Recent Advances in Exhaust Systems for Jet Suppression of High-Speed Aircraft

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Jet noise has been recognized as a major problem for supersonic transport aircraft. A considerable amount of technology has been developed in the past few years that is applicable to suppression of high-speed aircraft noise. This paper summarizes the types of activities that have been conducted and presents the results of a recent jet noise suppression demonstrator. These data are applied to the U.S. SST B2707-3000 airplane in order to evaluate the impact of current technology. It is shown that the suppressor is a viable nozzle system that would allow the noise levels of the SST to meet FAR Part 36 requirements. This is accomplished in a manner that would allow growth versions of the airplanes.

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 Fig. 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 permits growth versions of the initial airplane.

Reference 2 discusses the principles of suppression, the types of engines to be suppressed, the factors to be considered in selecting and designing a suppression system, typical suppression systems being considered, and finally, the economic impact of suppression systems. That discussion emphasizes the need for a systems approach in determining the suppressor; i.e., the engine and airplane constraints must be considered in choosing a nozzle system in order to achieve efficient jet noise reduction. The purpose of this paper is to present the advances that have been made in viable suppression systems. 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 Ref. 2 that bypass and multicycle engines are believed to require jet suppression, albeit less than that required for turbojet engines.

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[3,4] have shown it to be the only way to achieve high noise suppression levels at supersonic jet velocities. The program consisted of a technology development phase 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, and then the results of the demonstrator nozzle are shown.

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Jet Noise Suppression Technology

The basic suppression concept pursued in these studies consists of a multitube mixer nozzle with or without an ejector these, in turn, with mechanisms associated with noise and propulsion aspects. 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 such previous work was lacking.

Multitube Nozzles

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

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

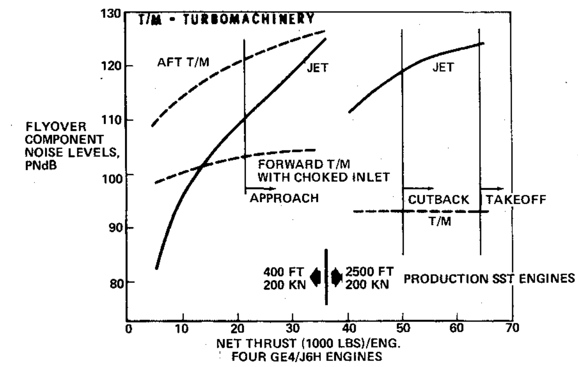

Fig. 1 U.S. SST predicted unsuppressed engine noise.

the jet. Acoustic effects of temperature and velocity profile control also were studied.

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 Ref. 5. Examination of the jet wake also was 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. This approach led to the identification of the various noise source components with certain jet flow regions as shown in Fig. 2. The studies have revealed the following jet noise sources (Fig. 3) to be present in the supersonic multitube suppressor system 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, and 5) facility/engine core noise.

The spectral characteristics of these noise sources are shown in Fig. 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 appears effectively to be "shielded" by the outer row jet turbulence.

The multitube nozzle jet postmerging noise radiates from a region which has flow similar to a simple jet. 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 tubulence noise has characteristics similar to a simple jet and agrees with theoretical predictions. Postmerged jet turbulence sound power levels can be normalized, as for a simple jet, by subtracting 10 $\log\rho^2 A$, where ρ is the gas density in the postmerged jet core. Figure 5 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 caused by the test facility "burner/core" noise.

Spiral mode flow instability noise postulated by Tam[6] for a round convergent nozzle supersonic jet 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 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 round convergent nozzle test spectra at supersonic jet velocities. For cold and low-temperature jets, shock noise also was 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 or its harmonics, there was significant amplification of both noise components.

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 burner, flow passages, structural obstructions, etc. This noise can be detected only at lower jet velocities; however, it can be a problem in multitube jet postmerged 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 the just-mentioned noise components.

