10. GROUND-RUNUP TESTS OF ACOUSTICALLY TREATED INLETS AND FAN DUCTS

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SUMMARY

Two configurations of full-scale acoustically treated inlet ducts and one set of treated fan-exhaust ducts were fabricated and tested. The ducts were installed on a Pratt & Whitney JT3D turbofan engine mounted on an engine test stand. Far-field sound pressure levels and engine-performance data were obtained to evaluate the effects of the duct linings. A description is given of the tests that were conducted and of the configurations of the treated and the reference ducts. The results are presented principally in terms of the quantities that were measured at the test stand, although some estimates of the changes in flyover perceived noise level and basic engine performance are also given. Based on analyses of the test results, a design for a nacelle modification consisting of an inlet duct (with absorptive linings on the surface of the cowl, the center body, and one ring vane) and a fan-exhaust duct (with absorptive linings on the surfaces of the inner and outer duct walls and the flow splitters) was selected for flight testing on a McDonnell Douglas DC-8 airplane.

INTRODUCTION

The development of acoustical duct-lining technology, prerequisite to the selection of a duct-lining configuration, was described in reference 1. Reference 2 presented a description of the mechanical property tests needed to study candidate duct-lining materials which must withstand the environmental conditions encountered in the inlet and fan-exhaust ducts installed on the Pratt & Whitney Aircraft (P&WA) JTSD engines on DC-8 airplanes. The purpose of this paper is to describe the ground-runup tests of the treated inlet and fan-exhaust ducts selected for full-scale testing as a result of the design-concept studies reported in reference 3. Testing and data analysis techniques developed over a period of several years were used in these tests. (See ref. 4.)

This paper will describe: (1) the test procedures used for acquiring and reducing acoustic and engine-performance data and (2) the components that were tested on a JT3D turbofan engine installed on an engine test stand. Four configurations of treated inlets and one set of treated fan-exhaust ducts were tested. The results are presented in terms of the measured differences from the reference DC-8 ducts (that is, the inlet and exhaust ducts of the existing short-duct nacelle design) and also in relation to the noise-reduction goals described in reference 5.

SYMBOLS

BPF	blade passage frequency, hertz
EPR	engine pressure ratio, P_{t7}/P_{t2}
F_n	net thrust, pounds
N_1	low-pressure-compressor rotor-shaft speed, revolutions/minute
P_{amb}	ambient pressure, pounds/square foot absolute
$P_{amb\ std}$	sea-level ambient pressure, 2116 pounds/square foot absolute
P_{t2}	total air pressure at engine inlet, pounds/square foot absolute
P_{t7}	total air pressure at inlet to primary-exhaust duct, pounds/square foot absolute
PNL	perceived noise level, perceived-noise decibels (PNdB)
SPL	sound pressure level, decibels (dB) (re 0.0002 microbar)
$T_{amb\ std}$	standard-day ambient air temperature, 518.7 degrees Rankine
T_{t2}	total air temperature at engine inlet, degrees Rankine
TSFC	thrust specific fuel consumption, (pounds/hour)/pound
δ_{amb}	ambient pressure ratio, $P_{amb}/P_{amb\ std}$
θ_{t2}	temperature ratio, $T_{t2}/T_{amb\ std}$

EXPERIMENTAL ARRANGEMENT

Engine-Noise Test Facilities

Engine test stand.- The McDonnell Douglas full-scale engine-noise test facilities are located at Edwards Air Force Base. Specifically, the engine test stand is situated at the edge of Rogers Dry Lake as shown in the aerial view in figure 1. The test engine is a P&WA JT3D-1 engine with modifications to permit operation at JT3D-3 thrust settings. The P&WA "hush-kit" was incorporated in the engine; as a result, there were 35 first-stage and 32 second-stage fan-compressor blades.

The engine is installed in a simulated DC-8 nacelle with the axis of the engine 5 feet above a concrete pad. The external nacelle surfaces aft of the fan-exhaust nozzle are simulated by an afterbody shroud that is separated from the engine case. The shroud surrounds the engine and primary-exhaust nozzle. The engine is supported by a thrust-instrumented structure designed to simulate the inboard left-hand wing-pylon section of a DC-8 airplane. The simulated wing is suspended from the test stand structure by means of flexures. These flexures permit thrust measurements by means of electronic load cells. However, the forces on the afterbody shroud are carried to the ground and are not included in the thrust balance. This procedure was necessary in order to evaluate internal engine performance separately from scrubbing forces of the fan-exhaust airflow passing over the nacelle afterbody.

The engine control and instrumentation building is located near the engine test stand. The building contains the engine operating controls, provisions for visual monitoring (by windows and closed-circuit television), and the test equipment for data signal conditioning and recording.

Acoustical range.- The acoustical range around the engine test stand has been designed for far-field noise measurements. Fourteen microphones are located on an arc centered at, and 150 feet from, the engine primary-exhaust nozzle. The 0° azimuth for the microphone locations is directly ahead of the engine air inlet. The microphones were located at azimuths between 15° and 157°, the nearest position to the exhaust jet for reliable sound pressure level (SPL) measurements. The surface of the ground plane has been constructed to minimize variations in ground effects in the propagation path between the engine and the microphones. The dirt surface (visible in fig. 1) beyond the concrete surface around the engine stand has been leveled to match the concrete, compacted, and stabilized by an oil covering. A plan view of the engine-noise test facilities is given in the diagram in figure 2.

Background noise and operating limitations.- Because of the meteorological constraints needed to insure valid data and to minimize test time, all acoustical data were acquired during the early morning hours (from 1 a.m. to 7 a.m.). Precautions were taken to preclude extraneous sounds from the noise field being recorded. An octave-band spectrum of the maximum ambient noise levels at the test facility is shown in figure 3. For an idle power setting (not a normal test condition), the noise radiated from the engine produced a minimum signal-to-background-noise ratio (S/N) of 20 dB over the ambient noise levels in the first and second octave bands (at 63 and 125 Hz); at all frequencies above the second octave band, the S/N ratio was typically 30 to 45 dB at the idle power setting. Thus, for all the normal engine power settings used for test purposes, the S/N ratio was adequate.

Weather conditions.- The high-altitude (2302 feet above sea level) desert location of the engine-noise test facilities, together with the restriction of the testing to the early morning hours, generally results in weather conditions acceptable for far-field noise measurements. Typically, surface winds are from the southwest direction, that is, the direction along which the engine is alined.

Low wind speeds (calm to 6 knots) occur 70 percent of the time (based on hourly measurements) from November to January and decrease to 25 percent of the time during May and June. The ambient air temperature during the early morning acoustical data recording periods ranges from a maximum of about 70° F in July and August to a minimum of about 30° F during December and January. The average moisture content, or absolute humidity, of the air around the noise test facility has been determined to be about 6 grams/meter^3, lower levels of absolute humidity being noted in the autumn and winter months.

The major environmental parameters monitored to determine an acceptable test environment arc the speed and stability of the surface wind. The maximum steady wind speed allowed for conducting tests is 8 miles per hour. Winds with speeds less than 8 mph, but with rapidly changing direction, are unsuitable for stable engine operation, and tests are not conducted under this condition.

Fan-exhaust and inlet-noise suppressor enclosures.- One important requirement in the evaluation of acoustical data from the static engine test stand was the need for independent assessments of the acoustical performance of each treated inlet and fan-exhaust duct. Two enclosures were required to satisfy this need: a fan-exhaust-noise suppressor enclosure and an inlet-noise suppressor enclosure. The former enclosure was installed when data were taken to evaluate the acoustical performance of the treated inlet ducts; the latter enclosure, to evaluate the acoustical performance of treated fan ducts.

The acoustical design criteria for the noise reduction to be achieved by each enclosure were established based upon estimates of the relative strengths of the inlet and fan-exhaust noise sources plus an estimate of the amount of noise reduction that the treatment in the inlets and fan-exhaust ducts might achieve plus a factor of 10 dB to ensure an adequate signal-to-noise ratio. The criteria were specified in terms of the change in SPL to be measured on the 150-foot arc in the 2000-Hz and the 4000-Hz octave bands. The required values were 15 dB in the aft quadrant for the inlet-noise suppressor enclosure and 17 dB in the forward quadrant for the fan-exhaust-noise suppressor enclosure.

The fan-exhaust enclosure, a five-sided structure (no rear wall) having approximate dimensions of 30 feet by 30 feet by 8 feet, was fabricated of 1-inch-thick plywood panels. The acoustical treatment used on the surfaces of the enclosure was unwrapped 4-inch-thick fiber-glass batts. The batts were covered with porous fabric and large-mesh wire screen to prevent erosion. All interior surfaces of the enclosure, including the floor, the ceiling, and the exterior surface of the front, were so treated. The front panel had an opening to allow for a 1-inch clearance around the engine. The opening was packed with fiber glass and soft felt. This flexible seal allowed engine movement yet provided an acoustical seal to eliminate noise leaks. The enclosure was braced to withstand a negative pressure of 0.5 psig within the structure. Figure 4 shows an interior view of the fan-exhaust enclosure.

