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QUIET ENGINE DEFINITION PROGRAM FINAL REPORT

BY
JOHN H. LEWIS, III, PROGRAM MANAGER

VOLUME I
SUMMARY

PREPARED FOR
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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

FINAL REPORT
ON THE
QUIET ENGINE DEFINITION PROGRAM
PWA-3516

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SUMMARY

prepared for

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NASA Lewis Research Center
Cleveland, Ohio
Propulsion Systems Acoustics Branch
J. J. Kramer
J. F. McBride

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD, CONNECTICUT

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PREFACE

The Final Report for the Quiet Engine Definition Program has been prepared in five volumes. This volume summarizes the Quiet Engine Definition Program. Brief discussions of all four tasks are contained in this volume as well as the over-all results of the program. The titles of the other four volumes are given below:

Volume II	Task I
Volume III	Task II
Volume IV	Task III
Volume V	QE-3 Performance

QUIET ENGINE DEFINITION PROGRAM
FINAL REPORT

by

John H. Lewis, III

ABSTRACT

The Quiet Engine Definition Program has defined a study engine whose noise is substantially reduced from the level of current commercial transport powerplants. The resultant Quiet Engine configuration evolved from a series of three tasks which narrowed the selection by stages from a broad parametric study, through four candidate engines to a final detailed design.

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The Quiet Engine program has defined a study engine with predicted noise levels substantially reduced from current powerplants.

Initiated in July 1967 by NASA - Lewis Research Center, the program's original goals were to achieve maximum practicable noise reductions from current long range transport aircraft.

Some fifteen months later, Pratt & Whitney Aircraft has completed an engine design which can potentially result in substantial noise reductions for such aircraft. While noise reduction features were of overriding importance, the Quiet Engine has been designed to ensure its practical application to commercial subsonic transport aircraft.

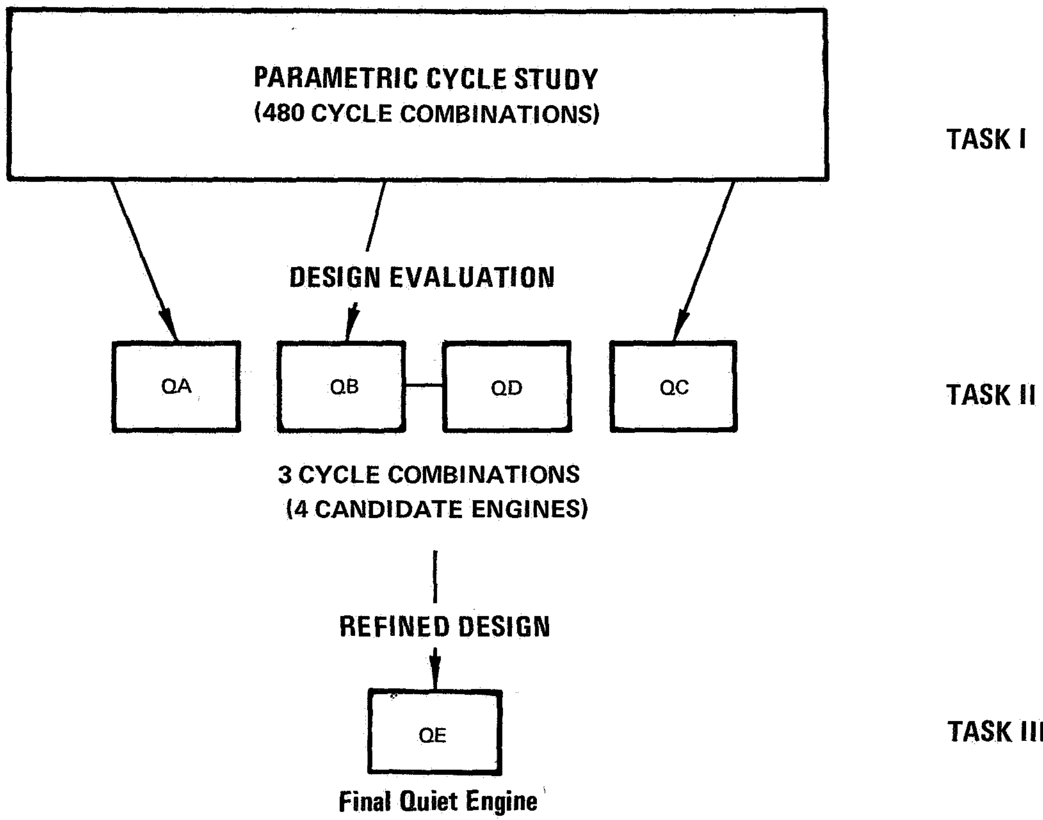
Definition of the Quiet Engine has involved a screening process broken into three separate tasks.

The first task evaluated a wide spectrum of cycle variables. Task I determined broadly the effects of varying the cycle design on noise, performance and engine weight and dimensions.

The second task evaluated designs of four candidate engines selected on the basis of the important trends revealed by the Task I results. Task II narrowed and refined the effects of cycle variation and evaluated variations in configuration arrangement.

The third task refined the design of a final selected engine whose characteristics were specified by the NASA Project Manager based on the Task II results and Pratt & Whitney Aircraft's contractor recommendations.

TASK SUMMARY



Task I, the parametric study, covered a wide range of advanced cycles:

TASK I

RANGE OF CYCLES COVERED

Turbine Inlet Temperature, °F	
Take–Off	**1600–2300**
Cruise	**1600–2100**
Bypass Ratio	**3–8**
Cycle Pressure Ratio	**15–30**
Fan Pressure Ratio	**1.3–1.7**

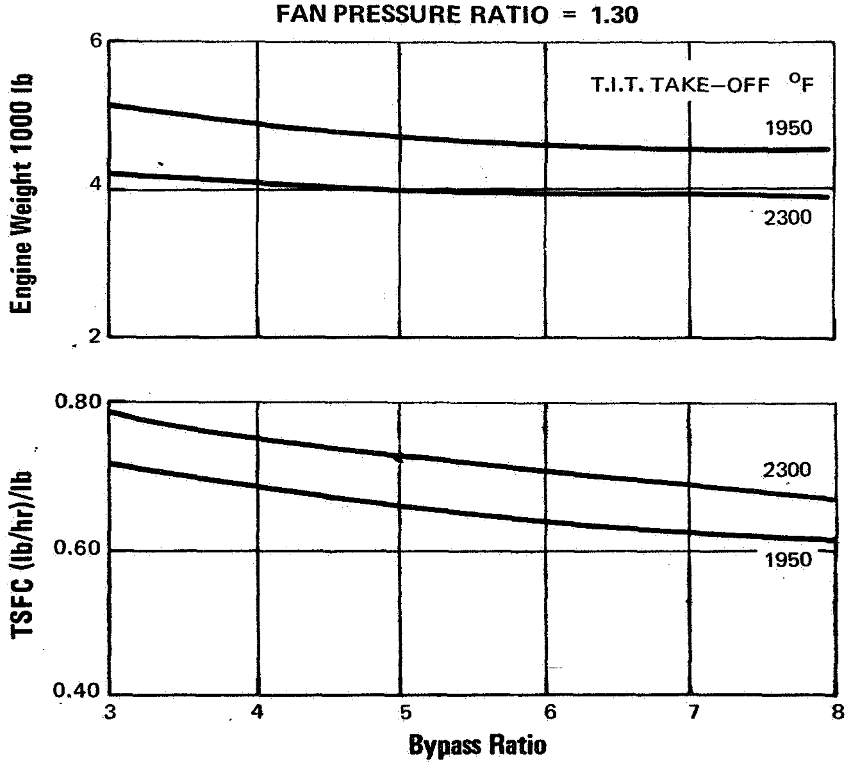
Covering such a wide range, Task I results required careful evaluation and interpretation. Trends of the influence of cycle variables are illustrated by the figure opposite which shows typical effects of varying turbine inlet temperature and bypass ratio for certain fixed pressure ratios. Evaluating such effects led to the determination of the important trends from both a performance and practical design standpoint

TYPICAL TASK I RESULTS
CRUISE TSFC AND ENGINE WEIGHT vs BYPASS RATIO AND T.I.T.

F_N CRUISE = 4900 LBS R_C = 24.5

F_N TAKE–OFF = 25,000 LBS

FAN PRESSURE RATIO = 1.30



The following figure illustrates trends of the influence of cycle variations on noise. In this case, bypass ratio alone is varied while each of the other variables is fixed at some level. While cycle performance considerations focus on cruise conditions where fuel consumption is most important, noise considerations are dictated by take-off, cutback and approach conditions. Task I results involved the effects of complex interactions of engine off-design matching with cycle design performance. However, as a net result variations in cycle parameters in the range of interest do not influence total noise to a significant extent.

