# Engine Compatibility Programs for the Supersonic Transport Propulsion System

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**The design and development of the propulsion system for the supersonic transport has required an engine system that is more fully integrated with the inlet duct and airframe than previous subsonic commercial engines. To date the GE4 engine compatibility program has been primarily directed toward testing of the engine under simulated inlet conditions and the evaluation of exhaust nozzle installation effects. Performance of the compressor has been evaluated with inflow distortion generated by 1) screens and 2) a centerbody venturi, which has a throat and subsonic diffuser section similar to the Boeing inlet duct. In addition, the engine has been tested with the Boeing inlet at takeoff and at intake sound suppression conditions. Results show the compressor has a high tolerance to steady state and dynamic distortion. Analysis and engine testing of jet sound suppression devices also is being carried out as a joint effort between Boeing and General Electric.**

## Nomenclature

$CFG_I$ = installed nozzle gross thrust coefficient
$F_n$ = net thrust, lb
GTOW = gross takeoff weight, lb
$h/\delta$ = height to boundary-layer thickness
$P_s$ = steady-state static pressure, psia
$P_T$ = steady-state total pressure, psia
$P_{TRMS}$ = rms value of time varying total pressure
$\Delta P_{rms}$ = $\left(\frac{1}{\tau}\int^{\tau} P(t)^2 dt\right)^{1/2}$
$\tau$ = period of measurement
$P(t)$ = time varying total pressure
rms = root mean square
$P_{T\,avg}$ or $\bar{P}_T$ = area weighted average total pressure at compressor face, psia
$P_{T\,min}$ = minimum total pressure at compressor face, psia
$P_{T\,max}$ = maximum total pressure at compressor face, psia
PNdb = units of perceived noise level (PNL)
PNL = perceived noise level, a subjective rating of noise
db = decibel, 0.002 dynes/cm²
stall margin = steady-state surge margin of compressor at constant corrected speed
% Δ stall margin = $\left[\left(\frac{P_3/P_2}{W_a}\right)_{stall} - \left(\frac{P_3/P_2}{W_a}\right)_{OP} \Big/ \left(\frac{P_3/P_2}{W_a}\right)_{OP}\right] \times 100$
$P_3/P_2$ = pressure ratio across compressor
OP = operating line
$W_a$ = airflow of compressor
$X_{ref}$ = axial distance, in.

## Introduction

ADVANCEMENT of commercial transport flight into the supersonic regime demands not only an efficient and reliable engine system, but requires the engine to be more fully integrated with the inlet and airframe than in a subsonic design (see Fig. 1). To realize the gains of supersonic flight, the major components of the propulsion system—inlet, engine, and exhaust nozzle—must be matched closely to result in an optimized single unit which will assure success of producing an acceptable system. During recent years, some of the most important gains in propulsion efficiency have resulted from the development of inlets, engines, and exhaust nozzles which permit matching over a broad range of operating conditions.[1]

The importance of the propulsion system for the Supersonic Transport can be realized by the fact that 50% or more of the aircraft gross weight will be comprised of propulsion system and fuel, and less than 10% will be payload. It is therefore of utmost importance to investigate all engine and airframe interface aspects at an early stage and initiate comprehensive test programs to verify analyses and search out the unknown problems that could potentially lead to more serious problems during the SST prototype flight program. To date, most of the testing effort has been on inlet-engine compatibility and exhaust nozzle installation effects; however, future testing will devote more attention to the airframe effects.

Performance of the GE4 compressor has been evaluated with uniform inlet flow and with various inlet distortion patterns generated by placing combinations of flat plates and screens approximately one diameter ahead of the compressor. To determine the aeromechanical limitations of the blading, the compressor has been tested with relatively high levels of distortion. A total of 450 hr of testing with 230 intentional stall points were recorded during the first and second full-scale compressor tests. The results indicated a high level of over-all performance and excellent aeromechanical blade stability characteristics with the following types of distortion patterns: hub radial, tip radial, one per revolution circumferential, four per revolution circumferential, and combined hub and tip radial and four per revolution circumferential.

