Investigation of Two-Dimensional Wedge Exhaust Nozzles for Advanced Aircraft

Donald L. Maiden*
NASA Langley Research Center, Hampton, Va.
and
John E. Petit†
Boeing Aerospace Company, Seattle, Wash.

Two-dimensional wedge nozzle performance characteristics were investigated in a series of wind-tunnel tests. An isolated single-engine/nozzle model was used to study the effects of internal expansion area ratio, aftbody cowl boattail angle, and wedge length. An integrated twin-engine/nozzle model, tested with and without empennage surfaces, included cruise, accleration, thurst-vectoring, and thrust-reversing nozzle operating modes. Results indicate that the thrust-minus-aftbody drag performance of the twin two-dimensional nozzle integration is significantly higher, for speeds greater than Mach 0.8, than the performance achieved with twin axisymmetric nozzle installations. Significant jet-induced lift was obtained on an aft-mounted lifting surface using a cambered wedge centerbody to vector thrust. The thrust reversing capabilities of reverser panels installed on the two-dimensional wedge centerbody were very effective for static or in-flight operation.

Nomenclature

A	= area
A_e	= nozzle exit area
A_m	= model maximum cross-sectional area
A_t	= nozzle throat area
C_L	= lift coefficient based on a wing reference area of 10 A_m
CRN	= crown line
C_v	= nozzle velocity coefficient, or T/F_i
D	= aftbody/nozzle drag
D_d	= duct diameter
D_p	= aftbody pressure drag
d_m	= maximum nozzle diameter
F_i	= ideal isentropic gross thrust
L_D	= transition duct length from circular cross section to two-dimensional throat
L_p	= wedge length from leading edge to throat
l	= nozzle length from start of boattail to exit
l_w	= length of aft-sloping wedge
M	= freestream Mach number
MNB	= maximum half-breadth
N	= order of elliptical equation
NPR	= nozzle pressure ratio (jet-total-pressure to free-stream static-pressure ratio)
T	= measured nozzle thrust
x	= axial station along model centerline
Y	= lateral distance from centerline of nozzle
Z	= vertical distance from centerline of nozzle
α	= angle of attack
β	= terminal boattail angle
β_c	= cowl terminal boattail angle
β	= wedge boattail or half-angle
σ	= resultant wedge camber angle

Presented as Paper 75-1317 at the AIAA/SAE 11th Propulsion Conference, Anaheim, Calif., Sept. 20-Oct. 1, 1975; submitted Oct. 1, 1975; revision received May 3, 1976.

Index categories: Aircraft Aerodynamics (including Component Aerodynamics); Aircraft Configuration Design; Aircraft Powerplant Design and Installation.

*Aerospace Engineer, High-Speed Aerodynamics Division. Member AIAA.

†Aerospace Engineer, Research and Engineering Division. Member AIAA.

‡Naval Air Propulsion Test Center, Trenton, N.J.

Introduction

JET aircraft that must operate at subsonic and supersonic speeds require exhaust nozzles with a variable geometry for high performance over a wide range of throttle power settings and Mach numbers. Because of the high internal performance (C_v) attainable with axisymmetric nozzles, this type of nozzle has been used in past and current aircraft designs. However, many airplane aft-end-closure drag problems occur in multiengine configurations because of the "round" nozzle integration with the afterbody.[1] These multiengine configurations inherently have a large boattailed "gutter" interfairing, or a base region, between the nozzles. This interfairing as well as the nozzle boattail are subject to adverse interference effects, especially if the external flow separates from the aftbody near the nozzle exits. Additon of empennage surfaces, particularly if mounted on booms that extend aft of the nozzle exit, further aggravate the aft-end drag problem with empennage-boom-nozzle flow interference.[2,3]

Two-dimensional wedge nozzles properly integrated with the air frame offer improved thrust-minus-drag performance by eliminating the large boattail gutter between the engine nacelles/nozzles or tail boom and nozzle. Figure 1 illustrates both the twin axisymmetric and the twin two-dimensional wedge nozzle installations in a typical fighter configuration. The two-dimensional wedge nozzle is inherently better suited than conventional nozzles for in-flight thrust reversing or thrust vectoring (with supercirculation lift if properly integrated with the airframe). The wedge centerbody can be used as a wing or horizontal tail carry-through structure and can be used to suppress infrared radiation by shielding the hot engine core.

Because of the synergistic potential of the two-dimensional-wedge nozzle/airframe integration, a joint Navy‡/Boeing/NASA exploratory wind tunnel investigation has been conducted in the Langley 16-ft transonic tunnel. The joint program was completed in two phases. The first phase of the investigation was conducted on an isolated nacelle integrated with a single two-dimensional wedge nozzle. The objectives of phase I were, (1) to determine if the two-dimensional wedge nozzle performance is competitive with axisymmetric nozzles, and (2) to study parameters that affect the internal as well as the external performance of the two-dimensional wedge nozzle concept. Two methods to vary the geometry of the nozzle were investigated. Figure 2 shows a sketch of the variable-

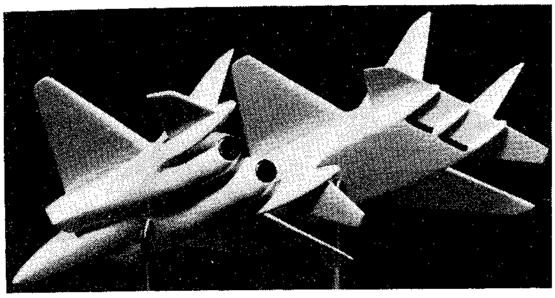

Fig. 1 Twin axisymmetric and two-dimensional wedge nozzle installation concepts.

geometry, two-dimensional wedge centerbody with a fixed-cowl aftbody. The nozzle geometry is varied by unique scissor-type linkages and hinges (U.S. Patent 3,774,868), which allows nozzle exit area to be varied independently of nozzle throat area. The mechanism also provides throat transfer capability, transferring the nozzle throat to the nozzle exit plane to maintain high performance at low nozzle pressure ratios. For afterburner power, the wedge is collapsed into the desired area ratio, depending on nozzle pressure ratio requirements. Another feature shown in Fig. 2 is a brief description of the design method used to define the internal contour lines of the variable-wedge fixed-cowl nozzle (discussed in Ref. 4). Figure 3 presents a sketch of the collapsing two-dimensional wedge centerbody with translating shroud. Variations of internal expansion area ratio are achieved by translating the shroud. For afterburner power, the wedge is collapsed, and the shroud is translated to achieve the desired internal expansion area ratio. The other design features shown in Fig. 3 are discussed in Ref. 5. Since no data base existed for these types of nozzle concepts, the fundamental geometric variables, internal expansion area ratio, cowl boattail angle, and wedge half-angle, were investigated.