TYPICAL TASK I RESULTS

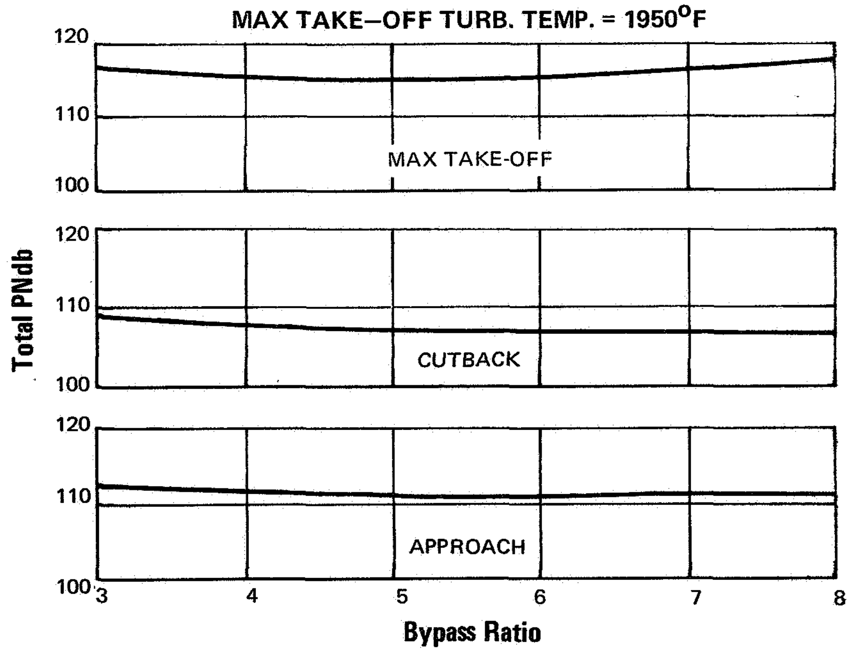
TOTAL NOISE vs BYPASS RATIO AND T.I.T.

F_NCRUISE = 4900 LBS R_C = 24.5

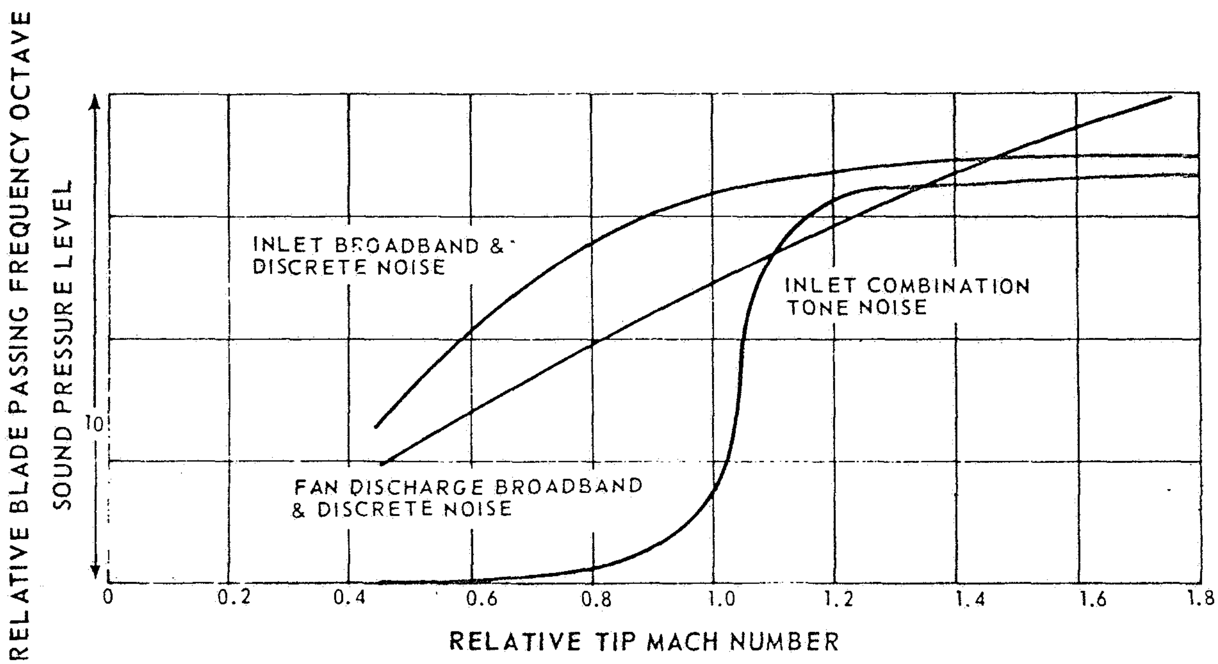
F_N TAKE-OFF = 20,000 LBS

FAN PRESSURE RATIO = 1.55

MAX TAKE–OFF TURB. TEMP. = 1950°F



The Task I study was predicated on experimental evidence which has correlated the prime sources of fan noise directly with mach number relative to the blade tip, thus tip speed:



This correllation came to be a dominant factor in the Task I results since no cycle combination manifested itself as the direct means for achieving the program objectives. In the range of practical cycles revealed by the Task I study, fan noise as influenced by tip speed remained the predominant source of engine noise.

TASK I

OVERALL NOISE RESULTS

Within Range of Variables Considered

- **Fan Noise is the Predominant Source**
- **Cycle Variations are Apparently Not a Major Influence**

CONCLUSIONS

- **Evaluate Cycle Bypass Ratio Variations in Task II Designs**
- **Keep Fan Tip Speed Low**
- **Use Lightly-Loaded Two-Stage Fans as Necessary to Maintain Low Tip Speed**

The candidate engines selected for Task II covered a wide range of bypass ratio in order to better evaluate the effects of that parameter.

Since Task I had proven its influence on noise to be negligible, a high level for overall pressure ratio was selected for all Task II engines to achieve good performance.

The mechanically simpler two-spool approach required a high pressure spool somewhat beyond demonstrated aerodynamic capability to achieve the high overall pressure ratio. A three-spool variant of the 5.0 bypass ratio engine represented one approach to divorcing the low speed fan spool from the gas generator.

The need for low fan tip speed underscored by the Task I results led to the selection of two-stage, lightly loaded fans for the two lower bypass ratio candidate engines.

TASK II

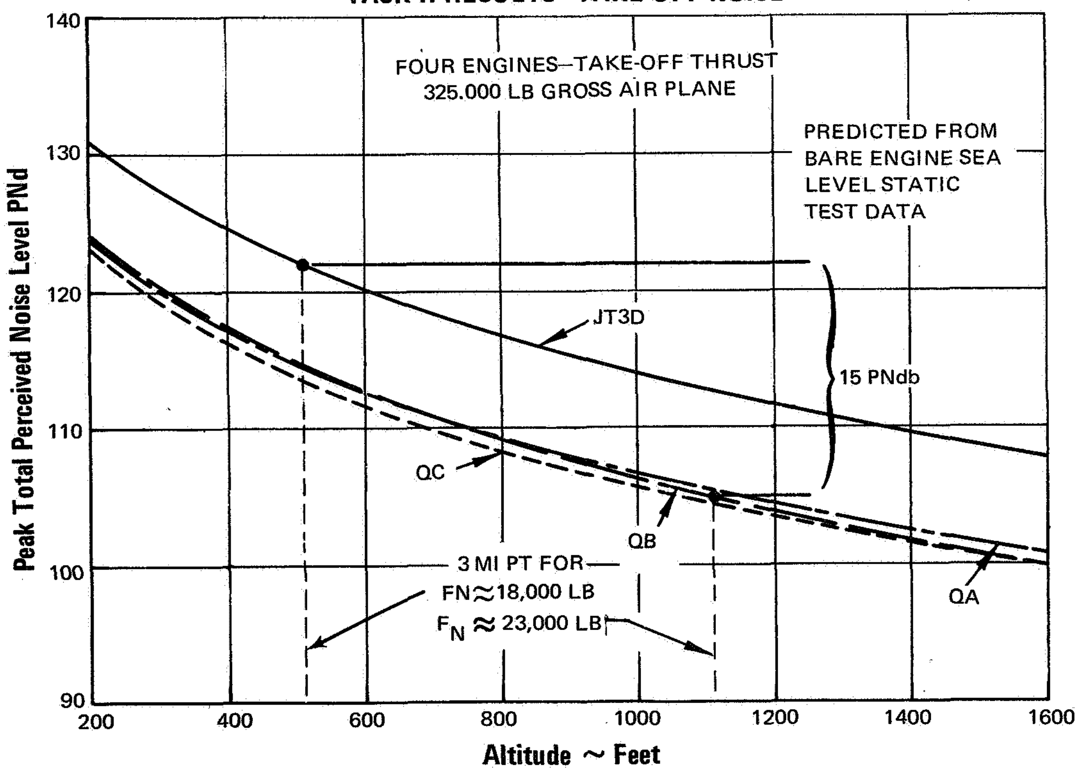
SUMMARY OF CANDIDATE ENGINES

P&WA Designation	QA	QB	QC	QD
Bypass Ratio	3.0	5.0	8.0	5.0
Overall Pressure Ratio	24.1 →			
Configuration	2 Stage Fan	2 Stage Fan	Single Stage Fan	2 Stage Fan Three Spool Version of QB