The purpose of the combined radial and circumferential pattern was to simulate the Boeing inlet at a supersonic off-design condition. Figure 2 shows a photograph of the screen-plate configuration used to produce this distortion pattern.

The effect of various distribution-flow distortion patterns on the steady-state stall margin of the compressor is shown in

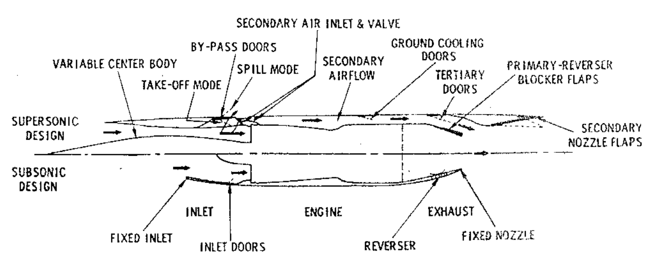


**Fig. 1 Propulsion system.**

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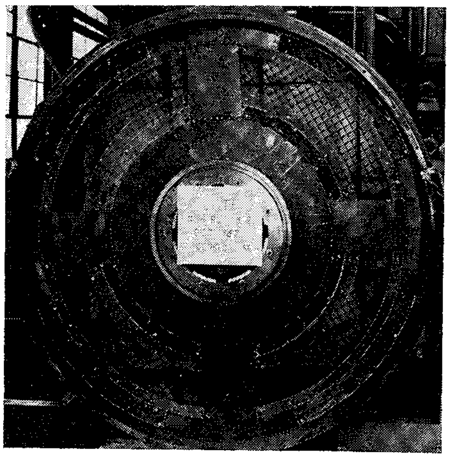

Fig. 2 Distortion screen—supersonic off design.

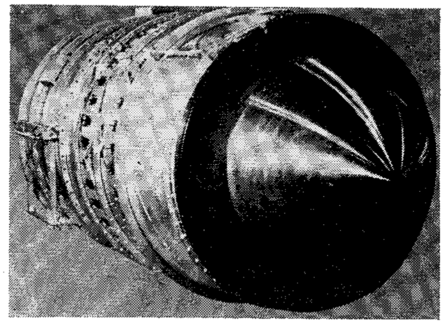

Fig. 4 Supersonic inlet simulator for compressor test.

Fig. 3 for the various patterns. These data are for operation at supersonic flight speeds; however, the compressor has been evaluated over the entire operating range. As predicted, the compressor is most sensitive to the one per revolution and the tip radial patterns at supersonic flight speeds. Because of the uniform extraction of secondary air from the outer wall of the inlet duct, it is expected that only a small amount of tip radial distortion will occur during normal operation at supersonic flight speeds. The hub radial and simulated inlet (combined radial and circumferential) patterns resulted in essentially no loss in compressor stall margin and performance. Thus, the steady-state characteristics of the GE4 prototype compressor are well matched to the Boeing axisymmetric inlet.

In addition to the screen test, the compressor has been tested with an intake device which simulates the throat and subsonic diffuser of the Boeing inlet duct. Figure 4 shows a front view of the inlet simulator with the bellmouth removed. The purpose of this test was to determine the effect of inlet generated steady-state and dynamic distortion on the low corrected speed performance of the compressor, and to compare the dynamic distortion generated by this simulator to that generated by distortion screens and supersonic inlet ducts. The simulator was tested with several throat areas and at corrected flow conditions which produced a normal shock at various axial locations in the throat region. Although the simulator did not have a means of bleeding boundary-layer air from the throat region, the velocity profile was similar to the Boeing axisymmetric inlet duct. Static-to-total pressure ratio at given axial distances along the centerbody and cowl of the simulator at the design throat area is shown in Fig. 5. For these data, the corrected airflow was substantially higher than the design value (6% supercritical compared to a design value of 3%) which gave a predominately hub radial and four per revolution circumferential distortion pattern. This was because of flow separation from the centerbody and four support struts.

