77-840

Static Performance of Vectoring/Reversing Nonaxisymmetric Nozzles

C.M. Willard*
McDonnell Aircraft Company, St. Louis, Mo.
F.J. Capone†
NASA Langley Research Center, Hampton, Va.
M. Konarski‡
General Electric Company, Cincinnati, Ohio
and
H.L. Stevens§
Pratt & Whitney Aircraft Group, West Palm Beach, Fla.

An experimental program sponsored by the Air Force Flight Dynamics Laboratory is currently in progress to determine the internal and installed performance characteristics of five different thrust-vectoring/reversing nonaxisymmetric nozzle concepts for tactical fighter aircraft applications. Internal performance characteristics for the five nonaxisymmetric nozzles and an advanced technology axisymmetric baseline nozzle were determined in static tests conducted in January 1977 at the NASA Langley Research Center. The nonaxisymmetric nozzle models were tested at thrust deflection angles of up to 30 deg from horizontal at throat areas associated with both dry and afterburning power. In addition, dry-power reverse-thrust geometries were tested for three of the concepts. The best designs demonstrated internal performance levels essentially equivalent to the baseline axisymmetric nozzle at unvectored conditions. The best designs also gave minimum performance losses due to vectoring, and reverse-thrust levels up to 50% of maximum dry-power forward thrust. The installed performance characteristics will be established based on wind tunnel testing to be conducted at Arnold Engineering Development Center in 1978.

Nomenclature

A_E = nozzle exit area
A_{max} = maximum cross-sectional area of model
A_T = nozzle throat area
Æ = nonaxisymmetric nozzle aspect ratio, width at throat divided by dry-power throat height
C_{f_g} = nozzle gross thrust coefficient $= F_g/F_i$
$C_{f_{g,R}}$ = reverse-thrust coefficient
$C_{f_{g,V}}$ = vectored-thrust coefficient
C_W = nozzle flow coefficient $= W_A/W_i$
F_A = axial component of gross thrust measured by the main balance
F_i = nozzle ideal thrust for complete isentropic expansion of actual jet flow to ambient static pressure
F_N = normal component of gross thrust measured by the main balance
F_g = measured nozzle resultant gross thrust $= \sqrt{F_A^2+F_N^2}$
NPR = nozzle total pressure ratio $= P_{T_N}/P_A$
P_A = ambient static pressure
P_{T_N} = nozzle total pressure
W_A = nozzle flow rate measured by facility turbine flowmeter
W_i = calculated ideal nozzle flow rate
ϵ = nozzle internal area expansion ratio $= A_E/A_T$
δ_V = effective jet turning (measured thrust vector angle) $= \tan^{-1}(F_N/F_A)$
δ_N = nozzle geometric turning angle (downward flow deflection positive)
Δ = incremental value

Presented as Paper 77-840 at the AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 11-13, 1977; submitted Sept. 8, 1977; revision received July 28, 1978.

Index categories: Deceleration Systems; Performance; Airbreathing Propulsion.

*Lead Engineer, Engineering Technology, Propulsion.
†Aerospace Engineer, High Speed Aerodynamics Division. Member AIAA.
‡Senior Aero-Thermo Design Engineer, Advanced Engineering.
§Assistant Project Engineer, Component Design and Integration.

Introduction

RECENT studies have identified potential payoffs for nonaxisymmetric nozzles in the areas of improved integration for installed drag reduction, thrust vectoring for maneuver enhancement and short-field takeoff, and thrust reversing for improved agility and handling. The integration advantages for a two-dimensional wedge nozzle installation were demonstrated several years ago in wind tunnel investigations conducted by McDonnell Aircraft Company (MCAIR) during early concept formulation studies on the FX (F-15) aircraft.[1] Additional experimental studies[2-4] conducted by NASA Langley Research Center (LaRC) have also identified drag reduction payoffs for nonaxisymmetric wedge nozzles, especially for twin-engine configurations.[4] Thrust vectoring has been shown to offer increased maneuverability[5,6] while significant in-flight thrust-reversal levels have been demonstrated for a nonaxisymmetric wedge nozzle.[4] Further, mechanical design studies have shown that the vectoring/reversing capability can be added to a two-dimensional shape at less penalty in complexity than an axisymmetric system. However, the true potential of nonaxisymmetric nozzles will be realized only if internal performance levels and weights comparable to conventional axisymmetric levels are achieved.

A number of promising nonaxisymmetric nozzle concepts were identified by McDonnell Aircraft Company (MCAIR) from 1973 through 1975 in an 18-month study program for the Air Force Flight Dynamics Laboratory (AFFDL).[7,8] A second AFFDL program, entitled "Experimental Evaluation of Non-Axisymmetric Exhaust Nozzles," (Contract F33615-76-C-3019), was awarded to MCAIR in May 1976. General Electric (GE) and Pratt & Whitney Aircraft Group (P&WA)

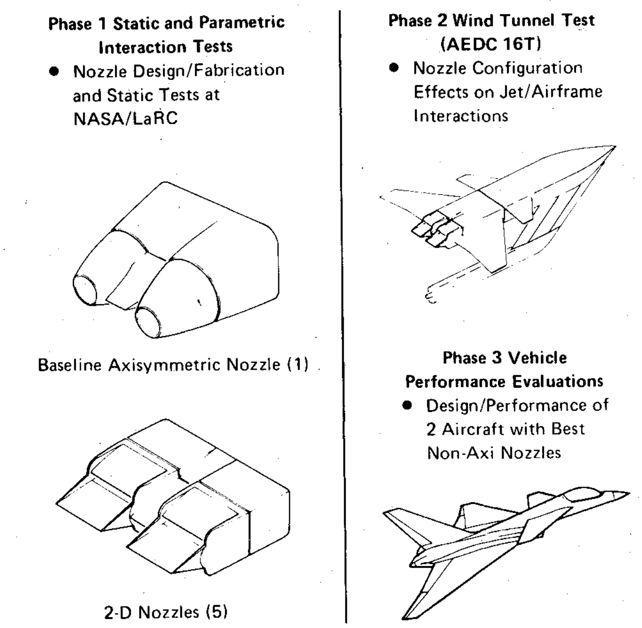

Fig. 1 Program approach.

