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# Evaluation of the Advanced Subsonic Technology Program Noise Reduction Benefits

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May 2005

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# 1.0 Introduction

## 1.1 Background

At the inception of the Advanced Subsonic Technology (AST) program, aircraft noise had become an international issue prompting airports to operate with stricter noise budgets and/or curfews. This resulted in restricting airline operations and loss of revenue. International treaty organizations were actively considering more stringent noise standards that would impact the growth of the worldwide air transportation system and would also impact the U.S. aircraft industry's competitiveness in the world market. Evidence of this increased stringency was the mandated phase-out of Stage 2 airplanes by the year 2000.

In February 1992, NASA and the FAA initiated a cosponsored, multiyear program focused on achieving significant advances in noise reduction technology. The goal of the AST program was to develop technologies that would reduce future subsonic transports noise levels 30 EPNdB (Effective Perceived Noise Level) by the year 2000. Development of such technologies would enhance U.S. engine and aircraft competitiveness for the next generation of subsonic transports. Success of the program was to be quantified relative to the noise levels of state of the art 1992 production aircraft. A joint effort between NASA, the FAA, and the U.S. Aircraft Industry was established to advance research in the technical areas concerning jet noise, nacelle aeroacoustics, turbomachinery noise, airframe noise, and flight operating procedures.

The AST program goal has been achieved via systematic development and validation of noise reduction technology. There has been strong coordination among Government, industry, and academia in the planning and execution of this noise reduction program. This close coordination has resulted in an orderly and effective transition of the noise reduction technologies to the U.S. industry.

## 1.2 Program Objectives and Goals

The objective of the program was to provide noise reduction technology readiness to achieve unrestrained market growth, increased U.S. market share, and compliance with international environmental requirements. To achieve this objective, NASA established a noise reduction goal of 10 EPNdB as measured at each of the three certification points relative to 1992 aircraft technology (30 EPNdB cumulative). This goal was achieved by assembling a team of industry, university, and government technologists working within an established noise technology infrastructure.

The Noise Reduction Program goal was achieved by combining noise reduction improvements in the engine systems, aircraft systems, and in aircraft operations. As seen in Figure 1.1, five program elements were directed toward three desired technology results: engine design for noise reduction, aircraft system noise minimization, and community noise impact minimization. A “Technical Working Group” team was established to assure communications between the program elements. This coordination resulted in the assurance that the desired results would contribute in a synergistic manner towards achieving the program noise reduction goals.

The chart in Figure 1.2 shows the noise reduction goals established for each of the technical areas. A summary of the goals and objectives for each of the technical program elements is given below.

### 1.3 Engine Noise Reduction

The goal of the engine noise reduction element was to provide technology to reduce engine noise levels 6 dB relative to 1992 technology. Research conducted in this area provided design techniques for lowering noise while maintaining high performance for advanced turbofan engines. The research addressed acoustic, aerodynamic, and structural disciplines and provided experimental data and analyses that lead to improved low-noise turbofan design methodology. Emphasis was put on the development of noise prediction methods in parallel with validation testing. A near term program goal for 1996 was to provide technology for reducing jet noise by 3 dB for engines with bypass ratios in the range from 3 to 6. In the same time frame, technology for reducing fan noise 3 dB was demonstrated in model scale for advanced fan designs with bypass ratios ranging from 6 to 15. In parallel with the engine validation tests, model scale tests and noise prediction development continued and were jointly used to meet the final program goals.

### 1.4 Nacelle Aeroacoustics

The goal of this research was to provide technology to increase the effectiveness of the nacelle in absorbing, canceling, or redirecting turbomachinery noise. Research included analytical modeling to estimate nacelle geometry effects on noise propagation, laboratory experiments to improve duct noise control treatments including passive, adaptive, and active control strategies, and scaling validation of noise control technologies through scale-model and full-scale tests. An intermediate program objective was to increase treatment efficiency by 25% by 1997. The ultimate objective was to achieve a 50% increase in suppression effectiveness that was determined later in the program to be equivalent to a 2 EPNdB reduction.  These technologies were demonstrated in full-scale static engine tests.

### 1.5 Acoustic/Aerodynamic Integration and System Evaluation

The goal of acoustic/aerodynamic integration and system evaluation effort was to develop and validate design methods and advanced concepts for low-noise, aerodynamically efficient aircraft and to update and improve prediction codes that were subsequently used to evaluate program progress. For the integration work, emphasis was on the acoustic and aerodynamic integration of turbofan engines with high-lift systems operating under both takeoff/climb-out and approach/landing conditions. Specific objectives included the development of technology to reduce airframe noise 4 dB below 1992 levels, elimination of potential noise penalties due to the interaction of the engine and the wing high-lift system while maintaining the current level of high-lift performance, and identification and elimination of areas of risk when model scale experiments are used to predict the performance of flight hardware under flight conditions. The implementation of new subcomponent airframe noise prediction codes was key to accommodate the evaluation of airframe noise reduction.

## 1.6 Interior Noise Reduction

The goal of the interior noise reduction technology development was to flight demonstrate technologies capable of yielding an overall interior noise reduction of 6 dB relative to 1992 technology. To achieve this, the interior noise reduction effort was to integrate into a cohesive program the research from source identification, interior noise prediction, and innovative and optimal noise control concepts. Source identification was to include the engine acoustic and vibration inputs into the structure, and the temporal and spatial loading characteristics of boundary layer and jet sources as they relate to aircraft interior noise. Studies of the acoustic/structural interaction were to guide the development of concepts to minimize this coupling. Near field acoustic-imaging technology was extended to flight test evaluations to identify the specific structural responses that generate objectionable interior noise levels. In this way noise control technologies could be optimized for maximum reductions with minimum weight added.

Noise control technology was planned to encompass both active and passive concepts. Finite element methods and energy methods were to be extended and used to investigate mechanisms of noise transmission. These were to be combined into design methodologies such that the effects of structural design parameters on interior noise could be taken into account in the overall aircraft design process. Active control was to be investigated and incorporated into a “smart structures” approach with improved actuators and sensors integrated with the structural elements for optimum performance.

This program element was dropped when the AST program was terminated and the work did not continue under the successor program effort as did the other elements as describe herein. The work accomplished has been included in an AST bibliography published under a separate cover.