It is of interest to note that the steady-state vs dynamic distortion produced by the inlet simulator and the supersonic off-design screen pattern were alike (Fig. 6). Also, the peak dynamic distortion was approximately twice the average value for both the simulator and screen tests. Dynamic distortion, or turbulence, is defined as the root mean square (rms) of the nonsteady pressure normalized to the average total pressure at the compressor inlet.

The loss in compressor stall margin with the inlet simulator operating at large and small throat areas is shown in Fig. 7 along with results from the screen tests. The inlet design is represented in Fig. 7 by the small throat area simulator data, previously shown in Fig. 6. The large throat area simulator produced more dynamic distortion than did the small throat area simulator.

At the anticipated nominal steady-state distortion levels of 10–20%, the loss in stall margin is small (less than 3%) for any of the test configurations in Fig. 7. This compares to an available stall margin of 20% for the GE4 engine. These results differ from an earlier test of a YJ93 engine with a centerbody simulator in which a larger loss in stall margin was encountered.[2] The YJ93 simulator had provisions for placing distortion screens downstream of the centerbody throat region in an effort to give combinations of steady-state distortion and additional dynamic distortion from shock boundary-layer separation. Results of this investigation showed that short-time periods of high dynamic distortion could substantially decrease the stall margin of the engine at a given steady-state distortion level. A time dependent characteristic of this magnitude was not observed during testing of the GE4 compressor simulator. To investigate increased dynamic distortion with the GE4 simulator, a solid plate fence arrangement was placed approximately $\frac{1}{3}$ of the circumferential distance around the centerbody. The stall margin of the compressor still correlated with a similar steady-state screen distortion pattern. At this time, there is only a partial understanding of the difference in results between the YJ93 and GE4. Thus, further analysis is being applied to correlate the magnitude and signature (frequency spectrum) of the dynamic inflows produced by the two simulators, as well as the configuration differences.

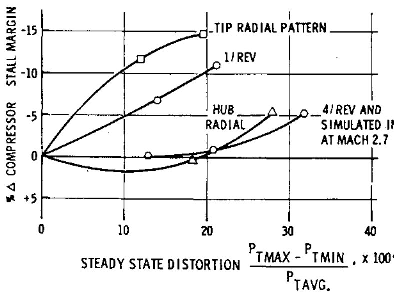


Fig. 3 Compressor distortion screen data.

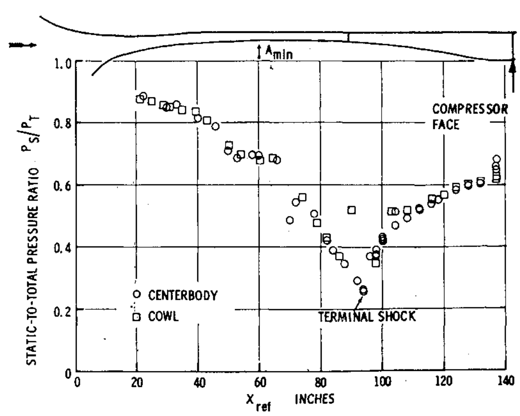


Fig. 5 Inlet simulator static pressure distribution—design throat area, data point A.

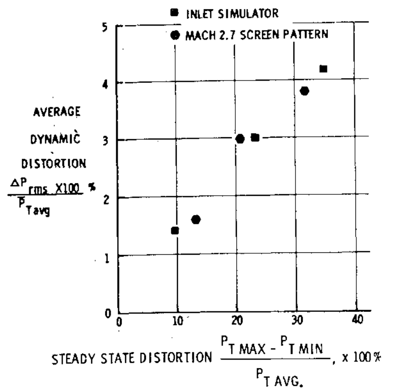


**Fig. 6 Comparison of distortion from inlet simulator and screen pattern.**

## Inlet-Engine Ground Test

The design requirements for the inlet duct are primarily established by the supersonic cruise condition. The sharp cowl lip and centerbody are necessary to provide minimum drag and a high internal flow recovery. Since this configuration is not efficient at very low flight speeds, takeoff doors are used to supply auxiliary air to the engine. These doors, which are located just forward of the engine face, decrease the primary intake airflow which in turn reduce the amount of flow separation from the sharp lip and in the subsonic diffuser for improved ram recovery and distortion. Boeing has tested several scale inlet models to obtain inlet-engine compatibility data at very low speeds. Some of the inlets were tested with a J85 engine. These results show that a substantial amount of turbulence is generated by both the sharp lip and mixing of the auxiliary flow with the primary intake flow. The most severe condition is static operation at maximum airflow.[3]

