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Perspective of SST Aircraft Noise Problem. I: Acoustic Design Considerations

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The current state of research concerning noise suppression for SST jet engines is presented. The noise of unsuppressed, augmented power engines is defined and compared with several engine types that have been used on subsonic aircraft. Results of an extensive research program of both model and large scale levels which has investigated many different noise suppressor concepts are described. Test results show several fundamental means to reduce jet noise at different frequency regions. Acoustic design charts have been developed for several suppressor types. Part II of this paper (to be published in the *Journal of Aircraft*) will cover thrust losses and some installation factors.

Introduction

During takeoffs and landings, the engines of the supersonic transport will produce community and airport noise. The control of this noise is of very great interest to all people involved in the design of the SST, and those involved in the problems of noise around airports. Most supersonic aircraft designs make use of jet engines, usually with afterburning, as contrasted to the turbofan engines now used in all recently produced subsonic jet aircraft. Low airport and community noise from the SST may require the application of complex jet exhaust and inlet noise suppression devices as well as the use of noise abatement operating procedures. The successful development of a very effective jet exhaust noise suppressor integrated into the propulsion system would be of great value in achieving low noise during SST takeoff, climbout, and landing.

In the absence of a jet noise suppression theory, The Boeing Company is conducting a suppressor research test program. This program is based on pioneering work in the 1950's. Recent investigations are identifying key variables, and the

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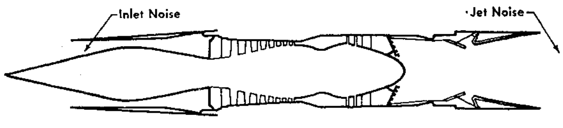

Fig. 1 Engine noise sources.

influence of these variables is reducing the jet exhaust noise of the SST turbojet engines.

Based on the systematic model suppressor tests and parametric studies of the test results, acoustic design charts have been generated, and suppressed jet noise spectra extrapolated to full scale to predict SST engine noise characteristics.

These acoustic design charts are of value in development of a working jet noise suppression theory, in assisting the nozzle designer in development of practical noise suppressors, and in studies of SST noise reduction effectiveness. Studies are underway to apply recently acquired suppression research knowledge to actual engines and actual SST airplanes. This paper will report on the noise research work which has already been accomplished and will give some indications of the direction in which work is likely to proceed in the future in this very interesting and important subject of SST engine noise control.

Part I will report research results on jet nozzle noise suppression devices. Part II, to be published later in the *Journal of Aircraft,* will report research results on suppressor nozzle thrust losses and upon some aspects of the application of suppression devices to an SST aircraft.

Noise of Jet Engines

The engines considered for most SST transport designs are simple-cycle turbojet engines, usually with an afterburner. Figure 1 is typical of the type of engine considered and shows a supersonic inlet and a convergent-divergent nozzle. Engine noise can come from the inlet as well as from the jet exhaust pipe. This paper will concentrate almost entirely upon the noise produced by the exiting jet of simple-cycle afterburning turbojet engines.

The principal factor controlling the noise level of a jet is the velocity of the jet. The velocity of the jet is determined by its temperature and the pressure ratio of the air exiting from the jet. Figure 2 shows the sound pressure level in decibels produced by jet exhausts as a function of exhaust velocity and thrust level. The simple-cycle turbojet engines used in the early series of subsonic jet transports had jet velocities of the order of 2100 fps, and thrusts of the order of 10,000 lb. The velocity, resulting from the higher temperatures and pressures of modern turbojet engines, such as would be used in the SST, is between 2100 and 2400 fps without afterburning, and up to 3350 fps with afterburning. These engines would be 4–6 times larger in thrust than the early subsonic jets. As shown on Fig. 2, the basic engines under consideration for SST type aircraft are substantially

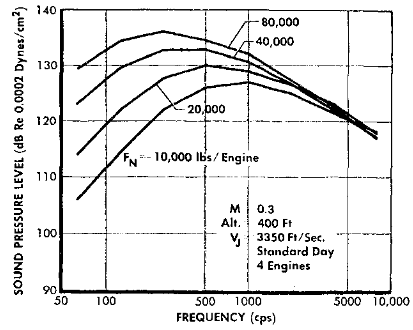

Fig. 3 Size effects—unsuppressed turbojet engine noise spectra.