Figure 5 shows the two major elements of the inlet-noise suppressor, a steel tunnel and a wooden fiber-glass-lined duct that absorbs and redirects the sound from the tunnel. The cylindrical tunnel is approximately 7 feet in diameter and 40 feet long and is fabricated of 3/16-inch-thick sheet steel. The tunnel is mounted on rails and casters to allow longitudinal movement and to facilitate connection to the engine inlet. To reduce the amplitude of sound reflections from the exterior surface of the steel tunnel and to minimize sound leaks, the inlet cowl of the engine and both ends of the tunnel were lagged with batts of 4-inch-thick, unwrapped fiber glass. The lined duct that fits over the screened entrance to the tunnel was fabricated of plywood and fiber glass to the same specifications established for the fan-exhaust suppressor enclosure. The five-sided enclosure functions as a "duct turn," lined on all interior surfaces with 4-inch-thick layers of fiber-glass batts.

An acoustical evaluation of the suppressor enclosures was made by using a high-intensity loudspeaker driven by a power amplifier, excited by octave bands of random noise at 2000 Hz and 4000 Hz. The measured changes in the far-field SPL exceeded the design criteria and the suppressor enclosures were judged to be acceptable.

Sound Pressure Level Measurements

Data acquisition.- The acoustical effectiveness of various nacelle treatments was determined by measuring the far-field acoustic pressures sensed by condenser microphones, 0.5 inch in diameter, located 5 feet above the ground surface along the 150-foot arc. The condenser microphones had a uniform pressure-frequency response and were oriented on stands to receive the acoustic pressure waves at grazing incidence with their diaphragms in a horizontal plane through the engine.

The microphone signals were routed into the engine control and instrumentation building and monitored, by using oscilloscopes and meters, for waveform and recording level. Amplifiers with 10-dB step-gain adjustments were utilized to set the microphone signals to the optimum levels for tape recording. A 14-channel tape recorder, with frequency-modulation recording capability, was used to record, simultaneously, all far-field microphone signals along with the voice annotation needed for relating the acoustical data with the engine data. Associated equipment, utilized for obtaining supporting data, included the instrumentation indicating the engine operating parameters and the weather conditions. A wind-measuring system, indicating speed and direction and mounted 24 feet above the ground on the roof of the engine control building, was monitored and the readings were tabulated. The air temperatures necessary for determining the moisture content of the air were measured by using hand-held fan-aspirated wet- and dry-bulb thermometers.

Acoustical calibration equipment utilized for the noise-measuring systems included both a precision sound source for system sensitivity calibration at 250 Hz and 124 dB and a variable-frequency constant-amplitude electrical signal source for system frequency response calibration.

Test procedures.- The engine was operated at nine different stabilized power settings to determine basic noise characteristics at referred rotor speeds $\left(N_1/\sqrt{\theta_{t2}}\right)$ ranging from 2200 rpm to 6300 rpm. To obtain acceptable statistical confidence in the measurements, three runs were made at each power setting. Referred rotor speed was used to specify the engine power setting because the ambient air-inlet temperature varies and because the noise level at the source is considered a direct function of the fan-tip Mach number. The procedure of operating the fan section at fixed values of $N_1/\sqrt{\theta_{t2}}$, to keep the tip Mach number constant, minimized the variations in the level of the noise source, but resulted in fundamental fan-blade-passage frequencies varying slightly with ambient temperature.

Even with optimum meteorological conditions, large-amplitude fluctuations were observed in the discrete-frequency far-field fan noise. These fluctuations required noise recordings having durations of 3 minutes at each test power setting to achieve a repeatable average.

Data processing.- Processing of the acoustical data was accomplished at a Douglas facility in Long Beach, California. A diagram of the equipment is shown in figure 6. The essential functions of the equipment include tape signal control and monitoring, 1/1-octave and/or 1/3-octave band filtering, root mean squaring, logarithmic conversion of the filtered signal, digitizing of the analog level, and recording on punch cards. By using an externally programed digital computer, the digitized records were converted into sound pressure levels corrected for variations in system frequency response. These sound pressure levels were filtered into four 1/1-octave bands with center frequencies of 63, 125, 250, and 500 Hz, and into eleven 1/3-octave bands with center frequencies ranging from 800 to 8000 Hz.

Accuracy and repeatability.- The data processing techniques included procedures for obtaining sound pressure levels having a high degree of statistical validity. These procedures were: (1) use of large values of damping available in the graphic level recorder, typically a pen writing speed of 4 millimeters/second; (2) arithmetic averaging of levels at 10 equally spaced intervals in a 25- to 50-second data sample selected at random from the 180-second data sample available for each microphone location and engine power setting; and (3) arithmetic averaging of comparable sound pressure levels measured for three separate ground-runup tests. Sample-graphic-level recorder traces of 1/3-octave band SPL fluctuations and the 10-sample averaging are shown in figure 7.

The accuracy of the SPL measurements is limited by the accuracy of the pistonphone calibration sound source, that is, about ±0.3 dB. The repeatability of the noise record/reproduce system is about ±0.3 dB. For a given data sample, the data processing techniques result in data repeatability to within ±0.6 dB for 90 percent of the data. The repeatability of the 3-run average 1/3-octave band sound pressure levels is ±1.8 dB for 90 percent of the data.

Engine-Performance Measurements

Data acquisition and reduction.- The test engine was instrumented to provide the data necessary for performance evaluations under static conditions and for "matching" of the effective areas of the fan-exhaust nozzles. Table I indicates the parameters measured and the general types of instrumentation used for performance tests. Instrumentation accuracy was equal to or better than that recommended by the engine manufacturer. In addition to performance instrumentation, instrumentation was available for monitoring engine operations and for observance of the engine operating instructions and limitations.

The large quantity of data obtained was recorded in a format suitable for processing by a digital computer. Instrument calibration corrections and the instructions for reducing the data to nondimensional parameters and to quantities referred to standard-day conditions were programed into the digital computer.

These data acquisition and reduction procedures gave faired results with good repeatability. For example, the repeatability of faired data for thrust specific fuel consumption (TSFC) is considered to be ±0.33 percent; the repeatability of the faired referred net thrust data, at a given EPR, is ±0.25 percent.

Specific test procedures.- Reference engine-performance data for three differing facility configurations had to be established because of the use of the noise suppressor enclosures. The fan-exhaust-noise suppressor enclosure, shown in figure 4, functioned as a zero-flow ejector; thus, the pressure on the aft portion of the engine was reduced by several inches of water relative to the ambient pressure. Because the resulting forces could not be accurately determined by analytical techniques, a reference was established, with the fan-exhaust-noise enclosure installed, to serve as a basis for performance comparisons during the testing of modified inlets.

Similarly, because the inlet-noise suppressor enclosure (fig. 5) affected thrust and fuel flow, reference performance data were established with the suppressor enclosure around the inlet as a basis for comparison of the tests on the modified fan-exhaust ducts.

The two references described were necessary for those tests where simultaneous measurements of noise and engine performance were made. Although care was taken to account for extraneous effects and although measurements were of a quality sufficient for rank-order evaluations of the effects of the various modified inlets and exhaust ducts on engine performance, slight inaccuracies existed because of unaccountable friction and pressure-area forces imposed by the presence of the inlet and exhaust-noise suppressor enclosures. Therefore, once the flight-test modified-nacelle configuration was selected, reference performance data were established again, but without the suppressor enclosures installed, for use in determining the effects of the modified nacelles on basic engine performance.

Components Tested

Inlets.- The engine air inlet used for a reference was the existing DC-8 cowl and center body described in reference 3. Schematic drawings of the two treated engine-air inlets are shown in figures 8 and 9. For convenience in construction, both inlets were made as bodies of revolution, axisymmetric about the inlet center line. The cowl length on the two-ring inlet was 45 inches; on the 47-percent "lightbulb," it was 65 inches. The two-ring inlet was tested with both rings in place, with only one ring (the outer ring) in place, and with both rings removed. The term 47 percent, describing the lightbulb inlet, refers to the percentage of the axial line-of-sight blockage provided by the enlarged center body. The area that is blocked is the annular area at the inlet-guide-vane station on the existing JT3D inlet cowl.

The acoustical treatment was located on the cowls, rings, and center bodies of the two inlet configurations as indicated in figures 8 and 9. The design concept selected by McDonnell Douglas for the duct lining used a single layer of porous stainless-steel fiber metal over air-filled cavities as shown in the two enlarged views in the figures. The acoustical parameters of the duct linings in the inlets are given in table II. The porous surfaces, fiber-glass honeycomb, and impervious backing structure were bonded together by using the techniques described in reference 2. The impervious backing-support structure consisted of a 0.25-inch-thick fiber-glass laminate.

Fan-exhaust ducts.- The short fan-exhaust ducts used as a reference were described in reference 3. Figure 10 illustrates the configuration of the 48-inch fan-exhaust ducts that were tested. The 48-inch dimension refers to the axial distance between the duct entrance and exit planes. Each duct has acoustical treatment on the outer wall, on the inner wall, on both sides of each of the four flow splitters, and on each "duct end" between the inner and outer walls.