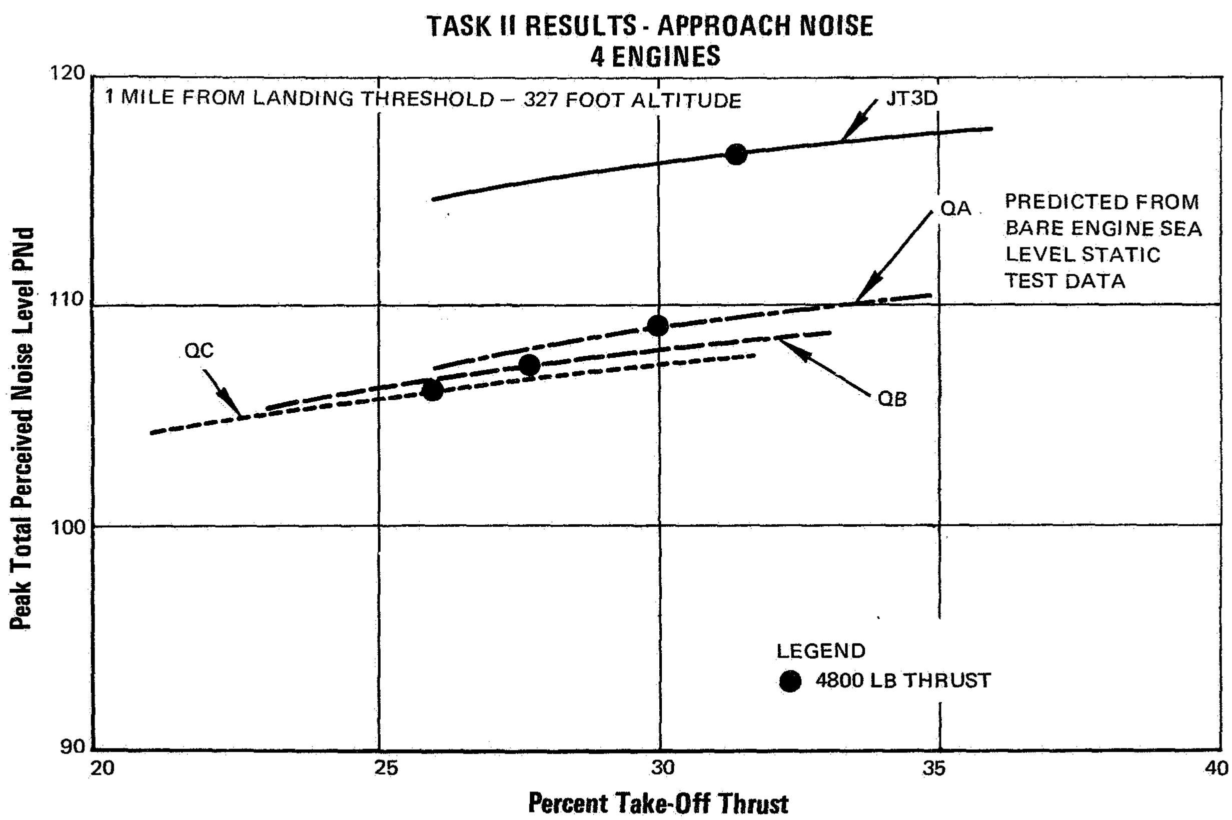
Results of noise calculations for the candidate engines are presented below as a function of altitude for take-off. All candidate engines tend to fall on about the same line simply as a result of being designed for the same fan tip speed.

The 23,000 lb thrust level of the Task II candidate engines compared to the JT3D's 18,000 lb will enable the airplane to climb out to a sufficiently high altitude that the noise on the ground is 15 PNdb below the current JT3D powered 707-DC8 type aircraft, even at full take-off power. The Task II engines, sized in thrust for the cruise condition, had the advantage of increased lapse rate from cruise to take-off inherent with higher bypass ratio.

TASK II RESULTS - TAKE-OFF NOISE

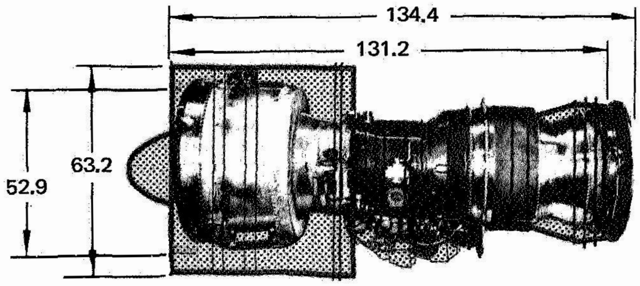


For the approach condition the noise of the engine installed in the airplane is primarily a function of the power setting. Landing height above ground is dictated by the maximum glide slope. For the landing approach at any one altitude the noise levels of the candidate engines compared with the JT3D are in roughly the same relative positions as for take-off. The take-off and approach noise comparisons are predicated on sea-level test data, which, when projected to the fan equivalent conditions in an actual aircraft, may not necessarily agree exactly with measured levels. However, being based on a common prediction system, the indicated relative levels are consistent for comparison purposes.

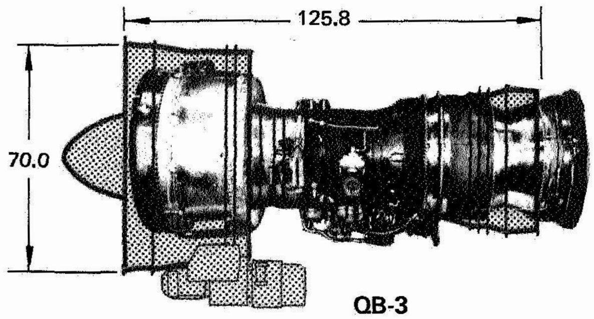


TASK II

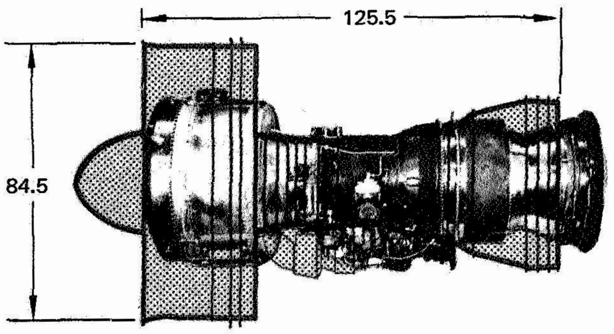
WEIGHTS AND DIMENSIONS SUMMARY



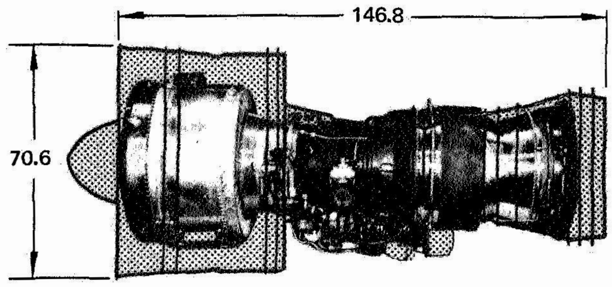
QA-1 (WEIGHT 5,000 LBS)
JT3D-3B (WEIGHT 4,260 LBS)



QB-3
(WEIGHT 5,420 LBS)



QC-3
(WEIGHT 5,610 LBS)

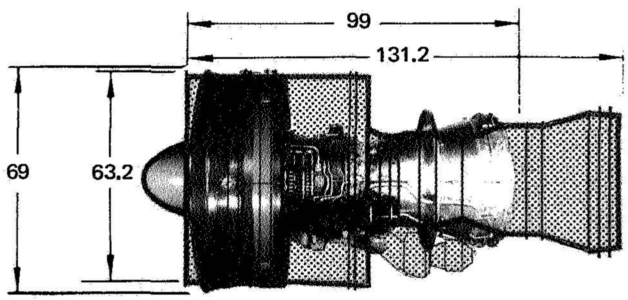


QD-1A
(WEIGHT 5,570 LBS)

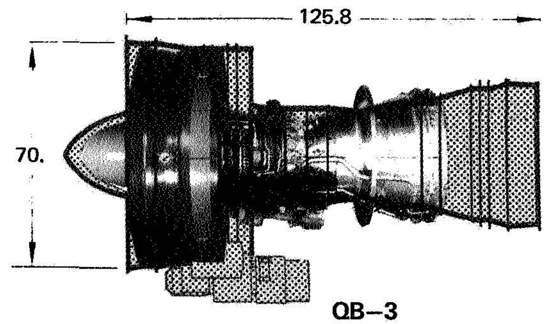
Outline schematics of the Task II designs superimposed over the current JT3D engine illustrate the physical dimensions of the Quiet Engine candidates. Parallel studies under NASA contract to McDonnell-Douglas Aircraft Corporation (NAS3-11151) are currently evaluating the installation characteristics of quiet engines in DC-8 type aircraft.

TASK II

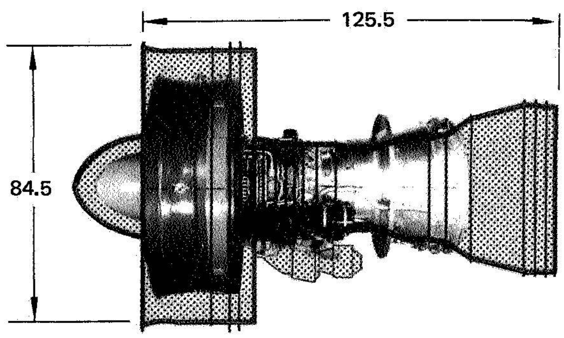
WEIGHTS AND DIMENSIONS SUMMARY



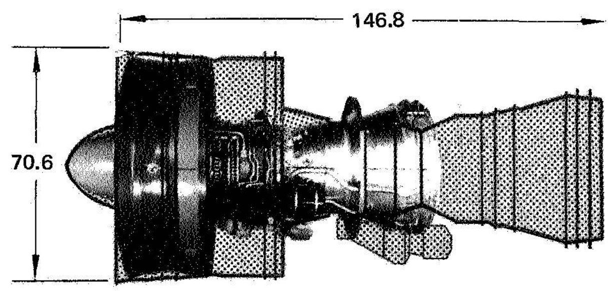
QA–1 (WEIGHT 5,000 LBS)
SCALED JT9D (WEIGHT 3,930 LBS)



QB–3
(WEIGHT 5,420 LBS)



QC–3
(WEIGHT 5,610 LBS)