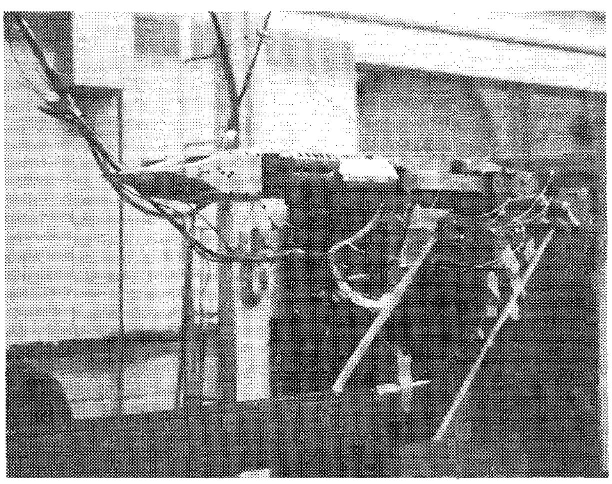

Fig. 2 Test Pod installation in NASA-LaRC 16T static test facility.

are major subcontractors in this program, with significant participation from NASA-LaRC. The objectives of this program are to experimentally determine the internal and installed performance levels of several nonaxisymmetric nozzle concepts and to quantify nozzle/airframe interactive effects for use in the development of aircraft configurations which take advantage of the benefits of these nozzle types. These objectives will be accomplished in a three-phase approach, as shown in Fig. 1.

Results of the Phase 1 static test are summarized in this paper. A general description of the basic test model is presented, and the static test program is described. The specific nozzle designs are discussed, together with the associated unvectored performance. Performance at vectored- and reverse-thrust conditions in then discussed, and conclusions presented.

General Model Description

An existing NASA jet effects model, designated the Test Pod, was utilized in this program. The Test Pod model was designed at the NASA-LaRC specifically for research on thrust-vectoring nozzles. It has been successfully used in numerous test programs,[4-6] and is described in detail in Ref. 6.

In the static tests, the twin-nozzle models were installed on the internal components of the Test Pod, as shown in Fig. 2. The nonaxisymmetric nozzle assemblies were mated to the Test Pod through common circular-to-square transition sections. Ideal thrust was calculated from total pressure and temperature measurements downstream of the transition, thus performance results do not include transition effects. Nozzle gross thrust direction and magnitude were measured by two strain gage balances, with one balance simply providing redundant check readings on the other.

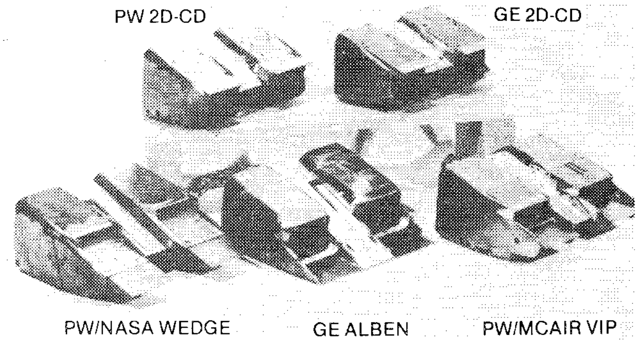

Fig. 3 Nonaxisymmetric nozzle models.

The five nonaxisymmetric nozzle models were based upon full-scale concepts furnished by the engine company subcontractors. General Electric furnished a single expansion ramp design, the augmented load-balanced exhaust nozzle (ALBEN), and a two-dimensional convergent-divergent nozzle (2-D C-D). Pratt and Whitney Aircraft provided a second 2-D C-D design, as well as two external expansion plug (wedge) nozzles designed in conjunction with MCAIR and NASA-LaRC. A photograph of all five nonaxisymmetric nozzle models is shown in Fig. 3.

Test Program

The test program was conducted in the static test facility of the 16-ft transonic tunnel at the NASA-Langley Research Center, Virginia, during January 1977. All five nonaxisymmetric models and the baseline axisymmetric model were tested on the Test Pod over a range of nozzle pressure ratios up to the model/facility airflow limits. All six nozzle models were tested at the three power settings indicated in Table 1 and at various thrust-vectoring/reversing positions. Reverser test configurations were fabricated and tested for three nozzle models (GE 2-D C-D, P&WA 2-D C-D, and P&WA/NASA plug). Vectoring configurations were tested only at the important low-Mach afterburning (A/B) power setting, representative of maximum A/B operation at subsonic maneuvering conditions, for the two 2-D C-D models.

Facility airflow restrictions prevented attainment of the design NPR with the high-Mach A/B power settings. Therefore, only the data at dry and low-Mach A/B power settings are presented.

Nozzle Design Descriptions and Unvectored Performance

The five nonaxisymmetric nozzle designs represent three generically different types of exhaust nozzles: 1) 2-D single-expansion ramp, with combined internal/external expansion, 2) two-dimensional convergent-divergent (2-D C-D), and 3) 2-D plug, or wedge, with combined internal/external expansion. The GE ALBEN 2-D single-expansion ramp nozzle is a vectoring derivative of the augmented deflector exhaust nozzle (ADEN). The ADEN was developed by GE and the Navy for V/STOL application. The 2-D C-D designs furnished by GE and P&WA incorporate both vectoring and reversing capabilities. The P&WA/MCAIR plug incorporates vectoring only. The P&WA/NASA plug design includes both vectoring and reversing. The axisymmetric baseline nozzle design (no vectoring or reversing)was furnished by P&WA, and is an advanced technology version of the nozzle used on the F-15 aircraft. Two of the nozzle models (GE ALBEN and

Table 1 Nozzle sizing

	Test pod nozzle models			Nominal F-15			
Power simulation	$2A_T/A_{max}$	A_T[a] (in.^{2})	NPR design	Flight condition	$2A_T/A_{max}$	A_T[b] (in.^{2})	NPR
Dry	0.11	2.43	3.5	Mach 0.875, 45,000 ft (cruise)	0.12	432	3.7
Low-Mach afterburning	0.19	4.19	5.0	Mach 0.9, 30,000 ft (max. power)	0.20	706	4.9
High-Mach afterburning	0.23	5.16	7.0	Mach 1.4, 30,000 ft (max power)	0.22	760	6.9

[a]Model scale, one side. [b]Full scale, one side.