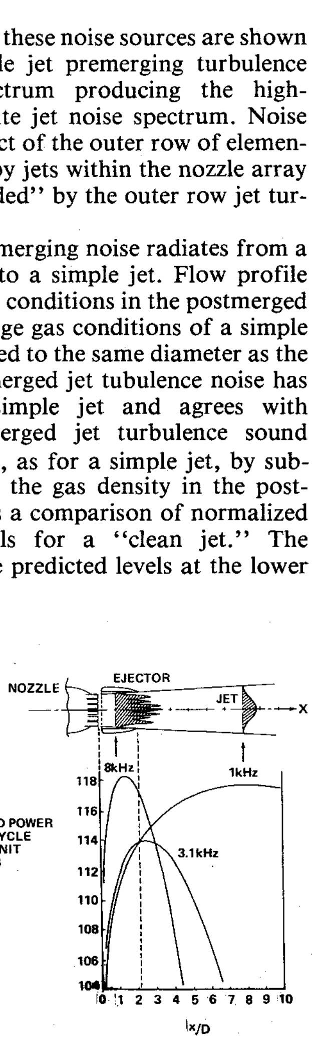

Fig. 2 37-tube, area ratio = 3.3 nozzle with L/D ejector at $T_T = 1150°F$, $PR = 3.0$.

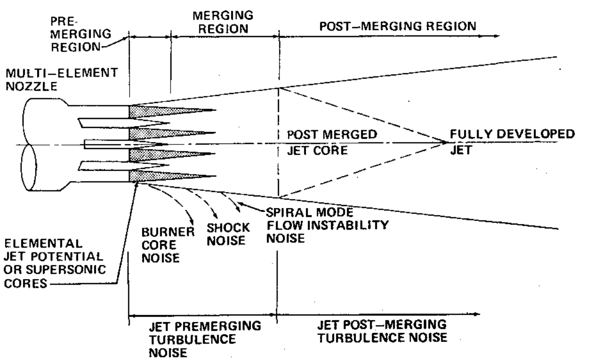

Fig. 3 Multielement jet nomenclature.

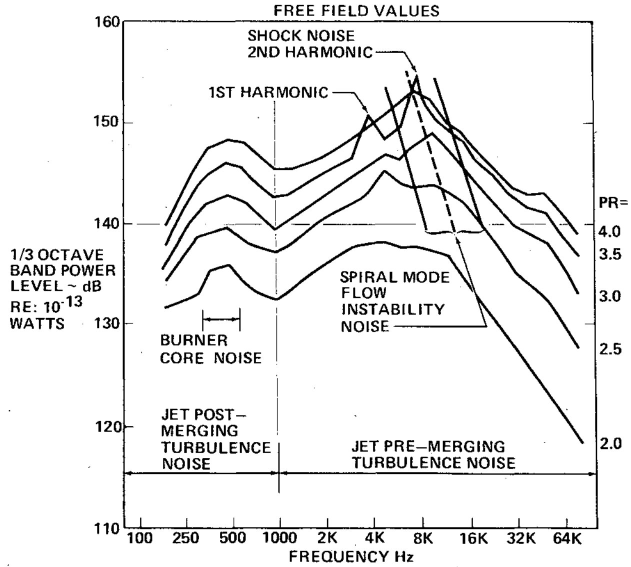

Fig. 4 Composite jet noise power spectra for the 7-tube, 3.3 area ratio nozzle; $T_T = 500°F$, $A_8 = 13.6$ in.^{2}.

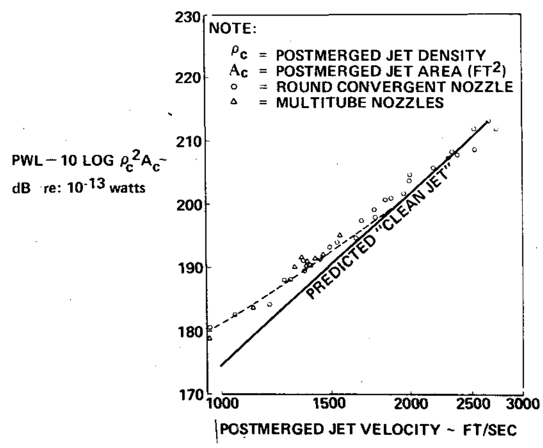

Fig. 5 Normalized postmerged jet noise power levels.

