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THE EFFECT OF NOISE CONSTRAINTS ON ENGINE CYCLE OPTIMIZATION FOR LONG-HAUL TRANSPORTS

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Abstract

Results are presented of NASA contractor studies to determine optimum engine cycles for noise levels of 10, 15, and 20 EPNdB below current FAA regulations. The study aircraft were 200-passenger trijets flying over ranges of 5556 and 10,200 km (3000 and 5500 n.mi.) at cruise speeds of Mach 0.90 to 0.98. The economic impact of reducing noise, the identification of needed advanced technology and the effect of these advances are presented. The studies showed that the noise constraints imposed compromises on the optimum cycle with resulting economic penalties. The application of advanced engine technologies, however, could effectively offset these economic penalties.

Introduction

Historically, the propulsion system has set the pace for advances in aircraft development. Therefore, propulsion system technology ranks high on the list of factors that affect advances in future long-haul, high subsonic transport development. Advances in technology, however, must be directed toward improved economics as well as performance and service. Furthermore, in view of the widespread and increased sensitivity to environmental problems, such as noise and exhaust pollution, future aircraft also must be readily accepted by the general public.

The recent Joint DOT-NASA Civil Aviation Research and Development Policy Study (CARD study, references 1 and 2) recommended stringent goals relative to aircraft noise and emissions. Current research indicates that significant reductions of these environmental factors can be accomplished, but, at the expense of some economic performance. However, regardless of the magnitude of such penalties, it is obviously desirable to utilize advanced technology to provide offsetting gains.

To identify the propulsion system technologies needed to achieve the noise goals with minimum economic penalty, NASA embarked on a study effort with two contractors to conduct engine studies in parallel with airframe system studies conducted by three airframe contractors. Engine system optimization required concurrent studies which surveyed a broad distribution of design variables including aircraft configuration, payload, range, speed, and the sensitivity of the aircraft to engine performance and weight. The engine optimization was also dependent on forecasts of the rate of advancement of the required technologies. Complex economic factors and maintainability requirements in commercial airline use further complicated engine design. Therefore, close coordination between the engine and airframe study contractors was maintained to ensure that the application of advanced technology was integrated into a total advanced transport system.

The engine design studies were to identify the propulsion system advances having the greatest payoff with respect to noise (and pollution) reduction and/or performance improvement. A further toal was to define the research required to assure the readiness of the advanced technologies for application to the next generation transport aircraft. Considered in the studies were technologies applicable to 136,000 kg (300,000 lb) class aircraft designed for carrying 200 passengers over ranges of 5556 and 10,200 km (3000 and 5000 n.mi.) at cruise speeds of Mach 0.90 to 0.98. The cruise speeds studied are higher than those for current long-haul transports. The contractors selected cycles with assumed technology levels commensurate with commercial certification dates of 1979 and 1985 with corresponding prescribed noise reduction objectives.

The object of this paper is to discuss the effect of noise constraints on cycle optimization for advanced long-haul transports as developed in the above-mentioned contractor studies. Covered will be the results of the parametric studies to achieve noise levels down 10 and 15 EPNdB below FAR Part 36, and studies to attain even lower noise levels. The economic impact of reducing noise, the identification of advanced technology needed, and the economic impact of these technology advances will also be shown. The individual portions of this overall study have been reported in detail in references 3 through 10.

Parametric Studies for Prescribed Noise Objectives

Objectives

The major objectives of the engine design study was to define, in terms of direct operating costs (DOC) and return on investment (ROI), the economically optimum conceptual propulsion systems to meet the noise objectives set for the certification dates of 1979 and 1985.

The noise objective for the 1979 engine was to meet 10 EPNdB below FAR Part 36 without the use of aircraft operational procedures. The 1985 engine was to meet a noise level objective of at least 15 EPNdB below FAR Part 36 without aircraft operational procedures. The 1985 engine study also included a noise goal of 20 EPNdB below FAR Part 36, which could be met by using both engine technology advances and aircraft operational procedures. Restricted pollution constraints were also included. The optimum cycle characteristics were found by conducting a parametric cycle study covering the cycle and aircraft mission variables and ranges shown in Table I.

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Selected Cycles

Based on the results of parametric cycle studies covering the variables indicated in Table I, each contractor selected the economically optimum cycles satisfying the noise objectives for the aircraft missions and certification dates specified.

Cycle description. Both contractors selected essentially the same basic fixed-area turbofan cycle for the respective certification dates. Detailed results of the parametric studies are reported in references 4 and 5. The ranges of the selected cycle parameters for the range of mission parameters covered are shown in Table II.

One contractor selected a highly loaded, high tip-speed, single-stage fan with a mixed flow exhaust (fan and core exhaust mixed before discharge), while the other chose a low-loaded, low tip-speed, two-stage fan with a separate (or non-mixed) flow exhaust. The differences in the number of fan stages were attributed to the individual assumptions of the source noise generation with respect to tip-speed and loading. Similarly, the differences in the exhaust systems resulted from varying assumptions for the effect of mixing, boattail drag, and weight on cruise performance. It was also apparent that the cruise fan pressure ratios of 1.8 to 2.0, which are higher than the values for the newest long-range aircraft (1.5 to 1.6) would be required.

