Transonic Investigation of Two-Dimensional Nozzles Designed for Supersonic Cruise

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Abstract

An experimental and computational investigation has been conducted to determine the off-design uninstalled drag characteristics of a two-dimensional convergent-divergent nozzle designed for a supersonic cruise civil transport. The overall objectives were to: (1) determine the effects of nozzle external flap curvature and sidewall boattail variations on boattail drag; (2) develop an experimental data base for 2D nozzles with long divergent flaps and small boattail angles and (3) provide data for correlating computational fluid dynamic predictions of nozzle boattail drag. The experimental investigation was conducted in the Langley 16-Foot Transonic Tunnel at Mach numbers from 0.80 to 1.20 at nozzle pressure ratios up to 9. Three-dimensional simulations of nozzle performance were obtained with the computational fluid dynamics code PAB3D using turbulence closure and nonlinear Reynolds stress modeling. The results of this investigation indicate that excellent correlation between experimental and predicted results was obtained for the nozzle with a moderate amount of boattail curvature. The nozzle with an external flap having a sharp shoulder (no curvature) had the lowest nozzle pressure drag. At a Mach number of 1.2, sidewall pressure drag doubled as sidewall boattail angle was increased from 4° to 8°. Reducing the height of the sidewall caused large decreases in both the sidewall and flap pressure drags.

Summary

An experimental and computational investigation has been conducted to determine the off-design uninstalled drag characteristics of a two-dimensional convergent-divergent nozzle designed for a supersonic cruise civil transport. The overall objectives were to: (1) determine the effects of nozzle external flap curvature and sidewall boattail variations on boattail drag; (2) develop an experimental data base for 2D nozzles with long divergent flaps and small boattail angles and (3) provide data for correlating computational fluid dynamics (CFD) predictions of nozzle boattail drag. The experimental investigation was conducted in the Langley 16-Foot Transonic Tunnel at Mach numbers from 0.80 to 1.20 at nozzle pressure ratios up to 9. Three-dimensional simulations of nozzle performance were obtained with the computational fluid dynamics code PAB3D using turbulence closure and nonlinear Reynolds stress modeling. The results of this investigation indicate that excellent correlation between experimental and predicted results was obtained for the nozzle with a moderate amount of boattail curvature. The nozzle with an external flap having a sharp shoulder (no curvature) had the lowest nozzle pressure drag. At a Mach number of 1.2, sidewall pressure drag doubled as sidewall boattail angle was increased from 4° to 8°. Reducing the height of the sidewall caused large decreases in both the sidewall and flap pressure drags.

Excellent correlation between experimental and CFD results were obtained for the nozzle with an external flap having a moderate amount of boattail curvature at all Mach numbers tested. At a Mach number of 1.20, agreement between the experimental and predicted pressures was excellent for the nozzle having a sharp corner on the external flap. The nozzle with an external flap having a sharp shoulder (no curvature) had the lowest nozzle pressure drag. Even though this nozzle had the greatest expansion of flow about the nozzle shoulder, it exhibited
more favorable pressure recovery characteristics when compared to the other three nozzles tested. At a Mach number of 1.2, sidewall pressure drag doubled as sidewall boattail angle was increased from 4° to 8°. Reducing the height of the sidewall caused large decreases in both the sidewall and flap pressure drag forces.

Introduction

The National Aeronautics and Space Administration sponsored a joint High-Speed Research Program with US airframe and propulsion companies to provide the critical high-risk technologies for a Mach 2.4, 300 passenger aircraft shown in (ref. 1). An artist concept of this aircraft is shown in figure 1(a). One task the NASA-industry team faced was what type of exhaust nozzle would be best suited for the High Speed Civil Transport (HSCT) propulsion system. The technical challenges addressed as part of the task involved developing a large nozzle with high aerodynamic efficiency, low noise, low weight and long life. Trade studies conducted during this program indicated that a very large two-dimensional convergent-divergent nozzle (2-D C-D) would be best suited to meet the very stringent noise requirements of the HSR program (fig. 1(b)). Additionally, a number of investigations conducted at both static (no external flow) and forward speeds have verified the performance characteristics of 2-D C-D nozzles (refs. 2 to 5).

The engine cycle chosen for the HSCT propulsion system was a mixed-flow turbofan. Although this cycle did have a moderate bypass ratio, a mixer-ejector type nozzle would be necessary to reduce engine noise at off-design conditions. One of the nozzle concepts considered, shown in figure 1(c), would employ a multi-lobe ejector that would entrain outside free-stream air at take-off conditions through bypass doors integrated with the nozzle. This arrangement will also help fill the nozzle at over expanded conditions. During transonic and supersonic cruise conditions, these doors would be closed since external air entrainment would not be necessary for noise abatement. Static performance of two multi-lobed mixer nozzles considered for the HSCT propulsion system is presented in reference 6.

A major problem in designing an exhaust system for a supersonic cruise vehicle is that the geometric shape must change as flight conditions vary. The nozzle exit area ratio has to be varied continuously to maintain high performance at all flight conditions from takeoff to supersonic cruise. Nozzle performance cannot be compromised at supersonic conditions since payload capacity is highly sensitive to nozzle efficiency. For example, a 1-percent decrease in nozzle performance has been estimated to be equivalent to about an 8-percent loss in payload for this class of aircraft (ref. 7).

The nozzle operates with the largest area ratio at supersonic cruise. In order to reduce flow angularity losses (flow not exiting parallel to nozzle center line), the divergent flap half-angle and thus, length, are set to provide maximum internal performance at the supersonic design point for a fully expanded area ratio. As seen in the schematic in figure 1(c), the nozzle would have very long divergent flaps and the nozzle boattail angle would essentially be at 0° at supersonic cruise conditions. At the subsonic/transonic cruise condition, the nozzle would operate at a much lower area ratio. At this condition, it is necessary to minimize nozzle boattail drag that results from not only the nozzle boattail angle but also the curvature at the start of the boattail.

The nozzle boattail drag can be a significant part of the overall drag at subsonic speeds. Several studies were also conducted that addressed installed nozzle boattail drag issues. These
studies suggested that nozzle boattail drag could be as much as 25 to 40 percent of the subsonic cruise drag (ref. 8) for the HSCT aircraft. Since limited experimental data existed for this class of nozzles, an experimental and computational program was initiated at NASA-Langley to determine the uninstalled drag characteristics of this nozzle concept. The overall objectives were to: (1) determine the effects of nozzle external flap curvature and sidewall boattail variations on boattail drag; (2) develop an experimental data base for 2D nozzles with long divergent flaps and small boattail angles and (3) provide data for correlating CFD predictions of nozzle boattail drag.

The experimental investigation was conducted in the Langley 16-Foot Transonic Tunnel at Mach numbers from 0.80 to 1.20 at nozzle pressure ratios up to 9. Three-dimensional simulations of nozzle performance were obtained with the computational fluid dynamics code PAB3D using turbulence closure and nonlinear Reynolds stress modeling.

Symbols and Abbreviations

All model forces and moments are referred to the stability axis system with the model moment reference center located at model station 35.39. A discussion of the data-reduction procedure and definitions of forces and propulsion relationships used herein are discussed in reference 9. Table 1 contains a listing of all reference dimensions.

- $A_e$: nozzle exit area, $\text{in}^2$
- $A_i$: internal area at metric break, $\text{in}^2$
- $A_{\text{max}}$: maximum model cross-sectional area, $\text{in}^2$
- $A_{\text{ref}}$: reference area, $\text{in}^2$
- $A_t$: measured nozzle throat area, $\text{in}^2$
- $A_e/A_i$: nozzle area ratio for ideally expanded flow
- $b_{\text{ref}}$: reference span, $\text{in}$
- $C_{D_f}$: nozzle skin friction drag coefficient
- $C_{D_p}$: measured nozzle drag coefficient
- $C_{D_{pf}}$: integrated nozzle pressure drag coefficient, $C_{D_{pf}} + C_{D_{ps}}$
- $C_{D_{pf}}$: integrated nozzle pressure drag plus estimated friction drag, $C_{D_p} + C_{D_f}$
- $C_{D_{ps}}$: integrated nozzle flap pressure drag coefficient (for both upper and lower flaps)
- $C_{D_{ps}}$: integrated nozzle sidewall pressure drag coefficient (for both sidewalls)
- $C_f$: computed thrust coefficient
- $C_{f,I}$: ideal thrust coefficient
- $C_{A_{pf}}$: integrated nozzle flap pressure axial force coefficient (both upper and lower flaps)
- $C_{A_{ps}}$: integrated nozzle sidewall pressure axial force coefficient (both upper and lower flaps)
- $C_{(F,D_n)}$: thrust-minus-nozzle drag force coefficient
$C_{L,p,f}$  integrated nozzle flap pressure lift coefficient (both upper and lower flaps)

$C_{L,p,s}$  integrated nozzle sidewall pressure lift coefficient (both upper and lower flaps)

$C_{N,p,f}$  integrated nozzle flap pressure normal force coefficient (both upper and lower flaps)

$C_{N,p,s}$  integrated nozzle sidewall pressure normal force coefficient (both upper and lower flaps)

$C_{p,f}$  nozzle flap pressure coefficient, $(p_f - p_o)/q_o$

$C_{p,s}$  nozzle sidewall pressure coefficient, $(p_s - p_o)/q_o$

$c_{ref}$  reference length, in.

$\Delta C_D$  increment in drag coefficient between measured and integrated nozzle pressure drag,

$C_{D,n} - C_{D,pf}$

$\Delta C_{D,p}$  jet effects parameter, $(C_{D,p})_{NPR} - (C_{D,p})_{Jet\ off}$

C-D  convergent-divergent

CFD  computational fluid dynamics

$D$  total center body-nozzle drag, lbf

$D_f$  center body friction drag, lbf

$D_n$  nozzle drag, lbf

EFD  experimental fluid dynamics

$F$  nozzle flap

$F$  thrust along stability axis, lbf

$F_A$  axial force, lbf

$(F-D_n)/F_i$  aeropropulsive parameter (thrust-minus-nozzle drag ratio)

$F/F_i$  static thrust ratio

$F_A$  axial force, lbf

$F_{A,bal}$  total axial force measured by force balance, lbf

$F_{A,mom}$  momentum tare axial force due to bellows, lbf

$F_{flux}$  CFD determined surface flux force, lbs

$F_{friction}$  CFD determined surface friction force, lbs

$F_i$  ideal isentropic gross thrust, lbf

$F_j$  measured thrust along the body axis, lbf

$F_N$  measured jet normal force, lbf
\( F_{\text{pressure}} \) CFD determined surface pressure force, lbs
\( F_{\text{t,b}} \) total body force vector, lbs
\( g \) gravitational constant, 32.174 ft/sec
\( h_e \) height of nozzle exit, in. (see fig. 3)
\( h_m \) height of nozzle, in. (see fig. 3)
\( h_t \) height of nozzle throat, in. (see fig. 3)
HSCT high-speed civil transport
HSR High Speed Research program
\( L_{\text{a,f}} \) circular arc portion of nozzle flap (see fig. 3), in.
\( L_{\text{a,s}} \) circular arc portion of sidewall (see fig. 4), in.
\( L_f \) length of flap (see fig. 3), in.
\( L_n \) length of nozzle (see fig. 3), in.
\( L_s \) length of sidewall flap (see fig. 4), in.
\( M \) free-stream Mach number
MS model station, in.
N nozzle
\( N \) unit normal vector
NPR nozzle pressure ratio, \( p_i/p_a \) or \( p_{i/f}/p_o \)
p surface static pressure, psi
\( p_f \) flap external static pressure, psi
\( p_i \) average internal static pressure, psi
\( p_0 \) free-stream static pressure, psi
\( p_s \) sidewall external static pressure, psi
\( p_{i,j} \) average jet total pressure, psi
\( q_0 \) free-stream dynamic pressure, psi
\( R \) specific gas constant, 1716 ft/sec °R
\( r_f \) flap radius of curvature (see fig. 3), in.
For the experimental portion of this study, the 2-D C-D nozzle was sized for testing on one of the existing single-engine, propulsion simulation systems with a rectangular body at the Langley 16-Foot Transonic Tunnel (ref. 10). The system chosen has a maximum height of 6.20 inches and a maximum width of 6.80 inches that results in the nozzle having an aspect ratio of 1.10 (width to height). However, some of the full-scale nozzle concepts being considered for the HSCT vehicle, like the ones shown in figure 1, had aspect ratios of about 1.05. To account for the difference in nozzle aspect ratio, the height of the model 2-D C-D nozzle was chosen for scaling purposes, since this parameter should better represent nozzle boattail closure. This
resulted in an 8.2-percent scale model of one of the Mach 2.4 passenger aircraft being studied in the HSR program. This aircraft was about 320 ft long with a reference area of 7200 ft\(^2\) and a reference chord of 1032.28 in. Using this model scale, an appropriate reference area was obtained to nondimensionalize nozzle drag in order to produce meaningful drag coefficients in terms of airplane drag counts (one drag count = 0.0001 in drag coefficient).

The two-dimensional convergent-divergent nozzle is a nonaxisymmetric exhaust system in which a symmetric contraction and expansion process takes place internally in the vertical plane. Basic nozzle components consist of upper and lower convergent and divergent flaps to regulate the contraction and expansion process and flat nozzle sidewalls to contain the flow laterally. The flap inner-surface (on full-scale hardware) can be varied or altered by actuators so that (1) the engine power setting (throat area) can be changed by varying the throat height and (2) the expansion surface angle (flat surface downstream of the throat) can be varied for optimum expansion of the exhaust flow. The overall nozzle geometry of the subscale 2-D C-D nozzle model is shown in figure 2 with a typical flap and sidewall setup. The overall length of the nozzle was 13.14 inches. The full-scale nozzle shown in figure 1(b) would be about 8 ft by 8 ft by 20 ft long.

All nozzles were tested with sidewalls. The height of the sidewall was fixed to a distance such that the nozzle internal flaps would not unport with the nozzle in the supersonic cruise position. In this position the boattail angle of the external flaps would be less than 4°. The sidewall cross sectional shape and maximum thickness were dictated by structural and actuation requirements for the full-scale nozzle.

**External Flap and Sidewall Geometry**

The geometric parameters used to define the nozzle external flap shape are shown in figure 3. The two geometric parameters varied during the test were nozzle external flap length \(L_f\) and flap radius of curvature \(r_f\). These two parameters were nondimensionalized by the nozzle height \(h_m\) and maximum radius of curvature \(r_{f,max}\). The baseline external flap had a length of 8.432 inches. A shorter flap length of 6.739 inches was also tested. Note that the overall length of the nozzle, which is representative of the full-scale nozzle, was not changed when nozzle flap length was varied. Nozzles with boattail curvature parameters \(r_f/r_{f,max}\) from 0 to 1 were tested. A nozzle with no curvature would probably be the simplest to build since this flap would have a simple hinge joint. If curvature were required, some type of a sliding mechanism at the hinge joint (fig. 1) would be necessary. The term \(L_{af}\) represents the portion of the nozzle flap that is a circular arc.

Nozzle flap F1 was considered the baseline flap for this investigation since pretest predictions indicated that a nozzle with this flap external geometry would have the lowest drag. The external coordinates and location of the pressure orifices on the nozzle flaps are presented in Appendix A.

