AD NUMBER
ADB004728
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FAA ltr, 26 Apr 1977

Report No. FAA-SS-73-11-1

SST Technology
Follow-On Program—Phase II
NOISE SUPPRESSOR/NOZZLE DEVELOPMENT
VOLUME I

PROGRAM SUMMARY

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D6-60283

March 1975

FINAL REPORT

Task III

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Prepared for
FEDERAL AVIATION ADMINISTRATION
Supersonic Transport Office
800 Independence Avenue, S.W.
Washington, D.C. 20590

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FAA-SS-73-11-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: SST TECHNOLOGY FOLLOW-ON PROGRAM—PHASE II, NOISE SUPPRESSOR/NOZZLE DEVELOPMENT, VOLUME I, PROGRAM SUMMARY		5. Report Date: Mar[redacted]975
		6. Performing Organization Code
7. Author(s): C. D. Simcox, R. S. Armstrong, J. Atvars		8. Performing Organization Report No. D6-60283
9. Performing Organization Name and Address: Boeing Commercial Airplane Company, P.O. Box 3707, Seattle, Washington 98124		10. Work Unit No.
		11. [redacted] DOT-FA-72WA-2893
		13. Type of Report and Period Covered: Final Report, Task III
12. Sponsoring Agency Name and Address: Federal Aviation Administration, Supersonic Transport Office, 800 Independence Avenue S.W., Washington, D.C. 20590		14. Sponsoring Agency Code

15. Supplementary Notes

S. Blatt, DOT/SST Technical Monitor

16. Abstract

An environmentally acceptable SST must have noise levels comparable to those of other large commercial transports operating in the same time period. A program has been conducted investigating a method of reducing high velocity jet noise associated with SST-type engines to levels below current regulations (FAR part 36). The study investigated the following technology areas: noise suppression, nozzle thrust performance, static to flight effects and design/mechanical feasibility requirements. This technology base is believed applicable to any engine cycle having a high-velocity exhaust. The program concluded with static testing of an advanced suppressor nozzle system on a J-58 (turbojet) demonstrating a noise reduction in excess of 16 PNdB for 0.75% thrust penalty at static conditions. These results were then applied to the B2707-300 airplane to indicate the advance in technology achieved by the current program.

17. Key Words	18. Distribution Statement
Supersonic transport Exhaust system Noise suppressor Multitube suppressor ejector	Approved for U.S. Government only. This document is exempted from public availability because of restrictions imposed by the Export Control Act. Transmittal of this document outside the U.S. Government must have prior approval of the Supersonic Transport Office.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	59	

Form DOT F 1700.7 (8-69)

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390145

PREFACE

This is one of a series of final reports on noise and propulsion technology submitted by the Boeing Commercial Airplane Company, Seattle, Washington, 98124, in fulfillment of Task III of Department of Transportation Contract DOT-FA-72WA-2893, dated 1 February 1972.

To benefit utilization of technical data developed by the noise suppressor and nozzle development program, the final report is divided into 10 volumes covering key technology areas and a summary of total program results. The 10 volumes are issued under the master title, "Noise Suppressor/Nozzle Development." Detailed volume breakdown is as follows:

			Report No.
Volume I	–	Program Summary	FAA-SS-73-11-1
Volume II	–	Noise Technology	FAA-SS-73-11-2
Volume III	–	Noise Technology–Backup Data Report	FAA-SS-73-11-3
Volume IV	–	Performance Technology Summary	FAA-SS-73-11-4
Volume V	–	Peformance Technology–The Effect of Initial Jet Conditions on a 2-D Constant Area Ejector	FAA-SS-73-11-5
Volume VI	–	Performance Technology–Thrust and Flow Characteristics of a Reference Multitube Nozzle With Ejector	FAA-SS-73-11-6
Volume VII	–	Performance Technology–A Guide to Multitube Suppressor Nozzle Static Performance: Trends and Trades	FAA-SS-73-11-7
Volume VIII	–	Performance Technology–Multitube Suppressor/Ejector Interaction Effects on Static Performance (Ambient and 1150° F Jet Temperature)	FAA-SS-73-11-8
Volume IX	–	Performance Technology–Analysis of the Low-Speed Performance of Multitube Suppressor/Ejector Nozzles (0-167 kn)	FAA-SS-73-11-9
Volume X	–	Advanced Suppressor Concepts and Full-Scale Tests	FAA-SS-73-11-10

This report is volume I of the series and was prepared by the Noise Technology and Propulsion Research Staff of the Boeing Commercial Airplane Company.

SUMMARY

Engine noise levels were a major problem for the U.S. SST at the termination of the prototype program. The large dry (nonafterburning) engine considered at the time had noise as one of the major constraints in defining its size and cycle. Particular emphasis was placed on the noise generated by the jet exhaust flow. The very high nozzle pressure ratio and exhaust temperature levels make this problem unique among the aircraft of today. For this reason, the Department of Transportation's SST office established a follow-on program to continue the technological development begun during the SST program. This report summarizes the final documentation of that study.

The objective during the current program was to develop a viable nozzle system capable of meeting Federal Air Regulation noise levels (FAR part 36) while minimizing thrust performance penalties. Included in the constraints were size, weight, and aerodynamic and mechanical feasibility considerations.

The approach followed in the program was to develop a theoretical and experimental technology base for the mechanisms of noise generation, suppression, and nozzle aerodynamics. The technology portion of the program is briefly described in volume I and in more detail in volumes II through IX. The technology development led to the construction of design trend and trade curves; these are described in volumes II and IV. Finally, nozzles were built, based on the design guides, and tested model scale. From these configurations a demonstrator system was selected and tested on a full-scale J-58 engine. This configuration, although boilerplate, was designed to meet airplane geometric constraints. This portion of the program is summarized in volume I and reported on in detail in volume X.

The following is a brief summary of the conclusions established during the technology development part of the program.

Noise technology:

- Five major sources of noise were identified and related to flow patterns and properties. These flow characteristics can in turn be related to nozzle geometry.
- The predominant sources, premerged and postmerged mixing noise, are primarily a function of number of elements and nozzle area ratio, respectively. There are optimal values of these parameters for a given set of airplane constraints.
- Acoustic shielding by multielement nozzles was established. Transmission effects were separated from source generation mechanisms.
- Hardwall ejectors were shown to provide additional noise suppression, apparently through a feedback mechanism. Ejectors were also shown to "focus" noise generated inside the ejector to an angle 70° from the jet axis.
- The effects of temperature and velocity profiles and of distributed noise sources on lining effectiveness in ejectors were established.

- Flight velocity effects were shown to be a function of the noise sources present in a particular configuration. These effects can be separated or summed in an analysis procedure.

Propulsion technology:

- Initial jet conditions (jet flow profile, base thickness, and turbulence level) can significantly affect the mixing process in suppressor/ejectors.

- Base drag is the largest contributor to static performance losses associated with multi-tube suppressor nozzles. Base drag is least when tubes are arranged in a radial array to maximize base ventilation.

- Given sufficient mixing length and inlet area, static ejector performance increases in proportion to secondary air handling which in turn is proportional to ejector area ratio.

- Secondary air handling is the dominant factor governing ejector-suppressor performance lapse rate (i.e., the rate of performance decay with forward velocity increases with increasing secondary air handling).

- The static thrust performance gains due to increasing ejector size always cause increasing penalties at some forward velocity because of increasing lapse rates. This trade between static performance and lapse rate must always be considered when selecting the ejector area ratio if the best takeoff performance is to be realized.

A measure of the advancement in the state-of-the-art of jet noise suppressor technology is the confirmation by test results of the predicted acoustic and performance characteristics. The current program has used as a goal the development of the noise and performance technology necessary to establish design trend curves. These curves were used to design and test advanced concepts. The configuration tested full scale was designed to produce 17 PNdB sideline noise suppression with no larger than 2% static thrust penalty.

Model tests yielded 16.4 PNdB at a thrust penalty of 3.2%. Full-scale (J-58) test results for the same configuration yielded 16 PNdB at 0.75% thrust penalty.

The implication of this study is that a suppressor system can be designed that is capable of meeting the required jet noise levels for an SST. Further, the performance characteristics are such that payload/range growth trades are available. It is recognized that future SST's might not have turbojet-type engines (e.g., multicycle or duct-burning turbofan engines). It is believed that whatever cycle is produced will require some jet noise suppression, and further, that this program has generated a technology base that could be applied to any of the cycles.

Recommended further work would include more fundamental studies, including broadband ejector linings, noise/flow mechanisms, initial jet conditions on mixing and ejector performance, temperature effects on ejector performance, and ground-to-flight effects on both noise and propulsion.

Selection of an appropriate engine cycle to give the lowest noise signature for a future SST would be the most efficient method of suppression. Further work in developing these cycles is recommended.

CONTENTS

FIGURES

SYMBOLS AND ABBREVIATIONS

A^*	Nozzle throat area
A_B	Suppressor base area, in^2, A_P(NAR − 1)
A_c	Postmerged jet area
A_E	Ejector flow area
A_J	Fully expanded jet cross-sectional area
AR	Area ratio
A_S	Total area between tubes in multitube suppressor outer tube row
A_8, A_P	Primary nozzle exit area
C_{Fg}	Gross thrust coefficient
CPA	Close-packed array
$C_{V\ int}$	Nozzle internal velocity coefficient; $C_{Fg} + D_{base}/F_{ID}$
dB	Decibel
D_{base}	Nozzle base drag in pounds, calculated from static pressure measurements taken at area-weighted taps on the base
D_c	Diameter of postmerged jet core
D_{eq}	Exit diameter of a single R/C nozzle having the same area as the total effective flow area of a multitube suppressor, in.
EAR	Ejector to primary nozzle area ratio, A_E/A_P
f	Frequency in Hertz
F_{ID}	Ideal primary nozzle thrust; $(W_P/g)V_{ID}$
F_{lip}	Ejector inlet lip suction force, lb; derived from static pressure measurement on lip
F_N	Net thrust
fps	Feet per second

Hz	Hertz, cycles per second
kHz	Kilohertz
kn	Knots
L	Ejector length
L/D	Ejector length-to-diameter ratio
L/D_{eq}	Ejector length to equivalent primary nozzle diameter ratio
L_T	Nozzle tube length measured on the outside of the tube; distance from exit to base plate
M	Mach number
M_J	Jet Mach number
MTW	Maximum takeoff weight
NAR	Nozzle area ratio
N_T	Total number of tubes in multitube nozzle
OASPL	Overall sound pressure level
O/B	Octave band
P	Pressure
P_{amb}	Ambient pressure
PNdB	Units of perceived noise level
PNL	Perceived noise level
P_T	Total pressure
P_{TP}, PR	Primary nozzle pressure ratio
P_{TS}	Secondary nozzle pressure ratio
P_{wall}	Ejector wall static pressure
PWL	Sound power level
RA	Radial array

R/C	Round convergent
Ref.	Reference
s, sec	Second
SB	Setback distance
SL	Sideline
SPL	Sound pressure level
T	Tube
T_J	Jet total temperature
t/m	Turbomachinery noise
T_o	Ambient sea level temperature
TOFL	Takeoff field length
T_T	Total temperature
V_c	Postmerged jet core velocity
V_J, V_{ID}	Fully expanded ideal jet velocity
V_R	Relative jet velocity, $V_J - V_\infty$
V_∞	Freestream velocity (wind tunnel) or airplane forward velocity
Wa	Engine airflow
W_P	Primary nozzle weight flow
ρ_c	Gas density

1.0 INTRODUCTION

Engine noise levels were a major problem for the U.S. SST at the termination of the program. The large dry (nonafterburning) engine considered at that time had noise as one of the major constraints in defining its size and cycle characteristics. Particular emphasis was placed on the noise generated by the jet exhaust flow. The very high nozzle pressure ratio and exhaust temperature levels make this problem unique among the aircraft of today. Reference 1 has addressed the status of jet noise for various types of aircraft.

Unsuppressed noise levels as a function of thrust, estimated for the U.S. SST, based on the planned production model envisioned at the program termination, are shown in figure 1 for approach and takeoff measuring stations. The jet noise obviously dominated, especially for the sideline and cutback conditions during takeoff. Thus for a successful supersonic transport, concepts must be developed for reducing jet noise very significantly to make the operating noise levels comparable to those of other large commercial transports that will be operating in the same time period. The reductions must be accomplished with minimal performance loss and in a manner to permit growth versions of the initial airplane.

Reference 2 discussed the principles of suppression, the types of engines to be suppressed, the factors to be considered in selecting and designing a suppression system, typical types of suppression systems being considered, and finally the economic impact of suppression systems. That discussion emphasized the need for a systems approach in determining the suppressor; the engine and airplane constraints must be considered in choosing a suppressor design that achieves the required noise reduction with minimum overall airplane performance penalty. No attempt is made in this program to select an engine cycle or type. Rather the large dry turbojet cycle considered at the termination of the U.S. SST program is used as a common vehicle to measure the advances in suppression technology. It is noted in reference 2 that bypass and multicycle engines are believed to require jet suppression, albeit less than that required for turbojet engines.

Suppressor technology has been derived that will allow an SST to meet FAR part 36 noise regulations. This report summarizes the advances resulting from an intensive program conducted at Boeing under this contract. A detailed accounting of the results of the program is provided in volumes II through X.

The basic suppression concept pursued in these studies consisted of a multitube mixer nozzle with or without an ejector shroud. Both hardwall and acoustically lined ejectors were investigated. The multitube concept was chosen because past studies (refs. 3, 4) have shown it to be the only known way to achieve high noise suppression levels at supersonic jet velocities. The program consisted of approximately two years of technology development and was culminated by a full-scale demonstrator nozzle system tested on a J-58 engine. A brief summary of the technology program is presented first, then the results of the demonstrator nozzle are shown.

2.0 JET NOISE SUPPRESSION TECHNOLOGY

The basic philosophy was to associate the geometric variations of nozzles and ejectors to flow patterns and these in turn to mechanisms associated with noise as described in volume II. In order to achieve this goal, a systematic, model-scale, experimental program was conducted to study the different jet noise sources by varying one test or geometric parameter at a time and then synthesizing the results to create a physical model of jet noise generation and suppression. The experimental program was supplemented with analytical studies to establish a solid foundation in areas where previous work was lacking.

2.1 MULTITUBE NOZZLES

The main emphasis in the experimental program was placed on static acoustic testing of parametrically related multitube nozzles and hardwall ejectors (sec. 4, vol. II). Thrust performance data were always acquired in conjunction with the acoustic data to assure data repeatability and to establish test conditions accurately.

In addition to the controlled nozzle parametric studies, more involved multitube suppressor designs were tested to establish the relative importance of various techniques for controlling the acoustic energy after it has been generated by the jet. Acoustic effects of temperature and velocity profile control were also studied (sec. 4.5, vol. II).

Insight into the jet noise-generating mechanisms was gained through studies of noise source frequency distributions along the jet axis using the wall isolation technique of reference 5. Examination of the jet wake was also conducted by measuring mean flow properties in both radial and axial directions and thus observing the mixing properties between the primary jet and ambient atmosphere (sec. 4.6, vol. II). This approach led to the identification of the various noise-source components with certain jet-flow regions as shown in figure 2. The studies have revealed the following jet noise sources (fig. 3) to be present in the supersonic multitube suppressor system's noise spectra:

1. Elemental jet premerging (and merging) turbulence noise
2. Postmerged jet turbulence noise
3. Spiral-mode flow-instability noise
4. Shock (screech) noise
5. Facility/engine core noise

The spectral characteristics of these noise sources are shown in figure 4.

The multitube nozzle jet premerging turbulence noise has a broadband spectrum producing the high-frequency peak of the composite jet noise spectrum. Noise level from this region is a product of the outer row of elemental jet mixing. Noise produced by jets within the nozzle array appear to be effectively *shielded* by the outer row jet turbulence, as will be discussed later.

A generalized spectrum shape of premerged jet noise is shown in figure 5. The peak frequency of premerged jet turbulence noise can be estimated by the following empirical equation:

$$f = \frac{(0.6 - 0.0043N_T)V_J}{d\left(\frac{A_J}{A^*}\right)^{0.5}\left(\frac{T_T}{T_o}\right)^{0.5}}, \text{ Hz}$$

where

- N_T is number of tubes in the array.
- d is the tube exit diameter.
- A^* is nozzle geometric area.
- A_J is fully expanded flow area.
- V_J is jet velocity.
- T_T is jet total temperature.
- T_o is ambient temperature.

Premerged jet noise PWL can be *normalized* by subtracting 10 log $(\rho + \rho_o)^2 A_J$ as shown in figure 6. This approach does not work for small area ratios where the elemental jet cores penetrate the postmerged jet region thus transferring jet kinetic energy from the premerged jet region to the postmerged jet region.

The multitube-nozzle jet postmerging noise radiates from a region which has flow similarities to a simple jet. The merged elemental jets form a low-velocity core of diameter equal to $(4A_8\ AR_8/\pi)^{0.5}$ where A_8 and AR_8 are nozzle exit area and area ratio respectively. Flow-profile measurements show that the gas conditions in the postmerged jet core correspond to the average gas conditions of a simple jet which has mixed and expanded to the same diameter as the postmerged jet core. The postmerged jet turbulence noise has characteristics similar to a simple jet and agree with theoretical predictions. Postmerged jet turbulence sound power levels can be normalized, as for a simple jet, by subtracting 10 log $\rho_c^2 A_J$ where ρ_c is the gas density in the postmerged jet core. Figure 7 shows a comparison of normalized test data with predicted levels for a "clean jet." The deviations of test data from the predicted levels at the lower jet velocities are due to the test facility's burner/core noise. A generalized spectrum shape for postmerged jet noise is shown in figure 8.

Postmerged jet turbulence peak frequency can be estimated by the empirical relation:

$$f = \frac{0.22\ V_c}{D_c}, \text{ Hz}$$

where

- D_c is the diameter of the postmerged jet core, i.e., $(4A_8\ AR_8/\pi)^{0.5}$
- V_c is the postmerged jet core velocity.

Spiral-mode flow-instability noise postulated by Christopher Tam (ref. 6) for R/C nozzle supersonic jets has been identified in multitube nozzle acoustic data also. This noise appears in the high frequency portion of the spectrum radiating in the direction of 90° to the nozzle inlet. Spiral-mode flow-instability peak frequency observed in the test data correlates well with predictions using a simplified form of Tam's equation:

$$f = \frac{1.202\, a_o}{d}\left[\left(\frac{M_J + 1}{M_J - 1}\right)\right]^{0.5} \times \left(1.436 - 0.361\,\frac{V_J}{a_o}\right)^{-1},\ \text{Hz}$$

where

- a_o is the speed of sound in air.
- d is the fully expanded flow diameter of an elemental jet.
- M_J is jet Mach number.
- V_J is the fully expanded jet velocity.

Spiral-mode flow-instability noise can have adverse effects on peak perceived noise levels and noise duration for supersonic jet conditions.

Shock or screech tones were present in the baseline R/C nozzle test spectra at supersonic jet velocities. For cold and low-temperature jets, shock noise was also detected in the multitube nozzle spectra. The multitube nozzles, however, showed no tendency to radiate shock noise under hot-flow conditions. When the spiral-mode flow-instability noise frequency coincided with the shock noise frequency or its harmonics there was significant amplification of both noise components. The following empirical equation has been derived from test data to predict the fundamental screech tone frequency in jet noise spectra.

$$f_M = \frac{a_o}{K\, d(PR - 1.89)^{0.5}},\ \text{for } PR > 1.89$$

where

a_o	=	speed of sound
d	=	fully expanded jet diameter from each tube or nozzle
PR	=	nozzle pressure ratio
K	=	constant
	=	1.57 for R/C nozzle
	=	2.74 for multitube nozzles

Hot jet model-test facilities as well as full-scale turbojet engines have low-frequency core noise radiating out of the exhaust nozzle which is associated with engine internal components such as burners, flow passages, and structural obstructions. This noise can only be detected at lower jet velocities. Core noise can be a problem in multitube-nozzle, postmerged jet noise analysis, because both occur in the same part of the frequency spectrum.

The amount of jet noise suppression that can be attained at a given jet velocity then depends on the judicious balancing of these various noise components.

2.2 MULTITUBE JET NOISE SHIELDING

Many investigators in the past have conjectured that the observed premerged jet noise-suppression characteristics of multitube nozzles were due to some form of shielding of the noise from the central cluster of jets by the outer row of jets.

Middleton and Clark (ref. 7) have suggested that the flow from a multitube nozzle which is visible to the observer is chiefly responsible for the noise radiated to the far field from the premerged jet region.

Gray, Gutierrez, and Walker (ref. 8) propose a premerged jet shielding hypothesis which assumes that noise generated within the jet cluster of a multitube nozzle cannot radiate through the outer mixing zone of a jet in the outer row. In order to achieve shielding it is further assumed that the spreading initial mixing zones of adjacent outer jets merge and form a *scalloped* shield upstream of the axial location of maximum noise generation. The spreading scalloped shield region generates the premerged jet noise observed by a far field observer.

Studies were conducted in this program to look into these shielding concepts to gain a better understanding of the noise suppression mechanisms of multinozzle jets. Tests were run with a multitube nozzle where the jet flows in the outer row of 24 tubes could be controlled independently of the central cluster of 37 tubes. An example of the results obtained is shown in figure 9.

The low-frequency peak of the spectrum, caused by the postmerged jet turbulence, experiences a large reduction in level when only the outer row of 24 tubes is operating. There is no significant difference in the premerged jet noise level apparent between the 24-tube and 61-tube cases. This provides good support to the argument that the outer row of jets from a multitube nozzle can effectively shield the premerged jet noise generated by the innermost jets. However, the total premerged jet noise power level measured for the annulus of 24 jets is 9.6 dB less than expected from an equivalent number of isolated jets. Neither method from references 7 or 8 comes close to predicting this amount of jet noise suppression. Consequently it is thought that in addition to the geometric shielding proposals of references 7 and 8 other mechanisms due to acoustic and/or flow-mutual coupling between adjacent jets have to be considered.

In addition to the above noise shielding effects which are inherent in all multitube jets, additional shielding benefits can be gained by controlling the jet velocity and temperature in the outer row of jets relative to the central cluster. For example, a higher temperature but lower velocity annulus of outer jets can be used to increase the shielding of the noise from a high-velocity cluster of core jets. Figure 10 illustrates a typical case where the lower velocity flow from the outer row of jets shields the higher noise levels originating from the central cluster of 37 tubes. Several other important characteristics can be observed in figure 10. The central array jets tend to dominate the 90° to 130° arc noise level, while the outer row jets tend to dominate the 140° to 160° arc noise level. The central-array jet noise is attenuated in the 90° to 120° arc by the outer row jet flow due to acoustic impedance (ρc) mismatch and turbulence scattering. In the 120° to 160° arc the central-array jet noise is greatly attenuated by severe refraction and reflection of noise by the outer row jet flow. There is probably a relative velocity effect on central-array jet noise levels which will tend to decrease that source of premerged jet noise also. There may be mutual coupling effects (flow and/or acoustic) between the outer row of jets and the inner array of jets which will affect premerged jet noise levels. The test data from this program, however, are insufficient to resolve quantitatively all the mechanisms involved in dual-flow premerged jet noise characteristics.