noisier than the jet engines used in the commercial jet transports which entered service in 1958. The effect of engine size upon noise for circular simple nozzles is shown on Fig. 3. The data presented here are for different sized engines, all with a 3350-fps exhaust velocity. The data show the sound pressure level vs frequency as it would be observed during a flyby of an airplane powered by such an engine. The effect of increasing engine size is primarily one of increasing the noise at low frequencies. The noise at high frequencies is not greatly affected by increasing the size of an engine. Acoustical engineers have developed a term known as "perceived noise level" (PNdb) which weighs the noise produced at different frequencies to give a measure of the extent to which a noise will be perceived by an average individual. The human ear does not hear well at very high frequencies or at very low frequencies. The PNdb scale of expressing noise gives particular attention to the noise produced in the frequency range between 1000 and 10,000 cps. It weights very lightly the noise made at frequencies above 10,000 cps and below 300 cps. The data from Figs. 2 and 3 can be replotted in terms of PNdb as shown in Fig. 4. It will be noted that when using the PNdb scale of measuring noise, there is very little effect of engine size upon perceived noise.

As a jet engine is throttled, the mass flow of air through the engine is reduced somewhat, but velocity reduction is the principal change occurring when the engine is throttled. Hence, there is a substantial effect of throttling upon the PNdb of a turbojet engine. Figure 5 shows the noise produced by the jet plume of an unsuppressed turbojet engine as a function of thrust for engines of four different sizes, all with a velocity of 3350 fps at maximum thrust, and with decreasing velocity and mass flow as would be appropriate to jet engine design practices. It is evident on Fig. 5 that there are very substantial effects of throttling an engine and of engine size upon the noise produced at a fixed thrust. Figure 5 ignores the background noise level which might be produced by the inlet of an engine, or by the compressor turbine and flame portions of an engine, and covers only the subject of the noise produced by the main jet plume. These other factors are of primary

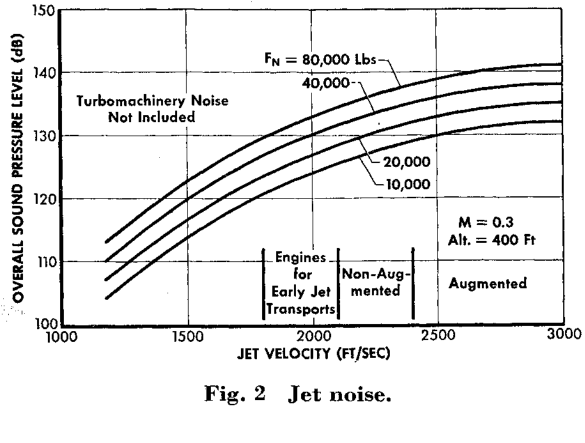

Fig. 2 Jet noise.

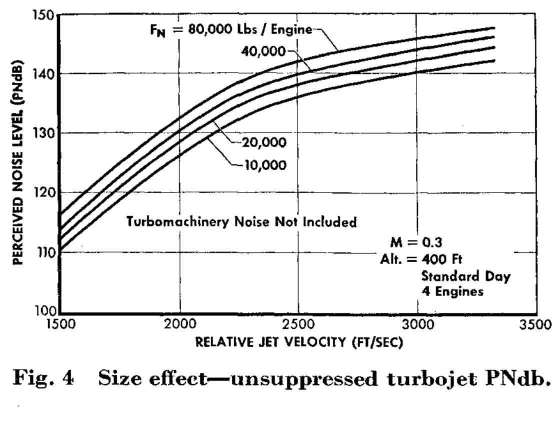

Fig. 4 Size effect—unsuppressed turbojet PNdb.

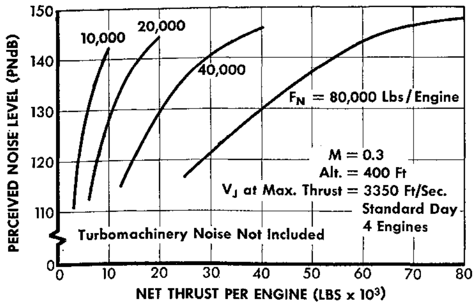

Fig. 5 Size effect—unsuppressed turbojet PNdb.

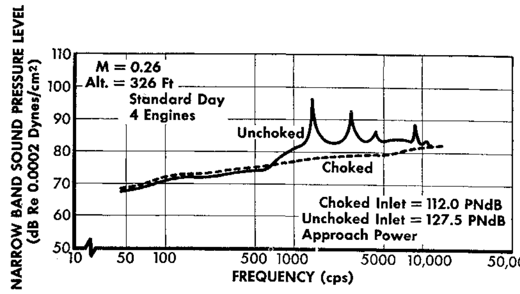

Fig. 7 Effect of choked inlet flow on inlet noise.

importance under some conditions, but except for a very brief note on the inlet will not be covered in this paper.

