Perspective of SST Aircraft Noise Problem. II: Thrust Losses and Installation Factors

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The current state of research concerning noise suppression for SST jet engines is presented. 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 covered in Part I (previously published in the *Journal of Aircraft*) show several fundamental means to reduce jet noise at different frequency regions. In Part II, means to reduce thrust losses associated with installed suppressor devices are shown. Installed noise suppressor designs are based on these charts. The factors which control noise levels for takeoff are examined. Substantial improvements in SST noise footprints are indicated as suppression development continues.

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 turbofan engines as 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 influence of these variables in reducing the jet exhaust noise of the SST turbojet engines.

Part I of this paper has reported research results on noise suppression nozzles. This paper (Part II) reports on the thrust losses associated with these noise suppression nozzles and considers their application to the SST.

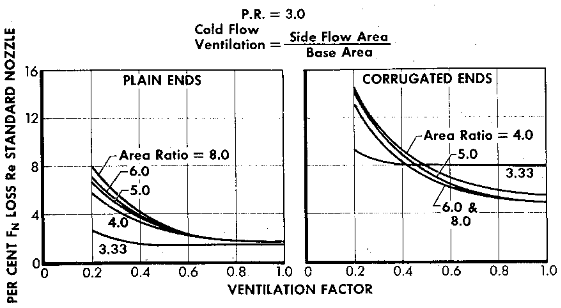

Fig. 1 Effect of ventilation on 37-tube nozzle performance.

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Performance Losses

Unfortunately, it has been found that there may be substantial thrust losses encountered with various suppression devices. Therefore, the performance of each of the nozzles reported in Part I was measured. The data for the various nozzles are shown on Figs. 1, 2, 3, and 4. These data show a substantial variation in thrust with tube length for the multitube nozzles. Tube length is expressed in Fig. 1 as a tube ventilation factor which is the side flow area of the tube array as a fraction of the base area of the tube array. Good side ventilation of the multitube nozzles gave low losses and short tubes gave high losses. Similar data for spoked nozzles are shown on Figs. 5 and 6. Here again, it was important to ventilate the nozzles to obtain good performance.

Mechanism of Thrust Losses

A number of factors are likely to cause the thrust loss. There will be internal losses in the nozzle related to the increased surface area and the skin-friction losses on this increased surface area. If there is a large temperature difference, the nozzle can cool the stream and produce some thrust loss. Experimental data have shown that the base pressure of a multitube or spoked nozzle is substantially below atmospheric pressure. Figure 7 shows some test data on base pressure and overall measured thrust performance of nozzles. When the base pressure data are converted into a force on the nozzle, it is found that a large portion of the thrust de-

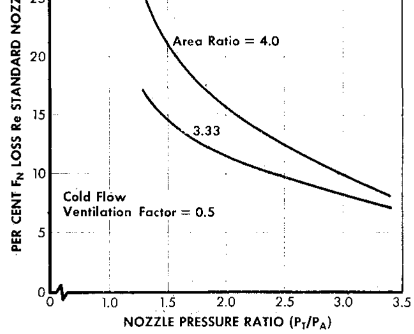

Fig. 2 Effect of pressure ratio on 37-tube nozzle performance.

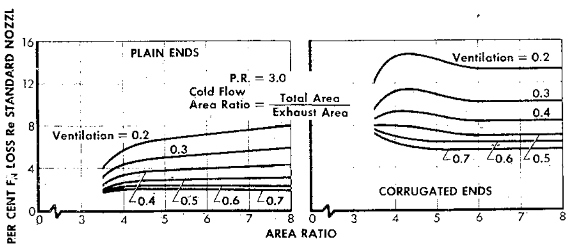

Fig. 3 Effect of area ratio on 37-tube nozzle performance.

ficiency of multitube and spoked nozzles is explained by the base pressure effect. Therefore, it is important to understand the mechanism by which the base pressures are reduced.

