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Quiet, Clean, Short-Haul, Experimental Engine (QCSEE)

Over-the-Wing (OTW) Engine Acoustic Design

June, 1978

by

H.D. Sowers and W.E. Coward

GENERAL ELECTRIC ...

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SECTION I

SUMMARY

An acoustic design has been defined for the QCSEE over-the-wing engine intended to enable a four-engine STOL aircraft to meet a noise goal of 95 EPNdB on a 152.4 m (500 ft) sideline. The predicted acoustic performance will be evaluated by ground static demonstration tests of the fully suppressed engine. The design incorporates fan source noise reduction features such as low fan tip speed, low fan pressure ratio, high bypass ratio, large rotor to outlet guide vane (OGV) spacing, and acoustic wall treatment between the rotor and OGV. Fan inlet noise suppression is obtained with a 0.79 throat Mach number inlet and wall treatment. Fan exhaust noise suppression is provided by treated exhaust duct walls and a 1-meter (40-inch) treated splitter. Core noise suppression is obtained by using a stacked treatment concept with thick, low-frequency combustion noise treatment underneath and integral with thin, high-frequency turbine treatment panels. The predicted noise levels and suppression estimates were obtained from various engine and scale model tests, many of which were in support of the QCSEE program.

SECTION II

INTRODUCTION

The Quiet, Clean, Short-Haul Experimental Engine (QCSEE) program has as its overall objective the development of the propulsion technology required for future aircraft incorporating powered lift wing/flap systems. The program includes the development of two separate systems, one an under-the-wing (UTW) configuration, and the other an over-the-wing (OTW) configuration; this latter system is the subject of this report. The acoustic goal of the program is to ensure that both configurations will meet the the total system noise requirements of 95 EPNdB on approach and takeoff, and 100 PNdB for reverse thrust, all on a 152.4 m (500 ft) sideline. The total system level includes both engine noise and jet/flap interaction noise associated with powered lift systems.

The basic OTW engine has been designed for low noise, incorporating a low tip speed, low pressure ratio fan, and a large rotor-OGV spacing. These features provide low source noise levels which are then reduced further with an acoustically treated nacelle to reach the noise goal.

The acoustic design of an engine system which will efficiently meet the noise requirements outlined for the QCSEE OTW engine requires, however, not only that the engine source noise levels be as low as possible, but also that advanced technology acoustic suppression concepts be applied. This requires that detailed predictions be made for all the possible engine noise sources, that accurate suppression estimates be made, and that careful attention be given to the methods used to obtain the in-flight total system. noise estimates from the static data predictions.

Existing component noise source predictions, based on data correlation from previous engine test experience, were used to arrive at the original unsuppressed engine noise estimates. Preliminary acoustic treatment designs, again based on past engine and laboratory duct tests, were defined for the purposes of total system noise optimization studies.

A series of scale model component noise test programs was concurrently run to study source noise and treatment effects, and laboratory duct tests of advanced treatment concepts were conducted. The results of these tests were employed to refine the system noise predictions and the treatment design procedures.

The first planned QCSEE propulsion system test was the UTW engine (Reference 1) with an acoustically treated boilerplate nacelle that had been designed on the basis of predicted spectra and component test data. The UTW boilerplace nacelle and the OTW nacelle are common in configuration, with the exception of the exhaust nozzle, and it was intended to use the removable acoustic treatment panels from the UTW nacelle on the OTW nacelle, with whatever modifications necessary to tune the treatment to improve the acoustic performance.

The results obtained from these first UTW acoustic tests would be used to determine the performance of the individual elements of the acoustic suppression in the actual engine environment. This information would then be employed to further refine the suppression estimates, and to arrive at the final design for the OTW treated boilerplate nacelle.

An engine failure occurred during the UTW boilerplate nacelle testing before acoustic data could be obtained. This prevented the use of actual engine data to tune the OTW treatment prior to selecting the final configuration. Without additional input, it was decided to use the same boilerplate nacelle treatment as had been used on the UTW engine.

The procedures employed in making all the preliminary estimates, conducting component development tests, and integrating them into a final OTW engine acoustic design are the subject of this report. This report is intended to give an "overview" of the entire OTW engine acoustic design process. Detailed information regarding specific component test programs, treatment development programs, and engine tests is covered in specific individual reports which are referenced throughout.

SECTION III

DESIGN GOALS

A. NOISE REQUIREMENTS

The noise requirements for the OTW engine are specified as a total system noise level (including jet/flap interaction noise) at the operating conditions associated with the takeoff and approach. A reverse thrust noise requirement is also specified for static aircraft conditions. These requirements are schematically outlined on Figure 1.

The takeoff system noise requirement is 95 EPNdB on a 152.4 m (500 ft) sideline with the engines at 100.085 kN (22,500 lb) of thrust. The approach system noise requirement is identical, with the exception that engine thrust is only 65% of takeoff. Table I is a summary of the other pertinent parameters defined for takeoff and approach. Included are such items as inlet angle of attack and upwash angles, which affect the fan inlet noise generation and high Mach inlet suppression, and blown flap angles, which affect the jet/flap noise generation. The takeoff flight path is defined as climbout at a constant angle of 0.218 rad (12.5°), with no power cutback; approach is at a constant angle of 0.105 rad (6°), again at a constant power setting. For preliminary design purposes, the aircraft altitude for which the sideline EPNL reaches the peak was assumed to be 61.0 m (200 ft). This assumption would be revised when engine data at all acoustic angles became available, thus allowing more sophisticated extrapolations to be employed.

The reverse thrust system sideline noise requirement is 100 PNdB at 35% reverse thrust, with the aircraft static. For the OTW engine, reverse thrust is obtained by actuating the upper surface of the forward thrust D-nozzle to form a block in the exhaust flow stream and deflecting the flow forward.

B. IN-FLIGHT EXTRAPOLATIONS AND CORRECTIONS PROCEDURES

The takeoff and approach contract noise goals are defined for in-flight conditions including jet/flap interaction noise. However, the demonstrated engine noise levels are to be measured during static testing with the engine alone (no wing/flap system). Arriving at the final demonstrated in-flight system noise levels therefore requires a lengthy extrapolation procedure. This procedure must be as accurate as possible. Accordingly, a detailed method has been established as part of the contract and defined in Appendix I to the Statement of Work (Reference 2, Vol. II, Appendix A). Appendix I establishes the following:

1. Jet/flap noise prediction procedures

2. Extrapolation procedures

    a) Inverse square law

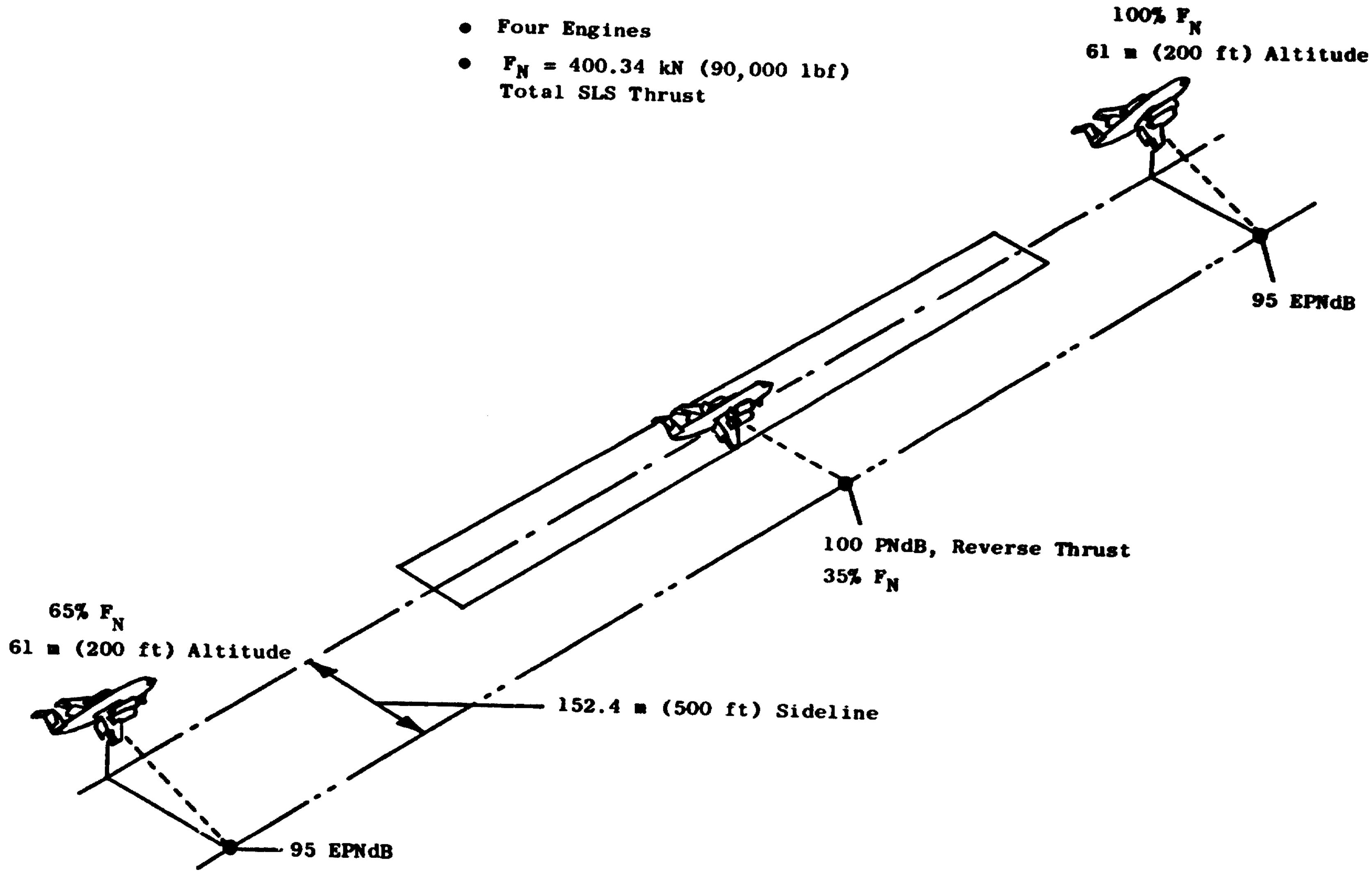

Figure 1. Acoustic Requirements.

Table I. Engine and Aircraft Flight Characteristics for Acoustic Calculations.

Flight Conditions	Takeoff	Landing
Aircraft speed, m/sec (knots)	41.15 (80)	41.15 (80)
Flap angle, radians (degrees)	0.514 (30)	1.047 (60)
Aircraft climb or glide angle, radians (degrees)	0.218 (12.5)	0.105 (6)
Angle of attack, radians (degrees)	0.105 (6)	0.035 (2)
Upwash angle, radians (degrees)	0.262 (15)	0.192 (11)
Installed net thrust, percent	100	65

b) Atmospheric attenuation
c) Extra ground attenuation

3. Static-to-flight corrections

    a) Doppler shift
    b) Dynamic effect
    c) In-flight cleanup and upwash angle correction
    d) Relative velocity effects on jet/flap noise
    e) Effect of soft ground

4. Acoustic shielding effects of aircraft structure (fuselage and wings)

5. Calculation of system EPNL

    a) Correction for number of engines
    b) Correction for engine-installed thrust
    c) Summation of component PNL's
    d) Calculation of EPNL from summed PNL's

This procedure has been employed for all noise estimates during the design of the OTW engine.

SECTION IV

BASIC ENGINE DESIGN

A. LOW SOURCE NOISE DESIGN FEATURES

Many features of the QCSEE OTW engine design have been selected based on the low system noise requirements for a 100.085-kilonewton (22,500-lb) thrust engine installed in an over-the-wing configuration. Figure 2, taken from Appendix I of the contract, is a sketch of the baseline wing/engine installation (inboard location) with the flap system at takeoff setting. The two major noise sources considered were the fan noise and the jet/flap noise.

Forward radiated fan noise has been shown to be primarily a function of fan tip speed. Previously published noise correlations (Volume I of Reference 2) have indicated that fan noise in the inlet quadrant can be reduced with lower tip speed, and further, that tip speeds lower than 366 m/sec (1200 ft/sec) avoid the increased noise levels due to multiple pure tones associated with supersonic tip speed fans. The lowest tip speed, 350 m/sec (1150 ft/sec) consistent with the other engine cycle requirements was therefore selected.

Aft radiated fan noise levels have been correlated primarily with fan pressure ratio (see Volume I of Reference 2). In addition to controlling aft fan noise, the fan pressure ratio also determines the fan jet velocity. Since the predicted jet/flap noise is directly proportional to the exhaust velocity to the sixth power, low fan pressure ratios result in greatly reduced aft system noise levels. Aft-generated fan noise can be suppressed with acoustic treatment, so the fan pressure ratio was selected primarily in order to achieve low jet/flap noise levels. The very nature of the over-the-wing installation of this engine provides an inherent shielding of the aft fan noise and partial shielding of the jet/flap noise by the wing; consequently, the selected fan pressure ratio was slightly higher than that acceptable for the UTW design.

In order to maintain a degree of commonality between the UTW and OTW systems, the engines share the same composite fan frame design. The frame vane number and spacing between vane and rotor were selected for the UTW fan. The vane-blade number ratio for the UTW engine was selected at a value of 1.83, in order to minimize the generation of the second harmonic tone noise. Using the CTW rotor with this frame results in a vane-blade ratio of 1.18 due to a larger number of rotor blades. This results in higher source noise generation, but is offset by the fact that the increased blade number also gives shorter-chord blades. Thus the rotor-OGV spacing is increased from 1.5 rotor chords to 1.93 rotor chords. This spacing increase results in a corresponding decrease in source noise generation. (The spacing in the UTW engine was not increased over 1.5 chords, since a corresponsing noise reduction could be gained by lengthening the treated exhaust splitter, without incurring the increased weight penalties inherent in lengthening the frame.)

- Inboard Engine
- Wing Chord = 5.46 m (17.9 ft)
- Dimensions Based on 93.4-kN (21,000-lb) Thrust Engine

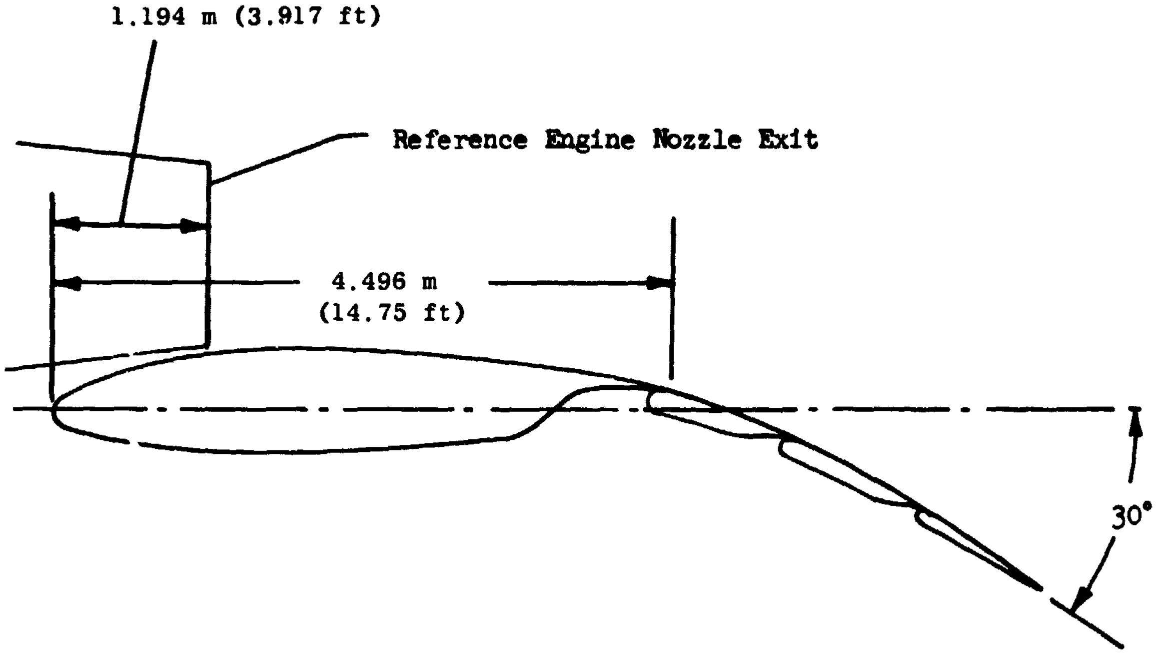

Figure 2. Propulsion System Takeoff Reference Nozzle, Wing, and Flap Location.