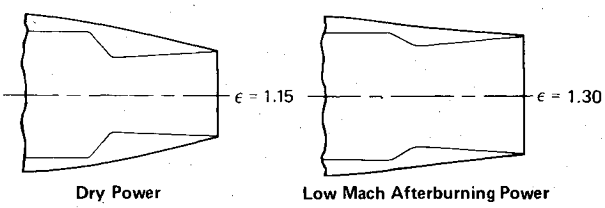

Fig. 4 Baseline axisymmetric nozzle, $\epsilon_{max} = 2$.

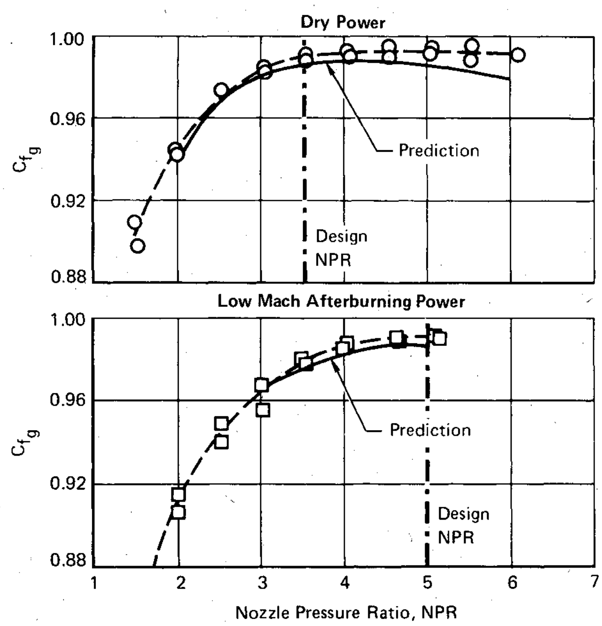

Fig. 5 Unvectored static performance for baseline axisymmetric nozzle model.

P&WA/MCAIR plug) were provided with remote control on the vectoring mechanism to minimize down-time during testing. The guidelines for the model designs were as follows:

1) *Vectoring/Reversing.* Geometric vectoring capability, where feasible, of ±30 deg from a horizontal direction for all concepts at all power settings. Full thrust-reversal simulation at dry power for three of the five concepts.

2) *Aspect Ratio.* An aspect ratio (nozzle width/dry power throat height) for all nozzle concepts of approximately 4 (square duct upstream of nozzle), consistent with a close-spaced buried-fuselage engine installation with an internozzle fairing (see Fig. 3).

3) *Sizing.* Nozzle throat area and area ratios consistent with advanced turbofan engine cycles. Three power settings and associated area ratios for each basic nozzle concept, consisting of one dry power setting, one setting for subsonic maximum afterburning (low-Mach A/B), and one for supersonic afterburning (high-Mach A/B). Nozzle closure at each power setting consistent with advanced fighter installations. The selected nozzle throat areas and closures ($2A_T/A_{max}$) are summarized in Table 1, compared to nominal F-15 values.

The six nozzle designs and their basic unvectored performance characteristics are discussed in detail in the following paragraphs. Performance is compared to the baseline axisymmetric nozzle and to pretest performance predictions. The pretest predictions were based upon available data where possible, supplemented by analytical predictions, including method of characteristic solutions.

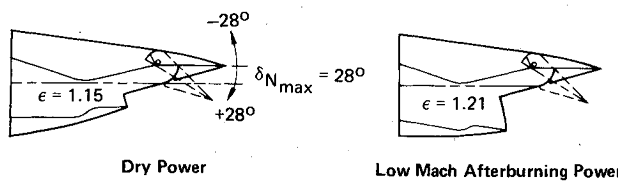

Fig. 6 GE ALBEN nozzle, $\epsilon_{max} = 1.27$.

Baseline Axisymmetric Nozzle

The baseline nozzle design (Fig. 4) simulates an advanced technology axisymmetric C-D design with fully variable area ratio control. In the full-scale design, optimum area ratio is provided for all operating pressure ratios up to 9.3 (maximum area ratio of 2).

The axisymmetric nozzle sets the performance standard, with design point C_{f_g} levels of 0.99 determined experimentally (Fig. 5). Excellent agreement with predictions is generally shown, although the dry-power test data at underexpanded conditions (NPR > 3.5) appear to be high by as much as 1%.

GE ALBEN

The GE ALBEN concept (Fig. 6) features elliptical throat and expansion surface contours. In the full-scale nozzle, the rotating lower flap is part of a swiveling pressure vessel with a continuous structure that proceeds up the sidewalls and through a pressurized cavity in the fixed geometry upper expansion ramp structure. This design innovation reduces actuation forces and maintains structurally efficient hoop stress in the area control flap.

In the model, the elliptical contours were approximated by a "racetrack" shaped flow path formed by semicircular and straight-line segments. Throat area and internal area ratio were set by an adjustable lower surface boattail flap and spacers, simulating rotation of the area control flap in the full-scale design. Thrust vectoring was controlled by remote actuation of the external expansion flap.

The GE ALBEN model C_{f_g} data in dry and low-Mach A/B modes are shown in Fig. 7 for two vectoring flap positions: the nominal flap position ($\delta_N = 0$ deg), and the vectoring flap position which produced the highest C_{f_g} at the design NPR.