Noise levels. The resulting predicted noise levels in EPNdB are presented for a 136,000 kg (300,000 lb) class tri-jet at sideline, approach, and takeoff with cutback power for the 1979 certification date in Figure 1, and for the 1985 certification date in Figure 2. Turbomachinery low noise features such as rotor-stator spacing and optimum blade-to vane ratios were included in all selected engine designs. The 1979 acoustic technology used for Figure 1 by both contractors included improved liner effectiveness over that of current technology treatment. Assumptions for the 1985 acoustic technology for Figure 2 however, were different. Application of an assumed source noise reduction of about 5 EPNdB was used for the single-stage fan, whereas, only further improvements in liner effectiveness were applied to the two-stage fan. The effect of the reduced source noise assumptions is evidenced by noting the lower single-stage untreated fan noise levels for the 1985 certification (Figure 2) as compared to that of the 1979 date (Figure 1). The treated noise estimates for the selected engines of both contractors however, were similar. As can be seen in these figures, the noise goals of 10 and 15 EPNdB below FAR Part 36 were "met" for the required certification dates.

Cycle Variations

The parametric cycle studies showed that the noise constraints imposed compromises on the optimum performance cycle for the certification dates and the aircraft mission specified. The following section will show the variations, considerations, and trade-offs that led to the selection of the cycles given in Table II.

Effect with current technology. The results of a bypass ratio variation at a constant overall pressure ratio and turbine inlet temperature for the high-speed (cruise Mach number of 0.98) application considered are presented in Figure 3. As can be seen, the optimum performance cycle for minimum takeoff gross weight without noise constraints would have been a bypass ratio of about 3 with a corresponding cruise fan pressure ratio greater than 2.

The resulting dominating noise level for this optimum cycle would have been 10 EPNdB above the current FAR Part 36 regulation as shown by the bare engine line in Figure 4. This noise level would be unacceptable for new commercial aircraft. The optimum cycle without noise constraints must now be compromised by increasing the bypass ratio and/or acoustic treatment (wall and splitter rings) must be added. Increasing the bypass ratio to 8 would almost achieve the FAR Part 36 level. Adding current technology (1972) acoustic treatment to the optimum bypass ratio 3 engine would also only allow for achievement of the FAR Part 36 level and would impose a weight penalty. To approach the 1979 objective of 10 EPNdB below FAR Part 36, it can be seen that a combination of increasing cycle bypass ratio to 8 and adding current technology acoustic treatment would be required.

The effect of bypass ratio on economics for **both** the bare engine and for the addition of current technology acoustic treatment is presented in Figure 5 in terms of relative takeoff gross weight. As compared to achieving the FAR Part 36 noise regulation with a bypass ratio of 3 and current technology acoustic treatment, the bypass ratio 8 cycle with current technology treatment achieving 10 EPNdB below FAR Part 36 would result in an increase in takeoff gross weight of about 14 percent. This was due to large drag, weights, and specific thrust penalties. These penalties amount to a 13 percent increase in direct operating costs and a 24 percent reduction in return on investment.

Thus it is clear that the 1979 objective of 10 EPNdB below FAR Part 36 cannot be achieved for the aircraft mission specified (Table I) without major economic penalty using current propulsion and acoustic technology.

Effect of advanced acoustic technology. The preceeding results indicated that to produce economically viable aircraft for the selected missions, application of advanced treatment and source noise reduction would be required. As stated earlier, the advances assumed for 1979 included improved liner effectiveness and increased attenuation bandwidth, while further liner effectiveness improvements and source noise reductions were assumed for 1985.

The effect of bypass ratio on cycle selection for the advanced bare engine and for treatment "available" in 1979 and 1985 are presented in terms of noise level relative to FAR Part 36 in Figure 6. As shown in the figure, the optimum bypass ratio 3 cycles with advanced technology treatment would have noise levels of 7 to 8 EPNdB below FAR Part 36. Since the noise objective for the 1979 certification date was 10 EPNdB below FAR Part 36, an increase in the bypass ratio of 4 to 4.5 would be necessary to meet the objective. Similarly, for the 1985 certification date, the bypass ratio would have to be about 6 to 6.5 to meet the noise objective of 15 EPNdB below FAR Part 36. The required increases in bypass ratio resulted in the fan pressure ratio dropping back to the 1.8 to 2.0 range. It is of interest to note that this fan pressure ratio range is where one-and two-stage fan concepts are directly competitive.