Another major factor influencing the PNdb produced by an unsuppressed afterburning turbojet engine is the distance between the observer and the engine. If the atmosphere did not absorb any of the noise, but only distributed it, there would be a basic reduction in noise of 6 db or 6 PNdb for each doubling of the distance between the observer and the engine. In addition to the 6 db per doubling, there will also be an attenuation of the higher-frequency noises by the absorption of the atmosphere. At 850 cps, this absorption is additionally one db per 1000 ft of distance. At 6800 cps, this increases to 11-db attentuation/1000 ft. Near the upper band of the frequencies which are reasonably highly weighted by the PNdb scale, 3400 cps, this attenuation is 6 db/1000 ft. All of these attenuations are over and above the 6 db per doubling of the distance. Increased distance helps with reducing noise at low frequencies and very rapidly attenuates the noise at high frequencies. For a typical unsuppressed afterburning turbojet engine, the PNdb vs distance is shown in Fig. 6 for varying thrust levels. These data are presented as a variation in altitude since they will be used predominately for the cases of an airplane flying above the observer. These data are equally applicable under most conditions to an observer to one side as long as the airplane is at more than 15° elevation above the observer. The reduction in jet noise from the reduction in engine thrust which comes about from increased altitude is not a major factor in this presentation. It will be noted, however, that the PNdb drops off faster than 6 db per doubling in altitude and that this effect is very substantial between 500 and 2000 ft of altitude.

The noise coming from the inlet of subsonic engine installations is a very important factor in determining approach noise and the noise during times when the engine is throttled. This is an important consideration in supersonic transports also. Fortunately, supersonic transports have variable geometry supersonic inlets which can be used to suppress the noise coming from the inlets at subsonic speeds. If these supersonic inlets are designed and operated so as to choke the inlet flow up to a supersonic velocity, and then slow it back down before entering the engine, then the engine inlet noise is substantially suppressed in subsonic flight. The engine noise cannot travel upstream against a flow which is at or above the speed of sound. This effect is called choking and substantially limits the noise coming from inlets which are operated at choked or supersonic speeds. This effect is shown in Fig. 7.

The principal and more obvious approaches to the solution of the SST jet engine noise requirements are 1) cutback to partial power, 2) noise suppressors to be used during takeoff and landing, and 3) placing the greatest distance possible between the airplane and the observer.

Although this paper does not treat of this subject, investigations are also underway at General Electric, as well as Boeing, to look for other engine cycles which might possibly provide better performance and noise results on the SST than those of the simple-cycle afterburning jets.

Technical Approach

The technical approach being used by The Boeing Company to design an SST power plant installation and airplane with acceptable noise levels is outlined in Table 1.

During the 6-yr period 1954–1960, The Boeing Company, Rolls-Royce, and others were very active in research on jet engine noise silencers. A great deal was learned in the course of extensive cut-and-try experimental tests, but little or no theory was evolved to explain the results of these tests. In any case, a number of jet transports were built using silencers which certainly improved the community acceptance of these airplanes. Figure 8 shows the 21-tube suppressor used on the 720 airplane. Research and development on jet plume noise came virtually to a standstill with the advent of the turbofan engine for subsonic transports. Jet engine suppression research has been resumed recently and a very concentrated program has been conducted by The Boeing Company and General Electric in the last two years. The goal of the Boeing pro-

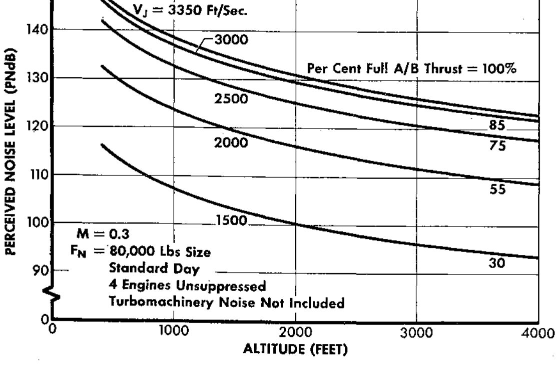

Fig. 6 Perceived noise level reduction with altitude.