As a follow-on program, a Boeing full-scale inlet duct was tested with the GE4 engine at the Peebles, Ohio, test site. Figure 8 shows a photograph of the Boeing inlet duct attached to the demonstrator engine. The unit was tested in the two modes: 1) takeoff with the centerbody full forward and 2) the auxiliary mode with the centerbody in intermediate positions and auxiliary inlet doors closed.

For takeoff, the steady-state distortion pattern formed 12 low-pressure regions equally spaced around the outer $\frac{1}{3}$ of the annulus area. The low-pressure regions were caused by flow separation from the aft lip of the auxiliary doors. Figure 9 shows an aft view of the inlet duct and auxiliary doors. Although the steady-state distortion was greater than 0.2 and may be considered high, the fact that the pattern is a 12 per revolution circumferential substantially reduced the adverse effects on compressor stall margin. It is believed that both the ram recovery and distortion can be improved by increasing the radius of the aft lip of the auxiliary inlet doors. During takeoff, the dynamic distortion is the highest in the outer portion of the flow annulus, as shown in Fig. 10. This is because of the mixing of the flows from the main intake and the 12 auxiliary inlets and separated flow from the sharp lip. The inlet was also tested with a bellmouth mounted to the lip of the inlet. Dynamic distortion at the engine face was noticeably reduced by the bellmouth as shown in Fig. 11.

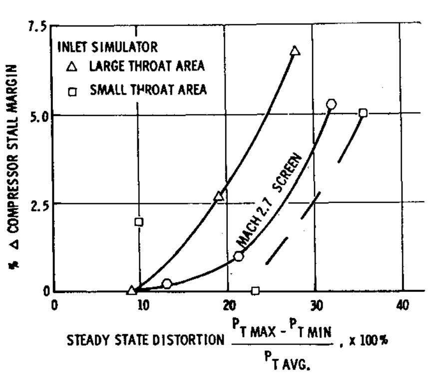


**Fig. 7 Comparison of distortion screen and inlet simulator data.**

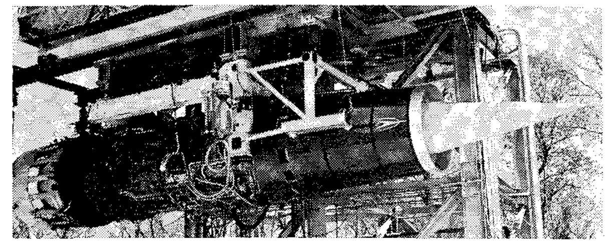

**Fig. 8 Boeing inlet—GE4 engine.**

During reduced power operation, over the community, the auxiliary inlet doors are closed and the centerbody of the inlet is moduluated to maintain near sonic flow conditions in the throat region. Such operation suppresses the compressor sound to an acceptable level. Test results indicated a small amount of flow separation from the outer cowl walls which gave a tip-radial distortion pattern at the engine face. Figure 12 shows the steady-state distortion pattern at one of the noise abatement operating conditions. To minimize distortion, the engine centerbody must be accurately positioned to maintain the minimum throat Mach number for sound suppressor purposes.

Ground testing was successful in that no stalls or other problems were encountered during throttle bursts from idle to selected higher rotor speed. The specific amount of stall margin loss for steady-state distortion levels up to 30% was not measured at this time. The relationship of dynamic to steady-state distortion is consistent with the screen and simulator test results shown in Fig. 6. Also, the maximum dynamic distortion recorded was two times the average value. This testing was done at static conditions. Later testing with an improved inlet duct and the flight test engine will be done under forward and crosswind conditions.