Wygnanski has shown experimentally and theoretically that there will be a loss in thrust in a jet nozzle which emanates from a body with a larger cross section than the jet area. This effect is caused by viscous aerodynamic effects. Wygnanski explains these viscous aerodynamic effects by computing the external flowfield for the air flowing over the outside of the nozzle and being entrained into the exhaust plumes of the jets. There would be no such flow in a potential flow nonviscous solution, but that is not the case in question, and in the real flow exhaust case there is a mixing of the jet plume with the external air. External air is entrained into the jets, and this results in slowing the jet. This flow, external to the jet, has the same characteristics as would be expected for an external flow of the same magnitude that is being entrained and going into a line of sinks along the axis of the individual jets as shown on Fig. 8. The strength of the sinks is directly related to the quantity of air entrained into the jet plume. The more air entrained, the stronger these sinks will be. If one computes the pressures in potential flow on the back end of the body as one would expect for air flowing into these sinks, one gets a measure of the origin and magnitude of the base pressure. Low base pressures and large thrust losses are occasioned by having the base close to the jet exit. Separating the base from the jet exit and permitting ventilation separates the bluff portions of the nozzle from the sources and materially reduces the base pressure. It seems likely that this is the mechanism by which the largest part of the jet nozzle losses can be explained.

Cooling

Materials which are available to engineers today include almost none which are suitable for prolonged operation at temperatures much above 2000°F. One of the principal tasks involved in designing and developing a successful jet engine is to cool all metal parts to temperatures well below 2000°F. The jet stream of an afterburning turbojet engine will operate at temperatures up to 3000°F. The practical success of such an engine will be measured by the extent to which the metal parts can be kept at temperatures below

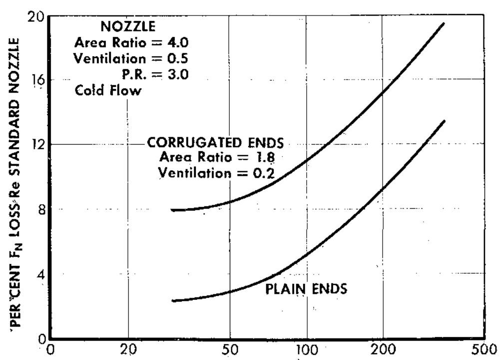

Fig. 4 Effect of number of tubes of nozzle performance.

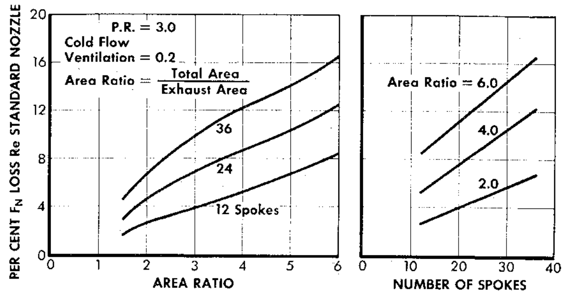

Fig. 5 Effect of area ratio on spoke nozzle performance.

2000°F while the gas temperatures are operating at 3000°F. This involves a lot of cooling and careful introduction of cooling gases to assure a protective film coating to all metal surfaces. The same cooling problem will apply to the use of complicated jet suppressor nozzles in a jet exhaust stream. The use of 3000°F afterburning temperatures will require a great deal of attention to cooling of the metal nozzle. Much attention is being devoted to this problem of cooling the nozzle and finding arrangements which do not require much cooling. Figure 9 is a picture of a nozzle operating at a gas temperature of 3000°F.

Applying Suppressor Technology to Engines

An understanding of suppressor technology and performance losses is a prerequisite to successful development of a silenced engine. Figure 10 summarizes the thrust loss and jet noise suppression data for the model research suppressors comprised of tubes, spokes, and chutes (streamlined shaped gutters cantilevered into the flow from the wall of the secondary nozzle). It can be seen that a great deal has been accomplished and that further suppression and performance gains are both desirable and probably possible. Whether these results can be accomplished in a practical commercial suppressor remains to be seen. Enough has been accomplished, however, to indicate that highly divided, well ventilated nozzles with a large area ratio can be expected to give noise suppression over a wide frequency range and with relatively low thrust losses.