The various parameters used to define the sidewall external shape are shown in figure 4. Sidewall boattail angle \(\beta_s\) and radius of curvature \(r_s\) were the two geometric parameters that varied during the test. The sidewall height at the nozzle exit was 5.946 in. (see fig. 2) for sidewalls S1 to S7. An additional sidewall S8 was provided to determine the effect of sidewall height. The height of this sidewall was varied to follow the external contour of nozzle flap N1. A sketch of the nozzle flap and sidewall geometry is shown in figure 5, which also lists the summary of nozzle configurations tested. Sidewall S1 was chosen to be the baseline sidewall for this investigation. This sidewall should have the lowest drag of all the full height sidewalls tested because it had the lowest boattail angle. For a full-scale nozzle, the sidewall needs to be wide.
enough to house the actuation system for the nozzle and provide structural integrity for the overall nozzle. Thus, sidewalls with larger boattail angles were provided to assess any drag penalty that might occur if such sidewalls were required for the full-scale nozzle. The external coordinates and location of the pressure orifices on the sidewalls are presented in Appendix A.

Nozzle Configurations Tested

A summary of all the nozzles tested is provided in figure 5. Nozzle configurations in which the external flap geometry was varied are presented in figure 6. The flap radius of curvature parameter was varied from 0 to 1.0 for nozzles N1, N2, N3, and N4 with the baseline flap length being held constant. The flap boattail angle $\beta_f$ varied from 11.72° to 23.44° for these configurations. Flap radius of curvature $r_f/r_{f,max}$ was also varied for the nozzles with the shorter flap length as indicated by nozzles N13 and N14, all of which were tested with sidewall S1. Nozzles N11 and N12 were tested with flaps F1 and F2 with the reduced height sidewall to determine whether a drag penalty may occur for the full height sidewalls. Photographs of nozzles N1 and N11 are presented in figure 7 to show the different sidewall heights.

The nozzle configurations used to investigate sidewall boattail angle $\beta_s$ and radius of curvature $r_s$ are shown in figure 8. Sidewall boattail angle was varied from 4° to 8° for nozzles N1, N5 and N6 with $r_s/r_{s,max} = 0$. The sidewall radius of curvature parameter $r_s/r_{s,max}$ was varied from 0 to 0.4 for nozzles N5, N7, and N9 with the boattail angle at 6°, and from 0 to 1.0 for nozzles N6, N8, and N10 with the boattail angle at 8°.

All nozzles tested had the same internal geometry, because one of the objectives of this investigation was to only vary the external nozzle flap contour. Thus, any changes to external nozzle performance such as nozzle drag, should only be attributed to external flow effects over the nozzle flaps. The nozzles had a nominal throat height $h_t$ of 2.02 inches, an exit height $h_e$ of 2.70 inches and an area ratio $A_e/A_t$ of 1.34 (fig. 2). The corresponding nozzle design pressure ratio was 5.0, which is where the flow in the nozzle is fully expanded and peak nozzle performance is generally expected. Static performance for each of the nozzles can be found in Appendix C. A comparison of all the nozzles static performance presented in figure 9 showed excellent agreement between all nozzles with differences of less than one-half percent in the static thrust ratio at any given pressure ratio. The maximum static pressure ratio reached was about 4.5 due to facility flow limitations.

Experimental Procedures

Wind Tunnel and Tests

The Langley 16-Foot Transonic Tunnel was a single-return atmospheric wind tunnel with a slotted octagonal test section and continuous air exchange. The wind tunnel had variable airspeeds up to a Mach number of 1.25 with test-section plenum suction used for speeds above a Mach number of 1.05. A complete description of this facility and operating characteristics can be found in reference 11.

This investigation was conducted at Mach numbers from 0.80 to 1.20. Nozzle pressure ratio was varied from jet-off up to 9, depending on Mach number. All nozzle configurations were tested at an angle of attack of 0°. Unit Reynolds number per foot varied from $3.8 \times 10^6$ to $4.2 \times 10^6$. All tests were conducted with a 0.10 in. wide boundary-layer trip consisting of a strip of No.
120 silicon carbide grit sparsely distributed in a thin film of lacquer located 1.00 in. from the tip of the forebody nose.

Air Simulation System

The nozzles were tested on an isolated, two-dimensional propulsion air-powered simulation system that was mounted in the wind tunnel by a sting/strut support system as shown in figure 10. A photograph showing this installation with nozzle N1 is presented in figure 11. The propulsion simulation system was composed of three major sections: a nose-forebody, a centerbody, and the nozzle. The nose-forebody section up to station 26.50 was nonmetric; that is, it was not attached to the strain-gage force balance. The centerbody section was made up of the low-pressure plenum, instrumentation section and transition section. The centerbody section from station 26.50 to 50.90 was rectangular in cross-section with rounded corners and had a constant width and height of 6.80 in. and 6.20 in., respectively. All sections downstream of station 26.50 were metric and mounted on the force balance. A flexible Teflon strip inserted into a circumferentially machined groove between the nose-forebody and low-pressure plenum impeded flow into or out of the internal cavity.

An external high-pressure air system provided a continuous flow of clean, dry air at a controlled temperature of about 540˚R in the nozzles. This high-pressure air was brought through the support strut by six tubes that connect to a high-pressure plenum chamber. As shown in figure 10, the air was then discharged perpendicularly into the model low-pressure plenum through eight multi-holed sonic nozzles equally spaced around the high-pressure plenum. This method was designed to minimize any forces imposed by the transfer of axial momentum as the air passed from the nonmetric high-pressure plenum to the metric (mounted on the force balance) low-pressure plenum. Two-flexible metal bellows were used as seals and served to compensate for axial forces caused by pressurization.

The air was then passed from the model low-pressure plenum, through a choke plate, an instrumentation section and a transition section that provided a smooth flow path for the airflow from the round low-pressure plenum to the rectangular nozzle entrance. All nozzle configurations were attached to the transition section at model station 50.90.

Instrumentation

The Langley 1631B six-component strain-gauge balance was used to measure forces and moments on the model downstream of station 26.50. The balance limits for this balance were ±600 lbs normal force, ±800 lbs axial force and ±4,000 inch-pounds pitching moment. Flow conditions in the nozzle were determined from ten area-weighted total pressure probes and one total temperature probe located at station 45.65 in the instrumentation section, aft of the choke plate. Nozzle total pressure was determined from the average of these measurements. Weight flow of the high-pressure air supplied to the exhaust nozzle was measured by a critical flow venturi (ref. 12). Eight internal static pressures, measured at the metric break, were used to account for pressure forces at this location. All the pressures noted above were measured with individual pressure transducers.

The nozzle flaps were extensively instrumented with pressure taps because one of the primary objectives of this investigation was to provide data for correlating CFD predictions of nozzle boattail drag. The nozzle upper and lower flaps were each instrumented with two rows of pressure taps with 25 taps per row. On the upper flap, one row was located on the flap centerline
and the other was located outboard near the sidewall. On the lower flap, one row was also located on the flap centerline and the other was located midway between the flap centerline and the outer edge of the flap. For each nozzle, one sidewall was instrumented with two rows of pressure taps with 20 taps per row. These pressures were measured with electronically scanning pressure devices. The locations of each pressure tap on all flaps and sidewalls were determined from actual measurements after the pressure taps were installed and are accurate to within ±0.005 inches. These locations are presented in detail in Appendix A.

**Calibration and Data Reduction Procedures**

**Calibration Procedure.** The force balance measures the combined forces and moments due to nozzle gross thrust and the external flow field of that portion of the model aft of MS 26.5 inches. Force and moment interactions exist between the bellows-flow transfer system (fig. 10) and the force balance. Consequently, single and combined loadings of normal force, axial force and pitching moment were made with and without the jets operating with Stratford calibration nozzles (ref. 10). The calibrations performed with the jets operating give a more realistic effect of pressurizing the bellows than simply capping off the nozzles and pressurizing the flow system. Thus, in addition to the usual balance-interaction corrections applied to the force balance under combined loads, another set of corrections was applied to account for the combined loading effect of the balance with the bellows system. These calibrations were performed over a range of expected normal forces and pitching moments. The balance data were then corrected in a manner similar to that discussed in references 9 and 10.

**Data Reduction.** All data were recorded simultaneously on magnetic tape. Approximately 50 frames of data, taken at a rate of 10 frames per second, were taken for each data point; average values were used in data reduction computations. The average value of jet total pressure was also used in all computations. As stated in the Nozzle Design section, the nozzles were scaled to an equivalent 8.2-percent HSCT airplane so that appropriate reference dimensions could be used subsequently to non-dimensionalize drag in order to produce meaningful drag coefficients in terms of airplane drag coefficients. Thus, all aerodynamic coefficients were referenced to an equivalent reference area of 6824.4 in² and chord of 84.337 in.

The axial force measured by the force balance must be corrected for both a pressure-area tare force acting on the model and for momentum tare forces caused by flow in the bellows in order to achieve desired axial-force terms. The internal pressure force on the model was obtained by multiplying the difference between the average internal pressure and free-stream pressure by the affected projected area normal to the model axis. The momentum tare force was determined from calibrations using the aforementioned Stratford calibration nozzles prior to the wind tunnel investigation.

At wind-on conditions, thrust-minus nozzle drag was obtained from equation 1

\[ F_A - F_j = F_{A,bal} + (p_i - p_0)A_i - F_{A,mom} + D_f \]  \hspace{1cm} (1)

where the first term \( F_{A,bal} \) includes all pressure and viscous forces (internal and external on the afterbody and nozzle and thrust system). The second term accounts for the interior pressure forces acting at the metric break. The internal pressure at any given set of test conditions was uniform throughout the inside of the model, thus indicating no cavity flow. The tare force \( F_{A,mom} \) is a momentum tare correction with the jet operating and is a function of the average bellows
internal pressure that varies with the internal chamber pressure in the supply pipe just ahead of the sonic nozzles (fig. 10). Although the bellows were designed to eliminate pressure and momentum tares, small bellows tares still exist with the jet operating. These tares result from a small pressure difference between the ends of the bellows when internal velocities are high and from small differences in the forward and aft bellows spring constants when the bellows are pressurized. The last term $D_j$ is the friction drag of the centerbody section from stations 26.50 to 50.90.

The adjusted forces and moments measured by the force balance are transferred from the body axis of the metric portion of the model to the stability axis. The attitude of the nonmetric forebody relative to gravity was determined from a calibrated attitude indicator located in the model nose. The angle of attack, $\alpha$, which is the angle between the centerbody/nozzle centerline and the relative wind, was determined by applying terms for centerbody deflection (caused when the model and balance bend under aerodynamic load) and a tunnel flow angularity term to the angle measured by the attitude indicator. The flow angularity correction was 0.1°, which is the average angle measured at the centerline of the 16-Foot Transonic Tunnel (ref. 11).

Thrust-removed (nozzle) forces and moments were obtained by subtracting the components of thrust in axial force, normal force, and pitching moment from the measured total (aerodynamic plus thrust) forces and moments. These thrust components at forward speed were determined from measured static data and were a function of free-stream and dynamic pressure. Total nozzle drag coefficient (including pressure and viscous forces) from balance measurements for only the nozzle (portion of model aft of model station 50.90) is then

$$C_{D,n} = C_{(F-D_s)} + C_F$$  \hspace{1cm} (2)

Nozzle flap and sidewall pressure drag coefficients were determined by integration of pressures over the respective surfaces in the body axis. Integrated axial (equation 3) and normal (equation 4) pressure force coefficients for the upper and lower flap of the nozzle are simply

$$C_{A,p,f} = \sum C_{p,f,j} \left( A_{A,j} \right) / A_{ref}$$  \hspace{1cm} (3)

$$C_{N,p,f} = \sum C_{p,f,j} \left( A_{N,j} \right) / A_{ref}$$  \hspace{1cm} (4)

and then converted to the stability axis

$$C_{D,p,f} = C_{A,p,f} \cos \alpha + C_{N,p,f} \sin \alpha$$  \hspace{1cm} (5)

Sidewall pressure drag coefficient would be obtained in a similar fashion

$$C_{D,p,S} = C_{A,p,S} \cos \alpha + C_{N,p,S} \sin \alpha$$  \hspace{1cm} (6)

Nozzle discharge coefficient $w_j/w_i$ is the ratio of measured weight flow to ideal weight flow, where ideal weight flow is based on average jet total pressure $p_{t,j}$, jet total temperature $T_{t,j}$, and the measured nozzle throat area $A$, for each individual nozzle tested. Nozzle discharge coefficient is then a measure of the ability of a nozzle to pass weight flow and is reduced by any momentum and vena contracta losses (effective throat area less than measured throat area). Using the measured weight flow, ideal thrust of the nozzle can be computed from equation 7.
Ideal thrust is then used to compute basic propulsion performance ratios such as static thrust ratio $F/F_i$.

**Data Repeatability.** Data for this investigation was acquired within a single wind tunnel entry of the model. Short-term repeatability has been quantified in terms of a 95% confidence level for nozzle N1. Examples of short-term repeatability of integrated pressure drag values are shown in figure 12 for nozzle N1 flap and sidewall pressure drag coefficients, respectively, at a Mach number of 0.90 for seven NPR sweeps. Four of the NPR sweeps were performed at the beginning of the test and the other three were taken at the end of the test period. These figures show the residuals of the integrated pressure drag values defined as the difference in the individual measured data points from the estimated mean of the group of repeated NPR sweeps. The estimated mean was the average of the grouped data based on a piecewise, 3rd order polynomial fit of the individual NPR sweeps. Also shown with the dashed lines, are the bounds of the 95% confidence interval as a function of NPR. In general, the residuals are small over the NPR range tested. The basic data in graphical form can be found in Appendix B.

**Computational Flow Solver**

**Governing Equations**

The PAB3D computer code solves the three-dimensional, Reynolds-averaged Navier-Stokes (RANS) equations and uses one of several turbulence models for closure of the RANS equations. The governing equations are written in generalized coordinates and in conservative form. In an effort to decrease computational resources, simplified, thin-layer Navier-Stokes equations are implemented into PAB3D. This approximation neglects derivatives in the viscous terms streamwise and parallel to the surface, since they are typically negligible in comparison to the derivatives normal to the surface. Extensive details of PAB3D are found in references 13 and 14.

The flow solver was written with three numerical schemes: the flux vector scheme of van Leer (ref. 15), the flux difference-splitting scheme of Roe (ref. 16), and a modified Roe scheme used primarily for space marching solutions. These schemes implement the finite volume principle to balance the fluxes across grid cells and the upwind biased scheme of van Leer or Roe to determine fluxes at the cell interfaces. Only the inviscid terms of the flux vectors are split and upwind differenced, while the diffusion terms of the Navier-Stokes equations are centrally differenced. The details and applications of these methods are given in references 13 and 14.

For this study and other typical three-dimensional simulations, the solutions are computed with the van Leer and Roe schemes. Each iteration to a steady state in the three-dimensional computational domain includes a forward and backward relaxation sweep in the streamwise direction, while implicitly updating each cross plane.
Turbulence Modeling

Turbulence modeling is required to predict solutions for many flow fields. The PAB3D code can perform several turbulence simulations by implementing either a 1- or 2-equation turbulence model with either a linear or nonlinear Reynolds stress model. For this study, the 2-equation, viscous model was chosen because this model has proven reliable in predicting propulsive flows with mixing, separated flow regions, and jet shear layers. The nonlinear Reynolds stress model of Girimaji (ref. 17) was implemented to capture anisotropic flow features that are not resolved with the standard, linear stress-strain relationships. A modified Jones and Launder form (ref. 18) of the damping function was utilized to treat the singularity at the wall. A high Reynolds number model with no damping function was implemented in the free stream blocks.