The second phase of the investigation was conducted on an isolated nacelle with twin two-dimensional wedge nozzles, with and without empennage surfaces. The objectives of phase II were, (1) to determine the effect of twin-nozzle installation and empennage interference on nozzle performance, (2) to explore thrust vectoring characteristics for this nozzle concept with a cambered wedge, and (3) to determine the thrust reversing capability of reverser panels on the wedge.

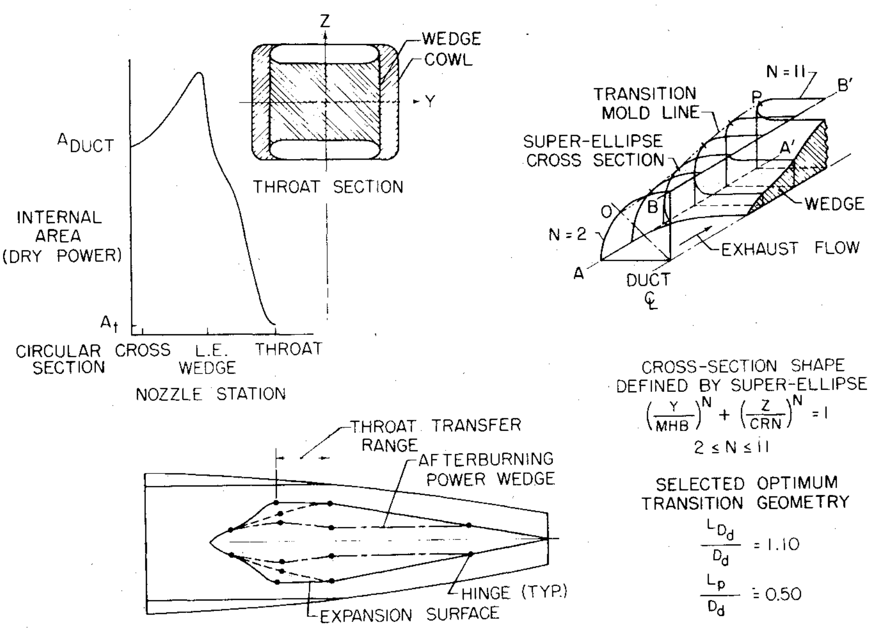

Fig. 2 Design features of variable-geometry two-dimensional wedge centerbody with a fixed cowl.

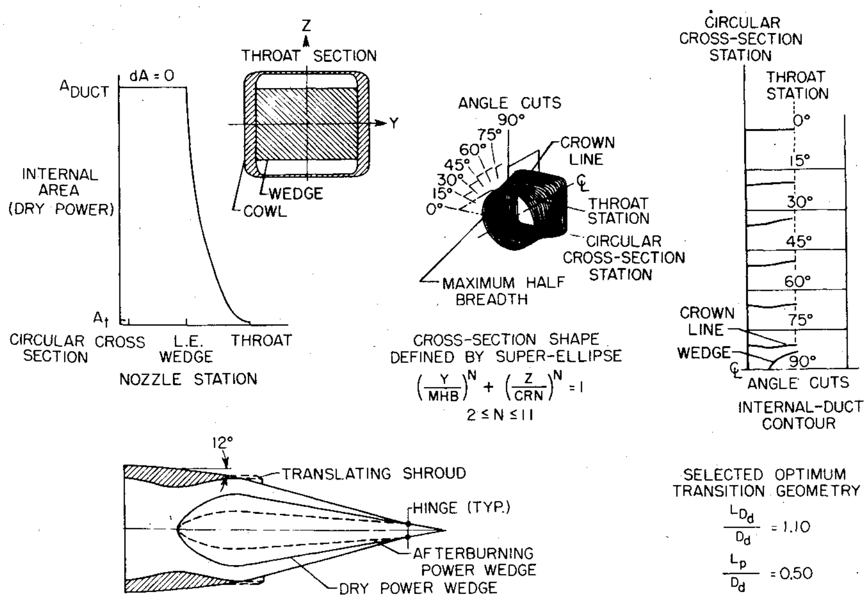

Fig. 3 Design features of variable-geometry two-dimensional wedge centerbody with a translating shroud.

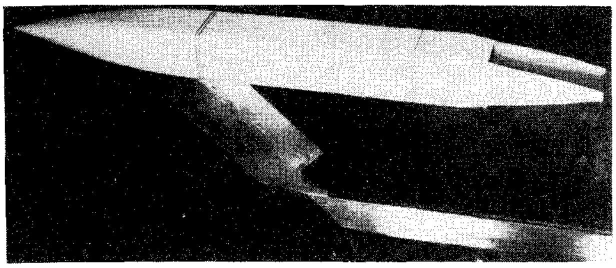

Fig. 4 Single-nozzle model installed in the Langley 16-ft transonic tunnel.

