COANNULAR NOZZLE NOISE CHARACTERISTICS AND APPLICATION TO ADVANCED SUPERSONIC TRANSPORT ENGINES

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SUMMARY

Recent programs in the field of jet noise, sponsored by the NASA Lewis Research Center, have indicated that the variable stream control engines (VSCE) which are being considered for advanced supersonic cruise aircraft have inherent jet noise advantages over earlier engines. This characteristic is associated with the exit velocity profile produced by such an engine. The high velocity fan stream, on the outer periphery, is acoustically dominant while the primary stream is held to a low velocity and therefore contributes little to the overall noise.

Scale model tests have indicated low noise levels. Operation under static conditions, as well as in a relative velocity field (simulating take-off speeds) has indicated large reductions are available from the coannular nozzle and the VSCE. The inherently low levels of jet noise prompted changes in the cycle, which allowed an increase in the amount of augmentation incorporated in the fan stream, without exceeding the suggested noise guidelines, thereby allowing the use of a considerably smaller engine, with obvious vehicle advantages.

INTRODUCTION

The aero/acoustic evaluation of coannular nozzles associated with the VSCE filled a technology void which previously existed in the area of jet noise from such a configuration. Earlier work on coannular nozzles had generally been done with a cold stream surrounding a hot center stream. The VSCE as illustrated in figure 1 produces a hot, high velocity stream surrounding a low temperature, low velocity primary stream. Extensive scale model tests and analyses have indicated the coannular nozzle operating under such conditions produces a low level of jet noise. It is much quieter than predictions used in the early system studies. Under many conditions it is also quieter than comparable convergent nozzles. The results of these evaluations are presented in reference 1.

SYMBOLS

Values are given in SI units only. The measurements and calculations were made in U.S. Customary Units.

A	area ~ m^2
A*	throat area ~ m^2
C-D	convergent-divergent
Cv	actual thrust/ideal thrust
EPNdB	effective perceived noise level in dB
FAR36	Federal Aviation Regulations - Part 36
LBE	low bypass engine
OASPL	overall sound pressure level ~ dB
P	pressure
PNL	perceived noise level
r	radius
SPL	sound pressure level ~ dB
T	temperature ~ °K
V	velocity ~ mps
VSCE	variable stream control engine
W	mass flow
ρ	density
θ	angle from inlet centerline
ω	correlating exponent

Subscripts:

a	ambient
ex	exit
f	fan stream
i	inner
o	outer
p	primary stream
t	total
∞	free stream

BASIC COANNULAR NOZZLE CHARACTERISTICS

The scale model tests simulating the VSCE in the take-off mode employed basic coannular nozzle configurations as illustrated typically in figure 2. The models used in the static phase of the study were approximately 1/10 of full scale size. In addition, an equivalent convergent nozzle was included to serve as a reference configuration.

The basic advantage of the coannular nozzle is illustrated in figure 3. The noise spectra of a coannular nozzle is compared to a convergent nozzle having the same area as the fan stream of the coannular nozzle, and operating at the same conditions. The primary stream in the coannular arrangement has a low velocity, and is therefore not acoustically significant itself. As illustrated, there is a very large, broadband reduction in sound pressure level associated with the coannular nozzle. A portion of this reduction is due to the presence of the primary stream, as evidenced by the increase in the sound pressure level when the primary stream was turned off (resulting in the annular configuration). The remainder of the original reduction is associated with the interaction of the fan stream with the ambient air. This therefore illustrates the inherent benefit of the coannular nozzle, in which the dominant noise stream is located near the outer periphery of the nozzle. The physical phenomenon causing the noise reduction is the rapid velocity decay produced in the coannular nozzle. This is illustrated in figure 4. The convergent nozzle velocity decays at a relatively slow rate and the region generating the peak noise (at the end of the potential core) is at a relatively high velocity. The coannular nozzle velocity however, decays at a very rapid rate, since the fan stream is being acted upon by both the outer ambient air and the primary flow in the core. The region of the plume from the coannular nozzle which is generating the peak noise is therefore at a low velocity and therefore produces a low noise level.

The use of a coannular nozzle does not introduce any significant thrust losses relative to a convergent nozzle. The aerodynamic performance of the coannular nozzle at static conditions is compared to that of the convergent nozzle in figure 5, where the average measured performance levels of the configurations are illustrated over a range of pressure ratios. The performance is presented in terms of mass averaged total pressure ratio so that both nozzles can be compared. The difference between the convergent nozzle and the coannular nozzle is due to the presence of a convergent-divergent nozzle in the primary stream of the coannular configuration, as well as the increased friction associated with the coannular nozzle. The primary nozzle incorporated a C-D section to reflect the design requirements of high flight speeds associated with a supersonic cruise vehicle while assuming a fixed geometry nozzle. The C-D nozzle ($A_{ex}/A^* = 1.1$) is overexpanded at the low primary pressure ratio (1.53) simulated in this series of tests. P&WA SCAR study engine designs employ variable geometry in the primary nozzle which will eliminate these overexpansion losses. The frictional losses are due to additional wetted area with the coannular nozzle. Therefore, the only inherent difference between the two nozzles is a small amount of friction, amounting to approximately 0.5% at take-off conditions.