The use of a "high speed" core engine driving the fan through a reduction gear mechanism also provides certain acoustic benefits. The blade-passing tones of the compressor and low pressure turbine are in the very high-frequency, low-annoyance-weighted bands -- even on approach. The core engine pressure ratio selection was also made with low jet velocities as a consideration, again to aid in minimizing jet/flap noise.

Table II shows the major engine design features which impact the predicted system noise levels in the OTW system. The considerations discussed above have produced an engine which is designed to provide low source noise levels while still meeting the performance and thrust-to-weight requirements.

B. COMPONENT AND MODEL SOURCE NOISE TEST PROGRAMS

Four separate acoustic test programs were carried out to investigate noise from the various components of the QCSEE engine. Two of these were scale model fan tests, both conducted in the anechoic chamber at the General Electric Corporate Research and Development Aero/Acoustic Facility in Schenectady, New York. The first series of tests employed a 50.8-cm (20-inch) diameter, low tip speed, low pressure ratio fan supplied by NASA in an investigation of aft radiated fan noise. The second series of tests employed a variable-pitch fan (of the same diameter) that was an exact scale model of the UTW fan, in an investigation of inlet-radiated fan noise. The third test program was the measurement of combustor and turbine noise from the same core engine to be employed to drive the QCSEE fans. The fourth program was a series of acoustic tests conducted on a scale model of the OTW "D"-shaped exhaust nozzle and target thrust reverser. These test programs are summarized in detail in the component reports, but a brief outline of some of the results, in relation to the full-scale engine acoustic design, is given here.

Aft Fan Noise Test

This test, References 3 and 4, was conducted in two stages; the first was devoted to the study of fan source noise changes due to variations in the fan frame configuration, and the second consisted of an extensive study of fan exhaust duct acoustic treatment design. The source noise testing employed a series of variations in rotor-OGV spacing, vane-blade ratio, and low-flow Mach number vane passages. The most important result from the source noise tests was the substantiation of the benefits obtainable with the proper selection of spacing and vane-blade ratio. Boilerplate nacelle treatment designs were selected on the basis of results from the treatment tests. Further detail is provided in Section V-A.

Inlet Fan Noise Test

As in the case of the aft noise tests, this program (Reference 5) was an investigation of both source noise generation and acoustic suppression effects. The fan, as has been pointed out, was a scale model of the UTW fan; the source

Table II. Acoustic Design Parameters.

- 41.2 m/sec (80 knots) Aircraft Speed
- 61 m (200 ft) Altitude
- Takeoff conditions

Number of Fan Blades	28
Fan Diameter	180.4 cm (71 in.)
Fan Pressure Ratio	1.34
Fan rpm	3738
Fan Tip Speed	350.5 m/sec (1150 ft/sec)
Number of OGV's	33 (32 + pylon)
Fan Weight Flow (Corrected)	405.5 kg/sec (894 lb/sec)
Inlet Mach Number (Throat)	0.79
Rotor-OGV Spacing	1.93 Rotor Tip Chords
Inlet Treatment Length/Fan Diameter	0.74
Exhaust Area	1.802 m^2 (2794 $in.^2$)
Gross Thrust SLS (Uninstalled)	93.4 kN (21,000 lb)
Blade Passing Frequency (Fan)	1744 Hz
Vane-Blade Ratio	1.179
Core Exhaust Flow	35.7 kg/sec (78.6 lb/sec)
Core Exhaust Velocity (Unmixed)	328 m/sec (1077 ft/sec)
Fan Exhaust Velocity (Unmixed)	219 m/sec (720 ft/sec)
Engine Exhaust Velocity (Mixed)	231 m/sec (757 ft/sec)
Bypass Ratio	10.3

noise results were thus of limited utility in defining absolute OTW noise levels. However, they were beneficial in providing confirmation of the noise prediction procedure. Results from the acoustic suppression tests were used in selection of treatment designs for the full-scale OTW boilerplate nacelle inlet. These suppression studies are further detailed in Section V-A.

Core Engine Noise Tests

Noise measurements were taken on a turbofan engine, Reference 6, which uses the same core employed on the QCSEE propulsion systems. Both near-field and far-field noise measurements were taken to determine the core internally generated noise levels. The resulting noise measurements were compared to predicted combustor and turbine noise levels, to check the applicability of these prediction procedures to the QCSEE propulsion systems. The results were somewhat qualitative, due to the difficulties inherent in attempting to extract the low core noise levels from a total noise signature that was dominated by other sources. In general, however, the results indicated that the combustor and turbine noise prediction procedures employed for the QCSEE system were acceptable for defining the levels of suppression required for the core.

Jet and Thrust Reverser Noise Tests

A scale model of the OTW "D"-shaped exhaust nozzle was run on a jet noise test facility, Reference 7; both the forward thrust and the reverse thrust configuration (with the thrust reverser deployed) were tested at the appropriate cycle conditions. Parametric variations of the thrust reverser geometry were employed to determine the quietest configuration consistent with performance requirements. The scaled-up data from this program were used to estimate jet noise in the reverse thrust mode. Forward thrust data were used to evaluate jet noise during static engine testing.

C. UNSUPPRESSED SYSTEM NOISE LEVEL PREDICTIONS

To obtain the predicted system noise levels, detailed predictions were made for each of several different sources.

Fan Inlet and Exhaust

Predictions were made by scaling measured acoustic data from full-scale fans and adjusting for weight flow, pressure ratio, and tip speed (Reference 2).

Low Pressure Turbine and Combustor

These predicted levels were obtained by the use of semiempirical prediction procedures developed by General Electric under separate contracts (Reference 8); as was indicated in Section IV-B, the applicability of these predictions was checked against measured data from a QCSEE-type core engine.

Jet/Flap

The jet/flap noise prediction procedure established in Appendix I to the Statement of Work (Reference 2, Vol. II, Appendix A) was developed by NASA through the use of semiempirical correlations with scale model and full-scale blown flap test data. The cycle mixed flow velocity was used to make the noise estimates in order to be consistent with the data correlations from the tests. In actuality, the mixer is designed to provide 17% mixing.

Jet Noise in Reverse Thrust

As already indicated, the exhaust noise levels incurred with the operation of the target thrust reverser were estimated from the scaled-up data from the model tests.

Core Compressor and Reduction Gearing

These sources were estimated from empirical data correlations; they were found to be extremely low in level and, hence, were not contributing to the total system noise.

Possible "Floors" for Suppressed Noise

These items included noise generated by the flow over the internally treated surfaces, and around the struts and fan exhaust splitter. One of the design constraints applied to the engine was that the fan exhaust duct Mach numbers be kept between 0.45 and 0.50. These low Mach numbers result in very low "flow noise" levels; thus flow noise does not contribute to suppressed systems noise. The results of flow noise studies are reported in References 3 and 4.

System and Component Noise Spectra

The resulting predicted unsuppressed major component noise levels on a 61 m (200 ft) sideline, at the maximum forward and maximum aft angles, are given in Table III for takeoff, approach, and reverse thrust conditions.

Figures 3 through 8 are presentations of these same predicted unsuppressed component noise sources, on a spectral basis. In these cases the spectra are presented at the appropriate noise measurement points defined in Section III. The corrections have been made for Doppler shift and dynamic effect (where applicable), but the other in-flight corrections defined in Appendix I to the Statement of Work have not been applied. In this extrapolation procedure, all corrections from this point on (excepting acoustic suppression) are made on the basis of ΔPNdB, not on a modification of spectral shape. In forward thrust, it is readily apparent that fan noise is the dominant high-frequency source, while jet/flap and combustor noise control in the lower frequencies. In reverse thrust operation, the jet noise dominates at all but the highest frequencies.

Table III. Unsuppressed Engine Component Noise Levels.

- 61 m (200 ft) Sideline
- Single Engine, Static
- Peak Noise Angle for Total System

	Maximum Forward Angle* PNdB				Jet or
	Fan		Turbine	Combustor	Jet/Flap
Takeoff Power	114.9		97.9	94.9	100.9
Approach Power (65% of Takeoff Thrust)	107.5		91.8	90.5	95.5
	Inlet	Exh.			
Reverse Thrust (35% of Takeoff Thrust)	112.5	111.3	96.6	95.7	110.8

	Maximum Aft Angle* PNdB				Jet or
	Fan		Turbine	Combustor	Jet/Flap
Takeoff Power	115.9		100.6	100.2	98.4
Approach Power	110.7		99.1	95.9	92.0
	Inlet	Exh.			
Reverse Thrust	105.0	107.5	90.4	95.9	108.1

*Maximum Forward Angle (for Total System Noise) Is 90° from Inlet on Takeoff and Approach, and 80° on Reverse Thrust. Maximum Aft Angle Is 120° for All Cases.

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- 90° Acoustic Angle
- 152.4 m (500 ft) Sideline
  at 61 m (200 ft) Altitude
- Single Engine (Through Step 4.4, Appendix I)
- 41.2 m/sec (80 knots) Aircraft Speed

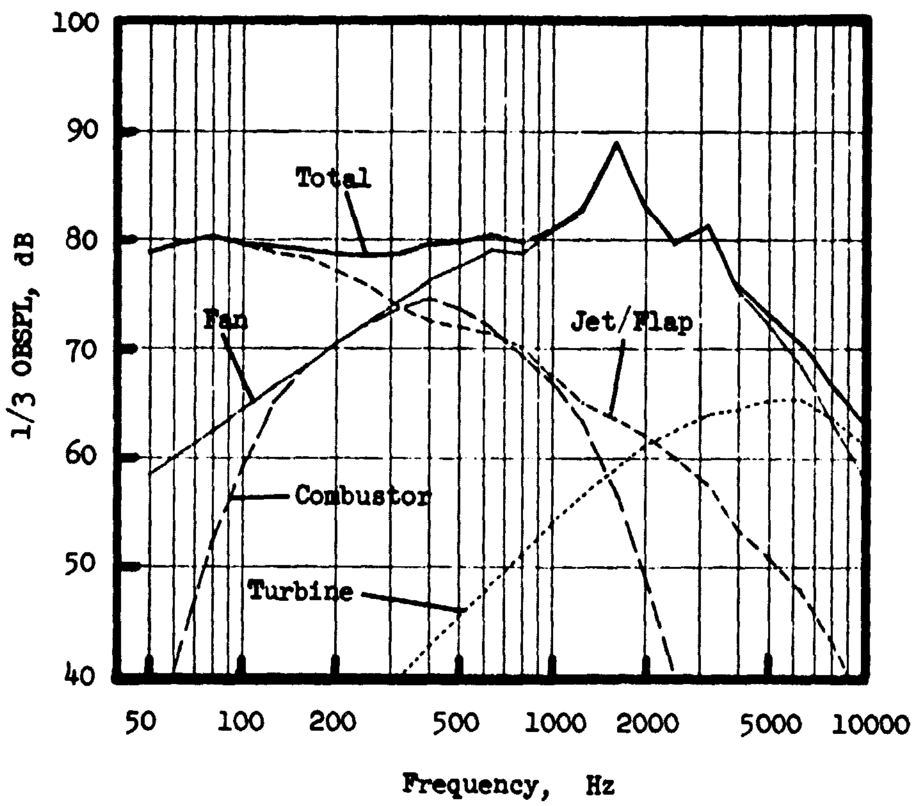

Figure 3. Takeoff Unsuppressed Spectra at 90° Acoustic Angle.

- 120° Acoustic Angle
- 152.4 m (500 ft) Sideline
  at 61 m (200 ft) Altitude
- Single Engine (Through Step 4.4, Appendix I)
- 41.2 m/sec (80 knots) Aircraft Speed

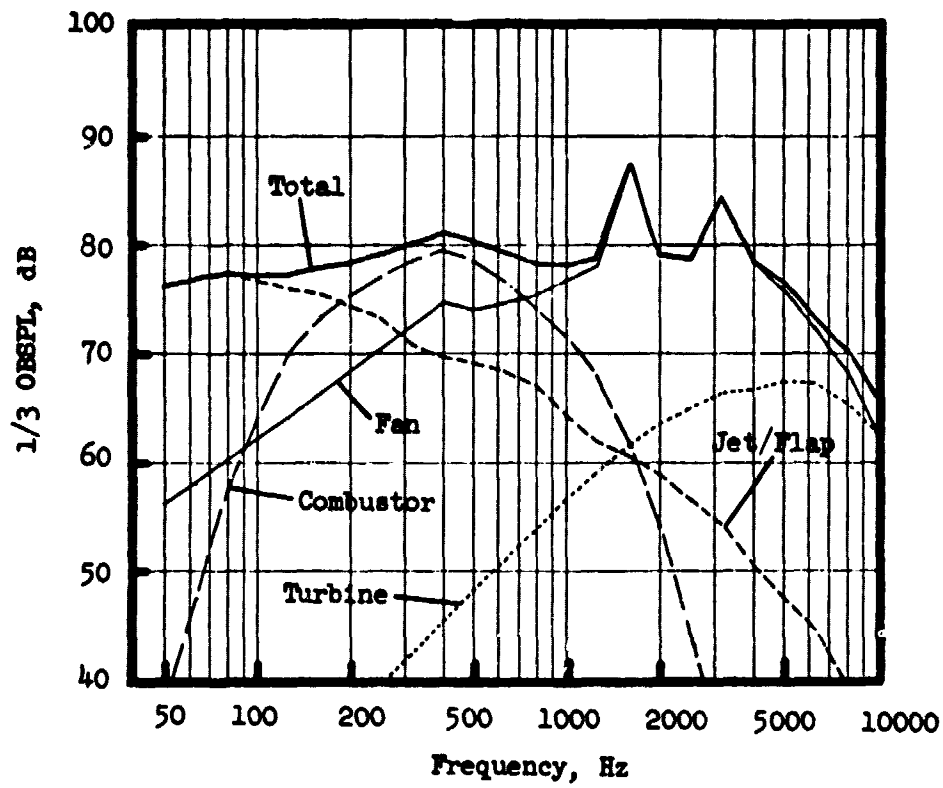

Figure 4. Takeoff Unsuppressed Spectra at 120° Acoustic Angle.