The duct-lining concept used in the fan-exhaust ducts was similar to that used in the treated inlet ducts, as can be seen by comparing the parameters listed in table III with those in table II. The treatment consisted of a single-layer design of porous stainless-steel fiber metal over air-filled cavities. The nominal flow resistance of the porous surfaces was chosen as 80 mks rayls compared with the 100 mks rayl fiber metal used in the inlet ducts. As indicated in figure 10 and in table III, the cavity depth on the outer duct wall was greater than that on the inner duct wall. The treatment used on the flow splitters was the same as that used on the ring vanes in the inlets, that is, two 0.5-inch-thick layers on either side of a thin, impervious, steel septum. The duct lining was a bonded construction and, like the inlet ducts, used 0.25-inch-thick fiber-glass laminate for backing-support structure.

RESULTS AND DISCUSSION

Treated Inlet Ducts

Noise level of the reference inlet (existing DC-8 inlet).- Figure 11 illustrates the spectra of the sound pressure levels observed in the forward quadrant at 60° from the inlet center line and 150 feet from the primary nozzle exit. The spectra are shown for the two engine power settings corresponding to those used for DC-8 operations during a landing approach (standard day) and during a take-off (hot day), that is, for referred low-pressure rotor speeds of 4600 and 6300 rpm, respectively. Acoustic performance results, in this and succeeding sections, are presented for one or both of these two engine power settings. The angle of 60° was chosen because estimates of the instantaneous flyover perceived noise level (PNL) during landing showed that the peak PNL of the noise from the existing inlet occurred at an angle of about 60°, when the 150-foot polar SPL measurements were projected to a 400-foot sideline, representative of a landing approach.

The far-field SPL spectra shown in figure 11 illustrate several characteristics of the sounds radiated from the inlet of the P&WA JT3D engine. At the landing power setting, the most prominent features are the intense sound pressure levels in the 1/3-octave bands centered at 2500 **Hz** and 5000 **Hz**, that is, in the bands containing the fundamental and the second harmonic of the blade-passage frequencies (BPF) from the two fan stages. The fundamental BPF tones in the 1/3-octave band at 2500 Hz are from 5 to 6 dB greater than the second harmonic of the BPF tones in the 1/3-octave band centered at 5000 Hz.

At the take-off power setting, the fundamental blade-passage frequencies are between 3400 Hz and 3700 Hz. The SPL at these frequencies contributes approximately equally to the SPL in the 1/3-octave bands centered at 3150 Hz and 4000 Hz. As with the landing power setting, the SPL of the fundamental is also 5 to 6 dB greater than the SPL of the second harmonic. The absolute value of the SPL at the fundamental BPF is less for the take-off than for the landing power setting.

Another interesting feature of the far-field spectra in figure 11 is the appearance of sound pressure levels at frequencies not related to blade passage. These sound pressure levels are technically referred to as combination tones and occur at frequencies which are integral multiples of the rotor speed. Combination tones are produced by a series of randomly spaced weak shock waves propagated forward of those sections of the fan blades that are rotating at supersonic relative tip Mach numbers. Reference 6 contains more detailed information on the formation of these combination tones and notes that the most intense combination tones are at frequencies that are 15 to 20 times the rotational speed of the low-pressure rotor. Thus, at the landing power setting, the combination tones lie within the 1/3-octave bands centered at 1000, 1250, and 1600 Hz and, at the take-off setting, in the 1/3-octave bands centered at 1600, 2000, and 2500 Hz.

Lastly, the broadband noise (in the octave bands centered at frequencies from 63 to 500 Hz) is much less at landing power settings than at take-off power settings. The principal source of broadband noise is normally the primary jet exhaust although with the fan-exhaust-noise suppressor enclosure around the engine, other sources may contribute significantly to the observed sound pressure levels.

Noise reduction of the two-ring inlet.- The noise reduction of the two-ring inlet at the landing power setting is shown in figure 12. In the 1/3-octave band centered at 2500 Hz, the noise reduction was 18 dB with two rings installed, 12 dB with one ring installed, and 3 dB with no rings installed; in the band centered at 5000 Hz, the corresponding noise reductions were 8, 5, and 1.5 dB. These results emphasize the importance of selecting channel heights to give small distances between absorptive surfaces in order to achieve large noise reductions at these high frequencies. The results tend to corroborate the trends that were shown in reference 1 based on transmission-loss tests using duct models with various channel heights and also the trends indicated by the design chart presented in reference 3.

The noise reductions in the 1/3-octave bands centered at 1000, 1250, and 1600 Hz are large because of the apparently efficient absorption of the combination tones by the treatment on the cowl wall. Addition of the treated rings only makes slight increases in the combination-tone noise reduction, probably because only the outer portions of the fan blades are near sonic speed at the 4600-rpm landing condition and, hence, the combination-tone energy may be concentrated near the cowl wall.

Noise reduction of the 47-percent lightbulb.- Figure 13 shows the acoustical performance at landing power of the lightbulb inlet compared with that of the two-ring inlet (with two rings). The noise reduction observed includes the effects of (1) the acoustical absorptivity of the treated surfaces, and (2) the line-of-sight blockage by the enlarged center body. The results did not indicate any significant additional attenuation from the 27 square feet of additional treatment in the lightbulb inlet, over that in the two-ring inlet, because of the large heights of the channels in which much of the acoustical lining is placed.

Noise reductions at take-off.- Noise reductions achieved at the take-off power setting for the four treated inlet configurations are presented in figure 14. The reductions at take-off are less than those obtained at the landing power setting (at the fundamental and second harmonic blade passage frequencies) because: (1) the sound pressure levels incident on the treated surfaces may be less at take-off than during landing; (2) the airflow velocity over the treated surfaces is greater at take-off; and (3) the absorptivity of the treatment at 3400 to 3700 Hz is less than the absorptivity at 2500 Hz.

The noise reductions at the fundamental and at the second harmonic of the BPF at the take-off power setting (that is, at the frequencies noted by the dashed lines) are approximately equal for each of the four configurations in figure 14. This result contrasts with those shown in figures 12 and 13, where as much as an 11-dB difference between the noise reduction at the fundamental and at the second harmonic was observed. The difference in results is attributed to the relative strength of the BPF tones at the two power settings.

Finally, it is noted that the effect of adding treated ring vanes on the noise reduction at the combination-tone frequencies is different at take-off than at landing. At the landing power setting, the cowl-wall treatment alone (no rings installed) achieved almost as much noise reduction as when the outer ring, or both outer and inner rings, were installed. However, at take-off (with combination tones in the 1/3-octave bands centered from 1600 to 2500 Hz), the reduction was considerably increased by the addition of the treated rings. This result may be related to a spreading out of the combination-tone energy throughout a larger portion of the inlet cowl at the take-off power setting compared with the energy distribution at the landing power setting. A larger portion of each fan blade is rotating supersonically at the take-off power setting than at the landing power setting.

Engine-performance tests.- Figure 15 shows the results of testing three of the four treated inlet configurations with the fan-exhaust-noise enclosure fitted to the test stand.

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Engine performance was measured while acoustic tests were being conducted. Referred thrust is shown as a function of engine pressure ratio. To simplify further discussion, the two-ring inlet with just the one outer ring installed is hereinafter referred to as the one-ring inlet.

Thrust decrements observed for the various treated inlets indicate the following rank ordering: (1) one-ring inlet, (2) two-ring inlet, and (3) 47-percent lightbulb inlet It is noted that the configurations producing the larger noise reductions tend to produce more thrust loss.

Pressure survey of one-ring inlet.- An adapter ring, incorporating fixed-position total-pressure rakes, was used to determine pressure recovery characteristics at the inlet station corresponding to the engine inlet. The adapter consisted of two concentric cylindrical sections, 8 inches long, fitted between the engine front flange and the inlet cowl and similarly between the engine hub flange and the center body. Rakes were installed to survey total pressures across the inlet annulus, near the center body and cowl surfaces, and behind the ring and ring-support struts. In addition, six static pressure taps were located with equal circumferential spacing around the adapter ring in the plane of the total-pressure probes.

Figure 16 shows the radial distribution of inlet total pressure. The influences of the cowl-wall boundary layer and the concentric-ring wake are indicated. Although not included in the graph, the wake of one of the ring-support struts was measured (rake 3) at a distance of about 13.5 inches radially from the center body. The peak pressure loss from the ring-support strut was only about one-fourth the loss produced by the acoustically treated ring.

Treated Fan-Exhaust Ducts

Noise level of the reference (existing DC-8) fan-exhaust ducts.- Figure 17 shows the spectra of the sound pressure levels observed at 110° on the 150-foot arc. The 110° angle corresponds approximately to the polar angle at which the peak instantaneous PNL is radiated from the existing short fan ducts during landing.