The influence of fan stream velocity on the reduced noise levels of a coannular nozzle is illustrated in figure 6. Actual coannular nozzle test data, scaled 10X, and adjusted to a sideline distance of 648.6m, are compared to the original prediction (i.e., coannular synthesis) and to data for a "mixed flow" configuration. The synthesis represents the early method of predicting coannular jet noise. In this method, the noise level of the coannular nozzle is said to be equal to the sum of the two streams analyzed independently of each other, as if each was a convergent nozzle operating at the appropriate conditions. The synthesized perceived noise level of the coannular nozzle is defined as:

$$\text{Perceived noise level (PNL)} = 10 \text{ Log} \left[\text{Log}^{-1} \left(\frac{\text{PNL}}{10}\right)_p + \text{Log}^{-1} \left(\frac{\text{PNL}}{10}\right)_f \right]$$

As illustrated in figure 6, the actual data are well below the synthesized level. The difference occurs because the synthesis approach ignores the shape of the jet and any interactions between the streams. It should be noted that this synthesis method was commonly used in early cycle and system studies.

The noise of the "mixed flow" nozzle was obtained from convergent nozzle test data at conditions which would exist if the two streams of the coannular nozzle were ideally totally mixed. It is presented to serve as another reference configuration in order to enhance the understanding of the coannular nozzle phenomena. In many cases, especially at high velocities, the coannular nozzle is quieter than the "mixed flow" convergent nozzle. However, the advantages of the coannular nozzle are dependent on both the fan and primary conditions. The difference between a coannular nozzle arrangement and the equivalent "mixed flow" convergent nozzle is illustrated typically in figure 7 over a range of conditions. The advantage of the coannular arrangement diminishes (for the same variation in fan velocities) as the primary velocity is decreased. When either stream has a very low velocity it would be beneficial from an acoustic viewpoint to mix the two streams producing one larger, but much lower velocity stream. However, for the engines projected for supersonic flight application, high velocities are desired in both streams, and under these conditions the coannular arrangement offers a distinct advantage.

The effect of an ejector on the peak PNL of the coannular nozzle is shown in figure 8. A slight (< 1 dB) reduction was obtained by adding a hardwall ejector. The presence of acoustical treatment in the ejector produced a small amount of additional suppression. Across the test range, 2 PNdB or less total suppression was obtained. Since the coannular nozzle results indicated that the high frequency noise was generated in the fan annular exhaust near the nozzle exit and the low frequencies in the mixed jet downstream, some shielding suppression of the high frequency noise was expected by addition of the ejector, and further reduction is consistent with the addition of acoustic treatment.

The peak PNL of the basic coannular nozzle has been correlated in terms of fan stream velocity and the fan-to-primary velocity ratio, as illustrated in figure 9. The noise level has been normalized for the effects of density by application of the factor 10 log $(\rho_f/\rho_a)^{\omega}$, where ω is based on the information presented in reference 2. The perceived noise level generally decreases as the velocity ratio is increased from 1.0 to 2.0. An increase in the velocity ratio beyond 2.0 is not beneficial.

Very recent model tests in a relative velocity environment have indicated that the advantages of the coannular nozzle, as identified in the earlier static evaluations, are maintained at take-off airspeeds. The impact of take-off speeds on the overall sound pressure level (OASPL) is illustrated in figure 10. The actual coannular nozzle data at both static and take-off conditions (V_{∞} = 104 mps) are presented along with the synthesized levels at each condition. The synthesized OASPL values are based on convergent nozzle test data, using the procedure described earlier (for PNL). The difference between the actual data and the synthesized levels, observed at static conditions, is essentially unchanged at take-off speeds. In other words, the coannular nozzle advantages are not attenuated by the introduction of take-off flight speed. At take-off speeds, both the synthesized values (based on convergent nozzle data) and the actual coannular data are considerably lower than the static levels since in general, the free stream velocity (V_{∞}) weakens the noise generating properties in the jet exhaust.

APPLICATION TO CYCLE STUDIES

The data generated under these NASA sponsored programs have allowed predictions of jet noise to be made, with improved accuracy, for the advanced engines being considered for application to supersonic cruise vehicles. The noise levels for an advanced VSCE are presented in figure 11 over a range of thrust at both static and take-off conditions. The reduction in peak perceived noise level, going from static to take-off conditions, is essentially constant as engine thrust is varied. The relative velocity effect seen with conventional subsonic jets would be expected to produce a decreasing reduction as thrust is increased (i.e., as exit velocity is increased). However since the shape of the jet noise spectra of a VSCE changes considerably with thrust, there are counteracting effects. At high thrust levels the jet noise is dominated by the low frequency contribution generated in the downstream plume. At the low thrust levels, the significance of shock noise (which is not reduced in-flight) increases. The net effect of these changing spectra, of this VSCE, is a nearly constant reduction in static noise levels, at all thrust settings. The anticipated noise level for a comparable low bypass ratio engine (LBE) is also illustrated. This engine has acoustic characteristics which are essentially the same as a turbojet. The impact of take-off speed is approximately the same as the VSCE, but the overall level is considerably higher. In this comparison, it should be noted that in both cases the engines are analyzed using only the basic nozzle arrangement and do not include secondary nozzle (e.g., ejector) influences. It is however expected that an acoustically treated ejector would be more beneficial to the VSCE since high frequency noise, which is amenable to treatment, tends to be dominant in the spectra of the VSCE coannular nozzle.