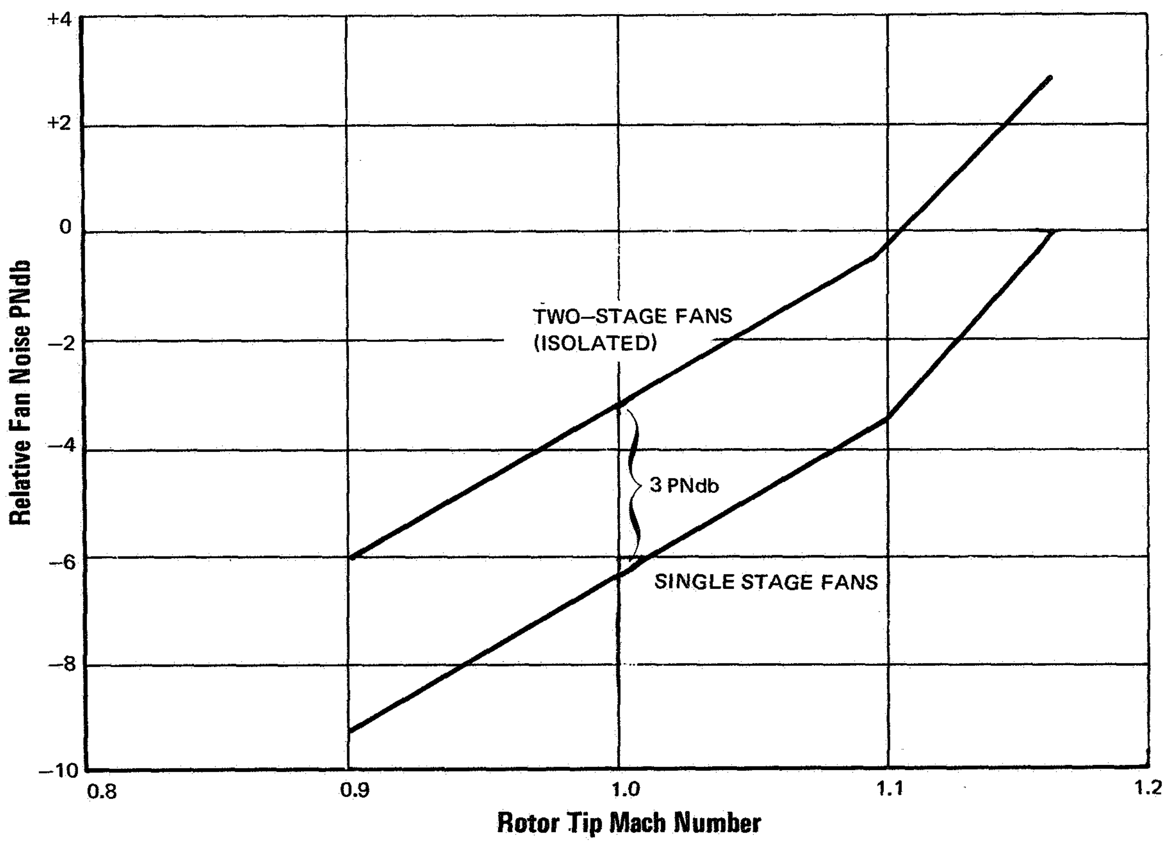
QD–1A
(WEIGHT 5,570 LBS)

This chart compares the Task II configurations with the JT9D engine scaled to the same thrust. Here comparison is made of Quiet Engine Candidates with an engine of comparable technology. On this basis, the candidate engines are appreciably larger and heavier. The extra size is chiefly attributable to the added fan stage and extra turbine stage required to compensate for the reduced rotational speed needed for low fan tip speed.

The Task II candidate engines were designed for considerably reduced tip speed in an effort to reduce relative tip Mach number. Experimental evidence indicates that this is a fundamental parameter in correlating noise generation. In consequence, the 3.0 and 5.0 bypass ratio engine fans required two lightly-loaded stages to produce at low speed pressure ratio levels consistent with their cycles. A two-stage fan generates noise from twice as many blade rows as a single stage fan. This effect is accounted for in the prediction system which indicates at lease 3 PNdb higher noise for two stages. In addition, without adequate spacing between rotors and stators, an interaction effect will result in an even larger difference than predicted.

Meeting the program goals argued strongly for maintaining low fan tip speed while realizing a high pressure ratio in a single stage fan. In addition, the single stage fan could lead to a more practical engine configuration arrangement.

SINGLE-STAGE FANS PRODUCE LESS NOISE THAN TWO-STAGE FANS



In summary, the Task II design demonstrated the mechanical design limitations incurred by a two-stage, low tip speed fan design. At the same time, the potential fan noise reduction from low tip speed with two stages was clearly not adequate, particularly for the landing approach condition.

The Task II study also revealed that in the bypass ratio range from 3 to 8 total engine noise can be made roughly equal by proper design. However, engines with bypass ratios less than about 5.0 exhibited jet noise levels which were considered excessively high if the engine were to be installed in an acoustically treated nacelle; while engines with bypass ratios greater than about 6.0 were considered too large for optimum aircraft installation.

The configuration characteristics selected for the final Quiet Engine design to be evaluated in Task III embodied all background experience and knowledge derived from Task I and Task II studies while not resembling any specific one of the Task II candidate engines.

Designated QE, the selected Task III Quiet Engine cycle lends itself both to low noise and a practical configuration arrangement.

To keep total noise levels low, a single stage low tip speed fan was selected.To keep jet exhaust noise levels well under the predominating fan noise (on the order of 10 PNdb), a 5.4 bypass ratio was selected. Jet noise became a dominant factor influencing the cycle selection in Task III in anticipation of potential installation of the engine in an acoustically designed nacelle. Although the use of the engine in an acoustically designed nacelle was then considered, all noise estimates in this report are based on engine noise without nacelle acoustical treatment.

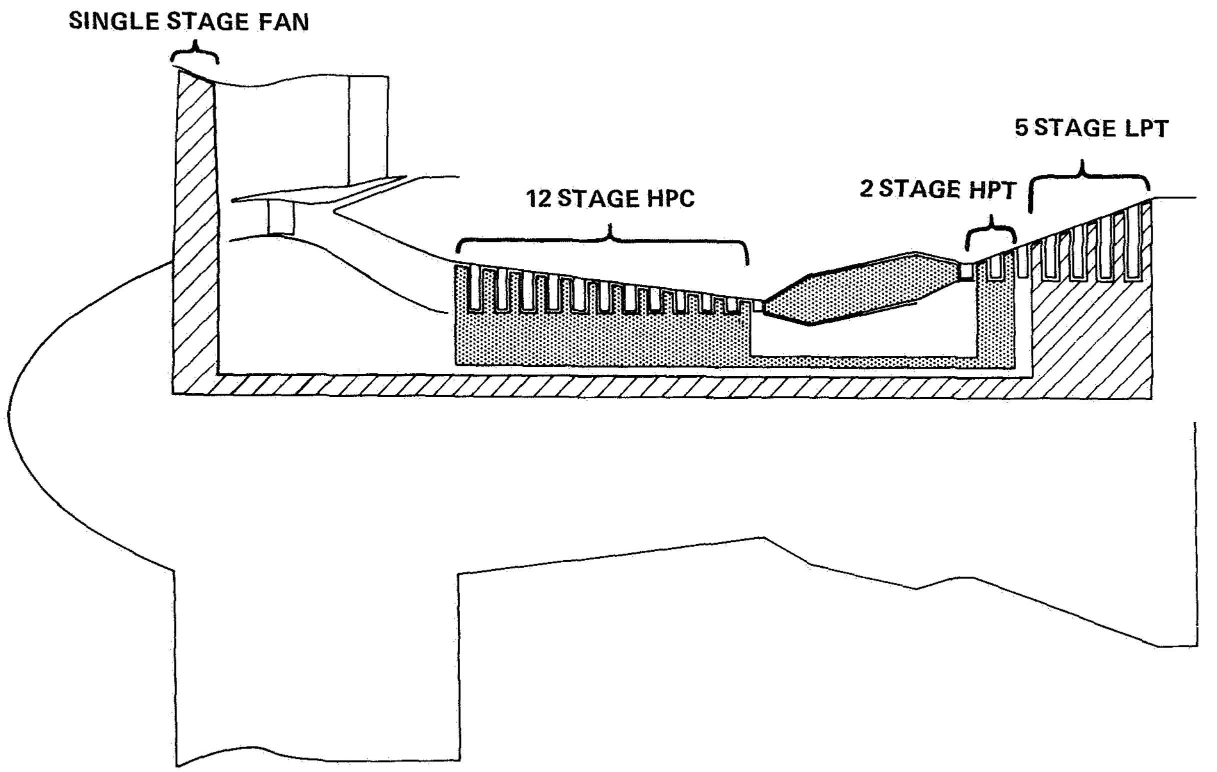
A two spool arrangement with the fan on a separate spool lends itself to a relatively compact, straightforward mechanical design. The 12 stage high pressure compressor is derived from current Pratt & Whitney Aircraft R&D technology and can be confidently expected to have minimum development risk.

The fan and high pressure compressor develop a combined pressure ratio of about 19:1. This level, coupled with the 5.4 bypass ratio, gives QE cycle performance that is equivalent to next-generation commercial transport engines.