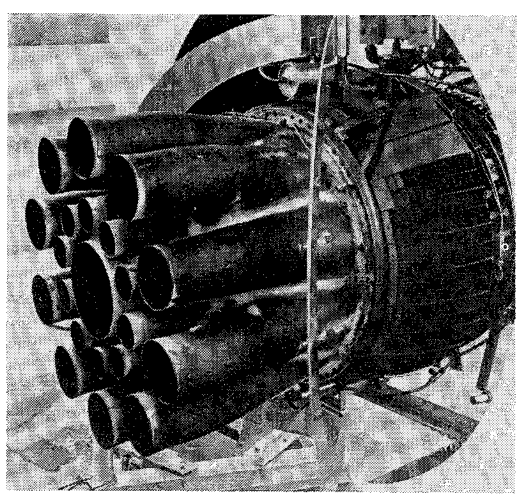

Fig. 8 21-tube Boeing jet noise suppressor.

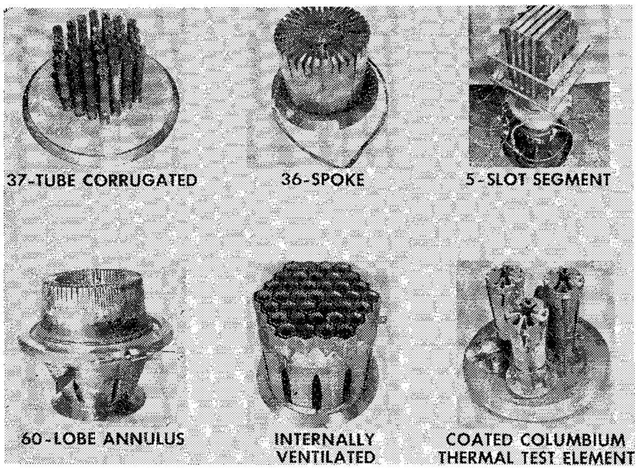

Fig. 9 Jet noise suppressor models.

gram is to develop and demonstrate by tests that a jet exhaust noise suppressor can be designed which will reduce airport and community noise to acceptable levels, and will be suitable for the production SST in commercial service. The target is to achieve 12–20 PNdb noise suppression along a 1500-ft sideline with thrust penalties of 10% or less. This goal may not be achieved, but every effort is being expended to determine how close we may get to this objective.

Test Program

Much of the Boeing research program is directed toward the measurement of acoustical and performance characteristics of scaled nozzles. The models were approximately $\frac{1}{8}$th scale. The Boeing test facility simulates the SST engine exhaust environment. Exhaust gas total temperature, pressure ratio, mass flow, base pressure, and thrust are measured during each test. Jet noise data are measured for each test condition simultaneously at a 25-ft polar distance in 10° increments from 30° to 80°, relative to the jet exhaust axis. Model data have been converted to full scale conditions and distances as indicated.

Afterburning turbojet engines such as might be used on the SST may have extreme thermal exhaust gas temperatures up to 3000°F. Jet acoustical and performance measurements are normally conducted at lower temperatures, but some tests have been conducted at these high temperatures to confirm the basic scale corrections for the test data.

Table 1 Technical approach to designing an SST power plant installation and airplane with acceptable noise levels

Review previous noise suppressor data
Design, fabricate, test, and analyze new suppressor model configurations having high-suppression potential
Establish suppressor acoustic and performance characteristics of basic suppressor concepts as a function of key variables
Conduct suppressor element thermal environment and cooling tests to establish required design criteria compatible with afterburning operation
Conduct design implementation studies to incorporate desired suppressor characteristics and define resulting installation penalties
Conduct engine cycle-airplane installation studies to define optimum compromise between noise level and airplane performance
Design, fabricate, test, and analyze suppressor configurations that reflect previous study results
Conduct large scale tests to verify small scale results
Design, fabricate, and test large scale demonstrator suppressor nozzle meeting program objectives and representing best over-all compromise between noise level and airplane performance

Noise Suppression

Model nozzles were tested to explore the acoustical suppression characteristics of a wide variety of different suppression schemes which have been proposed by various interested parties. Some of these are shown on Figs. 9–11. Most of these nozzles are either multitube nozzles, similar to that used on the 707, as shown on Fig. 8, or segmented nozzles as advocated by F. B. Greatrex, of Rolls-Royce, in his early pioneering work on suppressors, and also used on some 707's. Some of the more interesting configurations tested were a combination of the multiple-tube nozzle with the Greatrex type of spoked or fluted ends.