The overall improvements that the new advanced VSCE offers over the first generation unsuppressed turbojet engines are illustrated in figure 12. The same aircraft size and technology level was assumed for both cycles, with the basic variation in noise level with range due to engine sizing. The acoustic advantages of the coannular nozzle in the VSCE provide an 8 EPNdB reduction in sideline jet noise, while the cycle differences and component technology levels produce a 25% improvement in range capability. The variation in the range with the VSCE, at a given noise level, is associated with programmed throttle scheduling in combination with the detailed noise analysis of the system, involving ground attenuation and engine shielding assumptions. The band associated with the first generation turbojet engines reflects engine scaling uncertainties and cycle options. The noise prediction for the turbojet engines is based on the SAE procedure presented in reference 2. The VSCE noise levels are based on the parametric scaling relationships for coannular jet noise developed from the model test program conducted by P&WA. The flight effects for both sets of engines are based on procedures proposed to the SAE in reference 3. The latter procedure was employed, since the very recent relative velocity data generated by P&WA has not yet been incorporated into the computerized prediction system.

TECHNOLOGY REQUIREMENTS

In order to explore the full potential of the coannular nozzle, a program sponsored by the NASA Lewis Research Center is currently underway to systematically identify the interactions between basic nozzle geometry and aero/acoustic characteristics. As illustrated in figure 13 the radial placement of the fan stream (i.e., r_{if}/r_{of}) will be explored since it is felt this is an important variable in the noise reduction process. In addition, a centerbody will be introduced in the primary streams of several configurations, thereby altering in another manner the interaction between the two streams.

This will be combined with the earlier information, which centered on a few selected nozzle configurations, to formulate an aero/acoustic design system. This design system will then allow take-off noise considerations to be incorporated, in a consistent, quantitative manner, into the overall design process of an exhaust system suitable for powering a supersonic aircraft.

The next logical step in the study of coannular nozzles for the VSCE is a large scale exhaust system evaluation to confirm the aero/acoustic characteristics observed with laboratory models. As illustrated in figure 14, a technology test bed could be obtained by modifying an existing engine to resemble a VSCE. A comparison of the exhaust properties from the VSCE and those obtainable with the test bed engine is presented in table 1. As indicated, the temperatures and velocities of interest can be well covered, allowing the demonstration of not only the nozzle characteristics but also the duct burner emission characteristics.

Such a program would pave the way for a more complete exhaust system development program required for a successful aircraft.

CONCLUSION

The NASA sponsored programs to date, on the aero/acoustic characteristics of the coannular nozzle as incorporated in the VSCE, have greatly improved the acoustic outlook for future supersonic aircraft. The results of these technology programs have had a major impact on the design of the powerplant and have allowed substantial improvements in overall supersonic vehicle characteristics. It is important to the supersonic technology program to continue this activity and demonstrate these acoustic benefits in full scale, thus paving the way for a successful development program.

REFERENCES

(1) Kozlowski, H. and Packman, A.B.: Aero-Acoustic Tests of Duct-Burning Turbofan Exhaust Nozzles, Final Report, NASA CR-2628, 1977.

(2) Society of Automotive Engineers Inc., "Proposed ARP 876 Gas Turbine Jet Exhaust Noise Prediction:, SAE Committee Correspondence, April 1, 1975.

(3) Bushell, K.W., "Static to Flight Jet Noise Data for Presentation to the SAE A21 Jet Noise Subcommittee Meeting, October 2, 1974," SAE Committee Correspondence, 25 September 1974.

TABLE 1

COMPARISON OF VSCE AND TEST BED ENGINE PARAMETERS

	VSCE	Test Bed
T_{t_f}	444 – 1700°K	444 – 1700°K
T_{t_p}	811 – 978°K	756 – 922°K
V_f	457 – 945 mps	457 – 884 mps
V_p	366 – 610 mps	457 – 610 mps

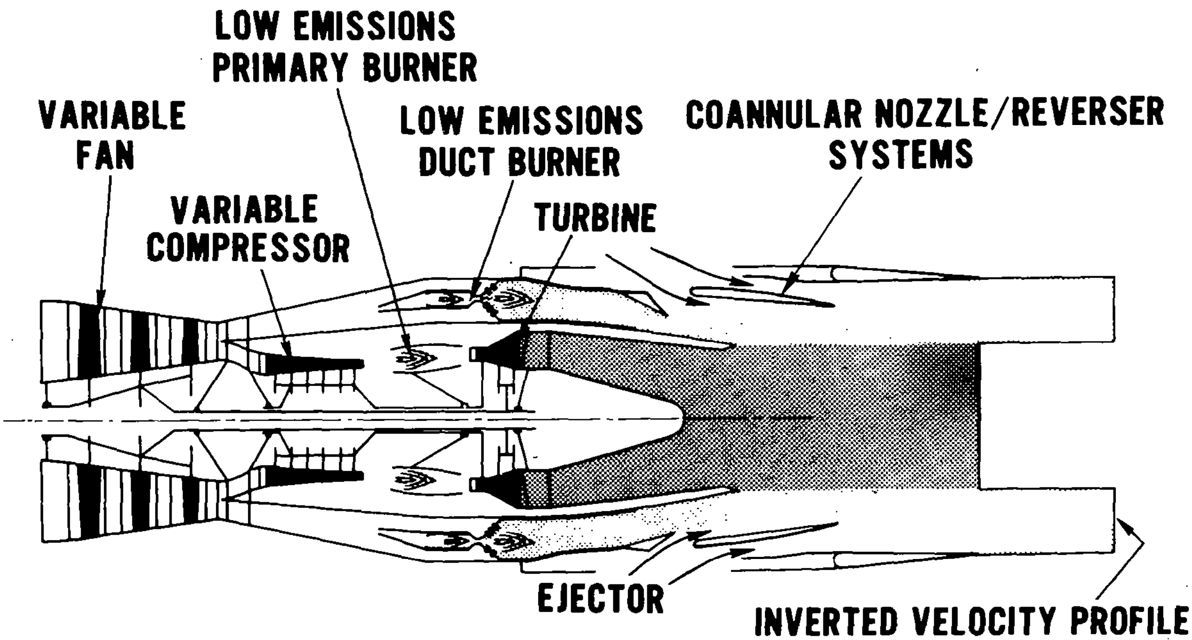


Figure 1.- Variable stream control engine.