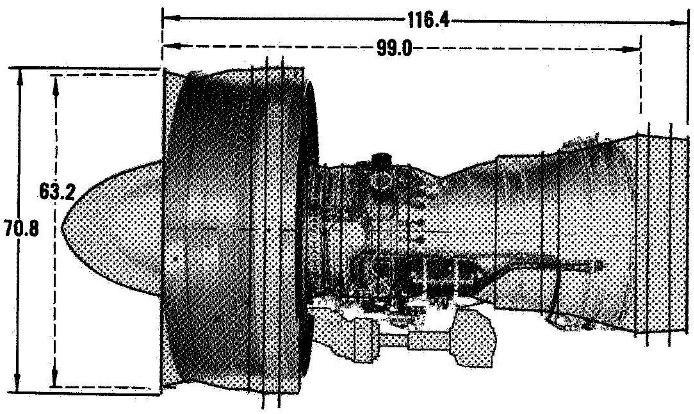
TASK III

QE–3 ENGINE

5.4 BYPASS RATIO 19.1 OVERALL PRESSURE RATIO



COMPARISON OF
QUIET ENGINE (QE-3) WITH SCALED JT9D



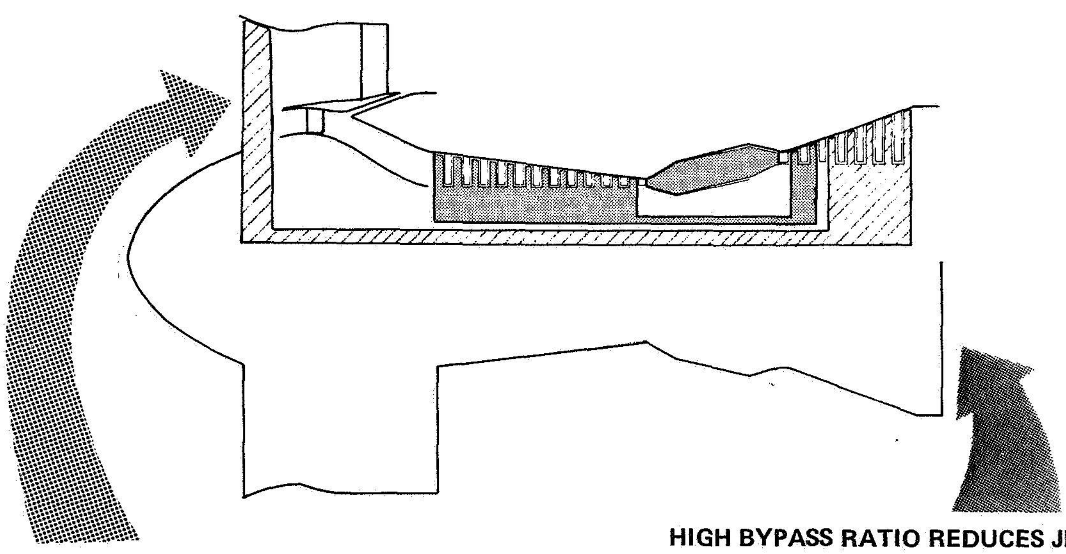
QE-3 (WEIGHT 4950 LBS)
SCALED JT9D (WEIGHT 3900 LBS)

As a Quiet Engine the QE-3 final Task III design features high bypass ratio and moderate turbine inlet temperature levels to reduce jet noise significantly from current levels. This is particularly important when considering the complete engine installation in the aircraft with external acoustical treatment.

Based on predicted results, the QE-3 low tip speed, single stage fan enables the Quiet Engine potentially to have fan noise, the predominant source in the turbofan engine, substantially reduced from current levels. In addition, a relatively compact design was achieved which, with the reduced jet noise, makes the engine suitable for acoustical treatment in its installation.

TASK III

QE-3 ENGINE DESIGN FEATURES

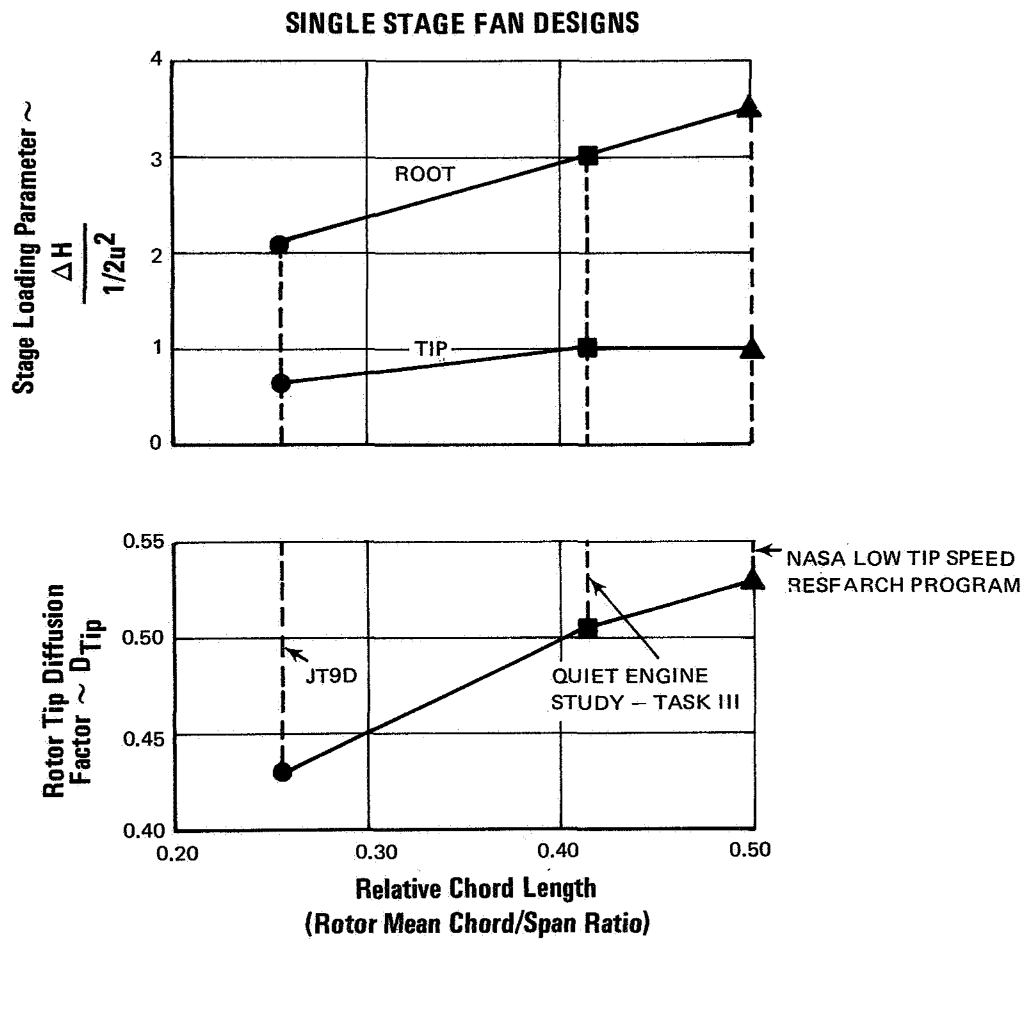


HIGH BYPASS RATIO REDUCES JET NOISE

LOW TIP SPEED SINGLE STAGE REDUCES FAN NOISE

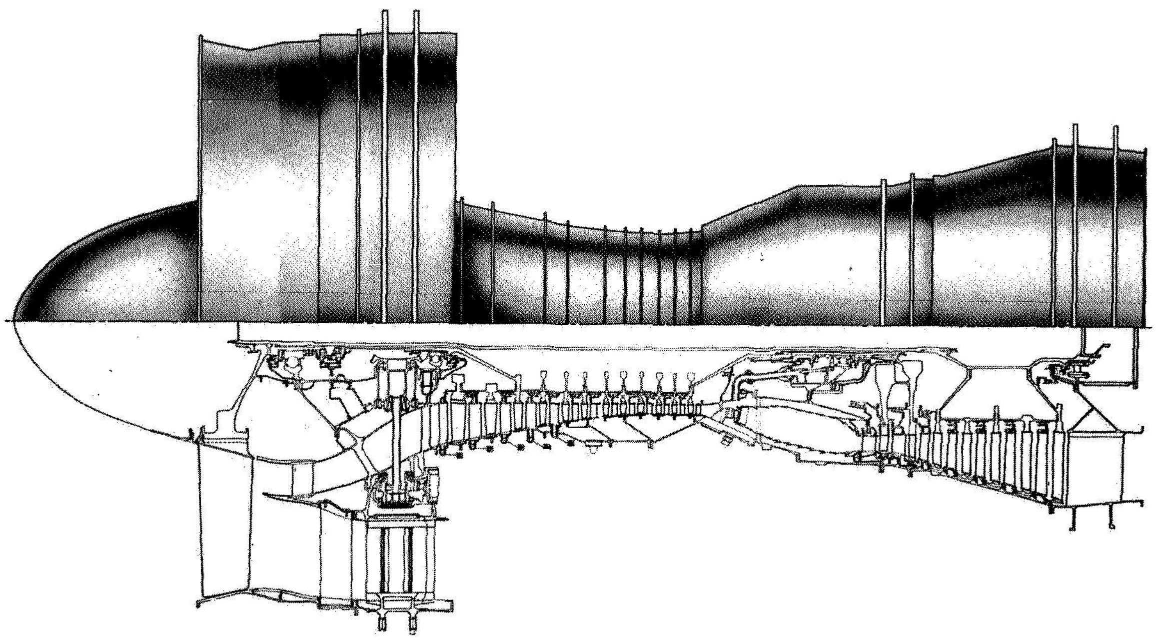
	JT3D	QE-3
Fan Stages	2	1
Tip Speed at take-off	1,430 FPS	1,000 FPS
Bypass Ratio	1.3	5.4
Jet Velocity at Take-off, 180 kts	1,400 FPS	900 FPS
Total noise at Take-off, 4 Eng. 3-mile (4.73-km) point	122 PNdb	104.5 PNdb
Approach Noise, 1 mile (1.61 km) from Touchdown	116.5 PNdb	104.5 PNdb

In order to realize a significant reduction in predicted noise from the current JT3D, the Quiet Engine design must depend on an advanced single stage, low tip speed, highly loaded fan. Such research programs as the NASA sponsored low tip speed single stage compressor program are already leading the way for more highly loaded technologies (as measured by "Diffusion Factor" and "Loading Parameter").