The application of advanced acoustic treatment can significantly reduce the economic penalties to achieve the noise objectives. For example, when compared to the optimum bypass ratio 3 cycle with advanced acoustic treatment, the study trends indicated that the takeoff gross weight and direct operating costs penalties were in the order of about only 2 percent to achieve the 10 EPNdB below FAR Part 36 objective. By comparison, for current technology (1972) acoustic treatment, as indicated earlier, the takeoff gross weight and direct operating costs penalties were in the order of about 14 percent for the achievement of the 10 EPNdB below FAR Part 36 objective.

Acoustic Treatment and Economics

The previous discussion considered the economic effect of the combination of increasing the cycle bypass ratio and adding acoustic treatment compared to the low bypass ratio optimum cycle cases. The economic effect of acoustic treatment configurations for the selected high bypass ratio cycles of Table II will now be considered.

Presented in Figure 7 is the economic effect, in terms of return on investment (ROI), of applying 1979 acoustic treatment options to the selected cycles for that certification date. As mentioned earlier, one contractor selected a high-speed single stage fan while the other a low-speed two-stage fan. Shown in the figure is the percentage point change in ROI (from the individual bare engine ROI level) for the addition of extent of wall treatment, and extent of inlet and exhaust duct splitter ring treatment to both specific selected bare engines. It should be noted that direct comparison of the ROI changes between the single-stage and two-stage fan engines cannot be properly made because the absolute ROI values of the bare engines were different.

Compared to the bare engine case, the addition of only wall treatment resulted in a 0.6 to 1 percentage point loss in ROI for noise reductions below FAR Part 36 of 8 and 5 EPNdB, respectively. The addition of splitter rings (inlet only for the single-stage fan) achieved the noise objective of 10 EPNdB below FAR Part 36 with an additional 1 to 1.5 percentage point loss in ROI.

Economic studies have indicated that for a fleet of 280 of the 0.98 cruise Mach number aircraft specified, a one percentage point change in ROI could amount to as much as 80 million dollars per year to the airlines. As can be seen, the figure shows that the relative "efficiency" of wall treatment only is better than that of splitter rings. The lower "efficiency" of the splitter rings is attributed to the large pressure losses imposed on the engine airflow as well as to additional weight and costs of the rings.

The economic effect of applying the 1985 acoustic treatment assumptions to both selected bare engines is shown in Figure 8. The addition of wall treatment resulted with only a 0.7 to 1 percentage point loss in ROI for noise reductions of 7 and 10 EPNdB below FAR Part 36. However, to reach the goal of a 15 EPNdB reduction below FAR Part 36, addition of both inlet and fan exhaust duct splitter rings resulted in an additional loss of 2 to 2 1/4 percentage points in ROI. As noted earlier, this loss in ROI could amount to a prohibitive dollar value loss to a commercial airline. Again, the relative "efficiency" of wall treatment is seen to be better than that of the inlet and fan exhaust duct splitter rings.

Thus, for the specified mission, the noise objectives of 10 and 15 EPNdB below FAR Part 36 could be met with compromises to the optimum engine cycle and the application of advanced acoustic technology. However, significant economic penalties would be incurred.

Advanced Technology Payoff

As shown in the previous section, the reduced noise objectives imposed significant economic penalties on the selected engines. As a means to offset the penalties involved in lowering the noise level of a given cycle, several advanced technologies in areas other than noise reduction were identified.

The studies showed that advances are needed in component aerodynamics to develop more efficient high pressure ratio fans and compressors, and high-load turbines. Improved component performance will mean fewer stages resulting in reduced weight and cost. Composite materials for application to compressor system blades, vanes, and disks, as well as high strength metals for turbines, need development. Advances also would be desirable in turbine cooling to provide higher temperature capabilities leading to improved cycle performance with reduced weight and costs.

Improved combustors which will provide high efficiency at all operating conditions with reduced emissions are also desirable. Advances in electronic controls will increase engine operating flexibility, increase parts life, and reduce aircraft work load providing for reduced costs. And the list goes on.

The studies investigated the effect of advanced technologies (such as mentioned above) on ROI for given noise levels. Results are illustrated in the bar graph in Figure 9. Shown in the figure are the changes in ROI, from the base line of current (1972) acoustic and component technology meeting FAR Part 36, for the application of various levels of advanced component and materials technology. For a noise level of 10 EPNdB below FAR Part 36, comparison of 1972, 1979, and 1985 technologies can be made. With current 1972 technology at 10 EPNdB below FAR Part 36, a loss of about 5 percent in ROI resulted. However, applying 1979 component and materials technology, the loss in ROI is reduced to about 2 percent. Now, for 1985 technology meeting 10 EPNdB below FAR Part 36, a gain of about 8 percent can be seen as compared to meeting FAR Part 36 with current technology.

Considering now meeting the 15 EPNdB below FAR Part 36 noise level, application of 1985 technology (4th bar) yields a gain of about 4 percent as compared to current technology at FAR Part 36. It can be seen by the above comparisons that engine technologies can show modest economic gains for 1979 engines and substantial gains for 1985 engines. The studies further pointed out that component technologies generally showed better economic gains than material technologies for both 1979 and 1985 engines. Also, engine cost proved to be a significant driver in assessing the relative importance of engine technologies.