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- 90° Acoustic Angle
- 152.4 m (500 ft) Sideline
  at 61 m (200 ft) Altitude
- Single Engine (Through Step 4.4, Appendix I)
- 41.2 m/sec (80 knots) Aircraft Speed
- 65% of Takeoff Thrust

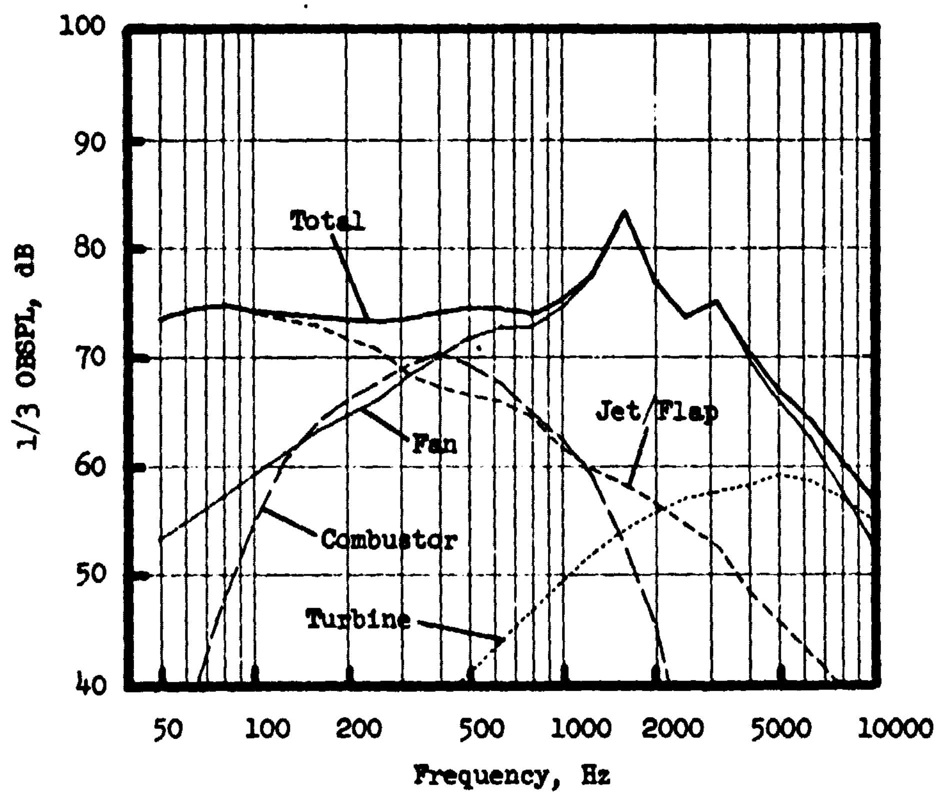

Figure 5. Approach Unsuppressed Spectra at 90° Acoustic Angle.

- 120° Acoustic Angle
- 152.4 m (500 ft) Sideline
  at 61 m (200 ft) Altitude
- Single Engine (Through Step 4.4, Appendix I)
- 41.2 m/sec (80 knots) Aircraft Speed
- 65% of Takeoff Thrust

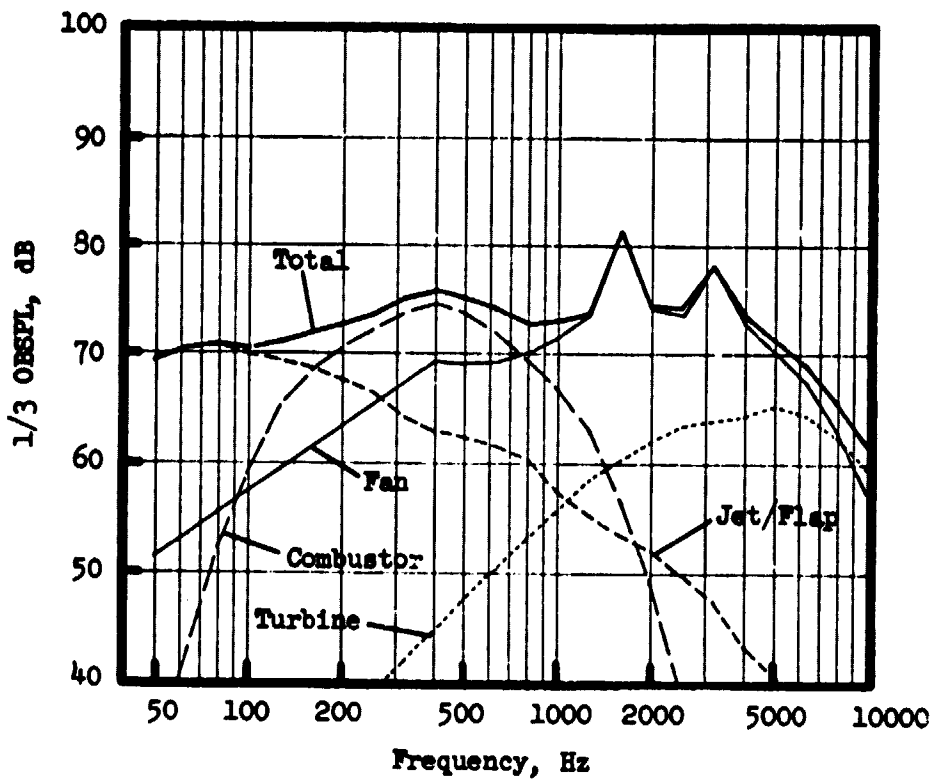

Figure 6. Approach Unsuppressed Spectra at 120° Acoustic Angle.

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- 80° Acoustic Angle
- 152.4 m (500 ft) Sideline
- Single Engine (Through Step 6.3, Appendix I)
- 35% of SLS Takeoff Thrust

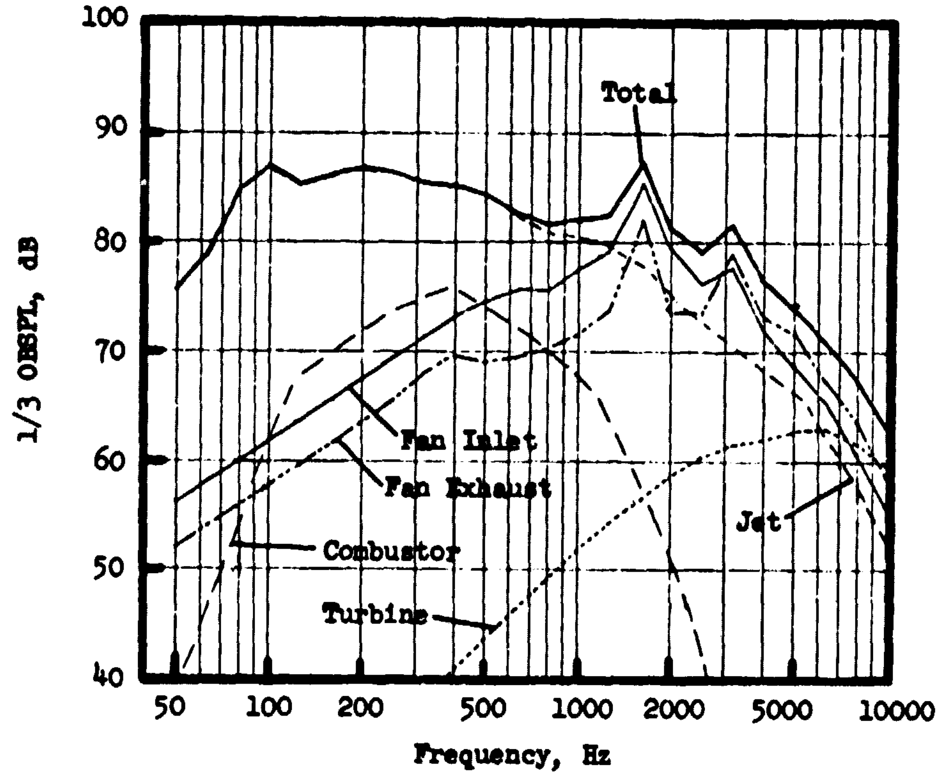

Figure 7. Reverse Thrust Unsuppressed Spectra at 80° Acoustic Angle.

- 120° Acoustic Angle
- 152.4 m (500 ft) Sideline
- Single Engine (Through Step 6.3, Appendix I)
- 35% of SLS Takeoff Thrust

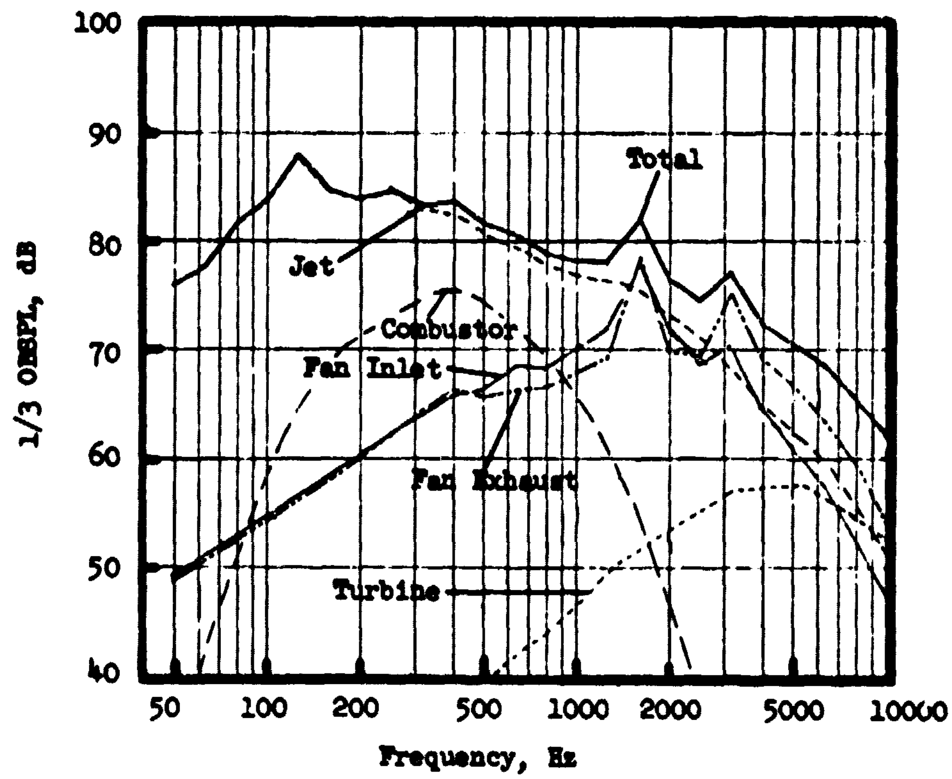

Figure 8. Reverse Thrust Unsuppressed Spectra at 120° Acoustic Angle.

SECTION V

NACELLE ACOUSTIC TREATMENT DESIGN

A. TREATMENT DESIGN AND DEVELOPMENT SUMMARY

The required component acoustic suppression levels were determined by evaluating the unsuppressed engine component noise levels, jet/flap noise, and the suppressed system noise goals. The treatment configurations employed in the OTW nacelle were designed to meet these component suppression requirements. The design and development work for the treatment was based on testing conducted during the previously referenced inlet and fan exhaust scale model tests, as well as laboratory duct tests and experience from other General Electric treatment development programs. The details of this treatment design procedure are given in Reference 9; it is, however, worthwhile to briefly summarize the methodology employed:

Fan Exhaust Duct

The acoustic treatment designs for the OTW boilerplate fan exhaust were based on the results of the scale model aft fan noise test program (Rotor 55, References 3 and 4), plus previous GE experience in laboratory duct testing, scale model fan tests, and full-scale engine tests. The results from the Rotor 55 scale model acoustic suppression tests yielded the following conclusions:

- Variable-depth treatment gives a wider suppression bandwidth, with less peak suppression, relative to constant-depth treatment. The suppression level at high frequencies is greater than would be expected for variable depth treatment with each section functioning independently.

- A faceplate porosity of 12% gave more suppression than 27% porosity, for both constant- and variable-depth configurations of the QCSEE models tested.

- Varying faceplate porosity with variable-depth treatment gave improved suppression, relative to variable depth with constant porosity.

- The losses in suppression due to blockages of the treated surface were much lower than the predicted loss based on linear extrapolation. The actual loss is only [illegible]5% to 50% of that predicted.

- The suppression levels achieved are independent of treatment orientation (i.e., treatment depth can either increase or decrease in the direction of flow).

- Treatment in the fan frame, between the rotor and OGV's is effective in reducing both tone and broadband without additional treatment in the fan exhaust. This effectiveness is still apparent (in ΔPNdB) even with a large amount of aft duct treatment.

These conclusions were used to develop a design procedure for the OTW fan exhaust treatment, as follows:

- Compare the measured Rotor 55 suppression results to the predicted suppressions made using the existing procedures (based on engine data).
- From the above comparisons, determine the adjustments to the existing engine data correlation (these adjustments included increases to the predicted high-frequency suppression, and reductions in the penalty imposed for treatment area blockage).
- Using the adjusted design procedure from above, design a treated duct that is optimized to give the most effective suppression in regard to the unsuppressed fan exhaust noise spectrum.
- Optimize the faceplate porosity for each treated panel of the above design, using a correlation of optimum porosity with the ratios of duct height to design frequency wave length (H/λ) developed from laboratory duct test data.

Figure 9 shows how the previous suppression prediction procedure fitted the measured Rotor 55 data and the closer fit achieved with the adjusted procedure. Figure 10 is a presentation of the predicted unsuppressed OTW fan exhaust noise spectrum shown both with and without "annoyance" weighting. The Noy-weighted spectrum shows the frequency bands that most affect the calculation of perceived noise levels, and it was used to determine the necessary treatment tuning requirement. Figure 11 shows the duct data used to determine the optimum faceplate porosity for the fan exhaust duct panels. Finally, Figure 12 is a typical example of the additional suppression due to rotor-OGV treatment that was measured on Rotor 55. These data were used to estimate the benefits of rotor-OGV treatment in the QCSEE fan frame.

Fan Inlet Duct

In order to provide the required suppression with a conventional treated inlet, the preliminary design studies indicated that the use of prohibitive inlet lengths, or of treated inlet splitters, was necessary. It was determined that with wall treatment only, the treated-length-to-fan-diameter ratio (L_T/D_F) would have to be much greater than 1.0. Previous tests had shown that large inlet suppressions were available from high throat Mach number effects; it was therefore decided that the best design approach would be to use an inlet with a throat Mach number of 0.79, with treated walls. This would provide the suppression at takeoff (high air flow) with both high throat Mach number and treatment while at approach the wall treatment alone would provide suppression. This "hybrid" inlet design approach allowed the use of a much shorter inlet ($L_T/D_F = 0.74$), without the need for splitters. The item of fundamental importance in the scale model inlet test program (UTW simulator, Reference 5) was, thus, to prove that such an inlet would provide the needed suppression. The design of the full-scale accelerating inlets for both the OTW and UTW engines was based on the results of these tests.