## 1.7 Community Noise Impact

The goal of the community noise impact element was to provide technology to reduce the noise impact of aircraft and airport operations on the airport community. This area included application of new aircraft technologies and operational procedures, improved noise impact modeling and prediction, and improved understanding of relationships between human response and aircraft noise exposure variables. An equivalent of a 3 EPNdB reduction in noise impact on the community was envisioned.

## 1.8 Minimum Success Requirements

The individual goals for each element make up the total goal of 10 EPNdB per certification point for the program. A minimum success requirement was established such that these less aggressive requirements would guarantee some recognition of success for the program. For the overall program goal of 10 EPNdB per point, the minimum success requirement was set to develop technology to reduce the per point noise impact by 7 EPNdB. This requirement was applied to determine minimum success requirements for each element as indicated in Figure 1.2.

## 1.9 Overview of Program Scope

The AST program goal was to develop technologies that would reduce aircraft noise by 10 EPNdB at each of the certification measurement points relative to 1992 aircraft technology levels (30 EPNdB cumulative). To meet this aggressive goal, research was conducted in three broad categories as was indicated in Figure 1.1, engine noise reduction, nacelle and liner technology, and airframe noise reduction. This work was augmented by the addition of further community noise reduction resulting from operating procedures. Progress was measured relative to baseline noise levels established at the beginning of the program (Reference 1). Four classes of commercial aircraft configurations were established for the evaluation procedure. The aircraft weights spanned from about 20,000 pounds for the Business Jet class to over 800,0000 pounds for the large four engine aircraft (Large Quad). This aircraft size variation permits a thorough evaluation of the implementation of the noise reduction technology on different size aircraft. The four aircraft classes included a Large Quad (LQ) (four) engine aircraft (such as a Boeing 747-400), a Medium Twin (MT) engine aircraft (such as a Boeing 767-200 or the Airbus A330 aircraft), a Small Twin (ST) engine aircraft (such as a Boeing 737-300), and a Business Jet (BJ) (such as the Learjet 25 aircraft).

A noise technology infrastructure had been developed over the years as NASA and the FAA worked with industry and universities to promote aircraft noise reduction studies. At the time of inception of the AST program, most aircraft in operation were still dominated mainly by the propulsion system noise. As the engines grow in size and thrust, the jet noise continues to be reduced but the fan noise becomes a larger share of the remaining dominant noise sources. As a result of this, about 75% of the resources of the AST program was directed into the propulsion system noise reduction. Furthermore, the success of past efforts for developing technology for reducing noise indicated that the noise technology infrastructure already being utilized was sufficient to carry forth further noise reduction studies of the magnitude envisioned by the ambitious AST goals.

Based primarily on the products they manufacture, General Electric Aircraft Engines (GEAE) and Pratt & Whitney Aircraft Engines (P&W) conducted tests and analyses associated primarily with propulsion systems for the larger transport aircraft that included the Large Quad aircraft, the Medium Twin aircraft, and the Small Twin aircraft. These engines have thrust capabilities of 30,000 lbs up to over 90,000 lbs. Honeywell Systems and Engines (Honeywell) and Rolls Royce Engines performed tests and analyses primarily associated with the smaller Business Jet. These latter engines generally have thrusts of about 15,000 lbs or less.

As engine noise research results in quieter propulsion systems, attention has to be focused on the airframe noise. Especially for the large aircraft that tend to have higher bypass ratio engines, airframe noise has become a problem during approach and landing. For the aircraft approach and landing configuration, the engine thrust is significantly reduced to help reduce the aircraft speed. This reduced engine thrust exposes or uncovers the airframe noise sources. The AST program apportioned some of its resources in evaluating the relative importance of and reducing the contribution from airframe noise sources.

Boeing concentrated primarily on the airframe noise sources as applicable to the larger aircraft that included the LQ, MT, and ST aircraft classes. The Boeing work also included analyses and tests of engine inlet noise reduction devices. Honeywell analyzed issues concerning airframe noise for the business jet. Because the predominant source of noise for the business jet has been propulsion noise, not much airframe acoustics information is available for this small aircraft class.

NASA's Ames Research Center (ARC), Glenn Research Center (GRC), and Langley Research Center (LaRC) all supported technology research and development for this program. LaRC was responsible for overall program implementation and management. As such, LaRC also had the responsibility to measure progress and report on the achievement of the program goals. Additionally, LaRC conducted airframe analyses and performed small model-scale testing of airframe noise reduction devices such as leading edge slats with various cove fillers. GRC performed in-house propulsion analyses and conducted static, flight, and wind tunnel tests to evaluate various engine noise reduction concepts. The GRC development also included work in engine source noise prediction, technology validation testing, liner development, and active noise control. NASA Ames conducted computer analyses of airframe noise components and conducted small model-scale tests of various airframe noise reduction devices. NASA Ames also conducted a larger scale (26%) test of a Boeing 777 wing semispan model. LaRC, GRC, and ARC were all intimately involved in the final evaluation of program success.

All of these aforementioned organizations used contracts and subcontracts with U.S. aircraft industries and universities to broaden the technology input base into the program. The chart in Figure 1.3 is a reasonably exhaustive list of the organizations that contributed to the AST program (program participation status as of 1995). The organizations and personnel participation did change during the course of the program. A technical working group was established to help guide NASA in the technical planning of the research thrusts in each of the five program elements. Working Group activities included identification of technology needs, teaming arrangements, test and analysis activities, and coordination among governments, industry, and academia. An Industry Steering Committee was also established to provide broad Industry guidance to NASA on the overall program direction and thrusts. This included advice on NASA customer needs, technical thrusts, balance of program technical efforts, implementation strategy, and program advocacy.

The results from all of the analyses and tests from all of the participants were used as input to predict the overall noise benefits of each of the four aircraft configurations. The noise reduction benefits are measured against the baseline levels from commercial technologies that were available and in use on 1992 aircraft.