Multitube Nozzles

Figure 12 shows the suppressor trends for plain round-ended multitube suppressors for various area ratios and number of tube elements. The data have been scaled to have all exhaust areas equivalent to that of a 33-in.-diam circular convergent nozzle. The tubes are uniformly spaced and have a small convergence just forward of the exit. The area ratio is a measure of the total area enclosed within the perimeter of all of the jet tubes to the exhaust area of the tubes. The dashed lines are estimated. It will be noted from Fig. 12 that the factor controlling suppression at low frequencies is area

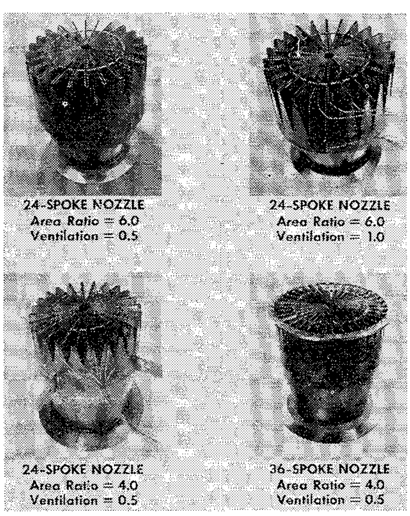

Fig. 10 Multispoke suppressor nozzles.

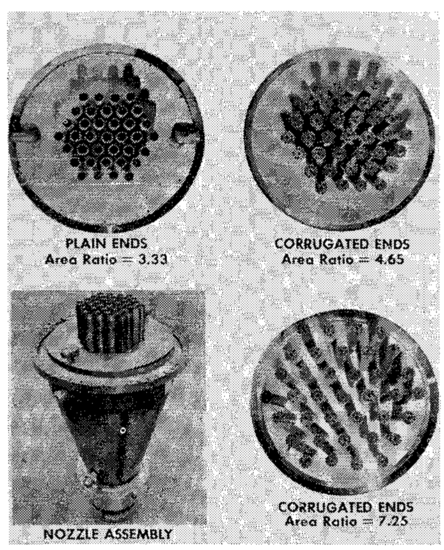

Fig. 11 Multitube suppressor nozzles.

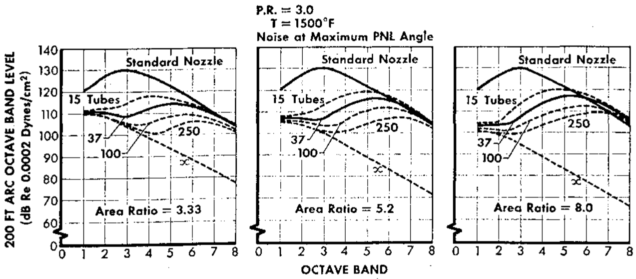

Fig. 12 Spectra of multitube nozzles—plain ends.

ratio, and that the factor controlling noise suppression in the middle frequency bands is number of tubes. Reasonable numbers of tubes did not materially change the noise in the highest frequency bands, i.e., in octave bands 7 and 8.

Figure 13 summarizes the acoustical design data for plain-ended tubes. The dashed lines are estimated. It shows that there is an optimum area ratio for each number of tubes and that the optimum area ratio increases with the number of tubes.

If a corrugated Greatrex type nozzle is applied to the ends of the multiple-tube nozzles, results such as those shown in Fig. 14 are obtained. The corrugated tube ends can provide suppression of the noise in the highest octave bands.

The high attenuation of high-frequency sounds by the atmosphere is not compensated for by available scaling test techniques. One must be very careful in analyzing scale model data to draw reasonable conclusions concerning the attenuation indicated at the higher frequencies. This problem is not limited to model scale but has its counterpart in full scale experience. Figure 15 shows the spectrum of a 37 plain ended tube suppressor at various altitudes. It will be noticed that the atmospheric absorption over and above the 6 db per doubling of distance very rapidly attenuates the upper two octave bands. Figure 14 has shown a substantial improvement in the upper octave bands as the result of using the corrugated ends as contrasted to a plain ended nozzle tube. Figure 15 shows that 1000 ft of distance, applied to these same frequencies, results in an attenuation amount equal to or greater than that provided by the use of the corrugated tube ends. It is obvious that the interpretation of multitube data with fancy tube ends will be very sensitive to the distance between the observer and the engines since fancy tube ends, to provide noise reduction in the highest frequency bands, will be of value only when the observer is substantially less than 1000 ft from the

