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# THE NASA QUIET ENGINE PROGRAM

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## ABSTRACT

The NASA Quiet Engine Program will incorporate all available noise-reduction technology into a propulsion system suitable for subsonic civil transport aircraft. Full-scale experimental hardware is being built and tested primarily for noise performance. The program is in process, and component and engine tests to date indicate that it is possible to achieve or exceed noise reduction objectives of 15-20 PNdB below the levels of 707/DC-8 long-range transport aircraft.

# INTRODUCTION

The NASA Quiet Engine is part of a coordinated government industry response to the rapidly mounting problem of aircraft engine noise. The objective of the Quiet Engine program was to develop engine noise reduction technology. All available noise reduction technology applicable to subsonic propulsion systems was to be consolidated into an experimental engine. Research on this engine will form part of the technology base for the development of future low-noise propulsion systems for civil subsonic transport aircraft.

The specific noise performance goal chosen for this experimental propulsion system was noise levels 15-20 PNdB below the noise levels of the long-range Boeing 707 and McDonnell-Douglas DC-8 transports under comparable operating conditions. Proper engine design characteristics and an acoustically treated nacelle would be used to effect this noise signature improvement. The three main technological advances which would make such a gain possible are: development of the high-bypass-ratio engine with its low jet noise signature, improved understanding of the fan noise generation process, and development of nacelle acoustic lining technology. The application of these developments to a complete propulsion system was thought to be an adequate basis for attainment of the previously stated noise goals of 15-20 PNdB below 707/DC-8 levels.

# QUIET ENGINE DESIGN STUDIES

The major characteristics of the quiet engine were determined by in-house and industry design studies carred out under NASA contracts. Pratt and Whitney Div., United Aircraft Corp., and Allison Div., General Motors Corp., conducted the contract studies. The results are reported in Refs. 1 and 2. Cycle characteristics were explored in detail, mechanical arrangements were screened, single- and two-stage fans were considered, engine weights were estimated and engine noise characteristics were predicted. Since engine technology is advanced to the point where a wide range of engine choices is available, an optimum system could be selected primarily on the basis of noise considerations.

The principal noise sources considered in the engine selection were the fan machinery noise and the fan and core jet noise. The fan machinery noise is generated by the interaction of the rotating and stationary blade rows of the fan with the airflow through these cascades. The generation process is not completely understood, but the noise is generated in close proximity to the blades and is propagated out the inlet and exhaust ducts of the nacelle. The noise from this source spans a wide range of frequencies and thus is said to be broadband. A large fraction of the radiated sound power is, however, present in a fundamental blade-passing frequency and its harmonics. The fundamental occurs in the range of a few thousand cycles per second for fans designed with currently available aerodynamic and mechanical design techniques. For supersonic tip speed operation of the fan, discrete tones appear in the spectrum at integral multiples of the shaft rotational frequency.

Nacelle acoustic lining can decrease the noise experienced by a far-field observer. The amount of reduction that is practical has not been defined by adequate system studies. The McDonnell-Douglas Co. has performed a detailed analysis of the integration of a quiet engine with the DC-8 airframe (3). Their design included acoustic lining to achieve a 10 PNdB suppression of the fan noise. A sketch of the installation is shown in Fig. 1. The general conclusion was that the use of the quiet engine with its current-technology, high-bypass cycle was feasible and resulted in an improvement in the DC-8 performance. Subsequent tests at NASA Lewis Research Center indicated that noise reductions of the order of 15 PNdB could be achieved on the high-bypass fan just as Boeing and McDonnell-Douglas had shown could be achieved on the low-bypass JT3D engine.

The other important components of the engine noise signature are generated by the fan jet and core jet mixing with the surrounding atmosphere. The principal correlating parameter for the jet mixing noise is the jet velocity. Recent work reported (4) indicates that the correlation is with jet velocity to the eighth power even in the low-velocity regime (below 1000 fps). By use of the correlations of Ref. 4, the jet mixing noise was estimated as a function of fan pressure ratio for typical engines. The suppressed fan machinery noise and jet mixing are reasonably well balanced in the neighborhood of a fan pressure ratio of 1.5. The corresponding engine bypass ratio is in the 5-8 range, depending on the characteristics of the core gas generator. From considerations such as these, a set of engine specifications was developed for a low-noise engine suitable for long-range conventional takeoff and landing (CTOL) aircraft.

More detail on the engine design studies is presented in Refs. 1 and 2 and is also summarized in Refs. 5-7. These design studies elucidated several points.