Multitube Nozzles with Hardwall Ejectors

In typical SST applications, engine nacelles have a variable area secondary exhaust nozzle which is required to optimize nozzle performance during the total flight envelope, i.e., takeoff, transonic acceleration, and supersonic cruise. During the takeoff phase, this secondary nozzle acts as an ejector relative to the primary flow nozzle. For jet noise suppressor installations, this secondary nozzle or ejector can be a bonus because a properly sized ejector with respect to the multitube nozzle can improve noise suppression. Secondly, the ejector provides a means of supporting acoustically absorbent materials which will attenuate jet exhaust noise further.

When the ratio of ejector diameter to nozzle array diameter approaches unity, noise suppression of 1-2 PNdB has been shown to be possible with a tight-fitting hardwall ejector.[3] Noise generated by multielement jets surrounded by a hardwall ejector apparently 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, thus providing some suppression of premerged jet noise because of a relative velocity effect. Properly sized "tight" ejectors have shown additional premerged 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. Fully mixed ejector configurations often also will reduce postmerged jet noise because of lower kinetic energy in the postmerged jet.

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 attenuate further 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, and the knowledge of noise source locations such that the acoustic lining can be tuned properly. There is, however, a limitation imposed on the maximum attenuation that can be observed in the far field because of the jet noise sources that occur downstream of the ejector exit.

Flight Effects on Jet Noise Suppression

An acoustic test program was conducted in a low-speed wind tunnel to determine forward flight effects on jet noise suppression at velocities typical of aircraft takeoffs. The acoustic flight effects are summarized in Fig. 6 for representative cases of an unsuppressed nozzle, a multitube nozzle, and a multitube nozzle with a hardwall ejector.

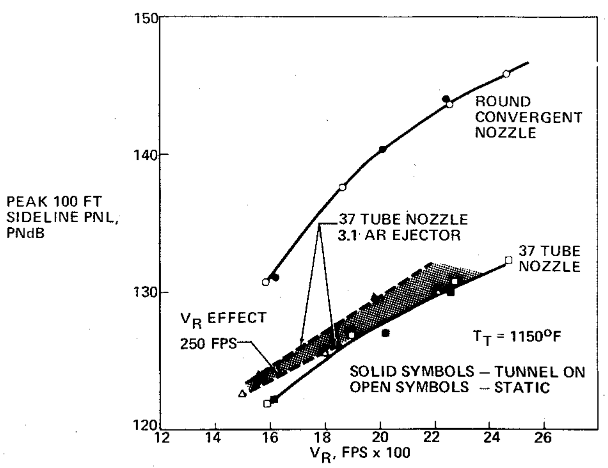

Fig. 6 Forward velocity effects on jet noise suppressor systems.

For the round convergent nozzle, the jet noise at the peak noise location is reduced by flight velocity in accordance with relative velocity. That is, the spectra shape and level, OASPL and PNL can be estimated by operating the nozzle statically at the flight relative velocity $(V_{j\text{istatic}} = V_{R\text{flight}} = V_{j\text{iflight}} - V_\infty)$. The flight effect at angles toward inlet is dependent upon the presence or absence of shock 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 shcok noise to the total noise signal. Test results indicate that shock noise is changed little because of external flow, whereas the jet mixing noise component will follow relative velocity.

The multitube suppressor results have to be examined in parts because of the dominance of two types of noise sources, i.e., the premerged and postmerged jet noise. The low-frequency postmerged noise has properties similar to a simple jet, and, consequently, this noise component is reduced in accordance with relative velocity $(V_{R_{\text{post}}} = V_{j_{\text{mix}}} - V_\infty)$. 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 premereged 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 this relative velocity relationship.