Boundary Conditions

The PAB3D code allows for several boundary conditions at the inflow, outflow, free stream, and wall and centerline boundaries. Nozzle total temperature and total pressure with a normal fluid flow angle was used for the jet inflow boundary conditions. A jet total temperature of 528.67°R was used for all jet calculations. Riemann invariants along characteristics were used as inflow and free stream boundary conditions. A constant pressure boundary condition for subsonic outflow was used far downstream as an outflow boundary condition. A no-slip adiabatic wall boundary condition was implemented on solid surfaces to obtain viscous solutions.

Performance Calculation

The PAB3D code contains a performance module (ref. 19) that utilizes the momentum theorem applied to a user-defined control volume to calculate nozzle or aerodynamic performance. Quantities such as lift, drag, thrust, moments, heat transfer and skin friction may be computed for many complex geometric configurations and multi-stream flows. Each quantity is updated throughout the solution development to monitor convergence.

Along flow-through sections of the control volume, mass and momentum fluxes, as well as pressure forces are integrated over cell with equations 8 and 9.

\[ w_p = \sum (\rho U \cdot N) \Delta A \]  \hspace{1cm} (8)

\[ F_{\text{flux}} = \sum [\rho U(U \cdot N) + (p - p_o)N] \Delta A \]  \hspace{1cm} (9)

where \( \Delta A \) is the cell face area and \( N \) is the cell face unit vector.

Along solid surfaces of the control volume, skin friction and pressure forces are calculated. Surface pressure force \( F_{\text{pressure}} \) is determined by multiplying cell static pressure by cell face area using equation 10.

\[ F_{\text{pressure}} = \sum [(p - p_o)N] \Delta A \]  \hspace{1cm} (10)

The cell surface static pressure is calculated by extrapolating the cell centered static pressure to the surface where the velocity is assumed to be zero.
The skin friction force $F_{friction}$ is calculated with only the velocity gradients tangential to the surface contributing to the velocity term of the viscous stress tensor. A two point difference method was used to determine the velocity gradients; one zero-magnitude velocity vector at the surface and a second at the cell center. Sutherland’s formula (ref. 20) was used to calculate the dynamic viscosity term at the surface by extrapolating the static temperature at a local cell center to the surface and using a reference viscosity and temperature condition. The total body force vector $F_{t,b}$ is defined in equation 11.

$$F_{t,b} = F_{flux} + F_{pressure} + F_{friction}$$  (11)

**Computational Procedure**

PAB3D was used to predict solutions for nozzles N1 and N3 at Mach numbers 0.90 and 1.20 with a nozzle pressure ratio of 5, which was the design pressure ratio.

The computational mesh was fully three-dimensional with 9+3 blocks defining the internal nozzle, and 9+3 blocks representing the free stream domain. The far field was located 10 body lengths upstream and downstream of the aerodynamic nose and nozzle exit, respectively. The upper and lower lateral far field boundary was located 6 body lengths above and below the aerodynamic body. The boundary layer was defined for a law-of-the-wall coordinate $y^+$ of 0.5 on the fine mesh spacing for adequate modeling of the boundary layer flow.

The base grid is a quarter plane representation of the experimental model with 1.57 million grid points in 12 blocks. A cut 222 grid is generated by using a database reduction scheme that eliminates every other grid point in the i, j, and k directions. This cuts each grid dimension by 2, which decreases the grid count to 207,437 and substantially reduces the memory required to run the flow solver. The cut grid can also be sequenced in each direction for improved convergence rates and for grid assessment. For example, the flow solver uses alternating points in the i direction and every point in the j and k directions in a 211 sequence. Generally, a user would begin sequencing on the cut 222 grid. A pattern of 222, 221, 211, and then 111, or no sequencing might be used to assess solution behavior as more points are utilized in a particular direction. The solution is developed until convergence requirements are met at each level. Once the solution is converged on the cut 222 grid, the solution may be extrapolated to the base grid and sequencing may again be utilized.

For example, a converged solution was developed within 16.4 hours on a cut grid for nozzle N1 at $M = 0.9$ and NPR = 5. However, the solution was extrapolated and converged on the base level to quantify the effect of grid density. Nozzle drag coefficient decreased a mere 0.00002 in another 30 hours of computer time. Therefore, the remaining solutions were computed using sequencing only on the cut grid since the aforementioned solution was minimally dependent on doubling the grid density beyond the cut 222 level. This technique allowed for quicker solution times due to the substantially smaller memory requirement of the cut grid. Figure 13 presents typical convergence histories for Nozzle 3, and although not shown, similar results were obtained for Nozzle 1. The spikes in the residual history for Nozzle N3 at $M = 0.9$ and NPR = 5 exhibit locations of solution extrapolation to a finer grid level. Accordingly, small adjustments in drag coefficient, $C_d$, were observed at these locations, also. The solution converged at the 222 grid level after 6500 iterations, with no further change in drag coefficient as the residual continued to decrease. Drag coefficient increased a mere 1.2 percent from the 422 grid level to the 222 grid level.
Presentation of Results

Summary Data

The effect of Mach number on nozzle aeropropulsive performance parameters for nozzle N1 is presented in figure 14. Comparative and summary results from this investigation are presented graphically in figures 15 to 36. The comparisons show the correlation between the experimental and predicted results, as well as showing the effects of varying nozzle geometric parameters on the nozzle integrated pressure drags and pressure distributions at the design nozzle pressure ratio of 5.0. Although the discussion of results at this pressure ratio would generally be applicable to other pressure ratios, the relative difference between comparisons may vary.

Basic Data

All the experimental results from this investigation are presented in graphical form in Appendices D to H. Basic nozzle performance parameters for each nozzle are presented in Appendix D. Appendix E presents the effects of varying nozzle geometric parameters on the nozzle integrated pressure drag. The effects of varying nozzle geometric parameters on the nozzle integrated pressure drag values at the scheduled NPR are presented in Appendix F. Jet-effects parameter for each nozzle are presented in Appendix G. Appendix H presents the external pressure distributions for each nozzle.

An examination of the force and pressure data plots for an individual nozzle will show that at times, the force data plot may not contain as many data points as the experimental pressure data plot. During this investigation, pressure fluctuations were observed in the critical flow venturi. At times, these fluctuations would produce a sinusoidal type variation in nozzle discharge coefficient as nozzle pressure ratio was varied. Normally, there would be no variation of discharge coefficient with nozzle pressure ratio as long as the nozzle has choked flow. There are two valves in the air system for jet testing in the 16-Foot Transonic Tunnel that are used to vary mass flow and set nozzle pressure to the exhaust nozzles. One valve regulates pressure in the air line and the other is used as a throttling valve. The pressure fluctuations were caused by the pressure-regulating valve in the air system and subsequent operator problems associated with trying to set nozzle pressure ratio when these fluctuations occurred. In the past, this system has proven to be very successful in providing a very stable source of air to the exhaust nozzles. Unfortunately, repairs to the pressure-regulating valve could not be made in a timely manner and a decision was made to continue the test. After the test was completed, all discharge coefficient measurements for each of the nozzles were carefully examined. Any data point that had a value of discharge coefficient that was ±0.015 different from the average was deleted from the data listing for the particular nozzle in question. Thus, the force data listings will not contain as many data points as the experimental pressure data listings. These pressure fluctuations should have no effect on the external pressure measurements.
Discussion of Results

Basic Nozzle Aeropropulsive Performance

Typical nozzle aeropropulsive characteristics for nozzle N1 are presented as a function of nozzle pressure ratio, NPR, for each of the Mach numbers tested in figure 14. Figure 14(a) presents the aeropropulsive parameter \((F-D_n)/F_i\) and nozzle discharge coefficient \(w_p/w_i\). As expected because of increased drag, the aeropropulsive parameter decreases with increasing Mach number. Nozzle discharge coefficient is a measure of the ability of the nozzle to pass mass flow and is reduced from a theoretical value of 1.0 by boundary-layer thickness and non-uniform flow at the nozzle throat. Since nozzle discharge coefficient is a function only of internal nozzle geometry, it is independent of both Mach number and nozzle pressure ratio when the nozzle is choked. In addition, changes in nozzle geometry that occur downstream of the nozzle throat (supersonic exhaust) usually do not affect nozzle discharge coefficient characteristics. Thrust minus nozzle drag coefficient \(C_{(F-D_n)}\) and nozzle drag coefficient \(C_{D,n}\) determined from the force balance measurements are present in figure 14(b). In general, the variation of nozzle drag coefficient with nozzle pressure ratio for a particular nozzle is similar to that of axisymmetric nozzles particularly at zero degrees angle of attack. Nozzle drag decreases with initial jet operation because there is a reduction in the external flow expansion required at the nozzle exit as the exhaust flow fills the nozzle base region. This reduced expansion generally results in higher pressures on the nozzle boattail regions. Figure 14(c) presents the pressure integrated nozzle flap drag \(C_{D,p,f}\), sidewall drag \(C_{D,p,s}\), and total pressure drag \(C_{D,p}\). Measured nozzle drag coefficient \(C_{D,n}\), nozzle pressure drag plus estimated friction drag coefficient \(C_{D,pf}\), and incremental drag coefficient \(DC_D\) are shown in figure 14(d). Ideally, the incremental drag coefficient should be equal to zero. However, the greatest differences seen are at jet-off conditions (NPR ~ 1.0) and result because of inaccuracies in measuring jet-off drag with the force balance. Typically, measured jet-off drag is about 2 to 3 percent of the maximum rated balance axial force where the balance has been sized to measure thrust.

Similar results for the other 13 nozzles that were tested as part of this investigation can be found in the Appendix D.

Experimental/Prediction Comparisons

Nozzle N1. A comparison between experimental and predicted pressures on flap F1 for nozzle N1 are presented in figure 15 at Mach numbers of 0.90 and 1.20 at the design nozzle pressure ratio of 5.0. At the design pressure ratio, the flow is expected to be fully expanded and peak nozzle internal performance usually occurs. The boattail radius of curvature parameter \(r/ r_{f,max}\) was 0.40 for this flap and the sidewall was S1. Pressure distributions are compared along the flap centerline, at the flap mid station, and at the flap outboard station. At \(M = 0.90\), the CFD computations tend to overpredict the expansion about the shoulder of the flap but do accurately predict the pressure recovery along the flap. Data indicates excellent agreement between predicted and experimental pressure data at \(M = 1.20\) at NPR = 5. In addition, the pressure distributions across the flap are nearly identical, indicating that nearly uniform flow exists across the flap. The full height sidewalls tend to act like fences in inhibiting any communication between the sidewall and flap flows. The effects of reducing sidewall height will be discussed later in this section of the report.
The experimental and predicted nozzle pressure drag coefficients are presented in figure 16 for nozzle N1 at NPR = 5.0. Shown in this figure are the flap, sidewall, and nozzle pressure drag coefficient values where nozzle pressure drag coefficient is simply the sum of the sidewall and flap pressure drag coefficient values. As would be expected from the excellent correlation of pressures, the predicted drag coefficient values are in excellent agreement with experimental drag coefficient values at $M = 0.9$ and within 0.3 of a drag count (one drag count equals 0.0001 drag coefficient) of the experimental drag coefficient value at $M = 1.2$.

A comparison of experimental and predicted nozzle total drag coefficients is also presented in figure 16 where the total drag coefficient includes skin friction. Skin friction drag coefficient for the prediction is computed within the performance module of the PAB3D code. The skin friction drag coefficient $C_{Df}$ is determined using the Frankl-Voishel skin friction coefficient as part of the wind tunnel standard data reduction system (ref. 9). The measured drag coefficient is obtained from the force data measurements. As was the case for the pressure drag coefficients, excellent agreement exits. The total drag coefficients agree to within one-half drag count (0.00005) at $M = 0.90$ and one drag count (0.0001) at $M = 1.20$.

**Nozzle N3.** Experimental and predicted pressure distribution comparisons for nozzle N3 are shown in figure 17. The boattail radius of curvature parameter was 0 for this flap, which meant it had a sharp corner at the start of the boattail. As can be seen, the agreement between the experimental and predicted pressures was not as good as was the case for nozzle N1 at $M = 0.90$. Consequently, there is a poorer correlation of flap pressure drag coefficient and nozzle total drag coefficient values (fig. 18). PAB3D predicts more flow expansion around the sharp corner than experimental data, which results in higher predicted drag. Another possible reason for this poor agreement of predicted and experimental data at $M = 0.90$ may be associated with treatment of the corner flow. Treatment of the corner flow is critical computationally at speeds less than Mach number 1. However, at $M = 1.20$, where geometrically matching the corner is not as important, agreement between the experimental and predicted pressures was similar to nozzle N1.

**Effect of Nozzle Boattail Curvature**

The effects of varying nozzle flap boattail radius of curvature on nozzle, flap, and sidewall pressure drag coefficient values are presented in figure 19 at the design nozzle pressure ratio of 5.0. These nozzles all had the baseline flap length $L_f/h_m = 1.4$ and were tested with sidewall S1. Although discussion of results at this pressure ratio would generally be applicable to other pressure ratios, the relative difference between comparisons may vary. Similar results at the scheduled nozzle pressure ratio can be found in Appendix F. Figure 19 also illustrates the typical breakdown of pressure drag between the nozzle flaps and the sidewalls. Generally, varying flap geometry had little or no effect on sidewall pressure drag. The breakdown of the pressure drag coefficient values is similar for the other nozzle configurations tested.

The lowest nozzle pressure drag was obtained on nozzle N3 with flap F3 that had no radius of curvature (fig. 19). This was an unexpected result because previous experience has shown that axisymmetric nozzles with a sharp shoulder generally have higher drag (ref. 8). Similar results were found for 2-D C-D nozzles in reference 22 and 23. However, these nozzles generally had shorter external flaps and because they were designed for use with subsonic cruise vehicles. In order to try to understand this result, one can examine the pressure distributions on these nozzles.

Pressure distributions along the centerline row of the top flap for nozzles N1, N2, N3, and N4 are presented at $M = 0.90$ and 1.20 at NPR = 5 in figure 20. What is shown is that even
though nozzle N3 with no curvature had the greatest expansion of flow about the nozzle shoulder, it exhibited more favorable pressure recovery characteristics when compared to the other three nozzles. Similar results were found for the pressure distributions along both the mid and outboard pressure rows (not shown).

The effects of varying nozzle flap boattail radius of curvature for nozzles with flap lengths of $L_f/h_m = 1.1$ are presented in figures 21 and 22. These nozzles were also tested with sidewall S1. Figure 21 shows flap pressure drag coefficient for the two nozzles tested with the smaller flap lengths. Except at $M = 1.20$, these two nozzles followed similar trends as the nozzles with the longer flap lengths. At $M = 0.90$ and 0.95, nozzle pressure drag decreased as the flap radius of curvature parameter was increased from 0.1 to 0.4.

**Effect of Nozzle Flap Length**

The effects of varying the nozzle flap length for flaps having a radius of curvature of 0.1 are shown in figures 23 and 24 and for those with a radius of curvature of 0.4 are illustrated in figures 25 and 26. Both nozzles (nozzles N13 and N14) with the shorter nozzle flap had higher total nozzle pressure drag at all the Mach numbers tested, except for N13 at $M = 1.20$. This was due primarily to these nozzles having steeper boattail angles than the nozzles with the longer flaps (nozzles N1 and N2). An examination of the pressure distributions in either figure 24 or 26 generally shows that the nozzles with the shorter flaps have poorer pressure recovery characteristics than those with the longer flaps. It is interesting to note that at $M = 0.80$ to 0.95, the increment in pressure drag due to the change in flap length is about the same for the nozzles having the two different radii of curvature.