- Rotor 55 Data
- 100% Corrected Fan Speed
- Max. Aft Angle

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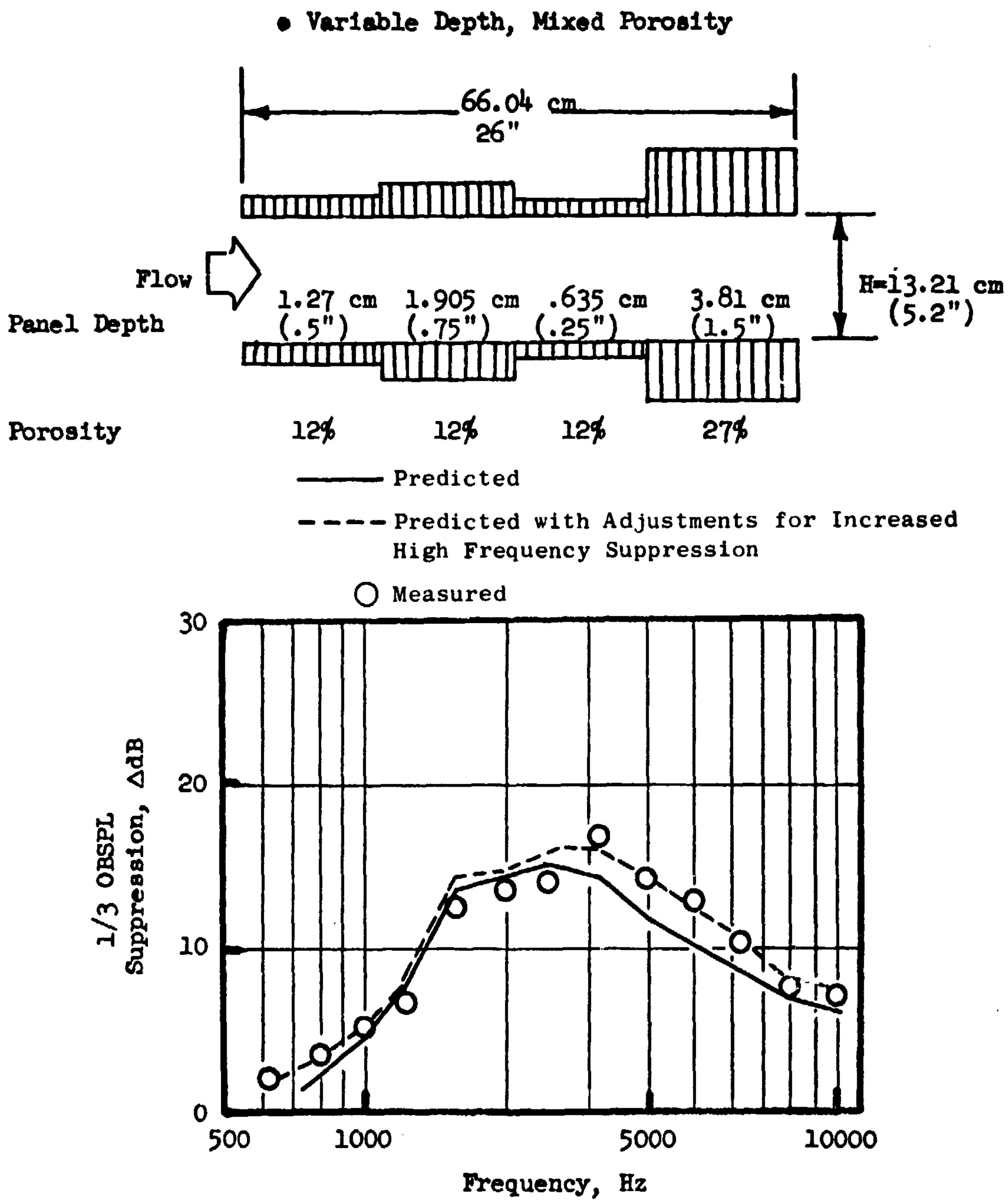

Figure 9. Scale Model Fan Exhaust Duct Predicted Vs. Measured Suppression.

- Max. Aft Angle
- 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude
- Takeoff Power

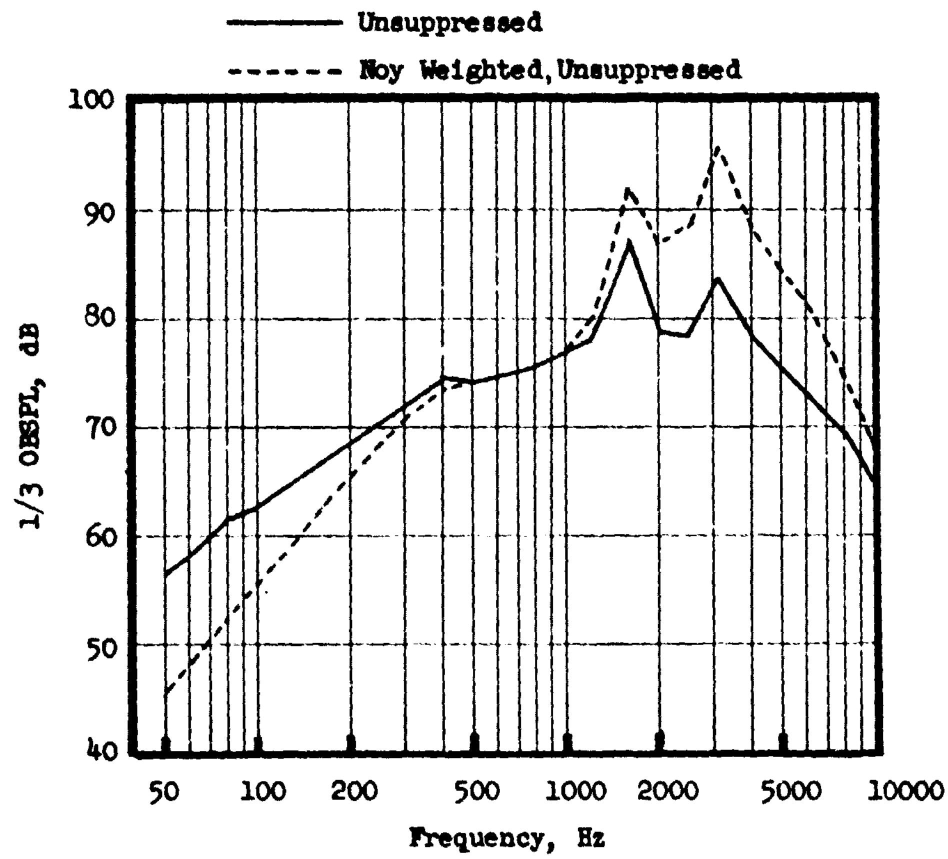

Figure 10. Unsuppressed Engine Fan Exhaust Spectra.

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- Based on Acoustic Duct Data
- Duct Mach No. = 0.4

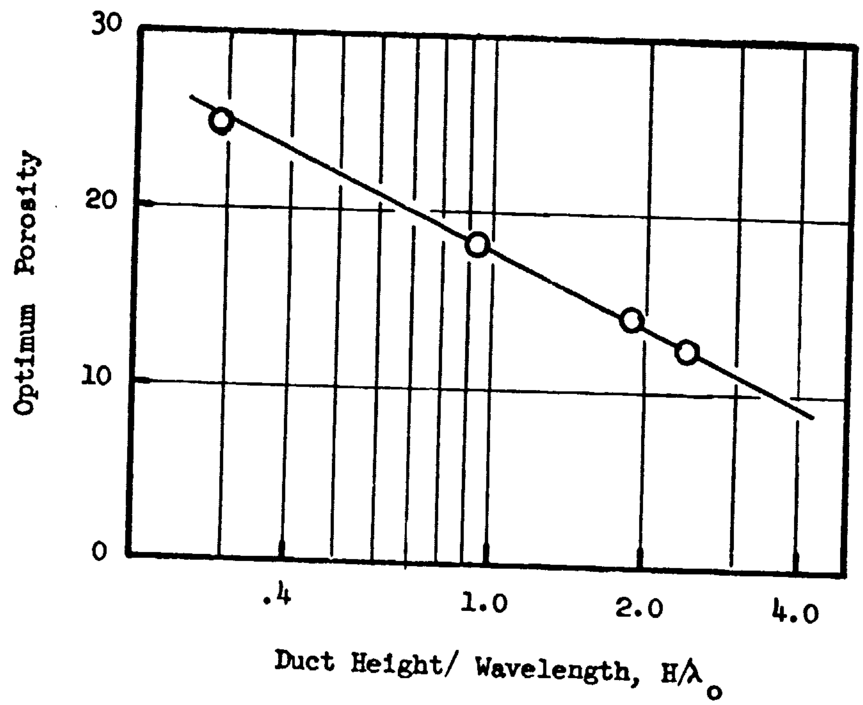

Figure 11. Optimum Porosity Vs. Duct Height/Wavelength.

* Rotor 55 Data
* 100% Corrected Fan Speed
* Max. Aft Angle

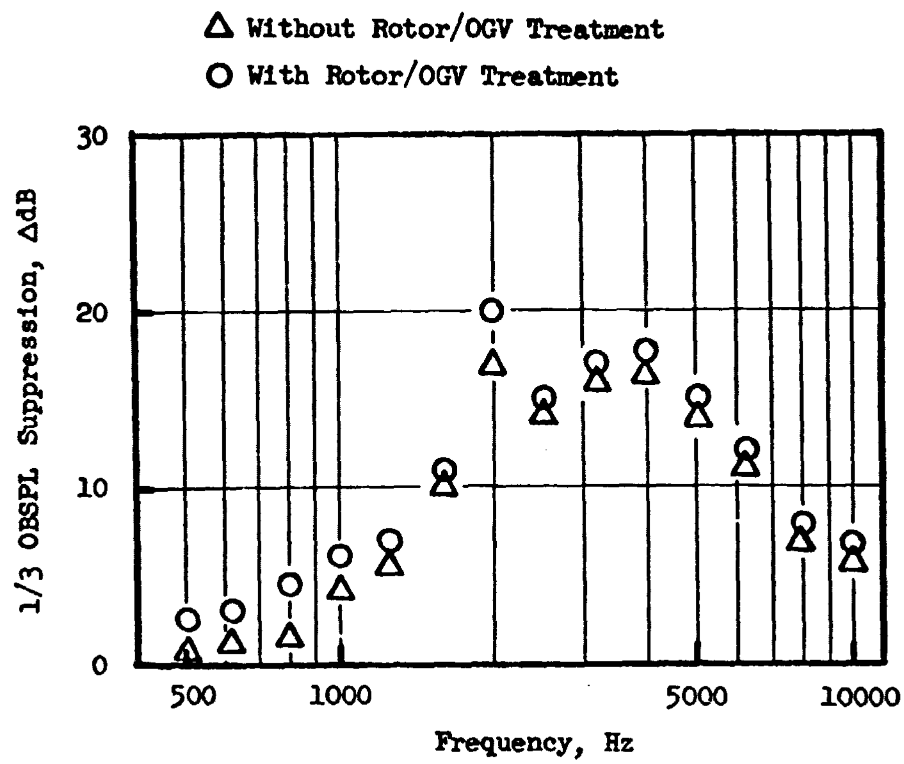

Figure 12. Scale Model Fan Exhaust Suppression with and Without Rotor/OGV Treatment.

Figure 13 shows the suppression obtained on the scale model UTW simulator for both a hardwall and treated wall high throat Mach number inlet. At low speeds (low throat Mach number) the inlet wall treatment is effective while no suppression is obtained from the hardwall inlet. At high speed, the throat Mach number suppression becomes effective (10-PNdB reduction obtained at 0.79 M_t), but the reduction due to treatment decreases. At 0.79 throat Mach number, the treatment reduction is approximately 3 PNdB. These data confirmed the hybrid inlet analysis for the UTW engine and were the basis for selecting the same design for the OTW engines.

The OTW engine has a fan tip speed at takeoff [350.5 m/sec (1150 ft/sec)] which is slightly supersonic. At this higher tip speed, the fan noise is greater than that of the UTW fan and contains multiple pure tones (MPT's) that are common to supersonic tip speed rotors. Although the test results of Figure 13 were encouraging, a means to obtain more suppression at all three operating points (takeoff, approach, and reverse thrust) was considered.

A bulk absorber wall treatment was studied as a replacement for the SDOF treatment tested on the simulator model. Experience with this type of treatment on other engine programs showed the inlet suppression to be significantly improved and MPT suppression to be increased. The design procedure used was based on methods and data from other General Electric programs. This procedure is presented in Reference 9.

Figures 14 and 15 present the Noy-weighted unsuppressed fan inlet noise spectra at takeoff and approach power. These spectra were used to select the treatment design frequencies for both conditions.

Core Exhaust Duct

The core exhaust provides a rather severe problem in acoustic suppression design. The unsuppressed source noise spectrum is composed of two parts: high frequency broadband noise from the low pressure turbine, and low frequency broadband noise from the combustor. Figure 16 shows these individual unsuppressed component spectra, along with the Noy-weighted total. It is apparent that, to obtain any meaningful noise reduction, the suppressor must attenuate both the high and low frequency noise simultaneously. Due to the relatively short length of the core duct, sufficient amounts of thick (low frequency) and thin (high frequency) treatment cannot be placed in tandem to give adequate suppression. It was decided, therefore, to adapt a new concept and employ a "stacked" treatment design. In this concept, the thin turbine treatment is placed along the duct walls and the thick combustor treatment is placed behind this turbine treatment, communicating to the duct by means of tubes passing through the turbine treatment. The resulting resonator treatment design for the combustor thus has an effectively large faceplate thickness (turbine treatment) which further results in lower frequency tuning from the available depth. Without such an approach, there is insufficient depth to obtain the required low-frequency tuning.

In order to determine the effectiveness of this design, a sample was built and tested in a laboratory high-temperature acoustic duct. Figure 17 shows a

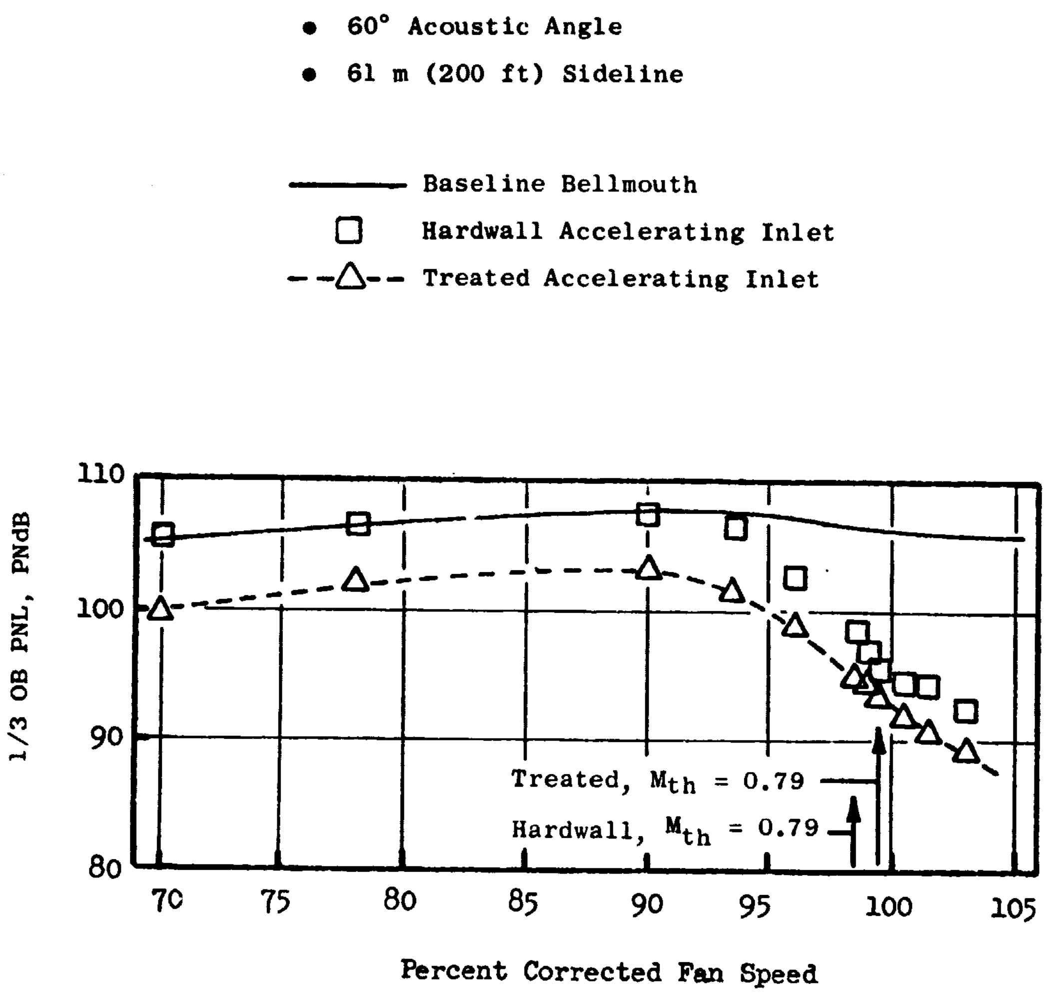

Figure 13. Treated Accelerating Inlet Suppression.

