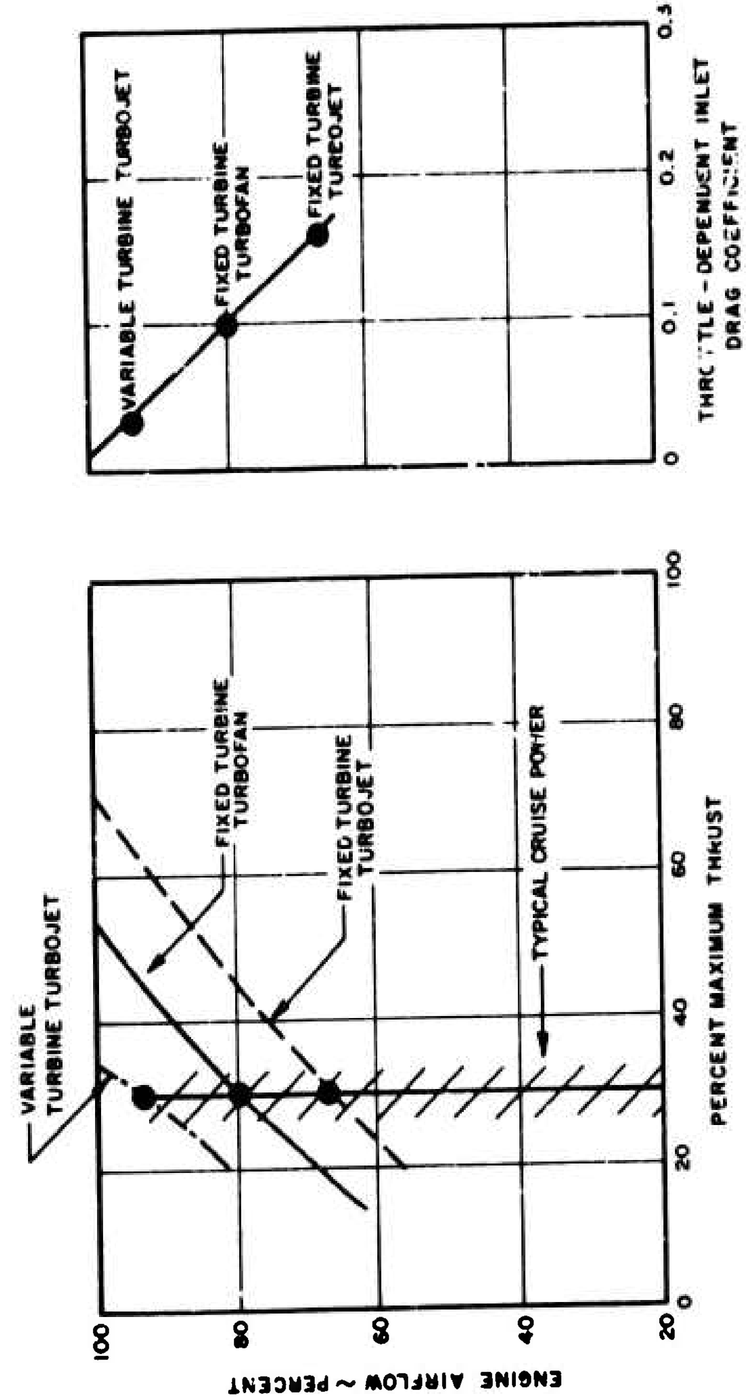

Figure 6. Throttle-Dependent Drag for Typical Inlets for Study Engines at 30,000 Feet During Mach 0.9 Flight