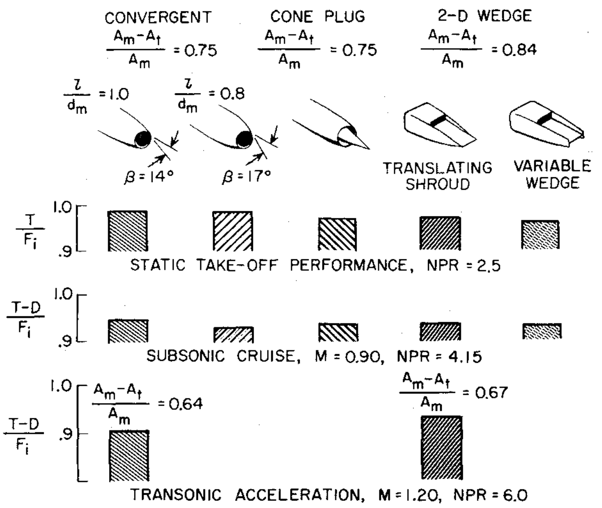

Fig. 5 Isloated nozzle performance.

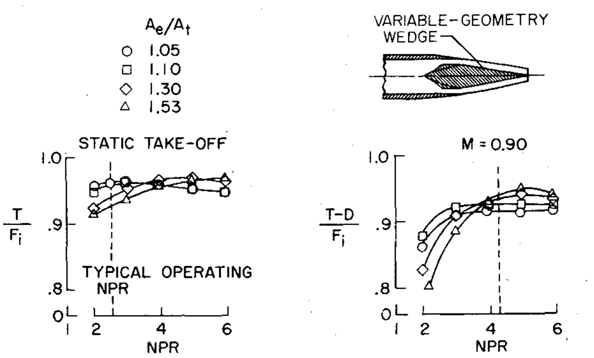

Fig. 6 Effect of internal expansion area ratio on variable-wedge/fixed cowl nozzle performance.

Single-Nozzle Performance

A photograph of the isolated single nacelle model installed in the 16-ft transonic wind tunnel is shown in Fig. 4. Nozzle exhaust flow was simulated by metered compressed air. Details of the model force balance and air supply system are presented in Ref. 5. Only the net thrust-minus-drag force aft of the metric break was measured in the test. The double stripes shown on the model in Fig. 4 denote the metric break.

Axisymmetric Comparisons

Isolated nozzle performance at typical engine operating pressure ratios for several axisymmetric nozzles and the two-dimensional wedge nozzle concepts is presented in Fig. 5. The data for the convergent nozzles were obtained from Refs. 6 and 7. The cone plug nozzle data were obtained from Ref. 8. Shown in Fig. 5 is the closure area ratio $(A_m - A_t)A_m$, which represents the amount of afterbody projected area which would result either in a boattailed fairing, base, or expansion surface. In every case for these comparisons, the closure area

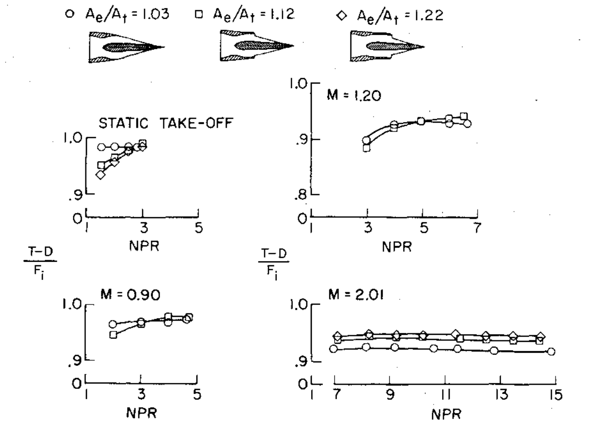

Fig. 7 Effect of internal expansion area ratio on collapsed-wedge/translated-shroud nozzle performance.

is greater for the two-dimensional wedge nozzles and thus may favor the axisymmetric thrust-minus-drag performance. The data of Fig. 5 indicate that at the static takeoff condition, the performance of the two-dimensional wedge nozzles is about 1½% to 2½% of ideal thrust lower than that of the convergent nozzles but is about the same as the axisymmetric cone plug nozzle. At subsonic cruise and transonic acceleration conditions, the two-dimensional wedge nozzles were found to be highly competitive with axisymmetric nozzles.

Effect of Internal Expansion Area Ratio

The effect of internal expansion area ratio A_e/A_t on variable wedge/fixed-cowl, dry power nozzle performance is shown in Fig. 6. The data indicate that the peak nozzle performance generally can be shifted to any desired nozzle pressure ratio by proper control of the internal expansion area ratio, similar to the operation of an axisymmetric convergent-divergent nozzle. The shift of peak nozzle performance means that, with a variable-geometry nozzle, an operating schedule of internal expansion area ratio can be established to achieve peak nozzle performance to coincide with airplane operating conditions (e.g., engine pressure ratio, Mach number, etc.). It should be noted that, inherent to the unique scissor-type mechanism design, discussed previously for Fig. 2, is a slight variation in the wedge half-angle as the internal expansion area is varied.

Figure 7 shows the effect of internal expansion area ratio A_e/A_t on the collapsed-wedge/translating-shroud afterburner power nozzle performance. Large values of internal expansion area ratio are difficult to obtain with the translated-shroud/collapsing-wedge concept because of the wedge half-angle. For example, with the shroud translated to achieve a dry power, internal expansion area of 1.53, the afterburner power A_e/A_t is only 1.12 with the shroud in the same position. Fortunately, the data of Fig. 7 indicate that, for afterburner power, small values of A_e/A_t are sufficient for this nozzle concept to shift the peak in-flight nozzle performance to most engine operating pressure ratios. At subsonic speeds, only small values of internal A_e/A_t are required, but at supersonic speeds a large value of internal are ratio is desirable. Large values of A_e/A_t will require long shroud lengths and may not be pratical from weight consideration.