2.3 MULTITUBE NOZZLES WITH EJECTORS

Typical SST engine installations require convergent-divergent nozzles for supersonic cruise. During takeoff the divergent portion of the exhaust nozzle is not used and generally serves as an ejector relative to the primary nozzle or for the multitube suppressor nozzle if one is installed. Consequently it is important to understand the impact of an ejector on the noise suppression characteristics of multitube nozzles and take advantage of them to further increase the jet noise suppression of the total system. It has been found that a properly sized hardwall ejector can improve noise suppression and secondly, the ejector provides a natural location for acoustically absorbent wall linings that will further attenuate the jet exhaust noise. The acoustic lining effectiveness, however, is severely limited by the relative balance of the jet noise generated within the ejector and that generated downstream of the ejector exit plane.

Noise generated by multielement jets surrounded by a hardwall ejector normally propagates downstream beyond the ejector exit and into the far field unaffected. When the ejector fits tightly around the jet efflux, the velocity of secondary flow between the elemental jets and ejector wall increases, providing some reduction of premerged jet noise due to a relative velocity effect. Properly sized "tight" ejectors have shown additional premerged jet noise suppression beyond what can be expected from the relative velocity effect. It is thought that under certain geometric conditions, noise reflections from the ejector wall back to the source region may be affecting the noise generation process as implied by the sharp attenuation peak for the 2.6 AR ejector in figure 11. It can also be seen that fully mixed ejector configurations will reduce the postmerged jet noise, probably due to a lowering of the kinetic energy in the postmerged jet.

Ejectors exhibit a very pronounced high-frequency directivity characteristic as shown in figure 12. The premerged jet noise that normally has a broad radiation pattern is refracted away from the jet axis to appear mainly at angles between 90° and 120° from the engine inlet. In all ejector test configurations a sharp peak at about 110° has shown up in the directivity patterns which invariably penalizes the sideline perceived noise levels which are important for noise certification purposes. This peak at 110° is associated with the refraction characteristics of the ejectors as shown in figure 12. Through the use of a jet isolation technique (ref. 5), noise measurements were made for that portion of the jet that exists beyond the ejector exit plane. It can be seen that the jet noise that is attributed to being generated inside the ejector radiates mainly to angles away from the jet axis, peaking at 110°.

2.4 MULTITUBE NOZZLES WITH ACOUSTICALLY LINED EJECTORS

Jet noise source location studies have shown that for multitube jets the high-frequency premerged jet noise sources occur relatively close to the nozzle. This close proximity allows for the successful use of acoustic linings in the ejector walls to further attenuate some of the jet noise. In general, the acoustic lining techniques developed for turbofan engine fan noise absorption in inlet and exhaust ducts have been found to be applicable in the ejector jet noise environment. The major differences that have to be accounted for are the distributed nature of jet noise sources, the flow gradients in the ejector (sec. 5, vol. II) and the knowledge of noise source locations so that the acoustic lining can be properly tuned. There is, however, a limitation imposed on the maximum attenuation that can be observed in the far field due to the jet noise sources that occur downstream of the ejector exit.

2.5 FLIGHT EFFECTS ON JET NOISE SUPPRESSION

An acoustic test program has been conducted in a low-speed wind tunnel to determine forward flight effects on jet noise suppression at velocities typical of aircraft takeoffs (sec. 4.7, vol. II). The acoustic flight effects are summarized in figure 13 for a representative case of an unsuppressed nozzle, a multitube nozzle, and a multitube nozzle with a hardwall ejector.

For the R/C nozzle, the jet noise at the peak noise location is reduced by flight velocity in accordance with relative velocity. That is, the spectrum shape and level, OASPL, and PNL can be estimated by operating the nozzle statically at the flight relative velocity. The flight effect at angles toward the inlet quadrant is dependent upon the presence or absence of shock noise and spiral-mode flow-instability noise. At subsonic or low supersonic jet conditions the in-flight noise will follow relative velocity at all angles. Where strong shock noise is present the in-flight noise will be reduced by a smaller amount, depending upon the contribution of the shock noise to the total noise signal. Test results indicate that shock noise is little changed by external flow.

The multitube nozzle suppressor results have to be examined separately for the premerged and postmerged jet noise. The low-frequency postmerged jet noise has properties similar to a simple jet and consequently this noise component follows the relative velocity defined as ($V_{R\ POST} = V_{J\ MIX} - V_{\infty}$). This relationship holds for the suppressor with and without the ejector. The high-frequency premerged jet noise is dominated by the noise from the outer row of jets. The premerged jet mixing noise is reduced in flight generally in accordance with the relative velocity of the outer row of tubes. The mixing noise appears to follow a V^8 type of reduction, therefore, the total noise from a multitube nozzle without an ejector also follows the above relative velocity relationship.

Multitube nozzles with ejectors do show a velocity effect depending on the ejector area relative to the nozzle flow area. The velocity effect is only associated with the premerged jet noise that is generated inside the ejector. That is to say, a small area ratio ejector experiences a very small change in relative velocity, while a large area ratio ejector experiences a moderate change, as shown in figure 13. This comparison shows that suppression potential is significantly reduced in flight as jet velocity (pressure ratio) is reduced and that the reduction is greater for the shrouded configurations.

3.0 SUPPRESSOR PERFORMANCE TECHNOLOGY

An advanced supersonic aircraft requires a variable convergent-divergent nozzle geometry to provide near-ideal engine exhaust expansion for maximum thrust performance at supersonic cruise. During takeoff a suppressor can be used in conjunction with an ejector, formed by the divergent part of the exhaust system, to provide required noise suppression and good takeoff thrust.

A critical factor in the development of jet noise suppression devices for exhaust nozzle systems is the maintenance of acceptable levels of thrust performance over the flight regime. Application to advanced supersonic aircraft demands that the suppressor cause little or no performance loss at cruise conditions. This constraint generally means that the suppressor must be retracted out of the jet stream at other than takeoff and approach flight modes, and this in turn severely limits the range of suppressor hardware parameters that can be considered for practical configurations.

This chapter provides an overview of the technology program that has been directed toward the establishment of performance design guidelines within mechanical design constraints and acoustic criteria for low-noise multitube suppressor exhaust systems. A complete summary of the performance technology program is provided in volume IV.

A matrix of multitube suppressor configurations was tested at model scale to develop a detailed understanding of performance loss mechanisms for design trade studies. Major parameters included number, length and array of tubes, size (area ratio) of array, and the effects of the addition of ejectors and of forward speed. Additional experiments were conducted to study detailed mixing phenomena in ejectors including evaluation of initial flow conditions on mixing and performance in a two-dimensional model and secondary air handling characteristics of axisymmetric configurations. The 2-D test program used a multi-slot nozzle and ejector to determine the effects of initial flow characteristics (velocity profiles, turbulence levels, initial base thickness) on ejector thrust augmentation, secondary air handling, and mixing rates.

3.1 EJECTOR MIXING STUDY

A two-dimensional ejector test setup was used to investigate the effects on initial jet flow conditions on mixing and ejector performance. An ejector apparatus was fabricated for use on the Boeing high ratio rig which consisted of an array of slot nozzles exhausting to a mixing section of rectangular cross section. Two opposite sides of the mixing section were of clear plastic to permit spark shadowgraph photos to be taken of the mixing flow. Both primary and secondary flows were metered and entered the mixing section through the nozzle assembly as substantially uniform and parallel flows.

Base thickness was varied by chamfering the plates separating primary and secondary streams. The velocity profile variation was accomplished by lengthening the nozzle throat, thus producing a larger initial boundary layer thickness. Turbulence intensity was changed by insertion of upstream blockages into the primary flow. Testing was conducted at ambient primary and secondary flow temperatures over a range of primary pressure ratios from 2 to 4.

The pressure of the secondary flow entering the mixing section was maintained equal to ambient.

Figure 14 is a comparison of ejector wall static pressure distribution as affected by the initial flow condition changes for pressure ratio 4. At low pressure ratios (not shown here but discussed in volume V) trends were undistinguished with minimum pressure occurring near the nozzle exit followed by a continuous rise to ambient at the ejector exit.

At the PR = 4 condition the static pressure remains relatively constant at a low level for some distance downstream. It then rises very steeply to ambient pressure at the exit. The axial location of this pressure rise is definitely affected by the initial condition of the primary flow. A high initial turbulence level permits the low ejector pressures to be maintained farther downstream than for any other configuration.

It was concluded from these results that differences in the initial flow condition could be important when comparing nozzle data from different facilities and further that these effects may be responsible for a part of the difference seen in comparison of scale-model performance with the full-scale suppressor testing reported on in volume X.

3.2 MULTITUBE NOZZLE/EJECTOR STUDY

A three-part experimental program investigated detailed performance mechanisms for a wide range of multitube suppressor/ejector geometry, jet conditions, and the effect of forward speed.

3.2.1 TEST PROGRAM DESCRIPTION

Multitube suppressor/ejector performance is dependent upon numerous geometric parameters as well as jet conditions and flight effects. A three-part set of experiments was conducted to investigate important parameters and establish performance design criteria for multitube suppressors. Initial testing considered the static performance interactions of suppressors without ejectors. Principal geometric variables were tube number, tube length, and nozzle area ratio and the array of placement of tubes.

The second test series studied the effects of ejector addition to the suppressors. Along with the nozzle parameters as before, ejector geometry variations included ejector area ratio, ejector length, and inlet area (controlled by ejector lip setback from the nozzle tube exit plane).

The concluding tests were conducted in the 9- by 9-ft low-speed wind tunnel to investigate flight effects. The same test hardware and geometry variations were considered as above.

Wind tunnel testing covered a range of velocities from 30 to 167 knots. All three test series investigated a range of pressure ratios from 2 to 4 at ambient and 1150°F jet temperatures.

3.2.2 MULTITUBE NOZZLES

To make the separation of variables manageable and avoid "cut and try," constraints were introduced to give the nozzles a family relationship. Suppressor tubes were arranged in two patterns. The first array of nearly equal tube spacing represented the most compact regular array of tube placement. This type of array as shown in figure 15 is referred to as a close-packed array. The other array in figure 15 is a radial array, deriving its name from the placement of tubes on radial lines to maximize the ventilation in the outer rows and minimize ventilating flow field obstructions.

The performance of multitube suppressor nozzles is strongly influenced by the lower-than-ambient pressure acting on the base area between nozzle elements. The reduced pressure is the result of air entrainment of each of the discrete primary jets. The extent of pressure reduction is largely dependent upon the ability to provide a sufficient quantity of ambient air to ventilate the base area which is heavily influenced by the geometry (array) of the jet elements.

A convenient measure of the amount of ventilation on any given nozzle is the physical ventilation parameter, A_S/A_B, where A_S is the total area between tubes in the outer row and A_B is the base area that must be ventilated. This parameter and another parameter including the area between the jet wakes have been used previously (ref. 9) in attempts to nondimensionalize base drag parameters. Figure 16 shows the ventilation parameter per unit of tube length as a function of tube number, area ratio, and tube shape. High ventilation parameters are associated with minimum base drag. It is most convenient that the physical ventilation parameter is reasonably independent of tube number. Tube length can be varied to acquire a wide range of A_S/A_B. The validity of the ventilation parameter as a base drag nondimensionalizer can be easily tested by varying tube number at a fixed tube length and area ratio.

The effect of area ratio on ventilation is very pronounced. For very small area ratios, the tubes touch and thus completely eliminate ventilation. The resulting $A_S/A_B = 0$ has the physical significance that the base area, though small, is going to feel a very low pressure, resulting in high base drag. At the other extreme as area ratio becomes very large there is plenty of area between the tubes to allow ventilating air onto the base but the base area becomes so large that small static pressure depressions due to the velocity of the air penetrating the base region result in a large base drag. Figure 16 shows that for close-packed arrays, the optimum ventilation parameter is primarily a function of tube shape. Thus the minimum base drag could be expected to occur near AR 5.0 for R/C tubes and AR 3.0 for elliptical convergent tubes or round, nonconverging tubes.

The ventilation parameter for the radial array is shown to increase rapidly as the area ratio is reduced, limited only by the minimum area ratio it is possible to build, i.e., by the space available between tubes. This suggests that optimum ventilation for a fixed stowable tube length requires a small area ratio radial array. Base drag becomes less sensitive to these parameters as tube length is increased beyond the stowable limits.

An example of the distribution of performance losses for multitube nozzles is shown in figure 17. The close-packed and radial array nozzles cited were designed with identical tube shapes so that the internal tube performance $C_{V\ int}$ is the same. Base drag, expressed as a percentage of ideal thrust, is seen to be the major loss contributor for short stowable tubes.

3.2.3 BARE SUPPRESSOR PERFORMANCE TRENDS

Overall performance trends for bare tubular suppressor nozzles within this study are established in volume VII. An example of these trends in figure 18 shows that tube number and especially length (which controls base ventilation) are the strongest performance variables for close-packed arrays. Where short (stowable) tubes are a configuration requirement, the use of radial tube arrays offers large performance improvements.

3.3 SUPPRESSOR/EJECTORS

3.3.1 RANGE OF VARIABLES

The suppressor nozzles discussed in section 3.2.2 were tested with a series of ejector configurations that encompassed practical hardware limits for SST engine application. The ejector area ratio was varied from 2.6 to 3.7. The majority of ejector studies were conducted with an ejector area ratio of 3.1 which is approximately the size anticipated for a practical SST installation. The smallest ejector was tested only with the 2.75 area ratio nozzles whose tube exit arrays fit within the ejector diameter.

The largest ejector area ratio tested was 3.7. Ejector length was varied from a scaled practical installation length of 8 in. to 24 in. ($L/D_{eq} = 2$) to establish performance trends with mixing length.

Ejector setback, defined as the axial distance from suppressor tube exits to highlight of the ejector lip, was varied from 0 to 1 in. ($SB/D_{eq} = 0$ to 0.25) for most configurations to ensure determination of performance with adequate ejector inlet area.

3.3.2 SUPPRESSOR/EJECTOR PERFORMANCE TRENDS

Setback was shown to be the strongest geometric parameter affecting performance because it directly affects the inlet area. The general trend of inlet area effect on performance is shown in figure 19.

If the inlet area is too small and choking occurs, the performance is severely penalized. Since the ejector air demand is a function of the nozzle operating conditions (e.g., pressure ratio and temperature) inlet choking may not be present except for certain limiting conditions. For this reason it is extremely important in the development of ejector-suppressor configurations that testing and analysis encompass the entire range of expected inservice operating conditions.

A chart format of data presentation has been developed in this program which shows general performance trends over a broad range of suppressor and ejector geometries. Each summary chart considers a particular suppressor array and identifies performance trends as a function of nozzle tube length, ejector area ratio and setback. The summaries for all nozzle configurations provided in volume VIII are based on a nozzle pressure ratio of 3 and ambient jet temperature. Hot jet effects are shown on the charts for representative configurations.

A sample summary performance chart is shown in figure 20. The example is based upon the 37-tube, NAR 2.75 close-packed array suppressor. The numbers within the boxes at the left of the chart are measured static gross thrust coefficients for the bare suppressor (primary alone) with various tube lengths. The effect of adding ejectors of increasing size is shown in the boxes to the right for the suppressor with given tube length. Performance with ejector setback of $SB/D_{eq} = 0.25$ is depicted in the dashed-line boxes. The arrows on lines connecting the boxes show the direction of increasing performance; the amount in percent is also shown.

3.4 LOW-SPEED PERFORMANCE

3.4.1 RANGE OF VARIABLES

The investigation of low-speed performance was conducted in the 9- by 9-ft induction wind tunnel at Boeing and is described in volume IX. Testing covered a range of pressure ratios from 2 to 4 at ambient jet temperatures. Limited testing at hot jet, 1150° F, conditions showed performance/noise trends although budget constraints did not allow for sufficient data to be taken to generalize the results. Suppressor and ejector hardware were the same as in the earlier static testing and similar geometric variables were examined.

Figure 21 typifies the results of these experiments and demonstrates an interesting characteristic of flight effects on ejector performance. First, the results shown are for a particular 31-tube nozzle with constant ejector length and various ejector area ratios. As expected, increasing ejector area ratio (EAR) at static conditions from 2.6 to 3.1 increases thrust due to increased secondary air handling, i.e., acceleration of induced ambient air producing thrust augmentation relative to that of the primary jet thrust. An apparent anomaly is observed since the static performance with a 3.7 AR ejector is less than that with a 3.1 AR ejector. This can be explained by the fact that the ejector length was insufficient to optimize mixing and thus thrust for this "large" ejector. It is also observed that the lapse rate, rate of decrease in performance with increasing external velocity, increases from the no ejector case to increasing EAR except that lapse rate decreases at EAR = 3.7 to the approximate level of the EAR 2.6 configuration. The lapse rate is almost entirely due to the air-handling capability of the ejector and independent of losses of the suppressor nozzle as illustrated by the following example.

3.4.2 EJECTOR PERFORMANCE EFFECT

Figure 22 shows the effect of ejector length on lapse rate for a 37-tube nozzle with a 3.7 AR ejector. Although the static performance is much lower for the short L/D = 1 ejector, the lapse rate is also lower than that when L/D = 3. The loss in performance between static and 160-kn conditions is seen to be 6% for the L/D = 1 ejector and 11% for the L/D = 3; a difference in lapse rates of 5%.

Integration of measured pressure distributions over the nozzle/ejector surfaces provides the component forces summarized in figure 23. Changes in ejector lip suction are shown in the example to be the dominant factor accounting for the difference in lapse rate.

In the example, the ejector is sufficiently large in diameter that the jets do not impinge upon the ejector lip and therefore the ejector lip force at static ambient conditions can only be attributed to induced secondary flow into the ejector. The effect of forward velocity is to reduce ejector inlet recovery and thus the secondary air handling. This in turn is reflected by the decreasing lip suction forces with forward velocity shown in figure 23.

4.0 MECHANICAL DESIGN CONSIDERATIONS

The design study (sec. 4.0, vol. X) was based on use of a nonaugmented GE4/J6H2 turbojet engine. The suppressor system was designed to be stowed into a variable convergent-divergent ejector nozzle during cruise-flight conditions in order that high performance could be maintained.

The number of tubes, length of tubes, and pattern of array for the suppressor are usually selected as the best compromise to achieve the noise reduction and thrust loss goals. The sizing and position of the shroud and secondary nozzle are selected to optimize nozzle performance within the constraints of the suppressor size, the space for stowage of suppressor, and the nacelle boattail considerations.

The parametric data from model tests showed that a suppressor with an area ratio of 2.9 and 56 tubes approximately 10 in. long and 3.1 AR ejector would satisfy the noise and performance goals.

The exhaust system having a maximum diameter of 100.0 in. attaches to the engine's aft-turbine flange and extends aft approximately 15.5 feet. Four longerons form the backbone of the exhaust system and transmit all loads from the thrust reverser, jet suppressor, and cruise nozzles to the main engine structure.

The exhaust system, of titanium and inconel, was configured to include a clamshell thrust reverser with cascade exits, a variable-area primary nozzle, a tube-type suppressor capable of being stowed, a convergent-divergent ejector nozzle with a variable throat and closure doors for the ejector inlet. Figure 24 is a schematic showing this system as configured to match the GE4/J6H2 engine.

A conventional-type clamshell thrust reverser, upstream of the primary nozzle, diverts the exhaust flow through cascade units in the upper and lower quadrants. This type of reverser is reliable and efficient, and the development and manufacturing aspects are well known. The side quadrants house the hydraulic actuation system for the reverser and contain ducts to carry secondary cooling air to the primary nozzle.

The 16-segment variable-area primary nozzle controls the engine flow area during all cruise regimes (subsonic and supersonic). During suppressor operation the nozzle segments open wide to seal against the outer lip of the suppressor and thereby complete the exhaust passage to the suppressor. Individual nozzle segments are interconnected through links to a unison ring which is moved by hydraulic actuators in a track supported under the longerons. The primary nozzle assembly is mounted on a bulkhead ring which is supported by the main longerons of the exhaust system. The bulkhead ring also serves as the aft portion of the thrust reverser.

The convergent-divergent ejector nozzle system requires control of its air inlet so that it is open during takeoff and approach and closed during cruise. This is accomplished by hinged doors in the front portion and a translating cowl ring in the aft portion. Each of the four quadrants between the longerons of the nacelle contains four hinged doors of the overlapping segment type. These doors are supported from a frame between the longerons and are operated by individual hydraulic actuators. The translating cowl ring is retained in tracks attached to the longerons and operated by ballscrew jacks driven by the suppressor segment actuators discussed below. When the system is closed for cruise the hinged doors are secured against the lip of the translating cowl and between translating cowl and ejector leading edge.

To enable the suppressor to be stowed during cruise it is divided into four hinged pie-shaped segments, each of which contains 14 tubes. The tube array has elliptical tubes on the outer row and circular tubes of two sizes on the inner rows. Tube lengths vary from 13.5 to 7 in. with the longest in the outer row. The elliptical tubes are of a constant section while the circular ones have conical nozzles at their ends. Each segment is structurally designed to carry the nozzle loads across the forward face of the tube array to the pivot bearings supported at each side through hinged links attached to the longerons of the exhaust system.

The convergent-divergent secondary nozzle and 3.1 AR shroud has 24 segments, the inner and outer surfaces of which are capable of independent motion, to provide the throat and exit configurations required during takeoff/landing, subsonic, and supersonic cruise. Each of the 24 inner segments is attached to its corresponding outer segment of pin joints at the aft end, while being independently hinged at the forward end. The inner surface segments are supported at the forward end by lever arms hinged from the front main frame which attaches to the longerons. The outer surface segments are hinged at the forward end from the rear main frame. Separate unison rings secure the inner segments and outer segments to their respective hydraulic actuation systems. Acoustic treatment is provided on the internal surfaces of alternate inner segments only, as considerable segment overlap is required to accommodate the diameter change between cruise and suppression positions. This treatment provides 45 ft^2 of lining with depths varying from 2-1/2 to 1 in.

The design studies have resulted in a suppressor system concept believed to have practical application to the exhaust system of a supersonic airplane propulsion installation. The area ratios of the suppressor and ejector fall within the constraints of nacelle size. Its performance is expected to meet noise reduction and performance goals. The envisioned manner of stowage of the suppressor permits cruise performance to be maintained without penalties.