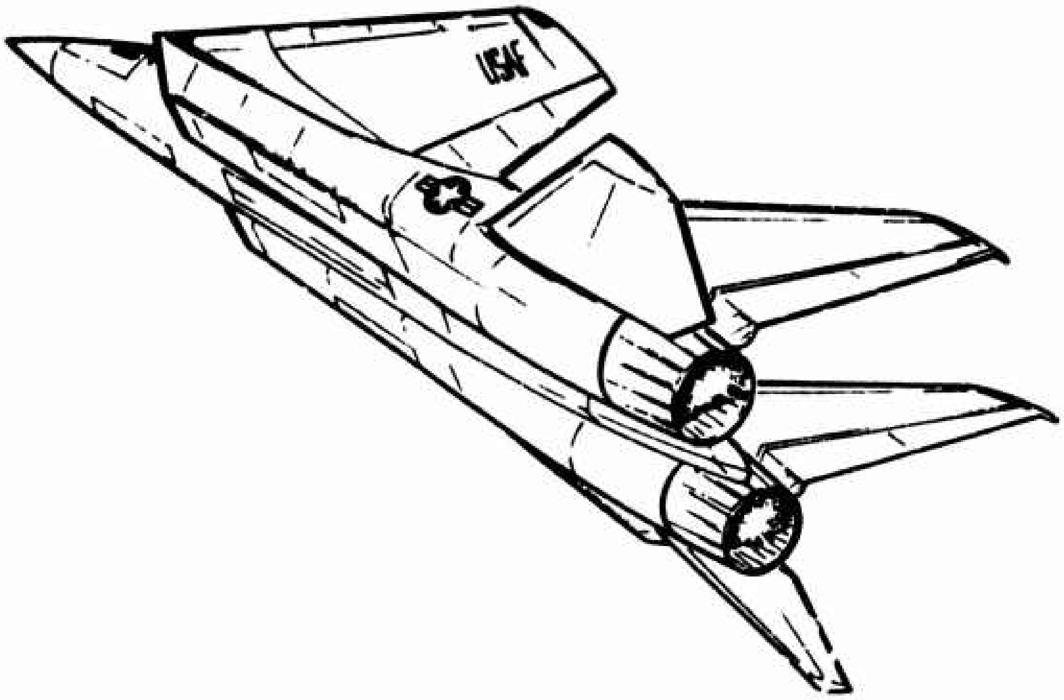

Figure 7. Twin Engine Installation Assumed for Study

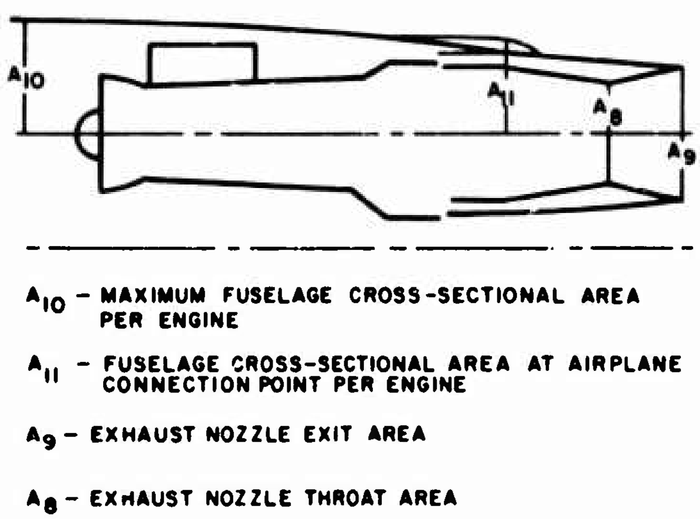

Figure 8. Afterbody Nomenclature Used for Study

The remaining terms used in calculating the nozzle thrust coefficient are functions of the nozzle geometry and the exhaust gas thermodynamic properties. The expression used is as follows:

$$C_v = \frac{C_s\left(\frac{\dot{m}V_9 + P_{s9}A_9}{P_{t8}A_8}\right) - \left(\frac{P_{s0}A_9}{P_{t8}A_8}\right)}{F_I/P_{t8}A_8}$$

where:

C_s = An empirical stream thrust coefficient correction factor as shown in Figure 9

m = Mass of the gas flow

V_9 = Gas flow exit velocity

P_{s0} = Free stream static pressure

P_{t8} = Total pressure at the exhaust nozzle throat

P_{s9} = Static pressure at the exhaust nozzle exit

A_8 = Exhaust nozzle throat area

A_9 = Exhaust nozzle exit area

F_I = Ideal thrust

The external aft-end drag was obtained by summing the pressure drag and the frictional drag over the entire aft-end of the airplane. Because of the interaction of the flow fields, it is important to include in this calculation the drag of the complete fuselage structure from the maximum cross-sectional area location, A_{10}, rearward to ensure that an accurate accounting of the engine installation effects and the throttle-dependent drag changes is obtained.

