19. QUIET ENGINE PROGRAM

DETAILED ENGINE DESIGNS

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SUMMARY

The engine design constraints developed to insure maximum turbofan engine quieting are reviewed. Two engines designed within these constraints are discussed and their noise levels estimated, The supporting fan noise research program is briefly discussed and some preliminary fan noise data presented.

INTRODUCTION

In the early part of the Quiet Engine Definition Program a rather wide range of engine configurations was examined as discussed in reference 1. Later, a set of design constraints was selected within which engines were designed in more detail under contract by Allison Division of General Motors Corporation (Contract NAS3-10496) and Pratt & Whitney Division of United Aircraft Corporation (Contract NAS3-10497). These engines are reviewed and the supporting fan noise research program is discussed in this paper.

QUIET ENGINE DESIGN CONSTRAINTS

The design constraints that were chosen for the final phase of the design study activity for the Quiet Engine Definition Program are given in table I. The general considerations which led to these constraints are discussed in this section.

Engine

The screening of various engine layout designs resulted in the conclusion that a quiet engine should have a bypass ratio in the range of 5 to 6. The cruise thrust was set at 4900 lb; the corresponding take-off thrust for such an engine, about 22 000 lb.

Fan

Because the fan dominates the noise output of such an engine, the specification of the fan design was a prime consideration. The anticipation that considerable information will be learned about fan noise in the next few years made it desirable to be able to incorporate that technology in the quiet engine as it was developed. Therefore, the fan was specified to be mounted on a shaft by itself with no compressor stages so that changes in fan configuration and speed could be achieved with the least impact on the rest of the engine.

The effect of blade loading on the fan noise production is not well known at this time. In order to have lightly loaded blades, it is necessary to use two or more fan stages. For a bypass-ratio-5 engine, the fan pressure ratio can be achieved with one heavily loaded stage. The noise predictions did not indicate a noise advantage for the two-stage fan, but these predictions have considerable uncertainty associated with them. A weight penalty is associated with a two-stage fan compared with a single-stage fan. A single-stage fan was selected for the engine design, but investigations of the noise performance of both two-stage fans and single-stage fans will be part of the supporting experimental program.

In order to minimize the noise associated with the single-stage fan, inlet guide vanes were ruled out and the spacing between rotor and stator blade rows was specified to be at least 2 rotor chords. It was desired to have the flow subsonic over the blades in order to eliminate the noise associated with supersonic relative velocities, the so-called "shock noise" or "buzz-saw noise." In order to achieve subsonic relative flow, the tip speed at take-off could be a maximum of about 1000 ft/sec. These engines operate so that the tip speed at take-off is about 10 percent lower than the value at the cruise condition. Thus, the take-off tip-speed limit of 1000 ft/sec corresponds to a cruise tip speed of 1100 ft/sec. The engine is designed for the cruise condition. In figure 1, fan pressure ratio is plotted against a blade loading parameter D factor for a tip speed of 1100 ft/sec. The present state of the art is such that allowable D factors are 0.5 or lower. Figure 1 shows that a fan pressure ratio of the order of 1.6 can be achieved with state-of-the-art blade loading limits with this tip-speed limitation.

In figure 2, engine specific fuel consumption is shown as a function of fan pressure ratio. There is a marked increase in fuel consumption at fan pressure ratios below 1.5 for an engine with a bypass ratio on the order of 5. Thus, for good economy a fan pressure ratio of 1.5 is required and reasonable blade loading limits the ratio to a maximum of 1.6.

Compressor

Parametric engine performance studies have indicated that the specific fuel consumption of these engines began to increase rapidly as the cycle pressure ratio (overall compression ratio) decreased below 18. The specific fuel consumption continued to decrease as cycle pressure ratio increased but not very rapidly as shown in figure 3. Therefore, the minimum cycle pressure ratio for good fuel economy, specific fuel consumption, was determined to be 18. In order to achieve an overall compression ratio of 18 with a fan pressure ratio of 1.5 the pressure ratio required of the compressor is 12. Both two-spool and three-spool engines were considered. They differ in that the main compressor is made up of one or two rotors. A limit of 12.5 was set as the maximum pressure ratio per compressor rotor in order to avoid any problems associated with high-pressure-ratio compressors. A two-spool engine with a 1.5-pressure-ratio fan and a single-rotor compressor with a 12:1-pressure-ratio compressor has an overall cycle pressure (compression) ratio of 18. Thus, this limit permits the use of a single-rotor compressor - that is, a two-spool engine. Dual-rotor compressors as used in a three-spool engine develop a pressure ratio across each rotor on the order of 4 or 5; therefore, the limiting value of 12.5 does not influence the three-spool engine.

