Status Report—Subsonic Aircraft Noise Reduction

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The design process for a subsonic commercial transport aircraft is discussed with emphasis on noise considerations. A review of the process for identifying component noise levels is followed by a description of the design for noise reduction of typical components. A discussion of system constraints in the practical application of noise-reduction concepts is followed by comments on the need to include a reasonable design tolerance. Some aspects of the trade between noise reduction and performance are described. Finally, a projection is made of future projected noise reductions based on yet-to-be-accomplished research programs.


Copies will be available until December 1, 1976.
INTRODUCTION

The promulgation of the FAR 36 aircraft noise certification rule in 1969 escalated aircraft noise design requirements to the status of a federally controlled environmental problem. Since that time numerous meetings, studies, technical papers, R&D contracts and airplane production programs have not only contributed to our knowledge on noise control techniques, but have generated unwarranted optimism about the potential for continuing the recent high rate of noise reduction progress. Early in this decade, there were discussions of noise reduction objectives, such as 1 dB per year with an eventual capability of obtaining noise levels 15 to 20 dB below FAR Part 36. Such statements are still being made. This paper will show why these objectives are not likely to be met in the next few years — even with a newly designed airplane.

The large noise reductions implemented on the 747 in 1971 are sometimes used as evidence to support the argument that significant additional near-term reductions can, in fact, be achieved. However, a clear understanding of the present aircraft noise situation will show that this particular 747 example is not applicable for projecting future noise reduction potential. The original 747 noise design objectives were aimed at significant noise reductions compared to 707's and DC-8's, and at levels thought to be near the then forthcoming FAR 36 rule. These noise objectives were thought to be obtainable, according to flight estimates from engine ground rig tests, by using a moderate amount of acoustic lining in the engine and nacelle. After promulgation of FAR Part 36 and application to the 747, substantial changes were required for the engine installation. The blow-in-door inlet was replaced with a fixed lip inlet providing a large reduction of the fan source noise while the surface area of the acoustic lining contained in the engine and nacelle was more than doubled. Since similar technology has now been incorporated into all current wide body aircraft, it is obvious that continuation of this noise reduction trend would require considerable additional source noise reductions and lining effectiveness improvements. This capability certainly has not been demonstrated to date and, as will be shown, is not anticipated for conventional turbofan engine powered airplanes in the foreseeable future.

The point is that quick and relatively simple noise reductions are behind us. The engineering development from straight turbojets to turbofans, then to high bypass ratio turbofans with sound suppression represented an immense step forward in noise reduction. For commercial air transportation in general, the swept wing combined with the turbine engine represented a major technological breakthrough. For noise reduction, the analogous breakthrough was the high bypass ratio engine equipped with sound absorbing lining. However, we are now well up on the noise-reduction learning curve, and subsequent noise reductions are going to be small, tedious, and expensive.

ENGINE CYCLE SELECTION FOR NEW AIRPLANES

The following discussion will illustrate how acoustic requirements, more than ever before, play a principal role in the definition of the engine cycle for new airplanes. This will be done by emphasizing one of many Boeing preliminary design studies of potential new commercial airplanes. In this study, the airplane incorporated foreseeable advances in aerodynamics, propulsion systems, avionics, and acoustics. An engine cycle matrix was established covering a wide span of turbine inlet temperatures, overall pressure ratios, and bypass ratios. In addition, each airplane was analyzed with various levels of acoustic treatment including a reference nacelle which had no acoustic treatment. Acoustic linings were added in discrete increments until the most thoroughly treated nacelle contained several inlet and fan duct acoustic splitters.

Some of the results are shown in Figs. 1, 2, 3 and 4 plotted over the range of bypass ratios.
requirements with higher BPR's. Similar information has been developed for the sideline and approach conditions. Sideline noise behaves much like takeoff noise. For the approach case, the study indicated that total airplane noise is essentially the same for all bypass ratios. As a result of the combined effect including the use of trades of all three noise levels, (takeoff, sideline, and approach), there is no significant difference in noise certification capability over a range of bypass ratios. 