The final bar on Figure 12 shows the effect of combined aircraft and engine component and materials technologies. Included in the aircraft technologies (for a statically stable aircraft) were supercritical aerodynamics and a utilization of graphite/epoxy composite material over 40 percent of the aircraft structural weight (less landing gear). The combined technologies meeting the objective of 15 EPNdB below FAR Part 36 show better than a 20 percent gain in ROI over a current technology aircraft which just meets the FAR Part 36 noise level. Therefore, although the noise constraints imposed economic penalties, the potential for offsetting these penalties with possible significant gains can be found by the application of advanced engine and airframe component and materials technologies.

Studies for Lower Noise Levels

In an attempt to realize noise levels lower than 15 EPNdB below FAR Part 36, further studies were conducted. These studies used the selected 1985 engine which included advanced components, materials, and acoustic treatment technologies. The aircraft mission specified was a 136,000 kg (300,000 lb) class tri-jet carrying 200 passengers over a 5556 km (3000 n. mi.) range at a cruise Mach number of 0.90. One study considered the use of aircraft operational procedures other than those presently in practise during landing and takeoff, while another considered the use of unconventional engines.

Aircraft Operational Procedures

The use of steeper glide slope angles during landing approach showed significant noise reductions (references 4 and 5). Presented in Figure 10 is the effect of increased glide slope angle (which would require reduced thrust levels) on approach noise. The use of a two-segment approach consisting of a 6 degree glide slope with a transition to a 3 degree glide slope about 1.85 km (1 nautical mile) from the runway threshold would result in a noise reduction of about 7 EPNdB. However, if a continuous 6 degree glide slope angle were maintained, a reduction of about 13 EPNdB could be attained. The studies also indicated that with the steeper glide slope, the rapid thrust response requirement in the event of an aborted landing would not need to be faster than the 4 to 5 second response found on the current high bypass ratio engines.

Another procedural possibility studied was the use of a two-position mixed-flow exhaust nozzle (mixed fan and core flow) for reduction in takeoff jet noise. A 20 percent increase in the exhaust nozzle area was found to result in a 3.5 EPNdB reduction in jet noise, as shown in Figure 11. Required takeoff thrust would be maintained by high-flowing the engine (increased fan speed and weight flow) but with a net reduction in jet velocity. Coupled with the two-position exhaust nozzle, an early wing flap retraction and acceleration system would be incorporated. This would allow the aircraft to achieve a higher speed over the community thereby permitting a greater amount of power cutback.

Unconventional Engines

Further studies to achieve noise levels down to 20 EPNdB below FAR Part 36 considered using unconventional engines which would be available in 1985. The propulsion systems considered during these studies included the following:

- VARIABLE GEOMETRY ENGINES
  - Variable bypass ratio
  - Variable fan and turbine geometry
  - Variable area inlets and nozzles (including sonic inlets)
- OTHER ENGINE CONFIGURATIONS
  - Geared fan
  - Aft fan
  - Three-spool turbofan

The pertinent results of the unconventional engine studies are presented in Figure 12. Shown on the figure are the percentage point change in ROI for various levels of noise reduction below FAR Part 36 for variable geometry bypass ratio 6 cycles with and without sonic inlets and a fixed geometry geared fan bypass ratio 10 cycle. For comparison, the 1985 fixed-geometry bypass ratio 6 cycle is also shown.

As can be seen, the noise goal of 20 EPNdB below FAR Part 36 could be achieved with a moderate bypass ratio of 6 turbofan incorporating variable geometry and advanced acoustic treatment. The variable geometry included variable pitch fan rotor along with a variable area inlet and variable area exhaust nozzle. The added weight and complexity of the variable geometry features, however, reduced the ROI about 4 percentage points below that obtained with the fixed-geometry bypass ratio 6 cycle meeting the 15 EPNdB below FAR Part 36 objective (1985 engine). The studies also indicated that the noise goal could be achieved with a fixed-geometry bypass ratio 10 cycle with a geared, two-stage fan. As compared to the 1985 fixed-geometry cycle with a 15 EPNdB reduction, the geared fan at 20 EPNdB below FAR Part 36 showed an additional loss in ROI of slightly over 2 percentage points.

In conjunction with the moderate bypass ratio variable-geometry cycles, several inlets were studied. The most promising inlet considered was a high-throat Mach number (sonic) type having a fixed external cowl and a variable internal surface. Trade studies comparing acoustic splitter rings and sonic-type inlets showed that significant economic gains could be achieved by use of a sonic inlet as evidenced in Figure 12. With 20 EPNdB below FAR Part 36 as a goal for a variable geometry cycle, the sonic inlet cycle showed about 1.5 percentage points less penalty in ROI than the variable geometry cycle without the sonic inlet.