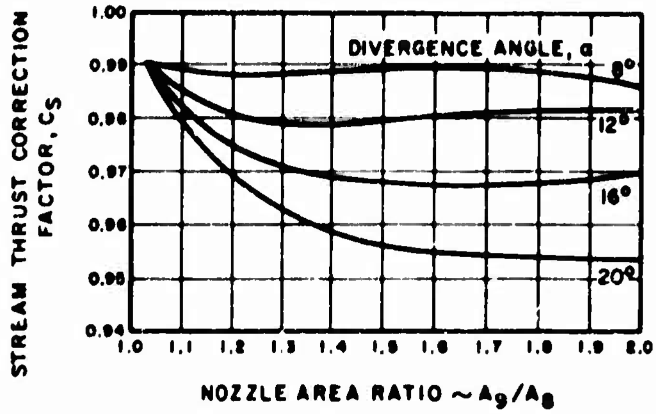

Figure 9. Stream Thrust Correction Factor for Internal Nozzle Thrust Coefficient Calculation

The pressure drag was determined using the Integral Mean Slope Technique described in a paper by Messrs. C. E. Swavely and J. F. Soileau and entitled "Aircraft Aft-End Body/Propulsion System Integration for Low Drag" presented at the AIAA/SAE Joint Propulsion Conference in New New Orleans on November 27 to December 1, 1972. This technique accounts for the fact that the total degree and the rate of closure of the airplane aft-end are the primary factors governing the exhaust system external performance. In using this technique, the local slopes on the aft-end are area-averaged to determine a correlating parameter defined as the "integral mean slope." This parameter is calculated using the following equation:

$$\text{Integral Mean Slope} = \frac{\displaystyle\int_{A_9/A_{10}}^{1.0} \left[\frac{d\left(\frac{A}{A_{10}}\right)}{d\left(\frac{R}{\sqrt{4A_{10}/\pi}}\right)} \right] d\left(\frac{A}{A_{10}}\right)}{1 - A_9/A_{10}}$$

Data correlations of pressure drag versus integral mean slope for various engine spacings, aft-end configurations, and nozzle types are then used to determine the installed pressure drag. A sample correlation for Mach 0.9 flight is shown in Figure 10 and is based on a close-spaced engine arrangement. This correlation was determined by the Boeing Company through a series of parametric aft-end tests as a part of Air Force Contract F33615-70-C-1450, "Exhaust System Interaction Program."

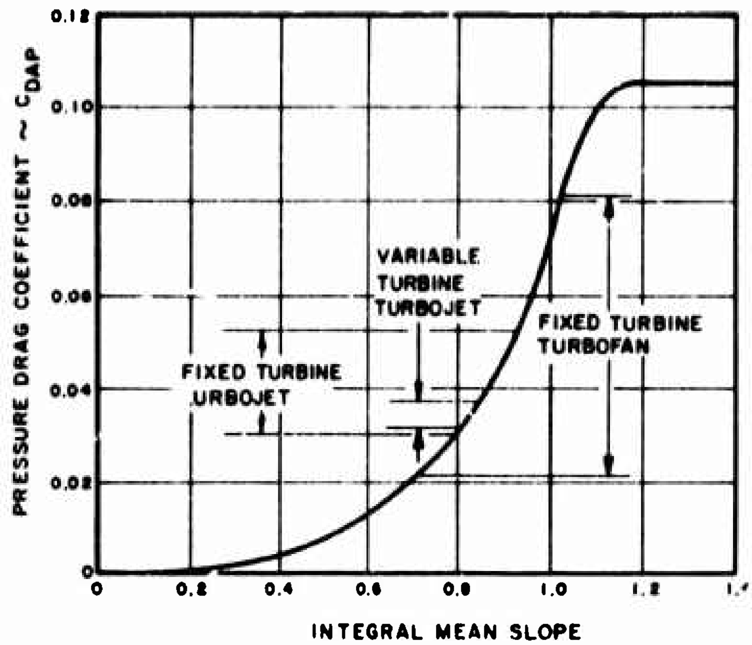

Figure 10. Aft-End Pressure Drag Correlation With Close-Spaced Nozzles During Mach 0.9 Flight Showing Operating Regions for Study Engine Nozzles