- Max. Forward Angle
- 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude
- Takeoff Power

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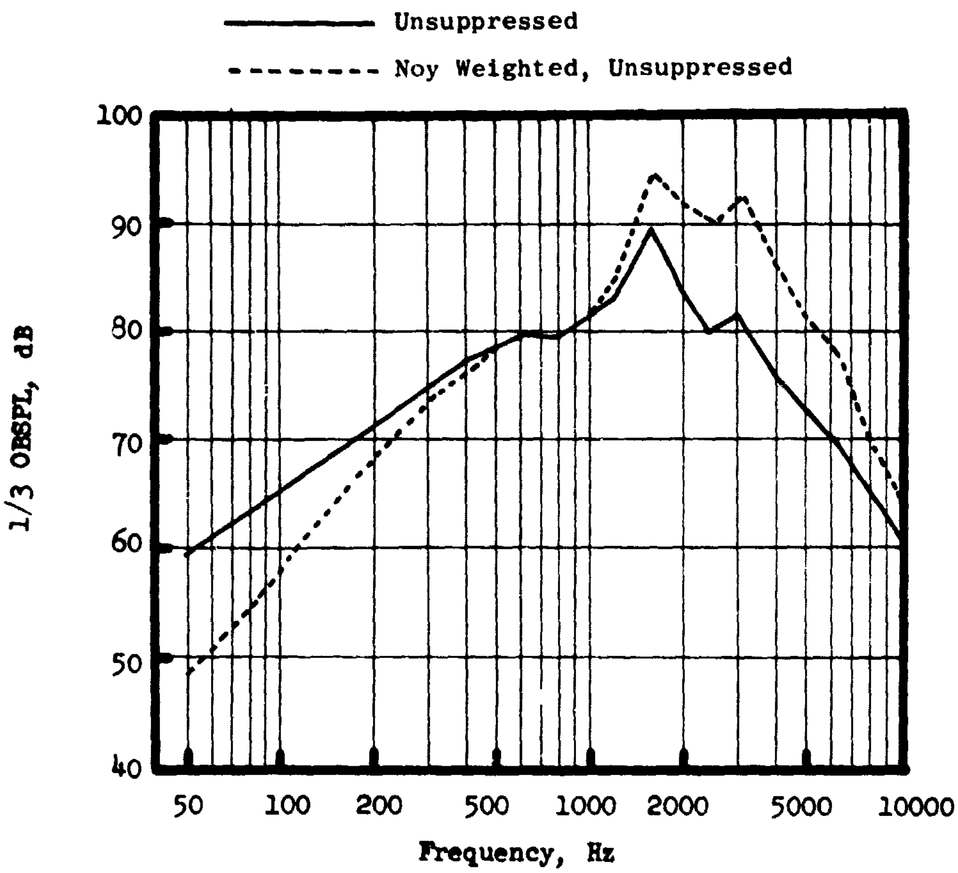


Figure 14. Unsuppressed Fan Inlet Spectra at Takeoff Power with Noy Weighting.

- Max. Aft Angle
- 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude
- Approach Power

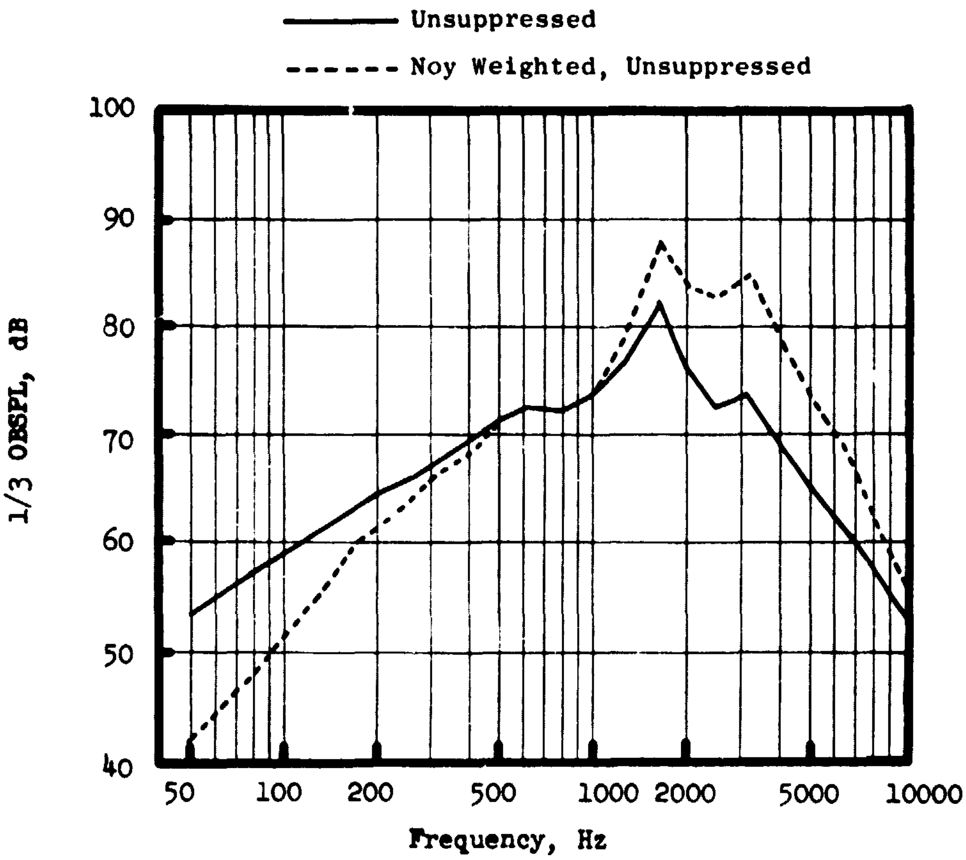


Figure 15. Unsuppressed Fan Inlet Spectra at Approach Power with Noy Weighting.

- Max. Aft Angle
- 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude
- Takeoff Power

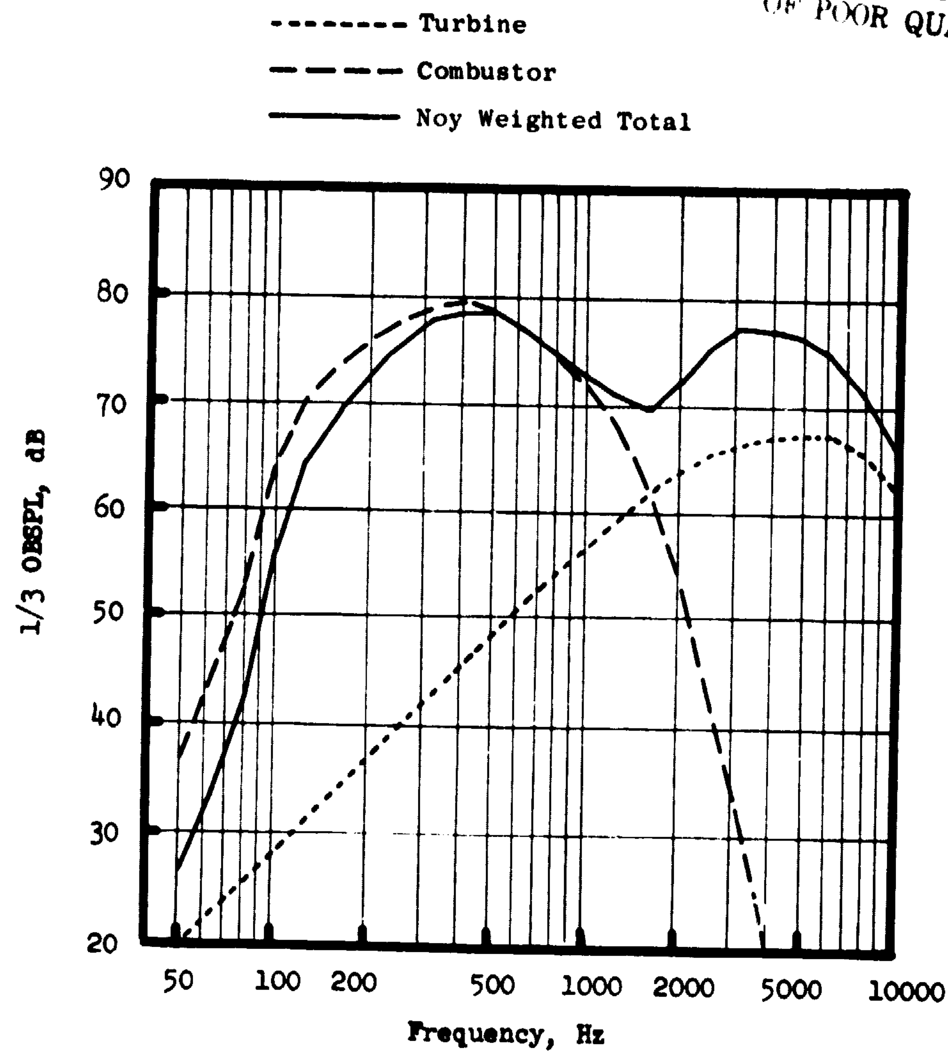
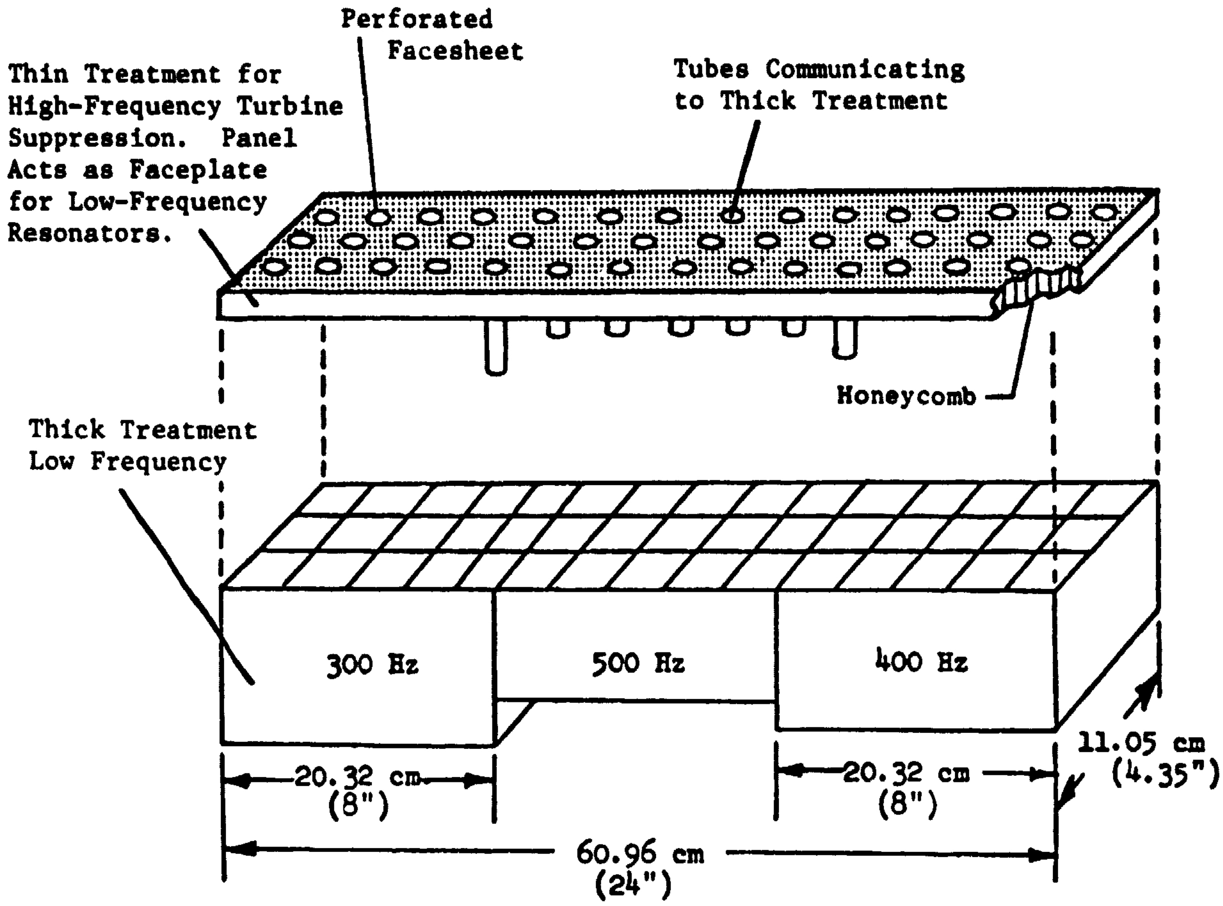


Figure 16. Unsuppressed Core Noise Spectra at Takeoff Power with Noy Weighting.



	Turbine Treatment	Combustor Treatment		
Tuning Freq., Hz	4000	300	400	500
Porosity =	22.5%	10%	10%	10%
Faceplate Thickness = or Neck Length	0.0813 cm (0.032 in.)	6.35 cm (2.5 in.)	5.08 cm (2.0 in.)	4.45 cm (1.75 in.)
Cavity Depth =	2.54 cm (1.0 in.)	1.52 cm (0.6 in.)	1.52 cm (0.6 in.)	1.52 cm (0.6 in.)
Hole Diameter =	0.1575 cm (0.062 in.)	10.16 cm (4.0 in.)	9.53 cm (3.75 in.)	7.62 cm (3.0 in.)

Figure 17. Core Treatment Laboratory Duct Test Configuration.

sketch of the test hardware. The test data indicated that the stacked treatment design would provide the required levels of suppression for both the high and low frequency regions. The design of the OTW nacelle core suppressor was developed from this test configuration. The same core hardware is also used on the UTW engine.

B. SUPPRESSED NACELLE CONFIGURATION

Figure 18 summarizes the main acoustic features of the OTW-treated nacelle. A high throat Mach number inlet (0.79 M) is used to suppress inlet noise at takeoff. Wall treatment having a length equal to 0.74 fan diameters is added to provide suppression during takeoff, approach, and reverse thrust. The fan exhaust suppression utilizes inner and outer wall treatment with varying thickness to obtain increased suppression bandwidth. As in the case of the UTW engine, a treated splitter in the fan exhaust duct is necessary to obtain the required suppression levels; however, due to the shielding effect of the wing on noise radiated from the exhaust, the OTW splitter length was evaluated at 76.2 cm (30 inches) as well as at 101.6 cm (40 inches). Acoustic treatment is also used in the fan frame passage between the rotor and outlet guide vanes, and on the pressure surfaces of the outlet guide vanes. A major concern in the aft duct is noise generated by flow over the treated surfaces, struts, and splitter. To keep these sources below the suppressed fan noise, the duct Mach number was limited to 0.47. The core exhaust suppression utilizes the aforementioned stacked treatment design to combine low- and high-frequency suppression in a relatively compact package. Treatment is also applied to the core inlet to reduce forward radiated compressor noise.

The basic boilerplate nacelle structure was designed for use with both the UTW and OTW engines. Treatment panels in the fan inlet and exhaust were made removable so that new panels could be built and installed as required to improve the treatment effectiveness. These replacement panels for the OTW engine were to be redesigned on the basis of test results from the UTW engine. Test data were not obtained with the suppressed UTW engine as discussed in Section II. Thus the OTW boilerplate design was determined using pretest predictions of unsuppressed noise characteristics and treatment effectiveness.