Turbine

The turbine temperatures at cruise and take-off are important because they set the jet noise level. The fan noise suppressor technology has progressed to the point where there is some hope that a 10-PNdB suppressor can be developed even for large-diameter engines. In order to achieve the quietest power plant possible, this quiet engine would be used with a fan inlet and exhaust suppressor. The hot jet mixing noise represents the floor for engine noise output. Reductions in fan noise below this floor are of no benefit to the observer. Therefore, the jet noise should be at least 10 PNdB below the fan noise if advantage is to be taken of the fan noise suppressor technology being developed. The rough estimate of the fan noise at 1000-ft altitude at take-off power was 105 PNdB; the jet noise maximum should then be 95 PNdB. In figure 4 the jet noise level in PNdB for an observer of a 1000-ft flyover is plotted against design turbine inlet temperature. The design turbine temperature must be 1775° F or lower in order to assure adequately low jet noise levels. This design-turbine-temperature limit of 1775° F corresponds to a take-off turbine temperature of 2000° F.

ENGINE DESIGNS

Allison Division of General Motors Corporation and Pratt & Whitney Division of United Aircraft Corporation conducted detailed design studies of these engines under contract for Lewis Research Center and did a complete aerodynamic and mechanical design of the fan.

The engine designed by Allison is a three-spool engine and is shown in figure 5. The single-stage fan develops a pressure ratio of 1.5 at cruise and has a diameter of 74 in. The tip speed at take-off is 1020 ft/sec. The fan blade has a chord at the tip of 6.2 in. and an aspect ratio of 3. The fan is driven by a five-stage turbine, offset somewhat from the gas generator turbine in order to obtain higher tip speed at a given rotational speed. The overall compression ratio of 24 is achieved with a 16:1 compressor consisting of two rotors having eight stages and pressure ratios of 4. Each rotor is driven by a single-stage turbine. The overall length is 153 in. and the weight is estimated at 4790 lb. The noise performance is summarized in table II. An observer on the ground 3 miles from the start of take-off roll would be subjected to 105 PNdB by a fully loaded four-engine airplane of the DC-8 type equipped with engines of this design without suppressors as it passed overhead at an altitude of 1000 ft. The jet noise is estimated at 93 PNdB so that further fan noise reduction with suppressors would be beneficial. The Allison noise estimation procedure is an empirical correlation based on several fan parameters, the most important of which is the flow Mach number relative to the blades. It takes into account the blade spacing, loading, and the presence of upstream blade rows, if any.

The Pratt & Whitney engine designed within the constraints given in table I is shown in figure 6. The single-stage fan has a take-off tip speed of 1000 ft/sec and develops a pressure ratio at cruise of 1.6. The rotor blade has a rather long chord at the tip, 7 in., and an aspect ratio of 2.2. The fan diameter is 68.9 in. The engine has two spools. The single-rotor compressor develops a pressure ratio of 12.5 and has five stages of variable stators. The compressor is driven by a two-stage high-pressure turbine. The first stator, first rotor, and second stator are air-cooled. This is also true of the Allison engine. The fan turbine is a five-stage in-line turbine. The overall length is 118 in. and the weight is 4950 lb.

The noise performance of this engine is summarized in table 11. A ground observer would hear 106 PNdB as a fully loaded four-engine airplane of the 707 type equipped with engines of this design passed overhead at an altitude of 1000 ft at take-off power. A mile from touchdown on approach an observer hears 104 PNdB. The corresponding jet noise levels at these observation points are 94 PNdB and 84 PNdB, respectively. The jet noise estimates for both the Pratt & Whitney and Allison engines are not as precise as the usual jet noise estimates because the jet velocities have been reduced to the point where the jet noise is not following the familiar eighth-power-of-velocity correlation law. Even at take-off power at 1000-ft altitude the jet velocity is less than 1000 ft/sec relative to the surrounding atmosphere.