Effect of Cowl Boattail Angle

Figure 8 shows the effect of cowl boattail angle on nozzle performance for the variable-wedge/fixed-cowl nozzle. The internal expansion area ratio was held constant at 1.10, which resulted in a 10° wedge half angle. To achieve the highest nozzle performance at subsonic speeds, the data indicate that the

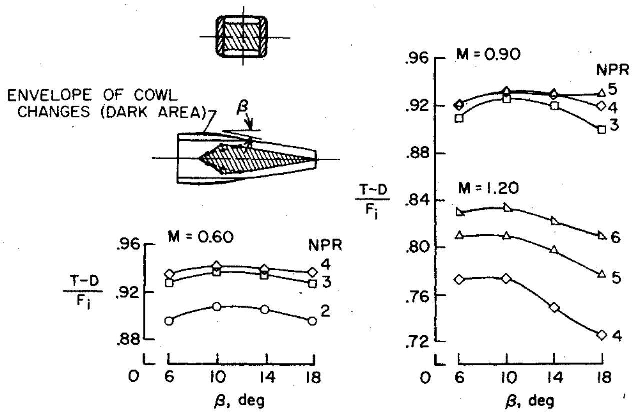

Fig. 8 Effect of cowl boattail angle on two-dimensional wedge nozzle performance.

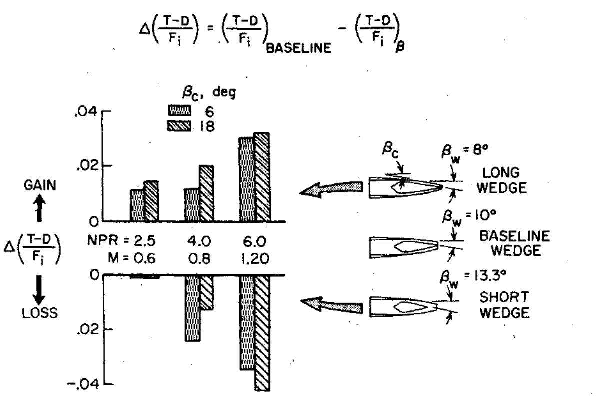

Fig. 9 Effect of wedge half-angle on two-dimensional wedge nozzle performance.

cowl boattail angle should be equal to or slightly greater than the wedge half-angle (10°); the performance differences (subsonically) between all cowl boattails were small. Cowl boattail angles equal to or slightly greater than the wedge half angle may be necessary in order to turn the subsonic extermal flow streamline toward the wedge surface. The turning streamline creates a favorable interaction between the external flow over the nozzle boattail and the nozzle exhaust flow which results in increased pressures along aft-sloping surface of the wedge. This favorable external flow effect causes an increase in thrust-minus-drag nozzle performance for $\beta_c = 10°$ and 14°. The decrease in performance for the highest boattail cowl angle (18°) is probably the result of high cowl drag. At supersonic speeds, the favorable effect of external flow disappears, as noted by the much lower thrust-minus-drag performance at $M = 1.20$ for all cowl boattail angles. The effect of cowl boattail angle at supersonic speeds is as expected: increasing drag with increasing boattail angle and thus lower nozzle thrust-minus-drag performance although the thrust-minus-drag performance of the 10° cowl was about the same as the 6° cowl.

Effect of Wedge Half-Angle

To study the effect of wedge half-angle, the 10° half-angle wedge, for which the cowl boattail angle study was made, was chosen as th baseline configuration. Alternate wedge half-angles of 8° and 13.3° were tested, and the results are presented in Fig. 9 in the form of a performance increment as compared to the 10° wedge half-angle baseline. The wedge design was as shown in Fig. 2. The data show that the wedge half-angle significantly affects two-dimensional wedge nozzle performance. Even with the increase in friction drag resulting from increased wetted area, the long, shallower half-angle wedge nozzle performance was higher than the 10° half-angle wedge baseline. Significant performance losses were obtained with the short, steep boattailed wedge. Thrust-minus-drag performance with cowl boattail angles of 6° and 18°, although varying the wedge half-angle, indicate the same trends as discussed previously for cowl boattail variation.

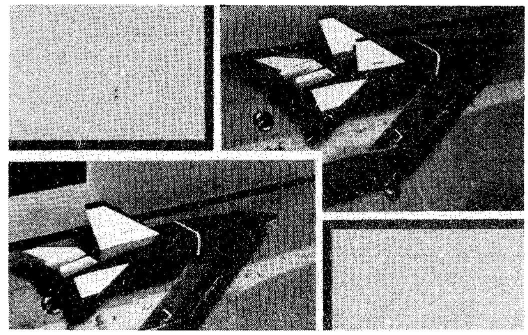
Fig. 10 Twin two-dimensional wedge nozzle installations in the Langly 16-ft transonic tunnel.

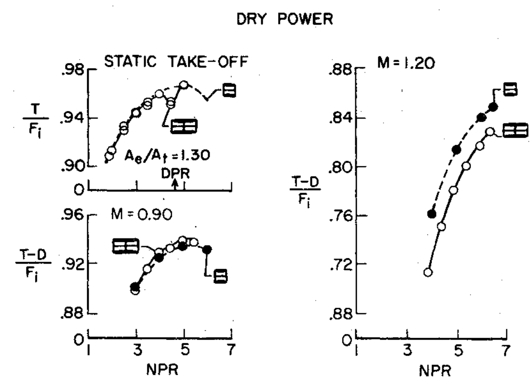

Fig. 11 Comparison of single and twin two-dimensional wedge nozzle performance.

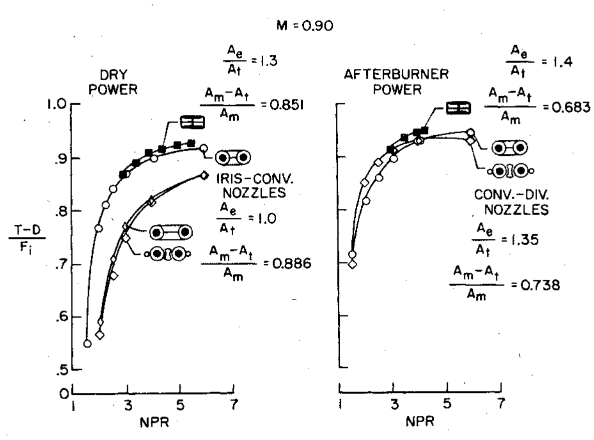

Fig. 12 Comparison of twin axisymmetric and twin two-dimensional wedge nozzle performance.

