Acoustics and Thrust of Separate-Flow Exhaust Nozzles With Mixing Devices for High-Bypass-Ratio Engines

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ACOUSTICS AND THRUST OF SEPARATE-FLOW EXHAUST NOZZLES WITH MIXING DEVICES FOR HIGH-BYPASS-RATIO ENGINES

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SUMMARY

The NASA Glenn Research Center recently completed an experimental study to reduce the jet noise from modern turbofan engines. The study concentrated on exhaust nozzle designs for high-bypass-ratio engines. These designs modified the core and fan nozzles individually and simultaneously. Several designs provided an ideal jet noise reduction of over 2.5 EPNdB for the effective perceived noise level (EPNL) metric.

Noise data, after correcting for takeoff thrust losses, indicated over a 2.0-EPNdB reduction for nine designs. Individually modifying the fan nozzle did not provide attractive EPNL reductions. Designs in which only the core nozzle was modified provided greater EPNL reductions. Designs in which core and fan nozzles were modified simultaneously provided the greatest EPNL reduction. The best nozzle design had a 2.7-EPNdB reduction (corrected for takeoff thrust loss) with a 0.06-point cruise thrust loss. This design simultaneously employed chevrons on the core and fan nozzles.

In comparison with chevrons, tabs appeared to be an inefficient method for reducing jet noise. Data trends indicate that the sum of the thrust losses from individually modifying core and fan nozzles did not generally equal the thrust loss from modifying them simultaneously. Flow blockage from tabs did not scale directly with cruise thrust loss and the interaction between fan flow and the core nozzle seemed to strongly affect noise and cruise performance. Finally, the nozzle configuration candidates for full-scale engine demonstrations are identified.

INTRODUCTION

The impetus for this study was the increasingly stringent noise regulations designed to protect the communities around airports from aircraft noise pollution. Jet exhaust is one of the dominant noise sources from modern turbofan engines (ref. 1), its dominance dramatically increasing with throttle push. These engines use two nozzles (fig. 1) to separately exhaust flow from the core and fan, hence the name separate-flow nozzles (SFN’s). Mixing these two flows into a single flow prior to exhausting provides a thrust benefit relative to two separate flows (ref. 2). However, integration factors associated with mixing the two flows (e.g., extra nacelle weight, drag and thrust reverser complexity) negate the thrust benefits for high-bypass-ratio engines.

The NASA Glenn Research Center (GRC) recently completed an exhaustive experimental study to evaluate the jet noise reduction from new SFN designs. This study, the Separate Flow Nozzle Test (SFNT), was part of...
NASA’s Advanced Subsonic Technology program and was a team effort between GRC, NASA Langley (LaRC), Pratt & Whitney (PW), United Technologies Research Corporation (UTRC), Boeing, General Electric (GE), Allison (AEC), and Aero Systems Engineering (ASE). The data from the study were collected on far-field acoustics, plume Schlieren images, exhaust plume pressures and temperatures, plume infrared signatures, jet noise source locations, and thrust performance.

Many of the new SFN designs attempted to reduce the fully expanded jet velocity by mixing (a) core flow with fan flow only, (b) fan flow with ambient flow only, or (c), (a) and (b) simultaneously. Based on the type of flow mixing attempted, these designs fell into two broad categories: tabs and chevrons. Very aggressive mixing characterized the tabs and very gentle, the chevrons. Remaining SFN designs attempted to shield the hot core jet using a scarfed fan and offset fan nozzles. The SFNT study tested 54 SFN configurations including various alterations of SFN designs within each category (tabs and chevrons).

Several of the 54 SFN configurations provided an “ideal” jet noise reduction of over 2.5 EPNdB on the basis of the EPNL metric (ref. 3). This assumed that the thrust performance remained identical between the baseline SFN and new SFN’s. This report considers the actual takeoff thrust performance in evaluating the EPNL benefits (reductions). It also recommends particular SFN’s that may be good candidates for further development via static engine tests and flight tests for possible implementation in commercial service.

OBJECTIVES

In this report, the ideal EPNL values were corrected for takeoff thrust performance. The corrections were made for several SFN configurations in which tab and chevron designs and their individual and simultaneous use on core and fan nozzles were varied.