In summary, the Quiet Engine Definition program has incorporated up-to-date commercial engine design techniques, and current Research and Development programs, including both rig and full-scale engine testing, into a comprehensive study program. Concentrating on the primary noise sources, the fan and jet exhaust, a Quiet Engine which represents modern technology in a practical design has been selected by narrowing down from a broad parametric study to a final design.

QE-3 ENGINE



SECTION I

TASK I

The results of the Task I parametric cycle study were trends of engine noise variations, along with variations in performance, weight, and dimensions, as influenced by the primary engine thermodynamic cycle variables. Representative noise, fuel consumption, thrust, and physical characteristic values were obtained for a set of combinations of bypass ratio, over-all compressor and fan pressure ratios, and take-off and cruise turbine inlet temperatures. Noise values included peak PNdb levels at take-off, approach, and cutback during climb-out conditions. In addition, noise contours in the vicinity of the airport were computed at each of the aforementioned conditions for four representative cycle combinations.

In total noise, performance, weights, and dimensions data have been tabulated for 242 combinations of cycle variables for each of two different levels of take-off thrust. A statistical regression analysis technique was used. With this technique, approximately forty cycle combinations were used as a sample set and trends for the remaining approximately two hundred combinations obtained by statistical inference. In this way, accurate performance, noise, weights, and dimensional trends could be found over a broad range of cycle parameters, while properly accounting for all their associated influences.

With such a complex study, general overall trends were difficult to discern, and each general conclusion drawn from the data can be found to have its exceptions. Nonetheless, certain broad trends were inferred and used as a basis for selection of the three candidate engines for further study in Task II. Some of these trends include:

- Lower noise levels occur with bypass ratio and fan pressure ratio combinations associated with lower cruise fuel consumption.
- Take-off turbine inlet temperature has an important influence on take-off noise levels.
- Cycle compression ratio has the least influence on noise levels of all cycle variables.
- Engines with lowest noise levels tend to be large and heavy.
- Particularly for cycle combinations suitably matched in cruise and take-off thrust levels, a wide range of cycle variation results in a relatively small variation in total noise level, which is fan dominated. This is true both for full power, take-off and for reduced power, approach conditions.

- For most cycle combinations fan noise predominates.
- With several promising cycles jet noise levels could be reduced from present levels by 15 PNdb for take-off and 20 PNdb for approach conditions.

The contractual effort centered on a specified range of values for the cycle variables and take-off thrust levels of 20,000 lb. and 25,000 lbs. for an engine to be applied to an aircraft representing the Boeing 707 and DC-8 type. The broad conclusions drawn are valid in range of parameters studied. However, because a wide range of cycle variations results in a relatively small variation in noise levels, the study results could be extended somewhat beyond the ranges covered.

A. PERFORMANCE

In turbofan engines with high bypass ratios, the cruise flight condition is usually the critical operating point from a performance standpoint. The cruise thrust determines the size of the engine and the cruise fuel consumption predominantly influences operating economics. Also, because of the lower exhaust expansion ratios of high-bypass-ratio turbofans, there is a relatively wide variation between the take-off and cruise aerodynamic operating points of the fan. For these reasons, the engine components are usually matched to give their best operating efficiency at cruise, rather than at take-off. For off-design conditions, performance was obtained by using established trial-and-error iterative techniques in which the values of cycle parameters (bypass ratio, cycle pressure ratio, and fan pressure ratio) and airflows were found to satisfy the cruise design values for controlling flow areas in high-and low-pressure turbines and in the engine and fan exhaust nozzles.

For a parametric study of this magnitude, certain simplifying assumptions had to be made. For the fan, a single-stage design was assumed, with a tip speed which increased with fan pressure ratio and an efficiency which decreased with fan pressure ratio. Other component efficiency assumptions are listed below:

- Polytropic compressor efficiency 89%
- Polytropic turbine efficiency 90%
- Engine exhaust pressure loss 1.6%
- Fan duct pressure loss 1.0%
- Nozzle velocity coefficient 0.99

- Burner pressure loss 4.7 - 14.0%
- Turbine cooling airflow (% of compressor airflow) 1.5 - 10.5%

Interpretation of the results involved analyzing combined effects of and interactions among five distinct cycle variables. A few representative trends are discussed as examples in the following paragraphs. The trends represent the middle of the range in each case. It must be emphasized that the trends will vary at the extremes of the ranges.

Figure 1 shows the effect of bypass ratio and take-off turbine inlet temperature on cruise fuel consumption. The curves are typical of turbofan cycle performance. They show that fuel consumption generally decreases with increasing bypass ratio, but increases again at the higher bypass ratios, where the turbine inlet temperature and fan pressure ratio are not optimum. Although the cruise turbine inlet temperature is not given on the curves, its value varies in the same direction as the take-off turbine inlet temperature because of the constant relationship between take-off and cruise thrust. At the highest levels of fan pressure ratio and bypass ratio, insufficient work is available to drive the fan at the specified over-all thrust levels and within the limits of cruise turbine inlet temperature defined by the work statement.

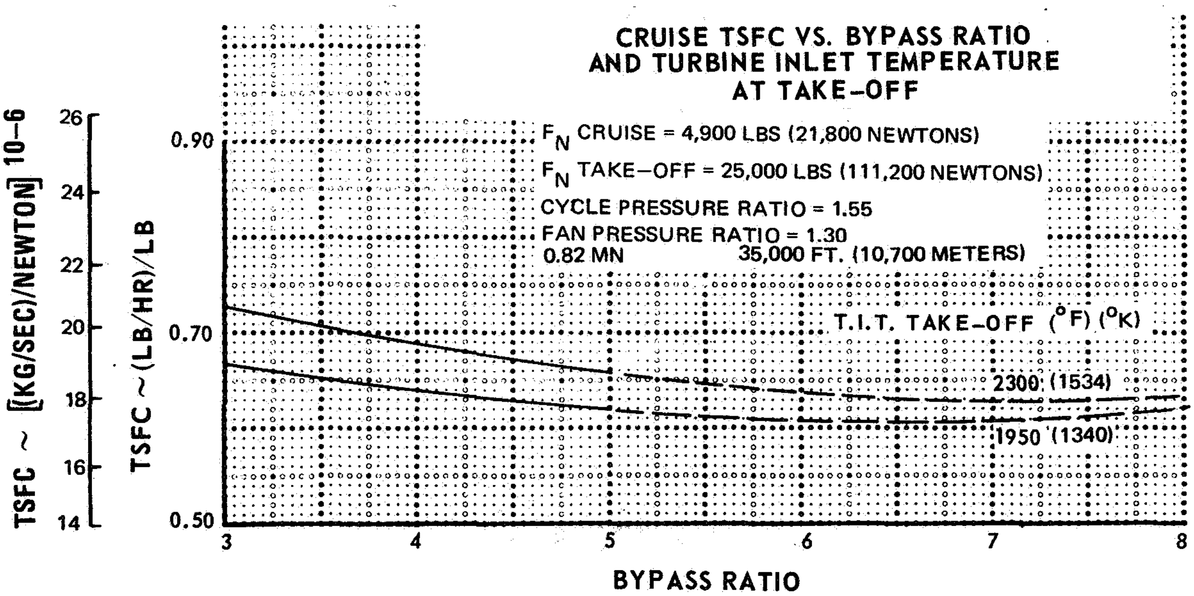


Figure 1 Effect of Bypass Ratio on Cruise TSFC with a Fan Pressure Ratio of 1.55

Figure 2 shows a representative effect of cycle pressure ratio on fuel consumption at the constant levels of thrust and constant values of the other cycle variables. The curve shows thrust-specific fuel consumption to be decreasing with increasing pressure ratio, but leveling off and starting to rise again at the high end. Analysis of the complete parametric study indicated that fuel consumption continued to improve at higher cycle pressure ratios in combination with higher turbine inlet temperatures.