In an attempt to achieve shorter cone-plug nozzles for lower cooling requirements and weight, axisymmetric plugs have been truncated without significant penalty up to about 30% of the plug length.[8] The effect of two-dimensional wedge truncation is that significantly lower nozzle performance will result from only small truncations of the wedge.[5]

Twin-Nozzle Performance

The twin-nozzle model simulated the variable-wedge/fixed-cowl nozzle concept illustrated in Fig. 2. Photographs of the twin-nozzle model installed in the Langley 16 ft. transonic tunnel are shown in Fig. 10. The effects of the two empennage arrangements shown were investigated. The twin-nozzle model arrangement is similar to the single-nozzle model discussed previously. Only the net trust-minus-drag force aft of the metric break was measured. The metric break is shown in the photographs by the 'mid-fuselage' white band. The internal parts of the model and their function, as well as necessary tare corrections, are discussed in detail in Ref. 9 The nozzle/aftbody design was based on the single fixed cowl geometry but at a smaller scale. The aftbody contours had a 10° boattail at the cowl trailing edge. Because of the data available from the single-nozzle test from which the effect of internal expansion area ratio was obtained, only one nozzle simulating dry power geometry, with $A_e/A_t = 1.30$, was tested. An afterburner power nozzle geometry also was tested which had an internal expansion area ratio of 1.40.

Comparison of Single-and Twin-Nozzle Dry Power Performance

A comparison of single and twin two-dimensional wedge nozzle performance is presented in Fig. 11. At static takeoff conditions, the single-nozzle performance line was established in phase I testing for an $A_e/A_t = 1.30$, and the twin-nozzle performance was obtained in phase II testing. The twin-nozzle performance was slightly lower (less than ½%) than the single-nozzle static performance. This difference is within the accuracy band of the two systems. The "dip" in the performance at a nozzle pressure ratio of 4.5 with the twin-nozzle model may be caused by shock interactions that reduce pressures acting on the external wedge surface. This characteristic was not discovered in phase I testing because data were not obtained at NPR = 4.5.

At Mach 0.9, the data indicate that the twin-nozzle performance is higher than the single-nozzle performance. The fact that the performance is higher represents a reversal of the traditional trend of installation penalites for twin-nozzle configurations. The reason for the higher twin-nozzle performance is attributed to the 25% reduction of external wetted area obtained by joining the twin nozzles. A comparison of thrust-minus-pressure drag (removing the external friction drag of the nozzles) indicates that the twin-nozzle installation does have a slight pressure drag penalty at $M = 0.9$. However, the reduction in wetted are for the twin installation more than compensates for the pressure drag penalty by a reduction in friction drag. It should be noted that the twin-nozzle data shown in Fig. 11 do not reflect the performance that could have been achieved by changing the nozzle internal area ratio. As shown in Fig. 6, optimum nozzle thrust-minus-drag performance at a particular Mach number is obtained by adjusting the internal expansion area ratio A_e/A_t to match the schedule of engine operating pressure ratio with Mach number.

Twin-nozzle performance levels at Mach 1.20 were about 3% lower than the single-nozzle model performance. This loss in performance for the twin installation is attributed to the difference in wave drag. The maximum cross-sectional area and overall length of both models were nearly the same. However, the twin- nozzle closure rate dA/dx was higher than the single-nozzle model which effectively increased the twin aftbody supersonic wave drag. A theoretical analysis was made and the results indicate that supersonic wave drag would increase to 2% ideal gross thrust.

Twin Axisymmetric/Two-Dimensional Wedge Nozzle Comparisons

Figure 12 presents twin axisymmetric/two-dimensional wedge nozzle comparisons at Mach 0.90. All axisymmetric data were obtained from Ref. 3, which indicates that the best subsonic dry power performance was obtained with a clean, close-spaced nozzle aftbody with circular-arc iris convergent nozzles installed. The best axisymmetric nozzle afterburner power performance was obtained with close-spaced, convergent-divergent nozzles. Both nozzle data are presented for several aftbody configurations for comparison to the dry and afterburner power two-dimensional wedge nozzle concepts. A correction was made to account for the difference in wetted area between the axisymmetric and two-dimensional wedge nozzle installations. Since the axisymmetric nozzle configurations were slightly wider than the two-dimensional wedge nozzle configuration, the closure area ratio $(A_m - A_t)/A_m$ also was higher, which would, as reasoned earlier, slightly favor the thrust-minus-drag performance of the two-dimensional wedge nozzle installation. In addition, the internal expansion area ratios are slightly different. A conservative comparison to determine the level of performance of the two-dimensional wedge nozzle relative to the axisymmetric nozzle installations is to compare peak nozzle/aftbody performance, since most of the axisymmetric nozzle peak internal performance can be shifted to a higher nozzle pressure ratio by varying the internal expansion area ratio. The axisymmetric nozzle/aftbody performance shown in Fig. 12 is essentially for the best and worst iris-nozzle/aftbody configurations tested in Ref. 3. The data at $M = 0.9$ indicate that the twin two-dimensional wedge nozzle performance generally is higher than the highest performance reported in Ref. 3 with the clean, close-spaced, iris-nozzle/aftbody. This is significant for a practical configuration; the addition of horizontal-tail booms to achieve extreme aft-mounted horizontal tails causes performance penalties that can be large, as shown in Fig. 12. Also shown in Fig. 12 is the performance of a clean, wide-spaced, iris-nozzle/aftbody that also shows a large performance penalty when compared to the clean close-spaced nozzles. Figure 13 presents a similar axisymmetric/two-dimensional wedge nozzle comparison at Mach 1.20 for dry and afterburner power settings. These data show that the dry-power two-dimensional wedge nozzle performance is clearly superior to the iris convergent nozzle installation, which, of course, does not have any expansion area. If the internal expansion area were increased to 1.30, to match engine operating NPR, then the axisymmetric nozzle/aftbody performance would be about 2% of ideal thrust higher at NPR = 6. Current aircraft do not cruise at supersonic speeds at dry power, but future aircraft may do so because of the high thrust-to-weight ratio of advanced aircraft. If supersonic, dry power cruise is desired, the two-dimensional wedge nozzle is an attractive installation because of its high performance at transonic/supersonic speeds.