5.0 SUPPRESSOR SYSTEM DEMONSTRATOR PROGRAM

The scale-model parametric testing and mechanical design studies led to the design and test of a full-scale fixed-position boilerplate suppressor-ejector nozzle in order to provide a static. noise/performance demonstration of SST state-of-the-art suppressor nozzle technology. The full-scale jet noise suppressor system demonstrator design (sec. 2, vol. X) resulted from trade studies that took into account mechanical feasibility, thrust performance, and acoustic requirements. From the jet noise point of view the jet flow beyond the nozzle exit plane had to be decelerated as rapidly as possible. This can be achieved by the use of multitube nozzles which enhance the normal mixing process with the ambient air. A large number of nozzle elements of small size are required to reduce the high-frequency (premerged) jet noise. A large nozzle area ratio is required to reduce the low-frequency (postmerged) jet noise. In order to maximize low-frequency noise suppression for a given nozzle area ratio the primary jet flow should be evenly distributed across the nozzle array.

A family of acoustic design curves derived from the technology studies (fig. 25) was used to choose the basic suppressor nozzle geometry of tube number and area ratio which, when configured to maximize thrust performance, gave an acceptable suppressor system.

The basic design (LNHP-2) that was conceived incorporated an area ratio 2.9, 57-tube nozzle and a 24-sided, area ratio 3.1 lined ejector. A schematic showing the nozzle tube array is shown in figure 26. The tubes were chosen of unequal size to meet the requirements of a desired high frequency spectral content from the outer row of tubes to maximize acoustic lining effectiveness while at the same time shielding the noise generated in the center of the array. The tube spacing was arranged to provide straight ventilation paths across the nozzle baseplate to minimize base pressure losses. Tube size and location were also influenced by the requirement for even primary flow distribution across the array in order not to jeopardize the postmerged jet noise characteristics.

Tubes in the outer row were of constant elliptical cross section, with the major axis aligned radially to maximize base ventilation. The remaining tubes were circular in cross section, with convergent exits to maximize internal performance. Tube exits were noncoplanar to conform to stowage requirements of an SST suppressor nozzle installation. The LNHP-2 suppressor was designed to achieve a 2% performance loss and 17 PNdB noise suppression at 2128-ft sideline for a thrust penalty of less than 2% relative to a 10° half-angle R/C reference nozzle.

5.1 MODEL-SCALE SUPPRESSOR DEMONSTRATION

A 1/8-scale (relative to the GE4/J6H2 engine) model of the LNHP-2 jet noise suppressor system was built and tested statically at a jet temperature of 1500° F and nozzle pressure ratio of 3.0 (sec. 3.0, vol. X). To demonstrate the flexibility of the acoustic and thrust performance technology gained in this program, two additional model-scale suppressor systems were designed and tested. An 85-tube, 3.4 area ratio nozzle (LNHP-3) coupled to a 3.7 area ratio lined ejector (fig. 27) was chosen to demonstrate the potential for increasing jet noise suppression provided that thrust performance and engine nacelle size constraints can be relaxed. Conversely a 31-tube, 2.7 AR nozzle (LNHP-4) (fig. 28) coupled to the original

3.1 AR lined ejector was chosen to demonstrate the potential for thrust performance improvements, provided that noise suppression goals are lowered.

The results of the model tests scaled up to the GE4/J6H2 engine size are presented in figure 29. They show that the 57-tube suppressor system achieved 16.4 PNdB of sideline jet noise suppression for 3.2% gross thrust loss. Higher noise suppression can be obtained by increasing the suppressor area ratio, as shown by the 85-tube system which achieved between 18.8 PNdB and 21 PNdB jet noise suppression. However, the increase in area ratio and tube number raised the thrust loss to 7.8%. Thrust performance can be improved by reducing the tube number as shown by the 31-tube system which had only a 1.2% thrust loss (statically), but this was achieved at the expense of noise suppression which dropped to 15 PNdB.

5.2 FULL-SCALE SUPPRESSOR DEMONSTRATION

The final evaluation of a jet noise suppressor system has to be performed full scale or at least on a large scale, using a turbojet engine (sec. 5, vol. X). This had to be done to overcome some deficiencies of model-scale testing. The main reasons are that engines have their own peculiar nozzle exhaust temperature profiles that can affect the suppressor performance and that full-scale hardware will have different Reynolds number effects on skin friction and ejector air handling. The full-scale acoustic lining surfaces can also be made smoother by choice of smaller perforations to further reduce thrust losses.

Because the GE4/J6H2 turbojet engines were never built, the only available engine today that comes anywhere near in performance characteristics is the J-58 (or JT11D). Therefore the 57-tube suppressor system was scaled to the J-58 engine size and tested at the maximum jet velocity of 2280 fps which is somewhat short of the suppressor design goal of 2550 fps. Figure 30 shows the full-scale test installation at the Boeing engine test site in Boardman, Oregon.

The full-scale tests confirmed the acoustic results of the model-scale program. The effectiveness of the suppressor system is shown very clearly by the sound power spectra in figure 31. The bare 57-tube nozzle shows a good balance in the spectrum between pre- and postmerged noise components. The addition of an acoustically lined ejector further suppresses the high-frequency premerged jet noise leaving the system as postmerged noise dominated. The only way known to attack the postmerged noise further is to increase the suppressor area ratio as demonstrated by the model-scale test series.

The sideline PNL beam patterns in figure 32 show the suppressor effectiveness from the point of noise certification requirements. For the J-58 engine cycle the maximum jet noise is suppressed by approximately 16 PNdB. Corresponding thrust performance results (figure 33) show the static gross thrust loss to be 0.75%. Full-scale performance exceeded model-scale results by 2% in gross thrust at maximum power conditions for the ejector configurations. About two-thirds of this difference can be accounted for by Reynolds number scaling effects and by known differences in primary nozzle geometry. The geometry differences are internal tube length and convergence rate which reflect the change in performance characteristics seen in the bare suppressor data. Finally, figure 34 shows good agreement between the acoustic model-scale and the full-scale test data, so that model-scale test results can be used with confidence to predict the noise performance of the suppressor system to higher jet velocities than could be attained with the J-58 engine.

6.0 SST APPLICATION

If the 57-tube suppressor system were to be installed on the 1971 version of the U.S. SST the following results would be obtained. The probable nacelle installation schematic is shown in figure 24. It shows the stowable features of the nozzle system in order to maintain high performance during supersonic cruise.

Based on the model- and full-scale test results it is estimated that the 57-tube suppressor system would suppress sideline noise by 16.5 PNdB for 0.75% gross thrust loss statically. With forward velocity during climbout, however, both the acoustic and thrust performance would be degraded. Current estimates of flight effects change the suppressor performance to 15-PNdB sideline noise suppression for 7% net thrust loss at 230-kn climbout velocity. Figure 35 compares the status sideline SST noise levels at the termination of the SST program in 1971 with the levels achieved during the current program by the demonstrator hardware. An 800 000-lb MTW airplane with 815-lb/sec airflow GE4/J6H2 turbojet engines could have achieved 110-EPNdB sideline noise levels through the use of a "chute" suppressor and with the engines throttled back. The 57-tube suppressor system on the same airplane would achieve a sideline noise level of 108-EPNdB and still leave it with excess thrust. This thrust could be used to increase the airplane MTW to 860 000 lb which would improve the airplane's economics either through increased payload or range or a combination of both.

7.0 CONCLUSIONS

Jet noise suppression, a major problem in the development of supersonic transports, has experienced a substantial technology advance since the termination of the U.S. SST program. Fundamental technology development has led to a better understanding of nozzle aerodynamics, noise generation, and noise transmission processes. The current program has allowed the development of a noise and performance design prediction that has been substantiated by model- and full-scale demonstrator programs. The results from the demonstrator programs were used to show that the application of such a suppressor system on the former Boeing B2707-300 SST would achieve FAR part 36 sideline noise levels. Further, it was shown that such an installation would allow a substantial increase in the airplane's maximum takeoff weight (7.5%) relative to previous designs, thereby improving airplane economics.

Demonstration of flightworthy operational hardware is required to confirm the mechanical feasibility study results presented herein for the variable geometry concepts.

The work described in these reports only addresses the jet noise problem. When an SST powerplant is developed at some future date, turbomachinery and core noise components will also have to be taken into account. In the case of the J-58 engine these were not found to be significant.

8.0 RECOMMENDATIONS

It is recommended that the LNHP-2 suppressor system be tested for relative velocity effects to substantiate methods of predicting suppressor nozzle forward flight noise and performance levels. The state of the art in adjusting static test data to predict relative velocity effects for ejectors is not well established in either acoustic or performance technologies as shown in particular by the conflicting claims in current literature for noise effects. This area of investigation should be emphasized in future research activities.

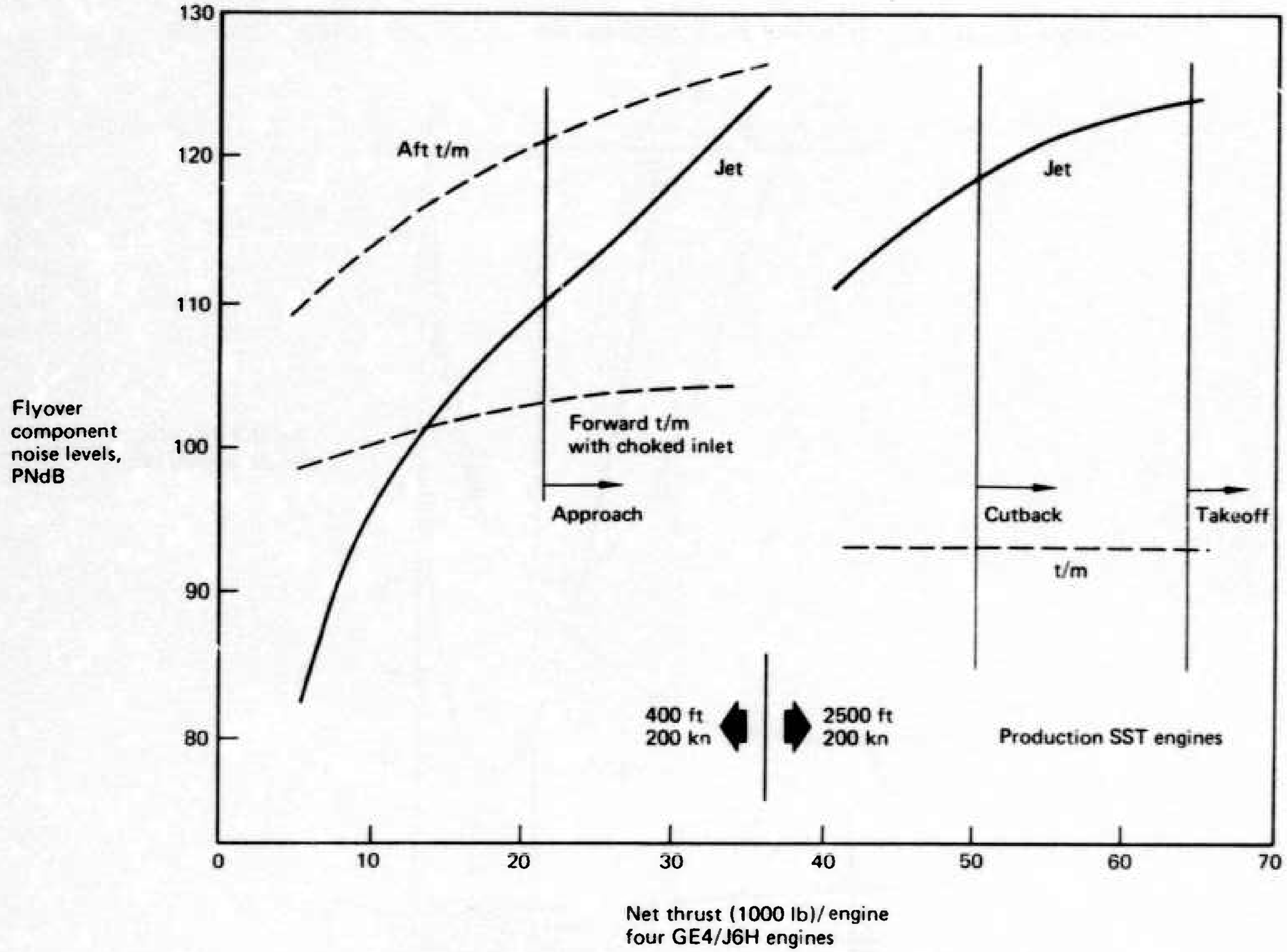


Figure 1.—U.S. SST Predicted Unsuppressed Engine Noise

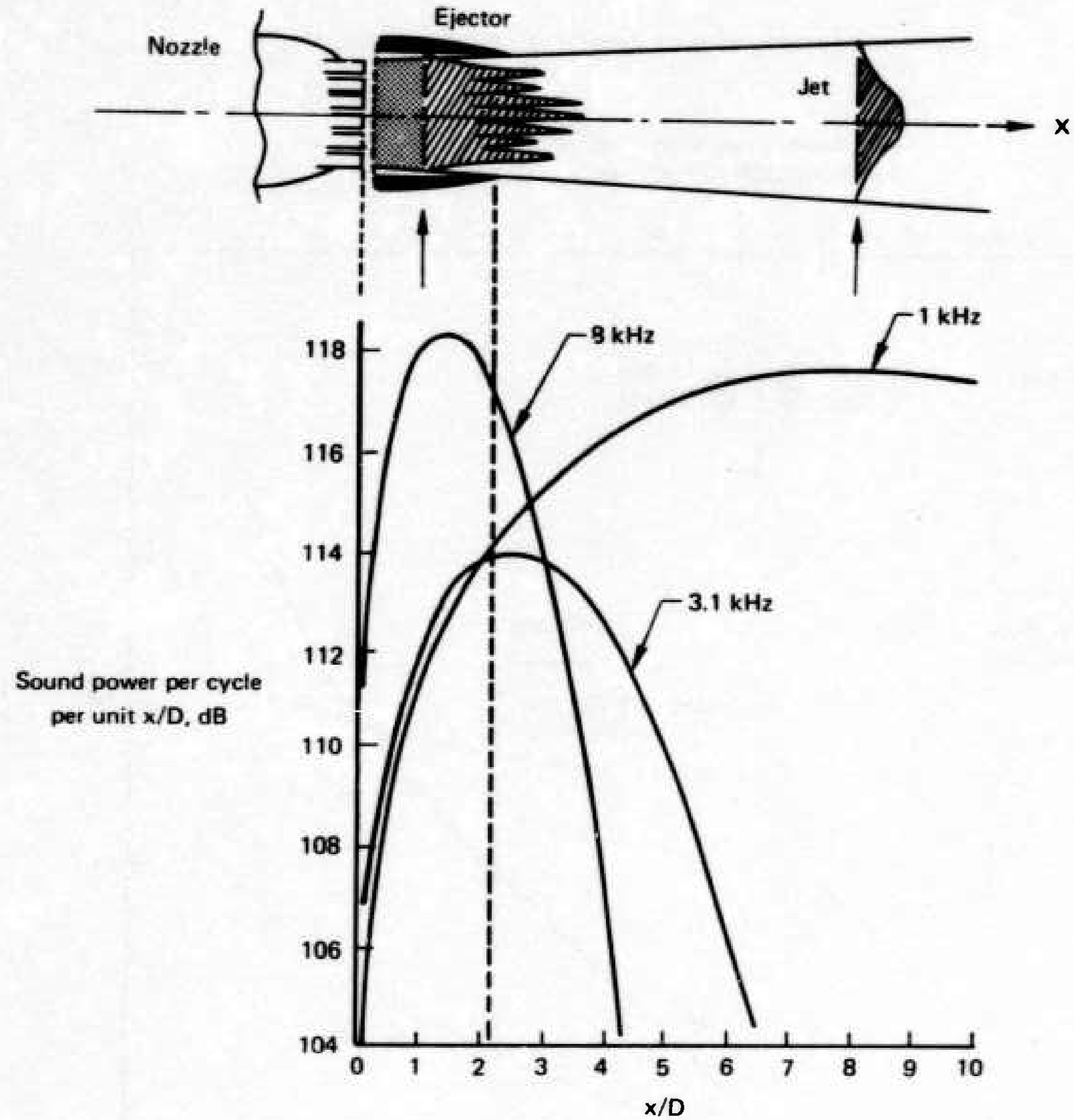


Figure 2.—37-Tube, AR = 3.3 Nozzle With L/D_{eq} = 2 Ejector at T_T = 1150° F, PR = 3.0