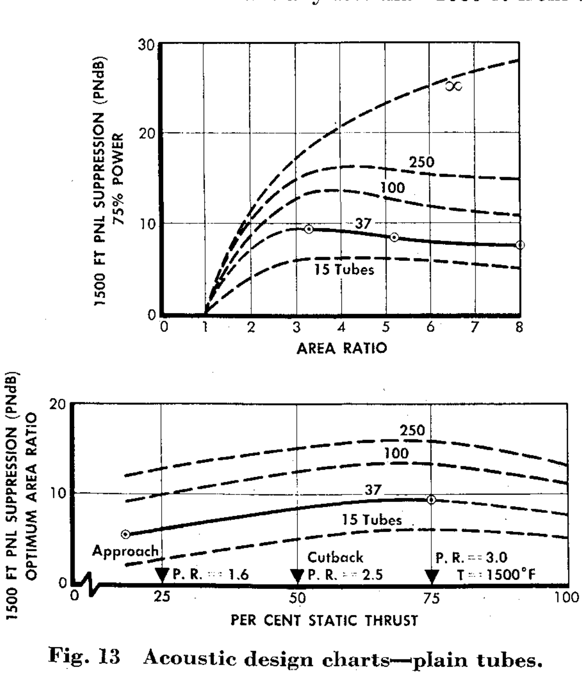

Fig. 13 Acoustic design charts—plain tubes.

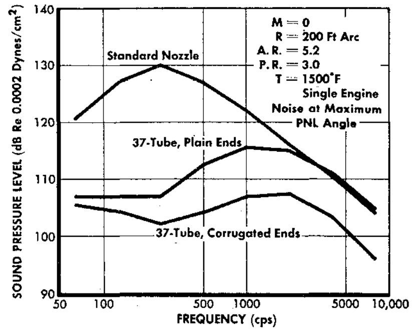

Fig. 14 Spectra of plain and corrugated tube nozzles.

engine. When the observer is more than 1000 ft from the engine, the atmosphere will attenuate the high-frequency bands so greatly that they will not be an important part in determining the PNdb noise level.

The suppression test data for multiple-tube nozzles with corrugated Greatrex terminations are shown on Fig. 16. Each tube termination had 12 spoked elements with an individual area ratio of 1.8. It will be noted that the corrugated tube ends materially reduced the noise at the high frequencies when used with a low area ratio, but were of no great value at high frequencies for high area ratios. Figure 17 is a design chart for corrugated tube suppression.

Spoked Nozzles

Tests were conducted on a large number of different spoked nozzles with varying numbers of spokes, varying area ratio, and varying degrees of immersion of the spoke into the stream. Figures 18 and 19 show typical noise spectra obtained during these model tests. Figure 20 is an acoustic design chart for these spoked nozzles.

Many afterburning engine test arrangements use a convergent-divergent nozzle with an ejector arrangement where substantial amounts of secondary air are admitted to the divergent portion of the nozzle. It was conceived that it might be useful to apply acoustic absorbing lining to the interior of this ejector tube or to some larger ejector tube built specially for the purpose. This lining would have the intended purpose of absorbing rather than reflecting the noise which impinged upon it, and thus make a substantial noise reduction at the

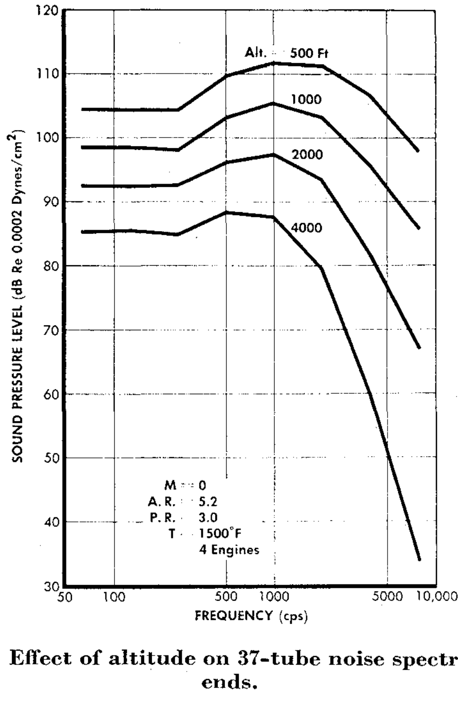

Fig. 15 Effect of altitude on 37-tube noise spectra—plain ends.

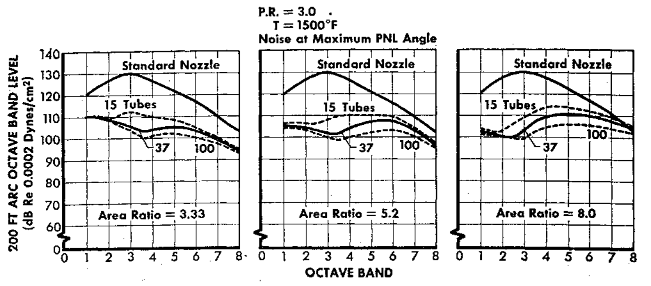

Fig. 16 Spectra of multitube nozzles—corrugated ends.