Fig. 3 shows the change in fuel usage as bypass ratio is varied. The most efficient use of fuel is provided by hardwall engines with a BPR between 6 and 7. It is also seen that acoustic treatment provides noise suppression at the expense of overall airplane efficiency. The optimum airplane has an engine with a slightly lower BPR than for the hardwall case. The loss of airplane fuel efficiency with increasing BPR occurs because engine size increases as BFR increases and the larger engines weigh more and produce more cruise drag. This more than offsets the decreased specific fuel consumption provided by higher BPR engines.

The curves shown in Fig. 4 describe another important aspect of overall aircraft efficiency, the ratio of payload carried to the gross weight of the aircraft (a representation of productivity). Greatest productivity for a fixed payload occurs at low BPR's because engine sizing is generally determined by cruise thrust which is adversely affected by an increasing lapse rate with increasing BFR. The higher the BPR, the larger the engine must be to provide necessary cruise thrust.

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Once again, the impact of acoustic treatment is seen as a significant detractor of airplane performance.

Based on results such as those shown in Figs. 1, 3, and 4, Boeing has devoted considerable effort to develop airplane design concepts which are well balanced with regard to environmental acceptability, fuel conservation, and operating costs. In addition, great effort is being exerted by the engine manufacturers to develop high bypass ratio engines that are compatible with the aforementioned balanced design objectives.

To illustrate what is meant by a balanced design, the following sections describe results from one of several Boeing new airplane preliminary design studies which incorporates three advanced technology, 20,000-lb thrust class high bypass ratio engines.

**NOISE COMPONENT ANALYSIS**

During airplane design, Boeing uses an acoustic analysis procedure which determines the characteristics of all the component noise sources associated with the noise design requirements for takeoff, sideline, and approach. The procedure uses details of airplane performance and the geometric and flow properties of the engine to establish hardwall noise components and resulting levels after acoustic linings are applied. This system has been under development for many years and is continually updated as new model and full-scale ground and flight data become available. It is estimated that the accuracy of the analysis procedure is approximately \( \pm 3 \) FMB for the new engines and airplanes assessed in the study.

Fig. 5 presents takeoff component noise data for the study airplane at full power at 1500-ft altitude relative to the total airplane noise level. The components that need the most suppression as well as the noise floors which limit the achievement of lower system noise become evident. In the takeoff case, forward and aft radiated fan noise are dominant, with jet and core noise somewhat lower. It should be noted that the airframe (non-propulsive) noise is a minor contributor to the total hardwall takeoff noise level. Fig. 6 is a similar plot at approach conditions (1 n.m. from threshold). It is obvious that jet noise is not significant; however, turbine and airframe noise would clearly prevent further reduction in total airplane noise unless they were reduced along with other components.

The Boeing study results are quite consistent with other recent government and industry programs involving high bypass ratio acoustic technology development and demonstration. A comparison between the NASA Quiet Engine Program (QEP) acoustic results and the Boeing study airplane results will serve to illustrate this point.

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The basic QEP objective was to develop and demonstrate advanced turbofan noise reduction technology on full-scale engines. The engines were physically sized in cruise thrust output to match that of the older (707, DC-8) four-engine long-range aircraft. This produced demonstrator engines in the same thrust class (approximately 22,000-lb static takeoff thrust) as used in the Boeing study. Two NASA ground test engines were constructed: Quiet Engine A had a low speed, low pressure ratio fan and four-stage low pressure turbine while Quiet Engine C had a higher tip speed and pressure ratio fan coupled with a two-stage LP turbine.

The Boeing study and QEP results have been compared by using Boeing estimates of the Engine A flight noise, and also by using the results of a GE/NASA flight engine design study. The GE/NASA flight engine design study was based on the QEP acoustic technology applied to a three-engine aircraft.