The basic problems of such nozzles are fundamental to the words, "highly divided." Highly divided nozzles will be difficult to cool, hard to ventilate, and possibly heavy. In any case, the mechanical designer now has the challenge to devise successful jet noise suppressor nozzles. Work on this subject is well started at Boeing and at the General Electric Company, but it is too early to report the results of this work in this paper.

A study has been made concerning the noise levels which might be accomplished when applying suppressors to an after-

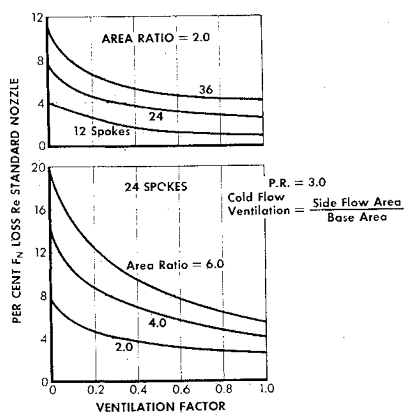

Fig. 6 Effect of ventilation on spoke nozzle performance.

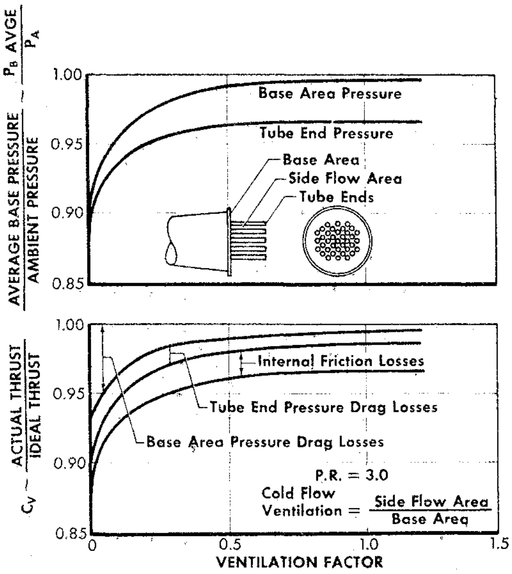

Fig. 7 Effect of base pressure on nozzle performance—37-tube plain ends.

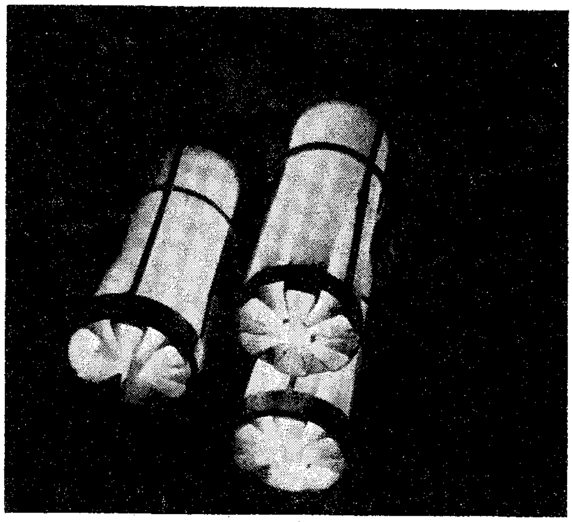

Fig. 9 Thermal test nozzle—3000°F.

burning turbojet engine. These are summarized on Fig. 11. The top line shows the noise level to be expected versus percent thrust for an unsuppressed afterburning turbojet. It seems likely that a small amount of suppression can be accomplished with a practical nozzle which can be cooled at full afterburning and will have low losses, but which will not divide the stream to the extent necessary to obtain large amounts of suppression. The performance of noise versus percent of thrust of a suppressed full afterburning engine is shown on Fig. 11. A still higher degree of flow division would be required in a medium effective suppressor, but such a suppressor is likely to have a maximum afterburning temperature limit substantially below that of an unsuppressed engine, and it has been conjectured that the maximum thrust obtainable for the medium size suppressor would be substantially below that of an unsuppressed engine due largely to the use of less afterburning and only partially to the losses in the suppressor. A high quality suppressor with large division of the stream can be envisioned which certainly would be usable at maximum nonafterburning power and which would give a large amount of suppression. Possibly, such a suppressor nozzle could not be cooled and would not permit much, if any, afterburning. This is the basis of the lowest curve on Fig. 11. Additionally, engines with large suppressors will have large weights for the suppressors and possibly large external or internal losses from the suppressors during cruising flight, even though the suppressors are retracted. Figure 11 is an indication of the type of performance studies which go along with studies of various mechanical designs of suppressors. The reports of suppression research covered in this paper are of an interim nature. A lot has been accomplished in the last year in terms of understanding how to obtain suppression on a model. The task that lies ahead is to find out how to obtain suppression on an engine and on an engine-airplane combination.