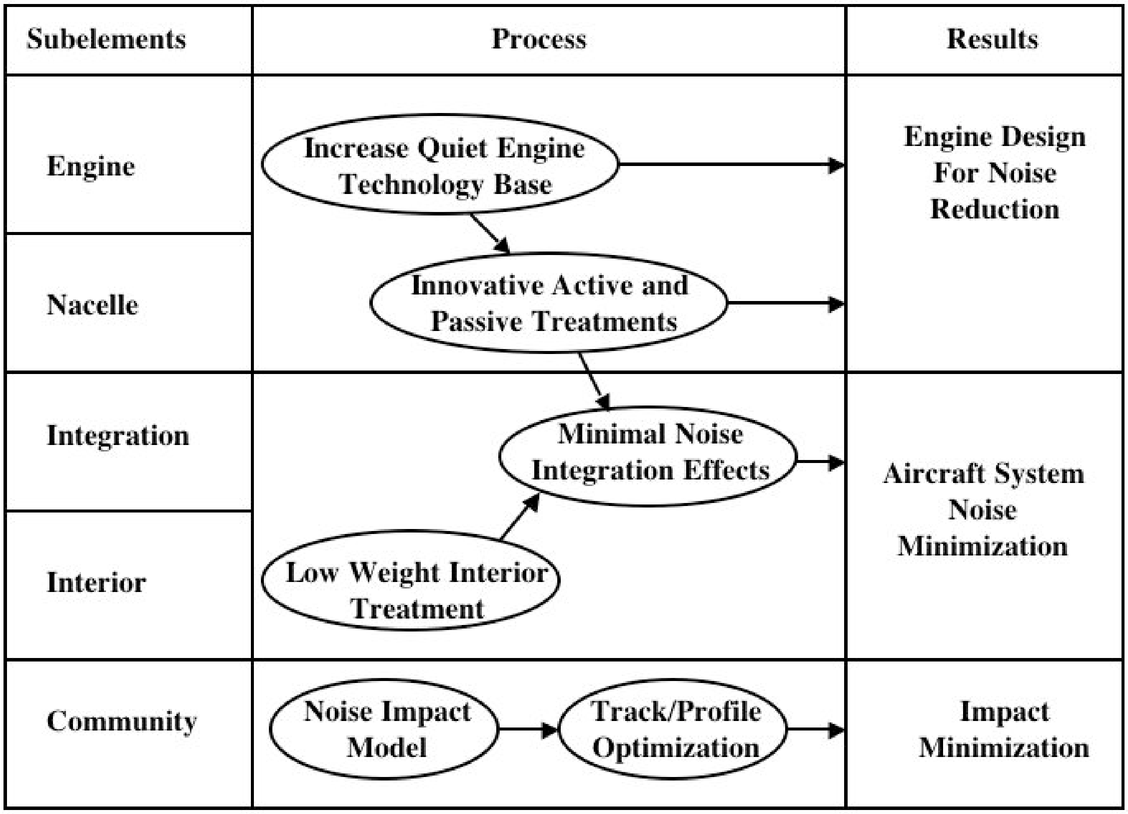



**Figure 1.1. Noise Reduction Technical Approach**

| Subelement | Objective | Minimum Success |
|---|---|---|
| Engine Noise Reduction | 6 dB Engine Noise Reduction* | 4 dB |
| Nacelle Aeroacoustics | 50% Liner Efficiency Improvement* | 35% |
| Airframe Noise Reduction | 4 dB Airframe Noise Reduction* | 2 dB |
| Interior Noise Reduction | 6 dB Interior Noise reduction* | 4 dB |
| Community Noise Impact | Community Noise Impact Minimization Model 3 dB (2 dB equivalent reduction through advanced operations) | 2 dB |
| Noise Reduction Program | 10 dB Community Noise Impact Reduction * | 7 dB |

* Relative to 1992 Production Technology

**Figure 1.2 Noise Reduction Goals for each Technical Area**

**Technical Working Group**

| Industry | | NASA | | FAA |
|---|---|---|---|---|
| AlliedSignal…….Weir | Lockheed……..Reddy | Corsiglia | Shepherd | Skalecky |
| Allison…………..Dalton | Northrop……...Parente | Huff | Silcox | |
| Boeing…………..Reed | P&W………….Mathews | Jones | Stephens | |
| Douglas…………Joshi | Rohr…………..Yu | Posey | Willshire | |

**Steering Committee**

| | | |
|---|---|---|
| Allison…………..Dalton | Douglas………..Haight/Joshi | Ex-Officio |
| ALPHA…………Davis | Gulf Aero……...Hilton | NASA…..Beach |
| Boeing…………..Craig | GEAE………….Gliebe | FAA…….Erickson |
| DFW…………….Robertson/Linn | N.O.I.S.E………Kane | |
| Delta……………..Bautz | P&W…………...Wagner | |

**Figure 1.3 Industry Participants /Working Group Members/ Steering Committee Members**

## 2.0 NASA Aircraft System Noise Evaluations

### 2.1 Establishment of the Baseline Levels

The goal of the AST program was to develop technology to reduce the noise levels by 10 EPNdB at each certification measurement point (i.e., approach, sideline, and cutback) relative to 1992 technology aircraft. Because the certification regulations allow trading of noise benefits between certification points, Industry and NASA agreed to express the final goal and the minimum success goal as a total noise reduction achieved by summing the three measurement points. Therefore, the final AST goal was set at a cumulative 30 EPNdB and the minimum success goal was set at 21 EPNdB, for each of the four aircraft configurations. The assessment methodology and data presented in this report are geared to the above criteria.

The baseline noise models established at the beginning of the AST Program represented fleet averages for each the four aircraft classes (Reference 1). The methodology for assessing the overall airplane system noise impact from noise reduction concepts is based on detailed component noise models that define the individual contributions from airframe noise and engine noise. This process allows for the assessment of the total airplane noise resulting from changes of the individual noise components.

Because the effectiveness of a noise reduction technology depends on the particular engine cycle, the baseline fleet average engine noise levels had to be eventually replaced by a specific engine cycle that had equivalent noise levels of each of the aircraft classes. GEAE, P & W, Honeywell, and Rolls Royce each selected one of their engine cycles that represented their 1992 technology.

These engines cycles were specifically tied to one of the airframes that were used as described below. For each of the company chosen engine cycles, each engine company provided one-third octave band spectra for each engine noise source for use by NASA to establish engine baseline levels from which program noise reduction accomplishments would be measured. These engine component noise levels determined by NASA then became the program 1992 technology baseline engine noise levels. In the final program evaluation, each of the engine noise reduction technology concepts was evaluated against these baseline levels.