## Exhaust Nozzle

The design of the exhaust nozzle system and its installation in the air-frame is of prime importance to the performance of the supersonic transport. For example, a one percent improvement in over-all thrust coefficient is equivalent to $3\frac{1}{2}\%$ in range. To meet the thermodynamic engine cycle and broad range of operational requirements, the exhaust system must have the following features: variable primary throat area, variable divergent secondary section, thrust reverser, and retractable sound suppressor.

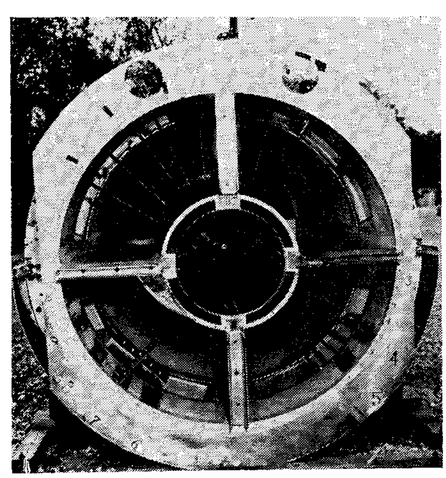

**Fig. 9 Aft view of inlet duct and auxiliary doors.**

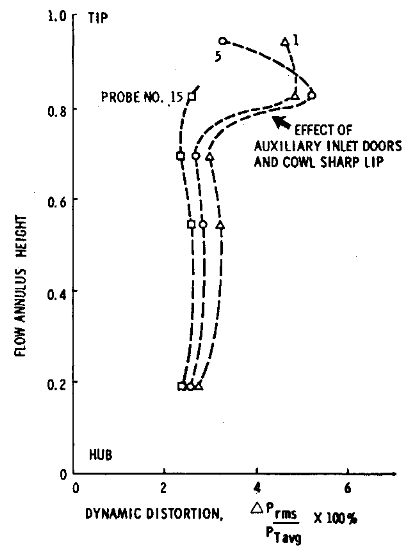


**Fig. 10 Inlet/engine ground test at takeoff airflows.**

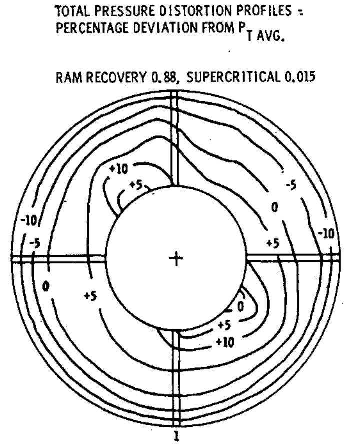


**Fig. 12 Inlet/engine ground test—noise abatement mode.**

Most supersonic exhaust systems have not incorporated reverse thrust and jet sound suppression; however, Military designs provide an excellent experience base for the other supersonic transport requirements.

The selection of the exhaust nozzle design depends to a large extent on the location of the engine on the airplane, design of the inlet, secondary air system and the required amount of reverse thrust and jet sound suppression. Tradeoff studies and testing of the long variable flap nozzle (Fig. 13) and a nozzle which utilizes tertiary air at subsonic speeds (Fig. 14) has been in progress for some period of time. Both of these nozzles use aerodynamic positioned secondary flaps for optimizing the subsonic and supersonic performance. Figure 15 shows flow path sketches of these nozzles.

In general, the long variable flap nozzle has higher performance at high subsonic and supersonic flight speeds and is less sensitive to installation effects; whereas, the two-stage ejector nozzle has higher performance at low subsonic speeds and a lower weight for some installations To achieve a high level of performance for the two-stage ejector nozzle, care must be taken in its installation to account for variations of the airplane local flowfield approaching the nozzle. To avoid potential installation problems common with this type of exhaust nozzle, its characteristics are being evaluated fully. Installation sensitivity tests which have been conducted are inlet door size, blockage, and stability; uniform and asymmetrical boundary layer heights; cylindrical and conical forebodies; wing-body effects; secondary-air pressure and flow variations.