The spectra are similar to those shown in figure 11 for the reference inlet configuration except that the sound pressure levels are greater by about 10 dB. Combination tones, which should propagate only out the inlet duct because they are related to the shock waves ahead of the supersonic parts of the fan blades, should not be present in the spectra of the noise from the fan ducts. The data presented in figure 17 do not show evidence of strong combination tones.

The noise spectra from the fan ducts also illustrate another important characteristic in that the SPL of the second harmonic of the BPF is now about equal to the SPL of the fundamental BPF at the landing power setting; whereas a 5- to 6-dB difference was noted in figure 11 between these two frequency components for the inlet noise.

Noise reduction of the 48-inch fan-exhaust ducts.- Figure 18 shows the noise reductions measured at the 110° angle at the landing and at the take-off power settings. At the fundamental BPF, the noise reduction is 23 dB at the landing power setting, and about 12 dB (by interpolation between the values shown for the 3150- and the 4000-Hz bands) at the take-off condition.

On the basis of (a) the relatively greater SPL noted in figure 17 for the second harmonic of the blade passage frequencies compared with the SPL of the fundamental blade passage frequencies and (b) the general results presented in reference 1 for the effects of SPL on the attenuation of sound propagated through treated ducts, it was expected that the noise reduction of the second harmonic tones, compared with that of the fundamental tones, would be relatively larger than was achieved by the treated inlets. As anticipated, at landing power, the noise reduction in figure 18 at the second harmonic of the BPF was relatively larger, compared with that at the fundamental, than the values presented for the treated inlets.

The data presented for the fan-exhaust ducts do not show the significant noise reductions noted for the treated inlet ducts in the 1/3-octave bands containing the intense combination tones. (See figs. 12 and 13.) This observation tends to validate the discussion of the treated inlet ducts that explained the large noise reductions observed in the 1/3-octave bands below the fundamental blade passage frequencies. Since combination tones are not found downstream of the fan blades, no large noise reductions would be expected at these frequencies in the aft quadrant.

Engine-performance tests of the 48-inch fan-exhaust ducts.- The engine-performance tests of the 48-inch treated fan-exhaust ducts, conducted concurrent with the acoustic tests, indicated thrust decrements relative to the existing fan-exhaust ducts of 0.25 percent, or less, at fixed values of engine pressure ratio (EPR). These indicated-fan-duct losses were considered to be less than the uncertainty in the accuracy of the performance measurements with the inlet-noise suppressor enclosure installed.

Relation of Component Test Results to Contract Goals and Inlet Selection

The noise alleviation goals for the modified nacelles, to be designed for the JT3D engine on the DC-8 airplane, were given in reference 5 in terms of a reduction in the peak instantaneous flyover PNL produced by the aircraft passing at an altitude of 370 feet over a listener stationed out of doors 1 nautical mile from the landing threshold. The conditions included an air temperature of 77° F, a runway at sea level, and a 3° landing glide slope. The aircraft specifications were flaps full down, maximum landing weight, and a net thrust per engine of about 5500 pounds. Perceived noise levels were to be calculated by using the sound-pressure-level—noisiness conversions given by the tables in the latest applicable revision of reference 7.

Although general procedures for accurately predicting the spectrum and directivity of flyover sound pressure levels (and hence the magnitude and time-dependence of instantaneous perceived noise levels) are not yet available, estimates were nevertheless made of the reductions required in peak PNL for the noise radiated from the existing fan-exhaust ducts and the existing inlet duct. These estimates, mentioned in reference 3, were that a reduction in peak instantaneous PNL, under the landing condition described, of about 10 PNdB would be required for the noise radiated from the fan ducts, and about 7 PNdB for the noise radiated from the inlet ducts.

Extrapolating from the 150-foot polar SPL measurements, additional estimates were made, by using the flyover noise prediction techniques described in reference 8, of the reduction in peak landing PNL that would be produced by the four configurations of treated inlet ducts and by the 48-inch treated fan-exhaust ducts. At the landing power setting,

(1) The reduction in peak PNL from the fan ducts would be about 11 PNdB

(2) The reduction in peak PNL from the inlet ducts would be:
  (a) For the two-ring inlet with no rings, about 2 PNdB; one ring, about 8 PNdB; two rings, about 11 PNdB
  (b) For the 47-percent lightbulb inlet, about 10 PNdB.

No change in peak flyover PNL was predicted at the take-off power condition specified in reference 5.

Based on the estimates presented above and on the preliminary results of the engine-performance tests made with the noise-suppressor enclosures around the engine, the combination of the one-ring treated inlet and the 48-inch treated fan ducts was selected for the modified-nacelle concept for the flight-test phase of the program.

Ground-Test Modified Nacelle

Figure 19 shows the selected components mounted on the JTSD engine simulating the flight-test modified nacelle. There were no noise-suppressor enclosures around the engine for the acoustic and engine-performance tests of the components in this configuration. The T-shaped device visible in figure 19, that is mounted on the ground in front of the engine air inlet, is a vortex barrier that was installed to minimize the effects of ground vortex systems in the inlet airflow on the generation of noise by the fan sections of the engine.

Noise reduction.- The acoustical performance of the existing and the modified JT3D nacelles, measured at the 110° angle, is shown in figures 20 and 21 for the landing and the take-off power settings, respectively. By projecting the sound pressure levels measured throughout the 150-foot arc to the specified landing approach condition, estimates showed that if the DC-8 were to be equipped with a nacelle modification with the same acoustical performance as the combination of the one-ring treated inlet and the 48-inch treated fan-exhaust ducts, the 7 to 10 PNdB perceived-noise-reduction goal during landing would be met. Reference 8 contains additional data on the effects of the nacelle modifications on airport community noise levels.

The spectra in figures 20 and 21 indicate an increase of 1.5 to 2 dB in the sound pressure levels at 63, 125, and 250 Hz. The cause for this increase in the low-frequency sound pressure levels is not known although it is probably related to the difference in the turbulence levels and shear gradients caused by extending the fan-exhaust nozzle 24 inches closer to the primary nozzle. When the fan nozzle on the JT3D engine was made coplanar (or almost coplanar) with the primary nozzle (as on the DC-8 model 62 and 63 airplanes), substantial reductions in low-frequency noise were obtained. Similar low-frequency noise reductions are expected for the long fan-exhaust duct installation being considered for the 707 and 720 turbofan-powered airplanes.

Engine performance.- Figures 22 and 23 present engine-performance data obtained in the tests of the nacelle with modified inlet and fan-exhaust ducts. Figure 22 gives the effects of the nacelle modifications on referred thrust specific fuel consumption (TSFC); figure 23 shows the effects on referred net thrust as a function of EPR. Since the results shown in these figures are for static engine performance only, additional analyses were conducted to provide more meaningful estimates of the effects of these nacelle modifications on airplane performance.

The TSFC penalty, at a constant value of referred net thrust, is considered to be due to the effects on thrust and fuel flow of the losses in total pressure within the inlet and the fan-exhaust ducts. Standard methods of extrapolating these losses to cruise conditions indicated that the cruise TSFC would be increased by about 1 percent for the modified nacelle relative to the existing nacelles.

Whereas the curves presented in figure 23 do indicate a thrust decrement at a given EPR, the decrement in rated power settings will be larger. At take-off rated power, although the data indicated 0.5-percent thrust loss at a constant EPR, reduced EPR settings would be required for the curves used to set take-off thrust for two reasons. First, for airplanes equipped with the existing nacelles, an increase of EPR at ratings over that specified for the basic engine was allowed. This increase was available only with the particular fan-exhaust-duct and fan-thrust-reverser arrangement supplied with the engine for the existing nacelles, and would not be available for the modified nacelles.

Second, an adjustment in EPR would be required to reduce power to prevent engine overboost due to inlet loss. The P_{t2} total-pressure probe in the inlet installation on the DC-8 is located where it does not sense loss in average inlet pressure. The engine, however, does experience inlet-pressure losses and, hence, actually operates at an EPR higher than that indicated by the EPR gage in the cockpit, since the actual average inlet pressure is less than that measured by the P_{t2} probe. Thus, since the parameters that limit the operation of the engine are related to the actual EPR rather than the indicated EPR, a reduction in indicated EPR is required to account for this inlet-pressure loss.

As a result, after making these adjustments to the indicated EPR allowable for the take-off rating and after including the thrust decrement of 0.5 percent once the rated EPR was established, the sea-level standard-day thrust available at the take-off rating will be reduced by an estimated 2.75 percent compared with that for the existing installation. By a similar analysis, on a standard day at an altitude of 35 000 feet, the maximum cruise thrust rating will be reduced by 2.5 percent. The decrease in take-off rated thrust will mean that at fixed distances from start of take-off, airplanes equipped with modified nacelles will be at lower altitudes than airplanes equipped with the existing nacelles and the same gross weight.

CONCLUDING REMARKS

The results of these tests have demonstrated that acoustically treated inlet and fan-exhaust ducts can be designed for the P&WA JT3D turbofan engine that will produce significant reductions in the far-field sound pressure levels, at blade passage frequencies, for landing-approach power settings. The engine-performance penalties associated with these treated ducts result in an increase in cruise thrust specific fuel consumption and a decrease in the thrust available at rated engine power settings. The decrease in thrust at rated take-off power will result in the modified aircraft having a slightly lower take-off flight path.