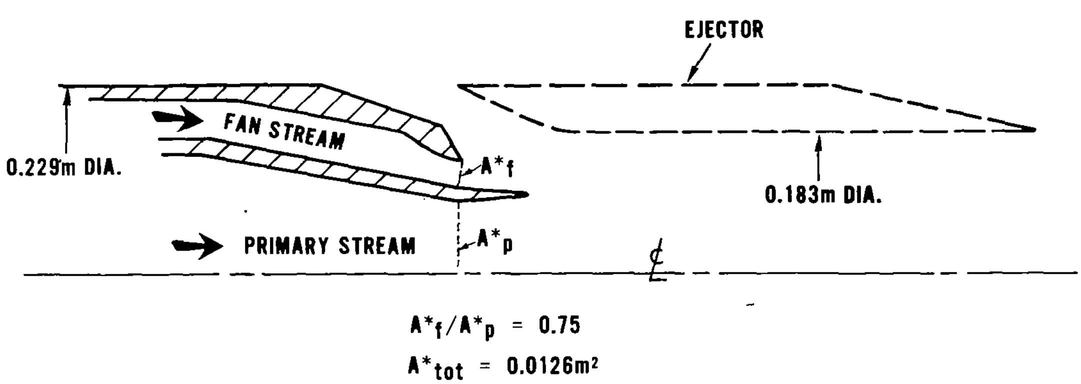


Figure 2.- Coannular nozzle model.

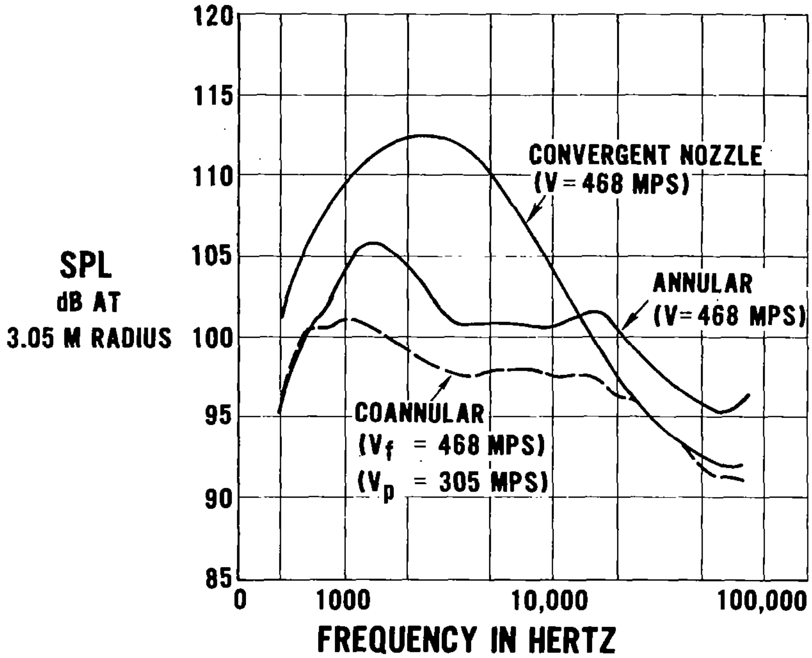


Figure 3.- Coannular benefit.

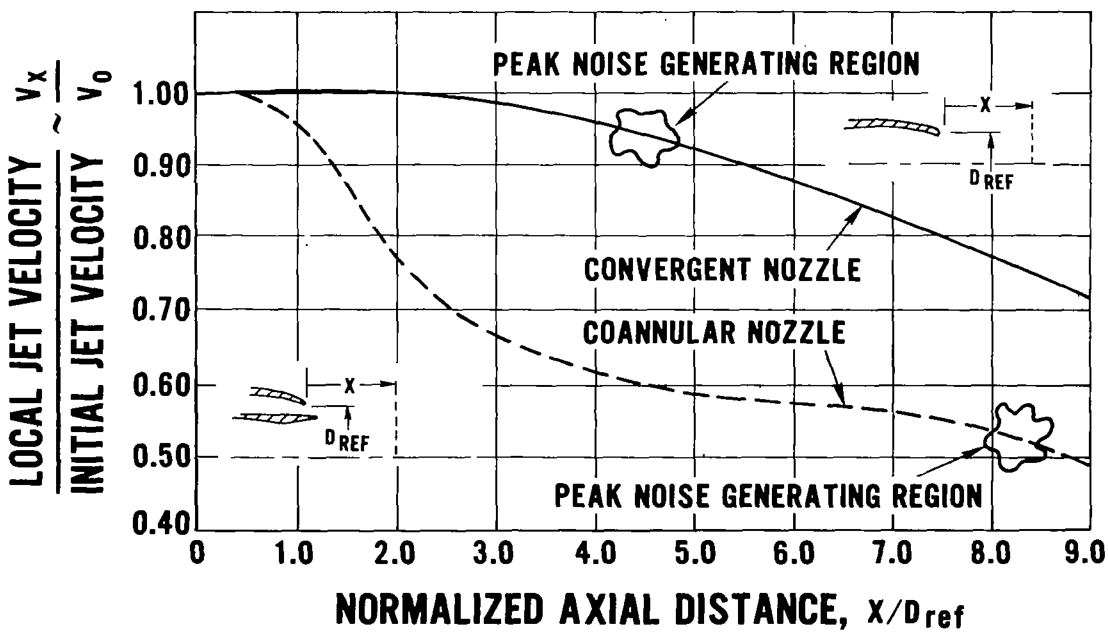


Figure 4.- Nozzle mixing characteristics.