The cruise thrust data were examined to determine the effect of specific SFN design parameters on cruise thrust performance. To allow greater variation in their specific designs, a few more SFN configurations were tested for cruise thrust data than were tested for takeoff thrust data.

ACOUSTIC TESTS AT NASA GLENN RESEARCH CENTER

Acoustic data were collected on 54 SFN configurations. These tests were conducted at a typical high-bypass-ratio cycle (fig. 2). The model spectra were scaled up by a factor of 8. Ideal EPNL values were calculated for level flyover at a 1500-ft altitude with a simulated flight speed of Mach 0.28. No ground corrections were applied because only relative EPNL’s were desired. These EPNL’s, spectra, and other details of the SFNT are presented in Janardan1 and in Low.2 The 54 SFN’s were reduced to 14 SFN’s for thrust performance tests. This selection was based on the EPNL metric and geometric variations among the configurations.

THRUST PERFORMANCE TESTS AT AERO SYSTEMS ENGINEERING

Figure 2 also shows the takeoff and cruise cycle points for the thrust performance tests. Unlike the acoustic tests, the thrust performance tests were not run hot because SFN’s utilize separate nozzles for core and fan flows, which do not mix within a mixing chamber. Consequently, the temperature of nonmixed flows has no impact on the nozzle thrust coefficient CTr:

\[ C_{Tr} = \frac{F^d_g}{F^i_g} \]

where \( F^d_g \) is the measured gross thrust with a force balance and \( F^i_g \) is the ideal gross thrust from

\[ F^i_g = \dot{m}_c v_{i,c} + \dot{m}_f v_{i,f} \]

where \( \dot{m}_c \) and \( \dot{m}_f \) are core and fan flow rates, respectively, and \( v_{i,c} \) and \( v_{i,f} \) are core and fan ideally expanded jet velocities, respectively. Therefore, \( C_{T_i} \) values from cold thrust performance tests would be identical to \( C_{T_i} \) values from hot thrust performance tests. Also, cold performance tests provide a stable model free of thermal expansion and and heat transfer between the ducts. Fluidyne quotes the accuracy to be ±0.25 points for absolute values of \( C_{T_i} \) at simulated flight.

The takeoff thrust performance data were acquired statically \((M \ 0.0)\) and at simulated flight \((M \ 0.28)\). Static data were acquired for SFN configurations in which only the core nozzle was modified. In these configurations simulated flight was not necessary because fan flow isolated the core nozzle from ambient flow. Simulated flight data were acquired for SFN configurations in which the fan nozzle was modified (either individually or simultaneously with the core nozzle).

The cruise thrust performance data were acquired at \(M \ 0.8\) for all SFN configurations.

**HARDWARE**


Figure 3 shows a test configuration of the baseline SFN (also known as 3BB) and its cross section at the core exit plane. The SFN hardware designation is 3-\(X_c\)-\(Y_f\), where 3 is the model number, \(X\) is the core nozzle designation, \(Y\) is the fan nozzle designation, and subscripts \(a\) and \(b\) refer to the number of tabs or chevrons on each nozzle. For example, \(3\ T_{a4}\ C_{b2}\) signifies that model 3 has a core nozzle with 48 tabs and a fan nozzle with 24 chevrons. All nozzles were convergent.

**Tabs: Core Nozzle**

Delta tabs were used to produce strong streamwise vortices to aggressively mix the core flow with the fan flow. Some tabs protruded into the core flow and some into the fan flow. The tab protrusion angle was \(30^\circ\) with respect to the core streamlines (ref. 4). Some tabs did not protrude into either flow; that is, they remained neutral with a protrusion angle of \(0^\circ\). Figure 4 shows two core nozzle tab configurations \((3\ T_{32B}\ and\ 3\ T_{48B})\). The six tabs protruding into the core flow for \(3\ T_{32B}\) blocked 2.9 percent of the core geometric throat area. The 12 tabs protruding into the core flow for \(3\ T_{48B}\) blocked 1.45 percent of the core geometric throat area.