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TABLE I.- INSTRUMENTATION FOR ENGINE-PERFORMANCE TESTS

Parameter	Instrumentation
Primary exhaust-duct-inlet total pressure	P&WA averaging rakes and mercury manometer
Engine-inlet total pressure	Probe at nose of center body and water manometer
Fan-duct-inlet total pressure	Six P&WA averaging rakes and mercury manometers
Low-pressure-compressor-exit static pressure	Sensitive manifold pressure gage, 0 to 400-inch mercury absolute
High-pressure-compressor-exit static pressure	Sensitive manifold pressure gage, 0 to 400-inch mercury absolute
Measured net thrust	Load cells and self-balancing indicator
Low-pressure-spool rotor speed	Electronic pulse counter
High-pressure-spool rotor speed	Electronic pulse counter
Fuel flow rate	Turbine flowmeter and electronic pulse counter
Fuel temperature	Iron-constantan thermocouple and precision potentiometer
Engine-inlet total temperature	Four shielded iron-constantan thermocouples and precision potentiometer
Primary-exhaust-duct-inlet total temperature	P&WA averaging probes and precision self-balancing potentiometer

TABLE II.- ACOUSTICAL DUCT-LINING PARAMETERS FOR TWO-RING OR 47-PERCENT LIGHTBULB INLETS

Parameter	Value
Nominal flow resistance of porous surfaces at 0.2 meter/second, mksrayls	100
Cavity depth on cowl and center body. inches	0.75
Cavity depth on either side of impervious steel septum for' ring vanes. inches	0.50
Node spacing (cell size) for fiber-glass honeycomb. inches	0.75
Design frequency for maximum noise reduction. hertz	2200 to 2800
Treated area for two-ring inlet. square feet:	
Cowl	35.5
Outer ring	24.0
Innerring	9.0
Center body	4.5
Total	73.0
Treated area for 47-percent lightbulb. square feet:	
Cowl	63.0
Ring	23.0
Centerbody	14.5
Total	100.5

TABLE III.- ACOUSTICAL DUCT-LINING PARAMETERS FOR 48-INCH FAN-EXHAUST DUCTS

Parameter	Value
Nominal flow resistance of porous surfaces at 0.2 meter/second, mks rayls	80
Cavity depth, inches:	
Outer duct wall	0.75
Inner duct wall	0.5
Flow splitters, either side of impervious septum	0.5
Duct ends (between inner and outer duct walls)	0.5
Node spacing (cell size) for fiber-glass honeycomb, inches	0.75
Design frequency for maximum noise reduction, hertz	2300 to 2900
Treated area, square feet:	
Outer duct wall	24.5
Inner duct wall	24.0
Flow splitters	19.5
Duct ends	2.5
Total	70.5