As the same assessment problem was encountered with the baseline airframe noise fleet averages, the fleet average airframe noise levels had to be replaced by noise levels for specific airframes representing each aircraft class. Boeing agreed to furnish data for the 747-400 to represent the Large Quad, the 767-300 to represent the Medium Twin, and the 737-300 to represent the Small Twin airframes. Boeing provided NASA with the one-third octave band spectra for the airframe noise components for all the above commercial transports to establish the program 1992 technology baseline airframe noise levels.

Honeywell and NASA Langley worked together to establish the airframe noise levels for the Business Jet. Honeywell used a newly developed Boeing airframe noise prediction code applied to a typical aft mounted twin engine Business jet airframe configuration. One-third octave band spectra were predicted for each airframe noise component for the Business Jet. NASA used these predicted values to determine 1992 technology baseline noise levels for the Business Jet.

Boeing was generating the baseline component airframe noise levels at the same time that the engine companies were generating their baseline engine noise levels; hence, the Boeing baseline component airframe noise levels were not available to the engine companies to use to calculate total aircraft noise. Consequently, the engine company's baseline evaluations were accomplished using the fleet average airframe noise levels established in reference 1. For the final AST baseline assessment, NASA had to combine the Boeing airframe levels with the appropriate engine noise levels appropriate for each aircraft class. This resulted in NASA creating six reference airframe/engine systems as follows:

1. 747-400 airframe with P&W 1992 Technology Engines
2. 747-400 airframe with GEAE 1992 Technology Engines
3. 767-300 airframe with GEAE 1992 Technology Engines
4. 737-300 airframe with GEAE 1992 Technology Engines
5. Business Jet Airframe with Honeywell 1992 Technology Engines
6. Business Jet Airframe with Rolls Royce 1992 Technology Engines

The NASA noise levels determined for these airframe/engine systems using company provided data established the baseline noise levels for the AST final assessments.

Using the Aircraft Noise Prediction Program (ANOPP), NASA Langley performed independent noise level assessments with industry supplied acoustic data. Since the prediction methodologies used by each of the aircraft companies and NASA are different in philosophy and process, predicted levels for components and aircraft totals were not expected to be identical. However, the levels were expected to be close. To ensure this, NASA continually compared the results of their noise predictions against the analyses performed and supplied by the companies. An example of the data comparisons performed is shown Figure 2.1. It includes all the various combinations of engines, airframes, and noise reduction technologies evaluated at the approach, sideline, and cutback operating conditions. It shows that NASA determined noise levels are always within ±1 EPNdB of the Industry calculated noise levels.

### 2.2 Evaluation of Noise Reduction Technologies

As indicated above, NASA Langley had to evaluate the six baseline airframe/engine systems and then subsequently reevaluate all of the airframe together with the proposed advanced engine cycles and adding the various technology noise reduction concepts. In the NASA bookkeeping, the engine "cycle effects" have been kept separate from the "other" noise reduction technologies. For the "other" engine technologies, in this report we booked the noise reduction results under "hardware noise reduction" technology. Hence, hardware noise reduction refers to any engine noise reduction technology modification other than a change in engine cycle.
Three of the engine companies provided NASA with noise levels for an advanced engine configuration. The advanced engine cycles utilized higher bypass ratios and lower fan tip speed to reduce the fan and jet noise levels. As will be shown for each case, the evaluations indicate that even the minimum success goal of 21 EPNdB could not be met with hardware noise reduction changes alone. The additional necessary noise reduction was achieved by changing the engine cycle.

The airframe noise reduction evaluations included analysis of Boeing supplied noise reduction technologies and noise reduction technologies developed in-house by NASA. NASA airframe noise reduction technology development was performed both at Ames and Langley Research Centers.

Roughly 75% of the AST program funds were expended on the engine noise reduction technology. This was required because the 1992 baseline aircraft were still predominately engine noise dominated. Hence, the noise reduction reported herein is weighted towards the engine noise reduction technologies. As these noise reduction technologies are incorporated into the newer engines, the airframe noise sources will become more of a problem especially at the approach operating conditions. The majority of the NASA engine noise reduction development was performed by Glenn Research Center.

### 2.3 Technology Readiness Levels (TRL) and Assessment Guidelines

In considering noise reduction technology readiness, it is important to recognize that NASA Research and Technology (R&T) development is only a part of a total aeronautics technology maturation process. There are nine levels of technology readiness defined by NASA as shown in Figure 2.2. The legitimate R&T role as defined by NASA includes research from observing basic principles to subsystem models or prototype demonstration in a relevant aircraft environment. This technology maturation process includes both a lower level (Levels 1 to 4) aeronautics R&T base to develop a discipline research foundation and a focused (higher levels of 5 to 6) R&T to further demonstrate generic capabilities. The purpose of the AST program, a focused R&T program, was to build on the aeronautics R&T base technologies and mature the technologies to one of the higher levels (5/6) of technology readiness in which NASA (and the U.S. Government) has a legitimate and necessary role. This technology maturation process, of course, does not end with NASA's participation, but continues in the industry and FAA participation with further technology development for selected higher-risk systems or subsystems. This technology maturation process is only completed with industry's full-scale development and "flight qualification" through test or during actual flight operations. Hence, the success of the AST program is measured by how well NASA meets its planned technology readiness levels, and provides the U.S. Aviation industry the risk reduction to allow final decisions regarding application of noise reduction technologies to their product lines.

The noise reduction technology evaluated in this report for AST goal attainment was required to be at a NASA defined technology readiness level of 5/6. Table 2.1 lists the engine and airframe technologies that were considered in the assessment process. Hence, these are the technology concepts evaluated as applicable to each of the six baseline airframe/engine combinations for each of the three-certification points. NASA worked closely with the engine and airframe companies to make sure that each of the technology concepts were being applied to the correct engine cycle and/or airframe. There were many other noise reduction technologies that were developed and worked with during the AST Program, but because they did not mature to a technology readiness level of 5/6 they are not included in this report nor are they in this list.

In Table 2.1, Active Noise Control (ANC) is included even though it has a TRL rating of 4. The AST program guidelines required technologies to achieve a NASA TRL of 5 or greater to be included in the assessment process. Clarification is required to explain the inclusion of ANC as a technology in the NASA system studies of the large quad, medium twin, and small twin aircraft. Early on in the AST program, NASA conducted numerous system study assessments that included noise reduction technologies with TRL ratings of 4, 5, and 6. Eight different ANC tests were conducted in the NASA Glenn Active Noise Control Fan (ANFC) rig. To varying degrees all of the tests demonstrated measurable reductions in fan noise levels in both the inlet and aft ducts. A summary of these tests can be found in Reference 2. Based on early successes, NASA anticipated that ANC would successfully achieve a TRL rating of 5 and thus included ANC in the early assessments.