Multitube nozzles with ejectors do show a velocity effect depending on the ejector diameter relative to the nozzle flow diameter. The velocity effect is associated only with the premerged jet noise that is generated inside the ejector. That is to say, the outer tube row of the unshrouded configuration experiences a large change in relative velocity (essentially full flight velocity), the loose-fitting ejector a moderate change (the order of 100 fps), and the tight-fitting ejector a small change (the order of 20 fps). This comparison shows that suppression potential is reduced significantly in flight as jet velocity (pressure ratio) is reduced and that the reduction is greater for the shrouded configurations.

Suppressor Propulsion Technology

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. Recent efforts have been directed toward the establishment of performance design capability within mechanical design constraints and acoustic criteria for low-noise multitube suppressor exhaust systems.

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.

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, representing the most compact regular array of tube placement, as shown in Fig. 7, is referred to as a close-packed array. The other array in Fig. 7 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 flowfield obstructions.

Previous test data[7] have shown that the performance of multitube suppressor nozzles is influenced strongly 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 dependent largely upon the ability to provide a sufficient quantity of ambient air to ventilate the base area which is influenced heavily 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[8] in attempts to nondimensionalize base drag parameters. Figure 8 shows the ventilation parameter per unit 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 tested easily 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, although 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, caused by the velocity of the air penetrating the base region, result in a large base drag. Figure 8 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 area ratio five for round convergent tubes and area ratio three for elliptical convergent tubes or round nonconverging tubes.

The ventilation parameter for the radial array is shown to increase rapidly as 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.

Another measure of the amount of ventilation on any given nozzle is the wake ventilation parameter A_V/A_B, where A_V is the total area between tubes in the outer row including the area between jet wakes, and A_B is the base area that must be ventilated. The parameter, although not completely adequate, does allow us to nondimensionalize base drag of close-paced arrays as a function of tube number and, to a lesser extent, with respect to area ratio and tube array as shown in Fig. 9.

An example of the distribution of performance losses for multitube nozzles is hown in Fig. 10. The close-paced 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.

Ejector and Forward Velocity Effects

Advanced supersonic aircraft require a convergent-divergent nozzle geometry to provide near ideal engine

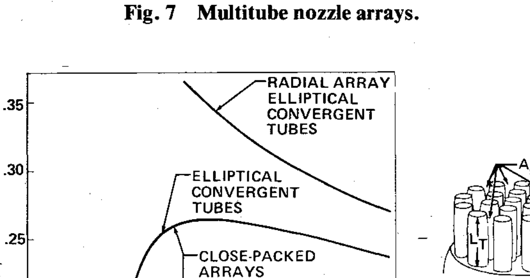

Fig. 7 Multitube nozzle arrays.

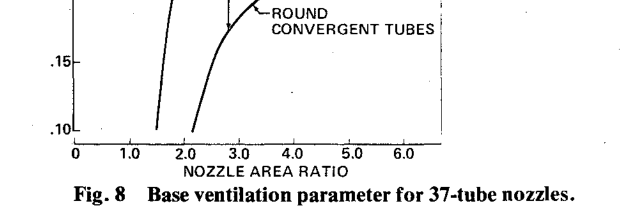

Fig. 8 Base ventilation parameter for 37-tube nozzles.