Similar results at the scheduled nozzle pressure ratio can be found in Appendix F.

**Effect of Sidewall Boattail Angle**

The effects of varying sidewall boattail angle on nozzle, flap, and sidewall pressure drag coefficients are summarized in figure 27. There are no definite trends to changing sidewall boattail angle. For example, at $M = 0.80$ and 0.90, nozzle N6 with sidewall S3 having $\beta_S = 8^\circ$ had the lowest sidewall pressure drag coefficient whereas, just the opposite was true at $M = 1.20$. At $M = 0.90$ (fig. 28), it is interesting to note that although sidewall S3 exhibited greater expansion of the flow about the boattail than sidewall S1, it exhibited somewhat better recovery and lower pressure drag. Figure 28 also shows that the flow across the sidewall is somewhat non-uniform in nature since expansion outboard about the boattail is greater for all the sidewalls than at the center of the sidewall. However, flow recovers to about the same pressure coefficient levels at both locations.

At $M = 1.20$, sidewall pressure drag for nozzle N6 with sidewall S4 was doubled that of nozzle N1 with sidewall S1 as sidewall drag increased from .000017 to .000035 (fig. 27). Examination of the pressure distributions of figure 28 at this Mach number reveals markedly different flow characteristics across the sidewall. Along the center of the sidewall, the flow is rather benign and shows relatively little differences as $\beta_S$ increased from 4° to 6°. Outboard on the sidewall, there is a rapid expansion of the flow about the shoulder for each of the boattail angles tested. The data indicates possible flow separation for the sidewalls with 6° and 8° boattail angles. Although the full-scale nozzle was designed to have a sidewall with 4° boattail angle, it became evident as the HSR program progressed that sidewalls with boattail angles
greater than 4° would probably be needed for both structural requirements and to house nozzle actuation hardware. This could pose a problem at supersonic cruise where the potential now exists for greater values of sidewall pressure drag to occur because of sidewall boattail angles would be greater than 4°.

Only at \( M = 0.95 \), did changing boattail angle appreciably affect flap pressure drag (fig. 27). Flap pressure drag coefficient increased 0.00011 as boattail angle increased from 4° to 6°, which was twice as large as the increase in sidewall pressure drag. This is a somewhat surprising result in that one would not expect such a strong effect of varying sidewall geometry on flap performance. This is because the full height sidewalls tend to act like fences and isolate the sidewall flow from the flow over the flap.

Similar results at the scheduled nozzle pressure ratio can be found in Appendix F.

**Effect of Sidewall Boattail Curvature**

Several sidewalls were tested with varying amounts of curvature with both 6° and 8° sidewall boattail angles. Some typical results for nozzles N5, N7, and N9 with \( \beta_s = 6° \) are presented in figures 29 and 30 and for nozzles N6, N8, and N10 with \( \beta_s = 8° \) in figures 31 and 32. Sidewall pressure drag decreased by 0.00014 as the sidewall radius of curvature \( r_s / r_{s,max} \) was increased from 0 to 1.0 at \( M = 1.20 \). This could prove to be significant if sidewalls with boattail angles greater than 4° are needed as discussed previously. Sidewalls with full curvature would be feasible for the full-scale aircraft since the sidewalls would be fixed.

Similar results at the scheduled nozzle pressure ratio can be found in the Appendix F.

**Effect of Sidewall Height**

The height of the sidewall was fixed so that the nozzle internal flaps would not unport when the nozzle was in the supersonic cruise position. This type sidewall was selected to prevent impingement of any unwanted lateral nozzle exhaust on adjacent aircraft surfaces. As such, these sidewalls are very large panels that account for about 60-percent of the nozzle skin friction drag. Since these sidewalls could be also large unsupported panels, there could be an additional structural weight penalty associated with using them. To assess what drag penalties might occur with the full height sidewalls, some tests were performed with reduced height or cutback sidewalls. The height of the cutback sidewall S8 was contoured to match the external shape of flap F1. Sidewall S8 was then tested with flaps F1 and F2 to form nozzles N11 and N12 respectively (fig. 6).

Nozzle, flap and sidewall pressure drag coefficients for nozzle N1 and N11 are presented in figures 33. Significant reductions in both sidewall and flap pressure drag were obtained for the cutoff sidewall over the entire Mach number test range. For example, at \( M = 0.90 \), there was a 0.00012 reduction in nozzle pressure drag coefficient \( C_{D,p} \) and a 0.00023 reduction in \( C_{D,p} \) at \( M = 1.20 \). This drag reduction for the cutoff sidewall would be equivalent to at least a 0.00092 reduction in drag coefficient for the HSCT vehicle with four engines. This does not include an additional, albeit small reduction in skin-friction drag.

The flow characteristics over the nozzle flap are different for the two sidewalls as shown in figure 34. With the reduced height sidewall, the flow along the sidewall tends to accelerate around the corner onto the flap where it can become three-dimensional. The full height sidewalls
tend to act like fences that inhibit communication between the sidewall and flap flows, which results in the flow over the flap being more uniform. This is typical flow behavior for nozzles similar to nozzle N11, which has been found both experimentally (refs. 5 and 23) and computationally (ref. 24).

Similar results were also obtained for nozzle N12; however, the reduction in pressure drag was smaller than that noted for nozzle N11. (See figures 35 and 36.) Similar results at the scheduled nozzle pressure ratio can be found in Appendix F.

Conclusions

An experimental and computational investigation has been conducted to determine the off-design uninstalled drag characteristics of a two-dimensional convergent-divergent nozzle designed for a supersonic cruise civil transport. The overall objectives were to: (1) determine the effects of nozzle external flap curvature and sidewall boattail variations; (2) develop an experimental data base for 2D nozzles with long divergent flaps and small boattail angles and (3) provide data for correlating computational predictions of nozzle boattail drag. The experimental investigation was conducted in the Langley 16-Foot Transonic Tunnel at Mach numbers from 0.80 to 1.20 at nozzle pressure ratios up to 9. Three-dimensional simulations of nozzle performance were obtained with the computational fluid dynamics code PAB3D using turbulence closure and nonlinear Reynolds stress modeling. Based on the discussion of results in this paper, the following conclusions are made:

1. Excellent correlation between experimental and CFD results were obtained for the nozzle with an external flap having a moderate amount of boattail curvature at the shoulder at all Mach numbers tested. At a Mach number of 1.20, agreement between the experimental and predicted pressures was excellent for the nozzle having a sharp corner on the external flap.

2. The nozzle with an external flap having a sharp shoulder (no curvature) had the lowest nozzle pressure drag. Even though this nozzle had the greatest expansion of flow about the nozzle shoulder, it exhibited more favorable pressure recovery characteristics when compared to the other three nozzles tested.

3. At a Mach number of 1.2, sidewall pressure drag doubled as sidewall boattail angle was increased from 4° to 8°.

4. Reducing the height of the sidewall caused large decreases in both the sidewall and flap pressure drags.

NASA Langley Research Center
Hampton, VA 23681-2199
July 2015
Appendix A

Flap and Sidewall External Coordinates and Location of Pressure Orifices

This appendix presents the external coordinates of both the nozzle flaps and sidewalls. After installation, the locations of each pressure tap on all flaps and sidewalls were determined from actual measurements and are accurate to within ±0.005 inches. External coordinates for each nozzle flap and sidewall are presented in figures 37 to 50 as follows:

<table>
<thead>
<tr>
<th>Flap or Sidewall</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap F1</td>
<td>37</td>
</tr>
<tr>
<td>Flap F2</td>
<td>38</td>
</tr>
<tr>
<td>Flap F3</td>
<td>39</td>
</tr>
<tr>
<td>Flap F4</td>
<td>40</td>
</tr>
<tr>
<td>Flap F5</td>
<td>41</td>
</tr>
<tr>
<td>Flap F6</td>
<td>42</td>
</tr>
<tr>
<td>Sidewall S1</td>
<td>43</td>
</tr>
<tr>
<td>Sidewall S2</td>
<td>44</td>
</tr>
<tr>
<td>Sidewall S3</td>
<td>45</td>
</tr>
<tr>
<td>Sidewall S4</td>
<td>46</td>
</tr>
<tr>
<td>Sidewall S5</td>
<td>47</td>
</tr>
<tr>
<td>Sidewall S6</td>
<td>48</td>
</tr>
<tr>
<td>Sidewall S7</td>
<td>49</td>
</tr>
<tr>
<td>Sidewall S8</td>
<td>50</td>
</tr>
</tbody>
</table>
Appendix B

Data Repeatability

This Appendix presents the repeat data from this investigation in figures 51 to 56 as follows:

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>Aeropropulsive performance data, nozzle N1</td>
</tr>
<tr>
<td>52</td>
<td>External pressure data, N1</td>
</tr>
<tr>
<td>53</td>
<td>Aeropropulsive performance data, nozzle N6</td>
</tr>
<tr>
<td>54</td>
<td>External pressure data, N6</td>
</tr>
<tr>
<td>55</td>
<td>Aeropropulsive performance data, nozzle N11</td>
</tr>
<tr>
<td>56</td>
<td>External pressure data, N11</td>
</tr>
</tbody>
</table>
Appendix C

Static Data

This appendix presents the static data for each nozzle as a function of nozzle pressure ratio, NPR. Included in each figure are the static performance parameter $F/F_i$ and nozzle discharge coefficient $w_p/w_i$. The static data are presented in figures 57 to 70 as follows:

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Figure</th>
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</thead>
<tbody>
<tr>
<td>N1</td>
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<td>N2</td>
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<td>N3</td>
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<td>N6</td>
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<td>N10</td>
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<td>N11</td>
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</tr>
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<td>N12</td>
<td>68</td>
</tr>
<tr>
<td>N13</td>
<td>69</td>
</tr>
<tr>
<td>N14</td>
<td>70</td>
</tr>
</tbody>
</table>
Appendix D

Aeropropulsive Performance Data

This Appendix presents the basic nozzle performance parameters for each nozzle as a function of nozzle pressure ratio, NPR, for each of the Mach numbers tested. Included in each figure are: (a) the aeropropulsive parameter \((F-D_n)/F_i\) and nozzle discharge coefficient \(w_p/w_i\); (b) thrust minus nozzle drag coefficient \(C_{(F-D_n)}\) and measured nozzle drag coefficient \(C_{D,n}\); (c) nozzle pressure drag coefficient \(C_{D,p}\), flap pressure drag coefficient \(C_{D,p,f}\), and sidewall pressure drag coefficient \(C_{D,p,s}\); and (d) nozzle pressure drag plus nozzle friction drag coefficient \(C_{D,pf}\), and incremental drag coefficient \(\Delta C_D\). The aeropropulsive performance data are presented in figures 71 to 84 as follows:

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
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<td>72</td>
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<td>N3</td>
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<td>N4</td>
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<td>N5</td>
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<td>N6</td>
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<td>N7</td>
<td>77</td>
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<td>N8</td>
<td>78</td>
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<tr>
<td>N9</td>
<td>79</td>
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<tr>
<td>N10</td>
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<tr>
<td>N11</td>
<td>81</td>
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<td>N12</td>
<td>82</td>
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<td>N13</td>
<td>83</td>
</tr>
<tr>
<td>N14</td>
<td>84</td>
</tr>
</tbody>
</table>
Appendix E

Integrated Pressure Drag Data

This appendix presents the effects of varying nozzle geometric parameters on the nozzle integrated pressure drags as a function of NPR. Included on each figure is: (a) integrated nozzle pressure drag coefficient, $C_{D,p}$; (b) integrated nozzle pressure drag plus estimated friction drag coefficient, $C_{D,pf}$; and (c) integrated nozzle sidewall pressure drag coefficient (for both sidewalls) $C_{D,p,s}$. The integrated pressure drag coefficient data are presented in figures 85 to 93 as follows:

<table>
<thead>
<tr>
<th>Effect of:</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap radius of curvature for nozzles N1, N2, N3, N4 with $L_f/h_m = 1.4$</td>
<td>85</td>
</tr>
<tr>
<td>Flap radius of curvature for nozzles N13, N14 with $L_f/h_m = 1.1$</td>
<td>86</td>
</tr>
<tr>
<td>Flap length for nozzles N2, N14 with $r_f/r_{f,max} = 0.1$</td>
<td>87</td>
</tr>
<tr>
<td>Flap length for nozzles N1, N13 with $r_f/r_{f,max} = 0.4$</td>
<td>88</td>
</tr>
<tr>
<td>Sidewall boattail angle for nozzles N1, N5, N6</td>
<td>89</td>
</tr>
<tr>
<td>Sidewall radius of curvature for nozzles N5, N7, N9 with $\beta_s = 6°$</td>
<td>90</td>
</tr>
<tr>
<td>Sidewall radius of curvature for nozzles N6, N8, N10 with $\beta_s = 8°$</td>
<td>91</td>
</tr>
<tr>
<td>Reduced sidewall height for nozzles N1, N11</td>
<td>92</td>
</tr>
<tr>
<td>Reduced sidewall height for nozzles N2, N12</td>
<td>93</td>
</tr>
</tbody>
</table>
Appendix F

Integrated Pressure Drag At Scheduled NPR

This appendix presents the effects of varying nozzle geometric parameters on the nozzle integrated pressure drags at the scheduled NPR. Scheduled nozzle pressure ratio is the pressure ratio that the nozzle operates at for a particular Mach number and is dependent on the engine cycle design. Included on part one of each figure are: (a) integrated nozzle pressure drag coefficient, $C_{D_p}$; (b) integrated nozzle pressure drag plus estimated friction drag coefficient, $C_{D_{pf}}$; and (c) integrated nozzle sidewall pressure drag coefficient (for both sidewalls) $C_{D_{ps}}$. Another part of the figure presents the corresponding pressure data. The integrated pressure drag coefficient data at scheduled pressure ratio are presented in figures 94 to 111 as follows:

Figure

Effect of:

- Flap radius of curvature for nozzles N1, N2, N3, N4, pressure drag coefficients .......... 94
- Flap radius of curvature for nozzles N1, N2, N3, N4, pressure coefficients ................. 95
- Flap radius of curvature for nozzles N13, N14, pressure drag coefficients .................. 96
- Flap radius of curvature for nozzles N13, N14, pressure coefficients .......................... 97
- Flap length for nozzles N2, N14, pressure drag coefficients ..................................... 98
- Flap length for nozzles N2, N14, pressure coefficients .............................................. 99
- Flap length for nozzles N1, N13, pressure drag coefficients ........................................ 100
- Flap length for nozzles N1, N13, pressure coefficients ............................................... 101
- Sidewall boattail angle for nozzles N1, N5, N6, pressure drag coefficients .............. 102
- Sidewall boattail angle for nozzles N1, N5, N6, pressure coefficients ............................ 103
- Sidewall radius of curvature for nozzles N5, N7, N9, pressure drag coefficients ........ 104
- Sidewall radius of curvature for nozzles N5, N7, N9, pressure coefficients .................... 105
- Sidewall radius of curvature for nozzles N6, N8, N10, pressure drag coefficients ...... 106
- Sidewall radius of curvature for nozzles N6, N8, N10, pressure coefficients ............... 107
- Reduced sidewall height for nozzles N1, N11, pressure drag coefficients ..................... 108
- Reduced sidewall height for nozzles N1, N11, pressure coefficients ............................ 109
- Reduced sidewall height for nozzles N2, N12, pressure drag coefficients ..................... 110
- Reduced sidewall height for nozzles N2, N12, pressure coefficients ............................ 111
Appendix G

Jet Effects Drag Data

This Appendix presents the jet-effects parameter $\Delta C_{D,p}$ for each nozzle at both the design and scheduled pressure ratio NPR for each of the Mach numbers tested. The jet-effects parameter $\Delta C_{D,p}$ data are presented for each nozzle in figures 112 to 125 as follows:

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Figure</th>
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<tbody>
<tr>
<td>N1</td>
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<td>N2</td>
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</tr>
<tr>
<td>N3</td>
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<td>115</td>
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<td>N5</td>
<td>116</td>
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<td>N6</td>
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<td>N7</td>
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<td>N8</td>
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<tr>
<td>N9</td>
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<td>N10</td>
<td>121</td>
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<tr>
<td>N11</td>
<td>122</td>
</tr>
<tr>
<td>N12</td>
<td>123</td>
</tr>
<tr>
<td>N13</td>
<td>124</td>
</tr>
<tr>
<td>N14</td>
<td>125</td>
</tr>
</tbody>
</table>
Appendix H

External Pressure Distributions

This appendix presents the external pressure distributions for each nozzle. Pressure distributions measured along the top and bottom of the nozzle flaps as well as those on the nozzle sidewall are shown for each Mach number tested and are presented at four of the nozzle pressure ratios tested from jet-off (NPR = 1) to either NPR = 5 or 6.6 depending on Mach number in figures 126 to 139 as follows:

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
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<td>N2</td>
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<tr>
<td>N3</td>
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<td>N4</td>
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<td>N5</td>
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<td>N6</td>
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<td>N7</td>
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<td>N8</td>
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<tr>
<td>N9</td>
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<td>N10</td>
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<td>N11</td>
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<td>N12</td>
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<td>N13</td>
<td>138</td>
</tr>
<tr>
<td>N14</td>
<td>139</td>
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</table>
References


Table 1. Reference dimensions.