ANC has been demonstrated to be very effective in situations where only one or two modes contribute to a targeted fan tone. As additional research was conducted, it became clear that as the number of contributing modes increased the effectiveness of ANC diminished. Because of the complex nature of the rotor-stator generated modes, multiple duct modes always have a unique phase relation that depends on the axial location in the duct. Hence, successful implementation of ANC becomes more complex and difficult in real engine environments (TRL 5/6). Success depends on the both the accuracy of the sensor arrays to measure this complex phase relation and the accuracy of the actuators to reproduce the canceling field. Since ANC was never successfully demonstrated in a relevant environment by the end of the AST program, ANC remained a TRL 4 technology.

With that brief overview on the research conducted on ANC, it should also be noted that NASA's requirement that all noise technologies meet a TRL criterion of 5 or greater occurred relatively late in the AST program assessment. NASA's final configuration for the large quad with the P&W engines was, in fact, completed prior to the determination that ANC would be rated as a TRL 4 technology. Because of the small assessment impact of the inclusion of ANC, no effort has been made to change this assessment in Section 5.2.

During the final editing of this report, the technologies used on the P&W engines were reexamined. The fan technology selected for the P&W ADP engine (as described in Table 5.2.14) was the swept and leaned fan with cut-on fan exit guide vanes (FEGV) with ANC. It was found that nearly the same noise reduction was achieved on this engine by using the swept and leaned fan with cutoff FEGV (i.e., no ANC effect included). The difference in aircraft noise benefit between the two fan configurations was 0.1 EPNdB at approach and cutback and 0.4 EPNdB at sideline. See Tables 5.2.3 and 5.2.5. Since this difference was well within the accuracy of the predictions, the decision was made not to change the final configuration used for the assessment of the large quad with P&W engines.

Because it was recognized early enough in the systems evaluations that ANC did not meet the AST required TRL, NASA dropped any further inclusion of ANC in the rolled-up technology results for any other aircraft/engine system evaluations. While the technology results tables show an ANC impact, the results are not included in the successive technology roll-up.
In Sections 3 and 4 of this report are descriptions and discussions of many of these technologies and how NASA viewed each technology in the noise reduction evaluation process. The actual detailed analysis of the combinations of the various engine cycles, airframes, and hardware technologies are presented in Section 5.

## 2.4 Noise Reduction Evaluations From Aircraft Operations

Part of the AST program goal (See Figure 1.2) had a requirement to demonstrate and quantify community noise reduction benefits achievable through advanced operational procedures. A flight test was executed during April/May, 2000, using the LaRC ARIES 757 (see Figure 2.3) aircraft to fly specific nonconventional takeoff and landing flight configurations/trajectories over arrays of ground-based microphones. The acoustic signals recorded from these aircraft flyovers of the ground-based microphones were correlated with the aircraft position, on-board aircraft measured engine and aircraft state parameters, and locally measured weather parameters. The resulting database of correlated acoustics information was analyzed to quantify the achieved community noise reduction benefits. The results from the tests were presented at the Fall 2000 AST Working Group Meeting. Based on the data presented, a consensus was reached by the Technical Working Group that a 2 EPNdB reduction would be applied at both the cutback and approach certification points.