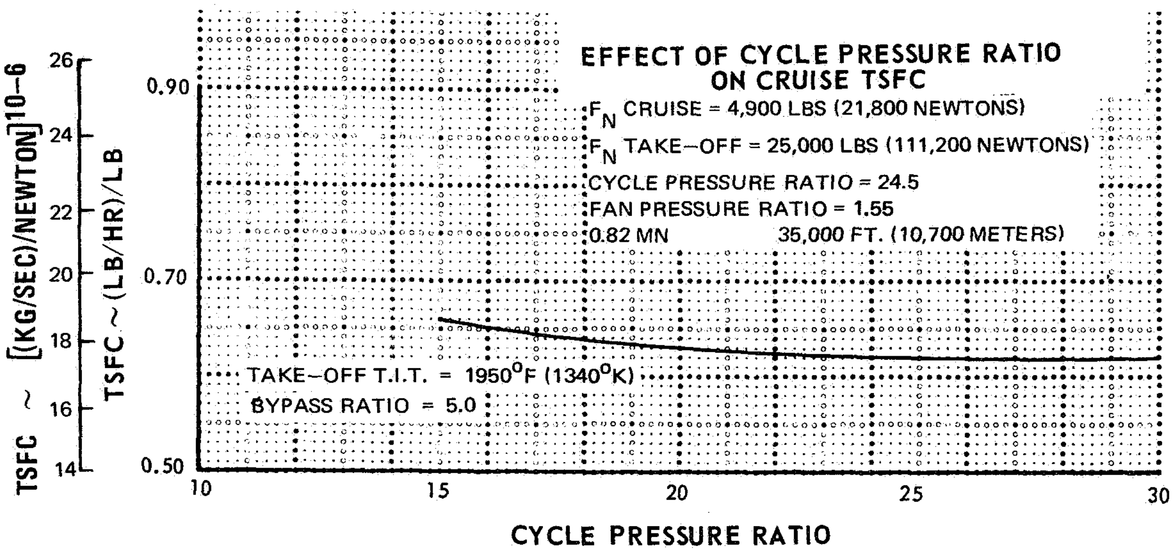


Figure 2 Effect of Cycle Pressure Ratio on Cruise TSFC

B. NOISE

Noise calculations in Task I used the most up-to-date turbofan prediction procedures available. Predictions in detail for 43 sample engine cycles served as the model for the regression analysis which provided noise estimated for the remaining cycles. Additional noise predictions were completed to validate the accuracy of the regression analysis technique.

Estimates of engine noise levels neglected the influence of all sources of noise ordinarily found to be inconsequential, and considered only jet exhaust noise and over-all fan noise as contributing sources. Jet exhaust noise levels were calculated by application of the Lighthill relationship and fan noise levels were approximated by using empirical correlations of noise level with fan tip Mach number. All cycles were assumed to have single-stage fans with the basic noise reduction features of no inlet guide vanes, optimum combinations of number of blades and vanes, and ample axial spacing between the fan blades and the exit guide vanes . The noise analysis revealed several trends. At take-off power, some cycles produce noise levels where the dominant source is the jet exhaust velocity, while in others, fan-generated noise dominates. Generally, low fan pressure ratio, low bypass ratio, and high turbine inlet temperature cycles tend to have high exhaust noise levels.

Fan noise is dominant at cutback take-off power for the majority of the engine cycles considered. It is dominant for all engine cycles at approach power.

Engine size is an important factor in determining take-off noise levels because of the effect of take-off thrust on airplane climb rate. Increased thrust provides lower perceived noise levels on the ground because the increase in attenuation at higher altitudes more than compensates for the increased absolute noise level. Another advantage of the engine with higher thrust is its ability to make larger reductions in power for the cutback to a climb rate of 1000 ft/min (305 m/min) at a shorter distance from the start of the take-off roll.

C. ENGINE WEIGHTS AND DIMENSIONS

The method of determining weights and dimensions for the 242 cycle combinations was based on a statistical regression analysis technique. In this technique, also used to calculate noise, a smaller sample set was evaluated in detail by an analysis of the actual mechanical configuration, and then variational trends were established by a statistical correlation. The determinations of weights consisted of the following sequential steps:

- Select sample combinations (35 in this case).
- Compute design performance and check off-design critical operation performance for each sample.
- Establish a general configuration arrangement by a rough analysis of components.
- Establish bearing and structural arrangements for each sample.
- From a known base configuration (the JT9D) vary weights of each component individually to reflect significant configuration changes such as the number of stages, airflow size, and radius ratios.
- Vary structural weights according to over-all structural arrangement.
- Synthesize individual component and structural weights into an over-all engine weight for each sample.

- Scale to 20,000-pound (80,900-newton) and 25,000-pound (111,000-newton) thrust sizes.

- By regression analysis, compute from the sample cycles weights for all 242 cycle combinations.

As would be expected, the engine weights are directly influenced by turbine inlet temperature levels, the lightest engines coming with the highest temperatures. The bypass ratio and fan pressure ratio effects are less obvious. Since increasing bypass ratio tends to improve propulsive efficiency, over-all engine size tends to decrease with increasing bypass ratio. However, this tendency is offset by the increased weight due to the larger diameters and larger fan drive turbines inherent with higher bypass ratios. As a net effect, there appears to be a gradual decrease in weight with bypass ratio at fan pressure ratios of about 1.3. At higher fan pressure ratios, there is an increase in weight with increasing bypass ratio. At these latter levels, propulsive efficiency does not improve so rapidly with increasing bypass ratio, and turbine work levels are higher, and require larger turbines.

The trend of weight with cycle pressure ratio shows first a slight decrease and then a sharper increase with increasing pressure ratio. This reflects the conflicting effects of reduced engine size with supercharging from the increased pressure ratio, and the increased number of stages required to handle the greater pressure ratio.

SECTION II

TASK II

The effort under Task II was initially devoted to preliminary design evaluations of three selected configurations. At the request of NASA, however, the contract was revised during the task to include an additional configuration.

The completed Task II results consist of mechanical design layouts and performance for four candidate engines. The three configurations initially selected for Task II studies were chiefly distinguished by their design bypass ratios. The design bypass ratios were 3.0, 5.0, and 8.0, and the associated engine designs were designated QA, QB, and QC, respectively. Each engine had an over-all design pressure ratio of 24.5, and the fan pressure ratios were selected to be best suited to each individual bypass ratio. Turbine inlet temperatures were chosen to be consistent with state-of-the-art technology representative of the next generation of commercial transports. These design characteristics were chosen by the NASA Project Manager to take the best advantage of the low noise features of the cycles.

In the selection of the original configurations, the NASA Project Manager further stipulated that the QA and QB configurations (with design bypass ratios of 3.0 and 5.0 respectively) were to be designed with two-stage low-tip-speed fans, while the QC (with a bypass ratio of 8.0) was to have a single-stage low-tip-speed fan. In each case, the low fan tip speed was dictated by the predominant influence of fan noise revealed in the Task I results. The two-stage fans were specified to ensure feasible fan designs with low tip speed and relatively high fan pressure ratios.

The low fan speed also increased the difficulty in realizing the designated 24.5 over-all cycle pressure ratio (to which the inner portion of the fan contributes directly) and shifts an added burden to the compressor section. To ensure that this burden could be met with minimum development risk, the NASA Project Manager added a fourth candidate configuration which employs the three-spool concept. This configuration, designated QD, had a cycle which was identical to the QB cycle, but rather than a single compressor spool with a high pressure ratio, it has the compressor split into two separately rotating spools with moderate pressure ratio.

Originally scheduled to last three months, Task II was extended to five months total duration to allow for adding the QD configuration to the effort. During this period, work on the QA, QB, QC, and QD configurations started with the selection of general arrangements, was followed by the preliminary design of the components, preliminary design layouts, and concluded with predictions of uninstalled performance and noise.

In choosing the general arrangement for each engine early in the task, a series of possible component arrangements was worked out on the basis of preliminary flowpaths, and the most suitable arrangement was selected in each case.

Following selection of the general arrangements, analytical design for each of the major components was undertaken. This phase of the effort was conducted in sufficient detail to define the performance and physical dimensions of the engine components, compressor, turbines, and burner. For the turbine components, such key design variables as blade aspect ratio, passage Mach numbers, and blade loadings were chosen.

Mechanical design layouts based on the completed analytical designs of components involved establishing the mechanical configuration in sufficient detail to define key dimensions, determine predicted weights, and ascertain mechanical integrity. To this end, certain static structures were checked under critical loading conditions and rotor dynamics were checked for adequate critical-speed margins.

Performance tabulations were compiled to define thrust, specific fuel consumption, and other key variables over a range of operating conditions from sea level to 45,000 feet (10,680 meters) and from 0 to 0.9 Mach numbers. These tabulations were submitted to NASA as separate booklets for each engine.

Noise presentation consisted of airport neighborhood contours representing take-off and landing conditions for each candidate engine. Calculations were based on the latest refined techniques of noise prediction developed from full-scale testing of the JT3D (two-stage fan) and the JT9D (single-stage fan).

Noise calculations and engine thrust sizing were also predicated on application of the candidate engine to the Boeing 707 and Douglas DC-8 class of commercial aircraft. Compared to the JT3D-3B engine currently powering these aircraft, all of the Quiet Engines offer appreciable reductions in over-all uninstalled noise at the expense of additional weight and larger physical dimensions, but with lower fuel consumption.

Table I summarizes the over-all configuration, physical characteristics, and performance results for the Task II engine designs.

TABLE I
SUMMARY OF TASK II ENGINE DESIGNS

Designation	QA	QB	QC	QD
Configuration				
Fan	2 stages	2 stages	1 stage	2 stages
Low-Pressure Compressor	3-stage axial	none	3-stage axial	6-stage axial
High-Pressure Compressor	11-stage axial	14-stage axial	14-stage axial	7-stage axial
Combustor	Annular burner with integral diffuser			
High-Pressure Turbine	2 stages	2 stages	2 stages	1 stage
Intermediate- and Low-Pressure Turbines	4 stages	5 stages	5 stages	6 stages
Physical Characteristics				
Weight (lb)	5,080	5,420	5,610	5,570
Weight (kg)	2,300	2,460	2,550	2,530
Maximum Diameter (in)	63.2	70.0	84.5	70.6
Maximum Diameter (cm)	160	178	215	180
Length (in)	131.2	125.8	125.5	146.8
Length (cm)	334	319	319	373
Performance				
Take-off Thrust (lb)	20,670	22,750	25,550	23,300
Take-off Thrust (N)	92,200	101,000	114,000	104,000
Cruise* Thrust (lb)	4,900	4,900	4,900	4,900
Cruise* Thrust (N)	21,800	21,800	21,800	21,800
Cruise* TSFC (hr^{-1})	0.64	0.61	0.60	0.62

* Cruise at 35,000 ft (10,680 m) and Mach 0.82

SECTION III
TASK III

The overall results and conclusion from the Task II study which led to the selection of a final engine for Task III can be summarized as follows:

Result

Two-stage lightly loaded fans add to mechanical complexity and engine length and weight with no obvious noise advantage

Conclusion

Design for a relatively highly loaded, single-stage fan

Result

Fan tip speed rather than bypass ratio has the more direct influence on overall engine noise.