Concluding Remarks

The final result of these studies of engine cycles for future long-haul transports showed that with forseeable advances in acoustic treatment technology, noise constraints to 10 and 15 EPNdB below FAR Part 36 can be accomodated, but at the expense of cycle selection compromises. These compromises and the addition of acoustic treatment would result in significant economic penalties. However, the application of advanced component and materials technology in the years to come has the potential to either compensate for, or, eventually more than offset these penalties. Unconventional engine cycles may also have a place in future engine design if further reductions in noise level are required. In either case, considerable research and development will be required to ensure engine technology readiness for future application into the commercial fleet.

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TABLE I - CYCLE AND MISSION VARIABLES

Bypass ratio	1 to 10
Cruise fan pressure ratio	1.4 to 2.5
One- and two-stage fans	
Overall pressure ratio	15 to 40
Turbine inlet temperature	980 to 1530°C (1800 to 2800°F)
Mixed and separate flow exhaust systems	
Payload	200 passengers
Range	5556 and 10,200 km (3000 and 5500 n.mi.)
Cruise Mach number	0.90 to 0.98

TABLE II - SELECTED CYCLE PARAMETERS

Certification date	1979	1985
EPNdB below FAR Part 36	-10	-15
Bypass ratio	4 to 4.5	5.5 to 6.5
Cruise fan pressure ratio	1.8 to 2.0	1.8 to 1.9
Overall pressure ratio	25 to 30	25 to 35
Turbine inlet temperature	1260 to 1480°C (2300 to 2700°F)	1370 to 1650°C (2500 to 3000°F)

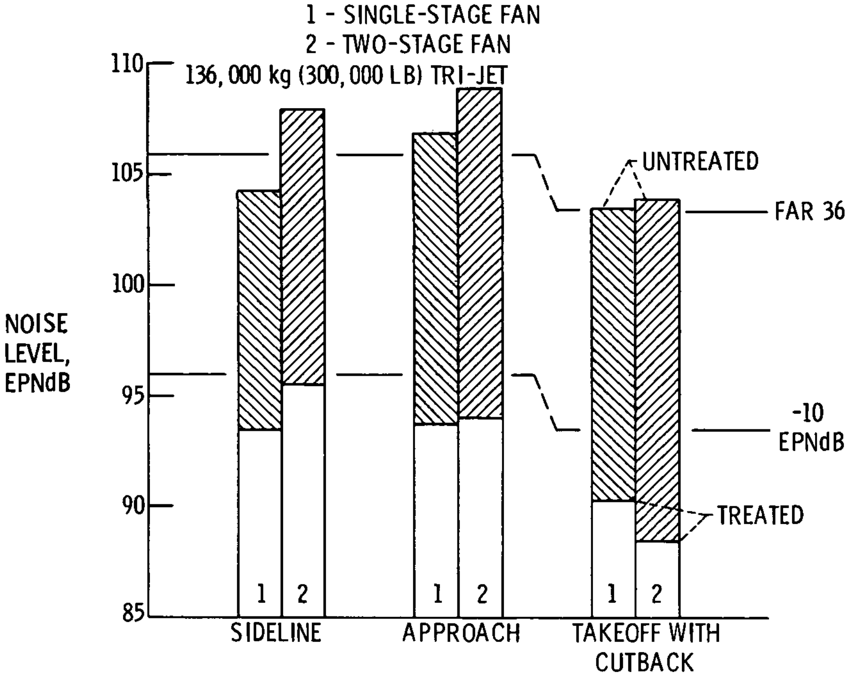

Figure 1. - Study results predicted noise levels for 1979 certification with selected engine cycles.

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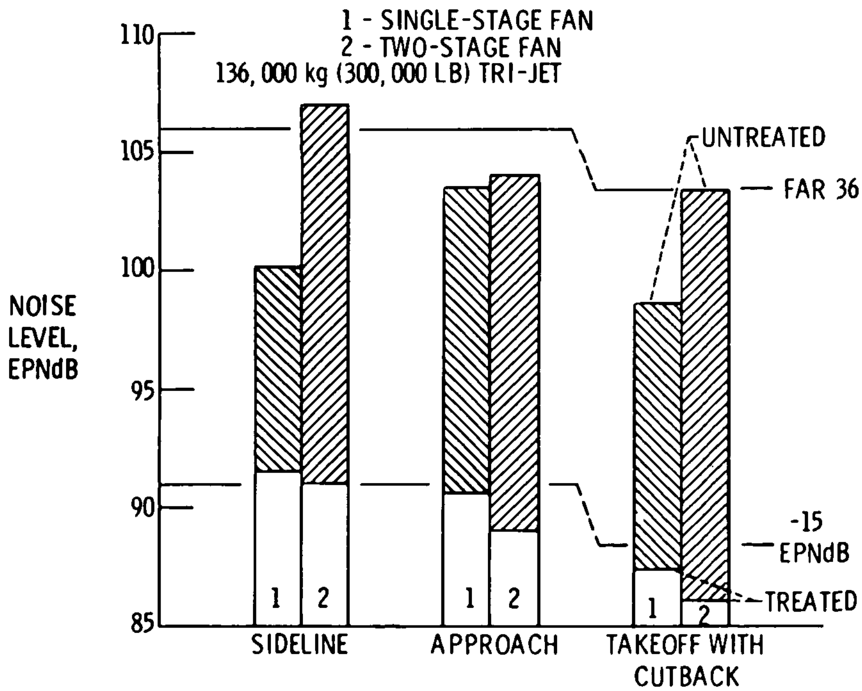

Figure 2. - Study results predicted noise levels for 1985 certification with selected engine cycles.