The internal nozzle performance was calculated in terms of a nondimensional thrust coefficient, C_V, which is defined as the ratio of the actual thrust to the ideal thrust. The actual thrust is reduced from the ideal thrust by the effects of leakage, flow separation, shocks, internal wall divergence, frictional losses along the internal nozzle walls, and any losses associated with either over expansion or under expansion of the flow. The internal nozzle losses are determined from an empirical correlation in terms of a stream thrust coefficient correction factor, C_S. The correlation used is shown in Figure 9. The correction factor is applied to an expression for the momentum of the flow, which is calculated using isentropic one-dimensional analysis and is a function of the nozzle area ratio.

In using the correlation shown in Figure 10, the integral mean slope range for each of the afterbodies was determined by integrating the area distributions shown in Figure 11 for the complete range of nozzle exit-to-maximum area ratios (A_9/A_{10}). The resulting ranges of pressure drag are shown in Figure 10.

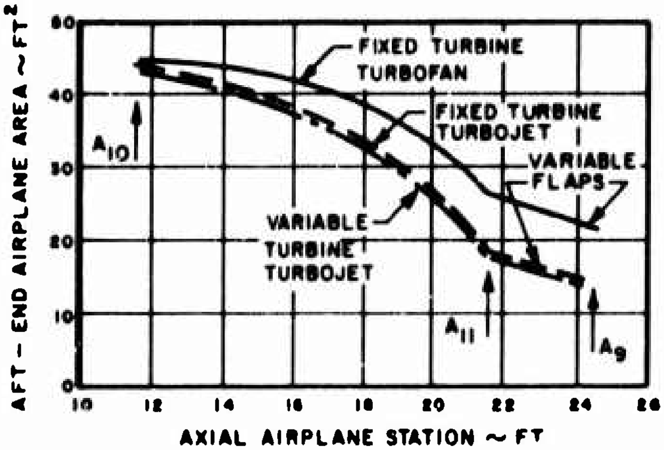

Figure 11. Airplane Aft-End Contours

The body friction drag was calculated by using a modified Reshotko-Tucker analysis. The aft-end body drag was found to be approximately equal to 0.022 for each of the three installations and was essentially independent of engine thrust.

Similar to the inlet drag, the external aft-end drag was defind in terms of a reference drag and a throttle-dependent drag. The reference drag level was defined as the drag resulting when the nozzle flaps were open to produce a cylindrical contour. Consequently, the remaining throttle-dependent drag represents the drag resulting from changes in the nozzle flaps from the cylindrical position. As shown in Figure 12, the amount of aft-end closure required for the assumed cruise condition at 30 percent of maximum thrust is similar for the fixed-turbine-geometry turbojet engine and the fixed-turbine-geometry turbofan engine. The throttle-dependent drag coefficient, however, is lower for the fixed-turbine-geometry turbojet engine than for the turbofan engine because the diameter of the turbofan engine is larger at the airplane connection point. This results in a greater closure rate over the nozzle flaps, resulting in a larger integral mean slope, and illustrates the importance of engine geometric shape on aft-end drag characteristics.