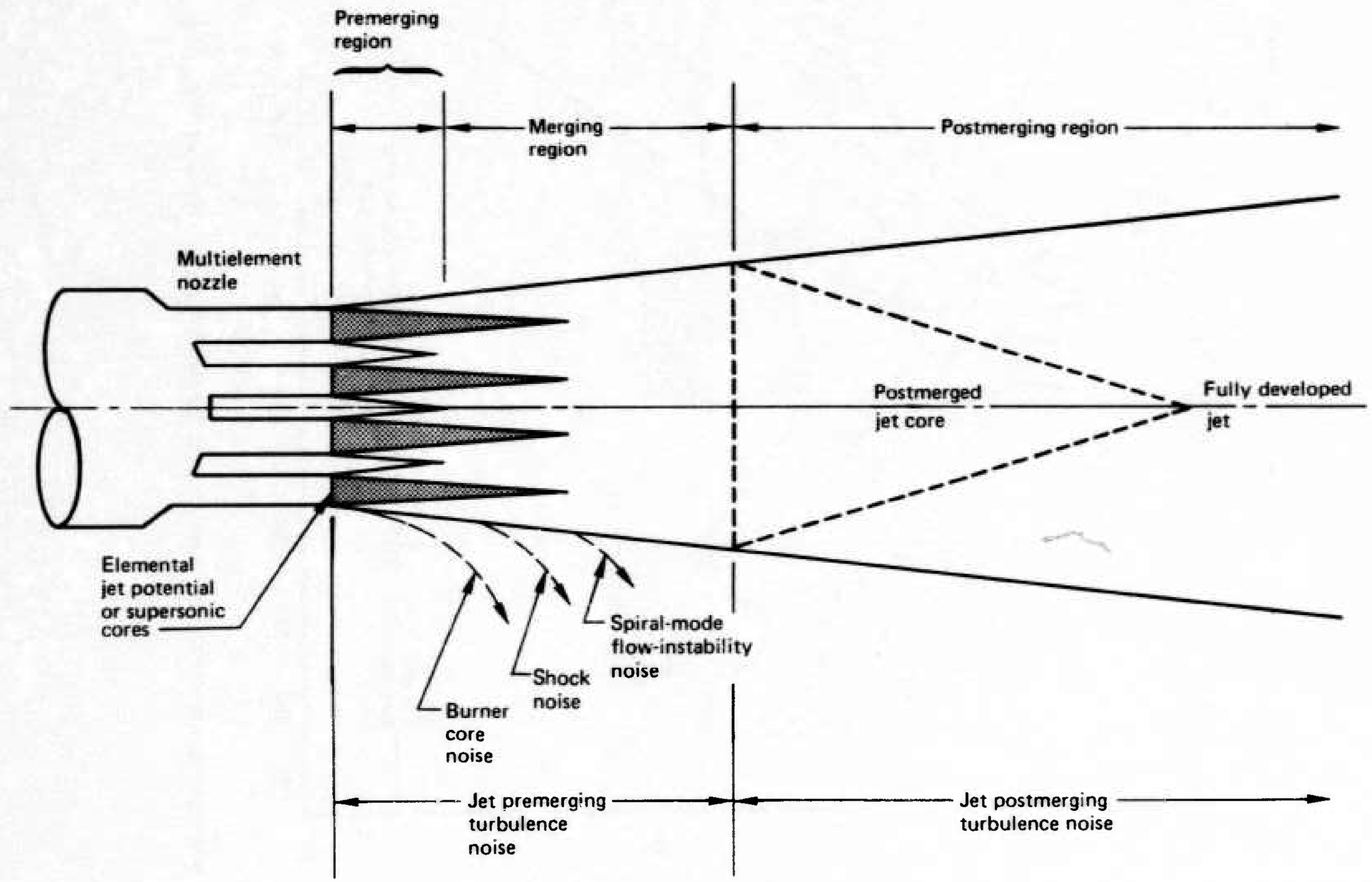


Figure 3.—Multielement Jet Nomenclature

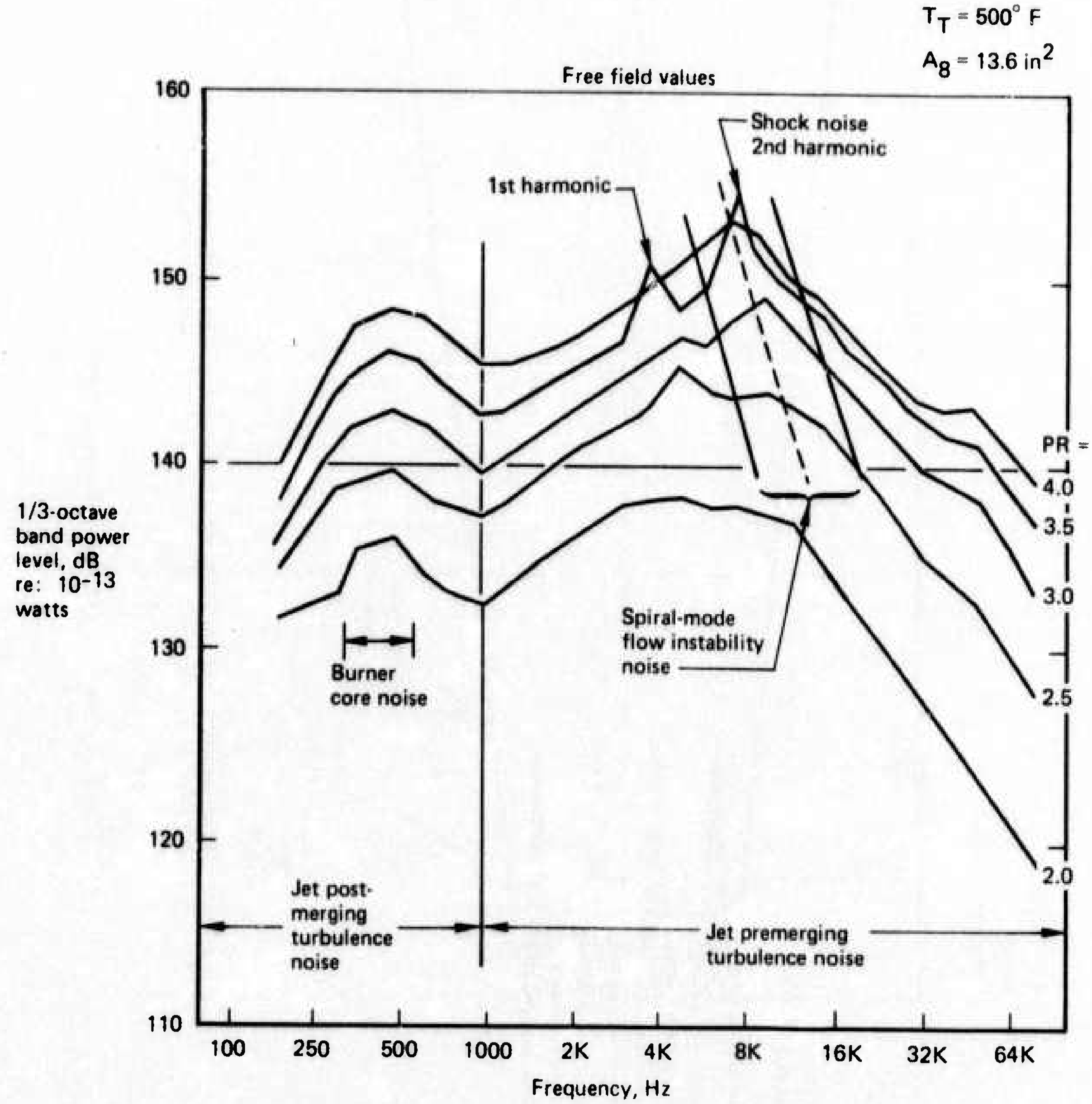
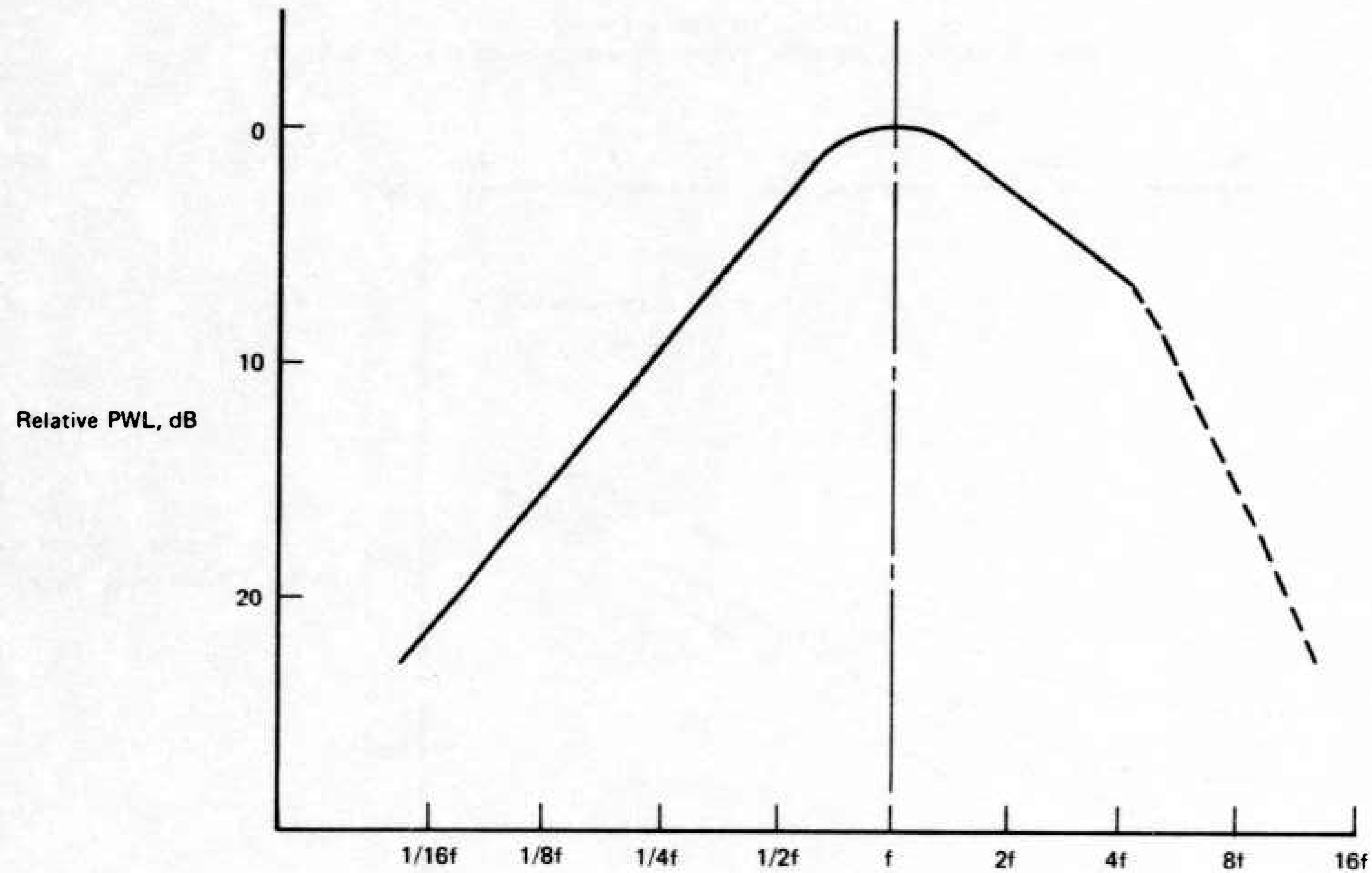


Figure 4.—Composite Jet Noise Power Spectra for the 7-Tube, 3.3 Area Ratio Nozzle



$$f = \frac{(0.6 - 0.0043\,N_T)\,V_J}{d\left(\frac{A_J}{A^*}\right)^{0.5}\left(\frac{T_T}{T_o}\right)}, \text{ for } M_J \geq 1$$

Figure 5.—Estimated Multitube Nozzle Premerged Jet Noise PWL 1/3-Octave-Band Spectrum Shape

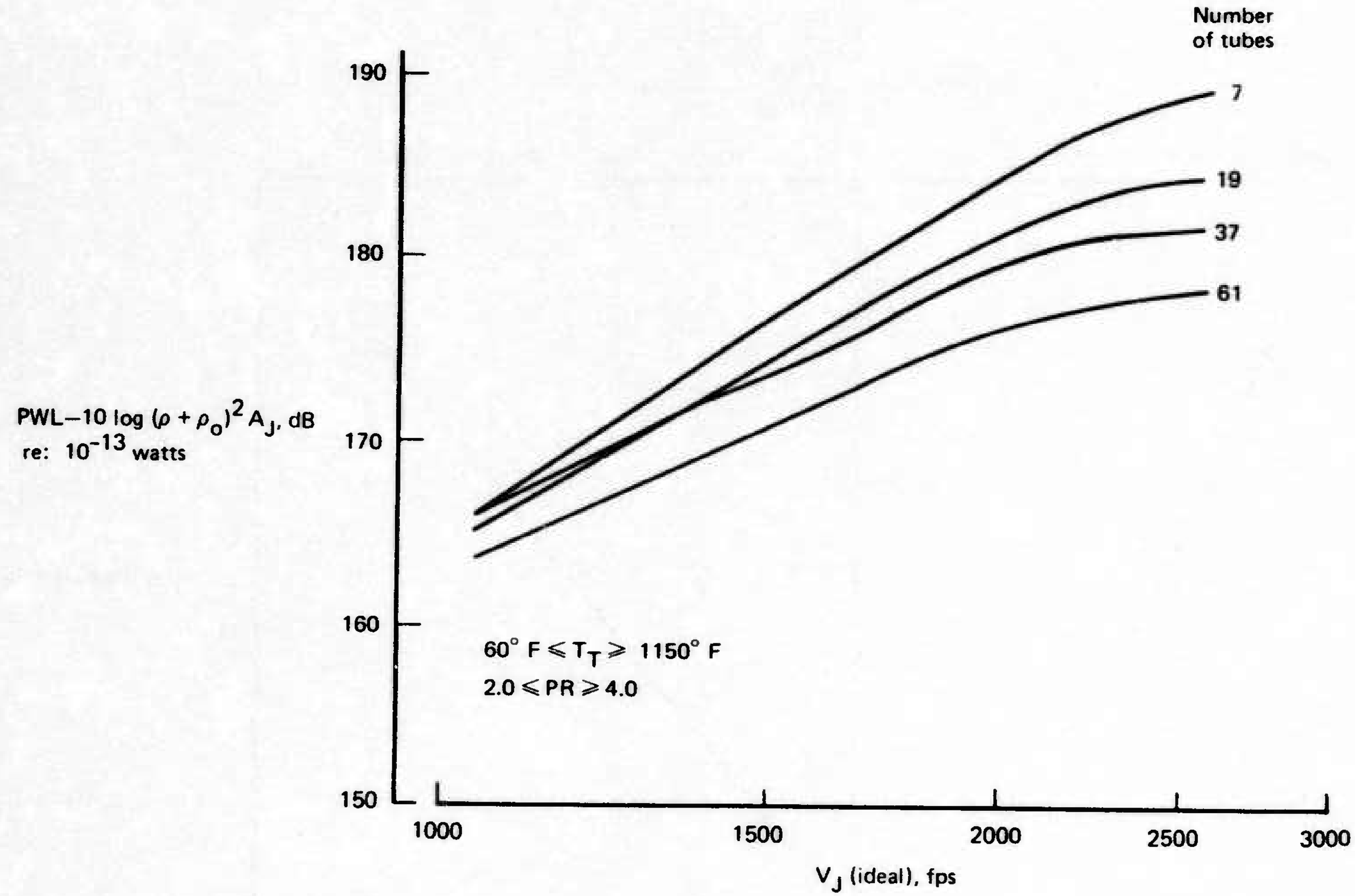


Figure 6.—Normalized Premerged Jet Noise Power Levels for 3.3 Area Ratio Nozzles

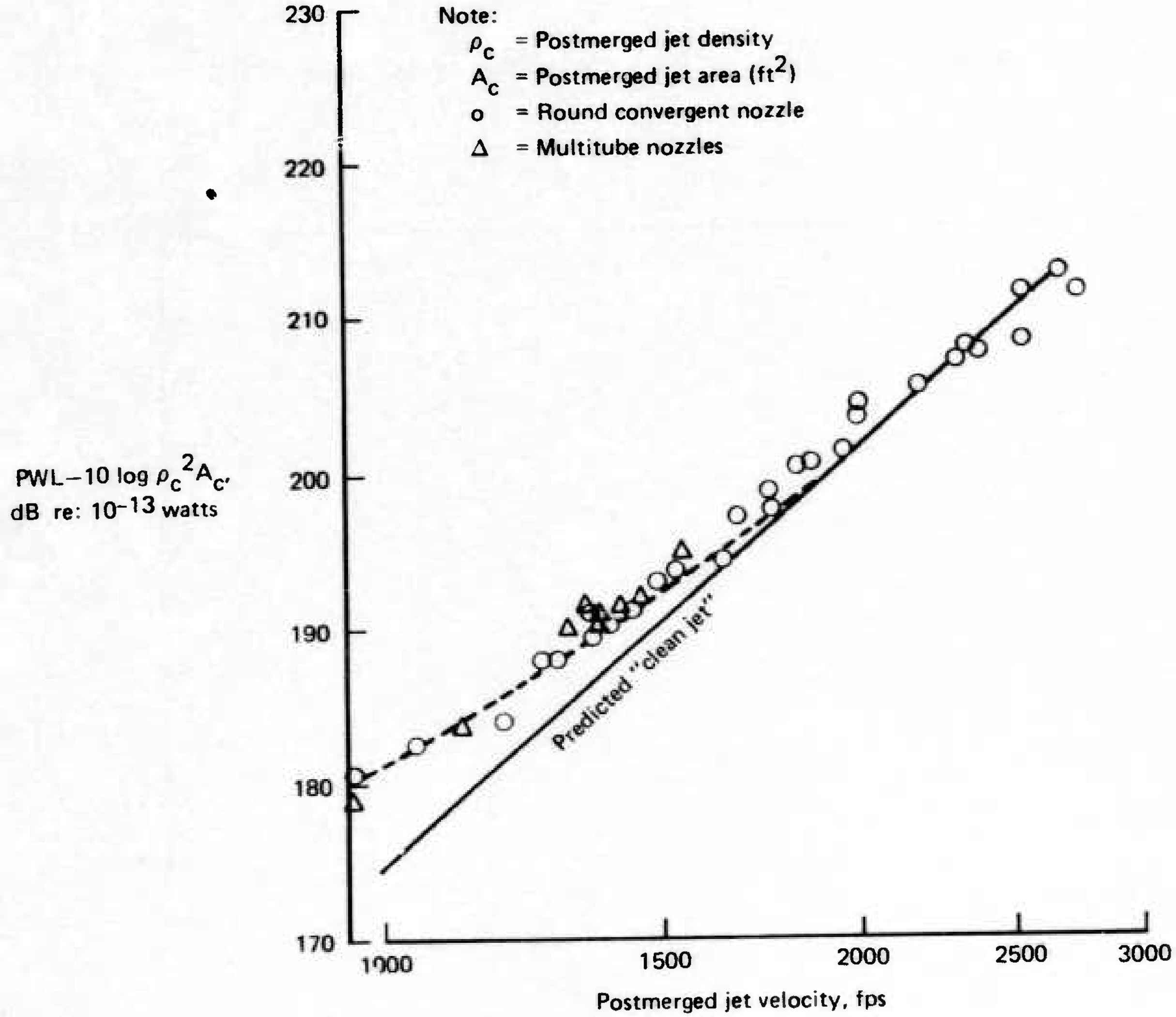


Figure 7.—Normalized Postmerged Jet Noise Power Levels

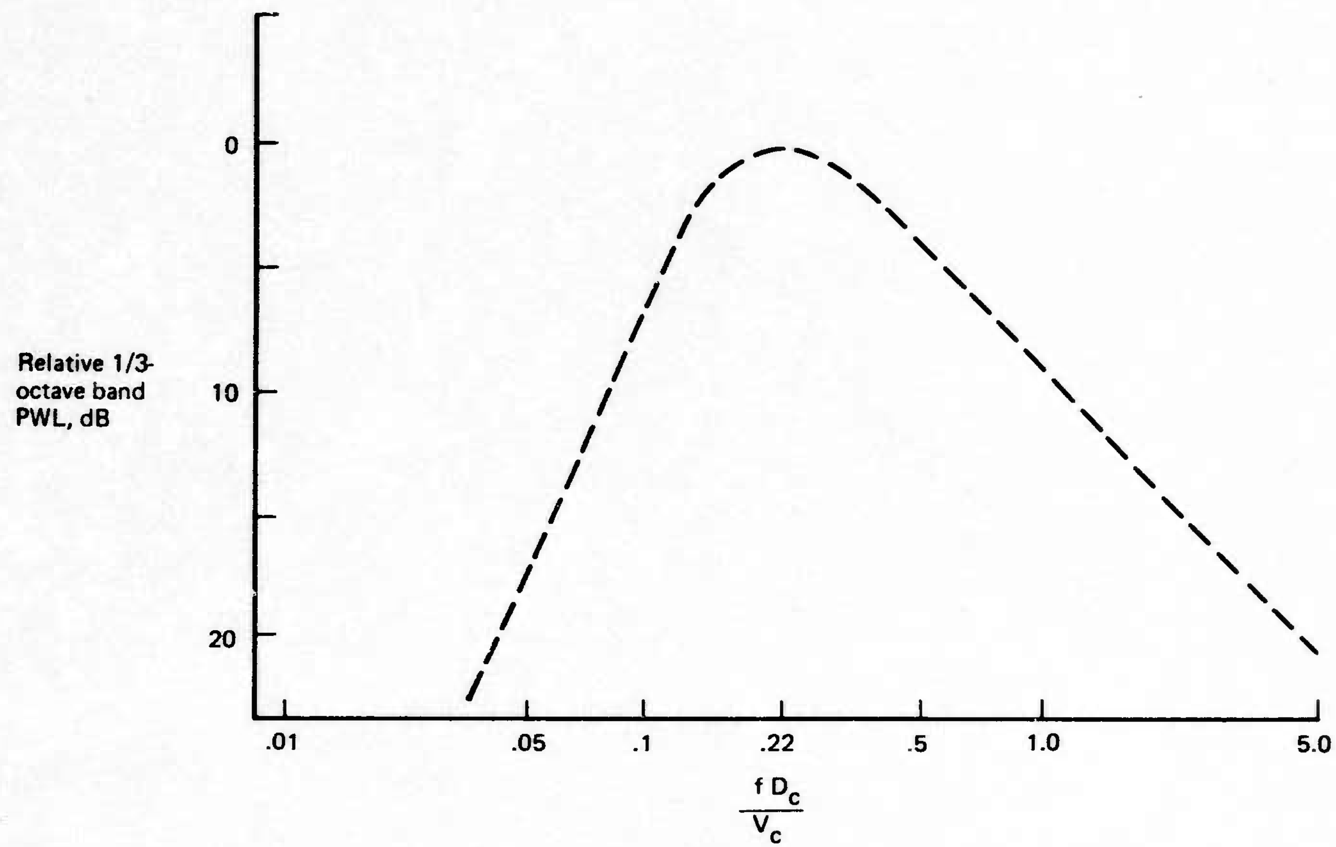


Figure 8.—Multitube Nozzle Postmerged Jet Noise Spectrum Shape

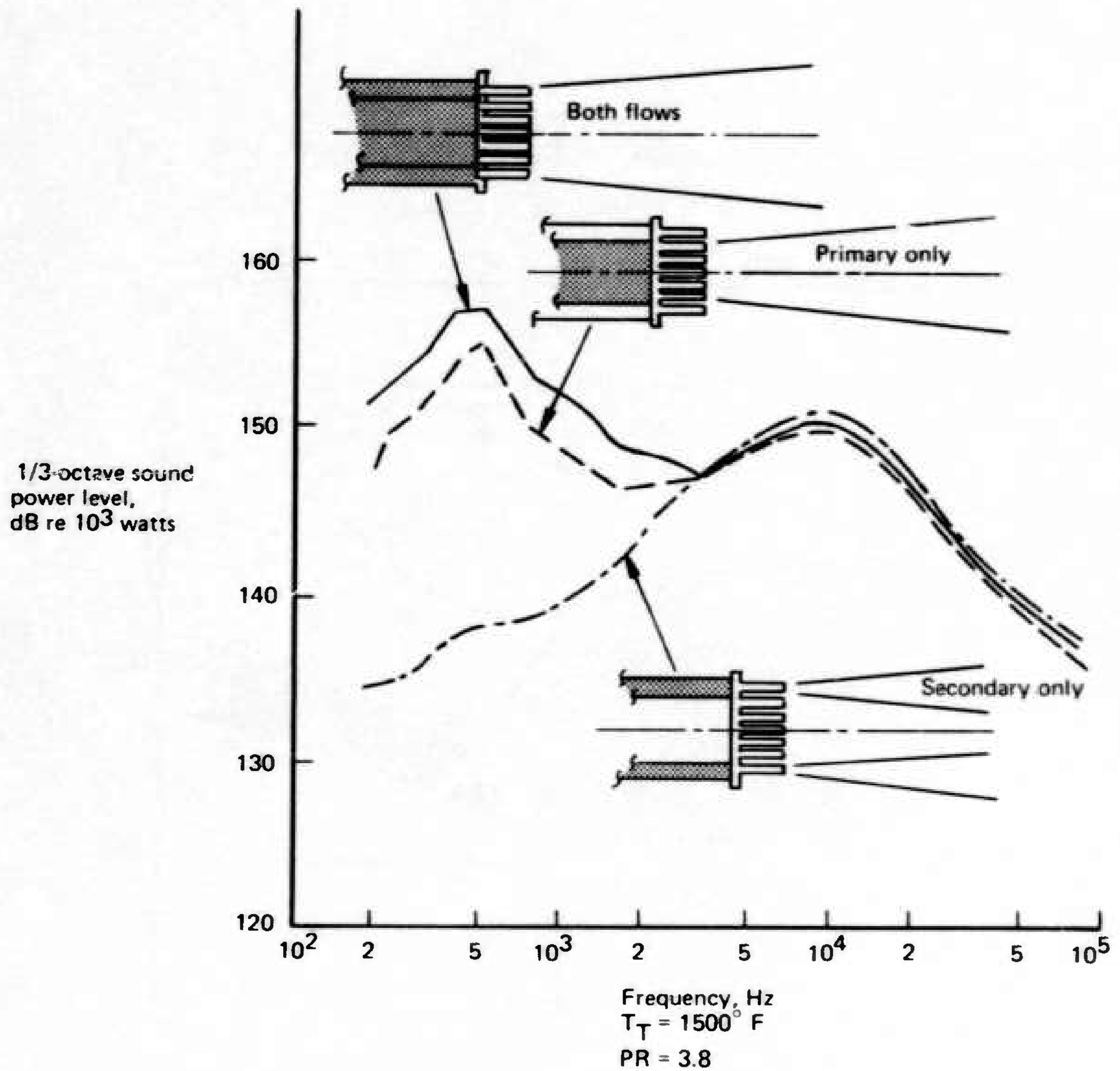


Figure 9.—Multielement Jet Component Noise Levels for a 61-Tube, Area 3.3 Area Ratio Nozzle