1. The suppressed fan noise was the component of the engine noise with the greatest uncertainty.

2. The estimated noise performance of the quiet engine propulsion system indicated that the program objectives of 15-20 PNdB noise reduction could be realized. A set of engine specifications was developed to guide the detailed design and fabrication of an experimental quiet engine.

3. The use of quiet engines on a DC-8 airframe would produce a superior aircraft. However, the lower fuel consumption of the aircraft with quiet engines would not be adequate by itself to justify economically the retrofitting of the DC-8 fleet.

The response to the first point was the development of an outdoor fan acoustic test facility capable of testing fans of full size (72-in. diameter) for the quiet engine. The facility and some of the early experimental results are discussed in Refs. 8-10. The facility has been modified to produce better noise measurements and now appears as in the photograph of Fig. 2 and the plot plan of Fig. 3.

The second point led to the start of a contract program to build and ground-test several models of the quiet engine.

## EXPERIMENTAL QUIET ENGINE

The engine design specifications developed in the design study phase are shown in Table 1. A competitive request for proposal was issued in October 1968 for the design, fabrication, and ground test of experimental engines built to these design specifications. The extent of the test program was defined as 250 hr of engine testing on 10 builds of the experimental engine hardware. In July 1969, a fixed-price contract for approximately $20 million was awarded to the Aircraft Engine Group of the General Electric Co. This contract provided for the aerodynamic and acoustic evaluation of three fans in full scale, a series of exploratory acoustic tests on one-half-scale models of two of these fans, a series of tests on 10 engine configurations, and delivery of a test engine with spare parts to Lewis Research Center. At Lewis, the quiet engine will be mated to an acoustically treated nacelle to form a low-noise propulsion system - the objective of the quiet engine program.

The design characteristics of the three fans called A, B, and C are listed in Table 2. Fans A and B are relatively low-speed units with high aerodynamic loadings to achieve the design 1.5 pressure ratio. Fan C, on the other hand, is a high-speed unit with moderate aerodynamic loading to achieve its 1.6 design pressure ratio. The two low-speed fans are driven by a moderately loaded four-stage turbine, while fan C is driven by a heavily loaded two-stage turbine. The gas generator used in the engine is that used in the TF-39 and CF-6 engines. For this application, it has excess capacity and is not a flight-weight vehicle. However, it duplicates the thermodynamic and aerodynamic parameters identified as desirable in the engine design studies. The use of this developed production core permits a substantial cost saving, decreases program risk, and does not compromise acoustic evaluation. A cutaway view of the vehicle with a low-speed fan is shown in Fig. 4. Acoustic linings are incorporated in the engine frame between the fan rotor and stator assembly and some distance upstream and downstream of the fan. Acoustic treatment lines the inlet duct to the core engine and the exhaust passage downstream of the fan turbine.

The schedule of these activities is displayed in the bar chart of Fig. 5. The design of the quiet engine was approved by NASA in December 1969. This design is reported in detail in Ref. 11. General Electric then proceeded to carry out the fabrication and test phase of the program. As of November 1, 1971, the program status is as follows:

1. Aerodynamic evaluation of fans A, B, and C is complete.

2. Acoustic evaluation of fans A, B, and C is complete.

3. Tests of fan casing boundary-layer suction and serrated leading edges on the half-scale B fan are complete.

4. Tests of the half-scale C far are underway.

5. Tests of the first engine with the A fan are nearing completion.

## Fan Tests

The aerodynamic performance of the three fans will be reported in NASA contractor reports. The overall performance characteristics of the three fans are summarized in Table 3. Comparison with the design predictions of Ref. 11 shows that all three fans dailed to meet their aerodynamic efficiency performance objectives in the hub region. The flow from this section of the fan is fed into the core engine (hot gas generator). In the bypass portion, fans B and C meet, and fan A exceeds objective efficiency. Over 80 percent of the flow is through the bypass duct in this high-bypass-ratio engine. Cruise specific fuel consumption is very sensitive to fan bypass efficiency and relatively insensitive to fan core flow efficiency. Thus the overall aero-performance of the fans is quite satisfactory, particularly in view of the limited amount of aerodynamic development provided for in the program.