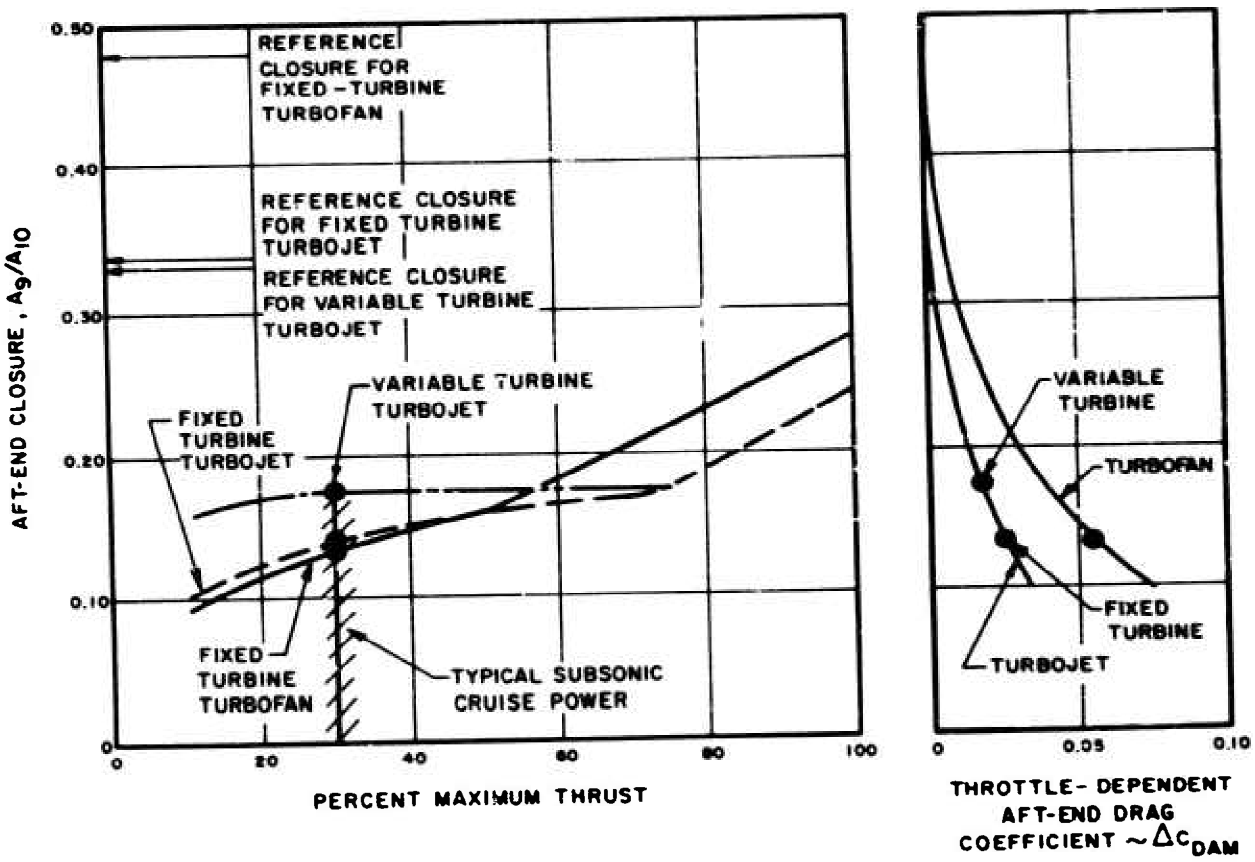

Figure 12. Throttle-Dependent Drag for Study Engine Nozzles at 30,000 Feet During Mach 0.9 Flight

The variable-turbine-geometry turbojet engine operates with a nozzle exit area that is nearly constant over most of the range of unaugmented thrust operation with the result that the integral mean slope and the aft-end drag coefficient do not increase until very low power settings are reached.

Calculation of Thrust Coefficients

To determine the installed engine performance from these data, the drag coefficient data must first be converted to thrust coefficients. These thrust coefficients are defined as follows:

$$C_{t\ inlet} = \frac{F_{GI} - \Delta C_D A_c q_0}{F_{GI}}$$

$$C_{t\ ext} = \frac{F_{GI} - \Delta C_{DAM} A_{10} q_0}{F_{GI}}$$

$$C_{t\ int} = \frac{F_{GI} - D_{int}}{F_{GI}}$$

where:

$C_{t\ inlet}$ = Inlet thrust coefficient

$C_{t\ ext}$ = Aft-end external thrust coefficient

$C_{t\ int}$ = Nozzle internal thrust coefficient

F_{GI} = Ideal gross thrust coefficient

ΔC_D = Throttle-dependent inlet drag coefficient

ΔC_{DAM} = Sum of throttle-dependent pressure and friction drags divided by $A_{10}q_0$

D_{int} = Internal nozzle drag

A_c = Inlet capture area

A_{10} = Maximum fuselage cross-sectional area per engine

q_0 = Free stream dynamic pressure

Plots of the thrust coefficients for each of the three engine cycles are shown in Figure 13 as a function of the thrust level. As shown, the internal nozzle thrust coefficients are similar for all of the engines since the internal contours of all of the nozzles are very near to being ideal. Both the external nozzle thrust coefficients and the inlet thrust coefficient, however, reflect the effects of changing airflow and matching requirements in the fixed-turbine-geometry cycles and show the essentially constant performance level down to a thrust level of approximately 35 percent of maximum thrust for the variable-turbine-geometry turbojet cycle.