<table>
<thead>
<tr>
<th>Reference Area</th>
<th>$A_{ref}$</th>
<th>6824.407 in$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Chord</td>
<td>$c_{ref}$</td>
<td>84.337 in.</td>
</tr>
<tr>
<td>Reference Span</td>
<td>$b_{ref}$</td>
<td>125.030 in.</td>
</tr>
<tr>
<td>Moment Reference Center</td>
<td></td>
<td>MS 35.39 in.</td>
</tr>
<tr>
<td>Maximum model cross-sectional area</td>
<td>$A_{max}$</td>
<td>40.635 in$^2$</td>
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<tr>
<td>Metric Break Cavity Area</td>
<td>$A_i$</td>
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</tr>
<tr>
<td>Nominal nozzle exit area</td>
<td>$A_e$</td>
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</table>

### Measured Throat Areas

<table>
<thead>
<tr>
<th>Configuration N-1</th>
<th>$A_i$</th>
<th>11.118 in$^2$</th>
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</thead>
<tbody>
<tr>
<td>Configuration N-2</td>
<td>$A_i$</td>
<td>11.141 in$^2$</td>
</tr>
<tr>
<td>Configuration N-3</td>
<td>$A_i$</td>
<td>11.192 in$^2$</td>
</tr>
<tr>
<td>Configuration N-4</td>
<td>$A_i$</td>
<td>11.113 in$^2$</td>
</tr>
<tr>
<td>Configuration N-5</td>
<td>$A_i$</td>
<td>11.144 in$^2$</td>
</tr>
<tr>
<td>Configuration N-6</td>
<td>$A_i$</td>
<td>11.145 in$^2$</td>
</tr>
<tr>
<td>Configuration N-7</td>
<td>$A_i$</td>
<td>11.147 in$^2$</td>
</tr>
<tr>
<td>Configuration N-8</td>
<td>$A_i$</td>
<td>11.155 in$^2$</td>
</tr>
<tr>
<td>Configuration N-9</td>
<td>$A_i$</td>
<td>11.152 in$^2$</td>
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<td>Configuration N-10</td>
<td>$A_i$</td>
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<td>Configuration N-11</td>
<td>$A_i$</td>
<td>11.149 in$^2$</td>
</tr>
<tr>
<td>Configuration N-12</td>
<td>$A_i$</td>
<td>11.098 in$^2$</td>
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<tr>
<td>Configuration N-13</td>
<td>$A_i$</td>
<td>11.104 in$^2$</td>
</tr>
<tr>
<td>Configuration N-14</td>
<td>$A_i$</td>
<td>11.115 in$^2$</td>
</tr>
</tbody>
</table>
(a). Conceptual HSCT airplane.

(b). Comparison of full-scale nozzle to a man.

Figure 1. Conceptual full-scale HSCT airplane exhaust nozzles.
Supersonic Cruise ($M = 2.4$)

Subsonic Cruise ($M = 0.9$)

(c). Sketches of full-scale nozzle concept at three flight conditions.

Figure 1. Concluded
Figure 2. Overall nozzle geometry. All linear dimensions in inches.
Figure 3. Definition of nozzle flap geometric parameters. All linear dimensions in inches.
Figure 4. Definition of nozzle sidewall geometric parameters. All linear dimensions in inches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S1</th>
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<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_s$, deg</td>
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<td>6.0</td>
<td>8.0</td>
<td>6.0</td>
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<td>4.0</td>
</tr>
<tr>
<td>$r_s/r_s,\text{max}$</td>
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<td>0</td>
<td>0</td>
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<td>0.1</td>
<td>0.4</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>$L_{a,s}$, in.</td>
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<td>0</td>
<td>1.208</td>
<td>0.906</td>
<td>4.209</td>
<td>9.055</td>
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<tr>
<td>$z_{a,s}$, in.</td>
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<td>0.654</td>
<td>0.654</td>
<td>0.590</td>
<td>0.590</td>
<td>0.433</td>
<td>0.020</td>
<td>0.654</td>
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<tr>
<td>$z_e$, in.</td>
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<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.102</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>$r_{s,\text{max}}$, in.</td>
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<td>115.65</td>
<td>65.10</td>
<td>100.73</td>
<td>65.10</td>
<td>260.09</td>
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<tr>
<td>$r_s$, in.</td>
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<td>0</td>
<td>0</td>
<td>11.565</td>
<td>6.510</td>
<td>40.292</td>
<td>65.102</td>
<td>0</td>
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</tbody>
</table>
Figure 5. Summary of nozzle configurations tested.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Nozzle Flap</th>
<th>Nozzle Sidewall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flap</td>
<td>$r_f/r_{f,max}$</td>
</tr>
<tr>
<td>N3</td>
<td>F3</td>
<td>0</td>
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<tr>
<td>N2</td>
<td>F2</td>
<td>0.1</td>
</tr>
<tr>
<td>N1</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
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<td>F4</td>
<td>1.0</td>
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<td>N14</td>
<td>F6</td>
<td>0.1</td>
</tr>
<tr>
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<td>F5</td>
<td>0.4</td>
</tr>
<tr>
<td>N5</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N7</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N9</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N6</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N8</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N10</td>
<td>F1</td>
<td>0.4</td>
</tr>
<tr>
<td>N12</td>
<td>F2</td>
<td>0.1</td>
</tr>
<tr>
<td>N11</td>
<td>F1</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Figure 6. Sketches of nozzle configurations where the flap was varied.
Figure 7. Photographs of nozzles N1 and N11.

Nozzle N1    Nozzle N11
Figure 8. Sketches of nozzle configurations where sidewall was varied.
<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Flap</th>
<th>$L_f/h_m$</th>
<th>$r_f/r_f_{max}$</th>
<th>$\beta_f$ deg</th>
<th>Sidewall</th>
<th>$r_s/r_{s_{max}}$</th>
<th>$\beta_s$ deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
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</tr>
<tr>
<td>N2 F2</td>
<td>1.4</td>
<td>0.1</td>
<td>12.88</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
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<tr>
<td>N3 F3</td>
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<td>0.0</td>
<td>11.72</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
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<td>N4 F4</td>
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<td>1.0</td>
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<td>S1</td>
<td>0</td>
<td>4.0</td>
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<tr>
<td>N5 F1</td>
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<td>0.4</td>
<td>16.38</td>
<td>S2</td>
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<td>6.0</td>
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<td>N6 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S3</td>
<td>0</td>
<td>8.0</td>
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</tr>
<tr>
<td>N7 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S4</td>
<td>0.1</td>
<td>6.0</td>
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</tr>
<tr>
<td>N8 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S5</td>
<td>0.1</td>
<td>8.0</td>
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</tr>
<tr>
<td>N9 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S6</td>
<td>0.4</td>
<td>6.0</td>
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<td>0.4</td>
<td>16.38</td>
<td>S7</td>
<td>1.0</td>
<td>8.0</td>
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<tr>
<td>N11 F1</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S8</td>
<td>0</td>
<td>4.0</td>
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<tr>
<td>N12 F2</td>
<td>1.4</td>
<td>0.4</td>
<td>16.38</td>
<td>S8</td>
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<td>4.0</td>
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<td>N13 F6</td>
<td>1.1</td>
<td>0.1</td>
<td>15.97</td>
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<td>0</td>
<td>4.0</td>
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<tr>
<td>N14 F5</td>
<td>1.1</td>
<td>0.4</td>
<td>20.30</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9. Static performance characteristics for all nozzles.
Figure 10. Propulsion simulation system with typical nozzle configuration installed. All linear dimensions are given in inches.
Figure 11. Model with nozzle N1 installed in the 16-Foot Transonic Tunnel.
Figure 12. Short term repeatability for flap and sidewall pressure drag coefficients for nozzle N1, $M = 0.90$. 

\[ \Delta C_{D,p,f} \]
\[ C_{D,p,f} \]
\[ \Delta C_{D,p,s} \]
\[ C_{D,p,s} \]
Figure 13. Residual and drag coefficient convergence history for nozzle N3.
Figure 14. Aeropropulsive performance for nozzle N1 with flap F1 and sidewall S1.

\( \frac{r_f}{r_{f,\text{max}}} = 0.4; \quad \beta_f = 16.38^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad r_s / r_{s,\text{max}} = 0. \)
Figure 14. Continued.

(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 14. Continued.
Figure 14. Continued.

(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 14. Concluded.
Figure 15. Comparison of experimental to predicted flap pressures for nozzle N1. $r_f/r_{f,\text{max}} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4.$
Figure 16. Comparison of experimental to predicted nozzle drag coefficients for nozzle N1. $r_f/r_{f,\text{max}} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4; \text{NPR} = 5.0.$
Figure 17. Comparison of experimental and predicted flap pressures for nozzle N3. $r_{f}/r_{f,\text{max}} = 0$; $\beta_{f} = 11.72^\circ$; $L_{f}/h_{m} = 1.4$. 

$M = 0.90$, NPR = 5

$M = 1.20$, NPR = 5
Figure 18. Comparison of experimental to predicted nozzle drag coefficients for nozzle N3. $r_f/r_{f,max} = 0$; $\beta_f = 11.72^\circ$; $L_f/h_m = 1.4$; NPR = 5.0.
Figure 19. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1 at design NPR.
Figure 20. Effect of flap radius of curvature on upper flap pressure distributions for nozzles with sidewall S1 at design NPR.
Figure 21. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1 at design NPR.
Figure 22. Effect of flap radius of curvature on upper flap pressure distributions for nozzles with sidewall S1 at design NPR.
Figure 23. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1 at design NPR.
Figure 24. Effect of flap length on upper flap pressure distributions for nozzles with sidewall S1 at design NPR.
Figure 25. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1 at design NPR.
Figure 26. Effect of flap length on upper flap pressure distributions for nozzles with sidewall S1 at design NPR.
Figure 27. Effect of sidewall boattail angle on pressure drag coefficients for nozzles with flap F1 at design nozzle pressure ratio.
Figure 28. Effect of sidewall boattail angle on sidewall pressure distributions for nozzles with flap F1 at design NPR.
Figure 29. Effect of sidewall radius of curvature and base on pressure drag coefficients for nozzles with flap F1 at design NPR.
Figure 30. Effect of sidewall radius of curvature and base on sidewall pressure distributions for nozzles with flap F1 at design NPR.
Figure 31. Effect of sidewall radius of curvature on pressure drag coefficients for nozzles with flap F1 at design NPR.
Figure 32. Effect of sidewall radius of curvature on sidewall pressure distributions for nozzles with flap F1 at design NPR.
Figure 33. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F1 at design NPR.
(a) Flap pressure distributions.

Figure 34. Effect of reduced sidewall height on nozzle pressure distributions for nozzles with flap F1 at design NPR.
Figure 34. Concluded.
Figure 35. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F2 at design NPR.

<table>
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<th>Flap</th>
<th>$L_f/h_m$</th>
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$C_{D,p}$

$C_{D,pf}$

$C_{D,ps}$
Figure 36. Effect of reduced sidewall height on upper flap pressure distributions for nozzles with flap F2 at design NPR.
(b) Sidewall pressure distributions at design NPR.