In Fig. 7, the Boeing calculated Engine A levels are shown to compare favorably with those calculated in the GE/NASA study. In addition, the noise level of Engine C is seen to be several EPNdB higher than for Engine A. The Boeing study airplane is seen to have a noise level that is bracketed by the flight engines of the QEP study. Footnote further shows a significant economic penalty for the lower fan pressure ratio of Engine A. This is due to the higher bypass ratio necessary to provide the required thrust, and is consistent with the results of the Boeing bypass ratio study. In summary, it is concluded that the technology advances in engine acoustics that have been developed and demonstrated by the NASA Quiet Engine Program are being included in engines now under study for new technology airplanes typified by the one described herein.

NOISE SUPPRESSION DESIGNS

Having selected a candidate engine design and determined its hardwall noise characteristics, the application of noise suppression technology was then considered. High bypass engines are well suited to the effective use of acoustic linings since the strongest noise sources are generated inside the engine where the linings can be installed. Obviously, nacelle linings can do nothing about jet exhaust noise created in the mixing zone behind the engine.

Since the study airplanes are being designed for production in the 1980's, past experience has shown that it would be appropriate to assume that acoustic lining designs will be available that are somewhat more advanced than those in service today. Such lining technology development has been underway at Boeing for many years and has been showing steady progress. The program objective and demonstrated progress are illustrated in Fig. 8 where lining effectiveness improvement versus calendar time is plotted. For the sake of convenience, the effectiveness of production quality liners of flight demonstrated performance are shown as unity at the start of 1971. By the end of 1975, it is expected that this program will demonstrate that inlet linings can be 50 percent more effective than they were 5 years ago. This means that an inlet designed in 1971 with 4-PNdB
suppression capability could now be designed to produce about 6 PNdB of suppression for the same treatment area. Sample data points have been shown on the figure to illustrate that, in fact, the acoustic improvements sought are being achieved as demonstrated on experimental hardware. Some of these developments and their application to the Boeing study airplane design are the subject of this section.

The nacelle concept shown in Fig. 9 has been examined extensively in the Boeing study. The attenuation of inlet noise, which is a combination of discrete tones, broadband noise due to the fan and stator system, and noise related to shock propagation (buzzsaw) will be described first. The inlet fan noise spectrum at 60 deg from the centerline forward is shown in Fig. 10 at approach power. Based on an analysis of results from the lining technology improvement program, it should be possible to achieve inlet noise attenuation of about 6 PNdB without resorting to unacceptably long inlets or inlet splitters with their attendant performance and maintenance problems.

Fig. 10 shows how the inlet spectrum could be attenuated to achieve an approach noise reduction of 6.3 PNdB. The shape of the attenuated spectrum between 1500 and 8000 Hz matches a constant NOY contour. The attenuation spectrum, that is the difference between the original hard-wall spectrum and the resultant suppressed spectrum, is plotted in Fig. 11. This attenuation spectrum was the target for the nacelle lining designer. The type of attenuation spectrum that usually results from conventional (current technology) single-layer resonant panel liners is shown as curve 1 in Fig. 11. The attenuation spectrum assumed in the Boeing study utilizes more suppression at all frequencies to compensate for the lack of desired attenuation at 4000 Hz (curve 2 in Fig. 11).

In order to validate the foregoing analysis, several linings were designed and tested on a current high bypass ratio engine on a ground test rig. Two of the linings are shown schematically in Fig. 12 with the measured attenuation spectra. At approach power, the linings perform very close to the approach design target shown in Fig. 11. The takeoff attenuation spectra show much more low frequency attenuation because the tested lining designs included special provision for large attenuation of the low frequency buzzsaw noise that occurs at takeoff powers.

The next major noise source to be discussed is aft fan noise. Fig. 13 shows the hardwall source spectrum and the target for the suppressed fan spectrum. Because the aft fan noise is the dominant engine noise source (Figs. 5 and 6), significant attenuation is required. The target attenuation spectrum thought feasible would require advanced technology linings and would provide a noise reduction of 13 PNdB at the maximum aft radiation angle. Advanced concept lining designs evaluated to date provide almost the desired amount, or about 11.4 PNdB. Linings installed in aircraft currently in service would, under the same circumstances, provide no more than 8- to 9-PNdB reduction. At this time, only model test results are available to confirm the performance of these advanced designs; engine demonstration tests are planned for the near future.