The thrust coefficients can be summed to obtain the total thrust coefficient, C_{tot}, by using the following equation:

$$C_{tot} = C_{t\ inlet} + C_{t\ ext} + C_{t\ int} - 2$$

When the results of this summation are expressed in terms of installation thrust loss at the cruise power setting of 30 percent of maximum thrust, the differences among the three types of engine are apparent, as shown in Figure 14. Over 12 percent of the ideal gross thrust of the fixed-turbine-geometry turbofan engine is lost through mismatching of the inlet and nozzle at this operating condition. The fixed-turbine-geometry turbojet loses a similar amount, but the variable-turbine-geometry turbojet engine loses only slightly more than 4 percent of its ideal gross thrust. The differences in net thrust and fuel consumption are even greater.

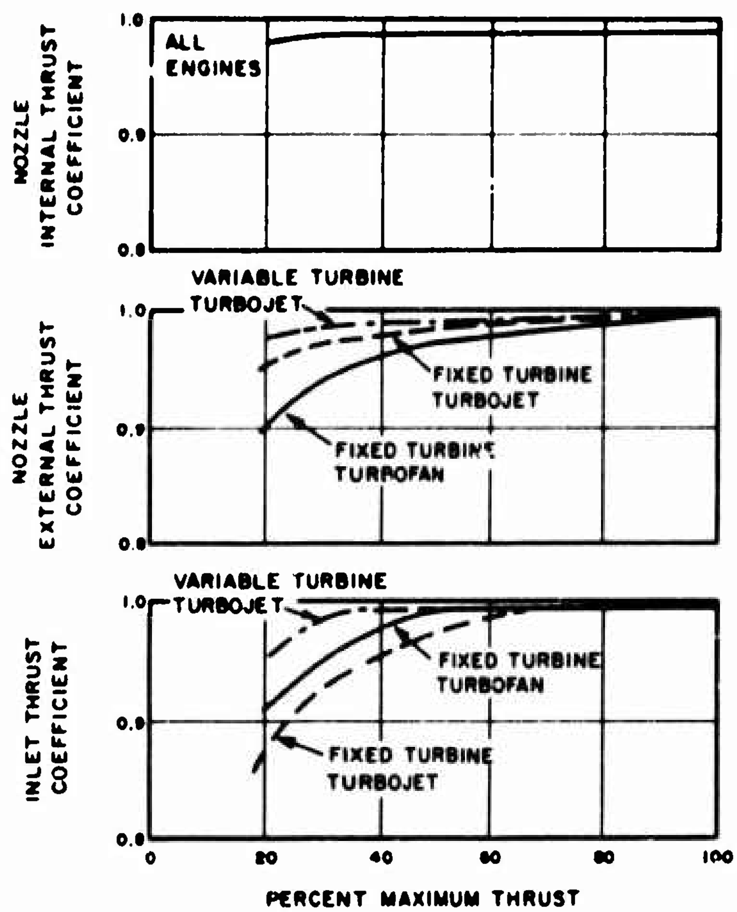

Figure 13. Installation Thrust Coefficients for Study Engines

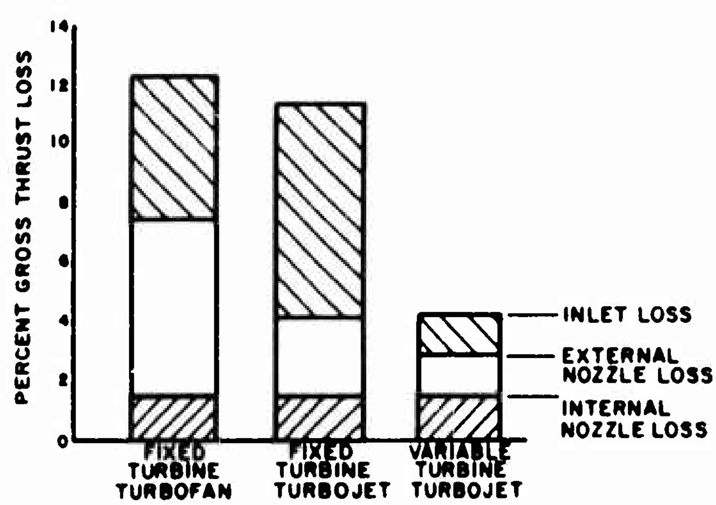

Figure 14. Installation Losses for Study Engines at 30,000 Feet During Mach 0.9 Flight at Cruise Power Setting