**Tabs: Fan Nozzle**

To aggressively mix the fan flow with the ambient flow, delta tabs were used to produce strong streamwise vortices. Some tabs protruded into the fan flow and some into the ambient flow. The tab protrusion angle was \(30^\circ\) with respect to the fan streamlines (ref. 4). Some tabs did not protrude into either flow but remained neutral with a protrusion angle of \(0^\circ\). Figure 5 shows tabs on fan nozzle configuration \(3\ BT_{48}\). The 12 tabs protruding into the fan flow blocked about 2 percent of the fan geometric throat area.

**Chevrons: Core Nozzle**

Chevrons are serrations on the nozzle exit plane for creating streamwise vortices, albeit much more gently than the delta tabs do. Figure 6 shows 3 configurations with 12 chevrons each \((3\ C_{12B},\ 3\ I_{12B},\ and\ 3\ A_{12B})\). The \(3\ C_{12B}\) configuration has simple serrations on the nozzle exit plane; these remain parallel with core streamlines. Chevrons from the \(3\ I_{12B}\) configuration protruded into the core flow only about one displacement thickness of the core boundary layer. They were inclined about \(3^\circ\) with respect to core streamlines, a very gradual inclination. Chevrons from the \(3\ A_{12B}\) configuration protruded into both the core flow and the fan flow. They were also gradually inclined about \(3^\circ\) with respect to core streamlines.

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3. \(B\), baseline; \(C\), chevron; \(T\), tab; \(I\), inward; \(A\), alternating.
Chevrons: Fan Nozzle

Figure 7 shows fan chevron configuration 3BC24. The 24 chevrons were simple serrations on the nozzle exit plane and remained parallel with fan streamlines. No other chevron design was tried.

Core and Fan Nozzles: Simultaneously

The hardware in the configurations described thus far modified the core and fan nozzles individually. Both nozzles were modified simultaneously for six tests. Figure 8 shows these six combinations: 3T24T4s, 3T48T4s, 3T48C4, 3I2C24, 3A12C24, and 3T24C24.

FACILITIES

The acoustic tests were conducted in the NASA Glenn Aeroacoustic Propulsion Laboratory (AAPL), a 65-ft-radius geodesic dome (fig. 9). Castner (ref. 5) and Cooper (ref. 6) give additional details about the dome. Since Cooper's report, the concrete floor of the AAPL was covered with 2-ft-high acoustic wedges to upgrade the facility to fully anechoic status. Located inside and at the center 10 ft above the concrete floor is the jet exit rig, which simulates hot engine flows and to which the test articles are attached. A 53-in.-diameter duct (free jet) surrounds the rig and provides the air to simulate flight on the rig and on the test article. The free jet and the jet exit rig comprise the Nozzle Acoustic Test Rig (NATR). A set of 1/4-in. microphones (26 total) located 10 ft above the concrete floor surround the rig from 40° (forward arc) to 165° (aft arc) in 5° increments. The microphones are located at a nominal radius of 50 ft from the test article.

The performance tests were conducted at ASE's FluiDyne Aerotest Laboratory. Static and simulated flight test setups are shown in figures 10(a) and (b), respectively.

EXPERIMENTAL RESULTS

This section presents the results of correcting the ideal acoustic performance of 14 SFN's (based on the EPNL metric) for takeoff thrust performance and the effects of SFN design parameters on cruise performance. Suggestions are made regarding the further development of candidate SFN's for possible implementation into service.

Thrust-Corrected Effective Perceived Noise Levels

The actual gross thrust at GRC $F^a_{g,GRC}$ during hot acoustic tests is now determined. First, the ideal gross thrust at ASE $F^i_{g,ASE}$ is corrected to standard sea level (SSL) pressure $F^i_{g,ASE}$. The behavior of $C_{Tr}$ as a function of $F^i_{g,ASE}$ is found next for each of the 14 SFN's by curve fitting $C_{Tr}$ and $F^i_{g,ASE}$ data:

$$C_{Tr} = f\left(F^i_{g,ASE}\right)_{SSL}$$

(3)

Then, the ideal gross thrust at GRC during hot acoustic tests $F^i_{g,GRC}$ is corrected to SSL pressure $F^i_{g,GRC}$ and equation (3) is evaluated at $F^i_{g,GRC}$:

$$C_{Tr} = f\left(F^i_{g,GRC}\right)_{SSL}$$

(4)