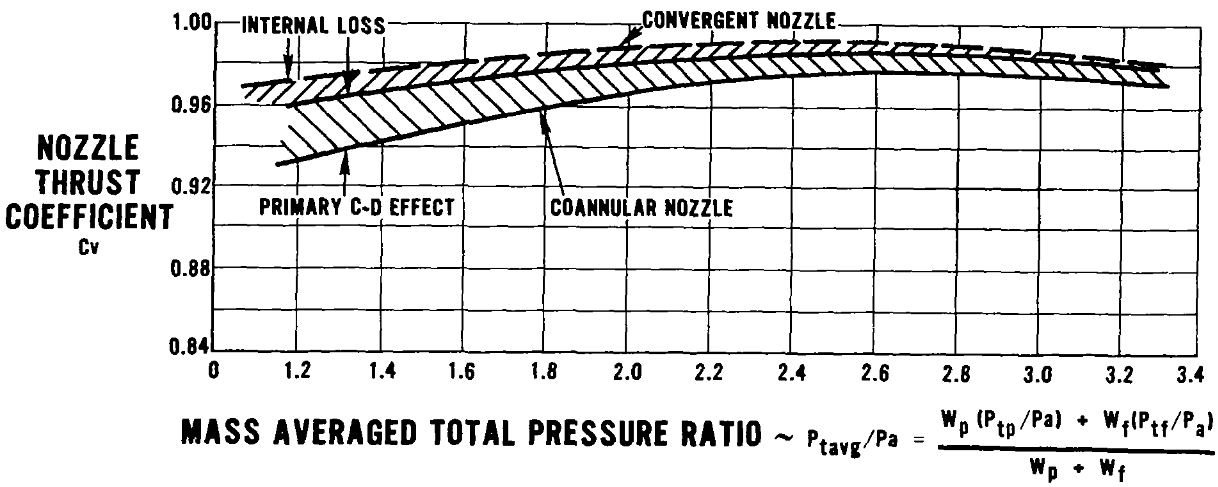


Figure 5.- Aerodynamic performance comparison.

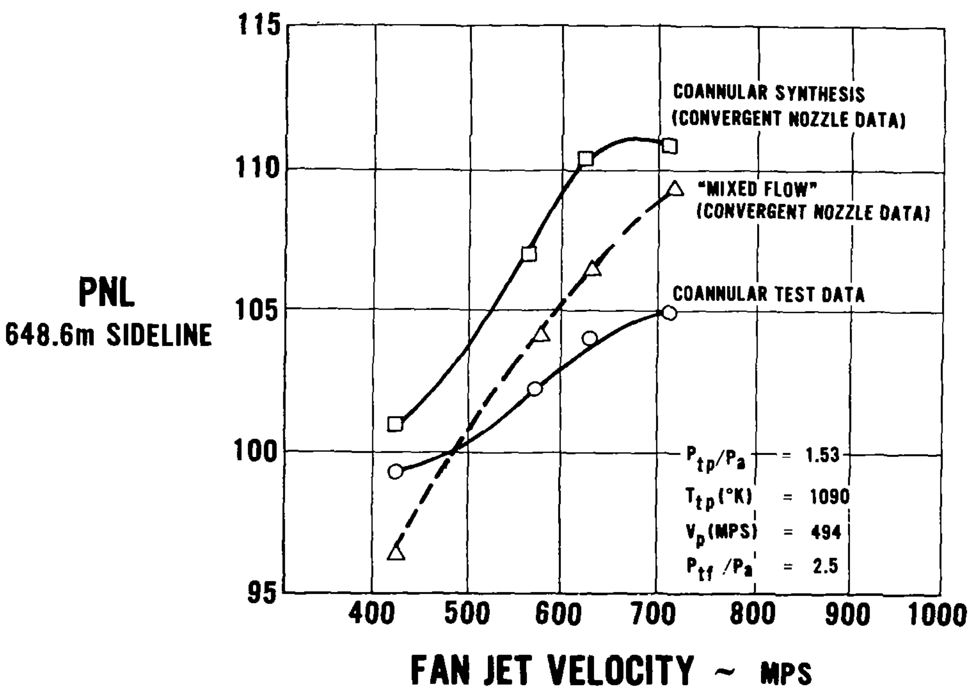


Figure 6.- Coannular nozzle characteristics.