The fan noise is still the dominant source and suppressors would benefit the ground observer. The fan noise prediction method at Pratt & Whitney is based on test data obtained with the JT3D and JT9D engines. The prime correlating parameter is the rotational tip speed of the fan. It is interesting that the estimated fan noise outputs from Pratt & Whitney and Allison are quite comparable although the prediction methods differ considerably in format.

These design studies have indicated several things. The combination of the high-bypass-ratio engine and moderate turbine temperatures result in sharp reductions in jet noise. Estimates of the fan noise reduction possible with a low-tip-speed fan are significant but the fan remains the dominant noise source. There is a weight penalty associated with the low-tip-speed fan but it is not such as to rule out the use of this quieting feature in practical aircraft propulsion systems.

The NASA plans to build and test several engines of the general character discussed herein. This experimental engine program will demonstrate the amount of quieting that can be achieved in complete engine systems.

FAN NOISE RESEARCH

The main noise problem is the fan. The experimental research program on fan noise supporting the Quiet Engine Program has begun. One of the fan experiments was conducted under contract by the General Electric Company (Contract NAS3-11166) with a modified version of the TF39 engine. The fan section of the unmodified TF39 engine is shown in figure 7. The inner portion of the fan is a two-stage device with no inlet guide vanes. The outer portion is a single stage with a row of inlet guide vanes. General Electric modified the fan section of a TF39 engine by removing the outer portion of the fan and spacing the blade rows of the inner portion to provide a distance of approximately 1 chord between rows. The modified fan is shown in figure 8. The inner portion of the fan developed a pressure ratio of 1.5 at a tip speed of 1000 ft/sec.

As mentioned previously, a single-stage fan was specified for the quiet engine design but tests of two-stage fans were to be part of the supporting research program. The modified TF39 engine was tested and some preliminary engine noise data are shown in figures 9 and 10. Figure 9 is a plot of perceived noise level as a function of angular position around the engine as measured at a 225-ft radius for take-off power setting. The maximum occurred at the 110° position at take-off power setting. The corresponding perceived noise levels for a four-engine airplane flying 1000 ft overhead at take-off power and at 325-ft altitude at approach power are 110 PNdB and 115 PNdB. These values are not as low as those estimated for the single-stage low-tip-speed fan.

In order to obtain data on single-stage fans such as this, a fan test rig is being constructed at Lewis in order to obtain far-field noise data. A sketch of the facility is shown in figure 11. It will drive 72-in-diameter fans up to tip speeds of 1200 ft/sec.

The first fan model to be tested in the facility has been designed and built at the Lewis Research Center. It is a single-stage device designed to produce a 1.5 pressure ratio and to operate at a take-off tip speed of 1000 ft/sec, has a chord of 5.5 inches and an aspect ratio of 3.5, and is designed to produce a uniform pressure ratio along the span. The blade loading is rather high and the blade turns approximately 15° past axial at the hub.

Following this initial test, the facility will be used to test a series of full-scale model fans and fan noise suppressors to be used with the quiet engine,

CONCLUDING REMARKS

The design study of turbofan engines for subsonic transport propulsion systems has indicated that substantial reductions in jet noise can be achieved by the proper selection of engine cycle parameters. Substantial fan noise reductions below current fan noise levels are predicted for engines with low-speed single-stage fans without inlet guide vanes and with large spacing between rotors and stators. Further reductions in fan noise resulting from the use of fan noise suppressors will result in overall installed powerplant noise levels about 20 PNdB lower than current levels.

REFERENCE

1. McBride, Joseph F.: Quiet Engine Program – Preliminary Engine Design and Aircraft Integration. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 18 herein.)