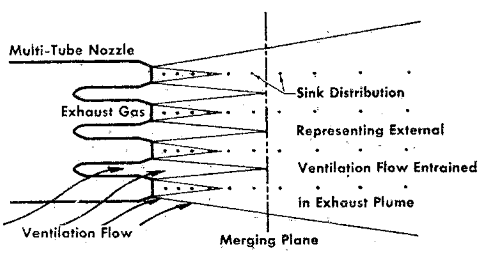

Fig. 8 Representation of entrainment process.

Application of Suppressors to Aircraft

The noise produced by an SST during takeoff is subject to a large number of variables. Only a few of the variables can be covered in this paper. The following material will give some of the principles controlling the noise directly beneath the flight path during takeoff. For brevity, the subject of noise to the side of the flight path and during the approach path will not be covered in this paper. The following examples show some of the considerations involved in the choice of an airplane-engine configuration as governed by takeoff noise. Figure 12 shows the climbout flight path of a typical SST. Shown is the altitude versus distance from brake release and the noise along the centerline of the flight path as expressed in PNdb. The upper curve in both cases is for a full power climb of a full afterburning turbojet engine without suppression. The airplane climbs rapidly and the engine makes a lot of noise. A lot of altitude is gained rapidly and the noise below the flight path, although high at first, falls off rapidly due to the steep climb. An alternate procedure for operating this same airplane might be to throttle back when attaining 1000 ft. of altitude to a climb slope of 0.06, which is less than one-half the 0.13 slope of the full power climb. In the case shown, it has been speculated that this amount of throttling back might reduce the engine noise by 12 PNdb. Since the airplane climbs slower following cutback, the noise will not drop off as rapidly following cutback as it did for the full power climb. If full power is applied again at the time the airplane reaches 5000 ft in altitude, there will be a substantial increase in noise on the ground beyond this point. The noise

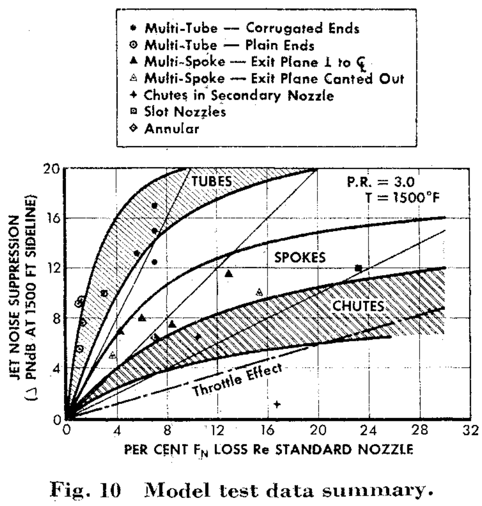

Fig. 10 Model test data summary.

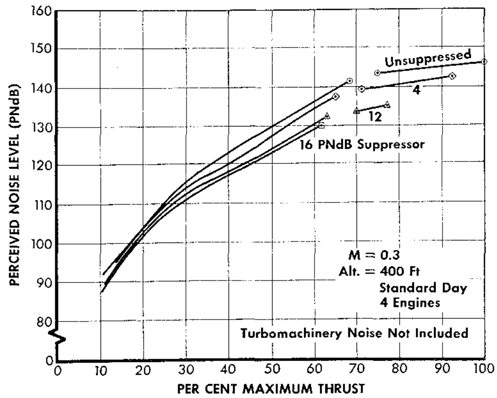

Fig. 11 Engine performance with various suppression levels.

produced upon reapplying power might be so great as to be unacceptable, and special procedures for prolonged and gradual reapplication of power will appear to be necessary.