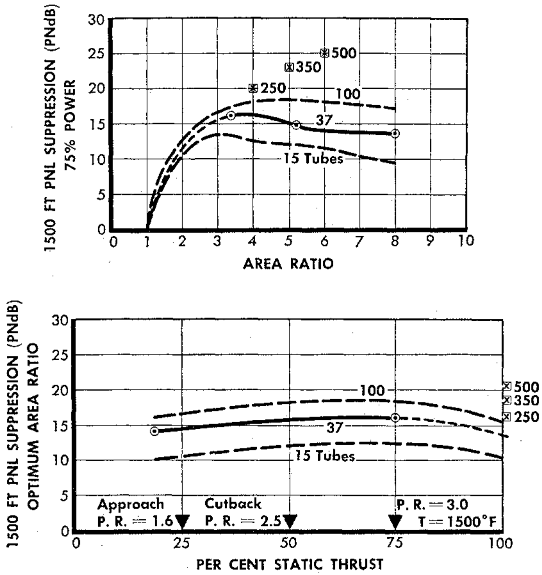

Fig. 17 Acoustic design charts—corrugated tubes.

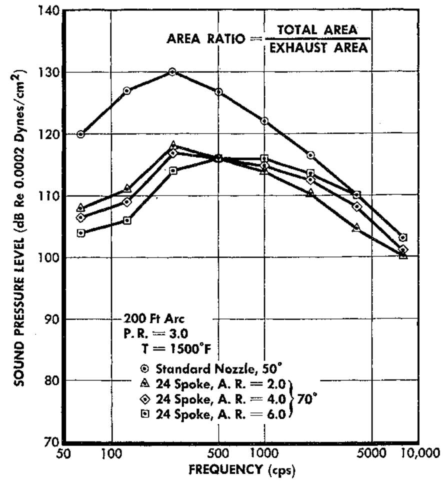

Fig. 19 Effect of area ratio on spectra.

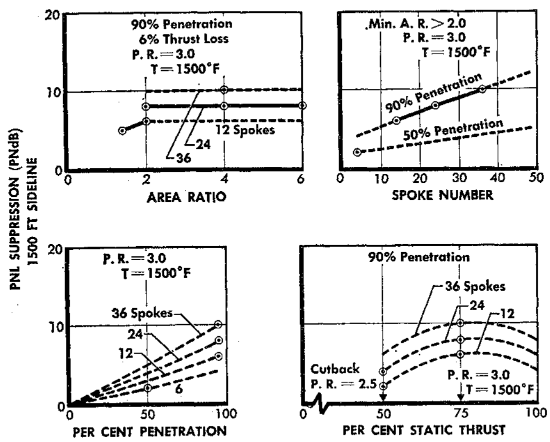

Fig. 20 Acoustic design charts—spoked nozzles.

frequencies where the lining was effective. Figure 21 is a picture of a 259-tube nozzle operating in conjunction with an acoustic absorbent lined ejector. Model test data for a related type of arrangement are shown on Fig. 22. The lining was effective at absorbing and materially reducing the noise at the high frequencies.

Based on the systematic model suppressor tests and parametric studies of the test results, acoustic design charts have been generated and suppressed jet noise spectra extrapolated to full scale to predict SST engine noise characteristics.

Mechanism of Jet Noise Suppression

The test data presented herein are sufficiently systematic to give some indication of the mechanism by which these various noise suppression nozzles function. A possible explanation is conjectured on Fig. 23 which shows the spectra of a simple, round convergent nozzle. For the case of multiple tubes, one can compute the noise to be expected from a number of separate convergent nozzles. The total noise level is the same as for a single tube but the spectrum is shifted to the right hypothetically by a ratio of the inverse of the tube diameters. The example shows the extent to which the total noise produced by 37 separate tubes of the same total area

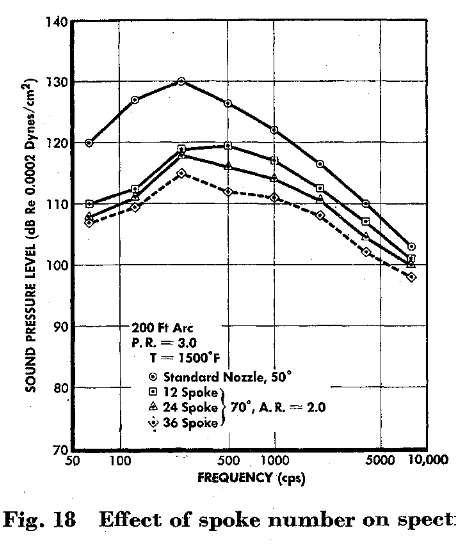

Fig. 18 Effect of spoke number on spectra.