The three fans have been evaluated acoustically at the Lewis Research Center. The overall performance of the fans was generally as anticipated, based on the design predictions. A complete report on noise performance of these fans exceeds the scope of this paper. Those performance results will be reported in detail in forthcoming NASA publications. The results of the half-scale test program will appear in NASA contractor reports. Noise spectra with and without nacelle suppression of the fans are shown in Fig. 6. The maximum perceived noise levels for the fans are shown in Table 4. The data were taken with acoustic linings installed in the fan frame extending from in front of the fan to aft of the fan stator, as shown in Fig. 4. For the nacelle suppression data, additional acoustic treatment was added in the form of three circular splitter rings and outer duct wall linings in front of the fan and one splitter ring and duct wall linings in the fan exhaust duct. The same inlet suppressor was used on all fans and is the same as that described in (10). The test data measured on a 100-ft radius are extrapolated to equivalent flyover noise levels for conditions of takeoff and approach. The measuring locations are those of the Federal Aviation Regulation Part 36(12). For takeoff, the observer is directly under the flight path at 3.5 n. miles from brake release; for approach, the observer is 1.0 n. mile from threshold. For these conditions, a DC-8 equipped with quiet engines is at an altitude of approximately 1000 ft. as it passes over the takeoff observer. For these data, the engine was assumed to be at full power (no cutback) during takeoff with the fan operating at 90 percent of its design speed. At approach, the airplane is at 375 ft. altitude and the fan is at 60 percent of its design speed. The fan data do not, of course, contain any core engine noise or fan turbine noise. That information can only be obtained from complete engine testing. Equivalent values for the DC-8 with its current engine are in the range of 115-120 PNdB. The quiet engine fans with nacelle acoustic treatment are about 20 PNdB below the production DC-8 levels.

The regulation controlling the noise levels of new aircraft (12) is stated in terms of effective perceived noise decibels (EPNdB), a noise-measuring unit which accounts for the duration of exposure to high noise levels and the presence of discrete frequencies in the noise spectrum. Table 5 displays the fan noise data in terms of EPNdB. The FAA regulation will permit a new aircraft of the DC-8 size (325,000 lb gross weight) to produce no more than 104 EPNdB at the takeoff location and no more than 106 EPNdB at approach. The levels generated by the fan alone of the quiet engine are approximately at these levels without any nacelle acoustic suppression. The use of nacelle acoustic treatment permits the achievement of noise levels about 10 EPNdB below the current FAA regulation levels.

## Engine Tests

The first version of the Quiet Engine to be assembled was one utilizing a low tip speed fan. Acoustic and aerodynamic performance data were available when a selection of either fans A or B was to be made. As shown in Table 4 and 5 there were no appreciable differences in overall fan acoustic performance. However, fan A was superior aerodynamically and mechanically to fan B. Therefore, the decision was made to assemble the Quiet Engine in the A configuration, that is, using fan A. Engine build-up was completed and tests initiated in August 1971. As this report is being written the engine A test series is underway and only preliminary overall acoustic data are available. Quiet Engine A with a thick-lip flight-type inlet mounted in the acoustic test stand at the General Electric Peebles test site is pictured in Fig. 7. In general the engine acoustic performance was as anticipated based on the fan component acoustic tests. Comparisons of the fan component and engine acoustic performance are shown in Fig. 8. These one-third octave spectra are shown for the 120° location on a 200 foot sideline. The sideline distance is of no particular significance. The 120° microphone data are shown because this is the position of maximum overall noise level for both the fan component and engine tests. The agreement between the component and engine results at both takeoff and approach power settings is quiet good at frequencies above 1000 Hertz. At low frequencies, a peak in the engine spectra occurs between 100 and 200 Hertz. This peak corresponds to the core jet mixing noise. The core jet is not simulated in the fan component tests. Consequently, no such peak occurs in the component data.

An acoustically treated nacelle designed for use with the Quiet Engine is being fabricated by the Boeing Airplane Co. (Wichita) and is sketched in Fig. 9. The treatment in the nacelle inlet includes wall treatment, three concentric splitters and treatment on a stationary inlet bullet-nose fairing. In the exhaust, treatment is placed on both walls and on a single splitter. It is estimated that this treatment will result in noise reductions of the order of 10 to 15 perceived noise decibels. This nacelle is scheduled for delivery in March 1972 and will be mated with Quiet Engine A for tests of the complete propulsion system at Lewis Research Center.