Figure 36. Concluded.
Figure 37. Flap F1 external coordinates and location of pressure orifices.

| Top centerline  
| $z/w_f/2 = 0$ | Top outboard  
| $z/w_f/2 = 0.95$ | Bottom centerline  
| $z/w_f/2 = 0$ | Bottom middle  
| $z/w_f/2 = 0.5$ |
|---|---|---|---|
| $y/h_w/2$ | $x/L_m$ | orifice | $x/L_m$ | orifice | $x/L_m$ | orifice | $x/L_m$ | orifice |
| 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.000 | 0.231 | CPF26 | 0.231 | CPF1 | 0.225 | CPF51 | 0.226 | CPF76 |
| 1.000 | 0.296 | CPF27 | 0.295 | CPF2 | 0.288 | CPF52 | 0.289 | CPF77 |
| 1.000 | 0.327 | CPF28 | 0.327 | CPF3 | 0.322 | CPF53 | 0.322 | CPF78 |
| 1.000 | 0.359 | CPF29 | 0.359 | CPF4 | 0.354 | CPF54 | 0.353 | CPF79 |
| 1.000 | 0.366 | CPF30 | 0.366 | CPF5 | 0.361 | CPF55 | 0.360 | CPF80 |
| 1.000 | 0.375 | CPF31 | 0.376 | CPF6 | 0.370 | CPF56 | 0.370 | CPF81 |
| 0.998 | 0.391 | CPF32 | 0.391 | CPF7 | 0.386 | CPF57 | 0.385 | CPF82 |
| 0.993 | 0.423 | CPF33 | 0.423 | CPF8 | 0.418 | CPF58 | 0.418 | CPF83 |
| 0.985 | 0.456 | CPF34 | 0.456 | CPF9 | 0.450 | CPF59 | 0.451 | CPF84 |
| 0.973 | 0.488 | CPF35 | 0.488 | CPF10 | 0.483 | CPF60 | 0.483 | CPF85 |
| 0.958 | 0.520 | CPF36 | 0.520 | CPF11 | 0.515 | CPF61 | 0.514 | CPF86 |
| 0.939 | 0.552 | CPF37 | 0.552 | CPF12 | 0.546 | CPF62 | 0.548 | CPF87 |
| 0.918 | 0.584 | CPF38 | 0.585 | CPF13 | 0.580 | CPF63 | 0.580 | CPF88 |
| 0.892 | 0.616 | CPF39 | 0.616 | CPF14 | 0.612 | CPF64 | 0.611 | CPF89 |
| 0.863 | 0.648 | CPF40 | 0.648 | CPF15 | 0.644 | CPF65 | 0.643 | CPF90 |
| 0.831 | 0.680 | CPF41 | 0.680 | CPF16 | 0.676 | CPF66 | 0.676 | CPF91 |
| 0.795 | 0.712 | CPF42 | 0.712 | CPF17 | 0.709 | CPF67 | 0.709 | CPF92 |
| 0.755 | 0.744 | CPF43 | 0.743 | CPF18 | 0.742 | CPF68 | 0.741 | CPF93 |
| 0.716 | 0.775 | CPF44 | 0.775 | CPF19 | 0.773 | CPF69 | 0.774 | CPF94 |
| 0.675 | 0.808 | CPF45 | 0.807 | CPF20 | 0.806 | CPF70 | 0.806 | CPF95 |
| 0.634 | 0.841 | CPF46 | 0.839 | CPF21 | 0.839 | CPF71 | 0.838 | CPF96 |
| 0.595 | 0.872 | CPF47 | 0.872 | CPF22 | 0.872 | CPF72 | 0.871 | CPF97 |
| 0.556 | 0.904 | CPF48 | 0.903 | CPF23 | 0.905 | CPF73 | 0.902 | CPF98 |
| 0.516 | 0.936 | CPF49 | 0.936 | CPF24 | 0.938 | CPF74 | 0.935 | CPF99 |
| 0.476 | 0.968 | CPF50 | 0.968 | CPF25 | 0.969 | CPF75 | 0.964 | CPF100 |
| 0.436 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

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Figure 37. Flap F1 external coordinates and location of pressure orifices.
Figure 38. Flap F2 external coordinates and location of pressure orifices.
Figure 39. Flap F3 external coordinates and location of pressure orifices.
Figure 40. Flap F4 external coordinates and location of pressure orifices.
Figure 41. Flap F5 external coordinates and location of pressure orifices
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Figure 42. Flap F6 external coordinates and location of pressure orifices
Figure 43. Sidewall S1 external coordinates and location of pressure orifices
Figure 44. Sidewall S2 external coordinates and location of pressure orifices.
Figure 45. Sidewall S3 external coordinates and location of pressure orifices
Figure 46. Sidewall S4 external coordinates and location of pressure orifices

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Figure 47. Sidewall S5 external coordinates and location of pressure orifices

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Figure 48. Sidewall S6 external coordinates and location of pressure orifices
Figure 49. Sidewall S7 external coordinates and location of pressure orifices.

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Figure 50. Sidewall S8 external coordinates and location of pressure orifices.
Figure 51. Aeropropulsive performance data repeatability for nozzle N1.

(a) Variation of \( (F_{Dn})/F_i \) and \( w_p/w_i \).
Figure 51. Continued.

(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 51. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 51. Concluded.
Figure 52. Nozzle N1 pressure coefficient repeatability from different runs.
(b) Flap top outboard row, $z/w_f/2 = 0.95$

Figure 52. Continued.
(c) Flap bottom center row, \( z/w_f/2 = 0 \).

Figure 52. Continued.
(d) Flap bottom middle row, $z/w_f/2 = 5$.

Figure 52. Continued.
Figure 52. Continued.

(e) Sidewall center row, $y/h_{in}/2 = 0.$
(f) Sidewall outboard row, $y/h_m/2 = -0.87$. 

Figure 52. Concluded.

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Figure 53. Aeropropulsive performance data repeatability for nozzle N6.

(a) Variation of \((F-D_n)/F_i\) and \(w_p/w_i\).
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 53. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 53. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 53. Concluded.
Figure 54. Nozzle N6 pressure coefficient repeatability from different runs.

(a) Flap top center row, $z/w_f/2 = 0$. 
(b) Flap top outboard row, $z/w_f/2 = 0.95$

Figure 54. Continued.
(c) Flap bottom center row, $z/w_f/2 = 0$.

Figure 54. Continued.
(d) Flap bottom middle row, $z/w_f/2 = 5$.

Figure 54. Continued.
(e) Sidewall center row, $y/h_m/2 = 0$.

Figure 54. Continued.
(f) Sidewall outboard row, $y/h_m/2 = -0.87$.

Figure 54. Concluded.
Figure 55. Aeropropulsive performance data repeatability for nozzle N11.

(a) Variation of \( \frac{(F-D_n)}{F_i} \) and \( \frac{w_p}{w_i} \).
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 55. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.
\[ \Delta C_D = C_{D,n} - C_{D,pf} \]

(d) Variation of \( C_{D,n} \), \( C_{D,pf} \), and \( \Delta C_D \).

Figure 55. Concluded.
Figure 56. Nozzle N11 pressure coefficient repeatability from different runs.

(a) Flap top center row, z/wf/2 = 0.
(b) Flap top outboard row, $z/w_f/2 = 0.95$

Figure 56. Continued.

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(c) Flap bottom center row, $z/w_f/2 = 0$.  

Figure 56. Continued.
(d) Flap bottom middle row, $z/w_f/2 = 5$.

Figure 56. Continued.
Figure 56. Continued.

(e) Sidewall center row, \(y/h_w/2 = 0\).
(f) Sidewall outboard row, $y/h_m/2 = -0.87$. 

Figure 56. Concluded.
Figure 57. Static performance for Nozzle N1 with flap F1 and sidewall S1.  
\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \quad \beta_f = 16.38^\circ; \quad L_f/h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad \frac{r_s}{r_{s,\text{max}}} = 0. \]
Figure 58. Static performance for Nozzle N2 with flap F2 and sidewall S1.

\( r_f/r_{f,max} = 0.1; \ \beta_f = 12.88^\circ; \ L_f/h_m = 1.4; \ \beta_s = 4.0^\circ; \ r_s/r_{s,max} = 0. \)
Figure 59. Static performance for Nozzle N3 with flap F3 and sidewall S1.
\[ \frac{r_f}{r_{f,\text{max}}} = 0; \quad \beta_f = 11.72^\circ; \quad \frac{L_f}{h_m} = 1.4; \quad \beta_s = 4.0^\circ; \quad \frac{r_s}{r_{s,\text{max}}} = 0. \]
Figure 60. Static performance for Nozzle N4 with flap F4 and sidewall S1. 
\( r_f/r_{f,\text{max}} = 1.0; \ \beta_f = 23.44^\circ; \ L_f/h_{m} = 1.4; \ \beta_s = 4.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)
Figure 61. Static performance for Nozzle N5 with flap F1 and sidewall S2. 
\( r_f/r_{f,\text{max}} = 0.4; \ \beta_f = 16.38^\circ; \ L_f/h_m = 1.4; \ \beta_s = 6.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)
Figure 62. Static performance for Nozzle N6 with flap F1 and sidewall S3. 

\( \frac{r_f}{r_{f,\text{max}}} = 0.4; \ \beta_f = 16.38^\circ; \ \frac{L_f}{h_m} = 1.4; \ \beta_s = 8.0^\circ; \ \frac{r_s}{r_{s,\text{max}}} = 0. \)
Figure 63. Static performance for Nozzle N7 with flap F1 and sidewall S4. 
\(r_f/r_{f,max} = 0.4; \ \beta_f = 16.38^\circ; \ \frac{L_f}{h_m} = 1.4; \ \beta_s = 6.0^\circ; \ r_s/r_{s,max} = 0.1\).
Figure 64. Static performance for Nozzle N8 with flap F1 and sidewall S5.
\( r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4; \beta_s = 8.0^\circ; r_s/r_{s,max} = 0.1. \)
Figure 65. Static performance for Nozzle N9 with flap F1 and sidewall S6.

$\frac{r_f}{r_{f,\text{max}}}=0.4$; $\beta_f=16.38^\circ$; $L_f/h_m=1.4$; $\beta_s=6.0^\circ$; $\frac{r_s}{r_{s,\text{max}}}=0.4.$
Figure 66. Static performance for Nozzle N10 with flap F1 and sidewall S7.

\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \quad \beta_f = 16.38^\circ; \quad \frac{L_f}{h_m} = 1.4; \quad \beta_s = 8.0^\circ; \quad \frac{r_s}{r_{s,\text{max}}} = 1.0. \]
Figure 67. Static performance for Nozzle N11 with flap F1 and sidewall S8.  
$r_f/r_{f,max} = 0.4$;  $\beta_f = 16.38^\circ$;  $L_f/h_m = 1.4$;  $\beta_s = 0^\circ$;  $r_s/r_{s,max} = 0$.  

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Figure 68. Static performance for Nozzle N12 with flap F2 and sidewall S8.

\[ r_f / r_f,\text{max} = 0.1; \quad \beta_f = 12.88^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 0^\circ; \quad r_s / r_s,\text{max} = 0. \]
Figure 69. Static performance for Nozzle N13 with flap F5 and sidewall S1. $r_f/r_{f,\text{max}} = 0.4; \beta_f = 20.30^\circ; L_f/h_m = 1.1; \beta_s = 4.0^\circ; r_s/r_{s,\text{max}} = 0.$
Figure 70. Static performance for Nozzle N14 with flap F6 and sidewall S1.

\( r_f/r_{f,\text{max}} = 0.1; \ \beta_f = 15.97^\circ; \ L_f/h_m = 1.1; \ \beta_s = 4.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)
Figure 71. Aeropropulsive performance for nozzle N1 with flap F1 and sidewall S1. 
\( r_f/r_{f,max} = 0.4; \ \beta_f = 16.38^\circ; \ L_f/h_m = 1.4; \ \beta_s = 4.0^\circ; \ r_s/r_{s,max} = 0. \)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 71. Continued.
Figure 71. Continued.

(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.
Figure 71. Concluded.

(d) Variation of \( C_{D,n}, C_{D,pf}, \) and \( \Delta C_D \).
(a) Variation of \((F-D_n)/F_i\) and \(w_p/w_i\).

Figure 72. Aeropropulsive performance for nozzle N2 with flap F2 and sidewall S1.

\(r_f/r_{f,max} = 0.1; \quad \beta_f = 12.88^\circ; \quad L_f/h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad r_s/r_{s,max} = 0.\)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 72. Continued.
Figure 72. Continued.

(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

$C_{D,p} = C_{D,p,f} + C_{D,p,s}$
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 72. Concluded.
Figure 73. Aeropropulsive performance for nozzle N3 with flap F3 and sidewall S1.

\[ \frac{(F-D_n)}{F_i} \]

\[ \frac{w_p}{w_i} \]

(a) Variation of \( \frac{(F-D_n)}{F_i} \) and \( \frac{w_p}{w_i} \).

Figure 73. Aeropropulsive performance for nozzle N3 with flap F3 and sidewall S1.

\[ \frac{r_f}{r_{f,\text{max}}} = 0; \quad \beta_f = 11.72^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad \frac{r_s}{r_{s,\text{max}}} = 0. \]
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 73. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 73. Continued.
Figure 73. Concluded.

(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 73. Concluded.
Figure 74. Aeropropulsive performance for nozzle N4 with flap F4 and sidewall S1.

\[ \frac{F-D_n}{F_i} \quad \text{and} \quad \frac{w_p}{w_i}. \]

(a) Variation of \( \frac{F-D_n}{F_i} \) and \( \frac{w_p}{w_i} \).

\( r_f/r_{f,\text{max}} = 1.0; \ \beta_f = 23.44^\circ; \ L_f/h_m = 1.4; \ \beta_s = 4.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 74. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 74. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 74. Concluded.
(a) Variation of $(F-D_n)/F_i$ and $w_p/w_i$.

Figure 75. Aeropropulsive performance for nozzle N5 with flap F1 and sidewall S2.

$r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4; \beta_s = 6.0^\circ; r_s/r_{s,max} = 0.$
Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 75. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 75. Continued.
Figure 75. Concluded.

(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$. 

Figure 75. Concluded.
Figure 76. Aeropropulsive performance for nozzle N6 with flap F1 and sidewall S3. $r_f/r_{f,max} = 0.4$; $\beta_f = 16.38^\circ$; $L_f/h_m = 1.4$; $\beta_s = 8.0^\circ$; $r_s/r_{s,max} = 0$. 

(a) Variation of $(F_D_n)/F_i$ and $w_p/w_i$. 

NPR
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 76. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 76. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 76. Concluded.
Figure 77. Aeropropulsive performance for nozzle N7 with flap F1 and sidewall S4.

\[ \frac{(F-D_n)}{F_i} \]

\[ \frac{w_p}{w_i} \]

(a) Variation of \( \frac{(F-D_n)}{F_i} \) and \( \frac{w_p}{w_i} \).

Figure 77. Aeropropulsive performance for nozzle N7 with flap F1 and sidewall S4.

\[ r_f/r_{f,max} = 0.4; \quad \beta_f = 16.38^\circ; \quad L_f/l_m = 1.4; \quad \beta_s = 6.0^\circ; \quad r_s/r_{s,max} = 0.1. \]
Figure 77. Continued.

(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.
Figure 77. Continued.

(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 77. Continued.
(d) Variation of $C_{D,n}$, $C_{D,\text{pf}}$, and $\Delta C_D$.

Figure 77. Concluded.
Figure 78. Aeropropulsive performance for nozzle N8 with flap F1 and sidewall S5.

(a) Variation of \( (F-D_n)/F_i \) and \( w_p/w_i \).

\( r_f/r_{f,max} = 0.4; \ \beta_f = 16.38^\circ; \ \text{L}_f/h_m = 1.4; \ \beta_s = 8.0^\circ; \ r_s/r_{s,max} = 0.1. \)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 78. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 78. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$. 

Figure 78. Concluded.
Figure 79. Aeropropulsive performance for nozzle N9 with flap F1 and sidewall S6.

\[ \frac{(F-D_n)}{F_i} \] and \[ \frac{w_p}{w_i} \].

- \( M \) values: circles: 0.80; squares: 0.90; diamonds: 0.95; triangles: 1.20.
- \( r_f/r_{f,\text{max}} = 0.4 \);
- \( \beta_f = 16.38^\circ \);
- \( L_f/h_m = 1.4 \);
- \( \beta_s = 6.0^\circ \);
- \( r_s/r_{s,\text{max}} = 0.4 \).
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 79. Continued.
\( C_{D,p} = C_{D,p,f} + C_{D,p,s} \)

Figure 79. Continued.

(c) Variation of \( C_{D,p} \), \( C_{D,p,f} \), and \( C_{D,p,s} \).
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 79. Concluded.
Figure 80. Aeropropulsive performance for nozzle N10 with flap F1 and sidewall S7.

\( r_{f}/r_{f,\text{max}} = 0.4; \quad \beta_{f} = 16.38^\circ; \quad L_{f}/L_{m} = 1.4; \quad \beta_{s} = 8.0^\circ; \quad r_{s}/r_{s,\text{max}} = 1.0. \)

(a) Variation of \((F-D_{n})/F_{i}\) and \(w_{p}/w_{i}\).
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 80. Continued.
(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 80. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 80. Concluded.
Figure 81. Aeropropulsive performance for nozzle N11 with flap F1 and sidewall S8.

\( \frac{F-D_n}{F_i} \) \( \frac{w_p}{w_i} \)

(a) Variation of \( \frac{F-D_n}{F_i} \) and \( \frac{w_p}{w_i} \).

Figure 81. Aeropropulsive performance for nozzle N11 with flap F1 and sidewall S8.