Analysis of the OTW unsuppressed spectra indicated relatively minor differences with regard to treatment tuning frequency requirements from those of the UTW engine. Use of the same treatment panels would be a cost efficient means of obtaining a suppressed OTW configuration, thus that design was selected as a first try at meeting the noise goals. The treatment was designed as outlined in the previous section. Results of the analysis are shown on Table IV. The suppressed system noise exceeds the noise goal by 0.6 EPNdB at takeoff, is below the noise goal by 3.9 EPNdB at approach, and exceeds the noise goal by 6.4 PNdB in reverse thrust. In order to increase the potential for achieving 95 EPNdB at takeoff, two modifications were made to the design, (1) a bulk absorber inlet wall treatment was used instead of honeycomb and (2) the exhaust, splitter length was increased from 30 inches to 40 inches. With these modifications, as shown on Table IV, the takeoff

- Fan Pressure Ratio = 1.34
- Fan Tip Speed = 350.5 m/sec (1150 ft/sec)
- Number of Fan Blades = 28

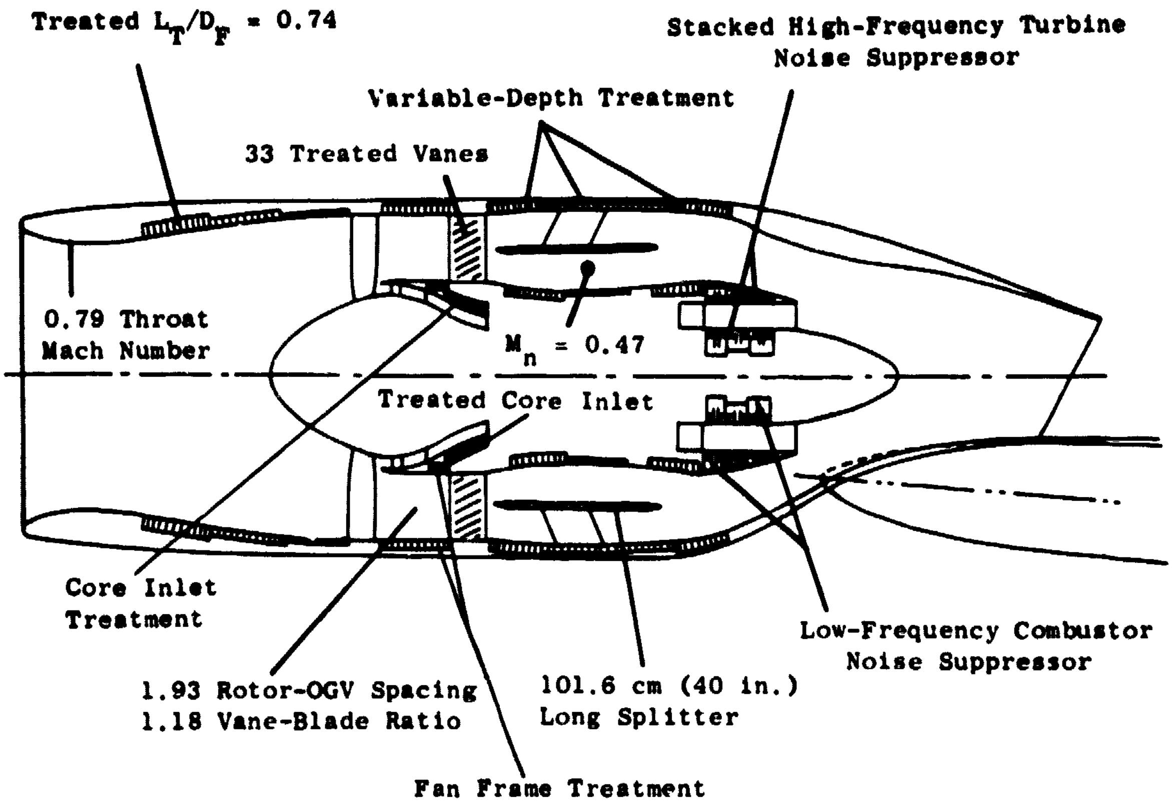


Figure 18. OTW Engine Acoustic Design.

Table IV. Suppressed System Noise Level Estimates.

	Fan Suppression ΔPNL's					
	Takeoff		Approach		Reverse/Thrust	
	Inlet	Exhaust	Inlet	Exhaust	Inlet	Exhaust
UTW Boilerplate Treatment No. 1 w/76.2 cm (30 in.) Splitter	12.9	12.8	7.7	12.8	7.7	12.8
UTW Boilerplate Treatment No. 1 w/101.6 cm (40 in.) Splitter and Bulk Absorber Inlet	13.5	13.9	10.4	13.9	10.4	13.9

	System EPNL's		
	Takeoff	Approach	Reverse Thrust
Noise Goals	95.0	95.0	100.0 (Max PNL)
UTW Boilerplate Treatment No. 1 w/76.2 cm (30 in.) Splitter	95.6	91.1	106.4 (Max PNL)
UTW Boilerplate Treatment No. 1 w/101.6 cm (40 in.) Splitter and Bulk Absorber Inlet	95.4	90.0	105.9 (Max PNL)

Note: Core Suppression Levels (All Power Settings) Are 5.1 PNdB on the Combustor Noise and 9.8 PNdB on the Turbine Noise.

noise goal is still exceeded by 0.4 EPNdB and approach is slightly reduced. In reverse thrust, the noise may be reduced if the 35% thrust level can be achieved at a lower power setting than indicated by the scale model test data. Lowering the engine power setting would reduce both the turbomachinery noise and the reverser efflux jet noise.

Inlet treatment design is shown in Figure 19 and the predicted suppression spectra in Figure 20. At takeoff the suppression includes both wall treatment and high throat Mach number effects but at approach only wall treatment. At low frequencies the approach suppression is predicted to be better than the combined effect at takeoff based on the scale model test results. The suppressed fan inlet noise takeoff spectrum is shown on Figure 21. This shows that the heavily Noy-weighted portion of the spectrum is effectively reduced such that the Noy weighted spectrum is balanced between low and high frequency.

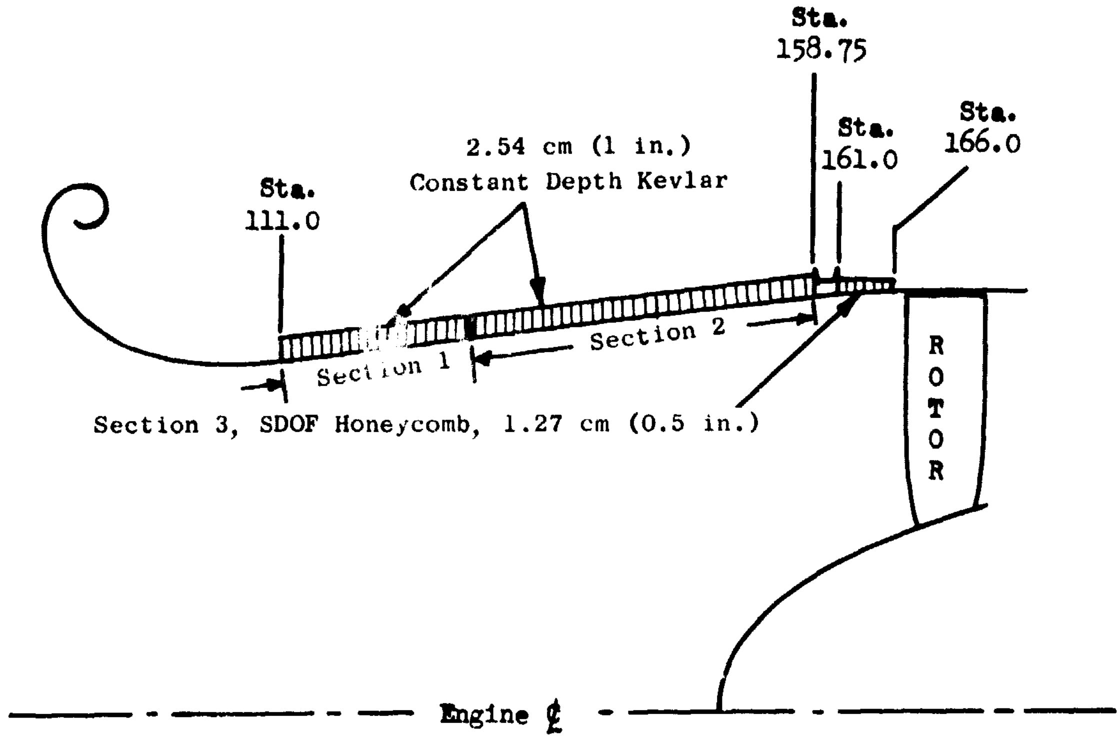
Fan exhaust duct treatment design is shown in Figure 22 and Table V and the predicted suppression on Figure 23. The suppression spectrum is tuned to the high Noy-weighted region which is also the location of the fan second harmonic. As a result the second harmonic suppression is greater than that of the BPF. Because the scale model studies indicated that tones were suppressed at a faster rate than broadband noise, the suppression spectrum was aimed at reducing peak broadband noise. Figure 24 shows the suppressed fan exhaust spectrum at takeoff. The resultant Noy-weighted spectrum is fairly flat thus eliminating a strong controlling frequency.

Core exhaust treatment design is shown in Figure 25 and the predicted suppression spectrum in Figure 26. The low-frequency suppression is aimed at combustor noise and the high-frequency suppression at turbine noise. The suppressed core noise spectrum at takeoff is given on Figure 27.

The core compressor treatment is shown on Figure 28. This treatment was applied to the core inlet to reduce compressor tones which might propagate into the aft duct.

System noise estimates with component PNdB levels and ΔPNdB suppression estimates are given on Tables VI, VII and VIII at takeoff, approach and reverse thrust respectively. These system levels correspond to those shown on Table IV for the modified design. At takeoff, the controlling component is jet/flap noise thus further engine noise reductions would be inefficient in reducing total system noise. This is also true at approach conditions. In reverse thrust, the jet noise is controlling and could only be reduced by lower power setting.

- **Treated $L_T/D_F = 0.74$**



Section	Length	Faceplate Thickness	Porosity	Hole Size	Tuning Frequency
1	38.10 cm (15 in.)	0.127 cm (0.050 in.)	14%	0.159 cm (0.0625 in.)	1600 Hz
2	82.55 cm (32.5 in.)	0.127 cm (0.050 in.)	22%	0.159 cm (0.0625 in.)	1600 Hz
3	12.7 cm (5 in.)	0.0813 cm (0.032 in.)	10%	0.159 cm (0.0625 in.)	2000 Hz

Figure 19. Engine Fan Inlet Treatment Design.

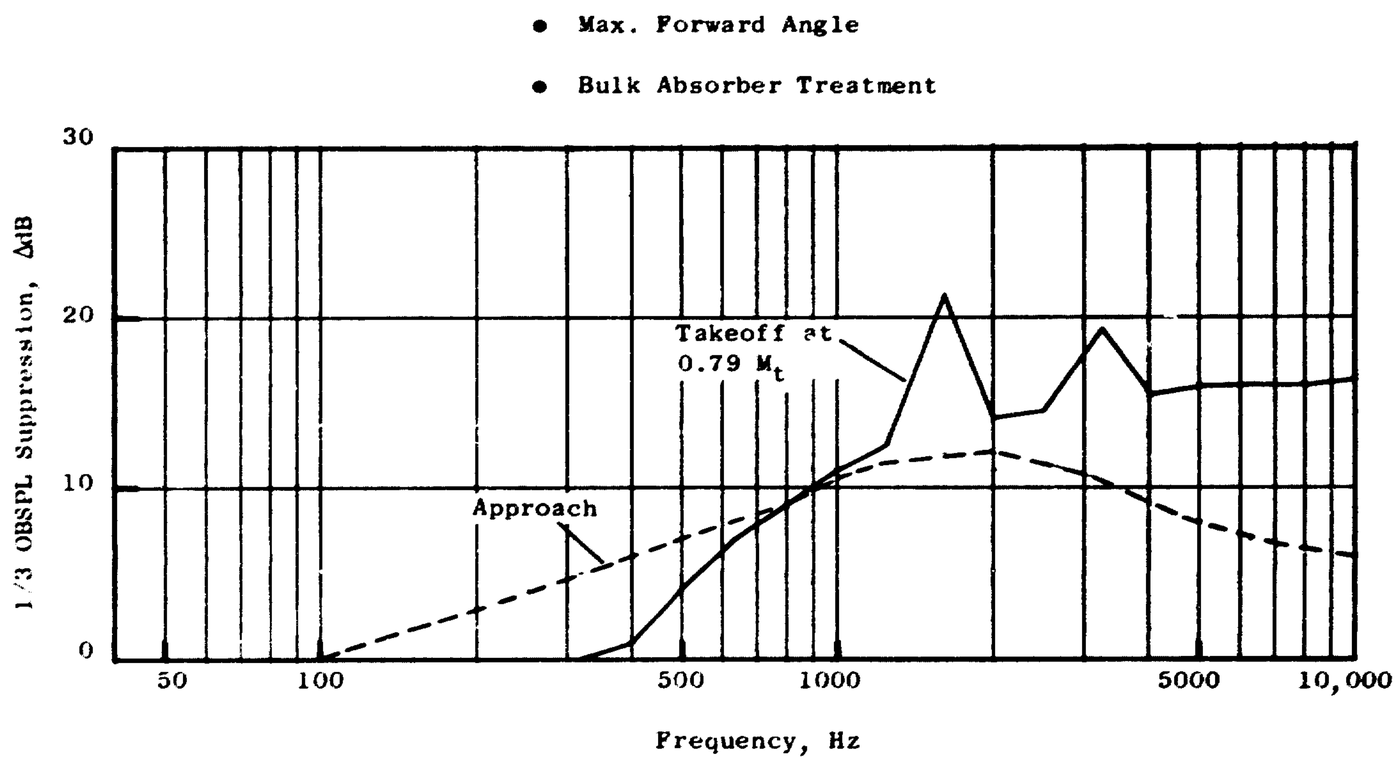


Figure 20. Engine Fan Inlet Predicted Suppression.