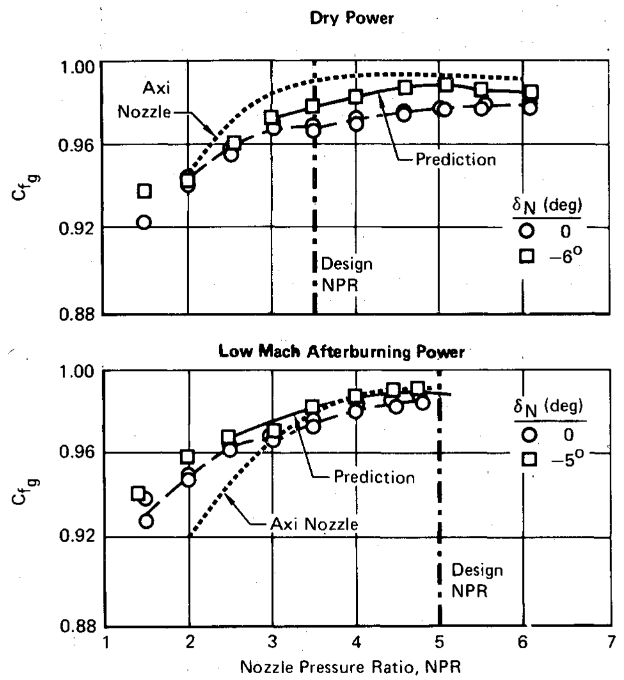

Fig. 7 Static performance for GE ALBEN nozzle model.

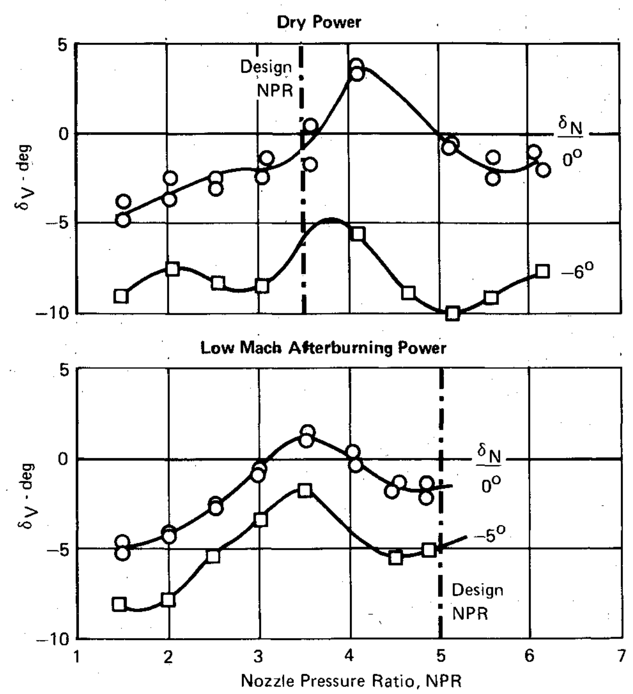

Fig. 8 Sensitivity of measured vector angle to nozzle pressure ratio for GE ALBEN model.

The performance improvement with the negative rotations results from the jets being overdeflected with $\delta_N = 0$ deg. The −6 and −5 deg positions eliminated an undesirable decelerating interference with the flow expansion, and provided effective overall area ratios which resulted in an increased exit momentum. However, with the negative thrust-vector angle when the performance is maximized, an undesirable negative normal (lift) force results. The ALBEN performance exhibits two "peaks," typical for nozzles of this type, occurring at nozzle pressure ratios which correspond to the internal and external area ratios. The ALBEN performance at the vector angle for peak C_{f_g} was slightly over 1% lower than the baseline at dry power and essentially equivalent at low-Mach A/B. The pretest predictions are generally in good agreement with the test data at the vector angle for peak C_{f_g}.

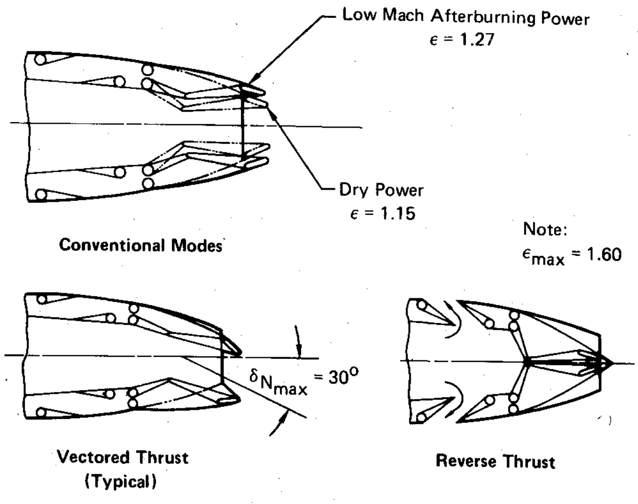

Fig. 9 GE 2-D C-D nozzle.

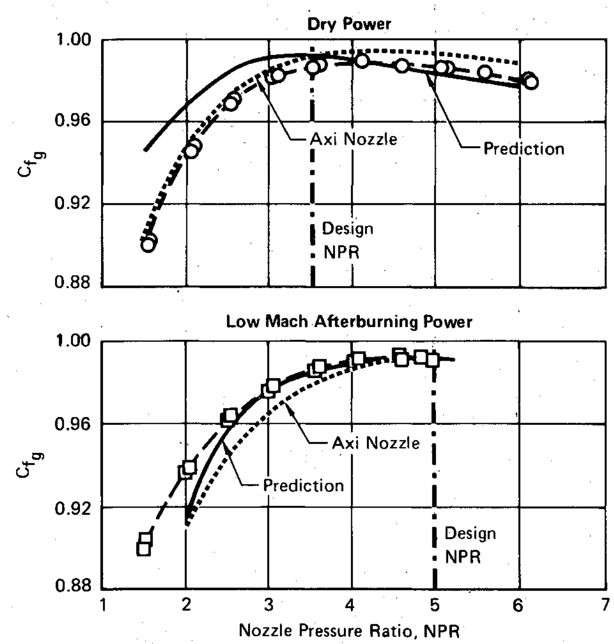

Fig. 10 Unvectored static performance for GE 2-D C-D nozzle model.

Corresponding measured thrust-vector angles (δ_v) are included in Fig. 8 for both ALBEN power settings to illustrate the vector angle sensitivity to NPR and vectoring flap position. The thrust-vector angle variations with NPR are caused by the asymmetric flow path (i.e., a "one-sided wedge" expansion surface). This results in unbalanced pressure forces which vary with NPR and with deflector position. Thus measured thrust-vector angle is actually the effective direction of the force produced by a combination of exit momentum and a pressure-area force exerted on the fixed and rotating external expansion surfaces.