Testing of the two-stage ejector nozzle showed that it is important to provide adequate inlet flow area for the tertiary flow. A 33% reduction in flow area resulted in a 0.058 and 0.015 reduction in installed thrust coefficient at Mach 0.5 and 0.85, respectively. However, the closing of several inlet doors did not adversely affect the performance if adequate flow area was provided by the remaining doors. An increase in the boundary layer, or angle of attack, at the entrance to the inlet doors caused a noticeable change in performance. The thicker boundary layer gave an improvement in performance, as would be expected from the reduction in ram drag of the lower-energy tertiary flow. The nozzle was also evaluated with a wing-nacelle, shown in Fig. 14, with a force balance measurement system that was independent of the wing. The combined effects of an asymmetrical boundary layer, adjacent wing and nacelle-forebody geometry were simultaneously evaluated with a nozzle model which had floating doors. The installed performance was slightly poorer than that of an isolated nacelle nozzle with a uniform flowfield. Some of the results of the installation sensitivity tests for the two-stage ejector nozzle are given in Fig. 16. It is important to note that the individual sensitivity effects are not additive. To further evaluate the installed performance of the exhaust nozzle, Boeing is planning to test a full airplane model in a wind tunnel. The use of the over-all airplane will better establish the nonuniformity of the pressure field in the vicinity of the exhaust nozzle.

To simplify the exhaust nozzle system, the GE4 design utilizes a primary nozzle plus an extension tab which translates aft to form the reverser blocker. The initial design had cascade boxes for turning of the exhaust gases, but it has been determined that cascades are not necessary to achieve the reverse thrust requirement. Figure 17 shows that 11 or 8 of the 13 inlet doors are used to discharge the exhaust gases in a pattern which is compatible with the airframe. To reduce reverser cutoff speed, it was necessary to use 8 rather than 11 doors and to discharge a majority of the gases over the wing and down to one side. Some flexibility is provided by the selection of any 8 doors, except those just under the wing. Boeing has conducted extensive reingestion tests with a scale

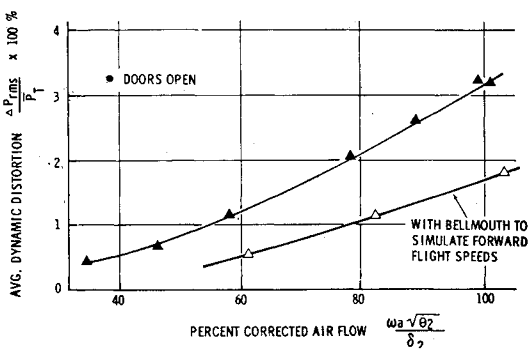


**Fig. 11 Inlet/engine ground test inlet lip turbulence.**

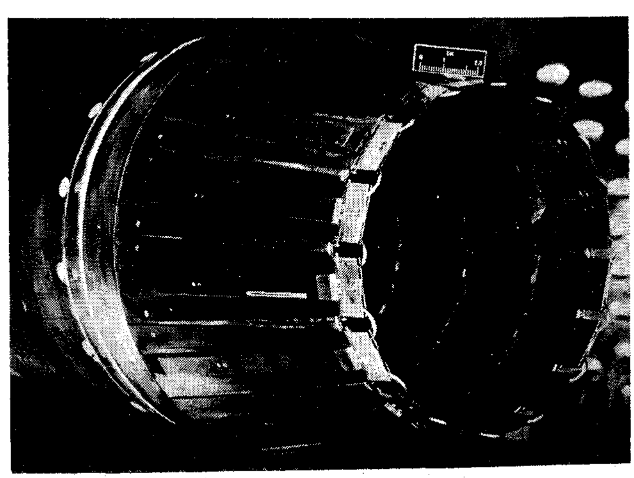

**Fig. 13 Three-finger variable flap ejector nozzle.**

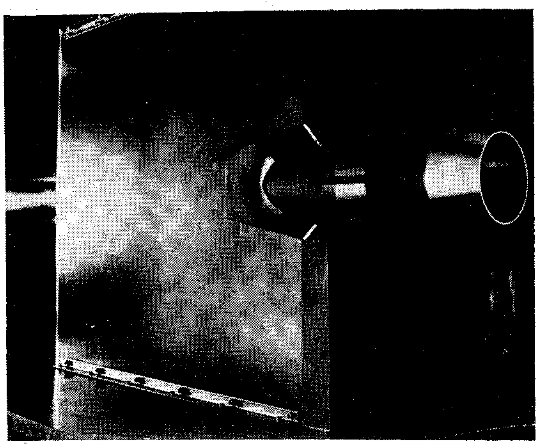

Fig. 14 Two-stage ejector nozzle.