TABLE I.- QUIET ENGINE DESIGN CONSTRAINTS

Engine:	
Bypass ratio	5 to 6
Cruise thrust, lb	4900
Take-off thrust, lb	22 000
Fan:	
Number of stages	1
Inlet guide vanes	None
Spacing between rotor and stators.	2 rotor chords
Tip speed -	
Take-off, ft/sec	1000
Cruise, ft/sec	1100
Pressure ratio, cruise.	1.5 to 1.6
Compressor:	
Rotors	1 or 2
Maximum pressure ratio per rotor	12.5
Turbine:	
Inlet temperature -	
Take-off, °F	2000
Cruise, °F	1775

TABLE II.- FLYOVER PERCENED NOISE LEVELS

	Allison		Pratt & Whitney	
	Total PNdB	Jet PNdB	Total PNdB	Jet PNdB
Take-off power, 1000-ft altitude	104	93	106	94
Approach power, 325-ft altitude	105	80	104	84

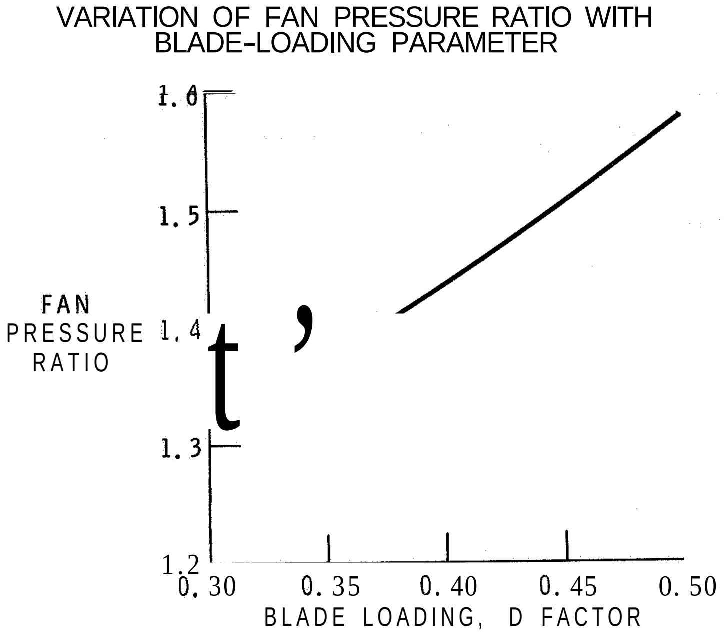

VARIATION OF FAN PRESSURE RATIO WITH BLADE-LOADING PARAMETER

Figure 1

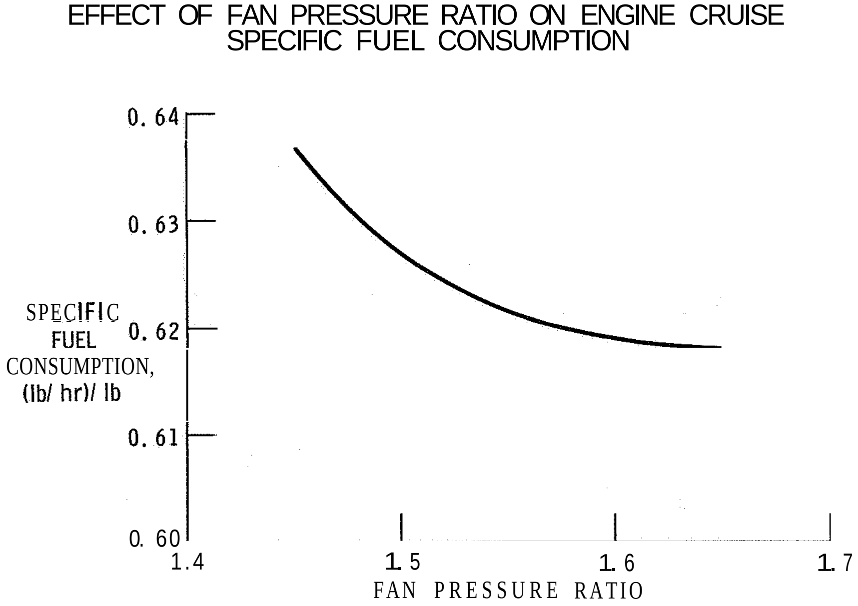
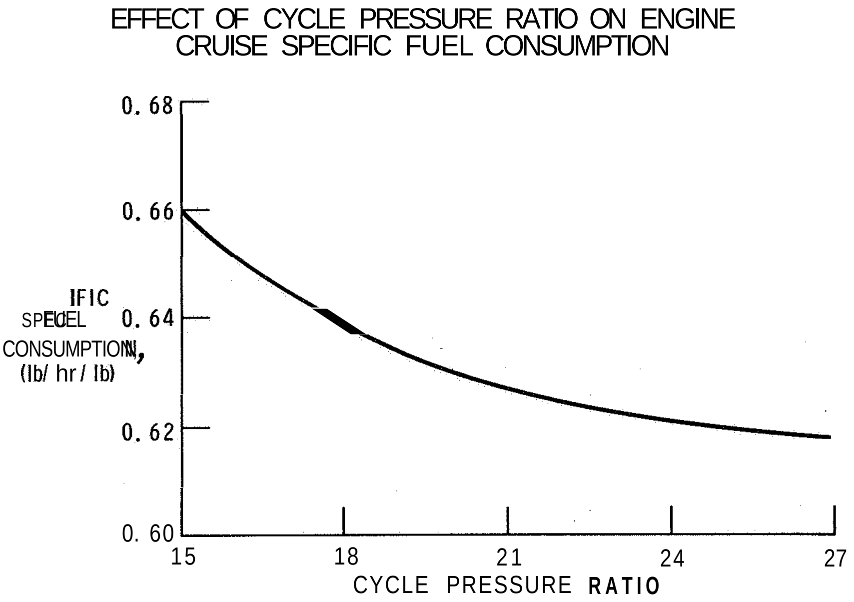
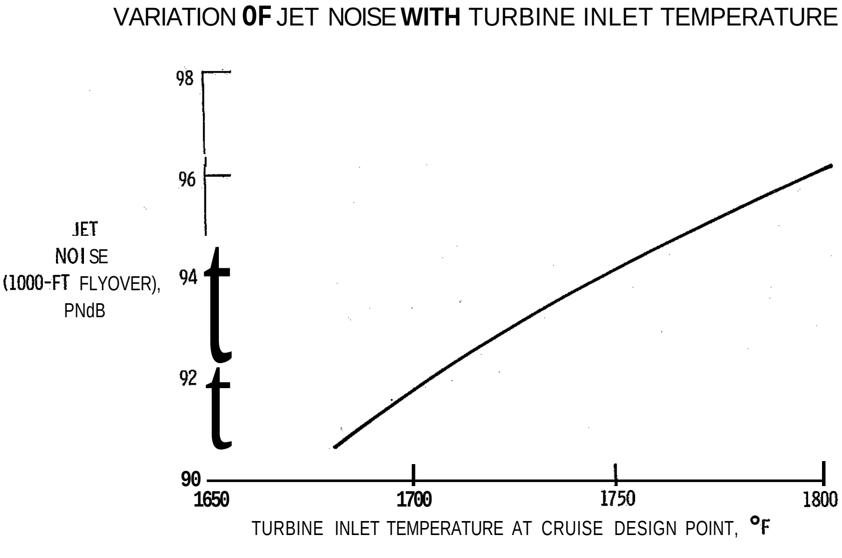