GE 2-D C-D Nozzle

The GE 2-D C-D nozzle full-scale design (Fig. 9) allows independent actuation of the convergent area control flaps and the divergent flaps, providing control of area ratio and thrust-vector angle independent of throat area. The design employs long divergent flaps to achieve a maximum internal area ratio of 1.6, and therefore provides good supersonic internal performance. The sidewalls are cut back to reduce weight and cooling requirements.

Performance is essentially equivalent to axisymmetric baseline levels at all tested pressure ratios. Test results for the unvectored dry and low-Mach A/B power settings are compared to the baseline nozzle performance and the pretest predictions in Fig. 10. The predicted thrust coefficients agree with test levels within 1% at NPR's of 3.0 and higher, with slightly greater differences occurring in the overexpanded low-pressure ratio regime. The excellent agreement with test results at and above the design NPR values is an indication that cutback sidewalls have little, if any, influence on internal performance.

P&WA 2-D C-D Nozzle

The P&WA 2-D C-D nozzle full-scale design (Fig. 11) utilizes rotary convergent flap actuation for jet area control and independent rotary actuation of the external boattail flaps for area ratio and vectoring control. The divergent flaps follow the boattail flaps through a sliding joint mechanism. A cutback sidewall geometry was also utilized by P&WA to reduce nozzle weight and cooled surface area. A short divergent flap design was selected for this second 2-D C-D nozzle to minimize weight and cooling requirements, at the expense of reduced area ratio ($\epsilon = 1.28$ at low-Mach A/B).

Unvectored performance data for the P&WA 2-D C-D nozzle (Fig. 12), is also essentially equivalent to the baseline axisymmetric nozzle performance. Pretest predictions were approximately 1% conservative, but trends with NPR were properly predicted. The expected losses associated with the higher internal divergence angles at low-Mach A/B were not observed.

P&WA/MCAIR VIP Nozzle

This wedge nozzle design, designated the variable incidence plug (VIP) (Fig. 13), employs a pair of load-balanced boattail flaps which are rotated to set throat area and internal area ratio simultaneously. A 12-deg half-angle two-piece wedge is utilized to control thrust-vector angle by programmed differential rotation of the two wedge segments about a common hinge location. This rotation scheme results in a redistribution of flow at the throat, increasing the percentage of flow through the lower throat passage and simultaneously canting the lower throat plane in the desired vectoring direction. The vectoring mechanism through the lower throat (combined subsonic turning and supersonic deflection) is more effective than the upper throat mechanism (supersonic Coanda turning). Thus vectoring effectiveness is improved compared to a design without rotation of the forward wedge segment. Although no thrust reverser was designed into the test concept, P&WA has developed alternate designs with reverser capability.

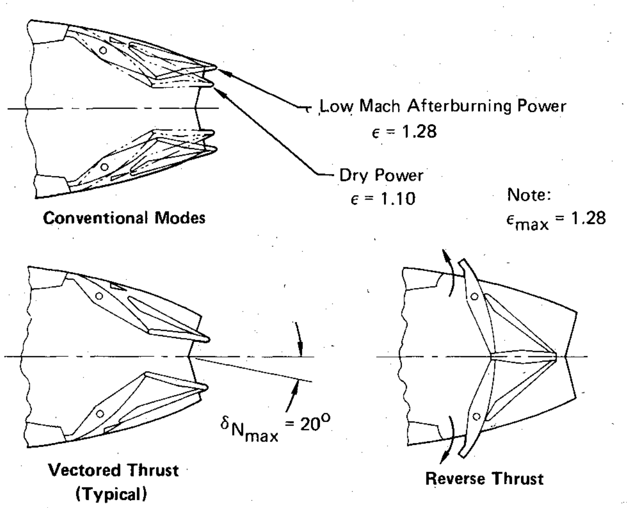

Fig. 11 P&WA 2-D C-D nozzle.

For the model design, the wedge was remotely actuated to provide continuous vectoring over ±30 deg of tail flap rotation for all three power settings. The wedge was hinged and linked by the actuation system such that the tail flap moved 2 deg for each 1 deg rotation of the forward wedge segment.

The VIP nozzle design point performance is 1-2% below comparable axisymmetric nozzle levels, as shown in the data comparisons of Fig. 14. The pretest predictions were based on results of MCAIR company sponsored tests of a similar nozzle geometry, and were within 1% of measured data at all NPR at dry power. However, the tested VIP model had an improved forward wedge segment geometry, which is believed responsible for the improved low-NPR performance on the low-Mach A/B configuration.

P&WA/NASA Plug Nozzle

This collapsing wedge nozzle, shown in Fig. 15, was designed to accomplish both dry power reversing and vectoring at all power settings. This nozzle was a modified version of a design developed at the NASA-LaRC.[2] The original design incorporated a boattail shroud with pure axial translation for internal area ratio control. The translating shroud was changed to a translating/rotating shroud to provide additional area ratio in the high-Mach A/B mode. The transition section upstream of the throat was also changed by eliminating corner radii to accommodate model installation requirements, although the basic area distribution was retained. Thrust vectoring is achieved in this concept with a "double-hinged" wedge to provide minimum loss through coanda turning on the upper surface and efficient supersonic deflection on the lower surface. Sidewall size was again minimized in the interest of avoiding weight and cooling penalties.