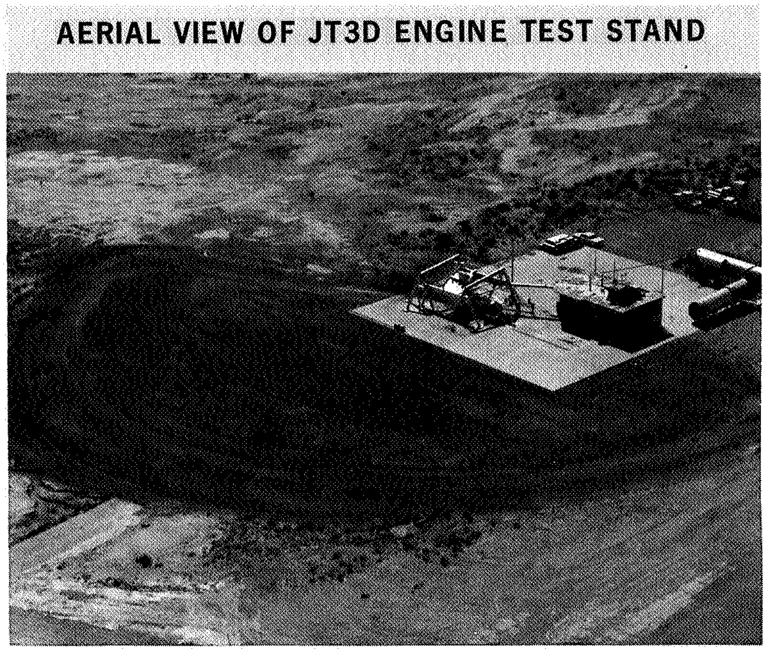

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Figure 1

ENGINE NOISE TEST FACILITIES

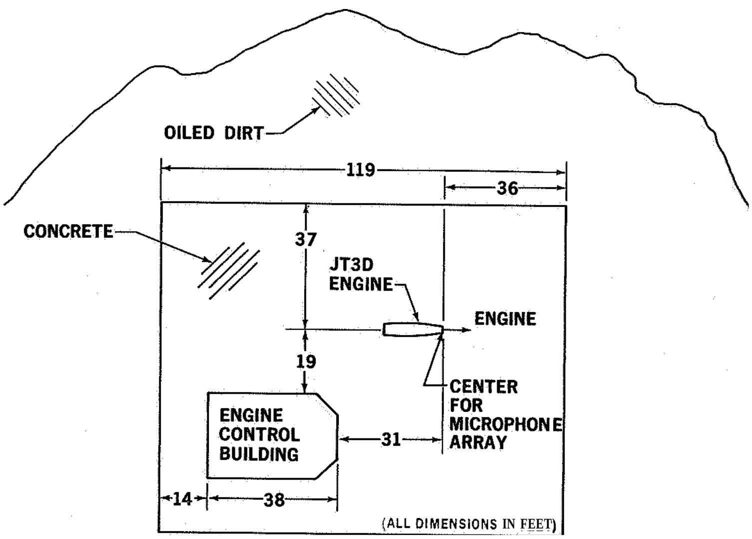

Figure 2

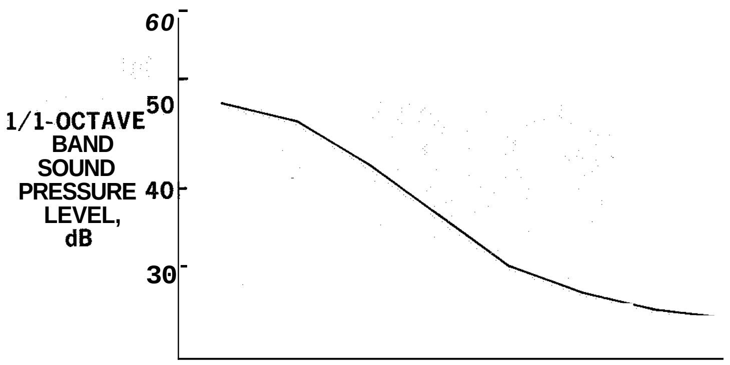

Figure 3

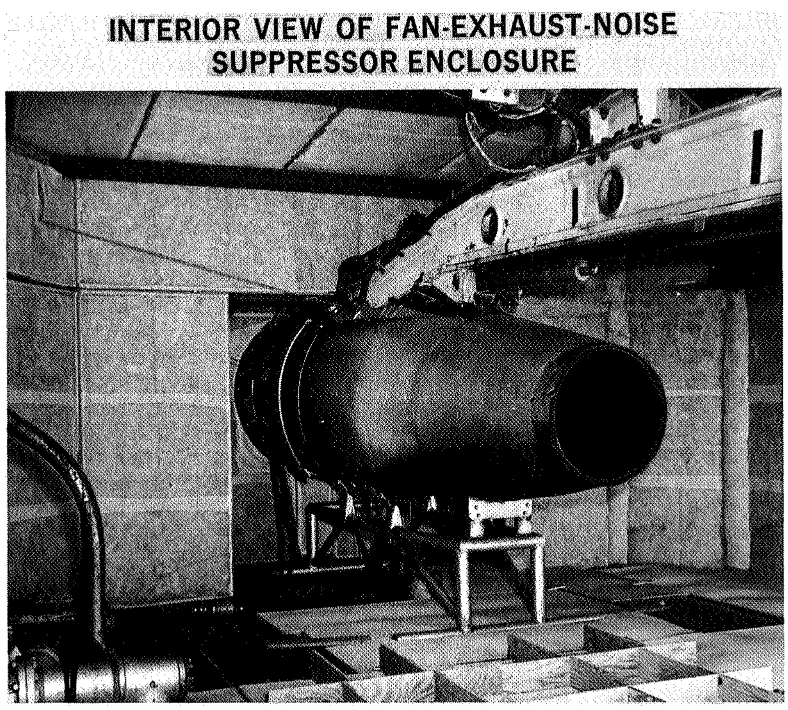

Figure 4 L-68-8561

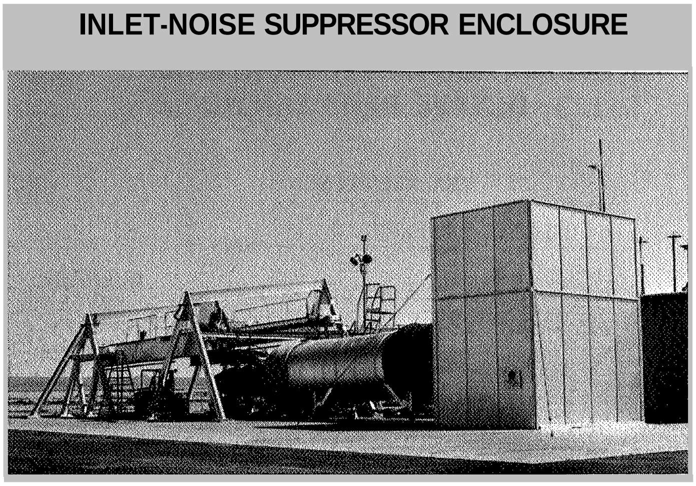

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Figure 5

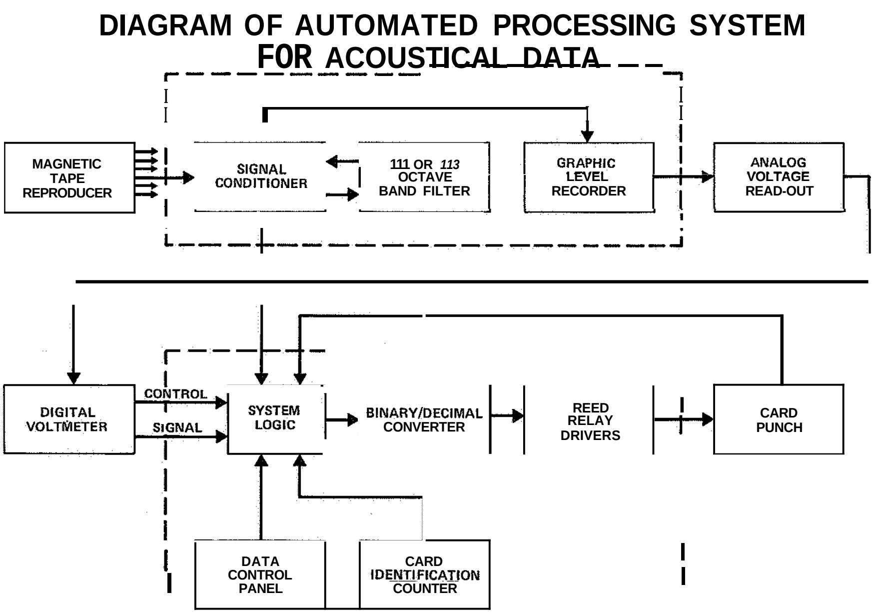

Figure 6

ILLUSTRATION OF FLUCTUATIONS IN 1/3- OCTAVE BAND FAN NOISE

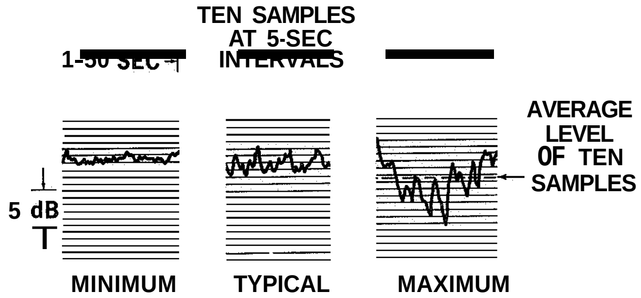

Figure 7

TWO-RING INLET

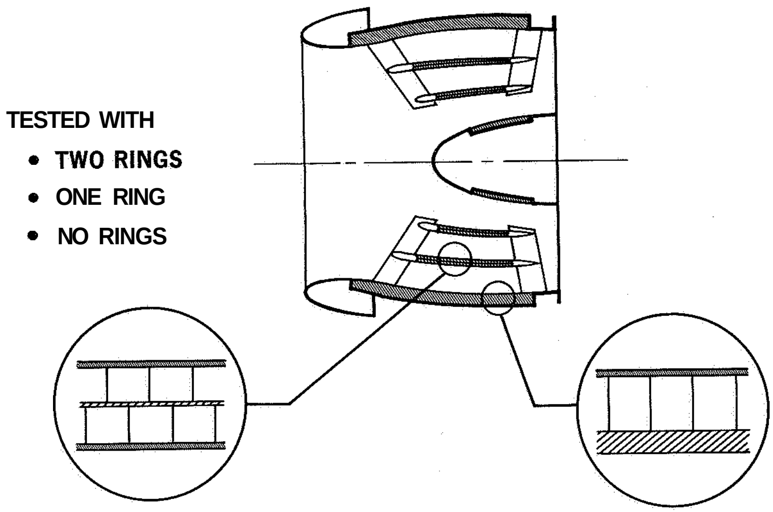

Figure a

47-PERCENT LIGHTBULB INLET

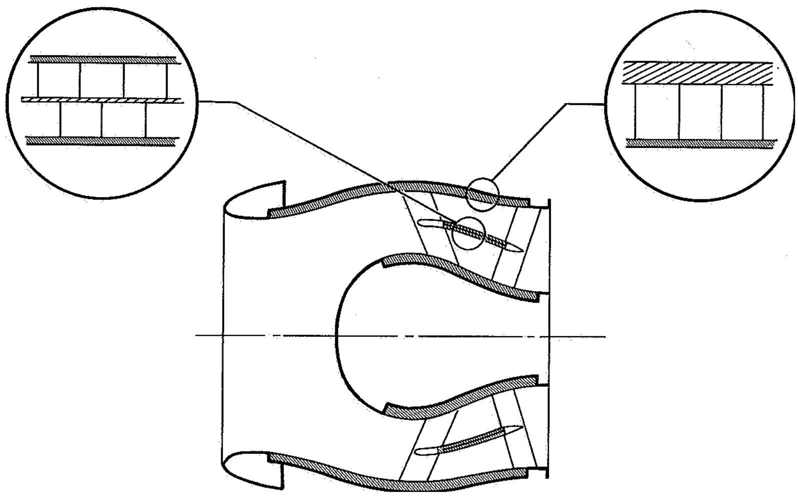

Figure *9*