The task of suppressing noise sources associated with the primary flow system is described next. One source is turbine broadband and tone noise generated in much the same manner as fan noise. The primary exhaust concept conventionally
used is shown in Fig. 14. Treatment would exist on both sides of the exhaust duct and would extend from near the turbine exit struts to near the primary nozzle. The lining would not extend into the nozzle due to the thrust performance loss that occurs when high Mach number flow passes over rough lining surfaces.

The core engine produces another major source of noise, namely, low-frequency core noise. Research has shown that core noise is predominantly generated by operation of the burner; however, it is possible there are other elements in the turbulent hot flow system that also contribute. In any event, reduction of core noise is required if projected noise reductions are to be achieved. The low frequency characteristics make practical hardware design very difficult due to large treatment depth requirements. Boeing has conducted an experimental program using models and a current high bypass ratio engine to develop suppression concepts and analysis methods. The common feature of these studies has been the utilization of the volume of the engine exhaust plug as a very deep acoustic lining, the depth being required to provide attenuation down to 100 Hz. Combination systems are being studied in which cowl depth is also used. Fig. 15 shows the target attenuation spectrum and results from two model tests. These results show that a precise match to the desired attenuation spectrum shape may not be achievable, but, the total system may provide the desired noise reduction by virtue of broad bandwidth.

Fig. 16 is a picture of an experimental core noise reduction device tested by Boeing on a current high bypass ratio engine to determine if core noise suppression was even possible. The device was 11 ft long (comparable to the length of the engine) and was mounted as a center plug in the primary nozzle. The surface was a perforated sheet giving entrance to a multacellular interior designed to absorb low frequency energy. The device provided about 1/2-PNdB suppression for each foot of length. A more practical design in terms of length and nozzle performance has subsequently been tested on another engine with comparable core noise reduction per foot.

The difficult task is to develop a concept that will utilize the available surfaces and volumes of the primary nozzle to suppress both turbine and core noise. The targets in the Boeing study were to reduce core noise by 6 PNdB and turbine noise by 8 PNdB. The design of such a suppression system is complete, and test results from full-scale demonstration hardware are expected in early 1976. Although 6-PNdB suppression of core noise may prove practical, the attenuated noise level then represents a noise floor comparable to jet and airframe noise as discussed in the following.

During the engine cycle selection process, the BPR finally chosen to reduce jet exhaust noise may be higher than performance and economics would dictate. There is no known way of further reducing the resulting jet noise to achieve worthwhile levels of suppression on low velocity jet flows if the fan and primary nozzles are separate and coannular. In fact, significant jet noise suppression, although the oldest noise reduction problem in aircraft jet engines, has to date been impossible to implement in a practical turbofan commercial design, even at moderate flow velocities. Some engine nacelle concepts have been studied in which the fan ducts are lengthened to provide a common nozzle for the primary and secondary flows. If a mixing device is used as a pri-
When the suppression concepts described are incorporated into a practical engine/nacelle system, the results are as shown in Figs. 17 and 18. Each noise component has been shown at its original hardwall level, and, where suppression is possible, the resultant reduction in component EPNL is shown. The total EPNL level for the system is shown on the right of the figures.

It must be emphasized that none of suppression levels shown here has been demonstrated as yet in flightworthy nacelles on the type of engines included in the Boeing study. All noise estimates describing airplanes in this study are based on two key assumptions: (a) new technology engines will have the predicted performance and noise characteristics anticipated, and (b) the advanced linings will perform as predicted. However, the projection is not based solely on theoretical concepts, but is based on lining design ideas that have been tested in the laboratory and have a reasonable chance of becoming practical elements of a commercially viable engine nacelle system. This situation leads to the need for noise estimation tolerances discussed in more detail later.