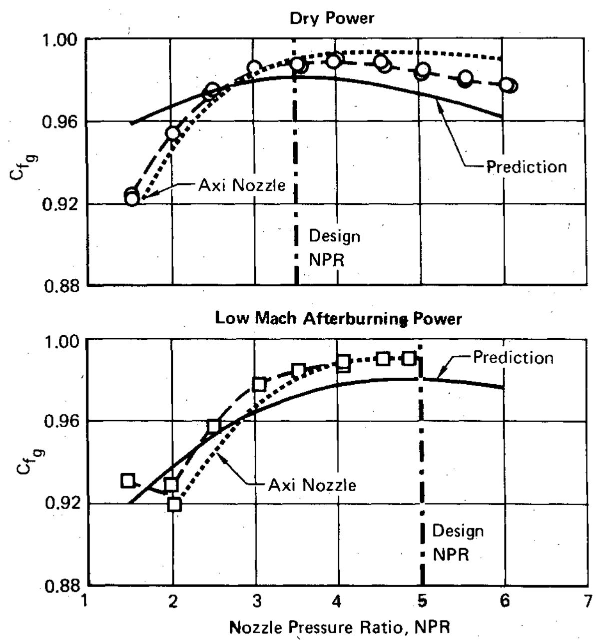

Fig. 12 Unvectored static performance for P&WA 2-D C-D nozzle model.

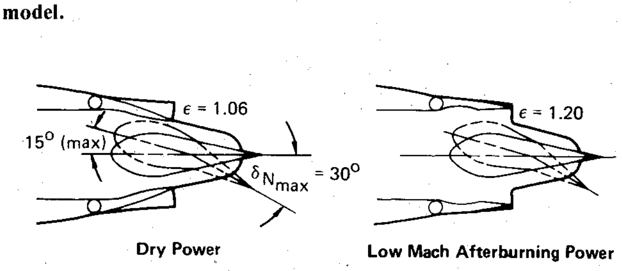

Fig. 13 P&WA/MCAIR 2-D plug (VIP) nozzle, $\epsilon_{max} = 1.28$

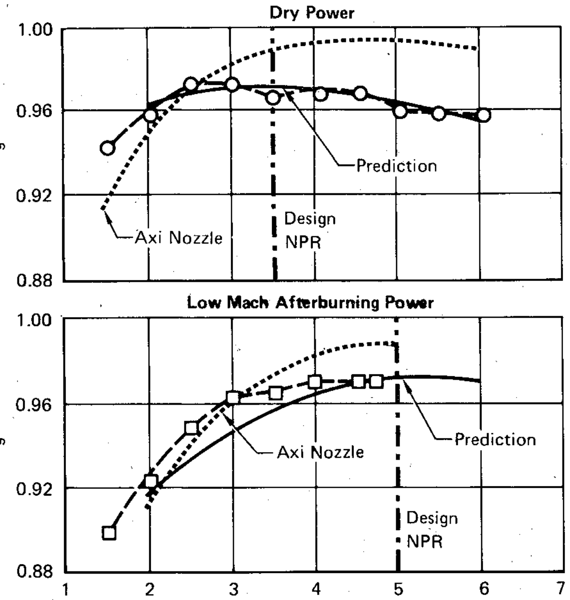

Fig. 14 Unvectored static performance for P&WA/MCAIR VIP nozzle model.

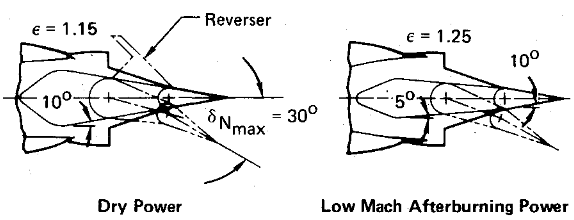

Fig. 15 P&WA/NASA 2-D plug nozzle, $\epsilon_{max} = 1.32$.

Performance of the P&WA/NASA plug nozzle was over 2% lower than the baseline at dry power, but less than 1% at low-Mach A/B (Fig. 16). Pretest performance predictions show good agreement with dry power data above an NPR of 3. The low-Mach A/B performance predictions are between 1 and 2% higher than the measured data. These predictions were based upon Ref. 2 NASA results with the purely translating boattail shroud and correspondingly lower internal area ratios. The translating/rotating boattail flap design of this study created some internal divergence with increased area ratio, resulting in greater overexpansion losses. However, performance at the design NPR of 5 was within 1% of expected performance.

In summary, unvectored static performance for all five nonaxisymmetric concepts is considered generally competitive with the axisymmetric levels. A comparative performance summary is shown in Table 2, giving the static internal performance levels at the design NPR for the two power settings.

Internal performance levels of the nonaxisymmetric nozzles are considered competitive when the C_{f_g} at design conditions is within 1% of the axisymmetric levels. For the low-Mach A/B power setting, four of the five designs meet this goal (Table 2), with the VIP nozzle about 1% too low. The high unvectored performance levels attained with both 2-D C-D models is somewhat surprising, particularly since no internal flow path corner radii were utilized.

At dry power, performance for the two 2-D C-D designs is again essentially equivalent to the axisymmetric nozzle, within about 0.4%. For the three nozzles with external expansion surfaces, static dry power performance at design conditions is 1.3 to 2.3% lower than axisymmetric levels. However, it is quite probable that external flow will have a beneficial effect for these nozzle types. This results from an incremental positive thrust force (typically 1-2% ΔC_{f_g}) on the exposed

Table 2 Summary of unvectored design point performance

Nozzle[a]	Dry power C_{f_g} at NPR = 3.5	Low-Mach afterburning C_{f_g} at NPR = 5.0
Baseline axisymmetric	0.990	0.992
P&WA 2-D C-D	0.988	0.990
GE 2-D C-D	0.986	0.992
GE ALBEN		
(δ_N for peak C_{f_g})[b]	0.977	0.989
P&WA/NASA plug	0.970	0.986
P&WA/MCAIR plug (VIP)	0.967	0.971

[a] $\delta_N = 0$ deg unless noted.
[b] $\delta_N = -6$ deg (dry), $\delta_N = -5$ deg (low-Mach afterburning).

expansion surface. This incremental force is over and above the pressure/area force felt at static conditions and is caused by a recompression effect of the external flow. A final assessment of the dry power internal performance (C_{f_g}) for the three external expansion nozzle types must therefore await results of the Phase 2 wind tunnel tests.

Vectored-Thrust Performance

One of the most significant potential benefits identified for nonaxisymmetric nozzles in prior studies[5-7] was supercirculation lift due to thrust vectoring. However, this potential for improved maneuvering capabilities can be easily offset by losses in nozzle internal performance associated with thrust vectoring. High vectored internal performance is therefore a requirement if the maneuver enhancement potential provided by thrust vectoring is to be realized.