If a suppressor were applied to this same airplane, flying at the same takeoff weight, with exactly the same basic engine, there would be of necessity a reduction in the amount of takeoff thrust caused partially by suppressor losses and partially by the use of less afterburning. The takeoff distance would be greater and the climbout slope would be flatter. Figure 13 shows an example of how a suppressor might change the data shown on Fig. 12. The data on Fig. 13 show that a suppressor is not all gain, and that the reduced power places the airplane closer to any observer near the takeoff point, and can, in fact, result in increased observed noise. Thus, cutback is less important in this particular case. The suppressor does provide very large improvements in noise at substantial distances from the takeoff point.

An additional technique for affecting the observed noise is to use a larger engine. Figure 14 duplicates a portion of the data from Fig. 13, and shows, in addition, the climb and noise performance which might be expected from using a larger engine, plus suppressor, plus cutback such that with a large engine and suppressor the same climbout flight paths were attained which were possible with the original unsuppressed full afterburning engine. It is seen that the advantages of both suppression and cutback are realized in this case where the airplane power has been re-established. Another possible technique which would have given substantially identical results in terms of noise would have been to off-load the suppressed airplane until its climb path was identical to that of the unsuppressed airplane.

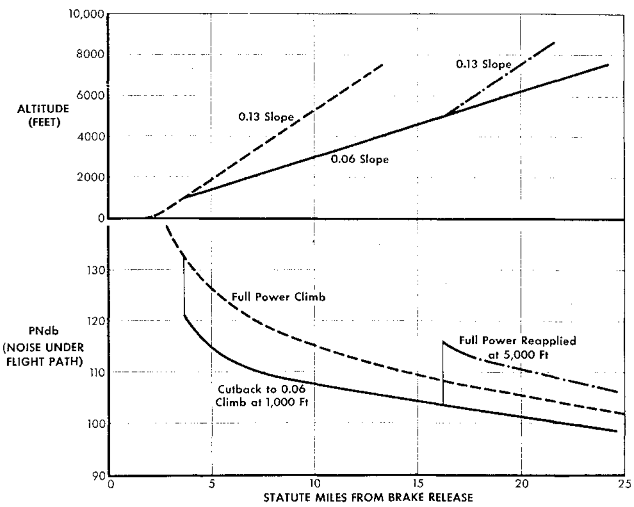

Fig. 12 Takeoff noise effect of power cutback.

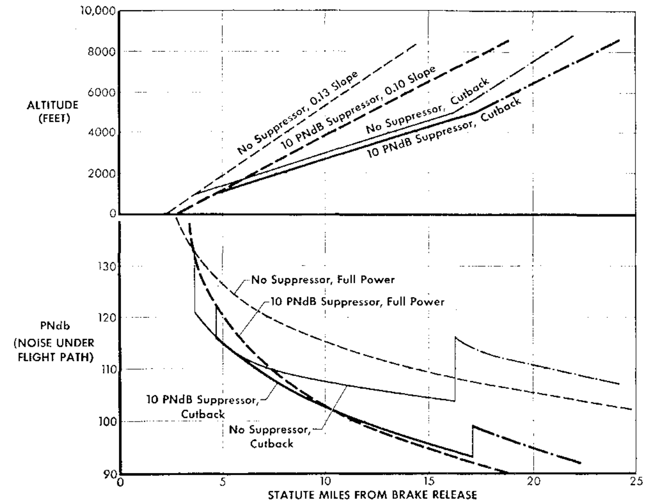

Fig. 13 Takeoff noise effect of noise suppressor.