For afterburner power, the two-dimensional wedge nozzle again exhibits high performance compared to axisymmetric convergent-divergent nozzles with a similar expansion area ratio. It should be noted that the afterbody with horizontal-tail booms and interfairing was designed for optimum performance at $M = 1.20$ (i.e., a 1.2 Mach design area distribution), which is demonstrated by the afterburner power nozzle/aftbody performance. The fact that the twin two-dimensional wedge nozzle aftbody performance at $M = 1.20$ is higher than the tail-boom configuration from Ref. 3 without the significantly lower subsonic performance offers excellent potenial for multimission aircraft design. It should be noted that the impact of nozzle cooling requirements on the installed engine and nozzle/aftbody performance has not been included in the afterburner power performance comparison and must be evaluted.

The comparisons of Figs. 12 and 13 show that the largest gains demonstrated to date by two-dimensional wedge nozzles relative to axisymmetric nozzles are in the transonic flight regime ($M > 0.8$) with dry power nozzle geometry, where the low aftbody drag advantage is the greatest. Improved thrust-minus-drag performance at $M = 1.2$ for the afterburner power two-dimensional wedge nozzle/aftbody should reduce transonic acceleration time, which is an important consideration for fighter aircraft applications.

Effect of Empennage Interfence

The twin-nozzle model was tested with and without tail surfaces to assess tail interference on thrust-minus-drag performance. The horizontal tails were installed adjacent to the nozzle two-dimensional wedge on the model centerline with the 0.25-M.A.C. nearly aligned with the nozzle exit plane (see

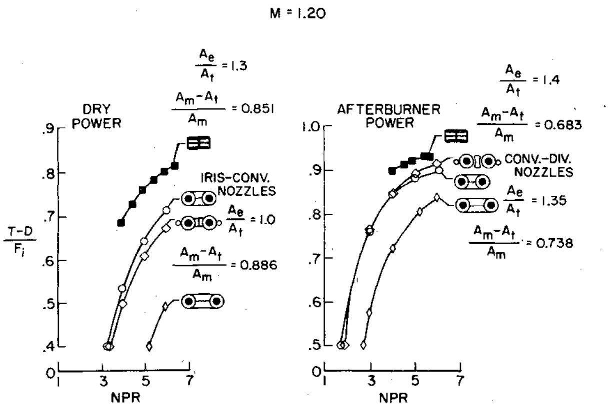

Fig. 13 Comparisons of twin axisymmetric and twin two-dimensional wedge nozzle performance.

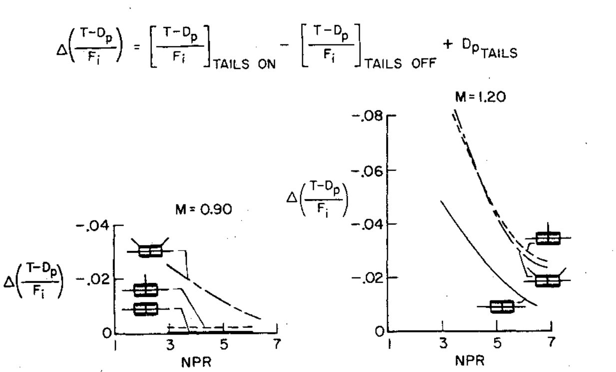

Fig. 14 Effect of empennage interference on two-dimensional wedge nozzle performance.

Fig. 10). The single vertical tail was mounted on the model centerline, and the twin vertical tails were installed canted outboard 15° to a vertical plane that intersected the outside wall of the internal flow duct. The single and twin vertical tails were sized to provide the same directional stability.

Thrust-minus-drag interfernce due to empennage surfaces is presented in Fig. 14 as an increment compared to the tails-off configuration. Tail surface skin friction and pressure drag (profile and wave drag) corrections have been applied, and so the performance increment discussed below is entirely the interference effect on thrust-minus pressure drag of the two-dimensional wedge nozzle/aftbody.

Above a Mach number of 0.8, the tail surfaces had significant effects on the nozzle/aftbody flowfield and thrust-minus-drag dry power performance. As shown in Fig. 14, the largest interference at Mach 0.90 was associated with the twin vertical tails and was approximately 1.8% of ideal thrust at a nozzle pressure ratio of 4.0, compared to 0.5% for the single vertical configuration. Flow visualization studies revealed that the twin vertical tails were not aligned with the local aftbody flow streamlines and that wake disturbances from the twin vertical tails were affecting flow on the aftbody cowl boattail. The wake disturbances could be minimized by tailoring the installation of the twin vertin tails by adjusting the toe and cant angles. The horizontal tails resulted in minimal interfence effects at Mach 0.90. At Mach 1.20, tail interference increased sharply, probably as a result of shock interactions on the aftbody and nozzle surfaces. Empennage interference causes a decrease in the dry power nozzle/aftbody thrust-minus-drag performance at $M = 1.20$ of about 3% of ideal thrust at NPR = 6. The interference resulting from the single or twin vertical tail installation is essentially the same,which may indicate that the tail interference is the result of tail cross-sectional area addition to the afterbody area distribution. The fuselage may require local contouring to achieve an optimum total em-

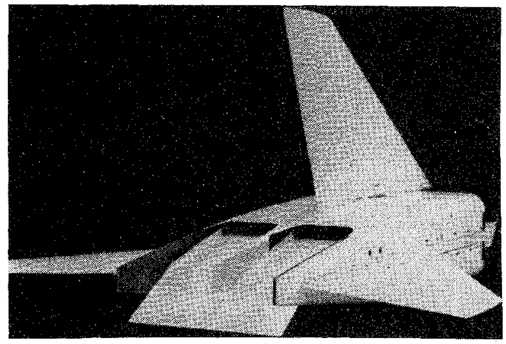

Fig. 15 Thrust-vectoring configuration with 24° cambered wedge.