Each of the five nonaxisymmetric nozzle concepts vector by independent actuation of the upper and lower flap systems, resulting in subsonic flow turning through a skewed throat. The ALBEN concept achieves vectoring by supersonic flow deflection downstream of the throat, while the P&WA/NASA concept combines supersonic deflection on the lower plug surface with supersonic Coanda turning on the upper surface. The P&WA/MCAIR VIP nozzle combines the latter vectoring scheme with efficient subsonic turning upstream of the nozzle throat.

The primary figure of merit in evaluating vectoring internal performance is the performance increment, ΔC_{f_g}, between the vectored and unvectored case. Past studies[7,8] have shown that a vectoring angle of about 15 deg is optimum at a subsonic maneuver condition from a thrust-minus-drag standpoint. These same studies also indicated that a ΔC_{f_g} loss greater than 2% for 15 deg of vectoring will substantially negate any supercirculation lift benefits. The 2% value thus represents a nominal upper limit for acceptable C_{f_g} vectoring losses in this study.

Comparison of vectored performance increments (Fig. 17) clearly shows the superiority of the subsonic flow turning process, with the 2% loss limit never exceeded for either of the 2-D C-D nozzles or the VIP nozzle. At the important low-Mach afterburning condition, where data were obtained for all nozzle models, the GE 2-D C-D exhibited the best performance. The greater loss ($\Delta C_{f_g} = 1.4\%$) for the P&WA 2-D C-D model is due to the shorter divergent flap design, which suppresses recompression in the initial overexpansion on the lower divergent flap. The VIP nozzle, with partial subsonic flow turning, achieved vectored performance comparable to the P&WA 2-D C-D models and was distinctly superior to the other two external expansion nozzle types.

The two external expansion concepts utilizing supersonic turning exclusively (GE ALBEN and P&WA/NASA plug) exhibited substantial losses in performance with increasing vector angle, which became even more pronounced as throat area/internal area ratio increased. This trend supports a theoretical analysis conducted by GE for the ALBEN nozzle

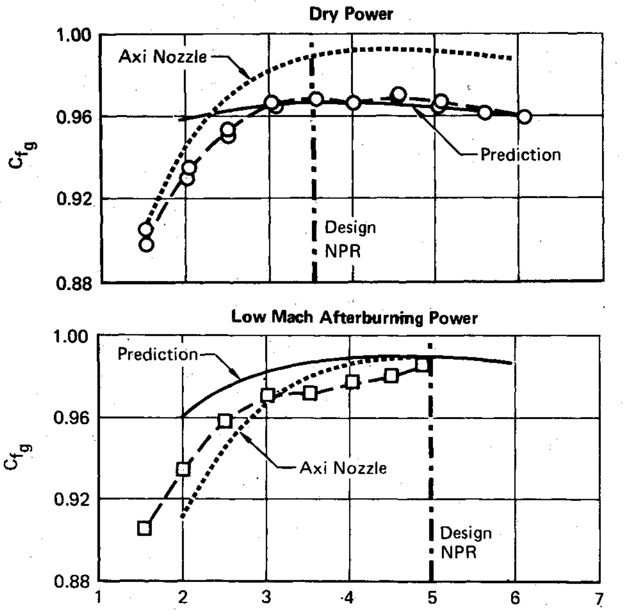

Fig. 16 Unvectored static performance for P&WA/NASA plug nozzle model.

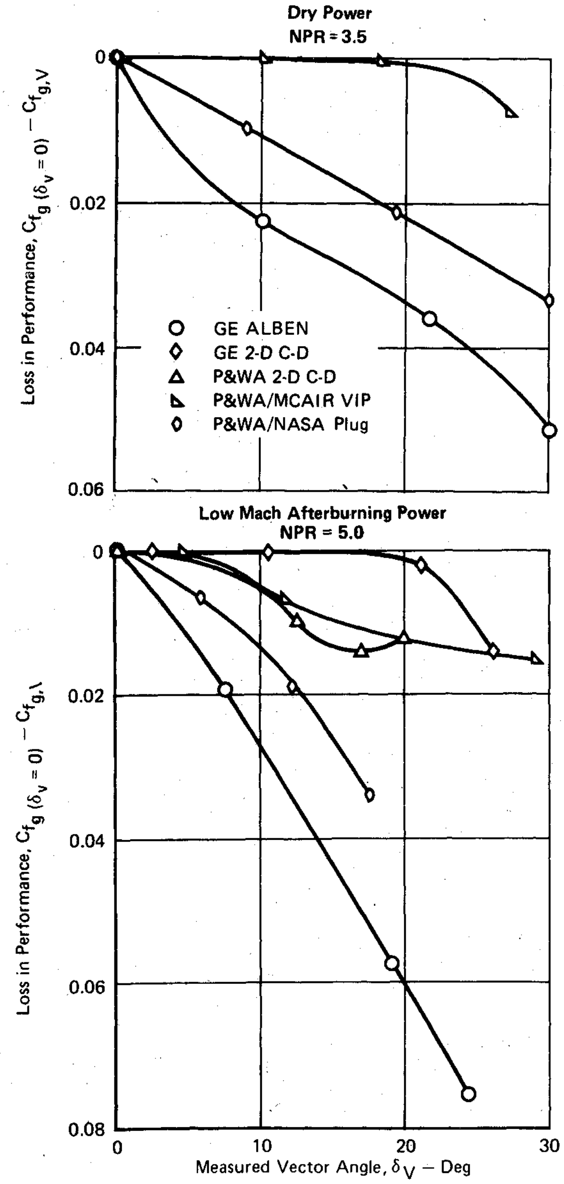

Fig. 17 Performance loss due to vectoring.