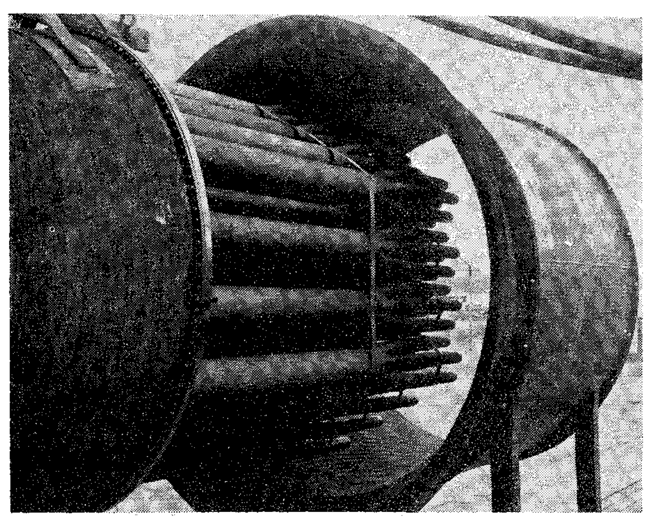

Fig. 21 Tubular suppressor and lined shroud.

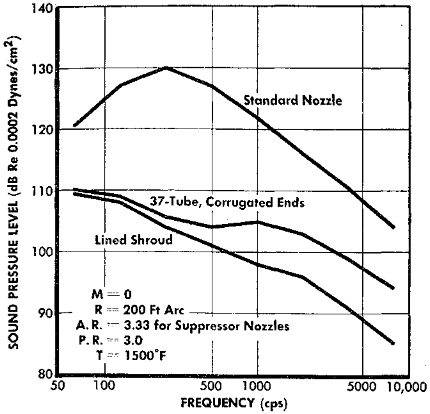

Fig. 22 Effect of lined shroud on spectra—corrugated ends.

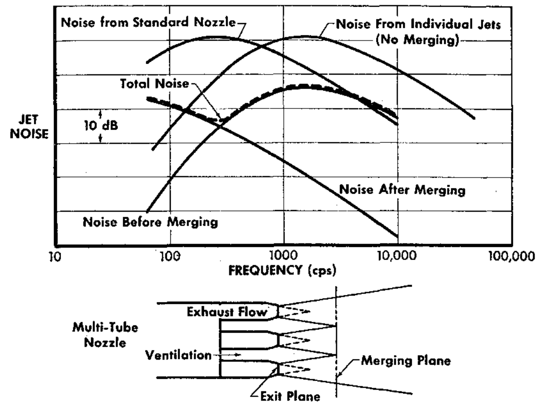

Fig. 23 Components of multitube nozzle spectrum.

would be shifted to the right as contrasted to a single, round convergent nozzle. In the multitube arrangements tested, the tubes were relatively close together and there was a merging of the exhaust streams from the tubes not far downstream from their exit plane. Between the exit plane and the merging plane, a great deal of external air was entrained, but in this region there was probably very little interference between the separate jets. Downstream of the merging plane, the flow can be expected to rapidly simulate the flow of a simple, circular nozzle made up of the basic airflow plus the airflow entrained prior to the merging plane. One can expect the noise produced downstream of the merging planes to be similar to that produced by a larger jet with a larger airflow but a slower velocity. Figure 23 shows hypothetically the amount of noise which might be produced downstream of the merging. This noise would be subject to computation if the amount of air entrained between the exit plane and the merging plane were known. The noise produced by the separate jets prior to reaching the merging plane will be less than that which these same jets would produce in their full length and assuming that they had not merged. The amount of this reduction will be very much dependent upon the spacing of the jets one from another or the area ratio of the nozzle. Thus, a high area ratio nozzle gives large spacing between the jets and should give little suppression of the high frequencies which are produced close to the exit plane. A lower area ratio gives jets closer together and a shorter distance to the merging plane and would be expected to show less generation of high-frequency noise. The model test data show similar trends. Hopefully, a theory of suppression can be developed in the near future.

Part II of this paper, which follows in a succeeding issue, contains information on thrust losses. Recommendations for future investigations and testing are offered. An understanding of suppressor technology and static performance losses are also summarized. The application of suppressors to aircraft and the resultant performance effects and cost of suppression are evaluated. Suppressor selection criteria, design goals, and special problems are outlined and discussed. Conclusions, based on Part I and Part II jointly, are listed at the end of Part II.