model airplane and engine configuration in a wind tunnel. This test rig simulated forward flight speed, extraction of inlet airflow and the discharge of exhaust gases. From an engine reingestion aspect, it is desirable to discharge a large percentage of the exhaust gases over the wing. However, this requires a larger cut out in the trailing edge of the wing which results in associated drag losses.

Studies of different reverser designs on the Boeing airplane simulator led to the conclusion that an ultra-fast acting reverser does not significantly reduce the required landing distance. Landing distance is more a function of the initial velocity of the airplane and the surface condition of the runway. The use of a slower acting reverser provides a weight saving and a reduction in the heat load of the hydraulic system as would be expected. This lower weight and heat load contribute to the performance of the SST.

## Airplane/Engine Noise

Airport and community noise is becoming a bigger problem as large airplanes with higher-thrust engines are placed in commercial service. In the case of the SST where a high specific thrust (high jet velocity) engine is necessary to meet the thrust requirements for supersonic acceleration, the incorporation of a jet sound suppression device may be required to meet future noise restrictions. A suppression device placed in the high-temperature exhaust gas stream would have to be retractable for economical inflight operation.

In most applications, the sound problem can be minimized by oversizing of the engine, but this unfortunately causes a sacrifice in aircraft economics. This is also true of the SST. Figure 18 shows a typical tradeoff in takeoff sideline and 3.5-mile community noise level where takeoff power loading (total thrust/airplane gross weight) is varied. Full power takeoff with no power cutback at 3.5 miles results in a slight increase in airport noise for a noticeable reduction in the 3.5-mile noise. In turn, the use of less than full takeoff power results in less airport noise at an increase in the 3.5-mile community noise level. In the latter case, the airplane would use the full available runway length and be at a relative low altitude at the 3.5-mile point. As can be noted, airport and 3.5-mile noise can be traded and gains can be made in both by oversizing the engine; however, the maximum range/payload of the airplane would be significantly penalized. The amount of oversizing of the engine depends to a large extent on the amount of high velocity jet suppression which can be incorporated in the engine. At approach conditions substantial reductions in jet noise can be obtained by engine oversizing of the engine, but at very low jet velocities turbomachinery noise may become a factor. Airplane wing loading, span, high-lift flaps, and operating techniques are also of importance. Thus, design studies are continuing on jet sound suppressors to evaluate various devices which have minimal associated weight and thrust penalties for different engine and airplane operating modes.

The jet sound suppression program has been concentrating on full-scale engine and component testing along with basic research effort to better understand the generation and suppression of sound for a supersonic jet stream. Figure 19 shows a photograph of the GE4 engine at full afterburning power without suppression. Note the series of widely separated "Shock Diamonds." Figure 20 shows the same engine with a sound suppressor device deployed, and again note the change in shock diamond formation. For a suppressed

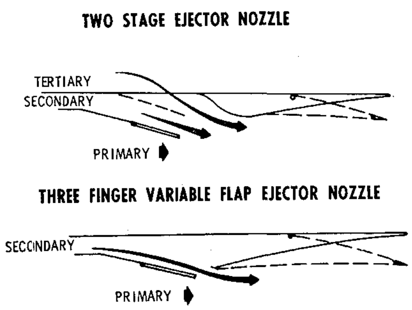


Fig. 15 Supersonic exhaust nozzles.

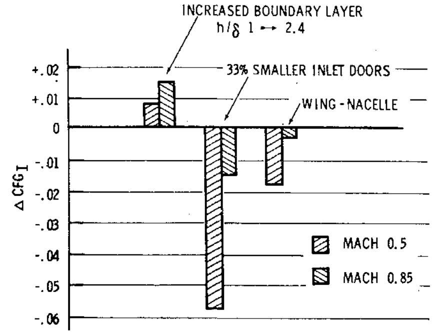


Fig. 16 Two-stage ejector nozzle installation effects.