A careful examination of Figs. 17 and 18 shows that the original goals for component attenuation result in balanced component levels. (Although not shown, the relative component levels for the 0.25 n.m. sideline noise reference point are essentially the same as for the takeoff case.) At takeoff, the four strongest noise components from the engine are within a spread of about 6 EPNdB. Thus, no single source remains which could be further suppressed to significantly reduce the total engine noise. For example, jet noise is the dominant engine noise source on takeoff for the suppressed airplane. Even if jet noise were completely eliminated, the total engine noise would be reduced less than 2.5 EPNdB. Likewise, if aft fan noise were somehow further reduced 5 EPNdB, total engine noise would lower by only 1 EPNdB.

On approach, the suppressed engine noise sources are further apart; however, total airplane noise reduction is limited by airframe noise. For example, 5 EPNdB additional inlet reduction, if possible, would only result in a total airplane reduction of about 1.5 EPNdB because of the airframe noise influence.

To explore this point further, Fig. 19 shows a chart developed to illustrate total approach noise sensitivity to changes in component attenuation. Fig. 19 shows that additional reductions
of the suppressed airplane EPNL would be very small even for very large additional reductions in components. Thus, this analysis shows the presence and consequence of noise "floors" which limit further practical noise reductions. It can tentatively be concluded, therefore, that the study engine/nacelle is reasonably well balanced acoustically since, for the combination of takeoff, approach, and sideline conditions, no single source dominates the noise signature. This is a result of engine cycle selection as well as acoustic treatment application. The next section of this paper will explore the design further in the context of airplane system constraints on the nacelle/noise design.

**NACELLE SELECTION/AIRPLANE DESIGN CONSTRAINTS**

The process has been described by which the general design of an airplane includes the choosing of an engine cycle with its associated acoustic properties prior to the application of the suppression system. After suppression has been applied to the attenuable noise sources, the total system noise results. At this stage, a baseline airplane concept has been defined. The detailed engineering design involving many technical disciplines can proceed with the objective of creating a final design that equals or exceeds the capabilities of the baseline. Seemingly small items can have a serious impact on the airplane. For example, if the jet noise level is determined to be higher than desired, the only known way of reducing it is to lower jet exhaust velocities by changing the basic engine cycle, which may not be an acceptable solution. In order to reduce jet velocity, the engine BPR must be increased. This usually dictates an engine oversized for takeoff to provide the cruise thrust required for the mission. For the larger engine, nacelle drag increases. The wing engines and nacelles cannot become larger in diameter without a corresponding growth in nacelle length to preserve aerodynamic performance, and a corresponding change in landing gear length to insure ground clearance. Thus, one seemingly simple and desirable change escalates throughout the design with an impact that is far reaching for the airplane.

Further, it should be recognized that even a larger engine is not always beneficial for reducing noise. If engine size is increased, the nacelle diameter will grow. When this happens, the effectiveness of the inlet and fan duct linings decreases because duct heights are larger, and wide ducts do not attenuate noise as effectively as narrow ducts for the same length. This is but one example of the delicate balancing act that is part of the design process. An even more critical consideration is that the design must be such that the product can be manufactured at a reasonable cost and must have adequate service life. In the process of developing advanced linings, several concepts having theoretical effectiveness have been discarded because no method of manufacturing serviceable parts at reasonable cost has yet been invented.

**PREDICTION/DESIGN/TEST EXPERIENCE**

As in all technical disciplines, noise analy-
sis and noise reduction engineering requires some
tolerance to account for uncertainties in engineering
to. For example, in predicting the range of a new airplane, even with wind tunnel model
data and several decades of experience in a mature
technology, airplane range allowances or tolerances
are required to account for uncertainties between
design stage predictions and subsequently demonstra-