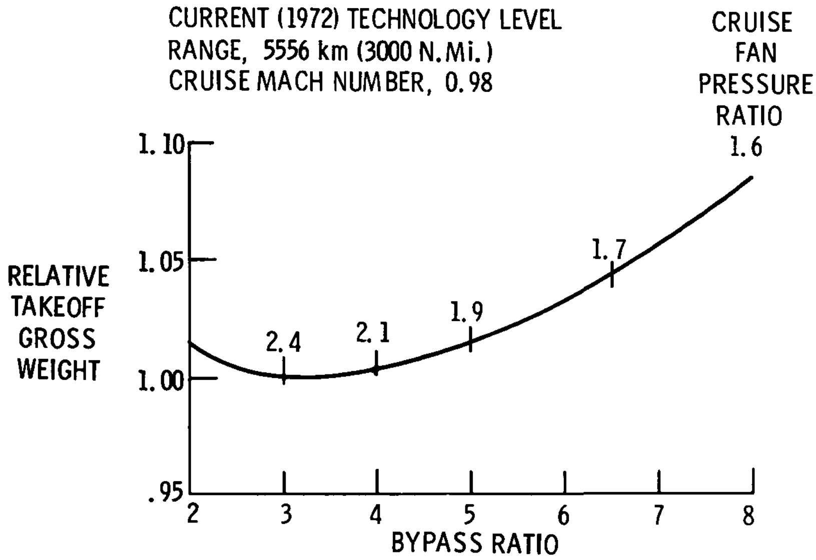

Figure 3. - Bypass ratio optimization without noise constraints.

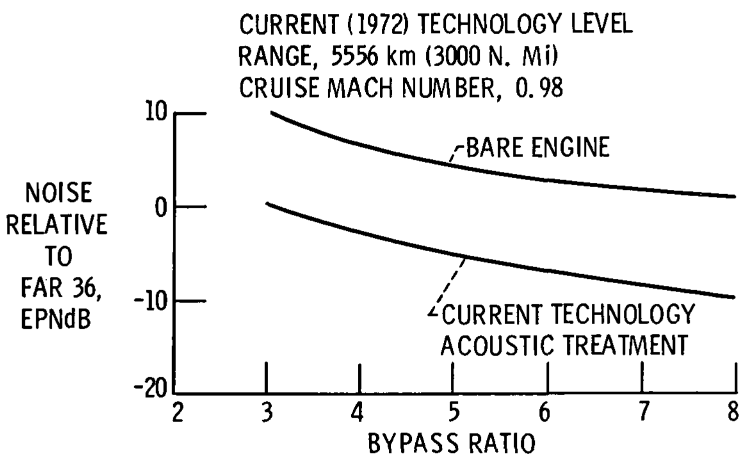

Figure 4. - Effect of cycle bypass ratio and acoustic treatment on noise.

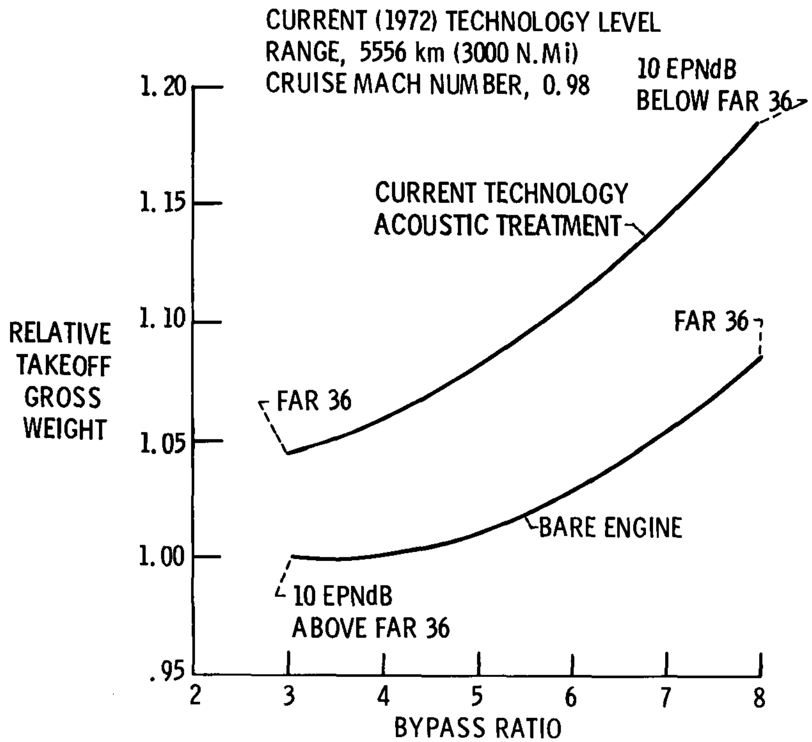

Figure 5. - The effect of cycle bypass ratio and acoustic treatment on takeoff gross weight.