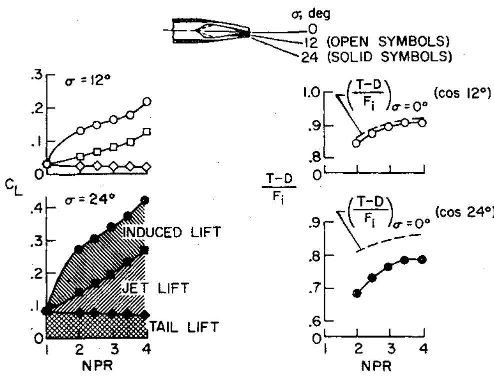

Fig. 16 Thrust-vectoring characteristics of cambered wedge.

pennage/afterbody supersonic area distribution. No attempt was made in this model design to tailor the nozzle/aftbody area distribution to an optimum supersionic area distribution, since most of the concentration was on local slope reduction.

Thrust Vectoring Characteristics

Recent nonaxisymmetric nozzle studies have shown that thrust vectoring can increase significantly the maneuverability of a fighter airplane. If lifting surfaces are integrated properly with the vectoring nozzle, jet-induced lift forces equal to or greater than the thrust lift vector can be achieved.[9] It should be noted that thrust vectoring is very effective at low speeds (i.e., at low dynamic pressure) where aerodynamic control surfaces are less efficient. With the ability to regain quickly a high energy level with the current high thrust-to-weight aircraft, the pilot may opt to slow his aircraft to very low speeds in maneuvering combat. Under these conditions, an equal aircraft without thrust vectoring capability is at a disadvantage.

To study the capability of the two-dimensional wedge nozzle to vector thrust by cambering the wedge, as illustrated in Fig. 15, thrust vectoring configurations were tested for wedge-vectoring designs without vertical tails at Mach 0.4, and results are presented in Fig. 16. Lift coefficient and the ratio of thrust-minus-drag to ideal thrust are presented as a function of nozzle pressure ratio. Lift coefficient was nondimensionalized by a typical wing reference area equal to $10A_m$. A component buildup of lift is given showng the tail lift, jet lift (thrust-lift vector) and the horizontal-tail, jet-induced lift variations with nozzle pressure ratio. As shown in Fig. 16, the jet-induced-lift increment is equal to or greater than the thrust-lift vector increment. The 24° vectored thrust configuration produced about twice the total lift increment as the 12° wedge-vectored thrust configuration (ΔC_L of 0.35 compared to 0.20); however, the 12° wedge-vectored thrust configuration was more efficient at producing jet-induced lift as compared to the jet lift increment. In addition, thrust-minus-drag losses for the 12° wedge-vectored thrust configuration were only about 1% of ideal thrust, compared to about 8% for the 24° wedge-vectored thrust configuration at

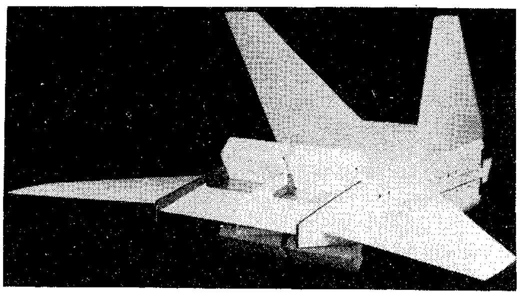

Fig. 17 Thrust-reversing configuration with reverser panels deployed 100%.

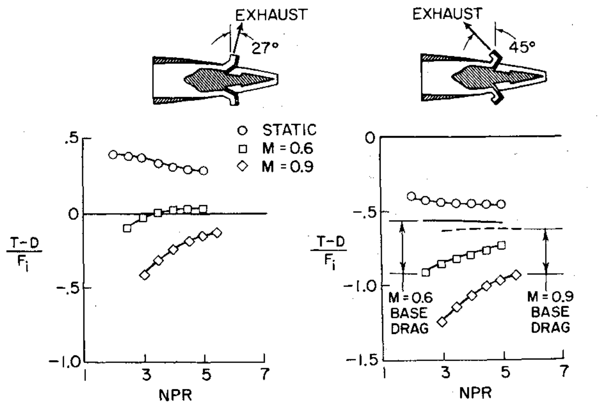

Fig. 18 Thrust-reversing characteristics at deployments of 50% and 100%.

flight nozzle pressure ratio. These losses are primarily from an increase in the drag of the wedge which resembles a speed brake and thrust spoiler when in a vectored mode. Since the thrust vectoring mode is transient, the thrust-minus-drag loss may not be as significant as normal flight performance at low subsonic speeds; however, as flight speed increases the thrust-minus-drag losses also increase, especially for the 24° vectored-wedge design.[10]

Empennage Effect on Jet-Induced Lift

The effect of vertical tail surfaces for the 12° wedge-vectored thrust configuration at $M=0.4$ does not reduce the jet-induced lift obtained with horizontal tails but, in fact, may slightly increase lift. The installation of the horizontal tails with either the single or twin vertical tails resulted in about ½% of ideal thrust decrease in thrust-minus-drag performance which was typical for the nonvectored wedge configuration.