In order to obtain some indication of the effects of nacelle acoustic treatment on the acoustic signature of the Quiet Engine before March 1972, Quiet Engine A was tested with an approximation of the nacelle shown in Fig. 9. The inlet had three treated rings but no treatment on the center-body. The exhaust duct treatment was not as long as in Fig. 9. There was an acoustic splitter but it was not as long as the one shown in figure 9. The inlet and exhaust duct splitters were cylindrical, not faired to align with flow stream-lines. This suppressor was made up in large part from available parts and did not represent an optimum acoustical design. The engine noise output in units of perceived noise decibels as a function of angular position is shown in Fig. 10. The noise data are shown for four engines flying over at 1000 feet at take-off power and at 375 feet at approach power. At front quadrant maximum noise positions (40°-50°) the suppressor results in noise reductions of about 10 PNdB. However, at rear quadrant maximum noise positions (110°-130°) the suppressor results in reductions of about 5 PNdB. These results indicate that the aft duct suppression was not balanced with respect to the inlet suppression However, the results do indicate the potentailly powerful influence of nacelle acoustic treatment on engine noise. Various engine noise levels are summarized in Table 6. The values are given in terms of effective perceived noise decibels (EPNdB) for the 707/DC-8, FAA certification levels for new aircraft of 325,000 lbs. gross weight (equal to 707/DC-8), and for the Quiet Engine with and without suppression. The bare Quiet Engine without nacelle acoustic treatment is 6 EPNdB below FAA certification levels. With the treatment tested, the Quiet Engine is 13-15 EPNdB below certification levels. The use of an acoustic nacelle tailored to the noise signature of the Quiet Engine will probably result in even lower noise levels. The data presented are preliminary results and may be revised as additional noise data are accumulated. The amount of treatment used in the suppressed engine test was greater than the amount used in the suppressed fan test, hence the suppressed engine noise levels shown in Table 6 are lower than those based on fan component tests shown in Table 5.

It should be recognized that nacelle acoustic treatment of the design used to achieve these noise results has the potential to penalize aircraft performance. Some of the obvious factors are added drag losses, nacelle weight, and anti-icing requirements. Also, the effects of the splitter rings on the aerodynamic performance of the fan or the engine have not been established. These factors will be investigated and assessed in terms of aircraft performance as the engine nacelle design is developed in the program.

## CONCLUDING REMARKS

Application of available noise control technology to a subsonic aircraft propulsion system can result in systems with noise substantially below current certification levels. This conclusion is based on full-scale fan and engine tests. The Quiet Engine will be tested with an optimized acoustically treated nacelle at the NASA Lewis Research Center in the second quarter of 1972.

## ACKNOWLEDGEMENT

The authors in making this progress report speak not only for their associates at the NASA Lewis Research Center, but also for those in industry who contribute to the achievements discussed here.

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12. "Noise Standards: Aircraft Type Certification." Vol. III, Part 36, Federal Aviation Regulations.

Table I. - Quiet Engine Design Characteristics

| | |
|---|---|
| **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 |
| Pressure ratio, cruise | 1.5 to 1.6 |
| **Compressor:** | |
| Rotors | 1 or 2 |
| Maximum pressure ratio per rotor | 12.5 |

Table 2 - Quiet Engine Fans Design Characteristics

| Design Parameter | Fan A | Fan B | Fan C |
|---|---|---|---|
| Corrected rotor tip speed, ft/sec | 1160 | 1160 | 1550 |
| Inlet hub/tip radius rotor | 0.465 | 0.465 | 0.360 |
| Rotor inlet tip diameter, inches | 73.354 | 73.354 | 68.300 |
| Corrected airflow, lb/sec | 950 | 950 | 915 |
| Inlet corrected specific flow, lb/sec-sq ft annulus area | 41.3 | 41.3 | 41.3 |
| Number of rotor chords axially separating rotor and outer OGV | 2.0 | 2.0 | 2.0 |
| Number of rotor chords axially separating rotor and inner OGV | 1.25 | 1.25 | 1.25 |
| Bypass portion total pressure ratio | 1.50 | 1.50 | 1.60 |
| Hub portion total pressure ratio | 1.32 | 1.43 | 1.49 |
| Bypass ratio: Design | 5.6 | 5.4 | 5.0 |
| Rotor aspect ratio | 2.32 | 1.71 | 2.09 |
| Rotor solidity: OD | 1.45 | 1.30 | 1.40 |
| ID | 2.50 | 2.16 | 2.45 |
| Objective bypass adiabatic efficiency | 0.865 | 0.870 | 0.842 |
| Number of rotor blades | 40 | 26 | 26 |
| Number of outer OGV's | 90 | 60 | 60 |
| Number of inner OGV's | 90 | 60 | 60 |