Values of $C_{Tr}$ from equation (4) could be used to determine actual gross thrust at GRC during hot acoustic tests corrected to SSL pressure $F^a_{g,GRC}$. Determining $F^a_{g,GRC}$ in terms of $F^i_{g,GRC}$ cancels the SSL pressure correction factor. Therefore, the value of $F^a_{g,GRC}$ is calculated from

$$F^a_{g,GRC} = C_{Tr}F^i_{g,GRC}$$

(5)

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Day-to-day changes in ambient conditions slightly alter $F_{g,GRC}$. All EPNL data are corrected by normalizing $F_{g,GRC}$ against a reference thrust of 100 lbf, which assures that variations in EPNL are from SFN designs and not from variations in $F_{g,GRC}$.

The normalized EPNL’s are plotted against the fully mixed jet velocity $V_{mix}$ normalized with the ambient speed of sound $C_{amb}$:

$$Z = \frac{V_{mix}}{C_{amb}}$$

(6)

where $V_{mix}$ is calculated from

$$V_{mix} = \frac{F_{g,GRC}}{\dot{m}_c + \dot{m}_f}$$

(7)

Takeoff Effective Perceived Noise Level Benefits

Acoustic tests of the 3BB SFN were repeated several times during the SFNT. Plotting these data as EPNL’s versus $Z$ collapsed the entire 3BB data set, so the data are represented by a curve fit rather than by symbols to avoid data clutter. The EPNL benefits are reductions in EPNL values relative to 3BB. Also, the value of 1.07 for $Z$, representing the average growth takeoff thrust, was selected for evaluating the EPNL benefits.

**Tabs: core nozzle.**—Figure 11 presents an EPNL plot for two SFN’s with core tabs (3T34B and 3T4B). The EPNL benefits appear to be a function of both tab size and thrust. The 3T4B EPNL benefits appear to become constant at 1.9 EPNdB beyond 1.05 $Z$. The 3T34B benefits, however, appear to continually increase with thrust, providing about 2.5 EPNdB at 1.07 $Z$. EPNL benefits seem to increase with tab size at high thrust values, and the trend is reversed at very low thrust values.

**Chevrons: core nozzle.**—Figure 12 presents EPNL plots for two core chevrons and shows an increase again in EPNL benefit with thrust. The 3I2B SFN provided a benefit of 2.1 EPNdB, which is significantly better than that obtained from 3C2B at 1.2 EPNdB. The obvious difference between these two configurations is that the 3I2B SFN penetrated the boundary layer and 3C2B SFN remained parallel with the core streamlines. It seems that some boundary layer penetration, however small, is needed for greater noise reduction.

**Tabs and chevrons: fan nozzle.**—The fan nozzle boattail angle was 14°. This high value was needed to assure that Glenn’s baseline acoustic data could be compared with similar data planned for NASA Langley’s Jet Noise Laboratory. Also, this value was a compromise among various nacelles because tests could not be repeated for particular nacelles from each aerospace company.

Figure 13 shows the fan cowl pressure coefficient $c_p$, at Mach 0.8 calculated from

$$c_p = \frac{P_{s,surface} - P_{s,tunnel}}{q}$$

(8)

where $P_{s,surface}$ is the surface static pressure, $P_{s,tunnel}$ is the tunnel static pressure, and $q$ is the tunnel dynamic pressure. Except for the last port, all static ports were flush with the surface. The nozzle lip was too thin to flush mount the last static port. Instead, tubing was attached to the nozzle surface, its opening flush with the nozzle base. The flow rapidly expands around the nozzle shoulder. Such high expansion is reasonable given that the afterbody was not tapered in these tests (refs. 9 to 11). There was no clear evidence of shocks and flow separation, and the expansion appears to recover smoothly. Slight over compression is seen in the last half of the nozzle.