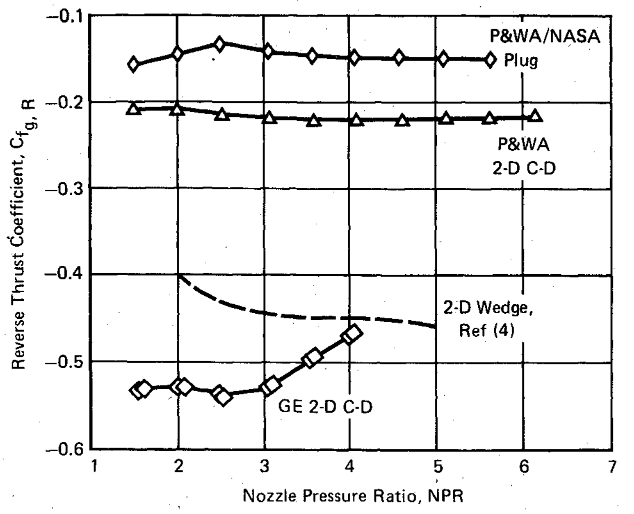

Fig. 18 Performance comparison for reverser configurations, dry power.

which related the performance increments to shock-induced momentum losses resulting from the supersonic flow turning process. As throat area and internal area ratio increase, the terminal Mach number must increase, resulting in higher momentum losses. The P&WA/NASA plug vectoring was slightly superior to the ALBEN performance because two discrete supersonic turns were utilized, reducing the overall momentum loss.

A secondary performance loss mechanism, sidewall spillage, was also identified in the GE analysis of the ALBEN performance. Sidewall spillage is a spanwise flow deflection which can occur when the deflected exhaust stream is not fully constrained by complete sidewalls. Complete sidewalls, although heavier and requiring more cooling flow, could improve the turning effectiveness of the P&WA/NASA plug and ALBEN models. However, external flow may act to constrain any sidewall spillage similar to solid sidewalls, therefore final conclusions must be based upon results of the wind tunnel tests.

Reversed-Thrust Performance

Thrust-reversal/modulation can provide rapid deceleration, both in flight and for landing. Significant potentials of thrust reversal for improved deceleration capabilities at all flight conditions were identified in analytical studies[7,8] for an assumed reverse-thrust performance of $C_{f_{g,R}} = -0.3$. However, for landing operations, $C_{f_{g,R}}$ levels on the order of -0.5 are desirable for effective ground roll reduction. The -0.5 level was thus chosen as the goal for this program. Maximum reverse-thrust performance was evaluated for the three nonaxisymmetric nozzle designs which included reverser geometries. The measured reverser performance met the goal for one nozzle design, and led to discovery of design deficiencies in the other two reversers.

The reverse-thrust performance goal was achieved with the GE 2-D C-D design (Fig. 18) up to a nozzle pressure ratio of 3.5. Although the reverser flow passages are essentially oblique convergent nozzles, the data exhibit a maximum negative C_{f_g} at NPR $=2.8$ rather than at 1.89 as in a convergent nozzle. This is caused by supersonic expansion within the reverse flow passage, which is about one throat height in length.

Reverser performance for the P&WA 2-D C-D design, also shown in Fig. 18, was significantly lower (less negative) than expected. Performance levels of approximately -0.2 were measured at all pressure ratios. The poor performance was attributed primarily to lack of sidewalls extending to the end of the convergent/reverser flap when in the reversing mode. Without sidewalls in this area, the flow as not constrained to fully turn before exiting the nozzle. Significant spanwise flow spillage was observed, confirming this hypothesis.

The P&WA/NASA plug nozzle reversing performance was also significantly lower than expected. Static reverse performance of -0.15 was measured, as compared to approximately -0.45 from the Ref. 4 tests of a similar reverser geometry. However, the configuration tested in this program lacked full reverser flap sidewalls to constrain the flow, again resulting in spanwise spillage losses.

Summary

The static performance characteristics of five different nonaxisymmetric nozzle concepts have been experimentally evaluated for unvectored, vectored, and reverse-thrust conditions in the initial phase of an AFFDL program to experimentally evaluate nonaxisymmetric exhaust nozzles. The test program objective to verify internal static performance levels was considered successfully achieved.

Unvectored internal performance was superior for the two 2-D C-D nozzle types with internal expansion, exhibiting C_{f_g} levels within 0.4% of the baseline axisymmetric nozzle at design NPR for both dry and low-Mach number afterburning power settings.

The best vectoring performance was exhibited on the nozzle types with either partial or complete subsonic flow turning. Maximum loss at low-Mach afterburning conditions for 15 deg of vectoring was only 1.4% for these three nozzle types. The most effective dry-power reverser performance, $C_{f_{g,R}} \geq 0.50$ (negative), was achieved with the GE 2-D C-D nozzle, where the reversed flow was fully constrained by sidewalls.

References

[1] Martens, R.E., "F-15 nozzle/Afterbody Integration, " *Journal of Aircraft,* Vol. 13, May 1976, pp. 327-333.

[2] 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 TND-7906, 1975.

[3] Maiden, D.L., "Performance of an Isolated Two-Dimensional Wedge Nozzle With Fixed Cowl and Variable Wedge Centerbody at Mach Number Up to 2.01," NASA TN D-8318, 1976.

[4] Capone, F.J. and Maiden, D.L., "Performance of Twin Two-Dimensional Wedge Nozzles Including Thrust Vectoring and Reversing Effects at Speeds Up to Mach 2.20," NASA TN D-8449, 1977.

[5] Capone, F.J., "Supercirculation Effects Induced by Vectoring a Partial-Span Rectangular Jet," *Journal of Aircraft,* Vol. 12, Aug. 1975, pp. 633-638.

[6] Capone, F.J., "The Effects on Propulsion-Induced Aerodynamic Forces of Vectoring a Partial-Span Rectangular Jet at Mach Numbers From 0.40 to 1.20," NASA TN D-8039, 1975.

[7] Hiley, P.E., Wallace, H.W., and Booz, D.E., "Non-Axisymmetric Nozzles Installed in Advanced Fighter Aircraft," *Journal of Aircraft,* Vol. 13, Dec. 1976, pp. 1000-1006.

[8] Hiley, P.E. and Wallace, H.W., "Investigation of Non-Axisymmetric Nozzles Installed in Tactical Aircraft," AFFDL-TR-75-61, June 1975.