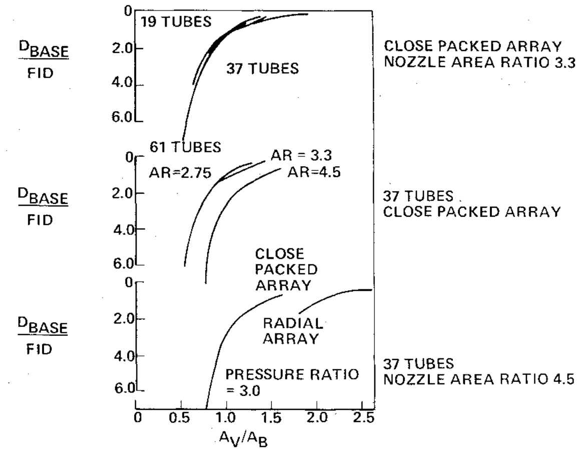

Fig. 9 Base drag vs wake ventilation parameter.

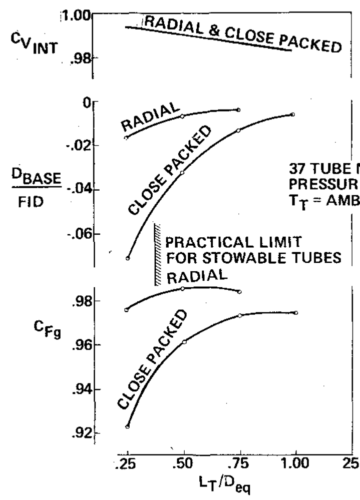

Fig. 10 Performance loss components.

exhaust expansion for maximum thrust performance at supersonic cruise. The variable convergent-divergent concept exhaust system provides this capability, and, while at takeoff, it provides a mechanism, in combination with a suitable suppressor configuration, for significant noise suppression with good takeoff thrust.

The experimental studies recently completed have investigated the performance and noise mechanisms associated with a range of ejector area ratios (ejector flow area divided by suppressor exit flow area) from 2.6-3.7. Testing in a 9-×9-ft low-speed wind tunnel provided performance lapse rate to the facility limit of 167 knots. Figure 11 typifies results of these experiments and demonstrates an interesting characteristic of flight effects on ejector performance. First, it is noted that 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 2.6-3.1 increases thrust because of 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 also is observed that the lapse rate (rate of decrease in performance with increasing external velocity) increases from the no-ejector case with 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 because of the air-handling capability of the ejector and independent of losses of the suppressor nozzle, as illustrated by the following example.

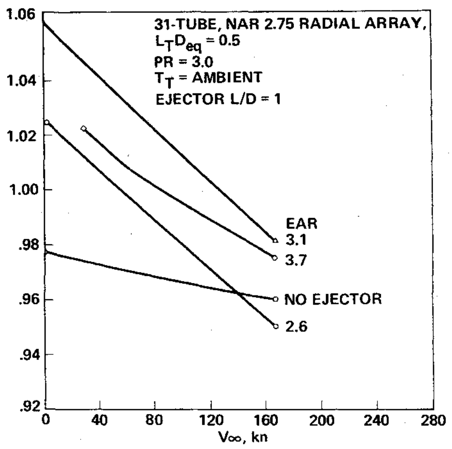

Fig. 11 Effect of ejector area ratio on performance at forward velocity.

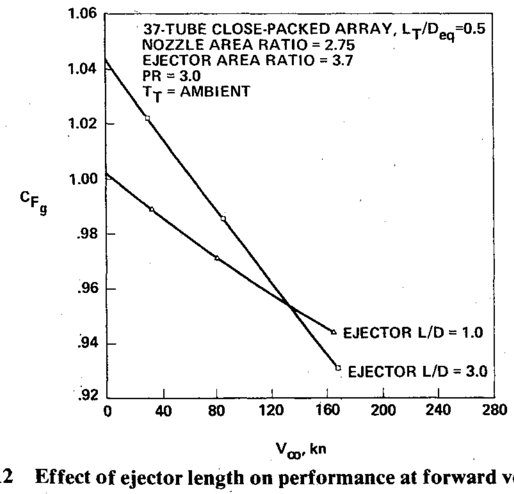

Fig. 12 Effect of ejector length on performance at forward velocity.