Thrust-Reversing Characteristics

The maneuvering benefits to be derived from in-flight thrust-modulation or thrust reversing are discussed in Ref. 11. A thrust-reversing or thrust-modulating system can be incorporated easily in the two-dimensional wedge nozzle by the installation of reverser panels in the manner shown in Fig. 17.

During the twin two-dimensional wedge nozzle investigation, two reverser-panel positions were studies on the dry power nozzle. One position represented a 50% deployment, which symmtrically directed the exhaust 27° aft of the vertical plane passing through the nozzle exit. The other represented a 100° deployment, which symmetrically directed the exahust 45° forward of the same vertical plane. The configuration shown in Fig. 17 is the 100° deployment. The thrust-reversing characteristics of the 50% and 100% deployed reverser geometry are shown in Fig. 18. The 50% deployed reverser geometry was intended to simulate a thrust spoiler position. The static thrust modulation or reverse thrust effectiveness is typical for current thrust reversers.[12-14] At flight speed, the reversing effectiveness sharply increases as a result of the base drag created by the reverser panels as they are deployed. Reverser base drag determined from static pressure orifices located on the aft side of the reverser panels contributes a substantial portion of the in-flight reverser effectiveness and is nearly constant with nozzle pressure ratio (see Fig. 18). The remaining contributors to in-flight reverse thrust are the reverser exhaust momentum (static) and an unaccounted-for component that probably is due to pressure drag acting on the wedge aft of the reverser panels. Because of the large base drag component, the in-flight reverse thrust effectiveness is very good.

Conclusions

An investigation to determine thrust-minus-drag performance, thrust vectoring characteristics, and thrust-reversing effectiveness of two-dimensional wedge nozzles has been conducted in a joint Navy/Boeing/NASA program at the Langley Research Center. The results of the investigation indicate the following: 1) For a single-nozzle installation, the thrust-minus-drag performance of a variable-geometry two-dimensional wedge nozzle is highly competitive with variable-geometry axisymmetric nozzles at transonic and supersonic speeds. At static takeoff and low subsonic speeds, the thrust-minus-drag of the variable-geometry two-dimensional wedge nozzle is slightly lower (approximately 2% of ideal thrust) compared to an ASME long-throat convergent nozzle.

2) For a twin-engine installation, the thrust-minus-aftbody drag performance of the twin two-dimensional nozzle integration is significantly higher, for speeds greater than a Mach number of 0.8, than the performance achieved with twin axisymmetric nozzle installations.

3) The thrust-minus-drag performace of the two-dimensional wedge nozzle is dependent on the internal-exit area to throat area, similar to axisymmetric convergent-divergent nozzle characteristics. The shallowest wedge half-angle incorporating an equal or slightly greater cowl boattail angle had the highest thrust-minus-drag performance for the two-dimensional wedge nozzles tested. A small amount of wedge truncation was found to reduce significantly two-dimensional wedge nozzle performance.

4) Significant jet-induced lift can be obtained on a aft-mounted lifting surface using a cambered two-dimensional wedge centerbody to vector jet exhaust thrust downward.

5) The thrust-reversing capabilities of reverser panels installed on the two-dimensional wedge centerbody are very effective for static or in-flight operation.

References

[1] Runckel, J.F., "Interference Between Exhaust System and Afterbody of Twin-Engine Fuselage Configurations," NASA TN D-7525, 1974.

[2] Berrier, L., "Effect of Empennage Interfence on Single Engine Afterbody/Nozzle Drag," AIAA Paper 75-1296, Anaheim, Calif., 1975.

[3] Mercer, C.E. and Berrier, B.L., "Effect of Afterbody Shape, Nozzle Type, and Engine Lateral Spacing on the Installed Performance of a Twin-Jet Afterbody Model," NASA TM X-1855, 1969.

[4] "Exploratory Development of an Integrated Engine Exhaust System," Boeing Company, Seattle, Wash., D180-18166-1 (Contract N00140-73-C-0027).

[5] Maiden, D.L., "Performance of an Isolated Two-Dimensional Variable-Geometry Wedge Nozzle With Translating Shroud and Collapsing Wedge at Speeds Up to Mach 2.01," NASA TN D-7906, 1975.

[6] Reubush, D.E. and Runckel, J.F., "Effect of Fineness Ratio on Boattail Drag of Circular-Arc Afterbodies Having Closure Ratios of 0.05 with Jet Exhaust at Mach Numbers Up to 1.30," NASA TN D-7192, 1973.

[7] Reubush, D.E., "Effect of Fineness and Closure Ratios on Boattail Drag of Circular-Arc Afterbody Models With Jet Exhaust at Mach Numbers Up to 1.3," NASA TN D-7163.

[8] Berrier, B.L., "Effect of Plug and Shroud Geometry Variables on Plug-Nozzle Performance at Transonic Speeds," NASA TN D-5098.

[9]Capone, F.J., "The Effects of Vectoring a Partial-Span Rectangular Jet on Propulsion-Induced Aerodynamic Forces at Mach Numbers From 0.40 to 1.20," NASA TN D-8039.

[10]Capone, F.J., "A Summary of Experimental Research on Propulsive-Life Concepts in the Langley 16-Foot Transonic Tunnel," this issue, pp. 803-808.

[11]Linderman, D.C. and Mount, J.S., "Development of an In-Flight Thrust Reverser for Tactical/Attack Airfraft," AIAA Paper 70-699, San Diego, Calif. 1970.

[12]Maiden, D.L. and Mercer, C.E., "Performance Characteristics of a Single-Engine Fighter Model Fitted With an In-Flight Thrust Reverser," NASA TN D-6460, 1971.

[13]Mercer, C.E. and Maiden, D.L., "Effects of an In-Flight Thrust Reverser on the Stability and Control Characteristics of a Single-Engine Fighter Airplane Model," NASA TN D-6886, 1973.

[14]Petit, J. E. and Scholey, M. B., "Thrust Reverser and Thrust Vectoring Literature Review," AFAPL-TR-72-11, April 1972.