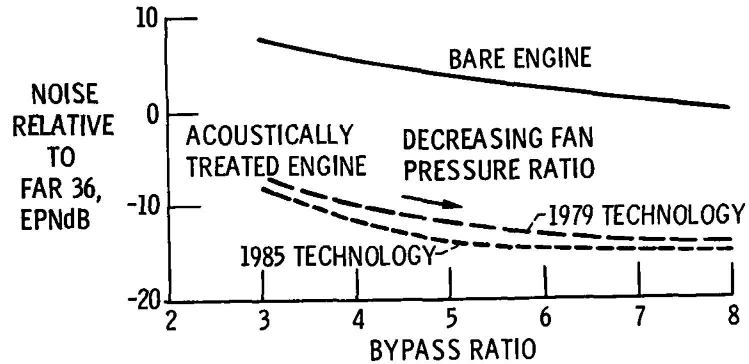

Figure 6. - Effect of cycle bypass ratio and advanced acoustic treatment technology on noise level.

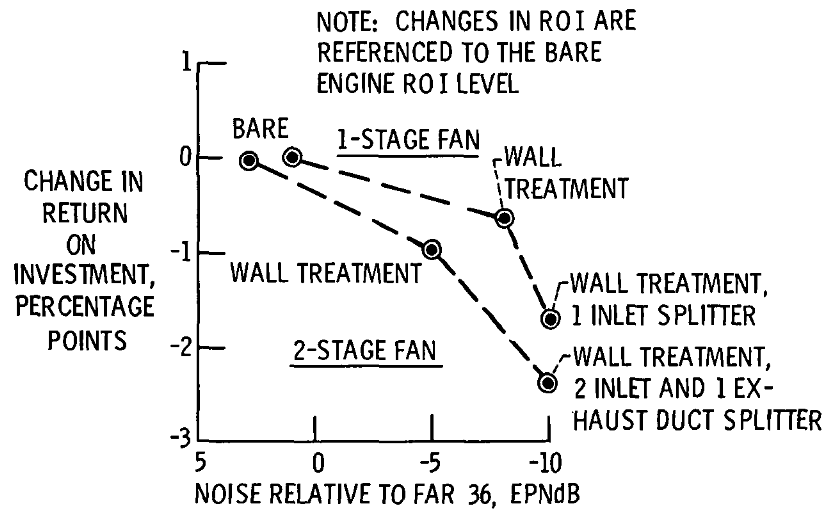

Figure 7. - Effect of 1979 acoustic treatment technology on economics of selected cycles.

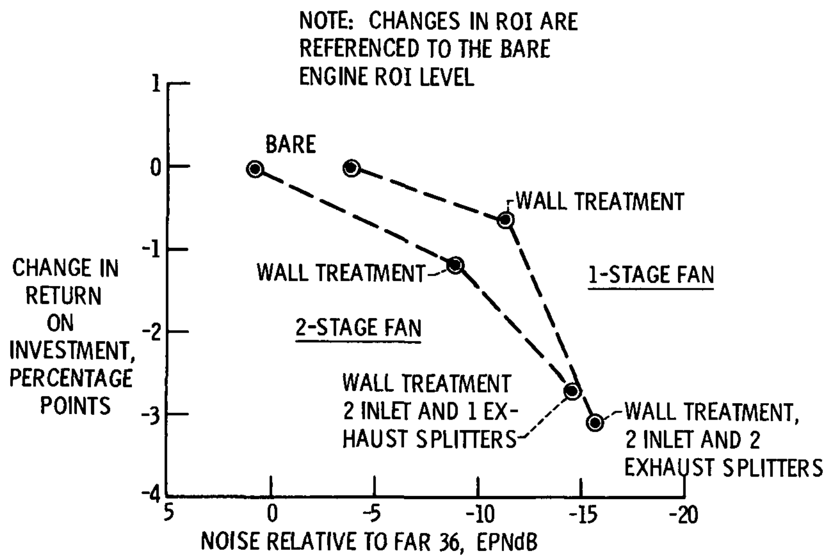

Figure 8. - Effect of 1985 acoustic treatment technology on economics of selected cycles.