Figure 12 shows the effect of ejector length on lapse rate for a 37-tube nozzle with a 3.7 = 1*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-knot conditions is seen to be 6% for the $L/D = 1$ ejector and 11% for the $L/D = 3$ ejector a difference in lapse rates of 5%.

Integration of measured pressure distributions over the nozzle/ejector provides the component forces summarized in Fig. 13. 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 diameters that the jets do not impinge upon the ejector lip, and, therefore, the ejector lip force at static ambient conditions can be attributed only 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 Fig. 13.

A corollary to the aforementioned is that lapse rate is nearly independent of primary nozzle performance. This is demonstrated in Fig. 14, which shows lapse rates for two different nozzles, each tested with the same ejector. The similar lapse rates exhibited by the two ejector/nozzle configurations imply similar air handling, even though the performance levels are much different.

Mechanical Design Considerations

The design study was based on use of a nonaugmented GE4J6H turbojet engine. The suppressor system is designed to be stowed into a variable convergent-divergent ejector nozzle during cruise flight conditions in order that high performance can be maintained. The exhaust system is configured to include a clamshell thrust reverser with cascade

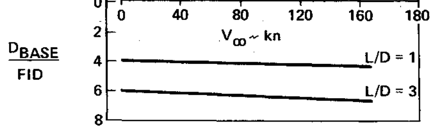

Fig. 13 Suppressor/ejector component forces at forward velocity.

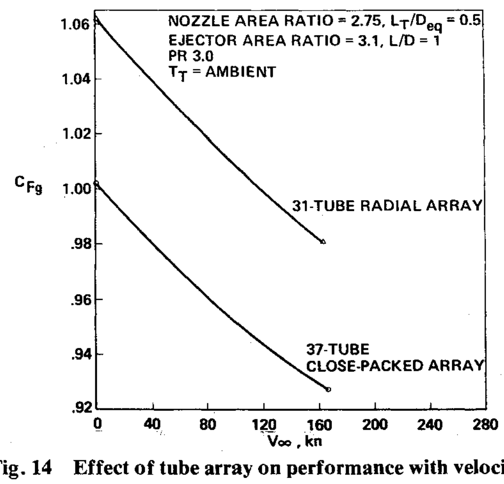

Fig. 14 Effect of tube array on performance with velocity.

exits, a variable area primary nozzle, a tube-type suppressor capable of being stowed, a convergent-divergent ejector nozzle with variable throat, and closure doors for the ejector inlet. Figure 15 is a drawing showing this system as configured. A more complete discussion of the mechanical design considerations is given in Ref. 9.

Full-Scale Demonstrator

The scale-model parametric testing and mechanical design studies led to the design and test of a full-scale boilerplate suppressor ejector nozzle in order to provide a static noise/performance demonstration of SST state-of-the-art suppressor nozzle technology. A 1/5-scale model of this configuration, designated LNHP-2, also was tested to provide detailed acoustic and performance scaling data.

The LNHP-2 design 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. The basic design that was conceived incorporated a 2.9-AR 57-tube nozzle and a 24-sided 3.1-AR lined ejector. The tubes chosen were 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 also took into consideration the requirement of 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. A schematic showing the nozzle tube array is shown in Fig. 16. Design of this nozzle was targeted to result in a 2% performance loss and 17-PNdB noise suppression at 2128-ft sideline, relative to a 10° half-angle round convergent reference nozzle.

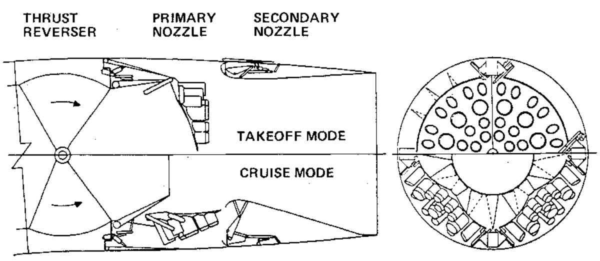

Fig. 15 Application of the 57-tube suppressor to an advanced SST exhaust system.