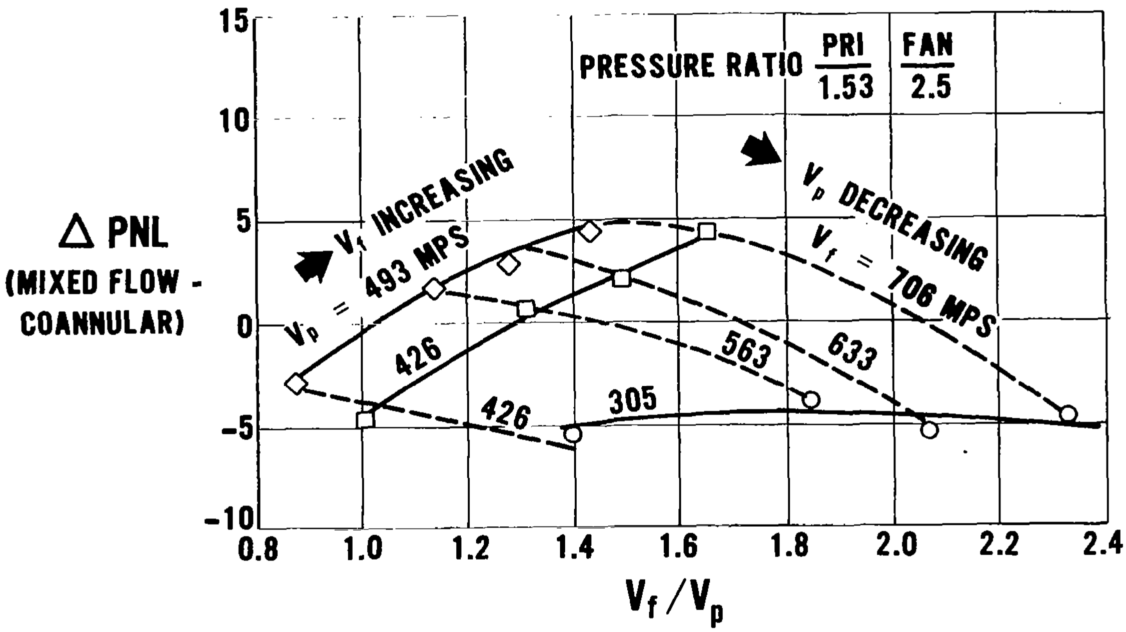


Figure 7.- Impact of operating conditions on jet noise comparison.

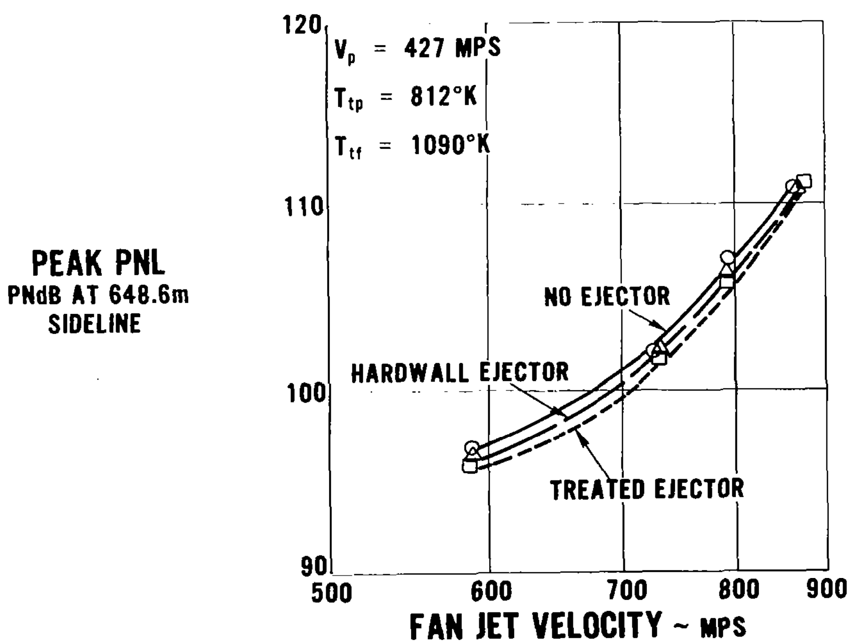


Figure 8.- Effect of ejector on peak PNL.

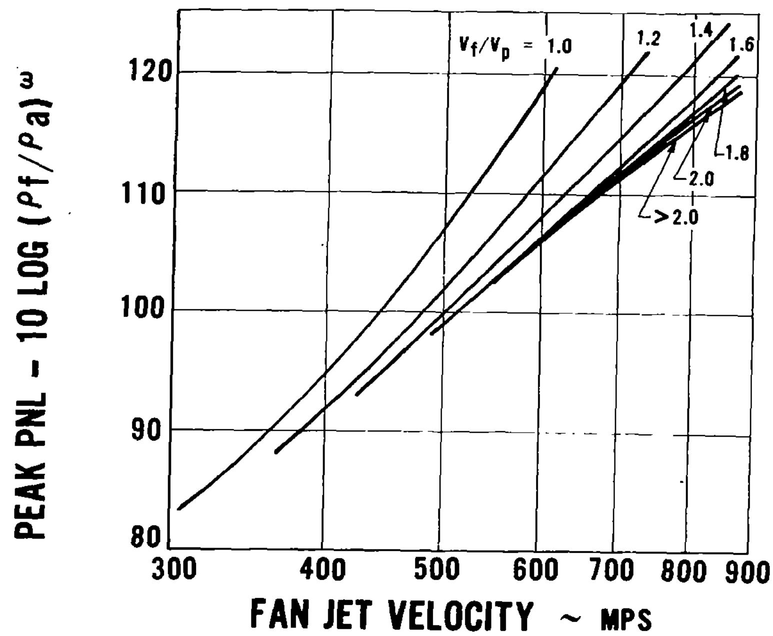


Figure 9.- Correlation of peak PNL.