Figure 14 presents an EPNL plot for fan chevrons (3BC4S) and fan tabs (3BT4S). Apparently, the 3BC4SFN was a little louder than 3BB, achieving an EPNL benefit of only -0.2 EPNdB. The 3BT4SFN, however, provided a benefit of about 1.1 EPNdB with respect to 3BB SFN at 1.07 $Z$ and a benefit of about -1.0 EPNdB at low thrust ($Z = 0.85$). At low thrust, the 48 tabs simply could not entrain air to slow the jet exhaust enough to cause a significant reduction in low-frequency jet noise; in fact, the attempt to do so created high-frequency noise.

Core chevrons with fan chevrons: simultaneously.—The EPNL benefits from individually modified core nozzles and fan nozzles were presented in the previous sections. The results of modifying these nozzles simultaneously are now presented. Figure 15 compares the EPNL’s from an SFN simultaneously using chevrons on core and fan nozzles (3L2C24) with 3BB. A benefit of about 2.7 EPNdB is seen at 1.07 Z and seems to remain constant beyond high thrusts. This figure also compares 3L2C24 data with that for 3L2B and 3BC24. Adding chevrons to the fan nozzle increased the EPNL benefit of 3L2B SFN from 2.1 to 2.7 EPNdB.

Core tabs with fan tabs: simultaneously.—Figure 16 compares the EPNL’s from an SFN simultaneously using tabs on the core and fan nozzles (3T24T48) with 3BB. The EPNL benefit of about 2.4 EPNdB is seen at growth takeoff thrust and seems to continually increase with thrust. This figure also compares 3T24T48 data with that from 3T24B and 3BT48. Adding tabs to the fan nozzle did not provide any EPNL benefits at high thrust, but doing so at low thrust (Z = 0.85) decreased the EPNL benefit from -1.0 to -1.4 EPNdB.

Cruise Performance

All cruise data were taken at Mach 0.8. Changes in $C_T$ values relative to 3BB are shown as $\Delta C_T$. The units of $\Delta C_T$ are in points with 1 point representing a 0.01 change in the $C_T$ value. For example, the $\Delta C_T$ for a nozzle with a $C_T$ value of 0.98 is 2.0 points relative to an ideal nozzle with a $C_T$ value of 1.0. In this section, the effects of SFN design parameters on $\Delta C_T$ are shown.

Tabs: core nozzle.—Figure 17 shows the effect of two tab designs (3T24B and 3T48B). The 3T24B SFN had a 0.99-point loss in $C_T$ and 3T48B SFN had a 0.77-point loss. The 3T24B SFN blocked 2.9 percent of the core flow and 3T48B SFN blocked 1.45 percent. Reducing the blockage by one-half did not reduce the $C_T$ loss by one-half probably because of additional losses from expansion.

Chevrons: core nozzle.—Figure 18 shows the effect of three chevron designs (3C12B, 3I2B, and 3A12B). The $C_T$ loss for 3C12B SFN was 0.55 point with the loss for 3I2B and 3A12B nearly identical at 0.32 and 0.34 point, respectively. The 3C12B SFN was less efficient than the other two core chevron designs even though it did not obstruct the flow.

Tabs and chevrons: fan nozzle.—Figure 19 compares a tab fan nozzle (3BT48) and a chevron fan nozzle (3BC24). Tabs had a 0.57-point loss and chevrons, a 0.18-point loss.

Core tabs with fan tabs: simultaneously.—Figure 20 shows the impact of adding fan tabs with two core tabs (3T24T48 and 3T48T48). The 3T24T48 SFN had a 0.99-point $C_T$ loss. Adding the fan nozzle with 48 tabs with its 0.57-point loss (3BT48) did not result in a 1.56-point loss for 3T24T48. Instead, the $C_T$ loss was 1.14 points for 3T24T48. The 3T48B SFN had a 0.77-point $C_T$ loss. If fan flow and core flow were independent of each other, the total loss should have been 1.34 points for 3T24T48; instead, the total loss was 1.1 points.

Core tabs with fan chevrons: simultaneously.—Figure 21 shows the impact of adding fan chevrons with two core tabs (3T24C24 and 3T48C24). The 3T24B SFN had a 0.99-point loss and 3BC24, a 0.18-point loss. Adding the fan nozzle with 24 chevrons to 3T24B did not yield a 1.17-point loss. Instead, the total $C_T$ loss for 3T24C24 was 0.43 point. Similarly, the $C_T$ loss with 3T48C24 was 0.51 point, not 0.95 point.