\( r_f/r_{f,\text{max}} = 0.4; \) \( \beta_f = 16.38^\circ; \) \( L_f/h_m = 1.4; \) \( \beta_s = 4^\circ; \) \( r_s/r_{s,\text{max}} = 0. \)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 81. Continued.
Figure 81. Continued.

(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

$C_{D,p} = C_{D,p,f} + C_{D,p,s}$
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 81. Concluded.
Figure 82. Aeropropulsive performance for nozzle N12 with flap F2 and sidewall S8.

\[ r_f/r_{f,max} = 0.1; \beta_f = 12.88^\circ; L_f/h_m = 1.4; \beta_s = 4^\circ; r_s/r_{s,max} = 0. \]

(a) Variation of \((F-D_n)/F_i\) and \(w_p/w_i\).
Figure 82. Continued.

(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 82. Continued.
Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 82. Continued.
Figure 82. Concluded.

(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 82. Concluded.
(a) Variation of \((F-D_n)/F_i\) and \(w_p/w_i\).

Figure 83. Aeropropulsive performance for nozzle N13 with flap F5 and sidewall S1.

\(r_f/r_{f,\text{max}} = 0.4; \beta_f = 20.30^\circ; \; L_f/h_m = 1.1; \; \beta_s = 4.0^\circ; \; r_s/r_{s,\text{max}} = 0.\)
(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 83. Continued.

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(c) Variation of $C_{D,p}$, $C_{D,p,f}$, and $C_{D,p,s}$.

Figure 83. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 83. Concluded.
(a) Variation of \((F-D_n)/F_i\) and \(w_p/w_i\).

Figure 84. Aeropropulsive performance for nozzle N14 with flap F6 and sidewall S1.

\(r_f/r_{f,\text{max}} = 0.1; \quad \beta_f = 15.97^\circ; \quad L_f/h_m = 1.1; \quad \beta_s = 4.0^\circ; \quad r_s/r_{s,\text{max}} = 0.\)
Figure 84. Continued.

(b) Variation of $C_{(F-D_n)}$ and $C_{D,n}$.

Figure 84. Continued.
\( C_{D,p} = C_{D,p,f} + C_{D,p,s} \)

(c) Variation of \( C_{D,p} \), \( C_{D,p,f} \), and \( C_{D,p,s} \).

Figure 84. Continued.
(d) Variation of $C_{D,n}$, $C_{D,pf}$, and $\Delta C_D$.

Figure 84. Concluded.
Figure 85. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1. $\beta_s = 4.0^\circ$; $r_s/r_{s,\text{max}} = 0$.

(a) $M = 0.80$. 

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<td>N2</td>
<td>F2</td>
<td>0.1</td>
<td>12.88</td>
<td>1.4</td>
</tr>
<tr>
<td>N1</td>
<td>F1</td>
<td>0.4</td>
<td>16.38</td>
<td>1.4</td>
</tr>
<tr>
<td>N4</td>
<td>F4</td>
<td>1.0</td>
<td>23.48</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Figure 85. Continued.

(b) $M = 0.90$.  

Nozzle Flap $r_f/r_{f,max}$ $\beta_f$ deg $L_f/h_m$

- N3 F3 0 11.72 1.4
- N2 F2 0.1 12.88 1.4
- N1 F1 0.4 16.38 1.4
- N4 F4 1.0 23.48 1.4
Figure 85. Continued.

(c) $M = 0.95$. 

Figure 85. Continued.
(d) $M = 1.20$.

Figure 85. Concluded.
Figure 86. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1. $\beta_s = 4.0^\circ$; $r_s/r_{s,\text{max}} = 0$.

(a) $M = 0.80$. 

Table: 

<table>
<thead>
<tr>
<th>Nozzle Flap</th>
<th>$r_f/r_{f,\text{max}}$</th>
<th>$\beta_f$, deg</th>
<th>$L_f/h_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N14, F6</td>
<td>0.1</td>
<td>15.97</td>
<td>1.1</td>
</tr>
<tr>
<td>N13, F5</td>
<td>0.4</td>
<td>20.30</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Figure 86. Continued.

(b) \( M = 0.90 \).

(b) \( M = 0.90 \).

Figure 86. Continued.
(c) $M = 0.95$.

Figure 86. Continued.
(d) $M = 1.20$.

Figure 86. Concluded.
Figure 87. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1. $\beta_s = 4.0^\circ; \ r_s/r_{s,max} = 0$.

(a) $M = 0.80$. 

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Flap</th>
<th>$L_f/h_m$</th>
<th>$\beta_f$ deg</th>
<th>$r_f/r_{f,max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>F2</td>
<td>1.4</td>
<td>12.88</td>
<td>0.1</td>
</tr>
<tr>
<td>N14</td>
<td>F6</td>
<td>1.1</td>
<td>15.97</td>
<td>0.1</td>
</tr>
</tbody>
</table>
(b) $M = 0.90$.

Figure 87. Continued.
Figure 87. Continued.

(c) $M = 0.95$. 

Figure 87. Continued.
Figure 87. Concluded.

(d) $M = 1.20$. 

Figure 87. Concluded.
Figure 88. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1. $\beta_s = 4.0^\circ$; $r_s/r_{s,max} = 0$.

(a) $M = 0.80$. 

Nozzle Flap $L_f/h_m$ $\beta_f$, deg $r_f/r_{f,max}$

- N1 F1 1.4 16.38 0.4
- N13 F5 1.1 20.30 0.4
Figure 88. Continued.

(b) $M = 0.90$. 

Figure 88. Continued.
(c) $M = 0.95$.

Figure 88. Continued.
(d) $M = 1.20$.

Figure 88. Concluded.
Figure 89. Effect of sidewall boattail angle on pressure drag coefficients for nozzles with flap F1. \( r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4. \)
Figure 89. Continued.

(b) $M = 0.90$. 

205
Figure 89. Continued.

(c) $M = 0.95$.  

206
Figure 89. Concluded.

(d) $M = 1.20$. 

Figure 89. Concluded.
Figure 90. Effect of sidewall radius of curvature on pressure drag coefficients for nozzles with flap F1. $r_f/r_{f,max} = 0.4$; $\beta_f = 16.38^\circ$; $L_f/h_m = 1.4$.
Figure 90. Continued.

(b) $M = 0.90$.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Sidewall</th>
<th>$r_s/r_{s,max}$</th>
<th>$\beta_s$ deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N5</td>
<td>S2</td>
<td>0</td>
<td>6.0</td>
</tr>
<tr>
<td>N7</td>
<td>S4</td>
<td>0.1</td>
<td>6.0</td>
</tr>
<tr>
<td>N9</td>
<td>S6</td>
<td>0.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Figure 90. Continued.

(c) $M = 0.95$. 

Figure 90. Continued.

210
Figure 90. Concluded.

(d) \( M = 1.20 \).

Figure 90. Concluded.
Figure 91. Effect of sidewall radius of curvature on pressure drag coefficients for nozzles with flap F1. \( r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4. \)
Figure 91. Continued.

(b) $M = 0.90$. 

Figure 91. Continued.
Figure 91. Continued.

(c) $M = 0.95$.

Figure 91. Continued.
(d) $M = 1.20$.

Figure 91. Concluded.
Figure 92. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F1. \( r_{f}/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4. \)

(a) \( M = 0.80. \)
Figure 92. Continued.

(b) $M = 0.90$.

217
Figure 92. Continued.

(c) $M = 0.95$.  

218
(d) $M = 1.20$.

Figure 92. Concluded.
Figure 93. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F2. $r_f/r_{f,max} = 0.1$; $\beta_f = 12.88^\circ$; $L_f/h_m = 1.4$.

(a) $M = 0.80$. 
Figure 93. Continued.

(b) $M = 0.90$.

Figure 93. Continued.
Figure 93. Continued.

(c) $M = 0.95$.

Figure 93. Continued.
Figure 93. Concluded.

\[ C_{D,p}, C_{D,p,f}, C_{D,p,s} \]

(d) \( M = 1.20 \).
Figure 94. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1 at scheduled NPR.
Figure 95. Effect of flap radius of curvature on upper flap pressure distributions for nozzles with sidewall S1 at scheduled NPR.
Figure 96. Effect of flap radius of curvature on pressure drag coefficients for nozzles with sidewall S1 at scheduled NPR.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Flap</th>
<th>$r_f/r_{f,max}$</th>
<th>$\beta_f$, deg</th>
<th>$L_f/h_m$</th>
<th>Sidewall</th>
<th>$r_s/r_{s,max}$</th>
<th>$\beta_s$, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N14</td>
<td>F6</td>
<td>0</td>
<td>15.97</td>
<td>1.4</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td>N13</td>
<td>F5</td>
<td>0.1</td>
<td>20.30</td>
<td>1.4</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Figure 97. Effect of flap radius of curvature on upper flap pressure distributions for nozzles with sidewall S1 at scheduled NPR.
Figure 98. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1 at scheduled pressure.
<table>
<thead>
<tr>
<th>Nozzle Flap</th>
<th>L_f/h_m</th>
<th>β_f, deg</th>
<th>r_f/r_f,max</th>
<th>Sidewall</th>
<th>r_s/r_s,max</th>
<th>β_s, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2, F6</td>
<td>1.4</td>
<td>12.88</td>
<td>0.1</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Flap top center row, z/w_f/2 = 0

\[ M = 0.80, \text{NPR} = 3.54 \]

\[ M = 0.90, \text{NPR} = 3.54 \]

\[ M = 0.95, \text{NPR} = 3.52 \]

\[ M = 1.20, \text{NPR} = 6.64 \]

Flap top outboard row, z/w_f/2 = 0.95

\[ M = 0.80, \text{NPR} = 3.54 \]

\[ M = 0.90, \text{NPR} = 3.54 \]

\[ M = 0.95, \text{NPR} = 3.52 \]

\[ M = 1.20, \text{NPR} = 6.33 \]

Figure 99. Effect of flap length on upper flap pressure distributions for nozzles with sidewall S1 at scheduled NPR.
Figure 100. Effect of flap length on pressure drag coefficients for nozzles with sidewall S1 at scheduled pressure.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Flap</th>
<th>$r_f/r_{f,\text{max}}$</th>
<th>$\beta_f$, deg</th>
<th>$L_f/h_m$</th>
<th>Sidewall</th>
<th>$r_s/r_{s,\text{max}}$</th>
<th>$\beta_s$, deg</th>
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</thead>
<tbody>
<tr>
<td>N1</td>
<td>F1</td>
<td>0.4</td>
<td>16.38</td>
<td>1.4</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td>N13</td>
<td>F5</td>
<td>0.4</td>
<td>20.30</td>
<td>1.1</td>
<td>S1</td>
<td>0</td>
<td>4.0</td>
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<tr>
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<td></td>
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</tr>
</tbody>
</table>

$M = 0.80$ $\text{NPR} = 3.54$ $M = 0.90$ $\text{NPR} = 3.54$ $M = 0.95$ $\text{NPR} = 3.54$ $M = 1.20$ $\text{NPR} = 6.6$
Figure 101. Effect of flap length on upper flap pressure distributions for nozzles with sidewall S1 at scheduled NPR.
Figure 102. Effect of sidewall boattail angle on pressure drag coefficients for nozzles with flap F1 at scheduled pressure ratio.
Figure 103. Effect of sidewall boattail angle on sidewall pressure distributions for nozzles with flap F1 at scheduled NPR.
Figure 104. Effect of sidewall radius of curvature and base on pressure drag coefficients for nozzles with flap F1 at scheduled pressure ratio.
Figure 105. Effect of sidewall radius of curvature and base on sidewall pressure distributions for nozzles with flap F1 at scheduled NPR.
Figure 106. Effect of sidewall radius of curvature on pressure drag coefficients for nozzles with flap F1 at scheduled pressure ratio.
Figure 107. Effect of sidewall radius of curvature on sidewall pressure distributions for nozzles with flap F1 at scheduled NPR.
Figure 108. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F1 at scheduled pressure ratio.
Figure 109. Effect of reduced sidewall height on nozzle pressure distributions for nozzles with flap F1 at scheduled NPR.
Figure 110. Effect of reduced sidewall height on pressure drag coefficients for nozzles with flap F2 at scheduled pressure ratio.
Flap top center row, $z/w_f = 0$

$M = 0.80$, NPR = 3.53

$M = 0.90$, NPR = 3.54

$M = 0.95$, NPR = 3.54

$M = 1.20$, NPR = 6.67

Flap top outboard row, $z/w_f = 0.95$

$M = 0.80$, NPR = 3.53

$M = 0.90$, NPR = 3.54

$M = 0.95$, NPR = 3.54

$M = 1.20$, NPR = 6.67

Figure 111. Effect of reduced sidewall height on nozzle pressure distributions for nozzles with flap F2 at scheduled NPR.
Figure 112. Incremental nozzle pressure drag for nozzle N1 with flap F1 and sidewall S1.

\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \ \beta_f = 16.38^\circ; \ \frac{L_f}{h_m} = 1.4; \ \beta_s = 4.0^\circ; \ \frac{r_s}{r_{s,\text{max}}} = 0. \]
Figure 113. Incremental nozzle pressure drag for nozzle N2 with flap F2 and sidewall S1.

\[
\frac{r_f}{r_{f,\text{max}}} = 0.1; \beta_f = 12.88^\circ; L_f / h_m = 1.4; \beta_s = 4.0^\circ; \frac{r_s}{r_{s,\text{max}}} = 0.
\]
Figure 114. Incremental nozzle pressure drag for nozzle N3 with flap F3 and sidewall S1. 
$r_f / r_{f,\text{max}} = 0; \beta_f = 11.72^\circ; L_f / h_m = 1.4; \beta_s = 4.0^\circ; r_s / r_{s,\text{max}} = 0.$
Figure 115. Incremental nozzle pressure drag for nozzle N4 with flap F4 and sidewall S1.

\[ \Delta C_{D,p} = (C_{D,p})_{\text{NPR}} - (C_{D,p})_{\text{jet-off}} \]

\[ \frac{r_f}{r_{f,\text{max}}} = 1.0; \quad \beta_f = 23.44^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad \frac{r_s}{r_{s,\text{max}}} = 0. \]
Figure 116. Incremental nozzle pressure drag for nozzle N5 with flap F1 and sidewall S2.

\[ \Delta C_{D,p} = (C_{D,p})_{NPR} - (C_{D,p})_{jet-off} \]

\[ r_f / r_{f,\text{max}} = 0.4; \quad \beta_f = 16.38^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 6.0^\circ; \quad r_s / r_{s,\text{max}} = 0. \]
Figure 117. Incremental nozzle pressure drag for nozzle N6 with flap F1 and sidewall S3. 

\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \, \beta_f = 16.38^\circ; \, L_f/ h_m = 1.4; \, \beta_s = 8.0^\circ; \, \frac{r_s}{r_{s,\text{max}}} = 0. \]
Figure 118. Incremental nozzle pressure drag for nozzle N7 with flap F1 and sidewall S4.

\[ \Delta C_{D,p} = (C_{D,p})_{\text{NPR}} - (C_{D,p})_{\text{jet-off}} \]

- \( r_f / r_{f,\text{max}} = 0.4 \)
- \( \beta_f = 16.38^\circ \)
- \( L_f / h_m = 1.4 \)
- \( \beta_s = 6.0^\circ \)
- \( r_s / r_{s,\text{max}} = 0.1 \)
Figure 119. Incremental nozzle pressure drag for nozzle N8 with flap F1 and sidewall S5.