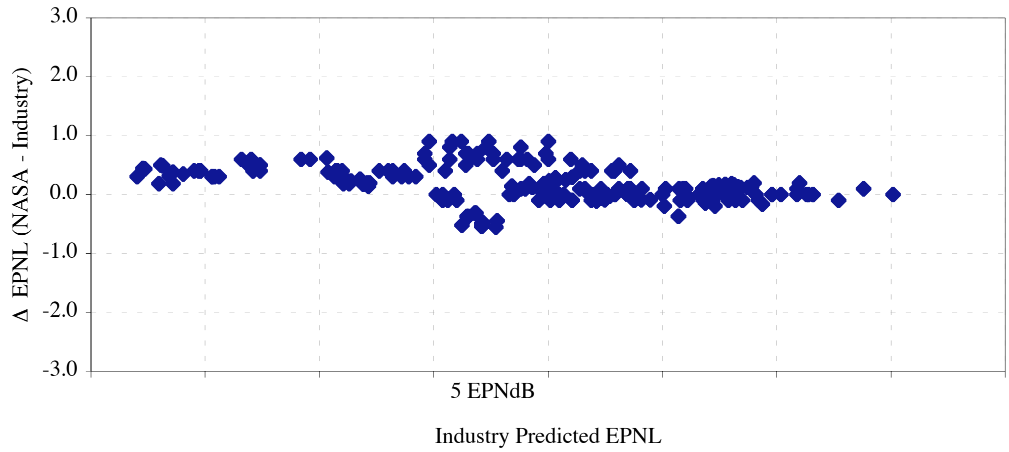



**Figure 2.1 Comparison of NASA and Industry Predicted EPNL**

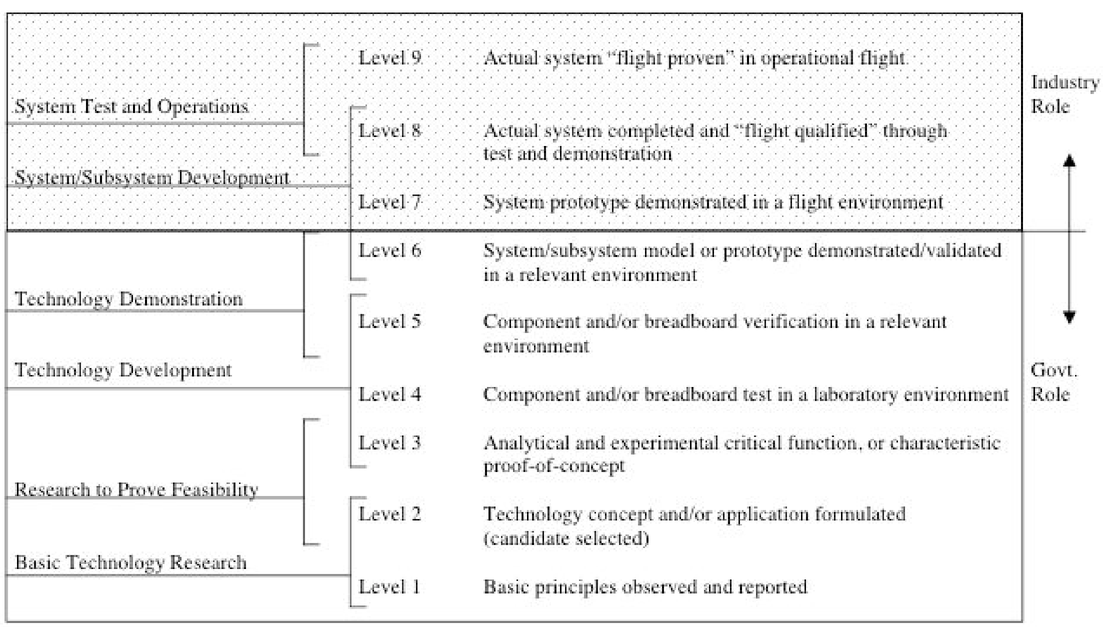



**Figure 2.2 NASA Technology Readiness Levels**

# NASA ARIES 757 AIRCRAFT


**Figure 2.3 Flight Demonstration of AST Noise Reduction Operations**

| Noise Source | Technology | TRL 4 | TRL 5 | TRL 6 |
|---|---|---|---|---|
| Engine Cycle | ADP (P&W) | | x | |
| | GE90 (GEAE) | | | x |
| | HBPR (Honeywell) | | x | |
| | HBPR (Rolls Royce) | | x | |
| Fan Inlet | Active Noise Control * | x | | |
| | Scarf Inlet | | x | |
| | Amax | | x | |
| | Lip Treatment | | x | |
| | Forward Swept Fan Rotor | | x | |
| | Swept Stators | | x | |
| | Swept and Leaned Stators | | x | |
| | HQ Tubes | | x | |
| Fan Exhaust | Aft Duct Treatment | | x | |
| | Forward Swept Fan Rotor | | x | |
| | Swept Stators | | x | |
| | Swept and Leaned Stators | | x | |
| Jet | Chevrons/Tabs | | | x |
| | Mixer Nozzle | | x | |
| | Variable Area Nozzle | | x | |
| Flaps | Porous Flaps | | x | |
| Slat | Cove Filler | | x | |
| Flight Ops * | | x | | |

*** See explanations in Sections 2.3 and 2.4 text**

**Table 2.1 Technology Readiness Levels Matrix**

## 3.0 Airframe Noise Reduction Technology Descriptions and Analysis Data

### 3.1 Introduction

Airframe noise was found to be a very significant noise source for the selected large 1992 technology commercial transports primarily during approach. For the 1992 baseline engines, airframe noise at approach was exceeded only by fan inlet noise. In 1995 NASA Langley began an intense research effort in airframe noise source reduction. NASA's airframe noise effort under the AST Noise Reduction Program involved many joint ventures with the airframe manufacturers. Achieving the AST goal of reducing airframe noise by 4 EPNdB would first require a fundamental understanding of the source mechanisms that cause airframe noise. Computational and experimental research conducted by NASA and Industry led to the identification of the airframe noise generating mechanisms. Data from small-scale and large-scale tunnel experiments provided valuable databases for improving noise prediction models. Validation of these prediction models provided scaling laws that enabled full-scale suppression spectrum to be modeled for both large and small aircraft. Better identification of the noise generating mechanisms and their relative magnitudes also provided guidance for researchers in the study and development of airframe noise reduction technologies. The following is a brief description of the airframe noise technology investigated and a description of the data that was used for the airframe noise reduction evaluation.

### 3.2 Airframe Noise Component Identification and Modeling

Boeing established the subcomponent airframe noise levels for the small twin, the medium twin and the large quad aircraft using the prediction method described in Reference 3. The specific airplanes selected to represent each of these categories were the Boeing 737-300, the Boeing 767-300, and the Boeing 747-400, respectively. The component prediction models are based on correlations of source strengths from elliptic-mirror data. The elliptic-mirror database consisted of wind tunnel data for five airframe scale models that included Boeing 737-300, Boeing 737-700, Boeing 757, Boeing 777, and the Boeing New Large Airplane. The airframe subcomponents as defined by Boeing are: leading edge slat noise, outboard flap side edge noise, inboard flap side edge noise, high-speed aileron noise, main landing gear noise, and nose landing gear noise.

Boeing used the component prediction models to generate one-third octave band sound pressure levels at a source radius of 1 foot for each subcomponent as a function of directivity angle, flight Mach number, and flap setting. NASA then used ANOPP to propagate the free field lossless source levels to the FAA certification points. The predicted component source levels were then adjusted to yield the approach certification levels. This component level adjustment procedure was performed for each of the three categories of large aircraft.

There is little known about the levels of airframe noise for the smaller Business Jet. The Business Jet airframe subcomponent sound pressure levels had to be established using a modified version of the Boeing airframe noise prediction model. The Boeing wing model assumes a configuration consisting of an inboard flap, high-speed aileron, and an outboard flap, which is appropriate for the large commercial transports. The typical business jet, however, only has one set of flaps, does not have a high-speed aileron, and the slat configuration (if it has one) is simplified compared to the slat on larger aircraft.

Therefore, the following assumptions were made in modeling the airframe noise for the Business Jet:

- No aileron noise
- No inboard flap noise
- Slat noise was reduced –2.9 db due to the lack of a cove and gap
- Flap noise was represented by the Boeing outboard flap model
- Landing gear was modeled by two main landing gear struts and a nose gear strut (each strut has two wheels)

The business jet subcomponent airframe levels were established through the combined efforts of Honeywell and NASA Langley. The approach airframe received noise time history spectra for each component were generated from the Boeing source noise spectra using ANOPP with the Honeywell supplied approach flight trajectory.

### 3.3 NASA Airframe Noise Suppression Analysis

Since the airframe noise suppression studies were all performed in wind tunnels at model scale, the technology noise reduction data supplied have limitations that need to be addressed to be able to apply the data to full-scale aircraft for flyover calculations. This section describes the process by which the noise suppression data from each of the noise reduction technologies were adjusted to apply to the full-scale aircraft at each of the certification operating conditions.