Table 3 - Quiet Engine Fan Aerodynamic Performance

| | Fan A | Fan B | Fan C |
|---|---|---|---|
| Air Flow at Design, lbs/sec | 977 | 983 | 915 |
| Pressure Ratio at Design | 1.480 | 1.484 | 1.625 |
| Bypass Efficiency at Design | .882 | .865 | .845 |
| Core Efficiency at Design | .830 | .771 | .820 |
| Stall Margin at Design Speed | 17 °/o | 23 °/o | 22 °/o |

Table 4 - Quiet Engine Noise Levels Based on Lewis Research Center Full-Scale Fan Noise Tests

| | PERCEIVED NOISE LEVEL, PNdB | | | | | |
|---|---|---|---|---|---|---|
| | APPROACH 375-FT ALTITUDE | | | TAKEOFF 1000-FT ALTITUDE | | |
| | A | B | C | A | B | C |
| 4 FANS | 104 | 104 | 106 | 104 | 104 | 111 |
| 4 FANS WITH NACELLE SUPPRESSION | 96 | 99 | 99 | 98 | 100 | 101 |

NOTE: CORE ENGINE NOISE NOT INCLUDED

Table 5 - Quiet Engine Noise Levels Based on Lewis Research Center Full-Scale Fan Noise Tests

| | NOISE, EPNdB | | | | | |
|---|---|---|---|---|---|---|
| | APPROACH 375-FT ALTITUDE | | | TAKEOFF 1000-FT ALTITUDE | | |
| | A | B | C | A | B | C |
| 4 FANS | 99 | 101 | 103 | 105 | 104 | 109 |
| 4 FANS WITH NACELLE SUPPRESSION | 92 | 93 | 94 | 96 | 96 | 101 |

NOTE: CORE ENGINE NOISE NOT INCLUDED.

Table 6 - Engine Noise Comparison

| | TAKE-OFF | APPROACH |
|---|---|---|
| | EPNdB | |
| 707/DC-8 | 116 | 118 |
| FAR 36 | 104 | 106 |
| QUIET ENGINE UNSUPPRESSED | 98 | 100 |
| QUIET ENGINE SUPPRESSED | 89 | 93 |

## LIST OF FIGURES

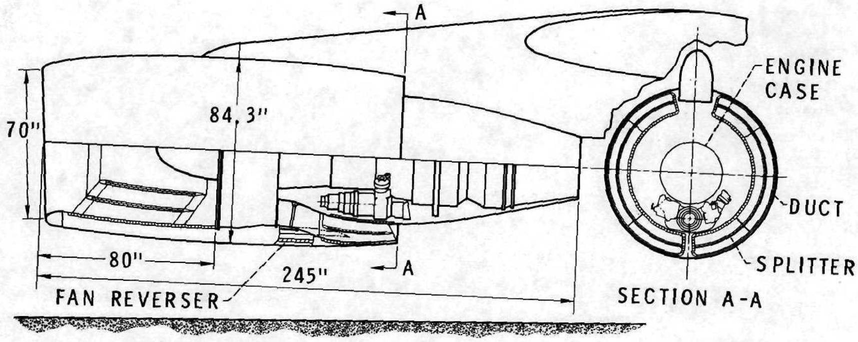


Figure 1. - DC-8 quiet engine nacelle.