\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \beta_f = 16.38^\circ; \frac{L_f}{h_m} = 1.4; \beta_s = 8.0^\circ; \frac{r_s}{r_{s,\text{max}}} = 0.1. \]
Figure 120. Incremental nozzle pressure drag for nozzle N9 with flap F1 and sidewall S6.
\[ r_f / r_{f,\text{max}} = 0.4; \beta_f = 16.38^\circ; L_f / h_m = 1.4; \beta_s = 6.0^\circ; r_s / r_{s,\text{max}} = 0.4. \]
Figure 121. Incremental nozzle pressure drag for nozzle N10 with flap F1 and sidewall S7.

\[ \frac{r_f}{r_{f,\text{max}}} = 0.4; \beta_f = 16.38^\circ; L_f / h_m = 1.4; \beta_s = 8.0^\circ; \frac{r_s}{r_{s,\text{max}}} = 1.0. \]
Figure 122. Incremental nozzle pressure drag for nozzle N11 with flap F1 and sidewall S8.

\[ \Delta C_{D,p} = (C_{D,p})_{\text{NPR}} - (C_{D,p})_{\text{jet-off}} \]

- \( r_f / r_{f,\text{max}} = 0.4 \), \( \beta_f = 16.38^\circ \), \( L_f / h = 1.4 \), \( \beta_s = 4^\circ \), \( r_s / r_{s,\text{max}} = 1.0 \).
Figure 123. Incremental nozzle pressure drag for nozzle N12 with flap F2 and sidewall S8. 
\[ r_f/r_{f,max} = 0.1; \beta_f = 12.88^\circ; L_f/h_m = 1.4; \beta_s = 4^\circ; \ r_s/r_{s,max} = 1.0. \]
Figure 124. Incremental nozzle pressure drag for nozzle N13 with flap F5 and sidewall S1. 

\[ \Delta C_{D,p} = (C_{D,p})_{\text{NPR}} - (C_{D,p})_{\text{jet-off}} \]

\[ r_f / r_{f,max} = 0.4; \beta_f = 20.30^\circ; L_f / h_m = 1.1; \beta_s = 4^\circ; r_s / r_{s,max} = 1.0. \]
Figure 125. Incremental nozzle pressure drag for nozzle N14 with flap F6 and sidewall S1.

\[ \frac{r_f}{r_{f,\text{max}}} = 0.1; \beta_f = 15.97^\circ; L_f / h_m = 1.1; \beta_s = 4^\circ; r_s / r_{s,\text{max}} = 1.0. \]
Figure 126. External pressure distributions for nozzle N1 with flap F1 and sidewall S1.

\( r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4; \beta_s = 4.0^\circ; r_s/r_{s,max} = 0. \)

(a) \( M = 0.80. \)
Figure 126. Continued.

(b) $M = 0.90$. 

257
Figure 126. Continued.

(c) $M = 0.95$. 

258
(d) $M = 1.20$.

Figure 126. Concluded.
Figure 127. External pressure distributions for nozzle N2 with flap F2 and sidewall S1.

\( r_f/r_{f,\text{max}} = 0.1; \ \beta_f = 12.88^\circ; \ L_f/h_m = 1.4; \ \beta_s = 4.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)

(a) \( M = 0.80. \)
Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_y/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

NPR
- $\circ 1.05$
- $\square 2.48$
- $\Diamond 3.56$
- $\triangle 5.03$

(b) $M = 0.90$.

Figure 127. Continued.
Figure 127. Continued.

(c) $M = 0.95$. 
Figure 127. Concluded.
Figure 128. External pressure distributions for nozzle N3 with flap F3 and sidewall S1.

\( r_f/r_f_{\text{max}} = 0; \quad \beta_f = 11.72^\circ; \quad L_f/h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad r_s/r_{s,\text{max}} = 0. \)

(a) \( M = 0.80. \)
Flap top center row, \( z/w_f/2 = 0 \)

Flap top outboard row, \( z/w_f/2 = 0.95 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = 0.87 \)

\[ (b) \ M = 0.90. \]

Figure 128. Continued.
Flap top center row, $z/w_f/2 = 0$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Flap top outboard row, $z/w_f/2 = 0.95$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = 0.87$

(c) $M = 0.95$.

Figure 128. Continued.
(d) $M = 1.20$.

Figure 128. Concluded.
Figure 129. External pressure distributions for nozzle N4 with flap F4 and sidewall S1.

\( r_f / r_{f,\text{max}} = 1.0; \quad \beta_f = 23.44^\circ; \quad L_f / h_m = 1.4; \quad \beta_s = 4.0^\circ; \quad r_s / r_{s,\text{max}} = 0. \)
NPR

- 1.07
- 2.52
- 3.60
- 4.92

(b) $M = 0.90$.

Figure 129. Continued.
Figure 129. Continued.

(c) $M = 0.95$. 

270
Figure 129. Concluded.
Figure 130. External pressure distributions for nozzle N5 with flap F1 and sidewall S2.

- Flap top center row, \( z/w_f = 0 \)
- Flap top outboard row, \( z/w_f = 0.95 \)
- Flap bottom center row, \( z/w_f = 0 \)
- Flap bottom middle row, \( z/w_f = 0.5 \)
- Sidewall center row, \( y/h_m = 0 \)
- Sidewall outboard row, \( y/h_m = -0.87 \)

(a) \( M = 0.80 \).

\( r_f/r_{f,\text{max}} = 0.4; \ \beta_f = 16.38^\circ; \ L_f/h_m = 1.4; \ \beta_s = 6.0^\circ; \ r_s/r_{s,\text{max}} = 0. \)
NPR

- 1.08
- 2.49
- 3.55
- 5.01

Flap top center row, $z/w_f = 0$

Flap bottom center row, $z/w_f = 0$

Flap top outboard row, $z/w_f = 0.95$

Flap bottom middle row, $z/w_f = 0.5$

Sidewall center row, $y/h_m = 0$

Sidewall outboard row, $y/h_m = 0.87$

(b) $M = 0.90$

Figure 130. Continued.
Figure 130. Continued.

(c) $M = 0.95$. 
Figure 130. Concluded.
Figure 131. External pressure distributions for nozzle N6 with flap F1 and sidewall S3.

(a) $M = 0.80$. 

$r_f / r_{f,max} = 0.4; \ \beta_f = 16.38^\circ; \ L_f / h_m = 1.4; \ \beta_s = 8.0^\circ; \ r_s / r_{s,max} = 0.$
Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

(b) $M = 0.90$.

Figure 131. Continued.
Flap top center row, \( z/w_f/2 = 0 \)

Flap top outboard row, \( z/w_f/2 = 0.95 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(c) \( M = 0.95 \).

Figure 131. Continued.
Figure 131. Concluded.

(d) $M = 1.20.$
Figure 132. External pressure distributions for nozzle N7 with flap F1 and sidewall S4.

- Flap top center row, \( z/w_f/2 = 0 \)
- Flap top outboard row, \( z/w_f/2 = 0.95 \)
- Flap bottom center row, \( z/w_f/2 = 0 \)
- Flap bottom middle row, \( z/w_f/2 = 0.5 \)
- Sidewall center row, \( y/h_m/2 = 0 \)
- Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(a) \( M = 0.80 \).

\( r_f/r_{f,max} = 0.4; \beta_f = 16.38^\circ; \ L_f/h_m = 1.4; \beta_s = 6.0^\circ; \ r_s/r_{s,max} = 0.1. \)
Figure 132. Continued.

(b) $M = 0.90$. 

281
(c) $M = 0.95$.

Figure 132. Continued.
Figure 132. Concluded.
Figure 133. External pressure distributions for nozzle N8 with flap F1 and sidewall S5. 
\( r_f/r_{f,\text{max}} = 0.4; \ \beta_f = 16.38^\circ; \ \L_f/\h_m = 1.4; \ \beta_s = 8.0^\circ; \ r_s/r_{s,\text{max}} = 0.1. \)
Figure 133. Continued.

(b) $M = 0.90$. 

285
Figure 133. Continued.

Flap top center row, $z/w_f/2 = 0$

Flap bottom center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

(c) $M = 0.95$.
Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

(d) $M = 1.20.$

Figure 133. Concluded.
Figure 134. External pressure distributions for nozzle N9 with flap F1 and sidewall S6.

- \( r_f/r_{f,max} = 0.4; \) βₐₙ = 16.38°; \( L_f/h_m = 1.4; \) \( \beta_s = 6.0°; \) \( r_s/r_{s,max} = 0.4. \)
NPR
- ○ 1.07
- □ 2.49
- ◇ 3.57
- △ 4.99

Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

Figure 134. Continued.
Flap top center row, $z/w_f/2 = 0$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Flap top outboard row, $z/w_f/2 = 0.95$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row, $y/h_m/2 = -0.87$

(c) $M = 0.95$.  

Figure 134. Continued.
NPR

- 0.91
- 3.54
- 5.03
- 6.65

(d) $M = 1.20$.

Figure 134. Concluded.
Flap top center row, \( z/w_f/2 = 0 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap top outboard row, \( z/w_f/2 = 0.95 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(a) \( M = 0.80 \).

Figure 135. External pressure distributions for nozzle N10 with flap F1 and sidewall S7.

\[ r_f/r_{f,\text{max}} = 0.4; \beta_f = 16.38^\circ; L_f/h_m = 1.4; \beta_s = 8.0^\circ; r_s/r_{s,\text{max}} = 1.0. \]
(b) $M = 0.90$.

Figure 135. Continued.
Flap top center row, \( z/w_f/2 = 0 \)

Flap topoutboard row, \( z/w_f/2 = 0.95 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(c) \( M = 0.95 \).

Figure 135. Continued.

294
Flap top center row, $z/w_f/2 = 0$
Flap top outboard row, $z/w_f/2 = 0.95$
Flap bottom center row, $z/w_f/2 = 0$
Flap bottom middle row, $z/w_f/2 = 0.5$
Sidewall center row, $y/h_m/2 = 0$
Sidewall outboard row, $y/h_m/2 = -0.87$

(d) $M = 1.20$.

Figure 135. Concluded.
Figure 136. External pressure distributions for nozzle N11 with flap F1 and sidewall S8.

For the flap top center row, $z/w_{f}/2 = 0$.

For the flap top outboard row, $z/w_{f}/2 = 0.95$.

For the flap bottom center row, $z/w_{f}/2 = 0$.

For the flap bottom middle row, $z/w_{f}/2 = 0.5$.

For the sidewall center row, $y/h_{m}/2 = 0$.

For the sidewall outboard row.

(a) $M = 0.80$.

$\frac{r_{f}}{r_{f,max}} = 0.4$; $\beta_{f} = 16.38^\circ$; $L_{f}/h_{m} = 1.4$; $\beta_{s} = 4.0^\circ$; $r_{s}/r_{s,max} = 0$. 

296
Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row

(b) $M = 0.90$.

Figure 136. Continued.
Flap top center row, $z/w_f/2 = 0$

Flap top outboard row, $z/w_f/2 = 0.95$

Flap bottom center row, $z/w_f/2 = 0$

Flap bottom middle row, $z/w_f/2 = 0.5$

Sidewall center row, $y/h_m/2 = 0$

Sidewall outboard row

Figure 136. Continued.

(c) $M = 0.95$. 

298
Figure 136. Concluded.
Figure 137. External pressure distributions for nozzle N12 with flap F2 and sidewall S8.

- $r_f/r_{f,\text{max}} = 0.1$; $\beta_f = 12.88^\circ$; $L_f/h_m = 1.4$; $\beta_s = 4.0^\circ$; $r_s/r_{s,\text{max}} = 0$. 

(a) $M = 0.80$. 

NPR

- $\bigcirc$ 1.02
- $\square$ 2.01
- $\lozenge$ 3.54
- $\triangle$ 5.01
Figure 137. Continued.

(b) $M = 0.90$. 
Figure 137. Continued.

(c) $M = 0.95$. 

302
Figure 137. Concluded.
Figure 138. External pressure distributions for nozzle N13 with flap F5 and sidewall S1.

- $r_{f}/r_{f,max} = 0.4$;
- $\beta_f = 20.30^\circ$;
- $L_{f}/h_m = 1.1$;
- $\beta_s = 4.0^\circ$;
- $r_{s}/r_{s,max} = 0$.

(a) $M = 0.80$. 

NPR
- $1.05$
- $2.00$
- $3.53$
- $5.06$

304
(b) $M = 0.90$.

Figure 138. Continued.
(c) $M = 0.95$.

Figure 138. Continued.
Flap top center row, $z/w_f = 0$

Flap bottom center row, $z/w_f = 0$

Flap top outboard row, $z/w_f = 0.95$

Flap bottom middle row, $z/w_f = 0.5$

Sidewall center row, $y/h_m = 0$

Sidewall outboard row, $y/h_m = -0.87$

(d) $M = 1.20$.

Figure 138. Concluded.
Figure 139. External pressure distributions for nozzle N14 with flap F6 and sidewall S1.

(a) $M = 0.80$.

$r_{f}/r_{f,\text{max}} = 0.1$; $\beta_f = 15.97^\circ$; $L_f/h_m = 1.1$; $\beta_s = 4.0^\circ$; $r_s/r_{s,\text{max}} = 0$. 

308
Flap top center row, \( z/w_f/2 = 0 \)

Flap top outboard row, \( z/w_f/2 = 0.95 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(b) \( M = 0.90 \).

Figure 139. Continued.
Flap top center row, \( z/w_f/2 = 0 \)

Flap top outboard row, \( z/w_f/2 = 0.95 \)

Flap bottom center row, \( z/w_f/2 = 0 \)

Flap bottom middle row, \( z/w_f/2 = 0.5 \)

Sidewall center row, \( y/h_m/2 = 0 \)

Sidewall outboard row, \( y/h_m/2 = -0.87 \)

(c) \( M = 0.95 \).

Figure 139. Continued.
Figure 139. Concluded.
# Transonic Investigation of Two-Dimensional Nozzles Designed for Supersonic Cruise

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**Performing Organization Report Number:**
L-20167

**Availability:**
Unclassified - Unlimited
Subject Category 02
Availability:  NASA STI Program (757) 864-9658

**Abstract:**
An experimental and computational investigation has been conducted to determine the offdesign uninstalled drag characteristics of a two-dimensional convergent-divergent nozzle designed for a supersonic cruise civil transport. The overall objectives were to: (1) determine the effects of nozzle external flap curvature and sidewall boattail variations on boattail drag; (2) develop an experimental data base for 2D nozzles with long divergent flaps and low boattail angles and (3) provide data for correlating computational fluid dynamic predictions of nozzle boattail drag. The experimental investigation was conducted in the Langley 16-Foot Transonic Tunnel at Mach numbers from 0.80 to 1.20 at nozzle pressure ratios up to 9. Three-dimensional simulations of nozzle performance were obtained with the computational fluid dynamics code PAB3D using turbulence closure and nonlinear Reynolds stress modeling. The results of this investigation indicate that excellent correlation between experimental and predicted results was obtained for the nozzle with a moderate amount of boattail curvature. The nozzle with an external flap having a sharp shoulder (no curvature) had the lowest nozzle pressure drag. At a Mach number of 1.2, sidewall pressure drag doubled as sidewall boattail angle was increased from 4° to 8°. Reducing the height of the sidewall caused large decreases in both the sidewall and flap pressure drags.

**Subject Terms:**
Boattails; Curvature; Flapping; Pressure drag

## Security Classification

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