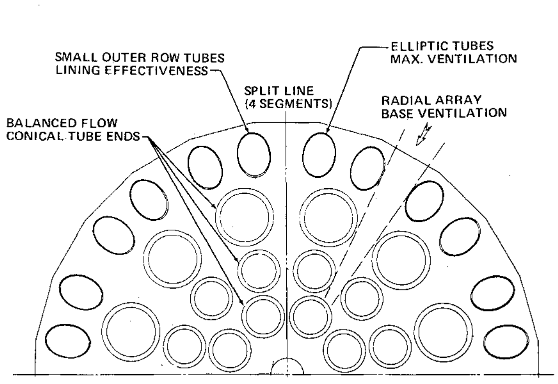

Fig. 16 57-tube nozzle array.

Figure 17 shows the full-scale test installation at the Boeing engine test site in Boardman, Ore. A J58 engine was utilized as a gas generator for suppressor noise and performance evaluations. This jet noise suppressor system was evaluated in model-scale (1/5 scale) and full-scale on a J-58 turbojet engine. The sideline noise suppression results derived from both sets of measurements are shown in Fig. 18. Quite good agreement is found between the two sets of data. The acoustically lined suppressor system reached a peak suppression of 16.4 PNdB model scale and about 16 PNdB full scale. The full-scale evaluation of the suppressor system, however, was limited to the J-58 engine cycle and a maximum jet velocity of 2300 fps. In a true SST application, jet velocities of 2500 fps or higher could be expected. The model-scale results indicated that the suppression characteristics peak at about 2500-fps jet velocity.

Model- and full-scale performance differences (C_{F_g}) between the reference nozzle and suppressor configurations are compared in Fig. 19. Engine operating limits did not allow for data comparisons above 2.5 pressure ratio. Similar performance relative to reference nozzle values is seen for the bare suppressor nozzle.

Performance of the suppressor with unlined (hardwall) ejector was improved by 1-2% over comparable scale-model results. This difference is attributed to Reynolds number effects on skin friction and ejector air handling. Larger differences are observed in comparing lined ejector results, because lining surface hole size was proportionately larger in the model, thus creating a "rougher" aerodynamic surface. This geometry difference resulted from the unavailability of

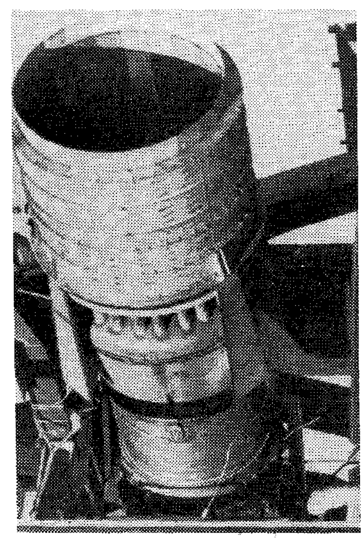

Fig. 17 Full-scale test installation.

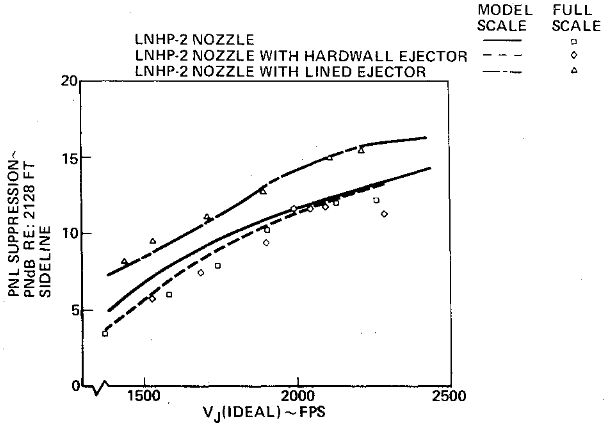

Fig. 18 Comparison of model and full-scale peak PNL suppression values.