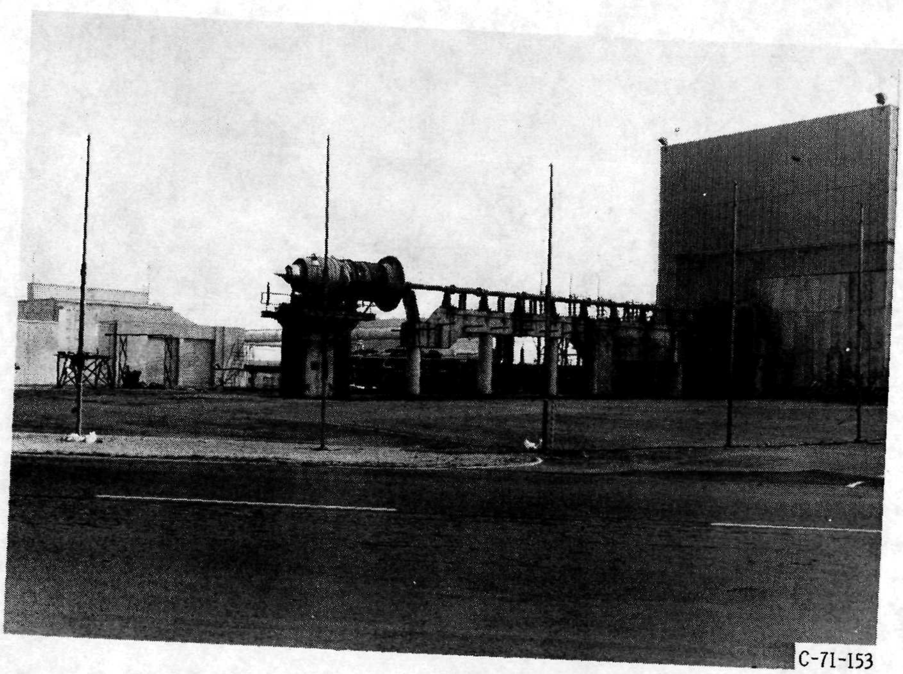

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Figure 2.

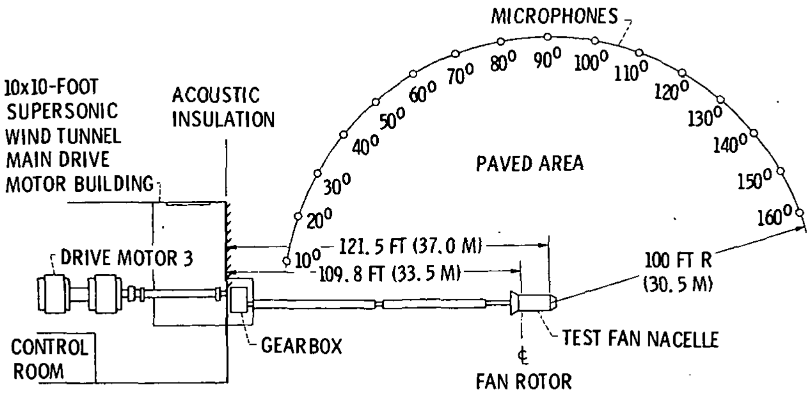


Figure 3. - Plan view of full-scale fan acoustic test facility.

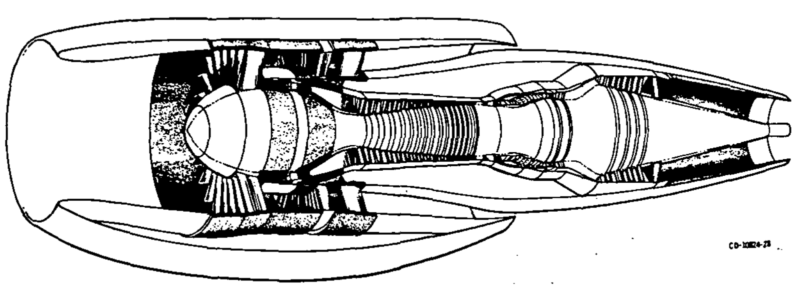

Figure 4. - Experimental quiet engine.

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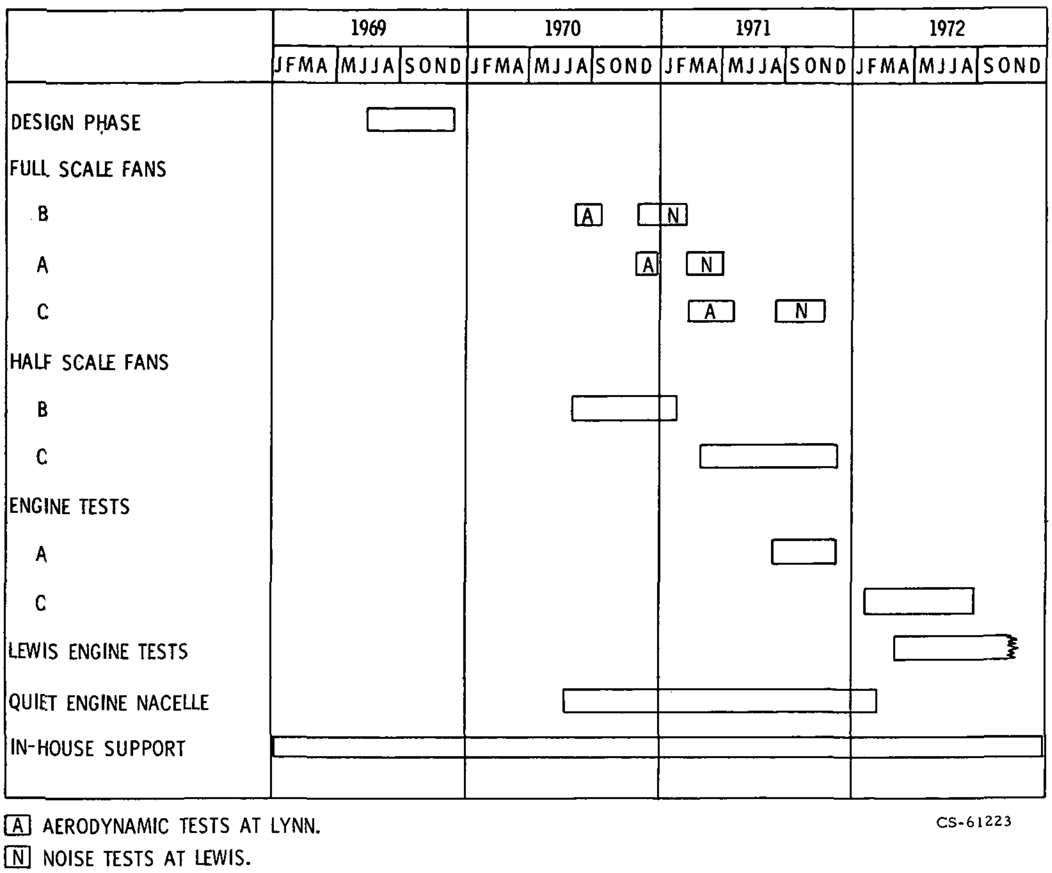