EFFECT OF FAN PRESSURE RATIO ON ENGINE CRUISE SPECIFIC FUEL CONSUMPTION

Figure 2



EFFECT OF CYCLE PRESSURE RATIO ON ENGINE CRUISE SPECIFIC FUEL CONSUMPTION

Figure 3



VARIATION OF JET NOISE WITH TURBINE INLET TEMPERATURE

Figure 4

ALLISON 5.5- BYPASS-RATIO ENGINE

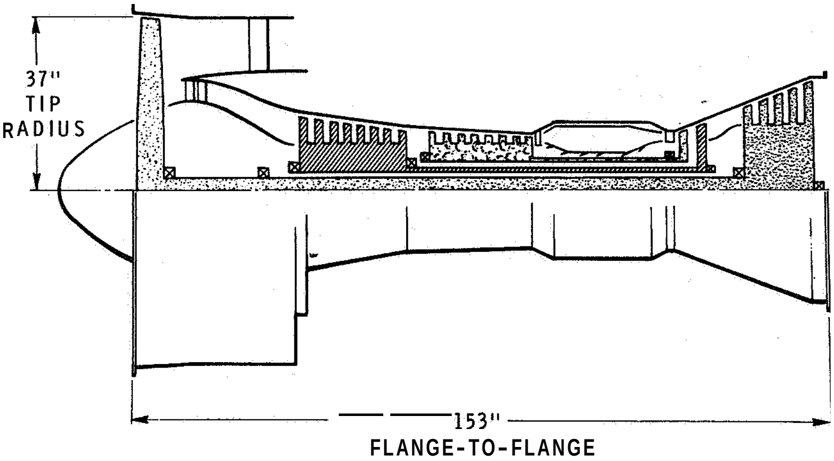


Figure 5

PRATT & WHITNEY 5.4-BYPASS-RATIO ENGINE

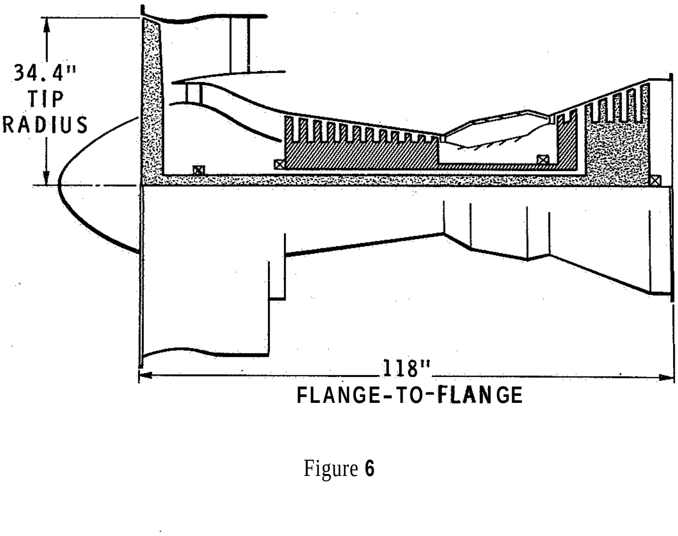


Figure 6

UNMODIFIED TF39 FAN

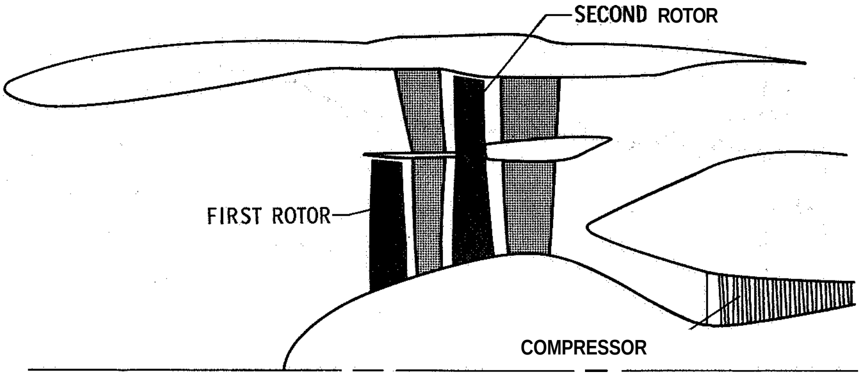