Cost of Suppression

Noise suppression for the SST airplane is likely to be very expensive. The reasons for this can be seen from some very simplified calculations. The payload of the supersonic transport on a typical flight is likely to be only 6% of the takeoff gross weight. The fuel consumed during the flight is likely to be 54% of the takeoff gross weight. The weight of the propulsion system of the SST will probably be about 10% of the takeoff gross weight. Any increase in fuel weight required because of increased drag or internal losses caused by the suppressor must come out of the payload. A 1% increase in fuel consumption must decrease the payload by 0.54% of the takeoff weight, which is 9% of the payload. A 9% reduction in payload is a 9% reduction in revenue and represents a 9% increase in the average cost of carrying a passenger on the flight. If the suppression scheme were to require an increase in propulsion weight of 10%, this would represent 1% of takeoff gross weight increase in weight empty which must be taken out of payload and reduces the payload 17%. Thus, a 10% increase in engine weight would represent a 17% loss in revenue or increase in average operating cost per passenger. Obviously, the greatest of care must be taken in order that the SST may be a reasonable, economic practicality. For this reason, it may not be feasible to design in the full capability of noise suppression indicated by the model results previously discussed.

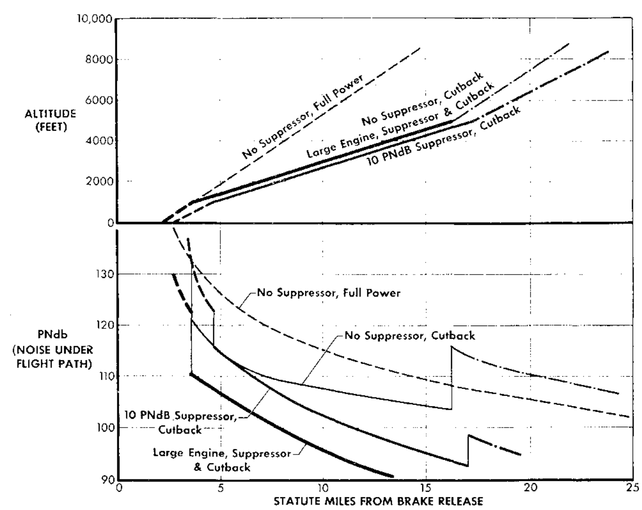

Fig. 14 Takeoff noise effect of larger engine.

Future Tests

The Boeing test program to develop an understanding of suppressor potential is a continuing program. Some key future tests are listed: 1) effect of tube arrangements; 2) effect of suppressor scaling $\frac{1}{8}$ scale to full scale; 3) effect of temperature on suppression $\frac{1}{8}$ scale—1500°F to 3000°F, 24 spoke model, 37 tube model; 4) effect of design considerations tube-spoke combinations; 5) effect of forward speed on performance and suppression; and 6) effect of nozzle shrouding on performance and suppression.

Suppressor Selection Considerations

The choice of a proper matching of suppressor to engine and airplane is a major task which lies ahead and to which much attention will be devoted by The Boeing Company and the General Electric Company. This paper has reported on suppressor research conducted at The Boeing Company. A similar program is underway by the General Electric Company. The two programs are complimentary and demonstrate the sincere interests of the managements of Boeing and General Electric to find a suitable noise solution to the SST design requirements. Among the selection considerations which will be involved in the final choice of suppressor for the SST are: design goals; adequate suppression, high performance, minimum weight, and minimum complexity; design problems; suppressor element cooling, 1) compressor discharge bleed, 2) water, and 3) fuel; materials selection; suppressor element stowage; integration of nozzle operational functions; suppression, transonic, cruise, reverse, and operating mode transition; and ground clearance.

Conclusions

1) The challenge is in the use of engines which are fundamentally about 15-db noisier than present turbojet engines and to provide suppression so as to give acceptable noise levels.

2) Significant progress has been made in the last year in developing models of nozzles which are quieter.

3) There is a beginning to an understanding of the mechanisms of suppression.

4) Progress has been made in the last year in reducing losses attendant with suppression.

5) The mechanism of losses is partially understood.

6) A start has been made at applying suppressor research knowledge to design of flight hardware.

7) Suppressors, or oversized engines, or off-loaded airplanes are currently very expensive in increased direct operating costs.

8) Progress in SST noise research has been favorable in the last year and gives promise that with continued effort the SST engine noise problem can be controlled within acceptable limits.