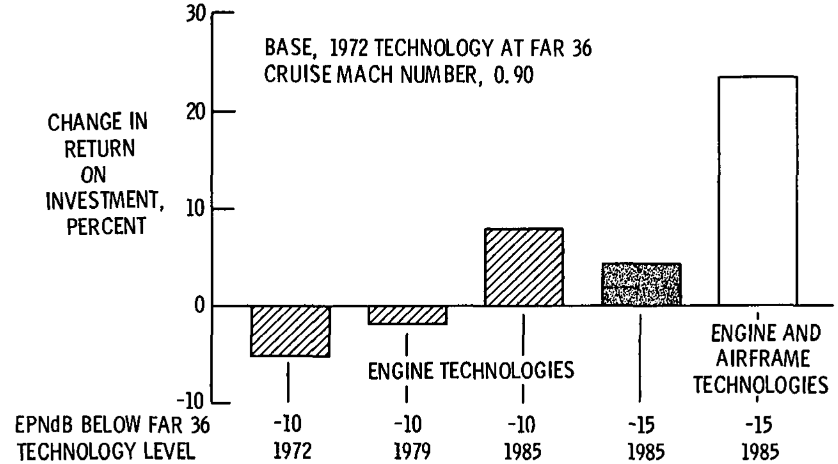

Figure 9. - Economic effect of advanced component and materials technologies.

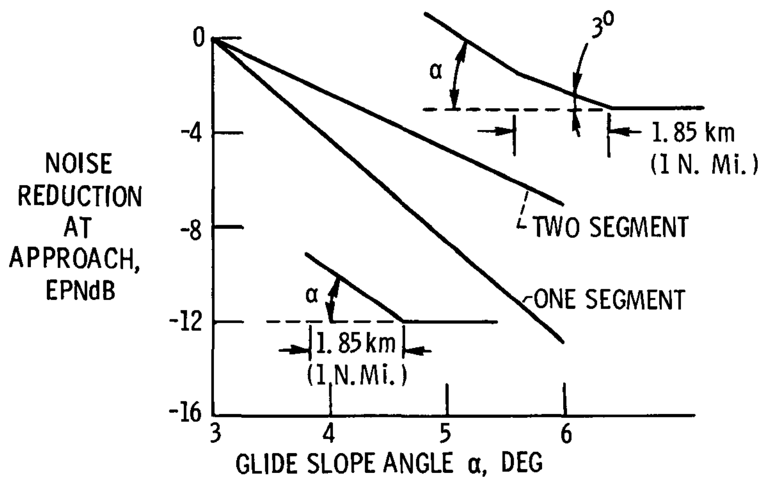

Figure 10. - Effect of increased glide slope angle on approach noise.

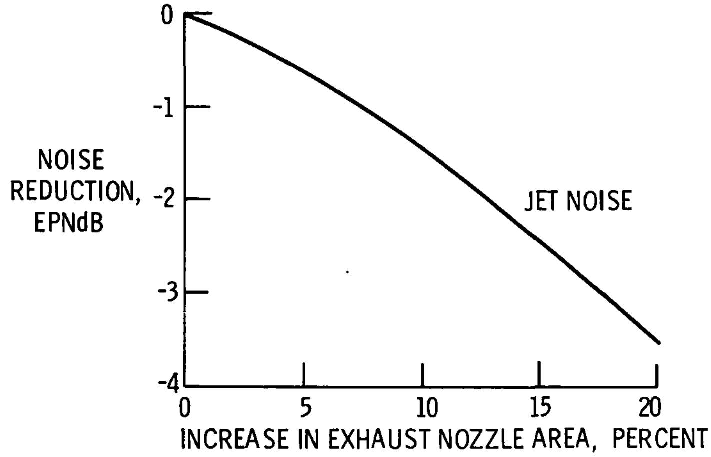

Figure 11. - Effect of exhaust nozzle area increase on takeoff noise levels. (At FAR 36 reference points.)

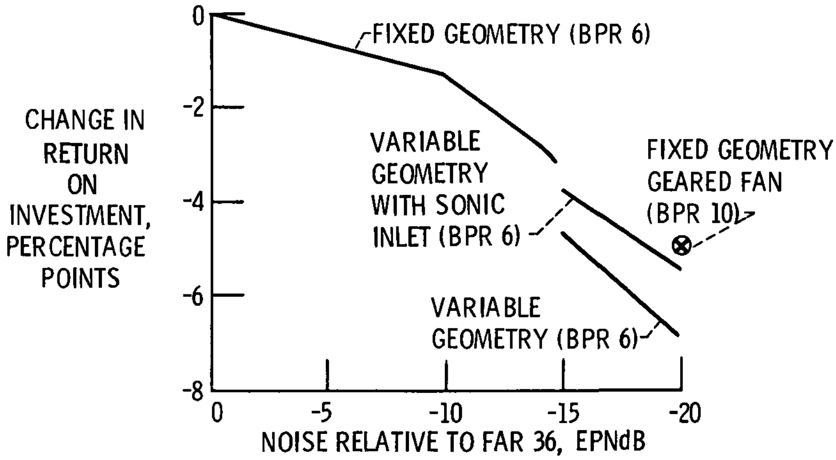

Figure 12. - Exonomic comparison of fixed and variable geometry cycles. (1985 acoustic treatment technology; cruise Mach number, 0.90.)

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