Figure 7

TWO-STAGE LOW TIP SPEED FAN

MODIFIED TF39 INNER PANEL ONLY

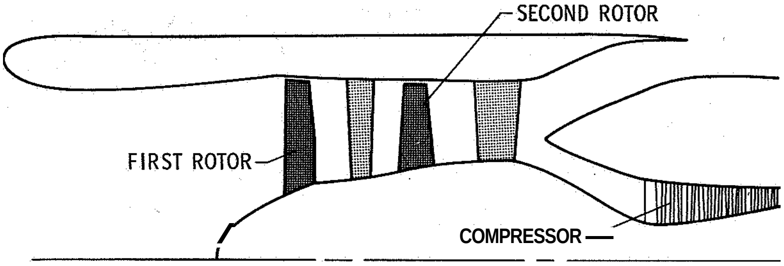


Figure 8

PERCEIVED NOISE LEVEL AS A FUNCTION
OF ANGULAR POSITION

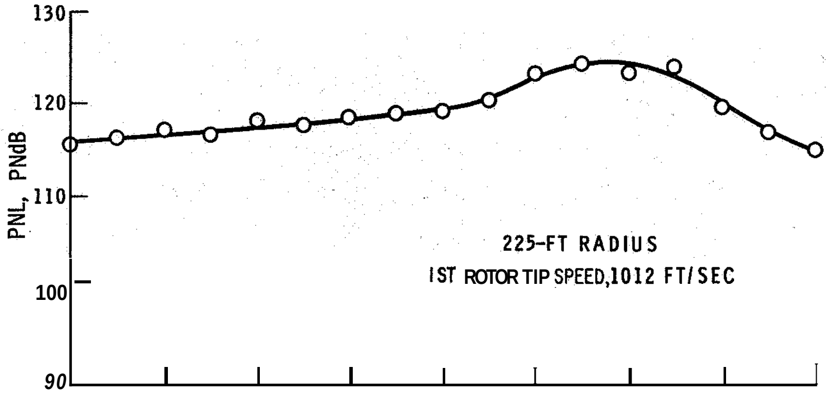


Figure 9

FREQUENCY SPECTRUM OF MODIFIED TF39 FAN
1/ 3-OCTAVE DATA; 225-FT RADIUS

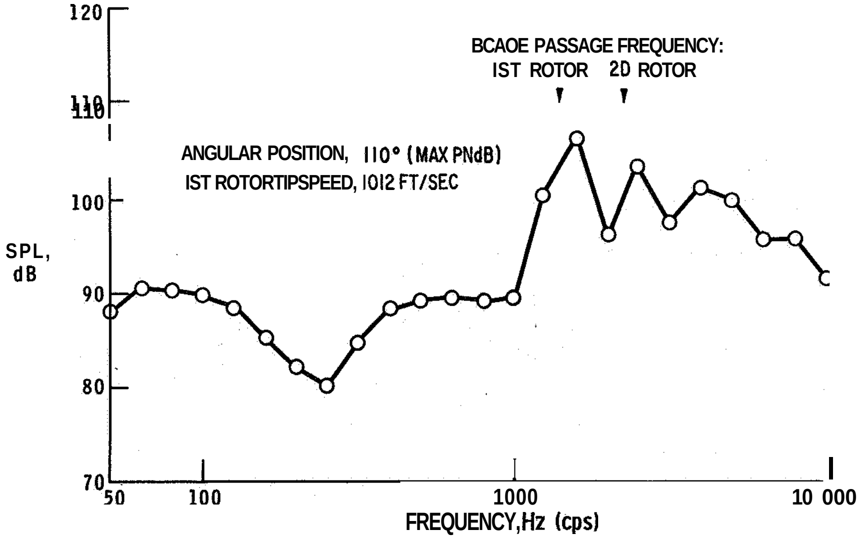


Figure 10

FAN-NOISE TEST FACILITY

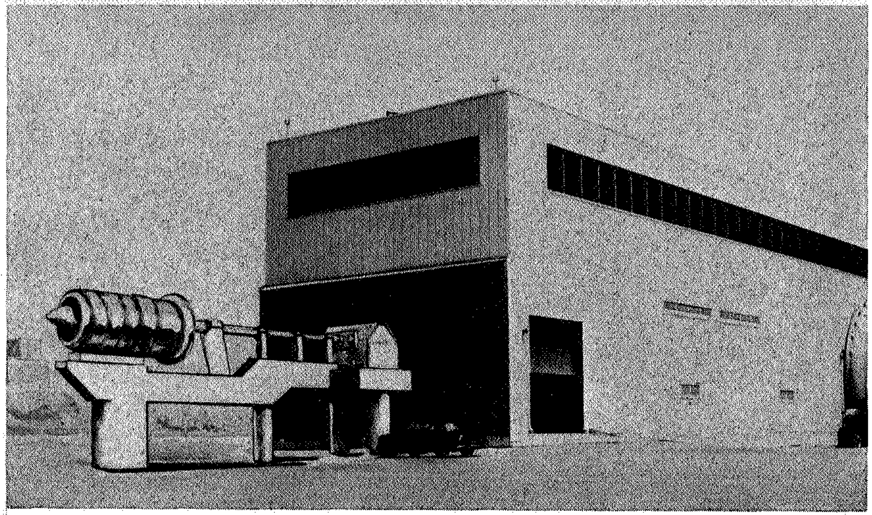


Figure 11 L-68-8575