Figure 5. - Quiet engine program.

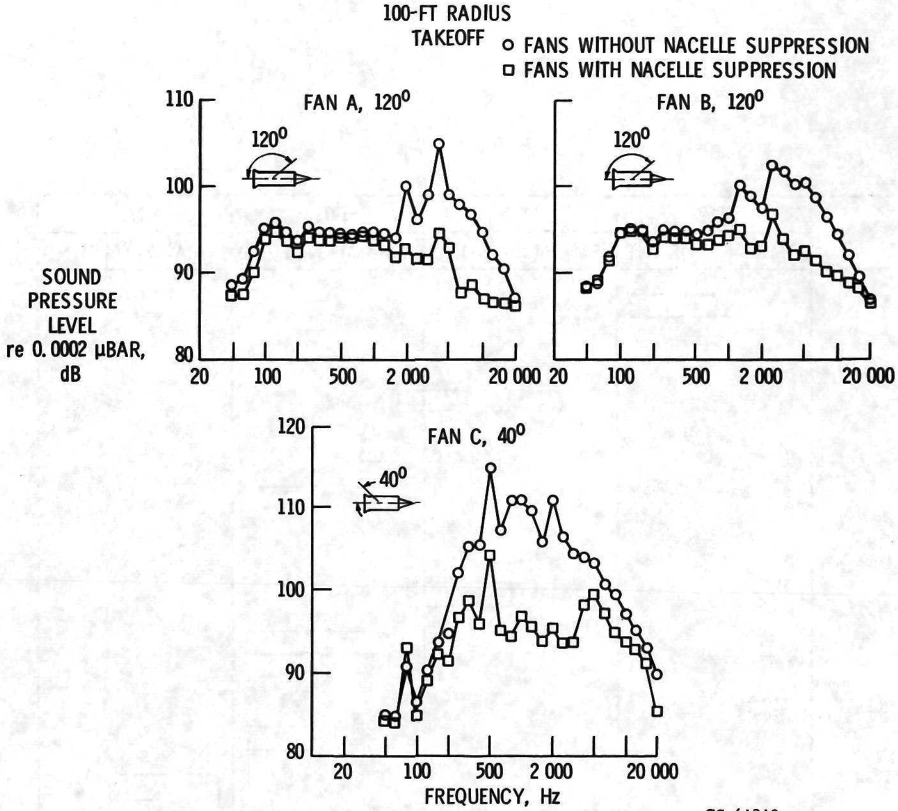


Figure 6. - Spectra at peak noise angles.