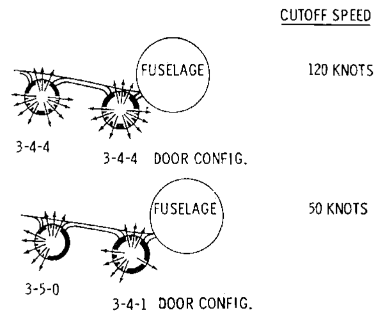


Fig. 17 Thrust reverser discharge pattern.

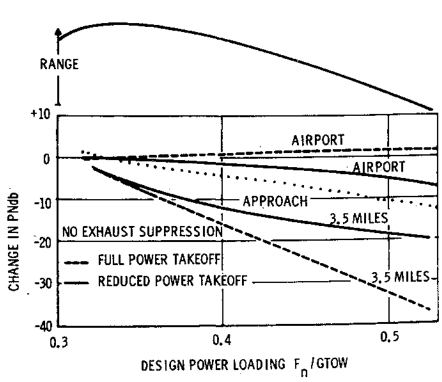


Fig. 18 Airport and community noise—typical airplane and engine.

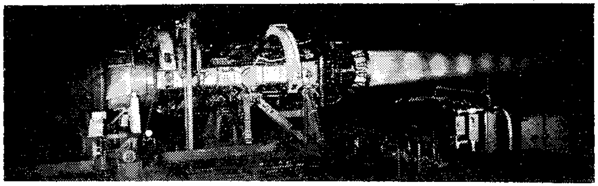

**Fig. 19 GE4 operating at maximum power—without suppression.**

supersonic jet stream, a larger portion of the sound can be contained within the length of the nozzle outer shroud, and increased mixing can be promoted with the secondary air to reduce the exit velocity. Figure 21 shows a typical secondary-chute type suppressor which was tested on the GE4 engine. Full-scale test data indicate that 4–7 PNdb suppression can be obtained with secondary chutes at takeoff power. Suppression levels greater than this have been demonstrated by high solidity spoke and multitube devices; however, a practical way to incorporate these into the supersonic nozzle of an augmented engine has not yet been achieved.

## Summary

The supersonic transport is definitely a more complex airplane than preceding subsonic transports. However, the technology required to overcome these complexities will be substantiated by the SST prototype flight program. The SST is being designed to provide not only safe, economical operation, but public acceptance. This requires, in many in-

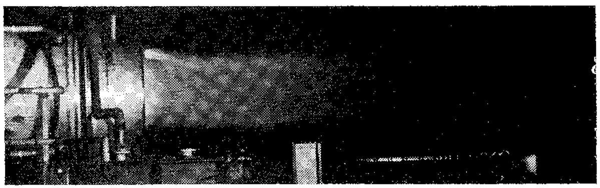

**Fig. 20 GE4 operating at maximum power—with suppression.**

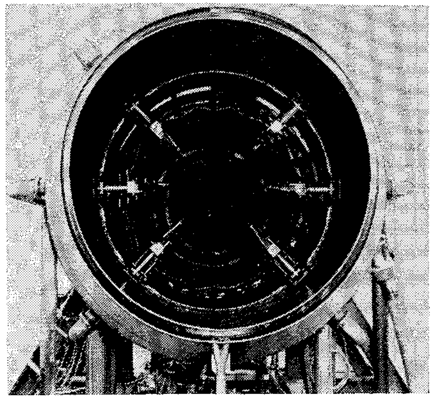

**Fig. 21 Secondary-chute type suppressor.**

stances, compromises to the design. Supersonic flight greatly increases the number of propulsion system interactions with the airframe, as well as placing greater demands on the installed propulsion system for higher component and higher over-all efficiency. The need for high efficiency usually conflicts with the broad flight environment of the airplane. An unparalleled amount of design and analysis, testing and close coordination between General Electric and Boeing will assure proper integration of the inlet duct, engine, and exhaust nozzle system for the supersonic transport.

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