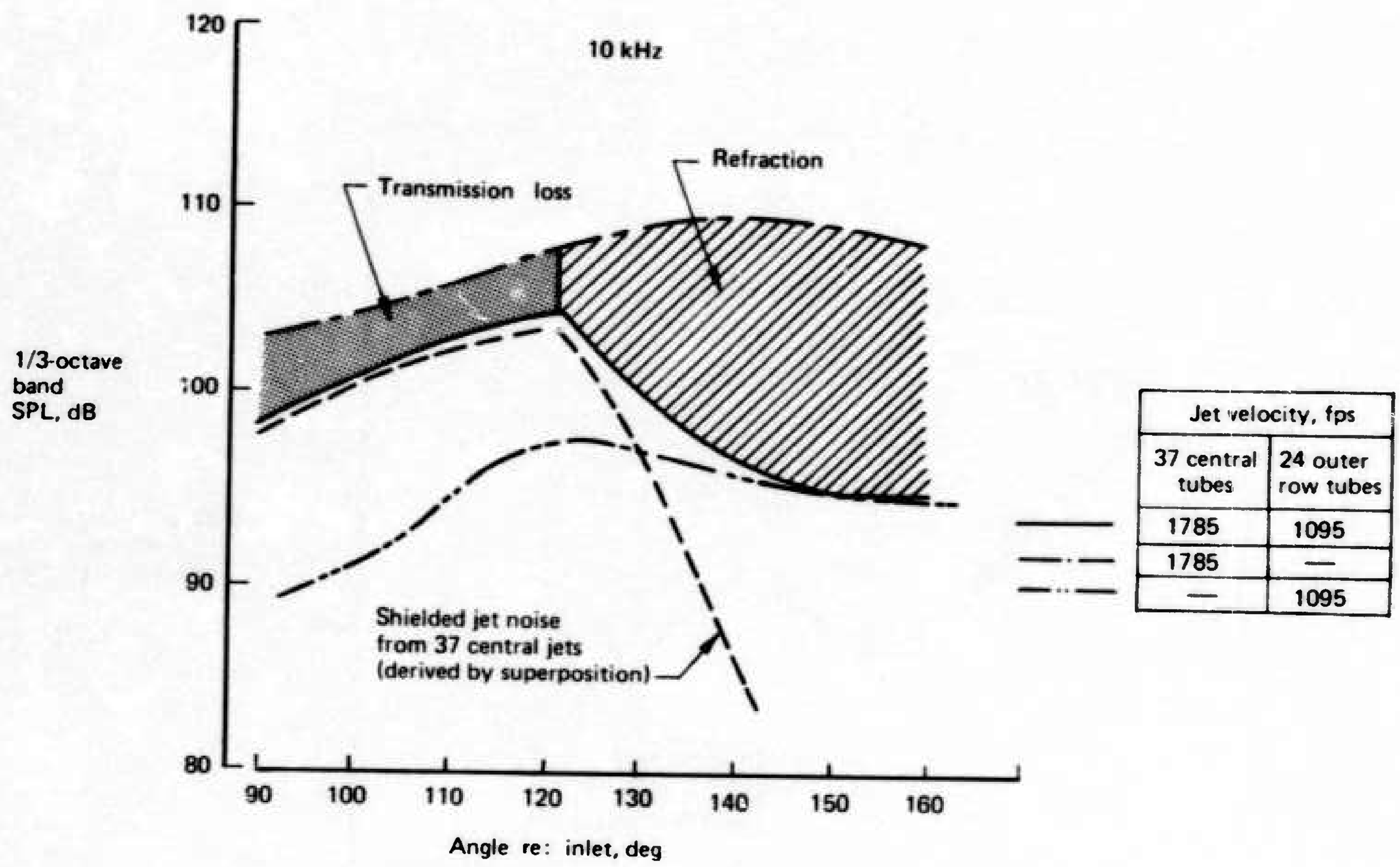


Figure 10.—Jet Noise Shielding by Outer Row of Jets in a 61-Tube Nozzle

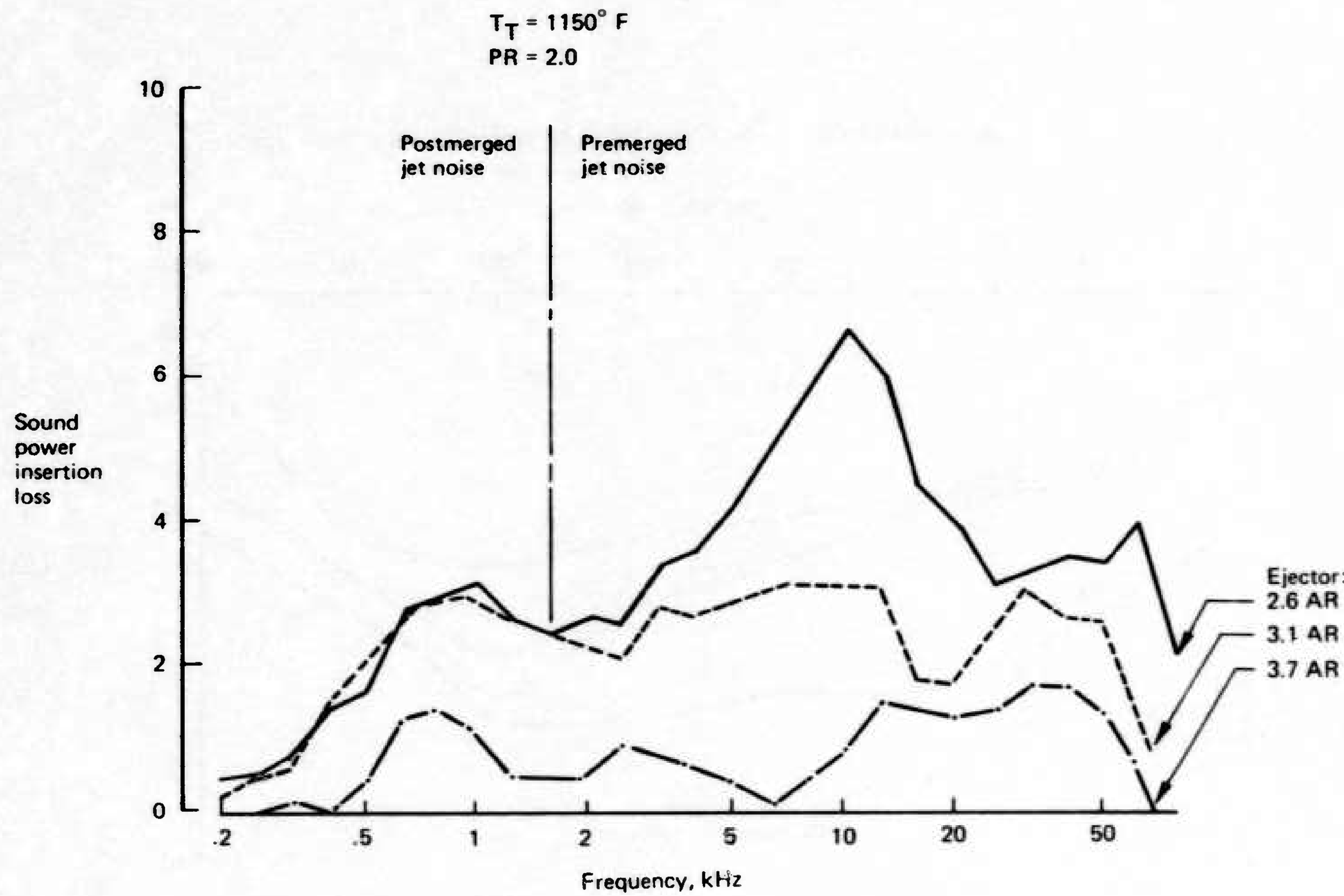


Figure 11.—Jet Noise Suppression Characteristics of Hardwall Ejectors Relative to 31-Tube, 2.75 Area Ratio Nozzle