48-INCH FAN-EXHAUST DUCTS

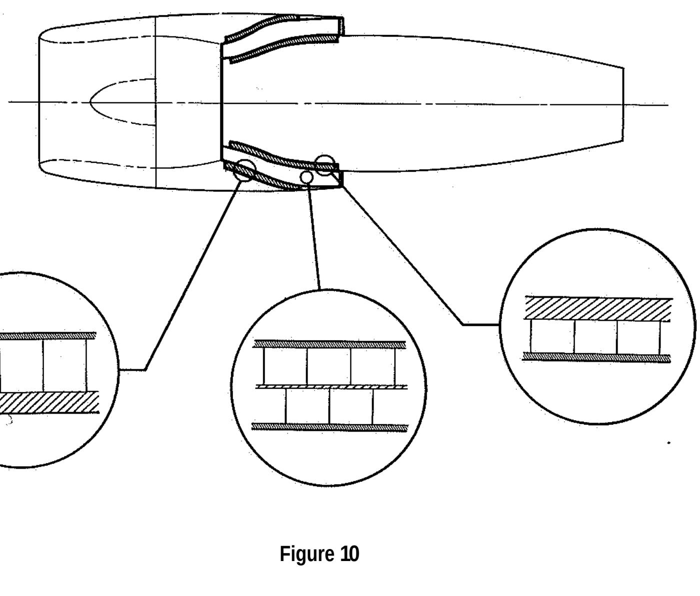

Figure 10

NOISE LEVELS OF EXISTING JT3D ENGINE AIR INLET

DATA AT 60° AND 150-FT RADIUS
FAN-EXHAUST-NOISE SUPPRESSOR ENCLOSURE INSTALLED

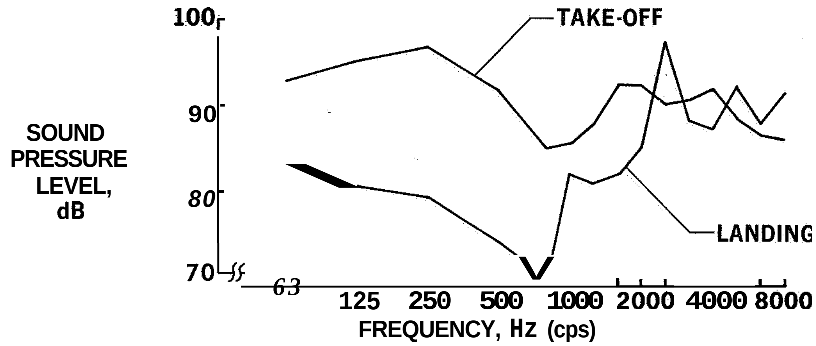

Figure 11

NOISE REDUCTION WITH TWO-RING INLET

DATA AT 60° AND 150-FT RADIUS; LANDING POWER;
FAN-EXHAUST-NOISE SUPPRESSOR ENCLOSURE INSTALLED

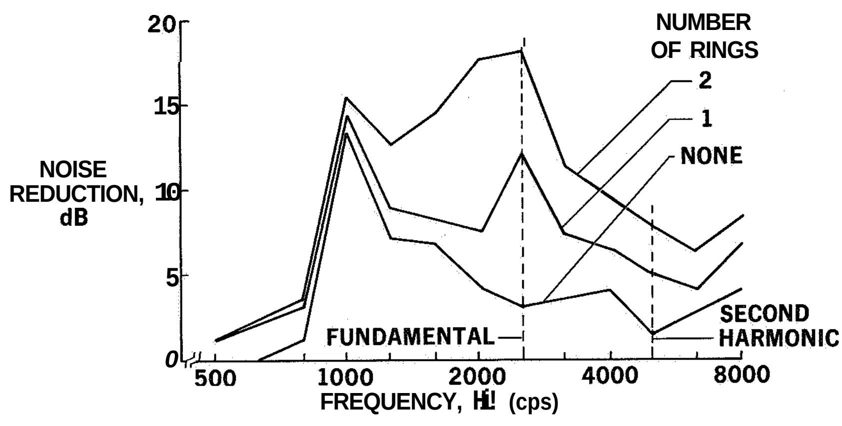

Figure 12

NOISE REDUCTION WITH TREATED INLETS

DATA AT 60° AND 150-FT RADIUS; LANDING POWER;
FAN-EXHAUST-NOISE SUPPRESSOR ENCLOSURE INSTALLED

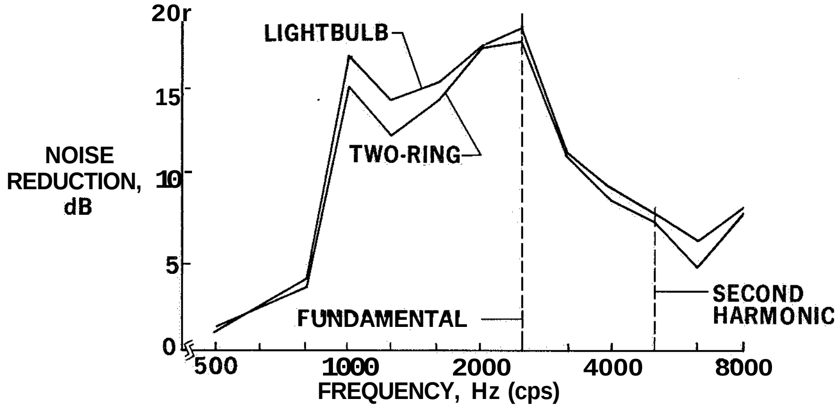

Figure 13

NOISE REDUCTION WITH TREATED INLETS

DATA AT 60° AND 150-FT RADIUS; TAKE-OFF POWER;