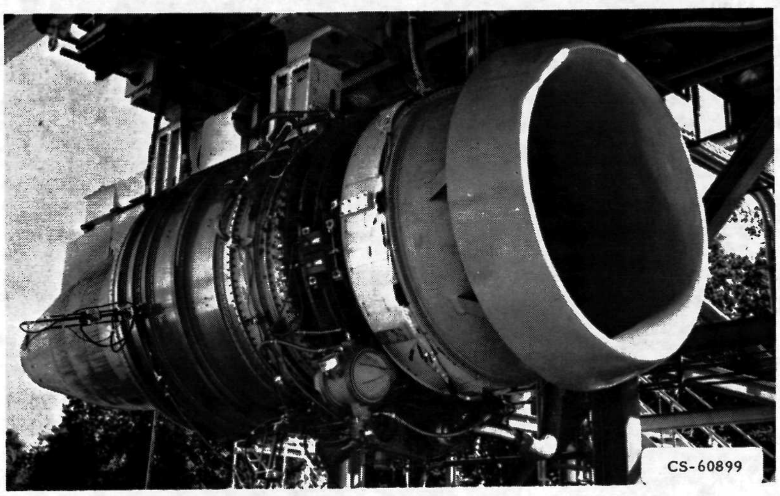


Figure 7. - Quiet engine.

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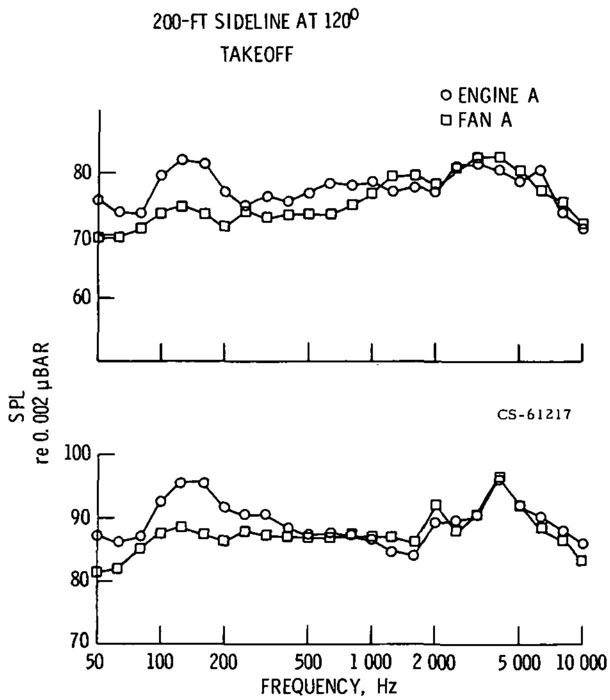


Figure 8. - Noise spectra.

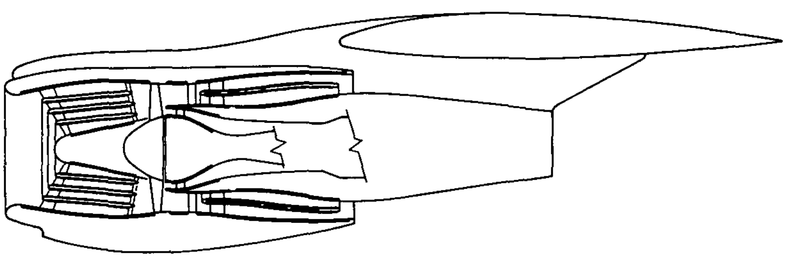

Figure 9. - Quiet engine nacelle.

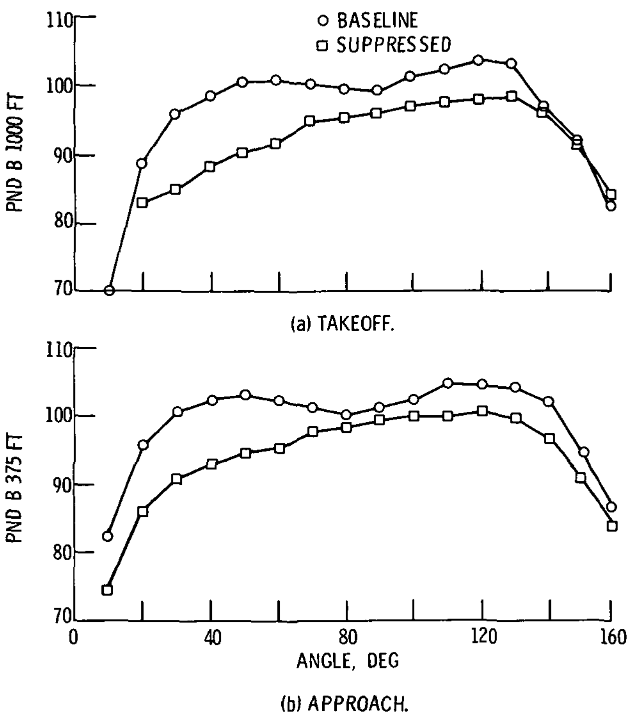


Figure 10. - Quiet engine A - 4 engines.