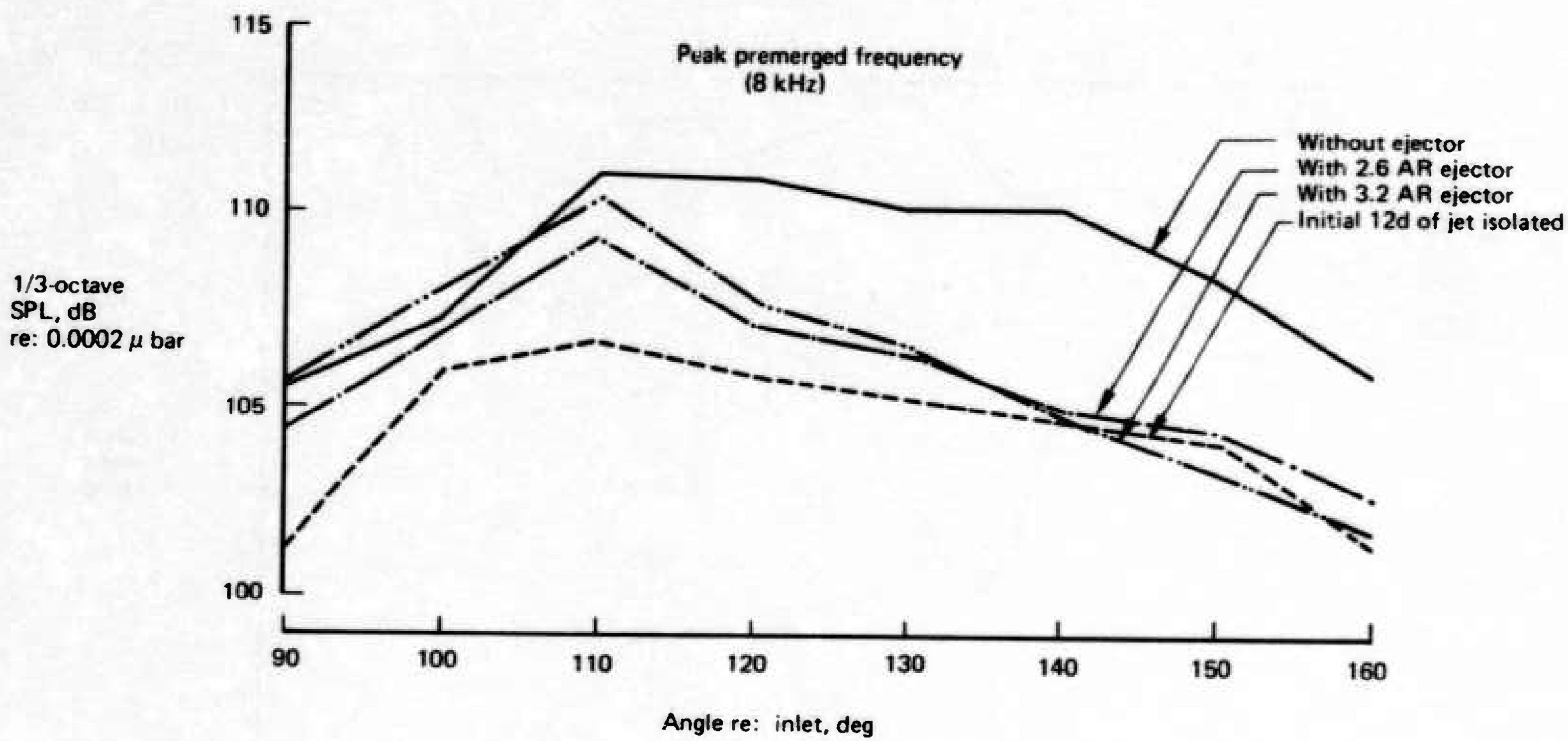


Figure 12.—37-Tube Nozzle and Ejector Directivity Characteristics

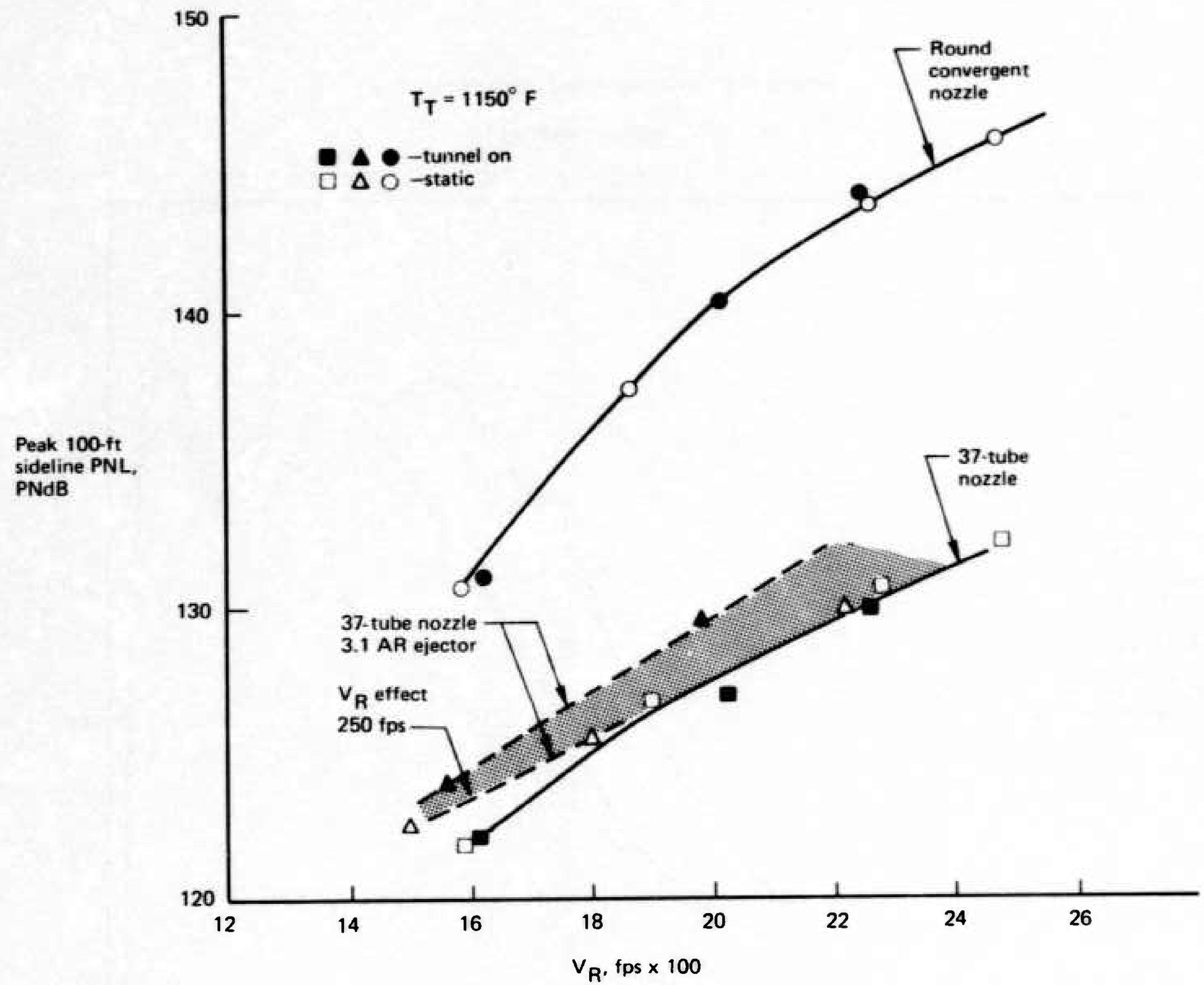


Figure 13.—Forward Velocity Effects on Jet Noise Suppressor Systems

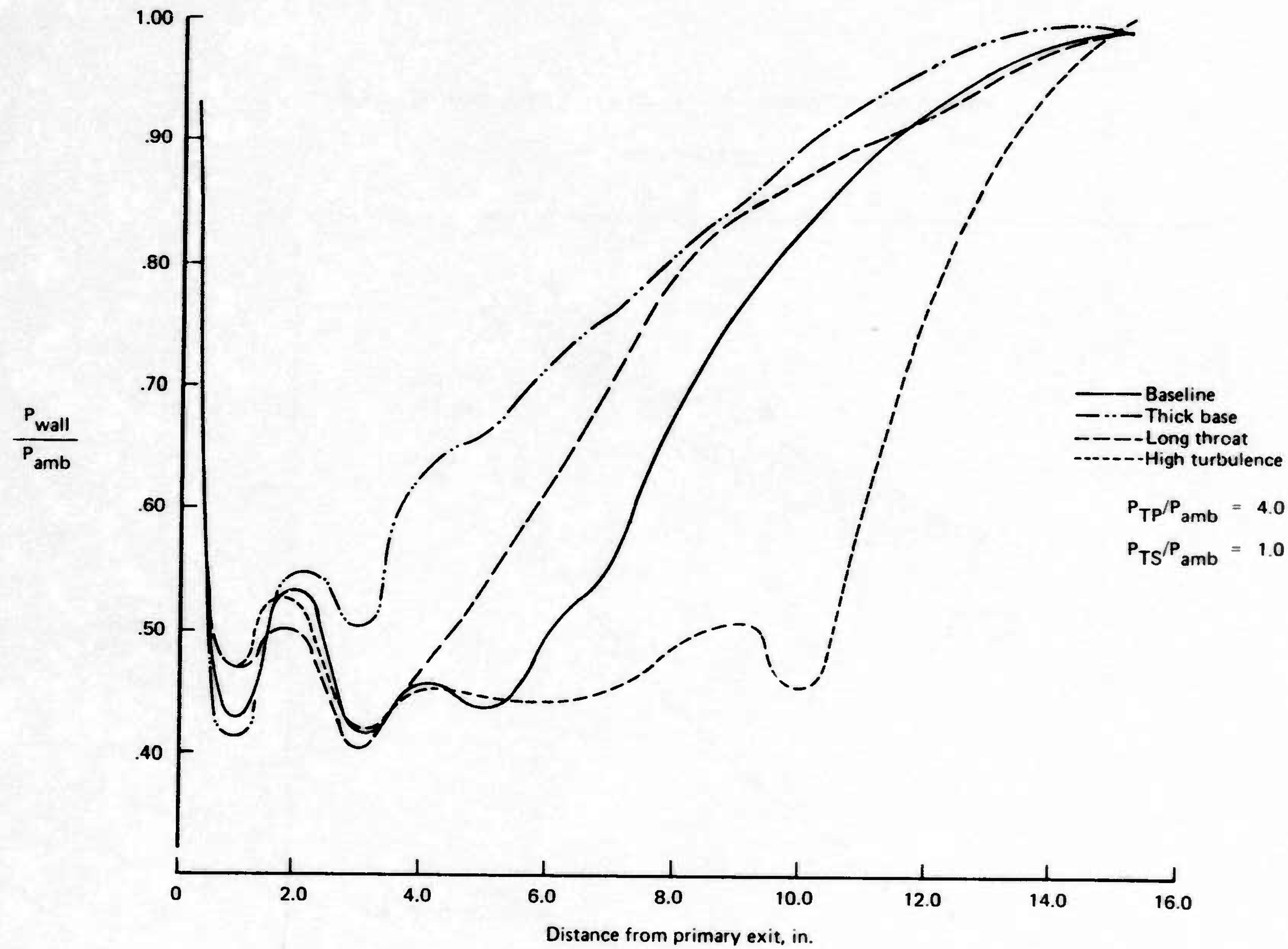


Figure 14.—Wall Static Pressure Distribution

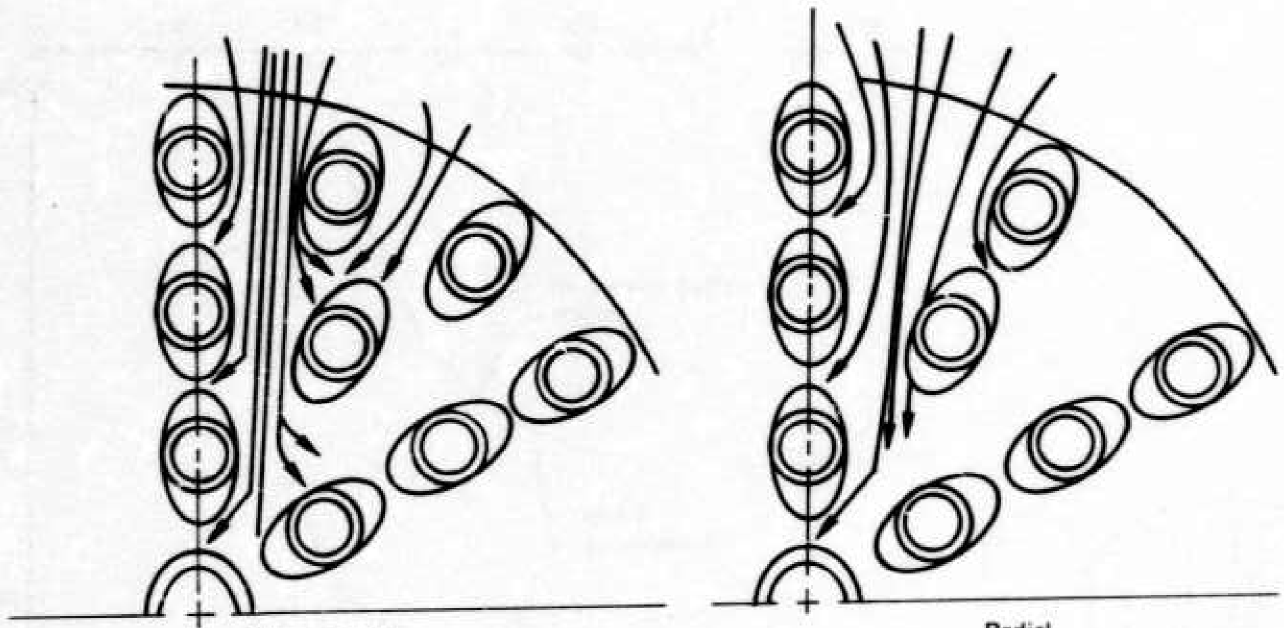


Figure 15.—Multitube Nozzle Arrays

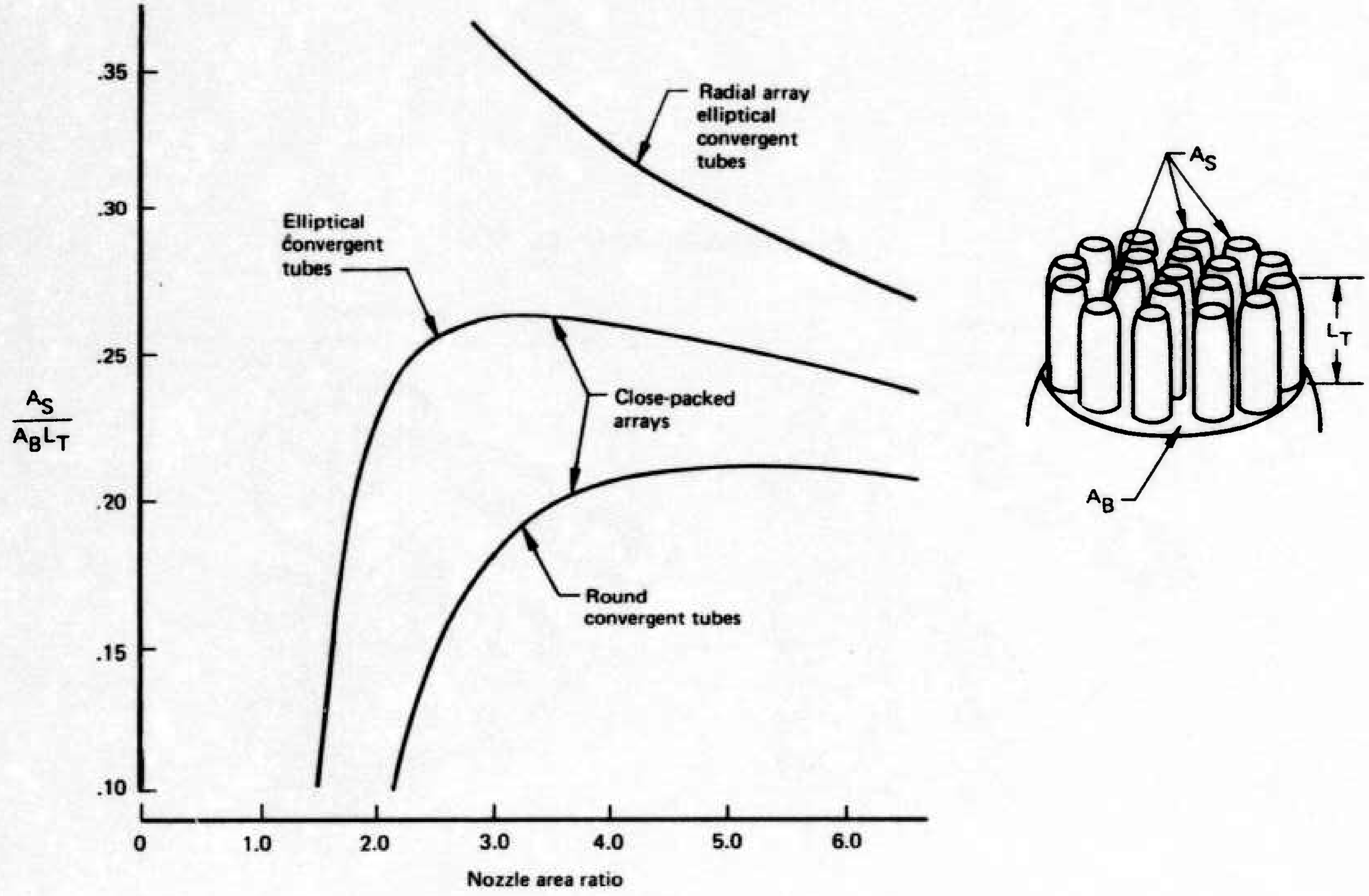


Figure 16.—Base Ventilation Parameter for 37-Tube Nozzles

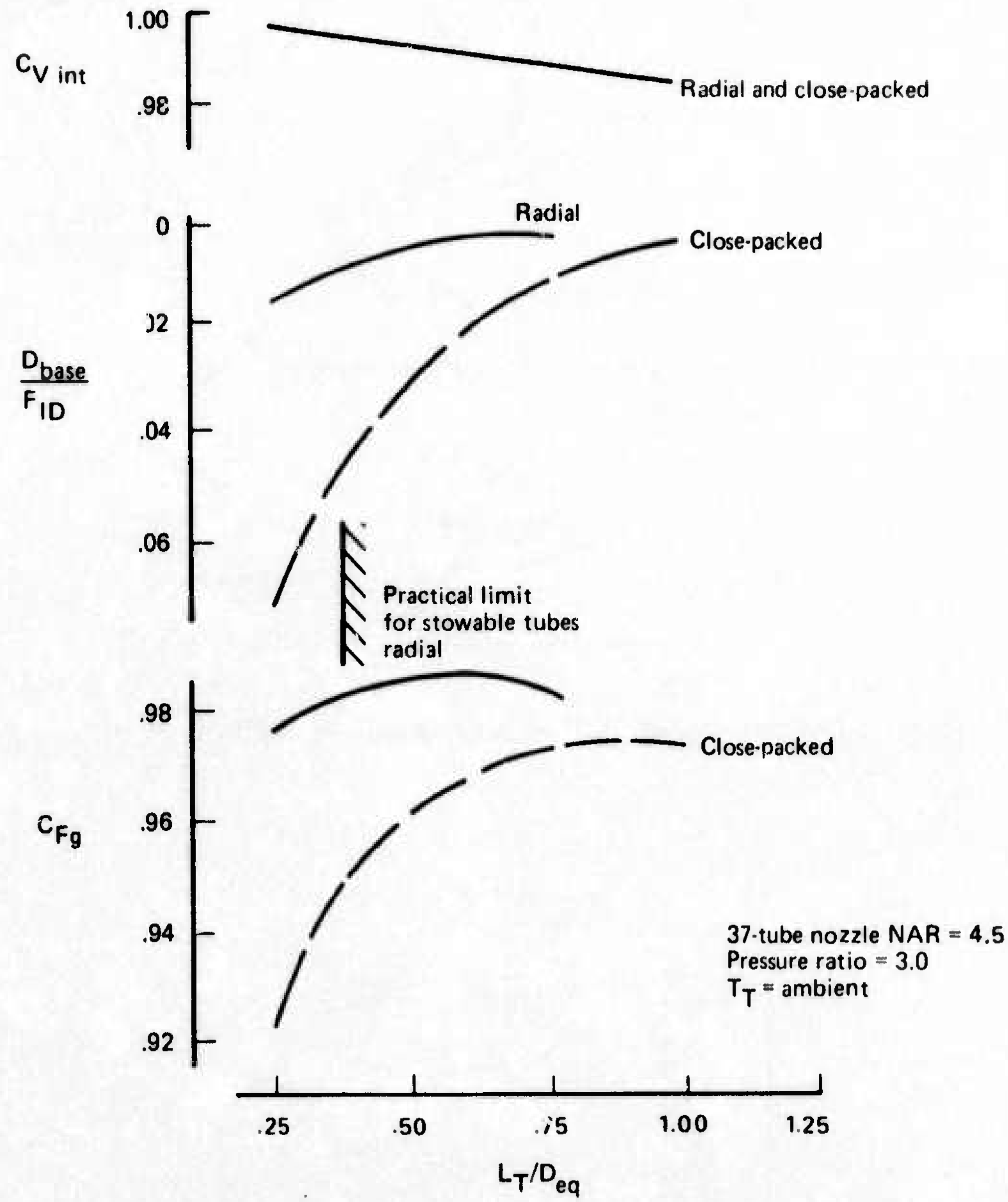


Figure 17.—Performance Loss Components

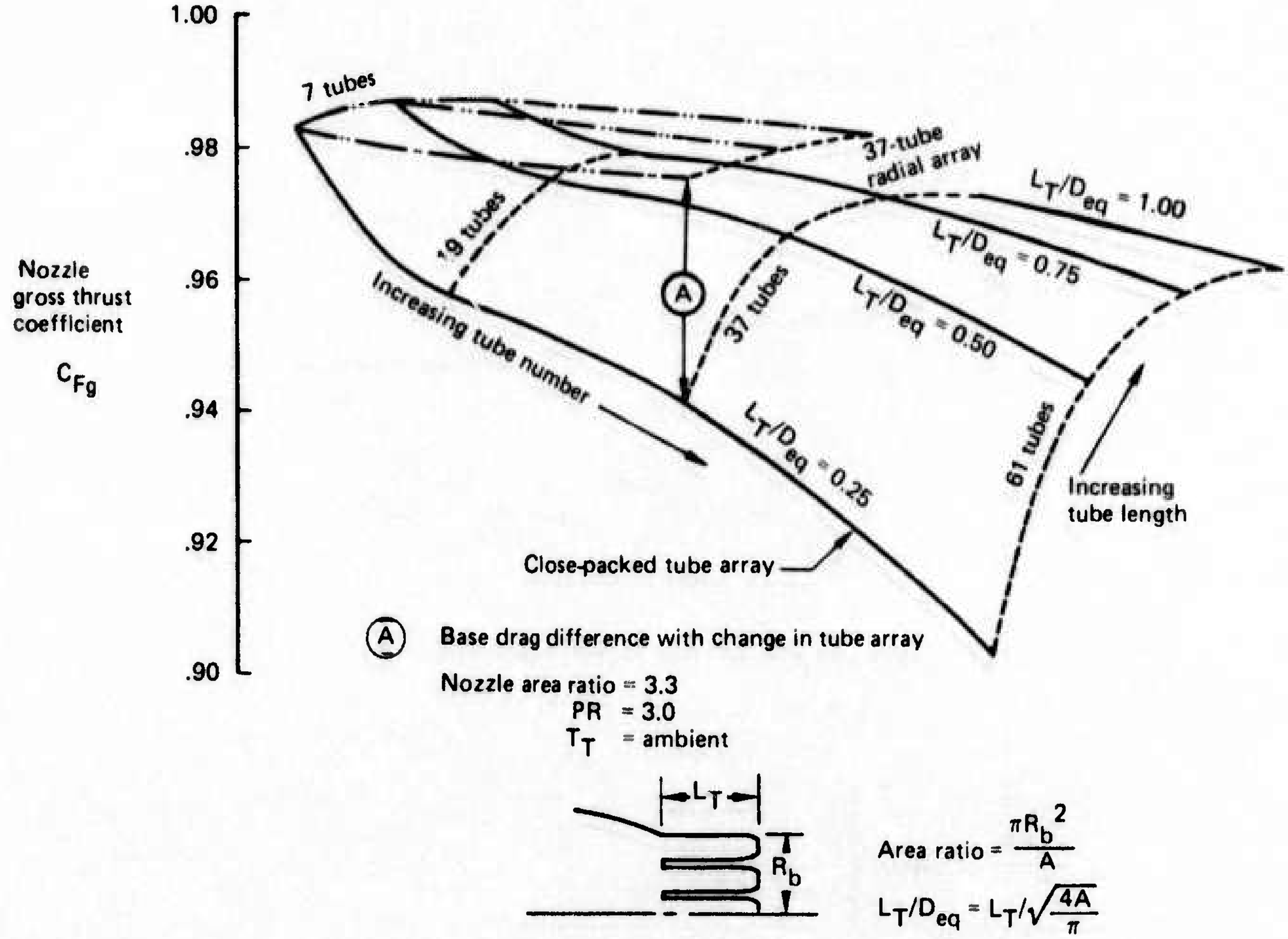


Figure 18.—Effect of Tube Number on Bare Suppressor Performance