Core chevrons with fan chevrons: simultaneously.—Figure 22 shows the impact of adding fan chevrons with two core chevrons (3I2C24 and 3A1C24). The 3L2B SFN had a 0.32-point loss and 3BC24, a 0.18-point loss. Together they totaled 0.5 point, but the loss for 3I2C24 SFN was a paltry 0.06 point.

The $C_T$ loss had a 0.34-point loss. Adding fan chevrons to this SFN should have produced a 0.52-point loss. Indeed, the total thrust loss was 0.49 point. Only in this configuration did linearly summing the $C_T$ losses from modifying individual flows equal $C_T$ losses from modifying them simultaneously. Some of the summing differences can be attributed to repeatability. However, the general trend shows that performance losses from simultaneous modifications were less than the sum of individual modifications.

Separate-Flow-Nozzle Candidates for Further Development

Jet noise reduction without thrust loss is a very challenging requirement. The constraints of a particular application dictate the jet noise reduction needed and the tolerable thrust loss. For this generic document, these limits are set as (a) a maximum cruise thrust loss of 0.5 point and (b) a minimum EPNL reduction of 2.5 EPNdB. Although no cruise thrust loss is desirable, SFN’s with $C_T$ losses above 0.5 point are likely to be extremely unfavorable. Jet noise reductions less than 2.5 EPNdB are likely to have a much smaller effect on the airplane total EPNL reductions. A particular application will dictate these limits; however, 0.5-point and 2.5-EPNdB limits provide a starting point.
Figure 23 shows $C_T$ losses and EPNL benefits from 13 SFN's relative to the SFN 14, the 3BB. The thrust-corrected EPNL benefits (actual EPNL benefits) are shown only for the first eight SFN's (3C2B to 3T24). Takeoff thrust data on remaining configurations was not acquired. This figure also shows the ideal EPNL benefits for all configurations. It appears that cruise thrust losses of up to 1.2 points do not significantly affect the actual EPNL benefits. The ideal EPNL benefits are shown for the remaining five SFN's (3A2B to 3T48C24) because takeoff thrust data were not taken for these configurations. Regardless of the configuration or cruise thrust loss, the EPNL benefits did not change much. This means that 3I2C24, 3T24C24, and 3A12C24 can easily meet the 0.5-point and 2.5-EPNdB limits. The 3A2B and 3T48C24 SFN's border on meeting the limits, so these five should be considered as candidates for further development and verification via static engine tests and flight tests. Table I summarizes the noise benefits and thrust penalties for all configurations.

**SUMMARY**

NASA Glenn recently completed an extensive experimental study to reduce jet noise. The study concentrated on exhaust nozzle designs for high-bypass-ratio turbofan engines with separate-flow nozzles. A total of 54 SFN's were tested by modifying the core nozzle alone, the fan nozzle alone, or both nozzles simultaneously. Increasing the number of core nozzle tabs (3T24B and 3T48B) seemed to limit the EPNL benefits to a constant beyond 1.02. Tests with two core chevrons (3I2B and 3C2B) showed that when the chevrons penetrated the core boundary layer (3I2B), they provided greater noise reduction than without penetration. Their EPNL benefits seemed to remain constant beyond 1.02. Chevrons on the fan nozzle (3BC24) were not as effective as they were on the core nozzle (3C2B). Tabs on the fan nozzle (3BT48) also were not as effective as they were on the core nozzle. Modifying the core and fan nozzles simultaneously provided a greater EPNL benefit than modifying either nozzle individually. Specifically, the 3I2C24 and 3T24T48 SFN's provided 2.7- and 2.5-EPNdB benefits, respectively.

Reducing the tab blockage from core tabs by one-half did not reduce the $C_T$ loss by one-half (3T24B and 3T48B). The design of the Chevron effected its particular loss (3C2B, 3I2B and 3A2B). The $C_T$ losses with chevrons on the fan nozzle were less than $C_T$ losses with tabs on the fan nozzle. The $C_T$ losses from modifying the core and fan nozzles simultaneously were not equal to the sum of $C_T$ losses from modifying them individually. Specifically, the 3I2C24 and 3T24T48 SFN's had 0.06- and 1.14-point $C_T$ losses, respectively. Table I summarizes the EPNL benefits and the cruise thrust losses.