In noise engineering, a myriad of uncertain-
ties and uncontrollable factors face the noise
reduction engineer. A partial list is shown in
Table 1 to clarify the elements of the noise engi-
neer's prediction-demonstration problem. There
is general agreement in the aircraft industry
that the noise tolerance required between predic-
tion and subsequent flight demonstration is some-
ting greater than zero. The magnitude of toler-
ance required varies with the type of airplane
program, and with the basis of knowledge from which
the prediction is made. It also depends on how

To establish a baseline tolerance, the
simplest case would be a repeat certification of
of an already certified airplane under the provi-
sions of FAR 36. This limitation would keep the
conditions under which the re-test is conducted
reasonably close to the original certification
and would, therefore, require a minimum toler-
ance. Boeing experience has demonstrated that this mini-

The original goal for the JTBD refan noise reduction
increment was roughly 10 EPNdB at each flight
point, based on initial Boeing research projections
for a program that contained necessary elements
of technology advancement. Adding 5 EPNdB toler-

Fig. 15 Comparison of model test results with
target attenuation for combined reduction of core
and turbine noise

Fig. 16 Experimental core noise reduction device
tested on current high bypass engine

100 percent) confidence that the airplane would
recertify at noise levels equal to or less than
the flight test requirement. It must be re-
emphasized that ± 2 EPNdB represents an abso-
ute minimum tolerance level, i.e., for a simple re-
test of an already certified airplane with no
change in the sound generation or suppression
system.

Using re-certification as a basis for es-
ablishing a minimum tolerance, it is axiomatic
that a flight test to certify a modification to
the airplane or its sound-suppression system
would require a larger tolerance. Based on an
extensive analysis of Boeing's past experience,
when flight measured levels are compared to ini-
tial predictions, the tolerance required is around
± 2.5 EPNdB at each flight point. It is important
to qualify the source of data corresponding to
this tolerance. Prior ground and/or flight test
data for the specific airplane/engine combination
must be the basis for the preflight prediction.

As one proceeds to more extensive modifications
such as the refan engine derived from the JTBD,
or to new type airplane designs using familiar
engine cycles, ± 3 EPNdB or more is the minimum
tolerance required for reasonable (still not 100
percent) confidence of a flight demonstration.
Finally, for programs in the concept selection
stage using engines outside our experience, or,
for projections of the application of future
research results, ± 5 EPNdB is probably realistic.

An example will serve to illustrate. The
formance, to place these estimates at a reasonable risk level, would have resulted in an initial estimate that a reduction of at least 5 EPNdB could be demonstrated (see Table 2).

In this case, to further compound the tolerance problem, the NASA contract funding level and program content were severely reduced after the original research projections. The ground test program has now been completed, and nominal flight estimates based on ground test data are available as shown in Table 2. For these ground demonstrated levels to represent reasonable risk estimates for certification or guarantee purposes on a new airplane program, a minimum tolerance of 3 EPNdB would have to be applied, as shown in the right column of Table 2. These are the only noise reduction increments that could, at this time, be used to establish commitment levels, for the JT9D-109 retrofit configuration. Use of greater reduction increments, such as the ground demonstration nominal values against a pass-fail requirement, would provide a risk for the manufacturer so great that it would be impossible to initiate the program.

AIRPLANE PERFORMANCE/NOISE REDUCTION TRADES

It was stated earlier in this paper that many new technology airplane designs have been studied at Boeing. Among other things, the acoustic performance of these airplanes was examined in terms of the ratio of payload to gross weight and the impact on the fuel used. The results are displayed in generalized form in Figs. 20 and 21 for one three-engine study airplane.

Fig. 20 shows takeoff noise reduction versus the decrease in payload/gross weight ratio for a range of acoustic treatments from hardwall to multi-splittered nacelles. It is seen that noise level (relative to current FAR 36) decreases only with increasing gross weight for a fixed payload. The curve turns sharply at 8 EPNdB below FAR 36. Noise reductions greater than about 8 EPNdB become prohibitively costly as the combined noise floors of jet noise and core noise (including an assumed suppressed core noise level) are reached. The weight penalty for achieving more than 8 EPNdB reduction, while accomplishing the design mission, is so high that it raises serious questions about commercial viability of the product.