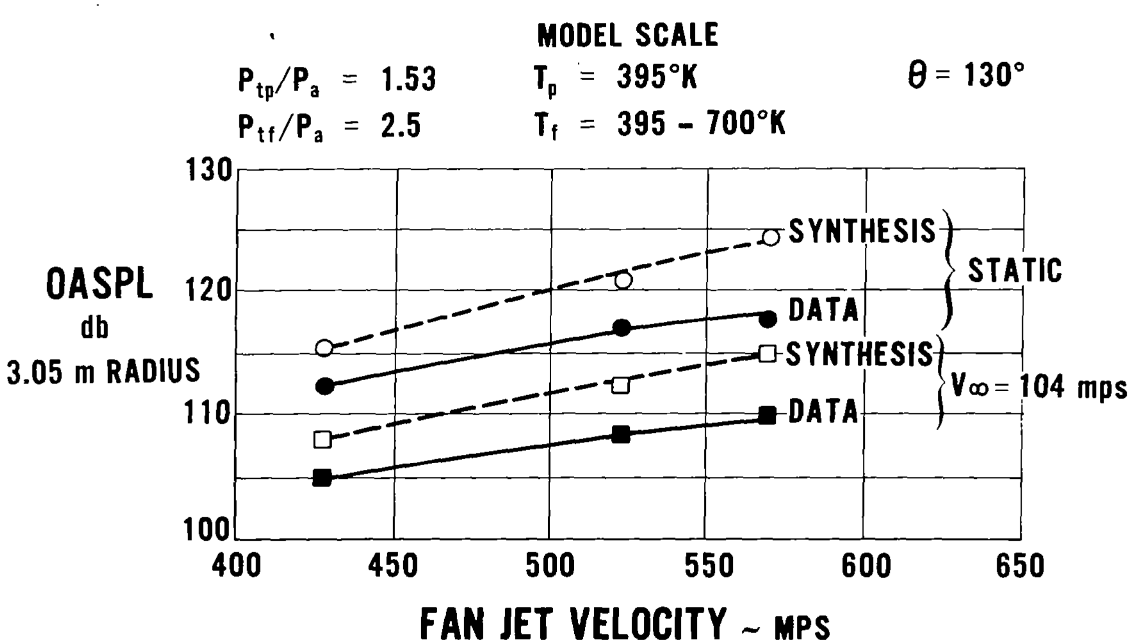


Figure 10.- Effect of take-off speed on OASPL of coannular nozzle.

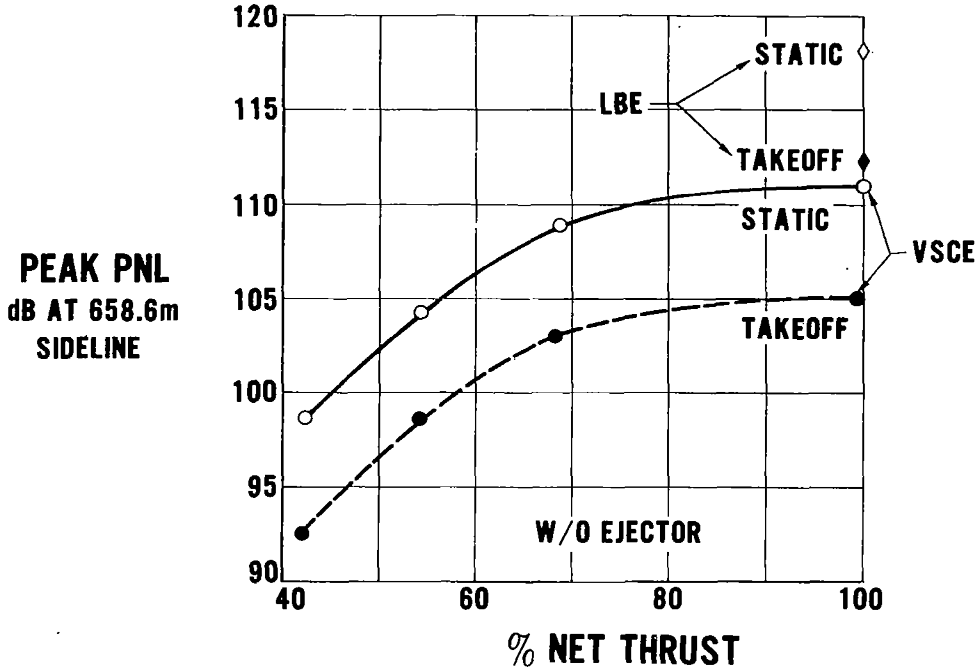


Figure 11.- Predicted peak PNL.