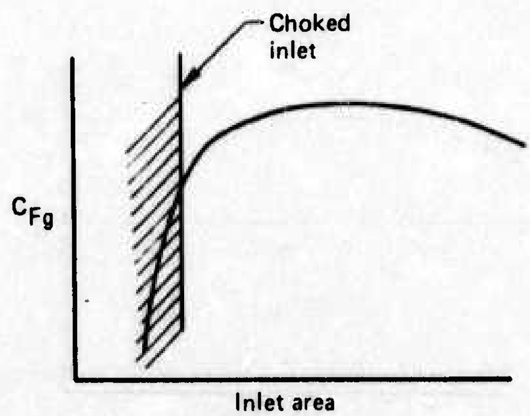


Figure 19.—Ejector Performance Trend

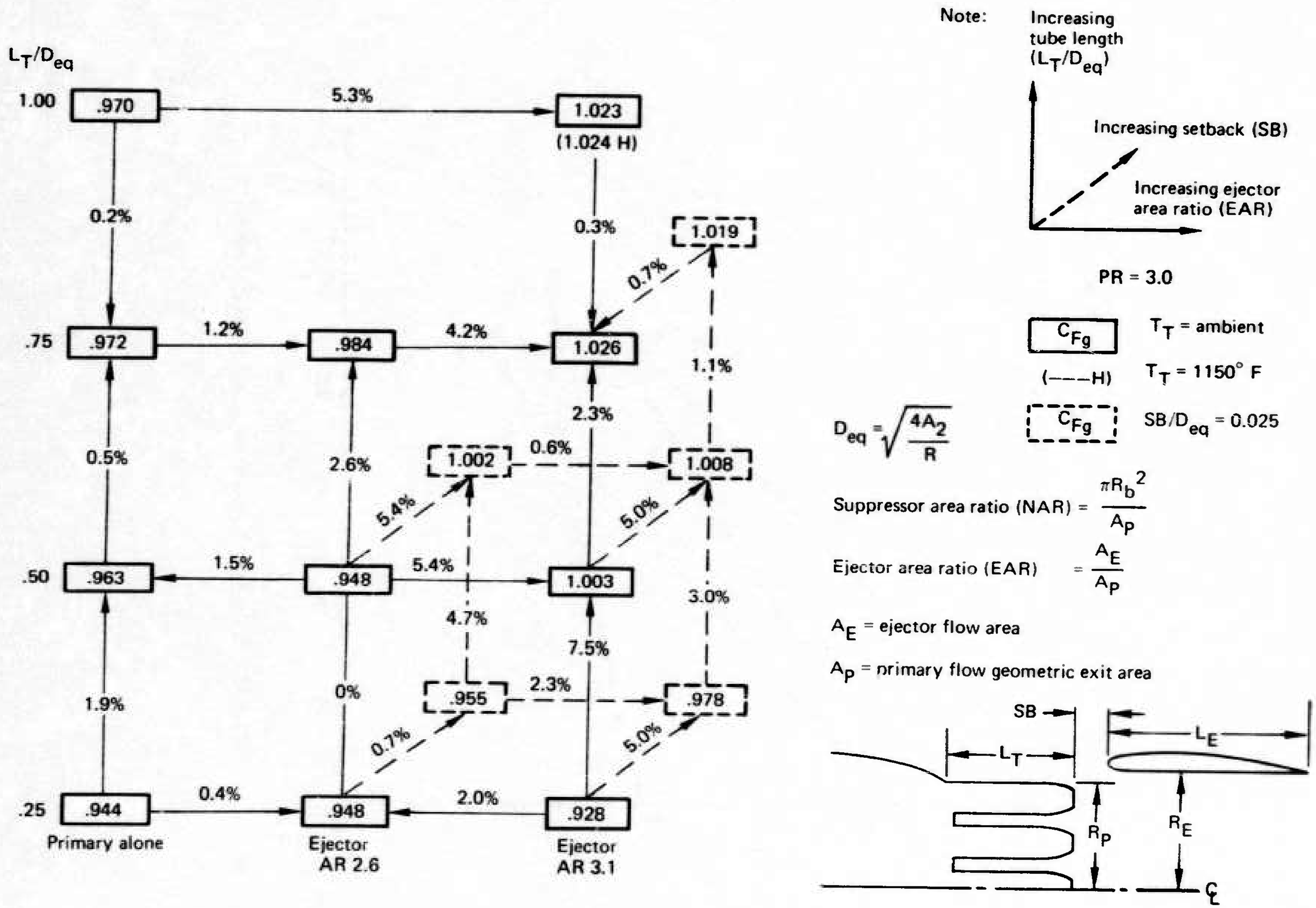


Figure 20.—Performance Matrix for 37-Tube, NAR = 2.75, Close-Packed Array

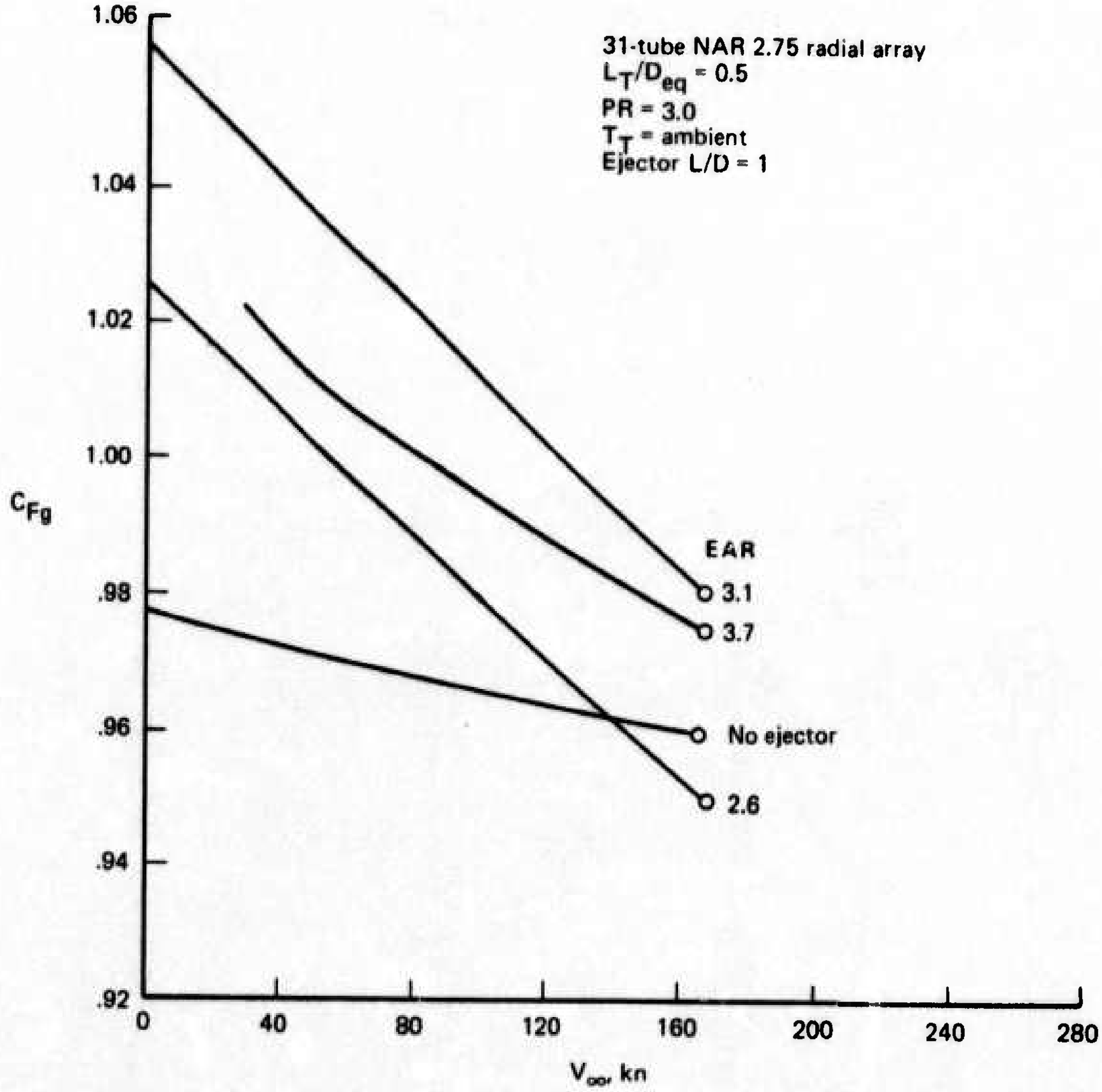


Figure 21.—Effect of Ejector Area Ratio on Performance at Forward Velocity

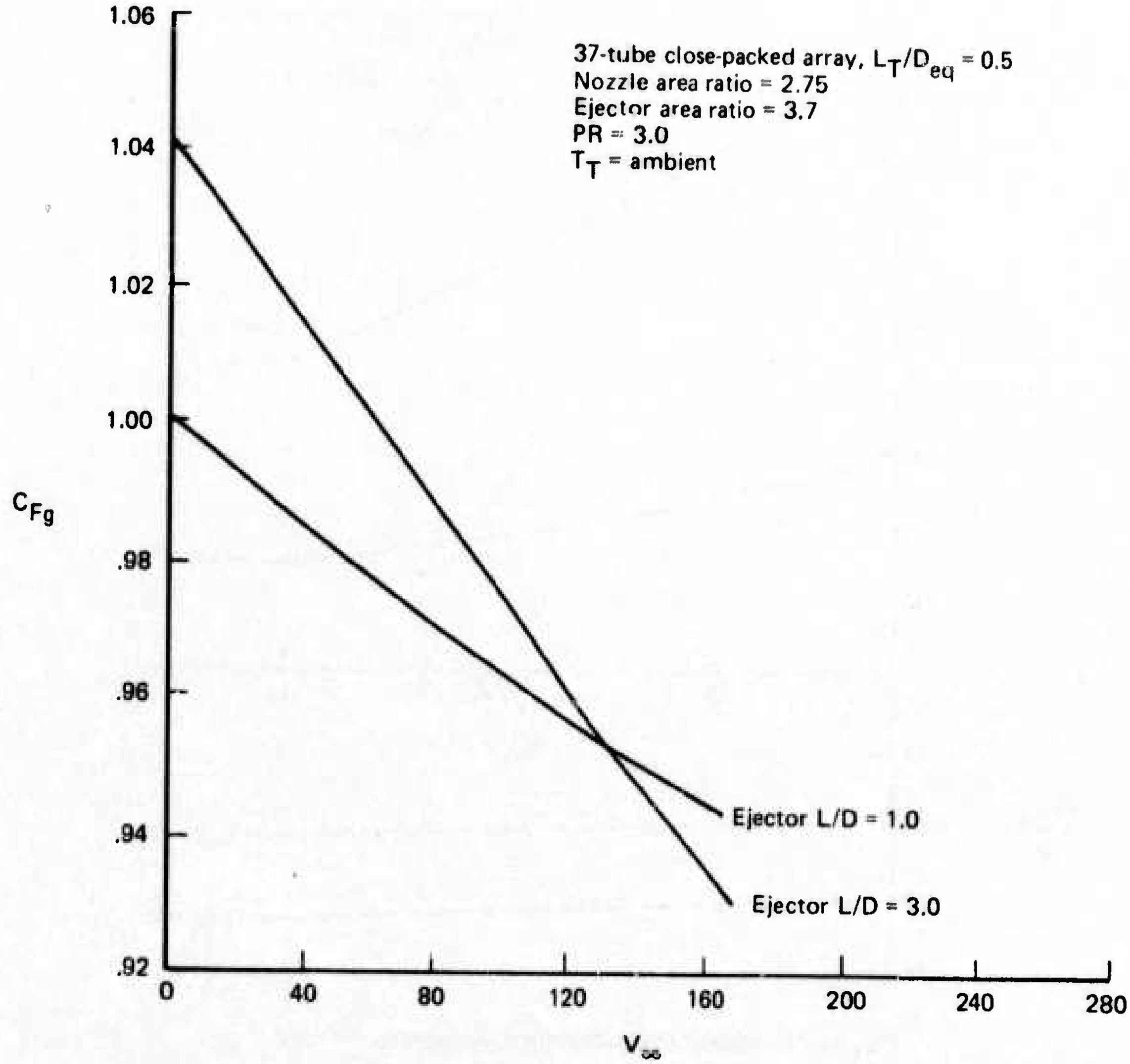


Figure 22.—Effec' ,f Ejector Length on Performance at Forward Velocity

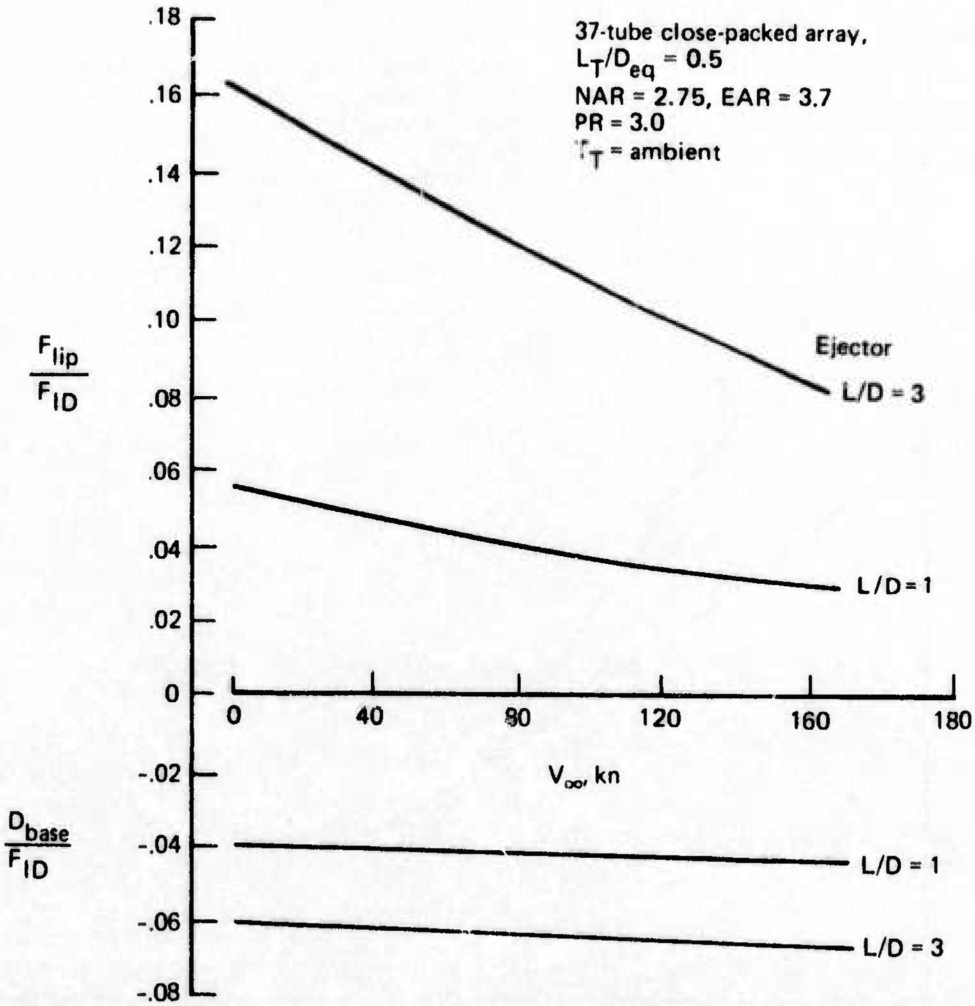


Figure 23.—Suppressor/Ejector Component Forces

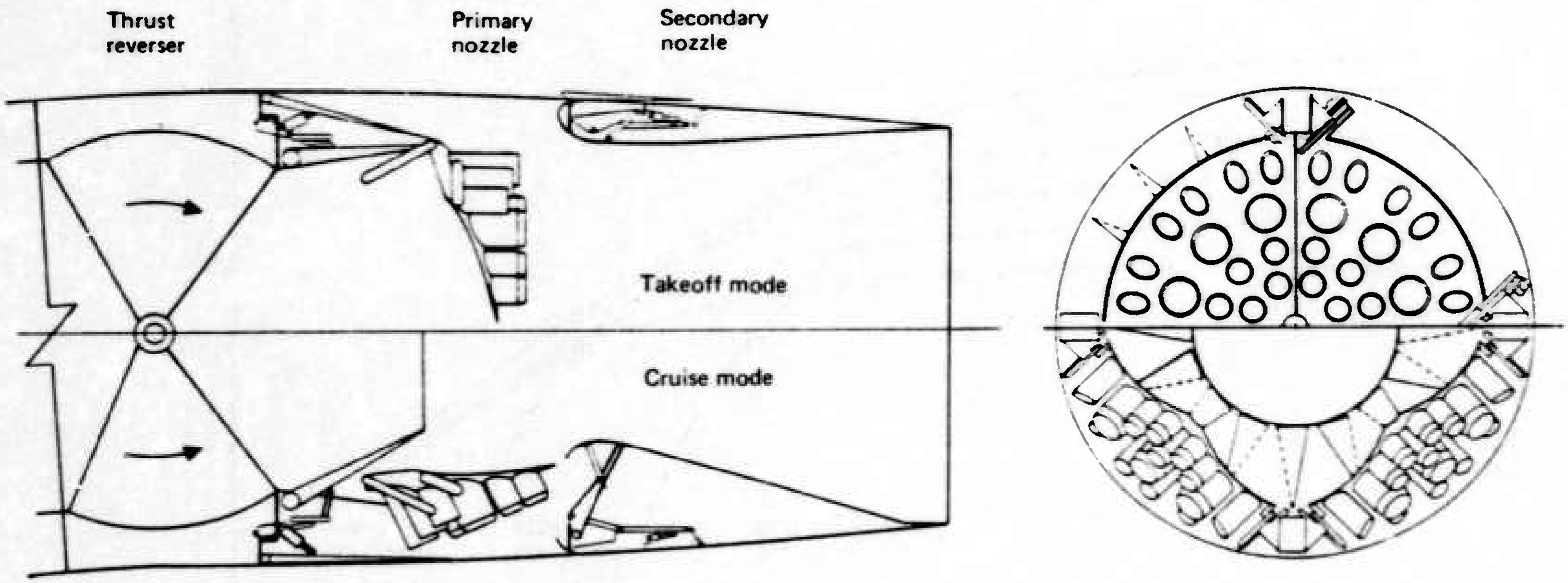


Figure 24.—Application of the 57-Tube Suppressor to an Advanced SST Exhaust System