A metric was selected to find the suitable SFN's for further development and verification via static engine tests and flight tests. The metric was the maximum $C_T$ loss of 0.5 point and the minimum EPNL benefit of 2.5 EPNdB. Five SFN's that achieved the metric and therefore should be considered for further development are 3I2C24, 3T24C24, 3A12C24, 3A12B, and 3T48C24.

**REFERENCES**

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<td>3.16</td>
<td>0.43</td>
</tr>
<tr>
<td>3T_{2,4}C_{2,4}</td>
<td>2.58</td>
<td>0.51</td>
</tr>
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Figure 1.—Typical high-bypass-ratio, separate flow engine.
Figure 2.—Cycle points for acoustic and thrust performance tests.

Figure 3.—Typical high-bypass-ratio, separate-flow nozzles. Area of fan, $A_{\text{fan}}$, 28.9 in.$^2$ Area of core, $A_{\text{core}}$, 10.5 in.$^2$
Figure 4.—Tabs on core nozzle only.

Figure 5.—Tabs on fan nozzle only.
Figure 6.—Chevrons on core nozzle only.
Figure 7.—Chevrons on fan nozzle only.

Figure 8.—Core and fan modifications simultaneously.
Figure 8.—Continued.
Figure 8.—Concluded.

Figure 9.—Aeroacoustic Propulsion Laboratory (AAPL). (a) Outside. (b) Inside.

Figure 10.—Thrust stands at Aero Systems Engineering Fluidyne Aerotest Group. (a) Static. (b) Flight.
Figure 11.—Effective perceived noise level benefits with tabs on core nozzle.

Figure 12.—Effective perceived noise level benefits with chevrons on core nozzle.

Figure 13.—Static pressure distribution on fan cowl at Mach 0.8.
Figure 14.—Effective perceived noise level benefits with tabs and chevrons on fan nozzle.

Figure 15.—Effective perceived noise level benefits with chevrons on core and nozzles simultaneously.

Figure 16.—Effective perceived noise level benefits with tabs on core and nozzles simultaneously.
Figure 17.—Tabs on core.

Figure 18.—Chevrons on core.

Figure 19.—Tabs and chevron fan.

Figure 20.—Tabs on both nozzles.
Figure 21.—Tabs with chevrons.

Figure 22.—Chevrons on both nozzles.

Figure 23.—Effective perceived noise level and cruise thrust losses relative to 3BB.
**Title and Subtitle**

Acoustics and Thrust of Separate-Flow Exhaust Nozzles With Mixing Devices for High-Bypass-Ratio Engines

**Authors**

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**Abstract**

The NASA Glenn Research Center recently completed an experimental study to reduce the jet noise from modern turbofan engines. The study concentrated on exhaust nozzle designs for high-bypass-ratio engines. These designs modified the core and fan nozzles individually and simultaneously. Several designs provided an ideal jet noise reduction of over 2.5 EPNdB for the effective perceived noise level (EPNL) metric. Noise data, after correcting for takeoff thrust losses, indicated over a 2.0-EPNdB reduction for nine designs. Individually modifying the fan nozzle did not provide attractive EPNL reductions. Designs in which only the core nozzle was modified provided greater EPNL reductions. Designs in which core and fan nozzles were modified simultaneously provided the greatest EPNL reduction. The best nozzle design had a 2.7-EPNdB reduction (corrected for takeoff thrust loss) with a 0.06-point cruise thrust loss. This design simultaneously employed chevrons on the core and fan nozzles. In comparison with chevrons, tabs appeared to be an inefficient method for reducing jet noise. Data trends indicate that the sum of the thrust losses from individually modifying core and fan nozzles did not generally equal the thrust loss from modifying them simultaneously. Flow blockage from tabs did not scale directly with cruise thrust loss and the interaction between fan flow and the core nozzle seemed to strongly affect noise and cruise performance. Finally, the nozzle configuration candidates for full-scale engine demonstrations are identified.

**Subject Terms**

Jet noise; Turbofan engines; Nozzles; Acoustics