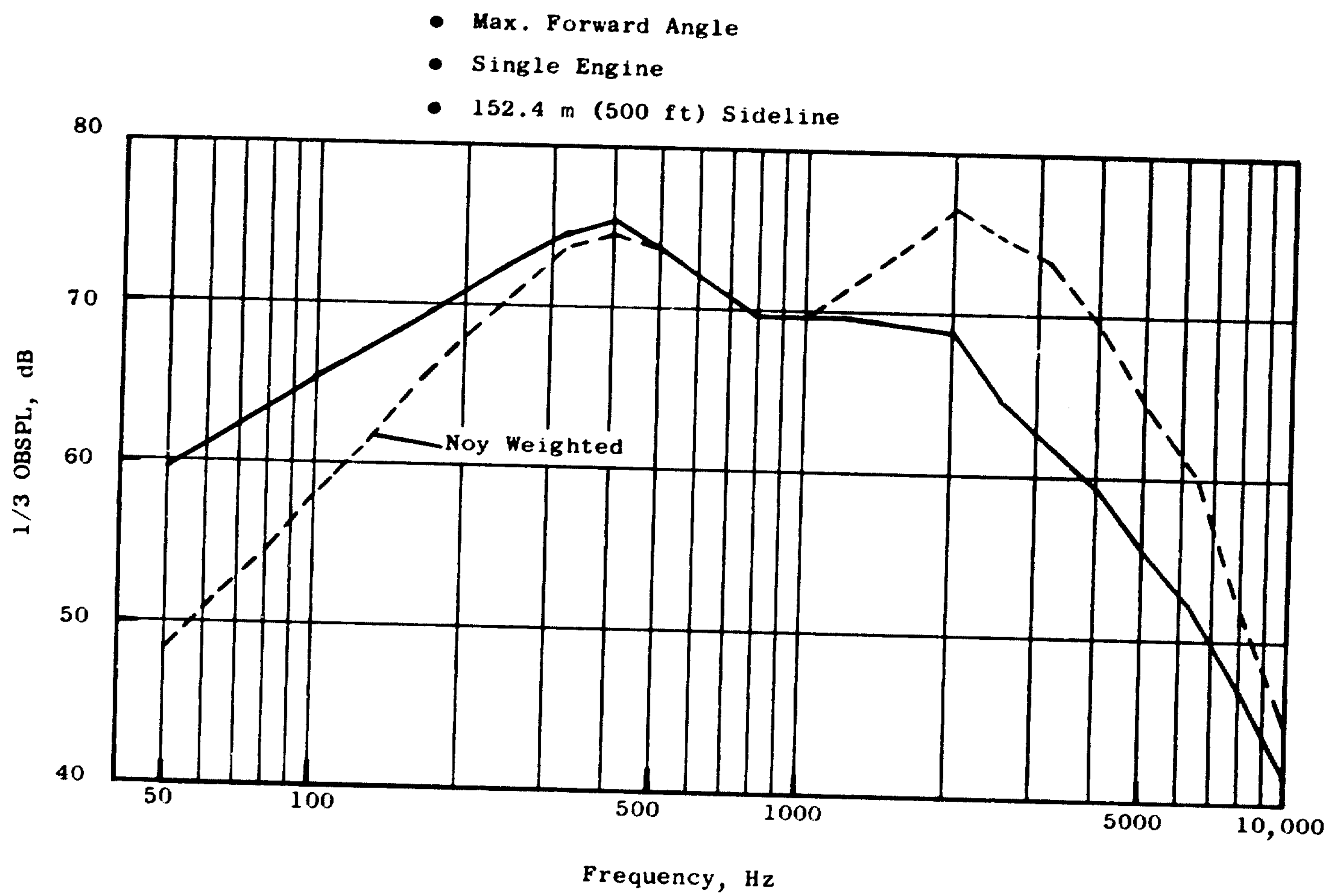
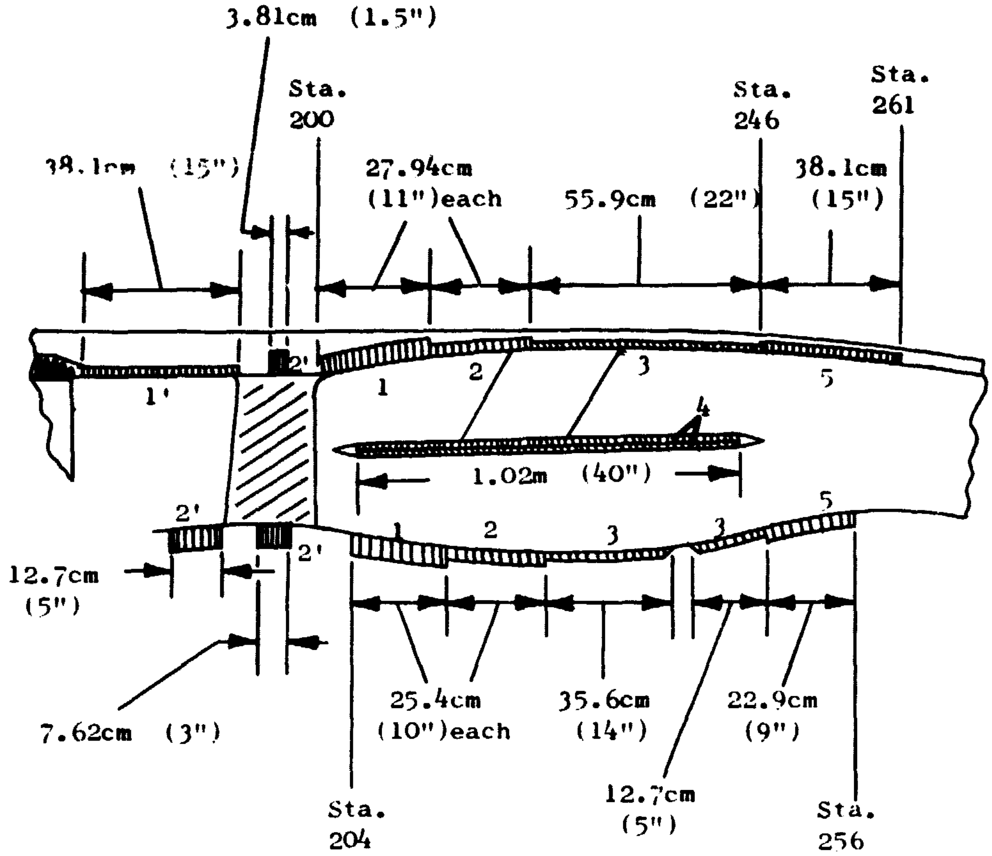


Figure 21. Suppressed Engine Fan Inlet Takeoff Spectrum.



	Depth	Porosity	Tuning Frequency
Fan Frame Treatment:			
Section 1'	1.90cm (.75")	10%	1600 Hz
" 2'	5.08cm (2")	10%	1000 Hz
Treated Vanes	0.76cm (.3")	10%	4000 Hz
Fan Exhaust Treatment:			
Section 1	5.08cm (2")	22%	1250 Hz
" 2	2.54cm (1")	15%	2000 Hz
" 3	1.90cm (.75")	15%	2500 Hz
" 4	1.27cm (.5")	11.5%	2500 Hz
" 5	2.54cm (1")	15.5%	1600 Hz

Figure 22. Engine Fan Exhaust Duct Treatment Design.

Table V. Engine Fan Exhaust Duct Treatment Design.

Section	Cavity Depth	Porosity	Hole Size	Faceplate Thickness
Fan Frame				
1	1.90 cm (0.75 in.)	10%	0.1589 cm (0.0625 in.)	0.0889 cm (0.035 in.)
2	5.08 cm (2 in.)	10%	0.1589 cm (0.0625 in.)	0.0889 cm (0.035 in.)
Treated Vanes (Pressure Side)	0.76 cm (0.3 in.)	10%	0.1589 cm (0.0625 in.)	0.127 cm (0.05 in.)
Fan Duct				
1	5.08 cm (2 in.)	22%	0.1589 cm (0.0625 in.)	0.1016 cm (0.040 in.)
2	2.54 cm (1 in.)	15%	0.1589 cm (0.0625 in.)	0.1016 cm (0.040 in.)
3	1.90 cm (0.75 in.)	15%	0.1589 cm (0.0625 in.)	0.1016 cm (0.040 in.)
4	1.27 cm (0.5 in.)	11.5%	0.198 cm (0.078 in.)	0.2032 cm (0.080 in.)
5	2.54 cm (1 in.)	15.5%	0.1589 cm (0.0625 in.)	0.1016 cm (0.040 in.)

* Reference Figure 20

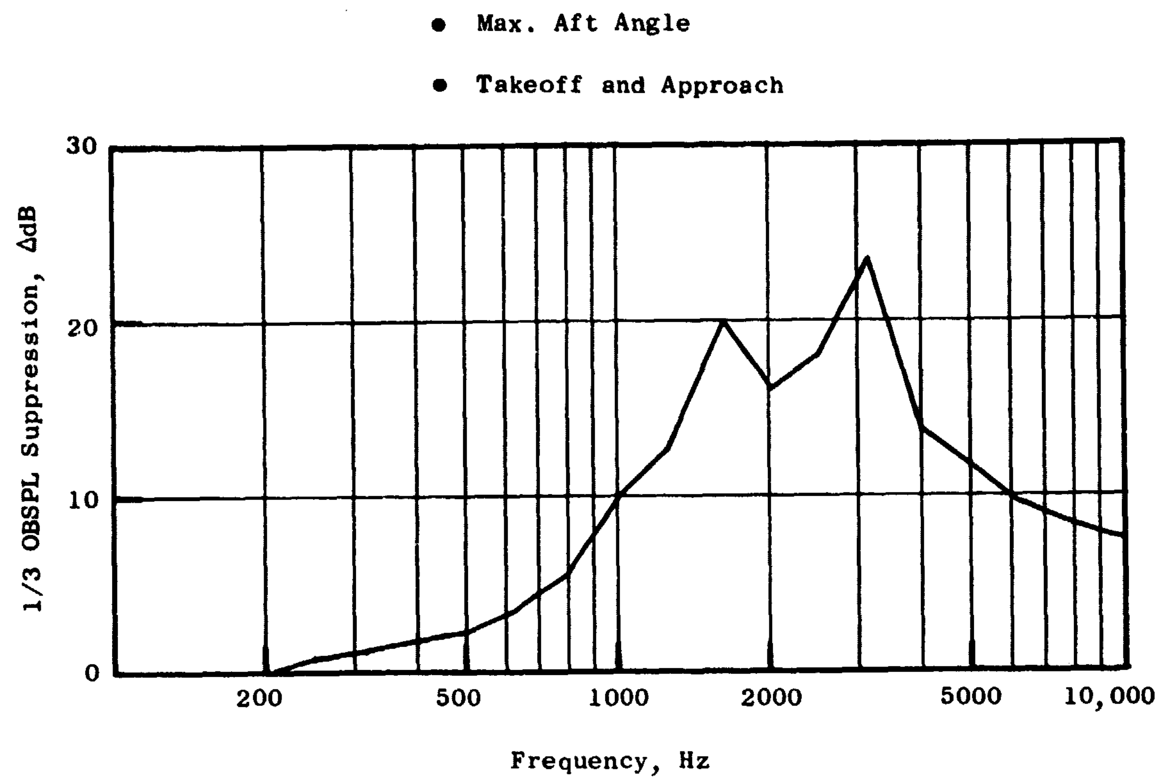


Figure 23. Engine Fan Exhaust Predicted Suppression.

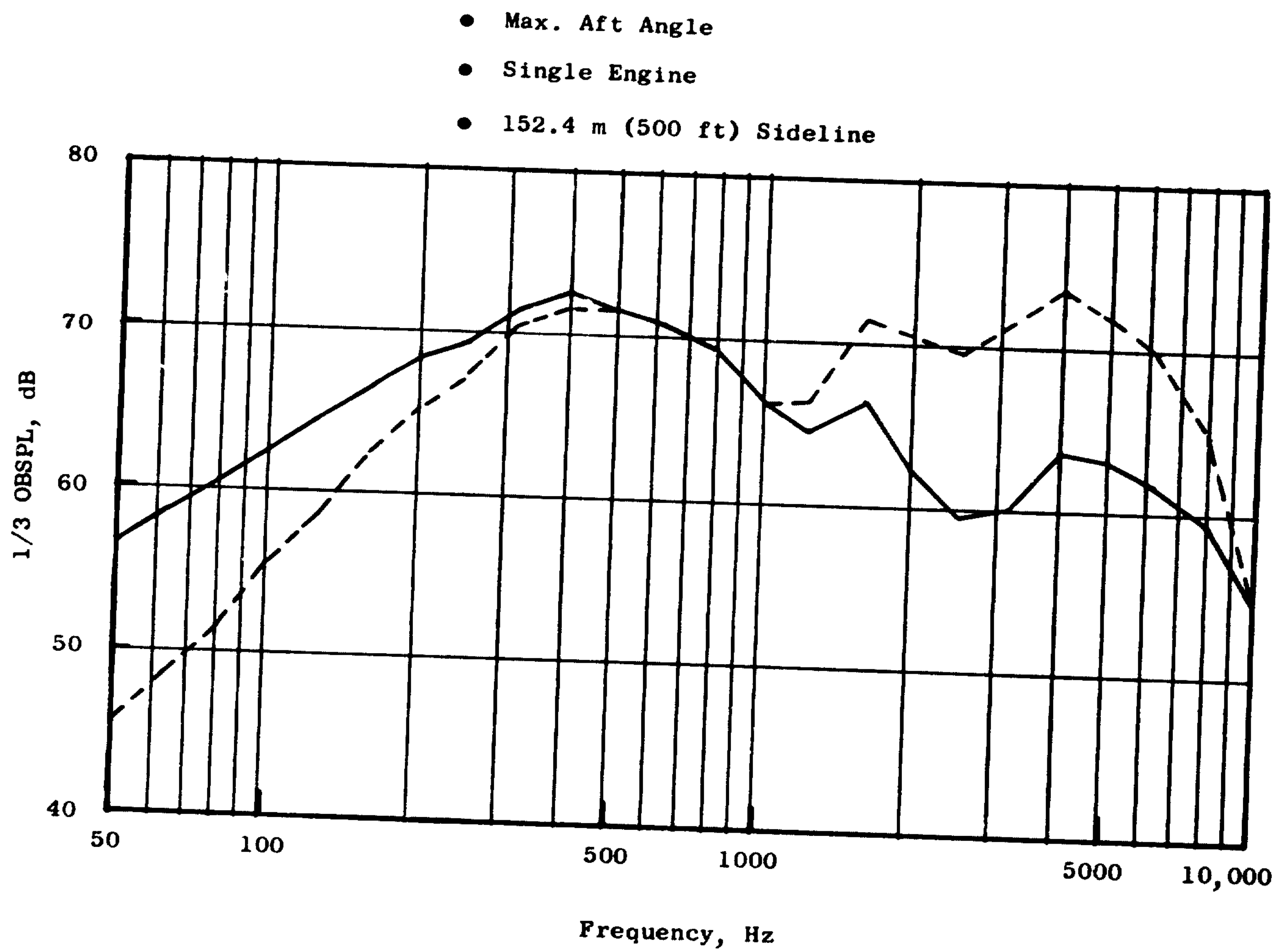
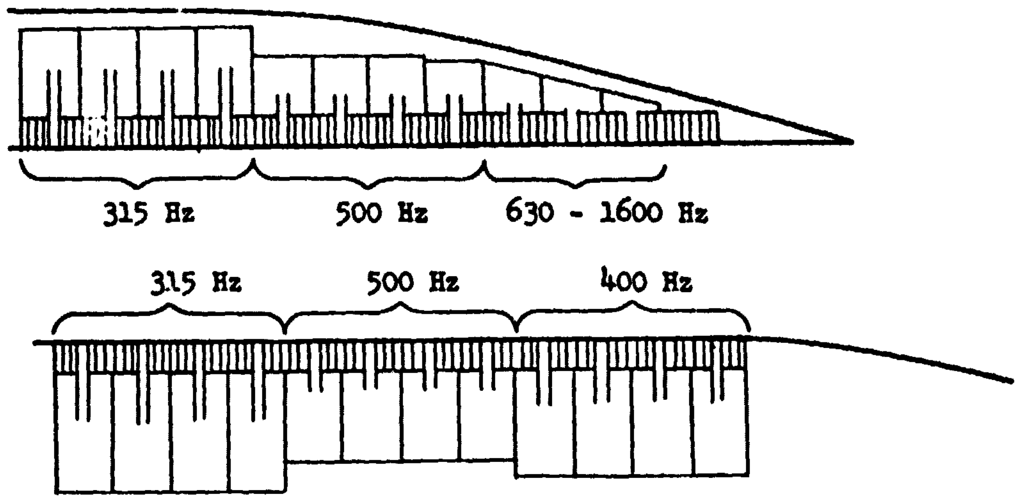


Figure 24. Suppressed Engine Fan Exhaust Takeoff Spectrum.