Calculation of Installed Engine Performance

Combining the inlet and nozzle thrust coefficients with the uninstalled engine performance characteristics permits calculation of the overall installed engine performance for each of the three engine cycles. The results are shown in Figure 15.

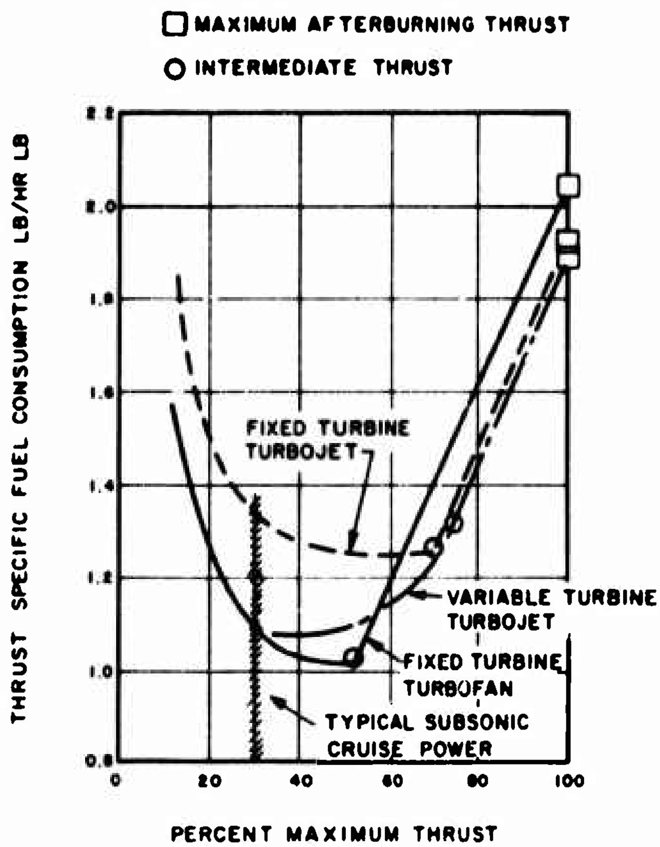

Figure 15. Installed Engine Performance for Study Engines at 30,000 Feet During Mach 0.9 Flight

These data show that the combination of improved uninstalled engine performance and reduced installation losses permits the variable-turbine-geometry turbojet engine to be extremely competitive with the fixed-turbine-geometry turbofan engine at cruise conditions while still providing the improved thrust specific fuel consumption that is characteristic of turbojet engines at maximum thrust conditions.

With respect to the fixed-turbine-geometry turbojet engine, the variable-turbine-geometry turbojet engine provides 18 percent lower thrust specific fuel consumption at a typical cruise condition.

In reviewing these data, the importance of using aft-end designs that are realistic structurally cannot be overemphasized. For example, an extremely clean aerodynamic aft-end could be drawn, as shown in Figure 16, although such a design would not be compatible with realistic airplane structural and packaging requirements. If the overly optimistic aft-end contours were used in the cycle selection studies, the benefits of variable turbine geometry would not be as great, as shown in Figure 17. This could lead to performance trend estimates that were not representative of the final airplane design, and to an erroneous cycle selection.