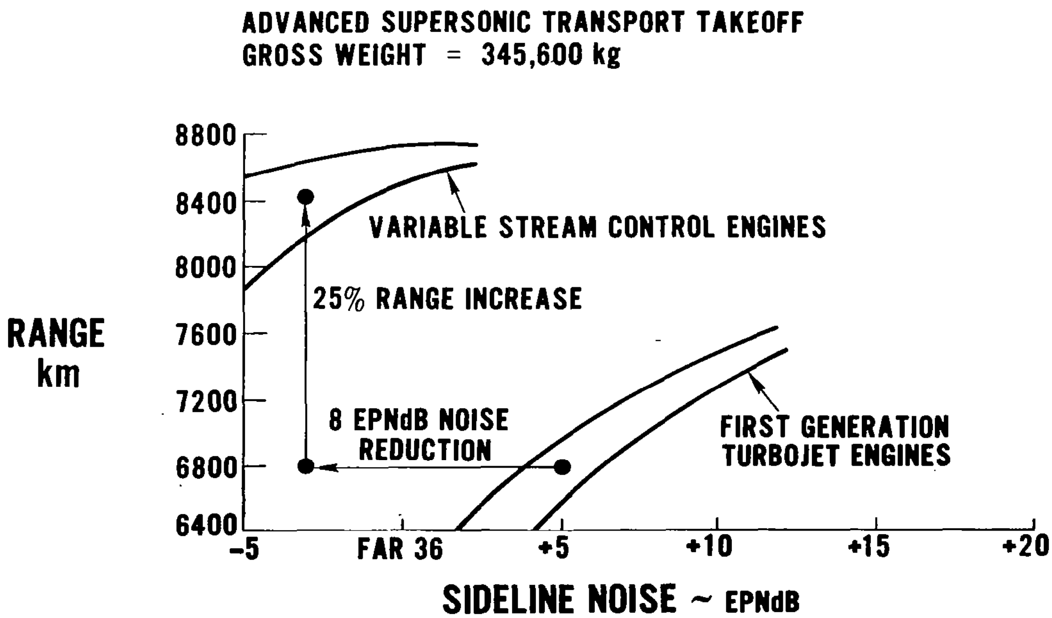
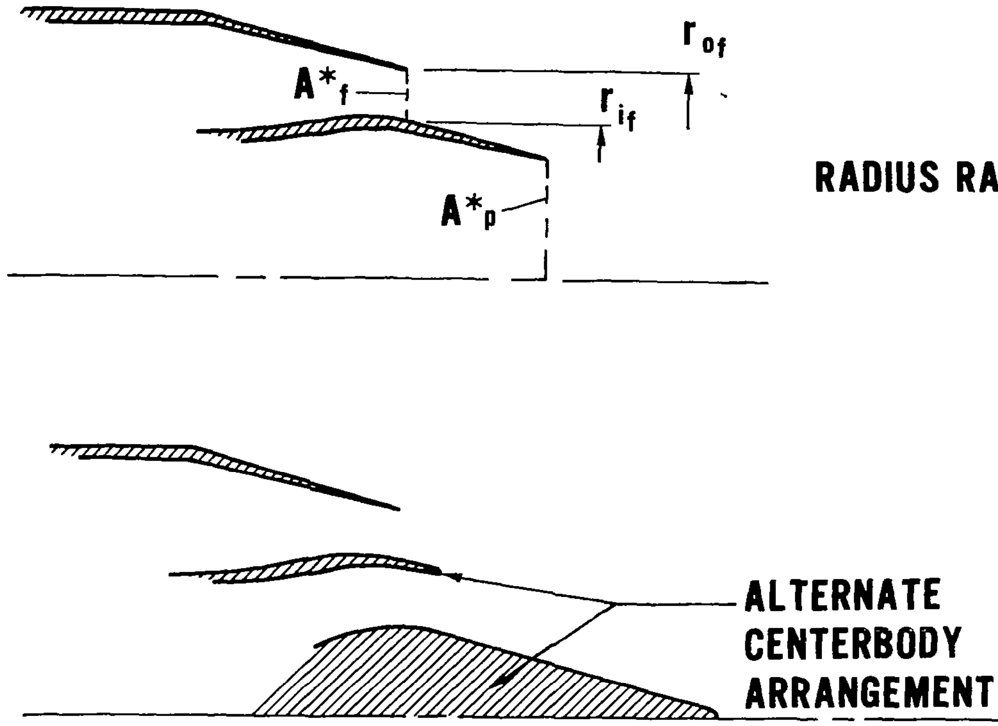


Figure 12.- Potential impact of advanced supersonic technology on aircraft range and noise.



$$\text{RADIUS RATIO} = \frac{r_{if}}{r_{of}}$$

Figure 13.- Variations planned to extend technology base.

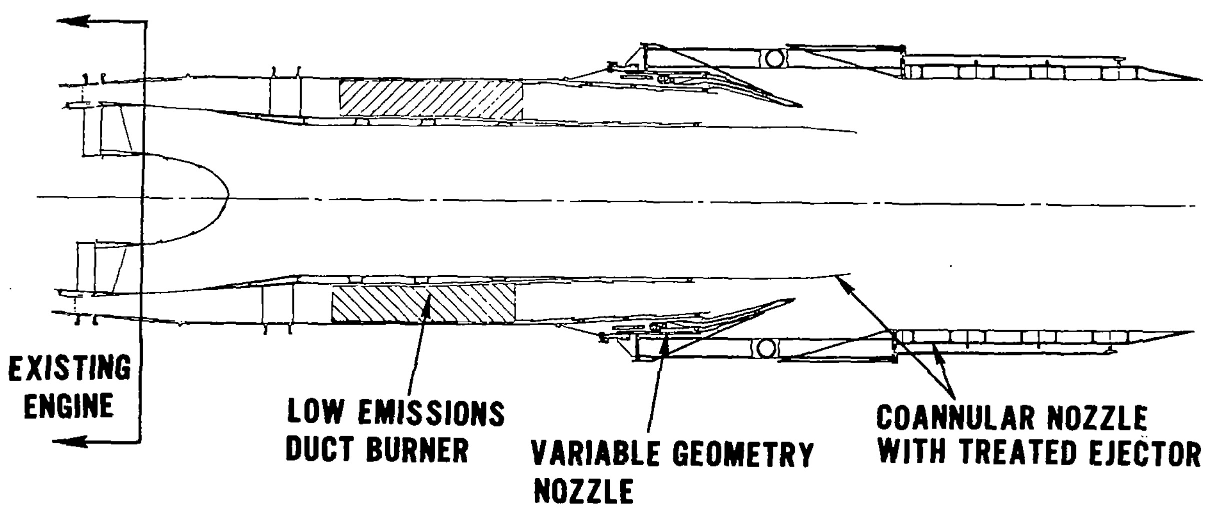


Figure 14.- Critical technology test bed program.