Numerical and experimental studies of airframe noise mechanisms associated with subsonic high-lift systems were performed at NASA Langley Research Center in the Low Turbulence Pressure Tunnel (LTPT). Investigations involved both steady and unsteady computations and experiments on small-scale, part-span flap models. The goal was to determine the fundamental noise source mechanisms by relating sound generation to fundamental fluid mechanics. Larger scale airframe experiments were conducted at NASA Ames Research Center in the 7x10 Low Speed Tunnel and the 40x80 Full Scale Tunnel.

The model scale experiments included a Flap Edge Noise Test (LTPT), a Slat Cove Fill Test (LTPT), a Porous Tip Flap test (7x10), a Landing Gear with Fairing test (7x10), a Slat Cove Fill Test (40x80), a Porous Tip Flap test (40x80), and a Landing Gear with Fairing test (40x80).

All of the airframe suppression data used in the NASA evaluations were obtained at model scale. In most cases, acoustic data were only measured directly under the model. In the ANOPP coordinate system, this corresponds to a polar directivity of $\theta = 90$ degrees and an azimuthal angle of $\phi = 0$ degrees. A frequency scaling law as well as a method of estimating directivity effects was required to project the model scale suppression to the full-scale aircraft.

NASA adopted the frequency scaling law recommended by Boeing (Reference 3). The Reynolds number dependent frequency law for a fully turbulent boundary layer is

$$f_{FULL} = \left( \frac{L_{MODEL}}{L_{FULL}} \right)^{0.8} f_{MODEL} \tag{3.1}$$

where $f$ denotes frequency and $L$ denotes a characteristic length. The lengths used for each test are defined in test description and the full-scale characteristic lengths are listed in Table 3.1.

The following equation was used to define the suppressed overall sound pressure levels as a function of directivity angle:

$$OASPL_{SUP}(\theta) = OASPL_{UNSUP}(\theta) \frac{OASPL_{SUP}(\theta = 90)}{OASPL_{UNSUP}(\theta = 90)} \tag{3.2}$$

Aircraft flight parameters used for EPNL noise reduction predictions in Section 5 for each of the three certification points for each of the aircraft/engine categories are provided in Table 3.2.

Although many airframe noise reduction technologies were investigated as shown earlier (Table 2.1), only two technology concepts were advanced to the technology readiness levels of 5/6 that could be included in the final AST evaluation. These two technology concepts are described in the following sections.

### 3.4 Porous Flap Tip Test and Suppression Data

An experimental investigation of a porous flap tip configuration was conducted in the NASA Ames 7 by 10 foot wind tunnel. Constructing the trailing edge corner of the flap from porous material reduces the impedance difference between the flap and the air, which in turn reduces the strength of the vortices at the side edge. The experimental setup consisted of a 30-inch chord length wing fitted with a 9-inch chord length Fowler flap and a 5.5-inch chord length leading edge slat. The wing and flap assembly were flush mounted between two walls 5 feet apart. The flap span was 2.5 feet with one end flush mounted to the wall. The flap deflection angle was 39 degrees and the wing angle of attack was 10 degrees. The test Mach number was 0.22. Noise measurements were made under the flap tip at a directivity angle of 90 degrees. Noise was measured with and without the porous tip flap in 500 Hz bandwidths from 2000 Hz to 38000 Hz. Figure 3.1 shows the 500 Hz bandwidth sound pressure level measurements as a function of frequency for the solid flap and the porous tip flap. Figure 3.2 shows the porous tip flap suppression results.

The 500 Hz bandwidth data were adjusted for application to the inboard and outboard flaps of the full-scale aircraft and converted to one-third octave bands. The inboard and outboard chord lengths of the Large Quad, the Medium Twin, and the Small Twin are listed in Table 3.2. The Business Jet has only an outboard flap that is included in this table. The minimum one-third-octave band frequency where the data applies varies from 200 Hz for the Large Quad inboard flap to 1000 Hz for the Business Jet outboard flap. The data were linearly extrapolated to obtain suppressions for frequencies below these minimum frequencies. Figures 3.3(a) and 3.3(b) show the one-third-octave band porous tip flap suppression for the inboard flaps and outboard flaps, respectively, at the polar directivity of 90 degrees. The figures show that at the lower frequencies the extrapolated suppression was cut off at 0 dB. These data were used as the technology noise reduction input in Section 5 for ANOPP prediction of the noise reduction levels achieved.

### 3.5 Slat Cove Filler Test and Suppression Data

A slat cove filler is illustrated in Figure 3.4. To reduce the lower frequency broadband noise from this noise component, a closed-surface filler was inserted into the slat cove. The cove was designed to make the gap between the slat and the main wing a smoothly converging flow duct. The slat cove filler was used in conjunction with a sharper slat trailing edge. Flow on the pressure side of the leading edge slat is inclined to separate at the slat cusp and then reattach at the trailing edge. Reattachment can produce strong fluctuations in the flow field. Tests and analyses found vortex shedding at the slat trailing edge caused high frequency noise. To reduce this noise, the slat trailing edge was sharpened.

Leading edge slat tests were performed in the NASA Langley LTPT using a leading edge slat model mounted to the NASA two-dimensional Energy Efficient Transport Wing. The chord length of the wing was 21.6 inches and the slat chord length was 3.3 inches. The slat deflection angle was 30 degrees. There was also a trailing edge flap that was mounted at a deflection angle of 30 degrees. The width of the model was 36 inches, which is the same width as the tunnel. The microphone was located at a distance of 39.4 inches from the slat at a directivity angle of 90 degrees relative to the tunnel flow. Data were collected in one-twelfth octave bandwidths with center band frequencies ranging from 971 Hz to 68,786 Hz. The test Mach number was 0.2. Two sets of tests were conducted, one with the wing angle of attack set was 6 degrees and the second with the wing angle of attack set to 9 degrees. Each test included the plain slats, and slats with a cove filler. Figure 3.5 shows the one-twelfth-octave band slat cove filler suppression for both the 6 degree and 9 degree angles of attack.