For example, in order to reduce the takeoff noise from FAR 36 minus 8 to FAR 36 minus 10, the changes required to the engine/nacelle would result in about a 9 percent increase in gross weight to do the same payload-range mission. Therefore, Fig. 20 shows that a nominal takeoff noise design goal for future three-engine aircraft could not realistically be set more than about 8 EPNdB below FAR 36.

Fig. 20 shows takeoff noise reduction versus the decrease in payload/gross weight ratio for a range of acoustic treatments from hardwall to multi-splittered nacelles. It is seen that noise level (relative to current FAR 36) decreases only with increasing gross weight for a fixed payload. The curve turns sharply at 8 EPNdB below FAR 36. Noise reductions greater than about 8 EPNdB become prohibitively costly as the combined noise floors of jet noise and core noise (including an assumed suppressed core noise level) are reached. The weight penalty for achieving more than 8 EPNdB reduction, while accomplishing the design mission, is so high that it raises serious questions about commercial viability of the product.

However, it was noted earlier that a product design must include a tolerance to provide a reasonable confidence of ultimate demonstration. Before a manufacturing commitment can be made for a new product, there must be a reasonable probability that all the requirements can be met. Noise levels relative to FAR 36 are but one of these requirements. Other requirements include
fuel efficiency, range, payload, and cruising speed. The values of aircraft noise performance described herein for the Boeing study airplane represent nominal estimates. In other words, there is only a 50 percent chance that flight test noise levels will be equal to or lower than the nominal values. A program cannot proceed with only 50 percent chance of success. On the other hand, a near 100 percent confidence level is not reasonable either since the product would be over-designed and would be hopelessly inefficient and expensive.

In the illustration in Fig. 20, a reasonable probability of success for a new three-engine airplane using conventional HBP engine cycles requires a design tolerance of about ±3 EPNdB for takeoff noise. This means that the lowest practical design goal for the airplane, due to the rapidly increasing penalty, is about 8 EPNdB below FAR 36. However, the maximum noise increment for which a design performance requirement (commitment) can be made is about 5 EPNdB below FAR 36. It is obvious that irrespective of what the final noise level is, the performance penalty associated with the original design goal has now become a critical part of the airplane.

Similar information is shown in Fig. 21 where approach noise levels relative to FAR 36 are shown versus fuel usage. Here it can be seen that approach noise reductions are limited by airframe noise. The dashed curve shows what would be the limiting case of engine-only noise if airframe noise were somehow eliminated without attendant performance penalties to the airplane.

The lowest practical design goal for approach noise is about 6 EPNdB below FAR 36 for a new technology three-engine airplane. A design tolerance of about ±3 EPNdB results in a reasonable certification requirement of 3 EPNdB below FAR 36. Thus, meeting the "certification requirement" levels indicated in Figs. 20 and 21 accomplishes even greater aircraft noise reduction because the aircraft manufacturer would be forced to design a configuration with a goal that would be at least 3 dB below these certification limits. The manufacturer would then have equal probability that his demonstrated levels would be above or below his design goal, but would also have the necessary margin to compensate for noise levels higher than he expected. The economic consequences of failure are too great to commit to production a design that just matches the certification requirement. The problem is such that an adverse turn of events would not be known until flight test day, when perhaps one billion dollars (including a two or three year pipeline of airplane parts) has been committed. Regulatory or guarantee levels below those shown in Figs. 20 and 21, i.e., levels that are too high up the cost curves, would result in unsaleable products. Obviously, the inability to offer and sell a new quieter airplane because of exorbitant penalties would result in the continued sale of additional older, and noisier, airplanes. Thus, requirements to reduce levels below what the technology and

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**Table 1 Noise Test Results Variability**

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market place can support will be counter-productive.

1990 RESEARCH PROJECTIONS

A projection has been made of potential noise reductions for the future. The projection was based on assumed research and development programs that will be adequately funded and directed, in such a way that useful new noise reduction hardware applicable to a conventional turbofan powered commercial product will result. The timeframe represents roughly ten years for R&D and five years for development and delivery of a new type of airplane and, therefore, represents a projection for airplanes delivered in the early 1990's.