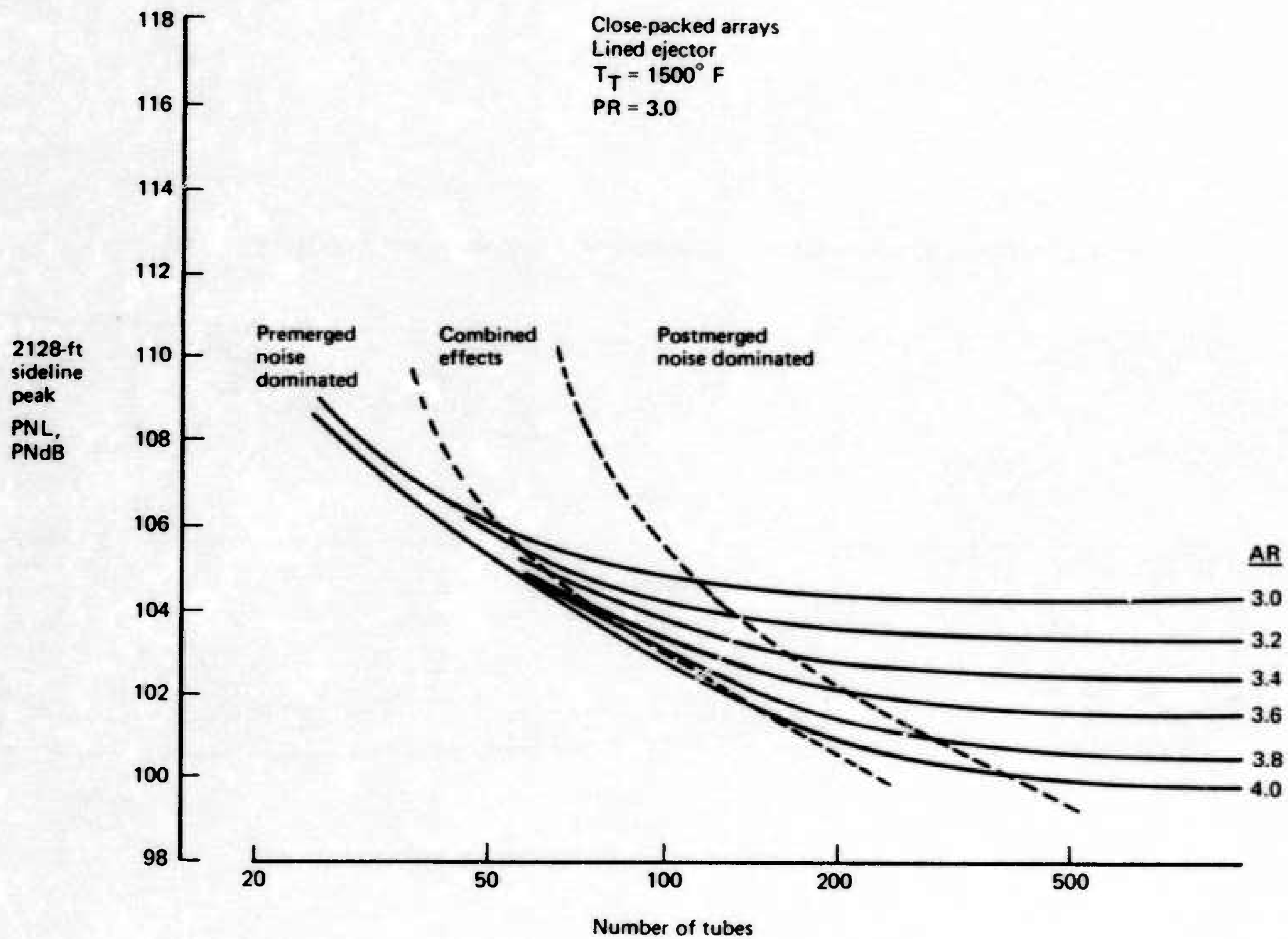


Figure 25.—Typical Jet Noise Suppressor System Trade Curves

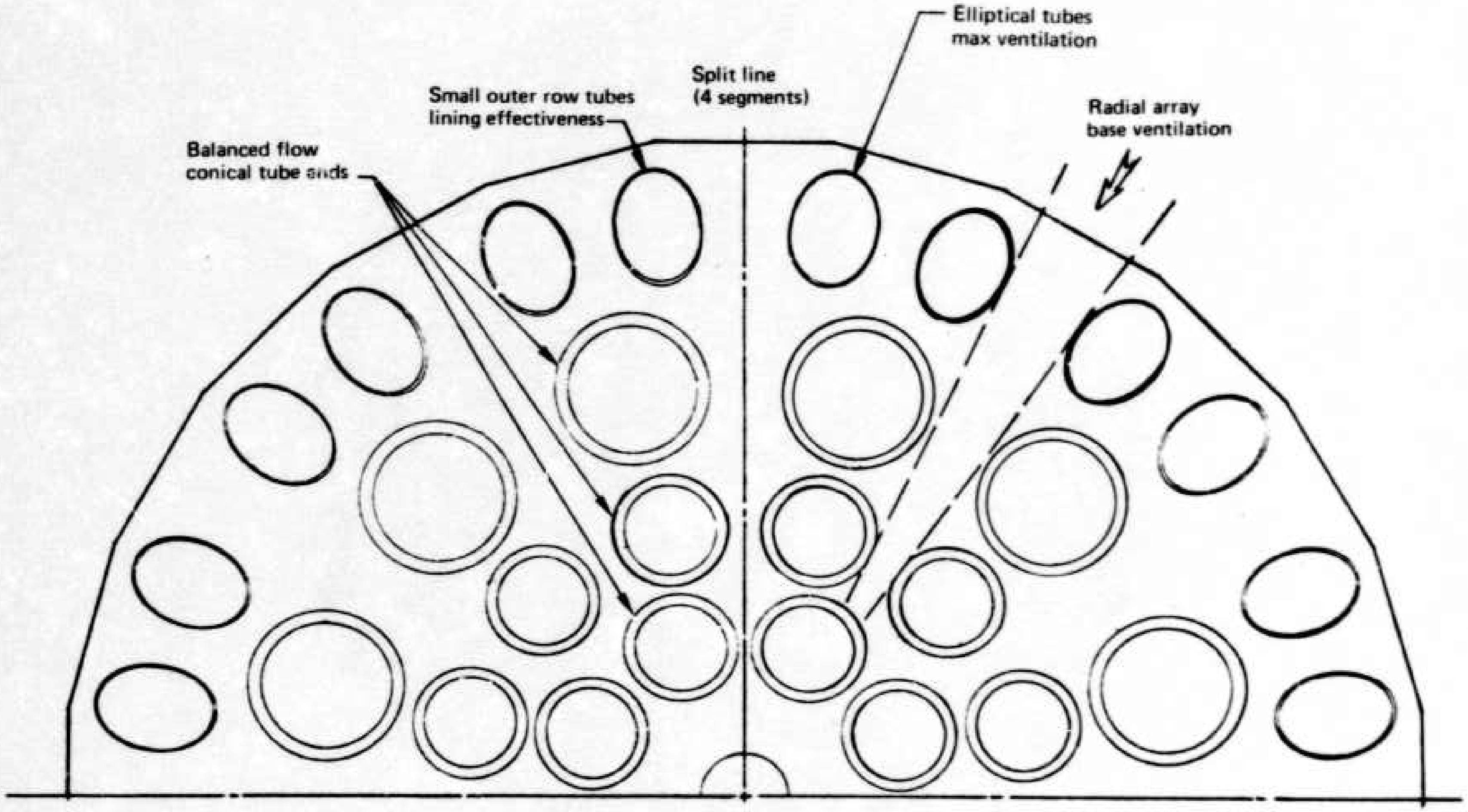


Figure 26.—57-Tube Array

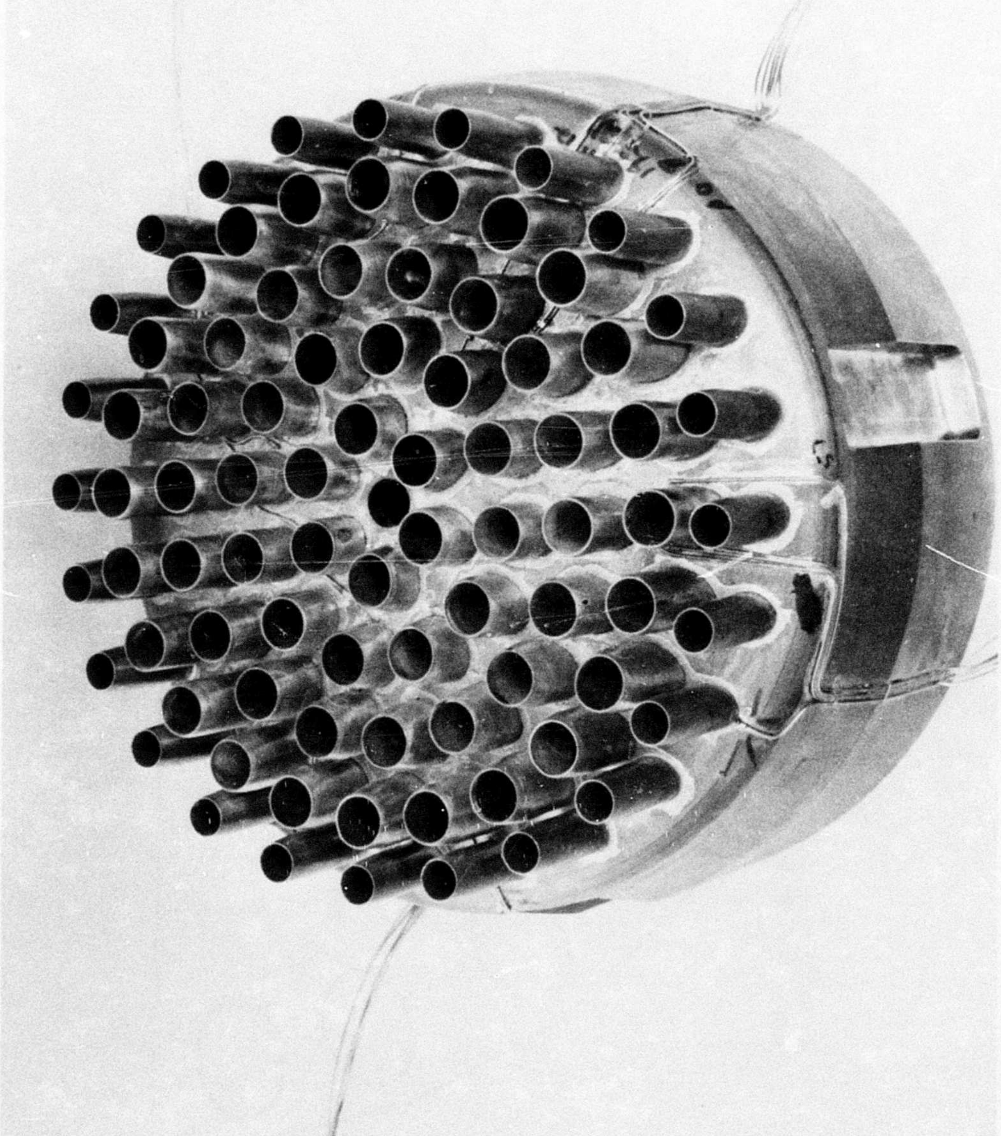


Figure 27.—85-Tube, 3.4 Area Ratio Nozzle

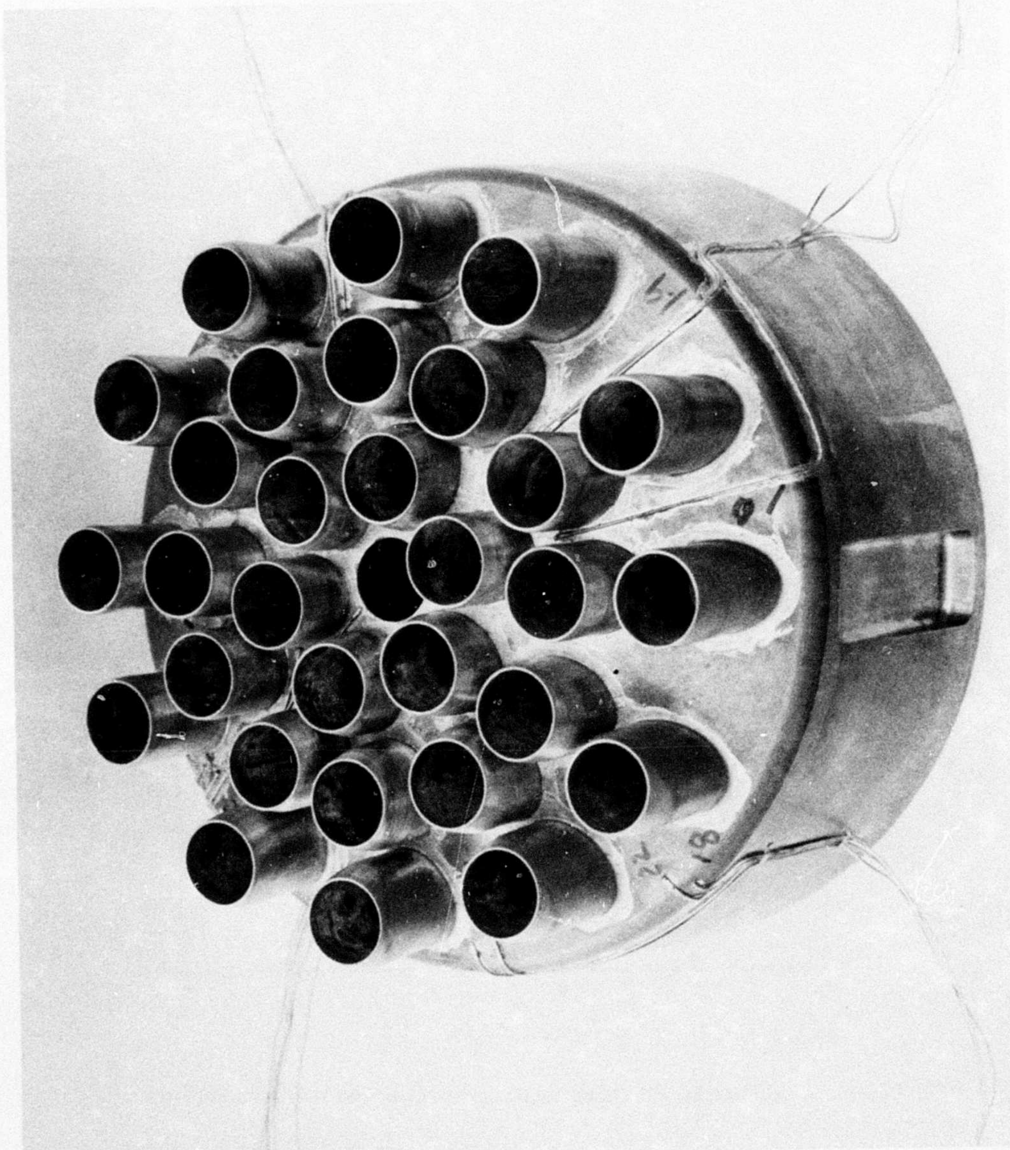


Figure 28.—31-Tube, 2.7 Area Ratio Nozzle

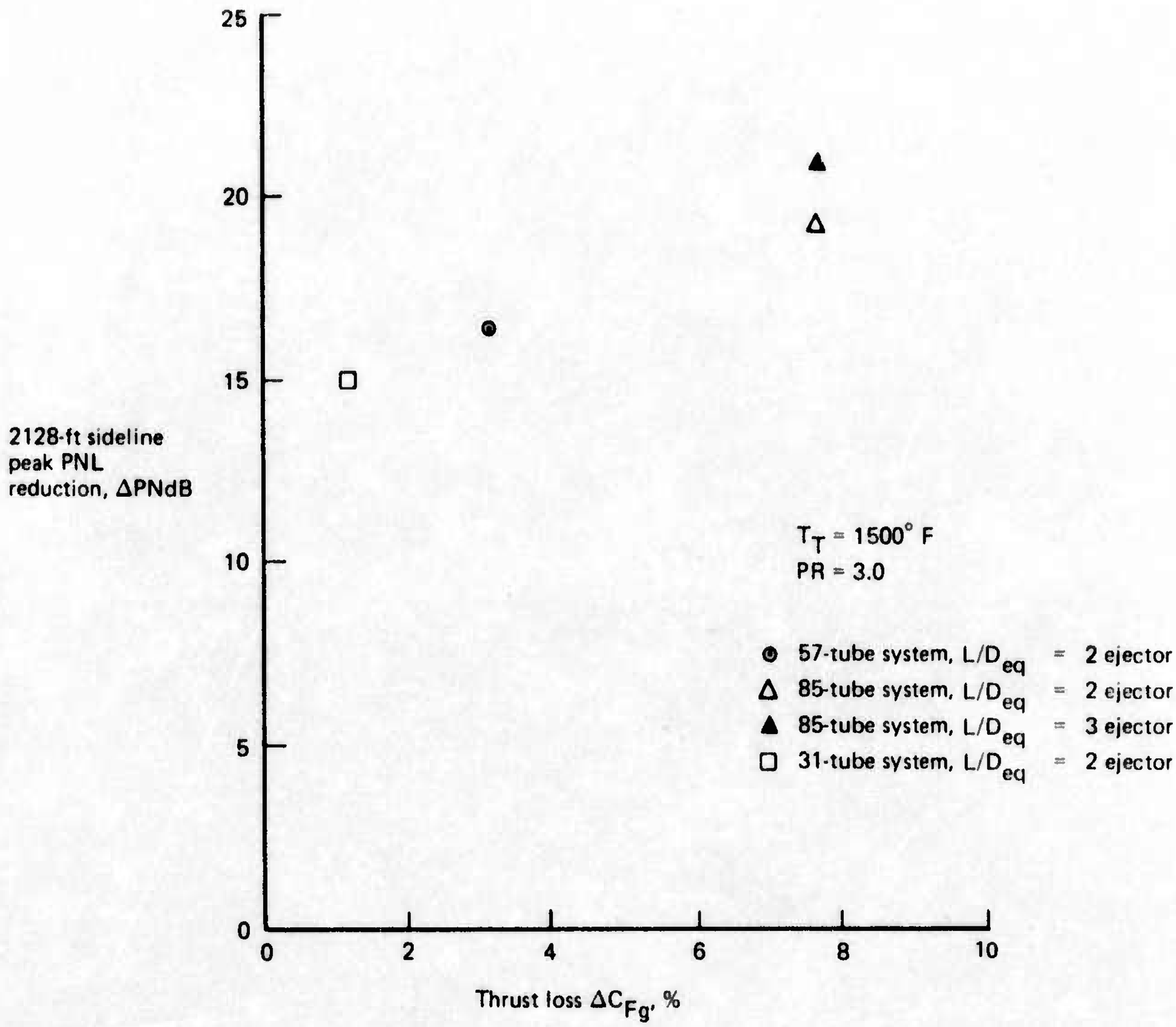


Figure 29.—Advanced Jet Noise Suppressor Noise/Performance Results

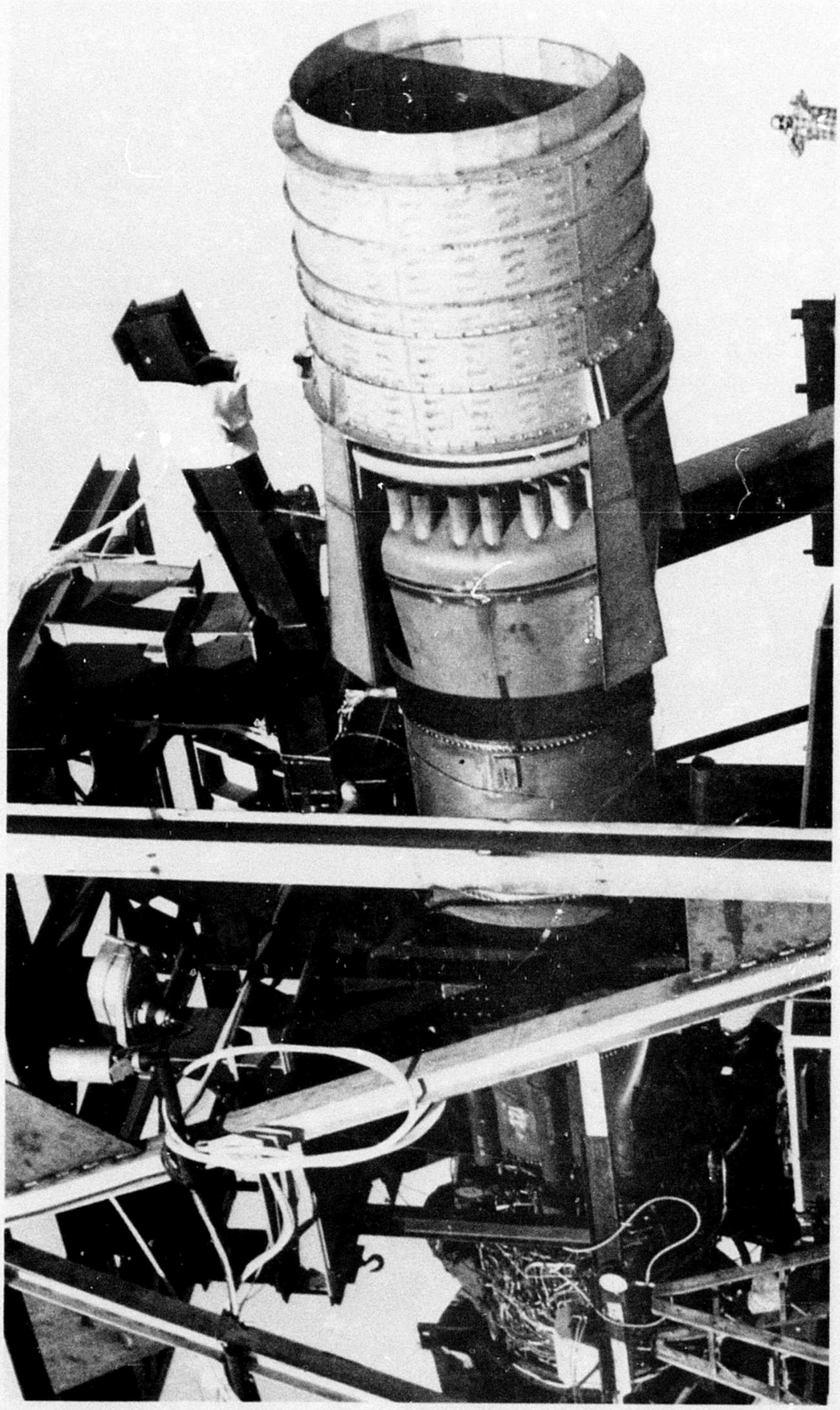


Figure 30.—J-58 Engine Installation of the 57-Tube Suppressor System

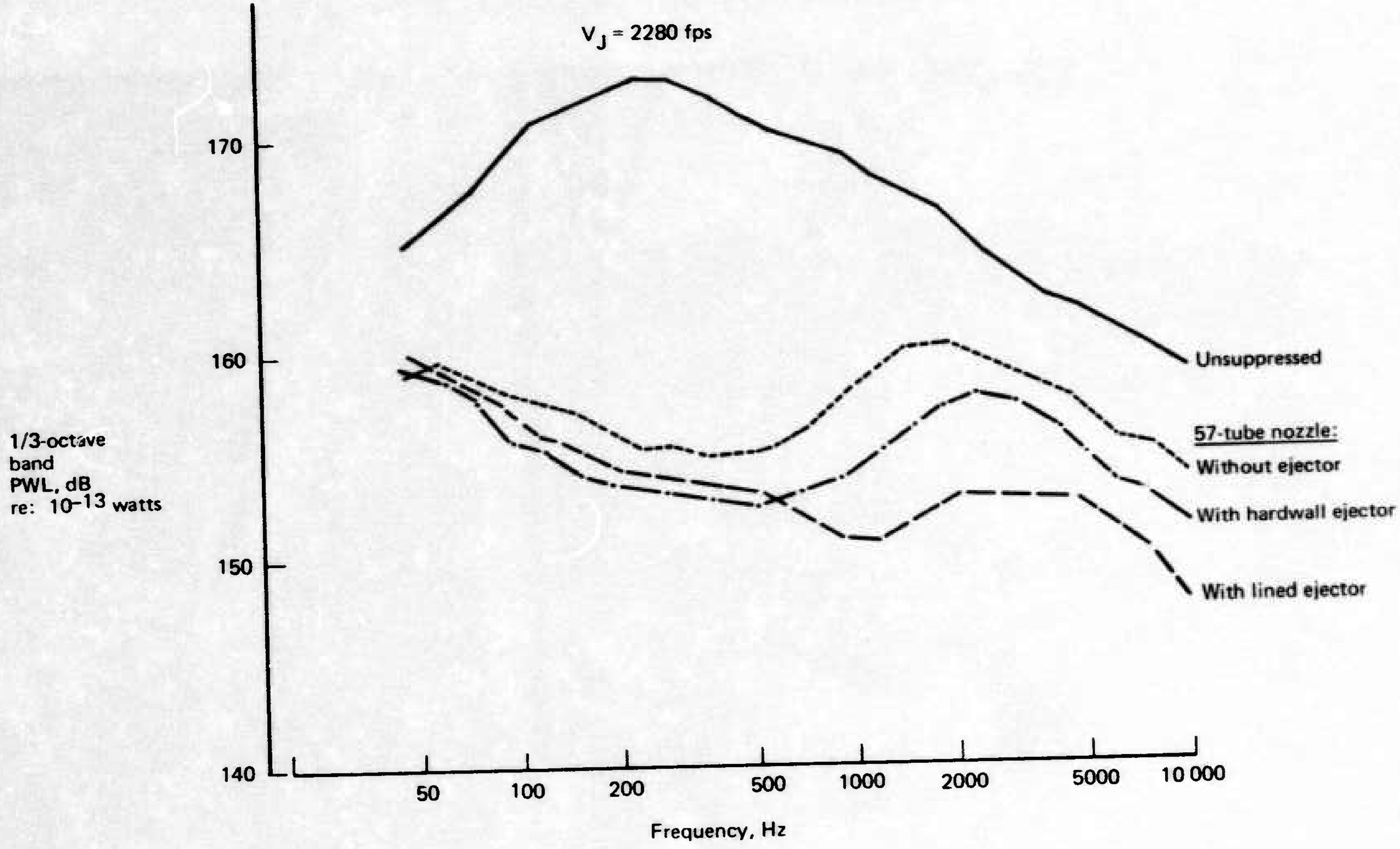


Figure 31.—Sound Power Spectra

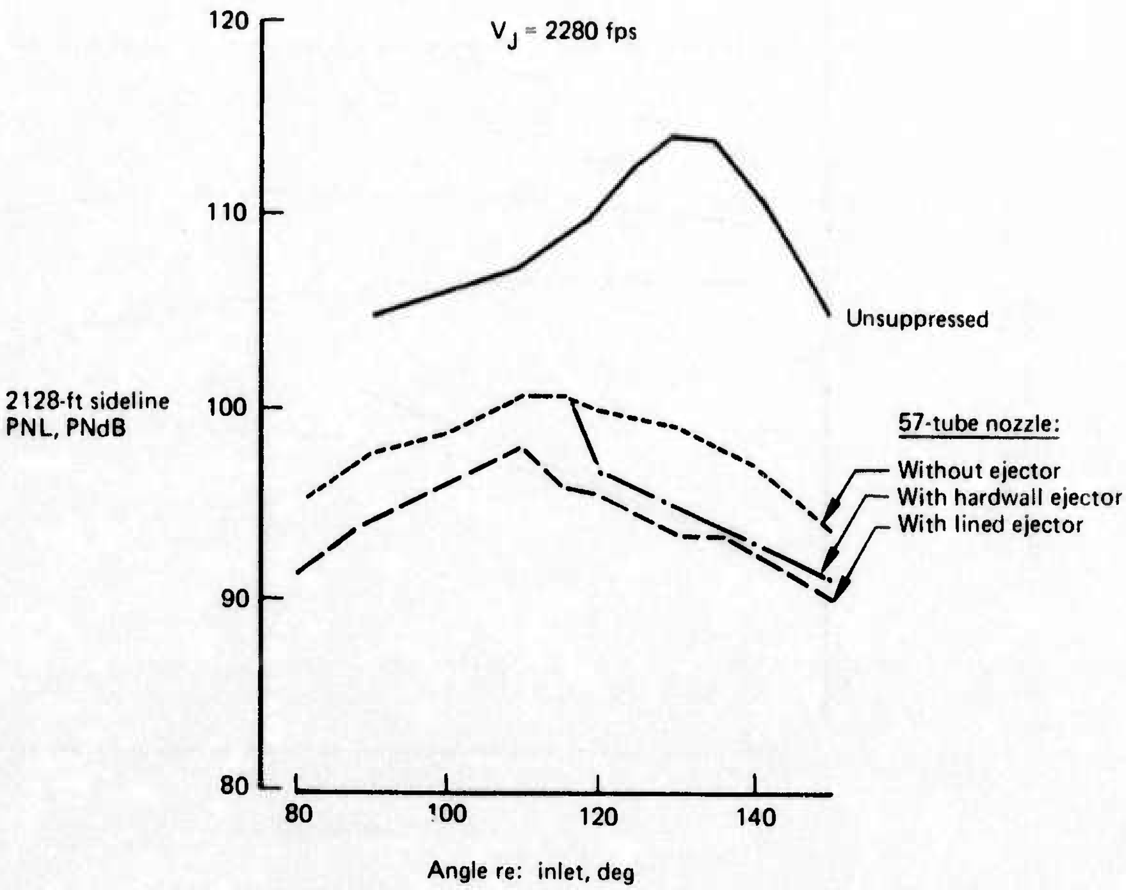


Figure 32.—Sideline Perceived Noise Level Beam Patterns

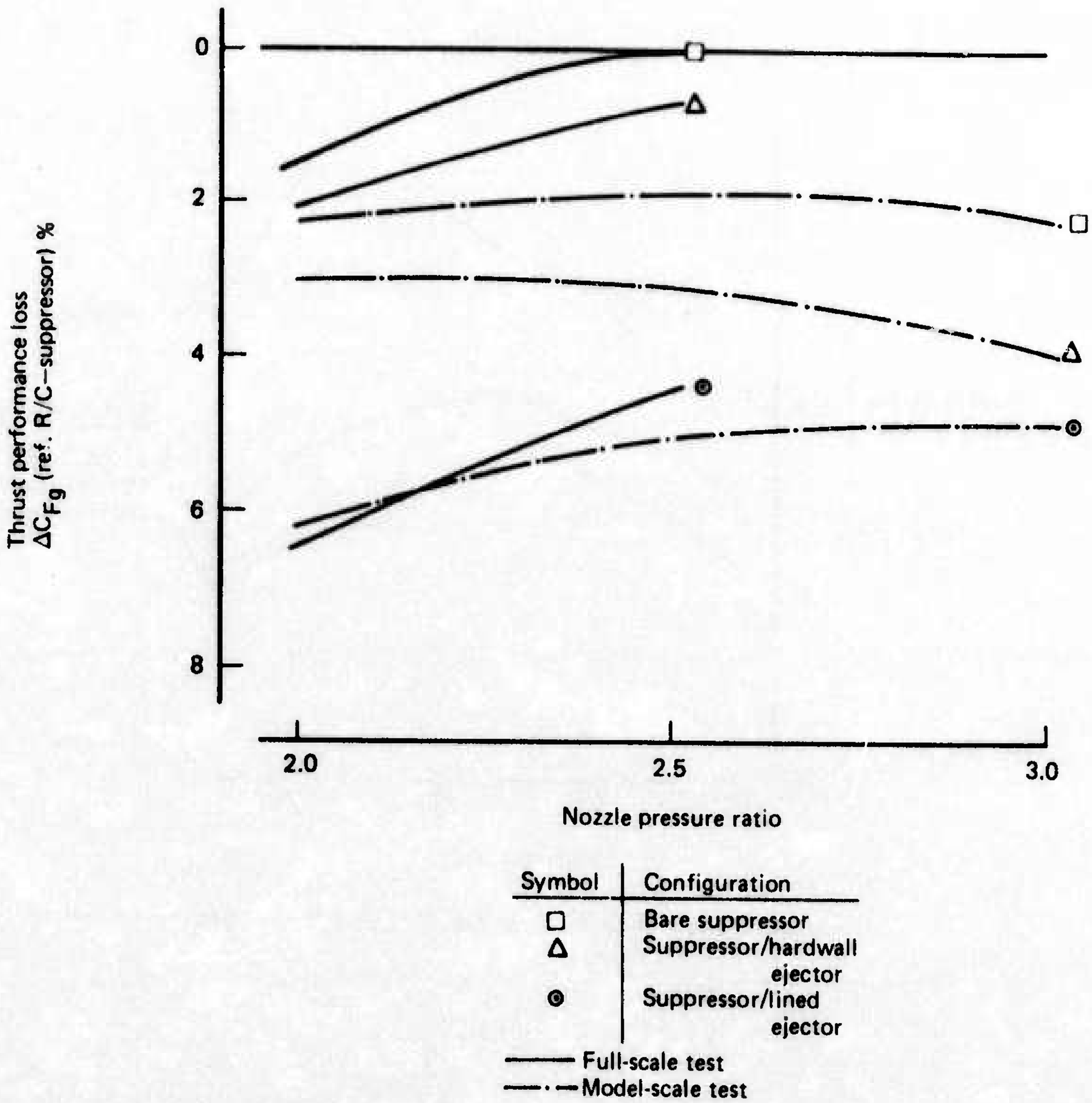


Figure 33.—Model- and Full-Scale Performance of LNHP-2 Nozzle/Ejector Configurations

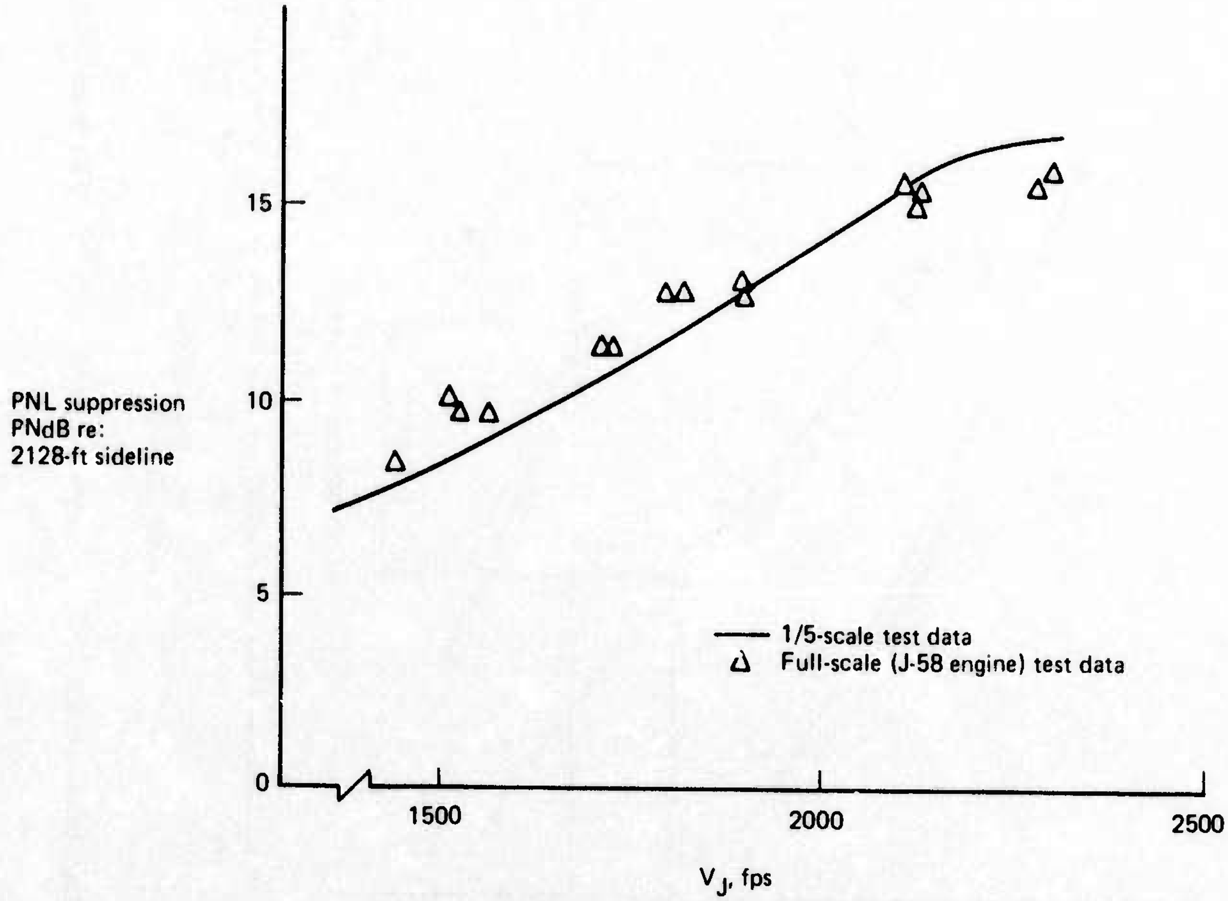


Figure 34.—Model- and Full-Scale Jet Noise Suppression Comparison for the 57-Tube Suppressor System

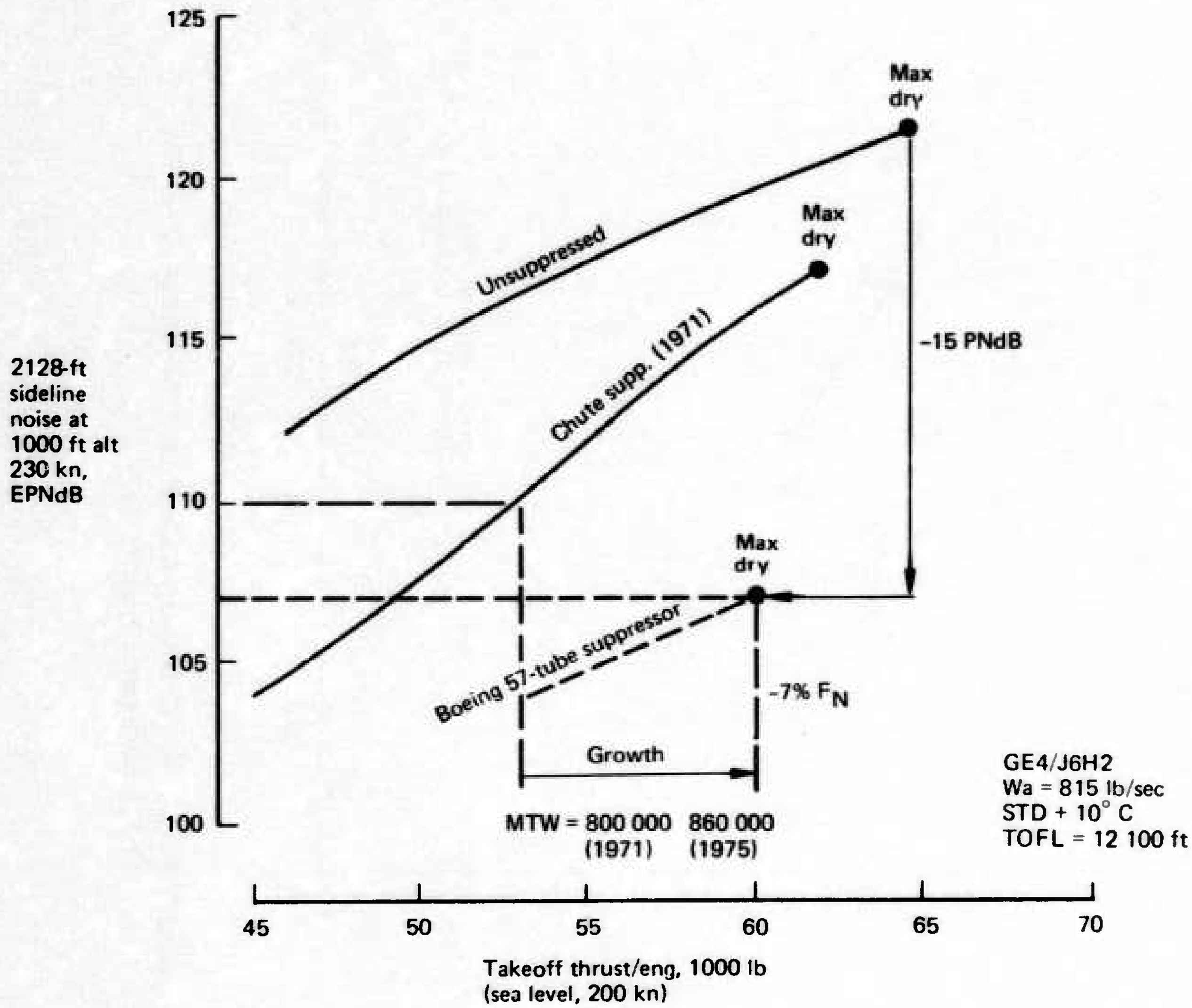


Figure 35.—Application of Multitube Suppressor System to SST Sideline Noise Reduction

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