Conclusion

Design for low tip speed with a cycle comparable to conventional, next-generation subsonic transport powerplants.

Result

Proper choice of the design cycle variables can result in a jet noise level well below the fan noise level to allow margin for external acoustical treatment

Conclusion

Select and modify the cycle design variables to ensure relatively low jet noise levels

Although the foregoing itemization tends to oversimplify a rather complex selection process, it does highlight some of the more salient factors leading to the final selection of the Quiet Engine characteristics and their initial specification by the NASA Project Manager. The selected characteristics specified by the NASA Project Manager which initiated the Task III effort were as follows:

• Nominal cycle bypass ratio	5.5
• Cruise design point turbine inlet temperature at 35,000 feet (10,069 meters), Mach 0.82	1750°F (1228°K)
• Standard day sea level take-off turbine inlet temperature	1950°F (1339°K)
• Primary jet exhaust noise level goal on take-off at the 3-mile point	90 PNdb
• Bypass portion fan pressure ratio (approximately)	1.5
• Configuration	two-rotor with single-stage fan on separate rotor
• Maximum design pressure ratio on one compressor rotor	12.5:1
• Overall cycle pressure ratio	to be determined by Task III studies within above constraints
• Maximum cruise rating thrust	4,900 pounds (21,800 N)

The overall Task III work effort to complete an engine design around these specified characteristics involved six main stages:

1. A "fine-tuning" study to define more precisely values for the design cycle variables which achieve an optimum arrangement within the constraints of maximum jet noise and maximum compressor-spool pressure ratio.

2. A fan integration study to determine fan design characteristics best suited to low noise and compatibility with the overall engine design.

3. A preliminary aerodynamic design analysis for each component.

4. Conceptual mechanical design leading to a preliminary engine structural arrangement.

5. Detailed aerodynamic design of the fan.

6. Detailed aeroelastic analysis and mechanical design of the fan.

These six main stages of effort represent the major work statement provisions and were completed in the listed sequence during the course of Task III. In addition, the work statement called for:

7. Determination of fan and engine noise minimization features.

8. Prediction of engine noise levels.

9. Tabulation of engine performance data.

10. Preparation of a design specification.

Broadly, undertaking these final items depended on the results of the overall mechanical and aerodynamic design effort, and they were individually completed towards the end of the Task.

The four candidate engines of Task II were identified by the designations QA, QB, QC, and QD. The final engine selected for the Task III refined design effort has been designated QE. Compared with the engines powering current large, subsonic transport aircraft, the QE-3 engine (the -3 signifies the third variation evolved during the course of the task) potentially is not only substantially quieter, but also has appreciably lower fuel consumption, and its weight and dimensions are expected to be within the requirements for practical application to future aircraft. Table II summarizes the performance and physical characteristics of the QE-3 design, which is illustrated in Figure 3.

TABLE II
SUMMARY OF QE-3 ENGINE CHARACTERISTICS

Performance

Design Bypass Ratio	-	5.4:1
Design Overall Pressure Ratio	-	18.9:1
Cruise* Thrust	-	4,900 pounds (21,800 N)
Cruise* Thrust-Specific Fuel Consumption (Minimum)	-	0.62 $hour^{-1}$
Take-off Thrust	-	22,000 pounds (97,800 N)

* 35,000 feet (10,069 meters) at Mach 0.82

Configuration Arrangement

Spool Arrangement		Two-spool, fan plus high-pressure compressor
No. Stages:		
Fan	-	1
High-Pressure Compressor	-	12
High-Pressure Turbine	-	2
Low-Pressure (fan driving) Turbine	-	5
Combustor	-	Annular

Physical Characteristics

Weight	-	4,950 pounds (2,240 Kg)
Max. Diameter	-	70.8 inches (180 cm)
Overall Length	-	116 inches (295 cm)

Predicted Peak Flyover Noise (4 Engines)

Take-off (1,000 feet* altitude):

Total Noise	-	103.5 PNdb
Jet Exhaust Noise	-	93.0 PNdb

Landing Approach (325 feet* altitude, 4800 pounds** thrust):

Total Noise	-	104.5 PNdb
Jet Exhaust Noise	-	84.0 PNdb

* 1000 feet = 305 meters
325 feet = 99 meters

**4800 pounds = 21,400 newtons

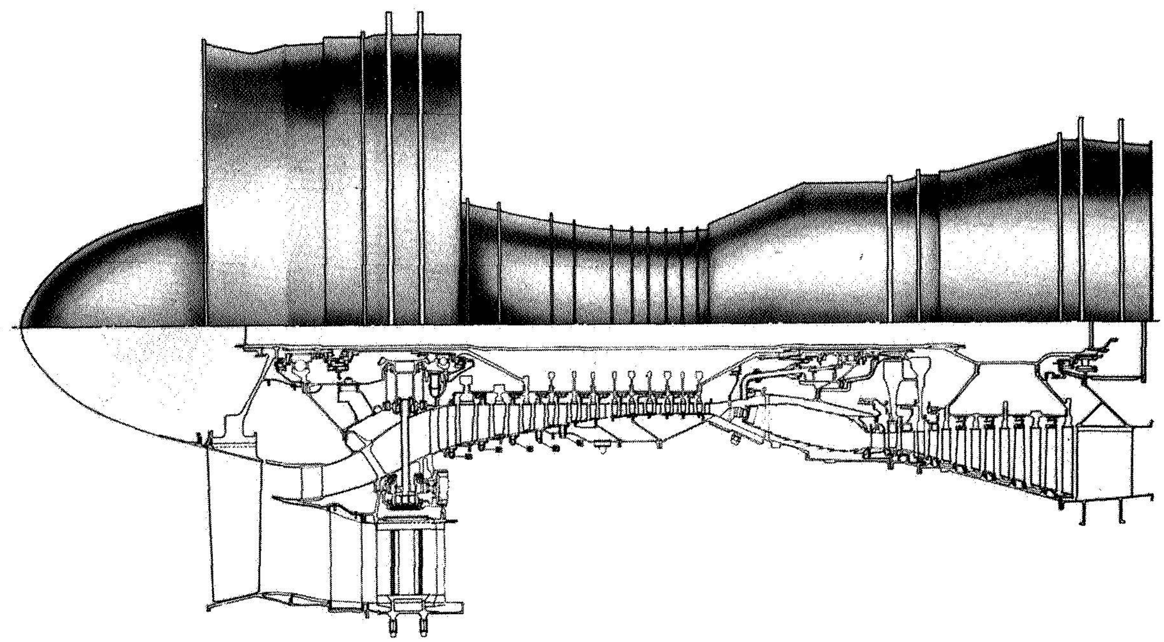


Figure 3 The QE-3 Engine

SECTION IV

TASK IV

The Task IV portion of the Quiet Engine Definition Program called for the preparation of a plan which would outline the research and development effort considered by the contractor to be a proper continuation of the work accomplished under the present program. Following the requirements of the Task IV work statement, this plan included content, time scheduling, and costs for both component and engine demonstration programs as well as a description and specification of test procedures.

In order to formulate a recommended follow-on program, a scope or end objective had to be defined. Engine development programs can vary greatly as end objectives change. Four development programs of three scopes were defined during Task IV: any of these programs would constitute an appropriate extension of the Quiet Engine Definition Program, depending solely on NASA's objectives and available funding. The three program scopes are discussed briefly below:

Scope I — Design a demonstrator engine which is suitable for testing advanced-technology low-noise fans and providing a technological base for the possible follow-on development of an engine capable of providing sole flight power for an aircraft similar to the Boeing 707 or Douglas DC-8. This engine is to be developed and tested to the point where mechanical integrity is established and to where reliability is enough to permit the engine to be used as a test vehicle for low-noise fans.

Scope II — Design a turbofan engine which is suitable for providing sole flight power for an aircraft similar to the Boeing 707 or Douglas DC-8. Development of a ground-test version of this engine shall be carried to a status equivalent to prototype qualification. This development level is judged to be the minimum acceptable for man-rating purposes. ("Man-rating" is approximately equivalent to the military Preliminary Flight Rating Test.) The test engine(s) may deviate from a flight version in regards to the design and arrangement of external components and aircraft installation compatibility. However, the test engine design shall not preclude the direct use of the basic structure for providing flight power for a Boeing 707 or Douglas DC-8 type of aircraft.

Scope III — Design, develop, and test a turbofan engine to the point where it is suitable for providing flight power for a Boeing 707 or Douglas DC-8 type of aircraft. This final development status will be equivalent to prototype qualification. The external engine components shall be flight prototypes, and the engine will be directly installable in a designated airplane. Official qualification of the engine is not within the scope.

In the Task IV work, four alternate development plans were prepared. Two of these plans were aimed at meeting the Scope I objectives outlined above. Single plans were prepared for meeting the Scope II and Scope III objectives. The Scope II and Scope III plans were based entirely on historical data and were presented to NASA for broad planning purposes only. The two Scope I demonstrator programs were developed in more detail and were capable of being used for more definitive planning by NASA.