The projection of technology benefits, by necessity, always includes simplifying assumptions. The projection results, although sometimes very instructive, must be viewed with these limitations clearly in mind. To scope the potential for possible future aircraft noise reductions, the study was conducted based on an actual in-service wide body transport as a starting point.

The estimated reductions are those that might be expected in 1990 on an engine/airplane combination with general engine and nacelle characteristics similar to those of the wide body aircraft in-service today. The study starting point was to develop the noise component description of the current technology engine/nacelle airplane combination. Estimates were then made of plausible noise reductions that could result from adequately funded research, development, design, and implementation programs for each component. Potential reductions were considered for all of the known major sources, such as fan, turbine, core, jet, and airframe. It should be noted that consideration could not be given to as yet unknown sources which, based on recent research experience, could be numerous. Advancements in lining technology were also assessed. The fact that concurrent incorporation of more than one reduction concept for a source would not usually provide the sum of the individual concept potentials was accounted for during the study. Some 20 advanced technology concepts were evaluated.

Based on the projections for each noise source, estimates were made of the takeoff and approach noise improvements from today's HBF airplane levels. The resulting nominal (50-50 probability) total airplane noise reductions were:

**Long-Term Research Goals**

- **Takeoff**: -7 EPNdB
- **Approach**: -9 EPNdB

Relative to the current operational commercial aircraft powered by current technology engines. Advances in other technologies (e.g., propulsion), changes in nacelle size/design and configuration variations could alter these noise increments. Also, the reader is cautioned that these research projections do not represent technical evidence of sufficient depth that they could be used to develop guarantee or regulatory noise levels.

The study results do indicate the following:
Table 2 Noise Reduction Increments from Untreated 727-200 for JT8D-109 Refan Retrofit Configuration (EPNdB)

<table>
<thead>
<tr>
<th>Approach 9</th>
<th>Original Research Projection</th>
<th>Initial Reasonable Confidence Predictions</th>
<th>Flight Estimates Based on 1975 Ground Demonstration (nominal)</th>
<th>1975 Reasonable Confidence Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>40° Flaps</td>
<td>-10</td>
<td>-5</td>
<td>-6.8</td>
<td>-3.8</td>
</tr>
<tr>
<td>20° Flaps</td>
<td>-10</td>
<td>-5</td>
<td>-7.5</td>
<td>-4.5</td>
</tr>
<tr>
<td>Takeoff/Cgback 9 3° Flaps</td>
<td>-10</td>
<td>-5</td>
<td>-6.3</td>
<td>-3.3</td>
</tr>
<tr>
<td>Full Power Takeoff 9 5° Flaps</td>
<td>-10</td>
<td>-5</td>
<td>-7.7</td>
<td>-4.7</td>
</tr>
<tr>
<td>Sideline 9 5° Flaps</td>
<td>-10</td>
<td>-5</td>
<td>-6.4</td>
<td>-3.4</td>
</tr>
</tbody>
</table>

1. Future noise improvement is going to be difficult because a number of components must be lowered simultaneously to provide meaningful reductions.
2. The progress will be slow, barring any major change in engine or airplane configuration or concepts.
3. The progress will be costly, requiring adequate R&D funding.

CONCLUDING REMARKS

The advent of the modern high bypass ratio engine with a noise suppression system represents a major advancement in reduced noise levels in airport communities. Currently, core noise, jet noise, and airframe noise represent floors preventing further practical noise reduction. Near-term prospects show some promise for small additional noise reductions, but larger advances require additional technology that can only come from intensive research and development programs. Noise reduction goals, such as regulatory and customer requirements must be set with an adequate appreciation of current technical capability, the need for design tolerances, and noise reduction-cost trades. Failure to adequately consider these realities will result in delayed noise reduction relief, and can prolong the use of older, noisier commercial aircraft.

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