	Combustor						Turbine
	Inner Wall			Outer Wall			Both Walls
Tuning Frequency, Hz	315	400	500	315	500	630 - 1600	3150
Neck Length, cm (Faceplate Thick.)(in.)	6.99 (2.75)	5.72 (2.25)	4.45 (1.75)	6.99 (2.75)	4.45 (1.75)	3.56 - 2.54 (1.4)-(1.0)	.08128 (.032)
Cavity Depth, cm (in.)	10.2 (4.0)	8.89 (3.5)	7.62 (3.0)	7.62 (3.0)	4.32 &5.08 (1.7) &(2)	4.06 - .51 (1.6)-(.2)	1.095 (.75)
Porosity	10%	10%	10%	7%	7%	7%	10%
Treatment Length cm (in)	20.32 (8.0)	20.32 (8.0)	20.32 (8.0)	20.32 (8.0)	15.24 &5.08 (6.0) &(2.0)	20.32 (8.0)	60.96 (24.0)
Hole Diameter, cm (in.)	1.52 (.6)	1.52 (.6)	1.52 (.6)	1.52 ((.6)	1.52 (.6)	1.52 (.6)	.1575 (.062)

Figure 25. Engine Core Exhaust Treatment Design.

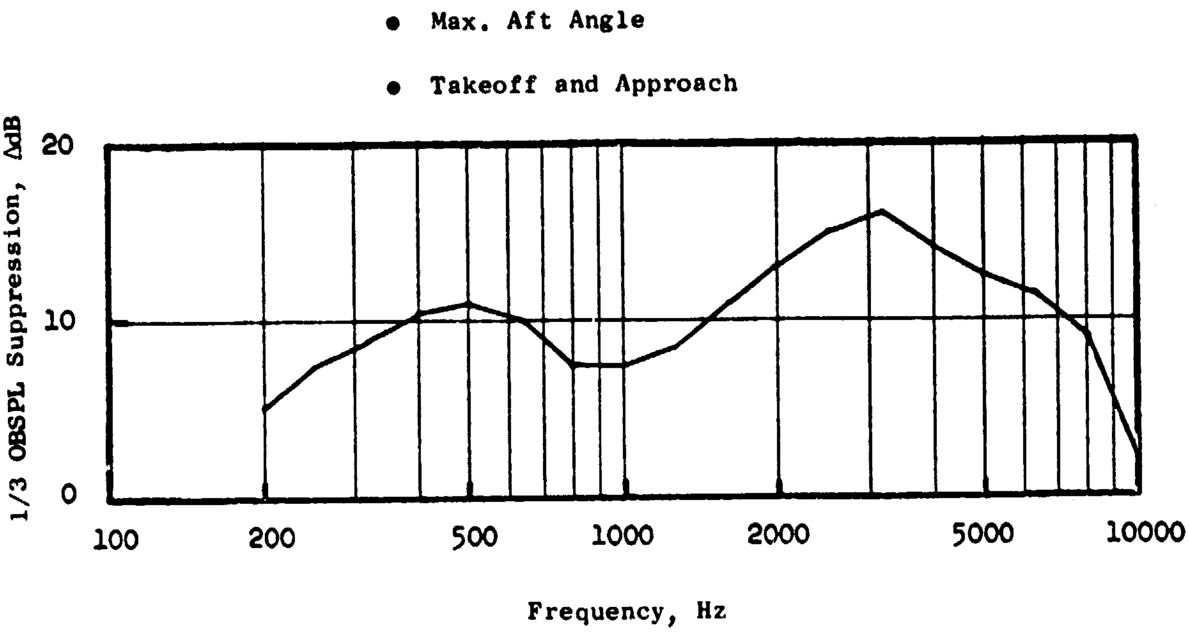


Figure 26. Engine Core Exhaust Predicted Suppression.

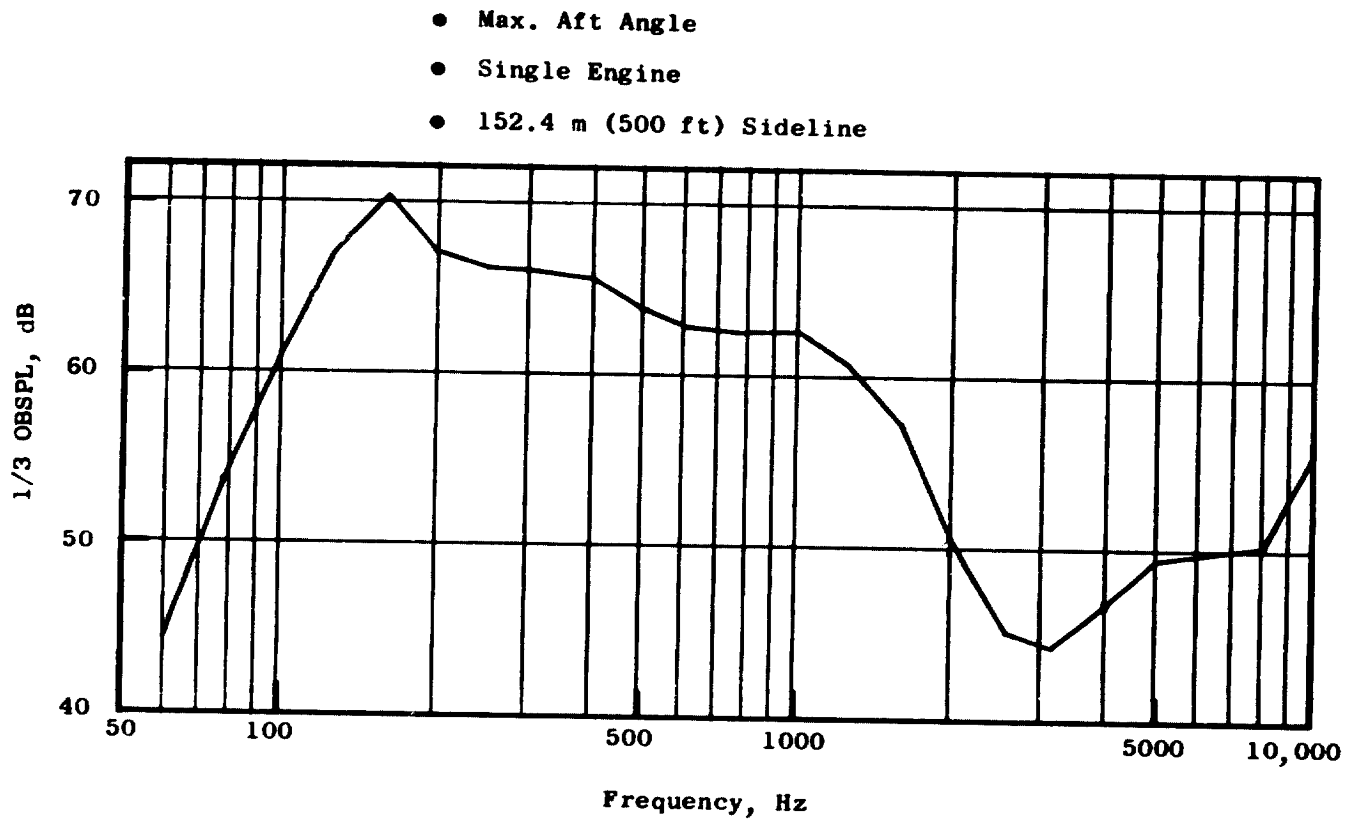
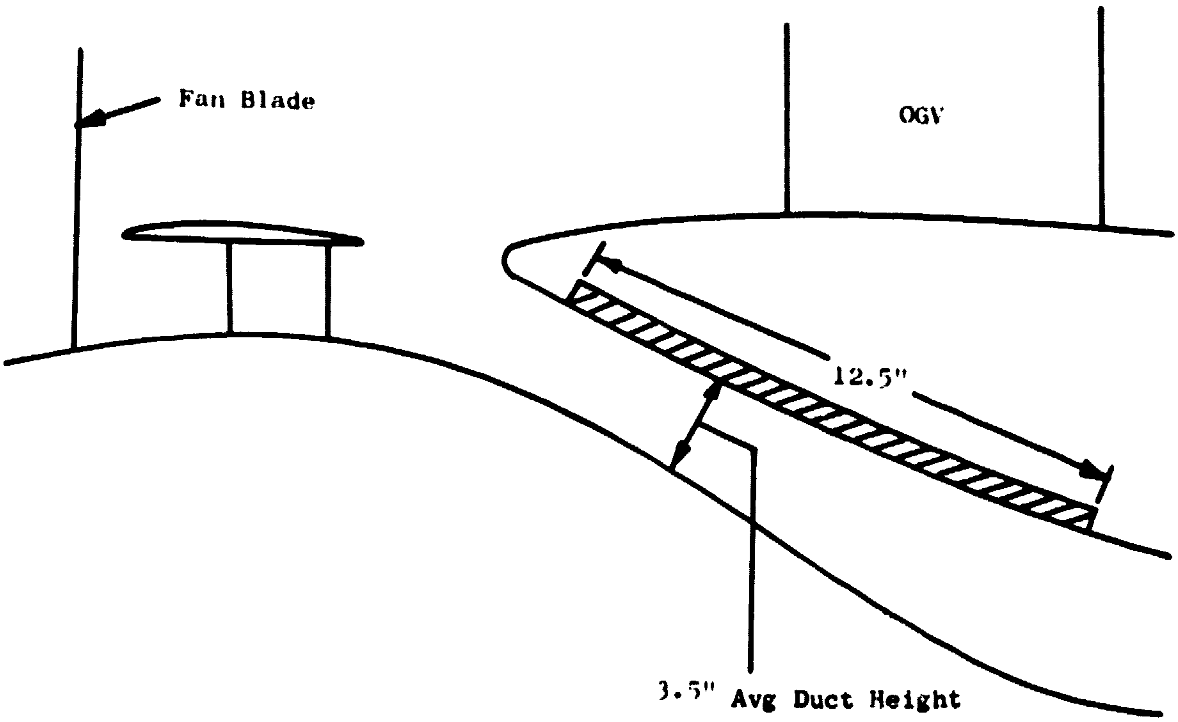


Figure 27. Suppressed Engine Core Noise Takeoff Spectrum.



SDOF Honeycomb, 0.500-cm (0.197-in.) Thick

8000-Hz Tuning Frequency

0.119-cm (0.047-in.) Faceplate Thickness

10% Porosity

0.159-cm (0.0625-in.) Hole Size

Figure 28. Engine Core Compressor Treatment Design.

Table VI. Predicted Takeoff Noise.

- 4-Engine Aircraft
- 90,000-lb Takeoff Thrust

	Maximum Forward Angle (90°) PNdB				Maximum Aft Angle (120°) PNdB			
	Fan	Turbine	Combustor	Jet/Flap	Fan	Turbine	Combustor	Jet/Flap
Single Engine, Unsuppressed 61 m (200 ft) Sideline	114.9	97.9	94.9	100.9	115.9	100.6	100.2	98.4
Total Corrections - Appendix I Procedure	-8.8	-13.5	-8.2	-6.6	-12.8	-14.9	-9.0	-7.6
Corrected Level - 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude	106.1	84.4	86.7	94.3	103.1	85.7	91.2	90.8
Suppression	13.5	9.8	5.1	---	13.9	9.8	5.1	---
Suppressed System	92.6	74.6	81.6	94.3	89.2	75.9	86.1	90.8
Sum of Constituents		97.3				94.6		
EPNL for System				95.4 EPNdB				

Table VII. Predicted Approach Noise.

- 4-Engine Aircraft
- 90,000-lb Takeoff Thrust
- 65% Power of Approach

	Maximum Forward Angle (90°), PNdB				Maximum Aft Angle (120°), PNdB			
	Fan	Turbine	Combustor	Jet/Flap	Fan	Turbine	Combustor	Jet/Flap
Single Engine, Unsuppressed 61 m (200 ft) Sideline	107.5	91.8	90.5	95.5	110.7	99.1	95.9	92.0
Total Corrections - Appendix I Procedure	-9.9	-13.4	-8.3	-6.5	-12.8	-14.9	-9.2	-7.7
Corrected Level - 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude	97.6	78.4	82.2	89.0	97.9	84.2	86.7	84.3
Suppression	10.4	9.8	5.1	---	13.9	9.8	5.1	---
Suppressed System	87.2	68.6	77.1	89.0	84.0	74.4	81.6	84.3
Sum of Constituents	92				89			
EPNL for System	90 EPNdB							

Table VIII. Predicted Reverse Thrust Noise

- 4-Engine Aircraft
- 90,000-lb Takeoff Thrust
- 35% Reverse Thrust

	Maximum Forward Angle (80°) PNdB				Maximum Aft Angle (120°) PNdB			
	Fan	Turbine	Combustor	Jet	Fan	Turbine	Combustor	Jet
Single Engine, Unsuppressed 61 m (200 ft) Sideline	114.9	96.6	95.7	110.8	109.4	90.4	95.9	108.1
Total Corrections - Appendix I Procedure	-7.2	-8.9	-6.1	-5.9	-7.2	-8.9	-6.1	-5.9
Corrected Level - 152.4 m (500 ft) Sideline at 61 m (200 ft) Altitude	107.7	87.7	89.6	104.9	102.2	81.5	89.8	102.2
Suppression	10.4	9.8	5.1	---	-13.9	9.8	5.1	---
Suppressed System	97.3	77.9	84.5	104.9	88.3	71.7	84.7	102.2
Sum of Constituents	105.9				102.7			

SECTION VI

CONCLUDING REMARKS

In the foregoing sections, an acoustic design has been defined for the QCSEE OTW engine. The design is intended to enable a four-engine STOL aircraft to meet a takeoff-and-approach noise goal of 95 EPNdB and a reverse thrust goal of 100-PNdB maximum, all measured on a 152.4 m (500 ft) sideline.

The QCSEE OTW acoustic design incorporates fan source noise reduction features such as low fan tip speed, low fan pressure ratio, high bypass ratio, large rotor to outlet guide vane (OGV) spacing, acoustic wall treatment between the rotor and OGV's, and acoustically treated stator vanes.

Fan inlet noise suppression is provided by a near-sonic (0.79 throat Mach number) inlet with multiple-thickness acoustically treated walls. Fan exhaust suppression is obtained by multiple-thickness treated exhaust walls and a 1-meter (40-inch) acoustically treated splitter. Core noise suppression is provided by using a "stacked treated" concept in which thick low-frequency combustor noise treatment is located under and integral with thin high-frequency turbine noise treatment panels.

The OTW acoustic design and the predicted noise levels and suppression estimates were based on various engine and scale model tests, and a number of laboratory flow duct tests, many of which were performed as part of the QCSEE program.

The original treatment development plan provided for UTW engine acoustic tests of an initial boilerplate (BP) nacelle treatment design followed by the test of a second BP nacelle treatment modified to better meet UTW engine acoustic suppression requirements as determined from the first BP nacelle acoustic tests. The acoustic treatment for the OTW boilerplate nacelle would then be made up from selected elements of the two UTW BP nacelle treatment design plus newly designed and fabricated additional elements as required to satisfy the predicted requirements of the OTW engine. However, the failure of the UTW engine exhaust nozzle flap prior to acoustic testing with consequent schedule and funding difficulties forced abolition of the plan. Consequently, the UTW BP nacelle acoustic treatment design will also be used as the OTW BP nacelle treatment design since the suppression requirements are only slightly different.

The predicted OTW takeoff noise level is 95.4 EPNdB, only slightly above the goal. The predicted approach value of 90 EPNdB is well below the 95-EPNdB goal. The maximum noise of 106.4 EPNdB during reverse thrust exceeds the 100-PNdB goal. As in the UTW engine, only a reduction in fan pressure ratio is likely to produce a significant reduction in reverse thrust noise. The actual engine acoustic performance will be determined by ground static demonstration tests of the fully suppressed engine.

SECTION VII

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