FAN-EXHAUST-NOISE SUPPRESSOR ENCLOSURE INSTALLED

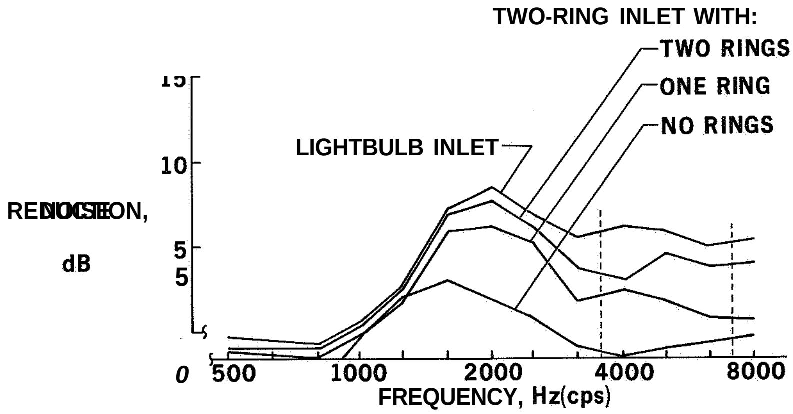

Figure 14

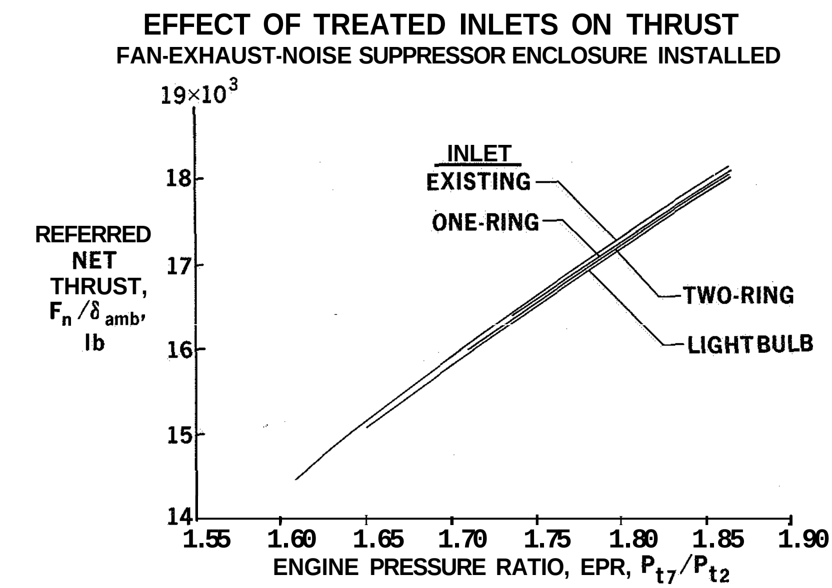

Figure 15

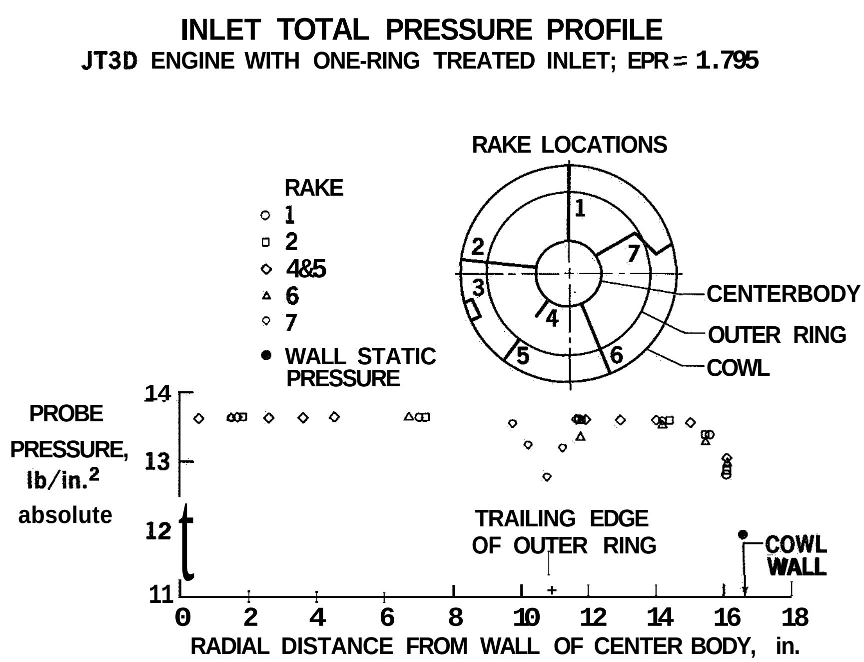

Figure 16

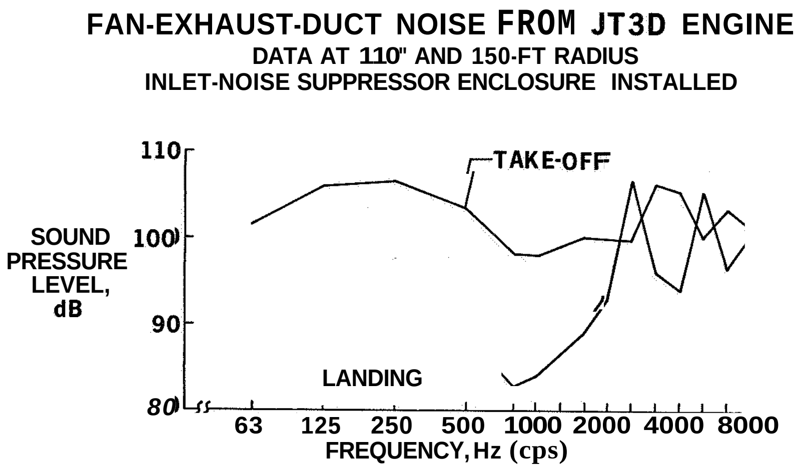

Figure 17

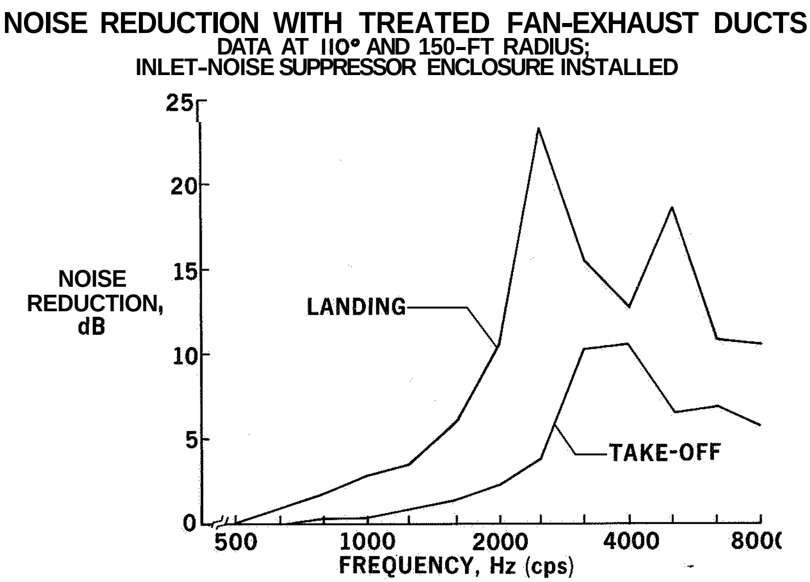

Figure 18

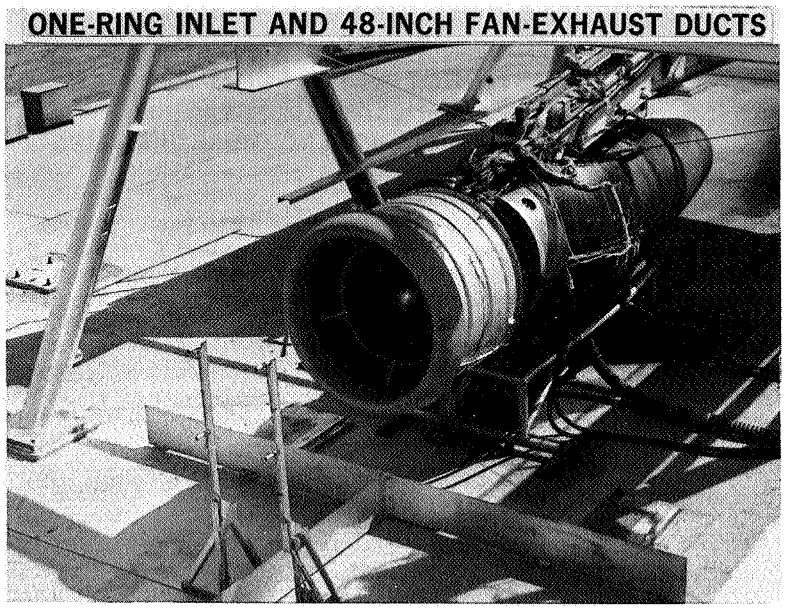

Figure 19 L-68-8560

NOISE LEVELS WITH JT3D NACELLES

DATA AT 110° AND 150-FT RADIUS LANDING POWER

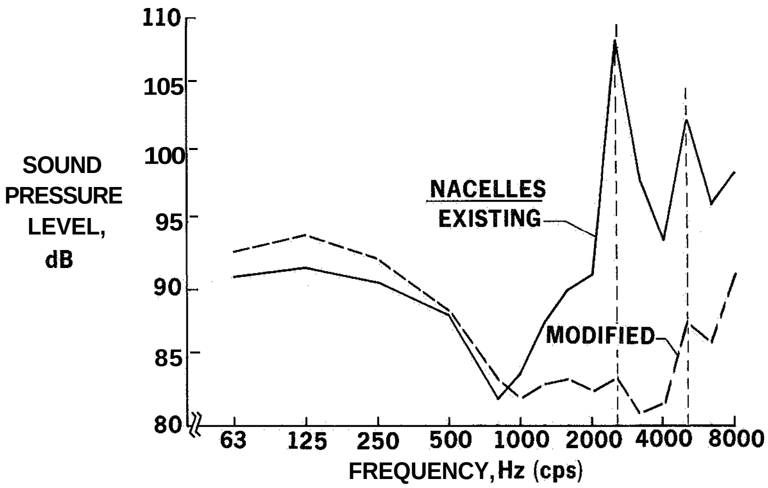

Figure 20

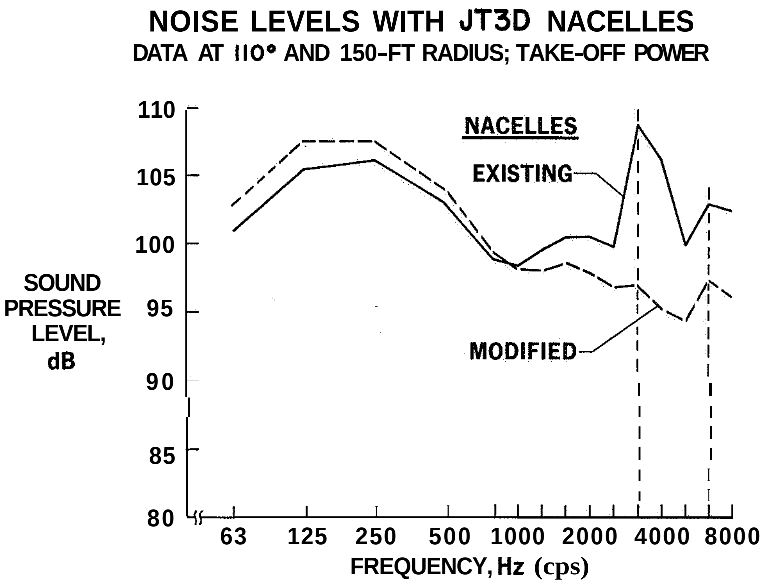

Figure 21

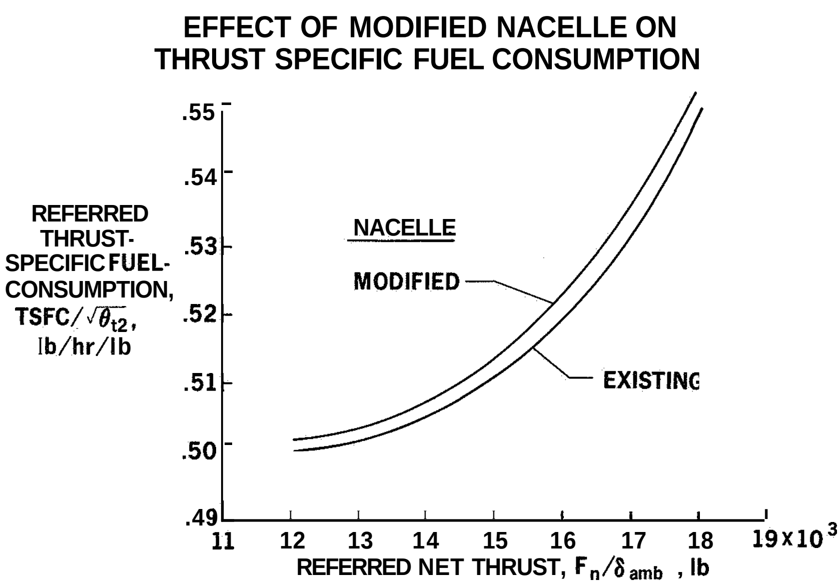

Figure 22

EFFECT OF MODIFIED NACELLE ON THRUST

NO SUPPRESSOR ENCLOSURES AROUND ENGINE

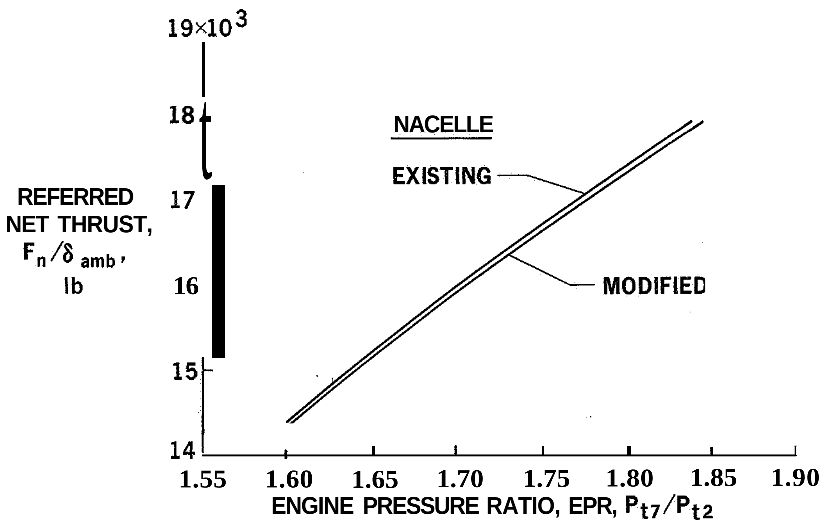

Figure 23