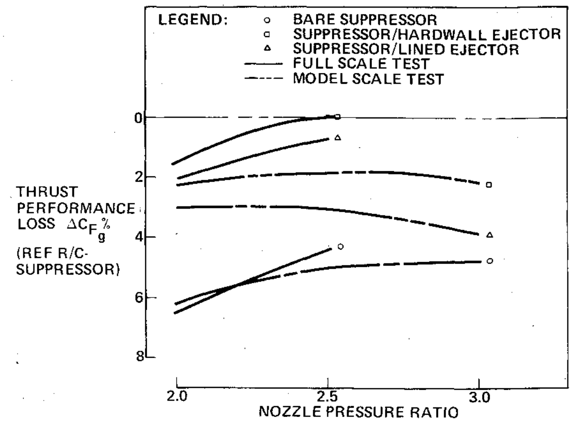

Fig. 19 Model and full-scale performance of LNHP-2 nozzle/ejector configurations.

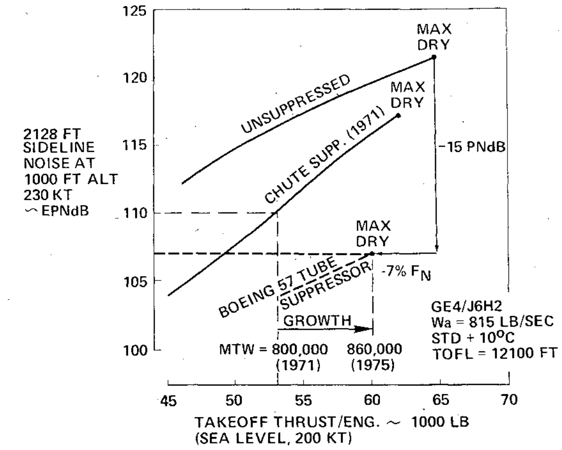

Fig. 20 Application of multitube suppressor system to SST sideline noise reduction.

perforated plates with sufficiently small hole size for proper geometric scaling.

From the analysis of model-scale and full-scale test results of the LNHP-2 suppressor system, it is concluded that the application of this suppressor to the 1971 version of the U.S. SST configuration 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 LNHP-2 performance to 15-PNdB sideline noise suppression for 7% net thrust loss at 230-knot climbout velocity. Figure 20 shows the sideline noise status at the termination of the SST program in 1971. 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 (LNHP-2) 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 grow the airplane MTW to 860,000 lb, which would improve the airplanes' economics through either increased payload or range or a combination of both.

Conclusions

Jet noise suppression, a major problem in the development of supersonic transports, has experienced a substantial technology change 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. A program is described that has related these processes to jet wake flowfields; the flowfields in turn have been related to nozzle system geometry.

It has been said that "progress in any profession is associated with the ability to predict and control."[10] The current program has allowed the development of design prediction that has been substantiated by model- and full-scale demonstrator programs. Perhaps this is the best measure of technology gain.

The demonstrator program was conducted on a J-58 engine. The concept tested has been studied to determine its mechanical feasibility and compatibility with the Boeing B2707-300. The data from the test program have been analyzed by applying them to this airplane in an effort to evaluate the impact of the technology gain.

It was shown that the airplane could now meet FAR Part 36 noise regulations. Furthermore, it was shown that the application of the subject nozzle system would allow a substantial increase of maximum takeoff weight (60,000 lb), other technologies being constant. This would allow for growth versions to have flexibility on payload and range.

Future work on engine noise will involve matching an engine and nozzle system to a particular airplane system. It also should be noted that the reduction of jet noise has produced evidence that there is a core (internal or excess) noise component, even for high-performance turbojet engines that also must be addressed if there are to be further engine noise reductions. Thus, future noise reductions will have to balance contributions from turbomachinery core and jet components. Additional work also should be conducted to study ground-to-flight effects and to demonstrate the concept reported herein in a flight mode.

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