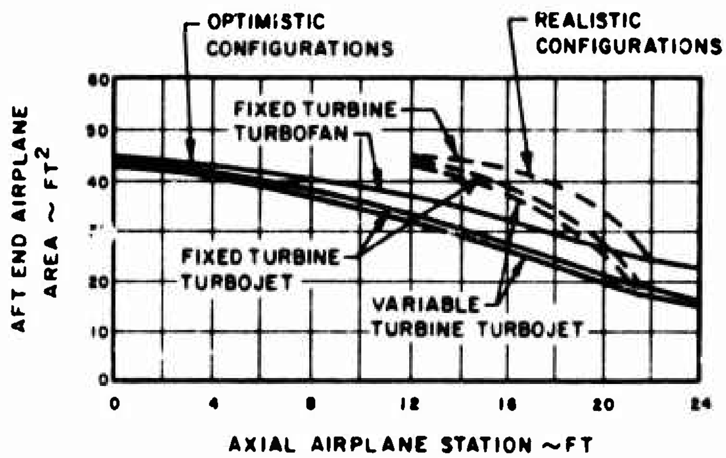

Figure 16. Effect of Structural Requirements on Aft-End Closure

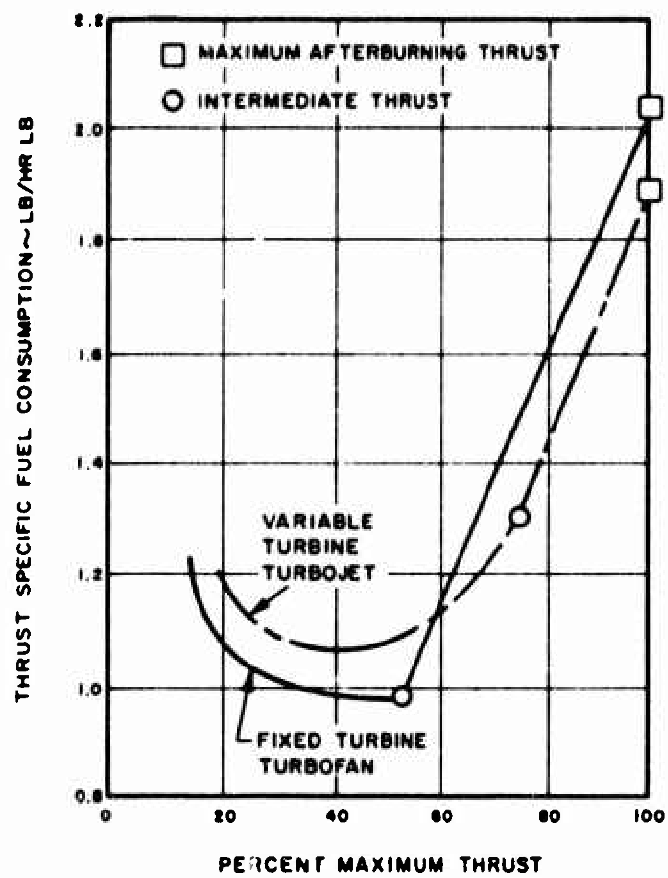

Figure 17. Installed Engine Performance for Study Engines When Optimistic Aft-End Designs are Assumed

SECTION IV

CONCLUSIONS

Variable turbine geometry has been shown to be an effective method for improving the off-design performance of installed engines, particularly with respect to inlet and nozzle losses.

The performance improvement results in part from the improvement in the internal engine performance since the variable turbine geometry permits the compressor to remain at its design pressure ratio during part-power operation. Equally important, however, is the reduction in inlet and nozzle losses achieved by maintaining the engine airflow at the design level over a wide range of power settings. In most practical installations, these losses represent a large proportion of the performance degradation associated with off-design operation, and their elimination, therefore, represents a large benefit.

Because variable turbine geometry improves the off-design performance, engines incorporating this feature provide good performance over a much broader range of operating conditions. As a result, airplanes designed for a specific mission, but incorporating variable-turbine-geometry engines, will have the flexibility to provide good performance for a wide variety of alternate missions. For example, a turbojet engine, which is usually considered to be primarily for supersonic point-design applications, can perform competitively with the turbofan engine during off-design part-power operation when variable turbine geometry is used in the turbojet.

Considerable additional effort is required before the potential of variable turbine geometry can be fully assessed and practical variable-turbine-geometry engines can be produced. These preliminary studies, however, indicate that the potential is large and that it may offer a solution to the growing requirement for engines capable of operating efficiently over wide ranges of thrust. At this time, a major effort leading to the development of the technology required to produce practical variable-turbine-geometry engines should be pursued if the performance requirements of the next generation of military engines are to be met.