As in the flap noise tests, the one-twelfth octave band data were adjusted for application to the full-scale airframe and converted to one-third octave bands. The slat chord lengths for the Large Quad, the Medium Twin, and the Small Twin are listed in Table 3.1. The minimum one-third octave band frequencies range from 160 Hz for the Large Quad to 300 Hz for the Small Twin. The SPLs at one-third octave band frequencies below these minimums were obtained by linear extrapolation. Figures 3.6(a) and 3.6(b) show the one-third octave band cove suppression data for the three aircraft configurations at the 6 degree and 9 degree angle of attack, respectively. The straight lines at the lower end of the spectra are the results of extrapolation. The minimum extrapolated SPL suppression value was set at 0 dB.

The leading edge slat on the Business Jet (if it has one) is relatively straight and thus does not have an underside cove. Consistent with our earlier modeling assumptions for the business jet, slat cove noise reduction was not used in its noise reduction analysis.

The suppression data shown in Figures 3.3, 3.5, and 3.6 were used as the technology noise reduction input in Section 5 for ANOPP prediction of the noise reduction levels.

## Table 3.1 Full-Scale Aircraft Component Dimensions

| | Flap Inboard Chord Length (inches) | Flap Outboard Chord Length (inches) | Slat Chord Length (inches) | Main Gear Tire Diameter (feet) | Nose Gear Tire Diameter (feet) |
|---|---|---|---|---|---|
| Large Quad | 150 | 114 | 31 | 3.17 | 2.84 |
| Medium Twin | 58.22 | 56.88 | 24 | 3.67 | 3.28 |
| Small Twin | 63 | 61.5 | 13.12 | 2.47 | 2.21 |
| Business Jet | N/A | 20 | N/A | 2.075 | 1.12 |

## Table 3.2 Aircraft Flight Parameters for AST Baseline Aircraft

| Aircraft | Mach Number | Velocity ft/sec | Flight Path Angle, deg. | Angle of Attack, deg. | Altitude at Measurement Point, ft. |
|---|---|---|---|---|---|
| Large Quad - P&W | | | | | |
| Approach | 0.254 | 288.0 | -3.0 | 1.4 | 394.0 |
| Cutback | 0.304 | 344.5 | 2.3 | 12.2 | 1030.0 |
| Sideline | 0.304 | 344.2 | 6.3 | 16.1 | 983.0 |
| Large Quad - GEAE | | | | | |
| Approach | 0.259 | 293.7 | -3.0 | 6.0 | 394.0 |
| Cutback | 0.305 | 345.2 | 2.0 | 10.0 | 1100.0 |
| Sideline | 0.305 | 345.2 | 7.0 | 10.0 | 1000.0 |
| Medium Twin - GEAE | | | | | |
| Approach | 0.237 | 268.7 | -3.0 | 4.0 | 394.0 |
| Cutback | 0.291 | 328.4 | 4.0 | 8.0 | 1800.0 |
| Sideline | 0.282 | 319.1 | 9.0 | 7.0 | 1000.0 |
| Small Twin - GEAE | | | | | |
| Approach | 0.222 | 251.7 | -3.0 | 5.0 | 394.0 |
| Cutback | 0.276 | 311.2 | 5.0 | 13.0 | 2100.0 |
| Sideline | 0.275 | 311.2 | 9.0 | 13.0 | 1000.0 |
| Business Jet - Honeywell | | | | | |
| Approach | 0.212 | 242.2 | -3.0 | 4.0 | 394.0 |
| Cutback | 0.229 | 259.6 | 8.7 | 10.2 | 2559.2 |
| Sideline | 0.229 | 259.6 | 9.3 | 10.2 | 1043.2 |
| Business Jet - Rolls-Royce | | | | | |
| Approach | 0.208 | 235.3 | -3.0 | 4.4 | 394.0 |
| Cutback | 0.239 | 270.0 | 8.7 | 6.7 | 2697.4 |
| Sideline | 0.234 | 265.0 | 9.3 | 7.2 | 983.1 |

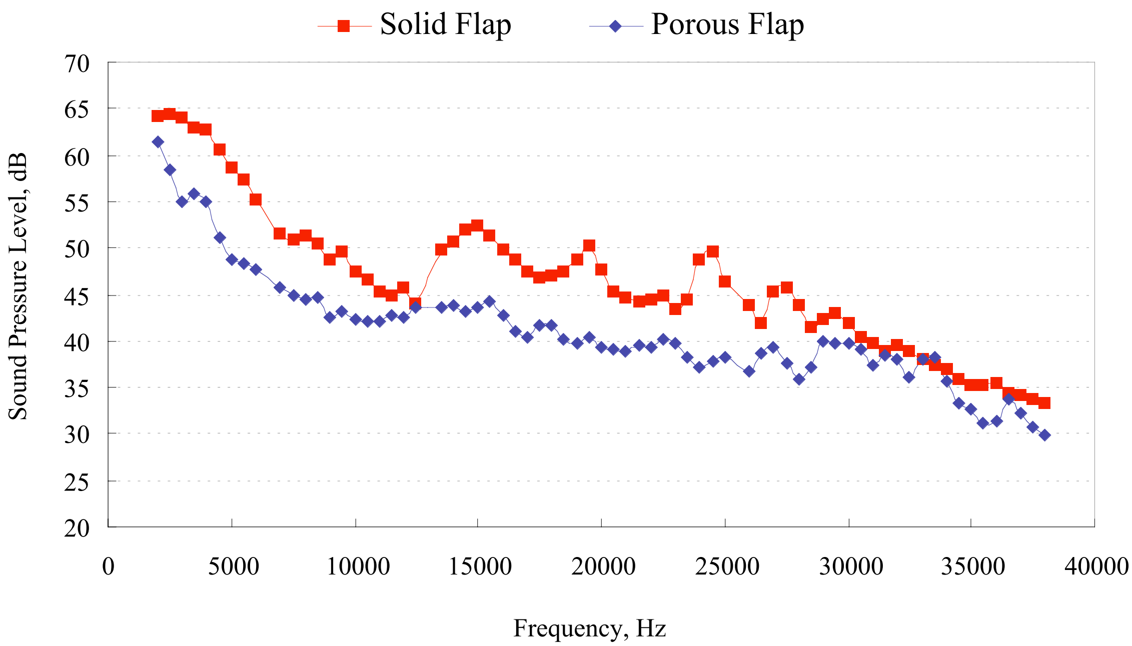



**Figure 3.1 Porous Flap Tip Measurements from NASA Ames Model Scale Test**

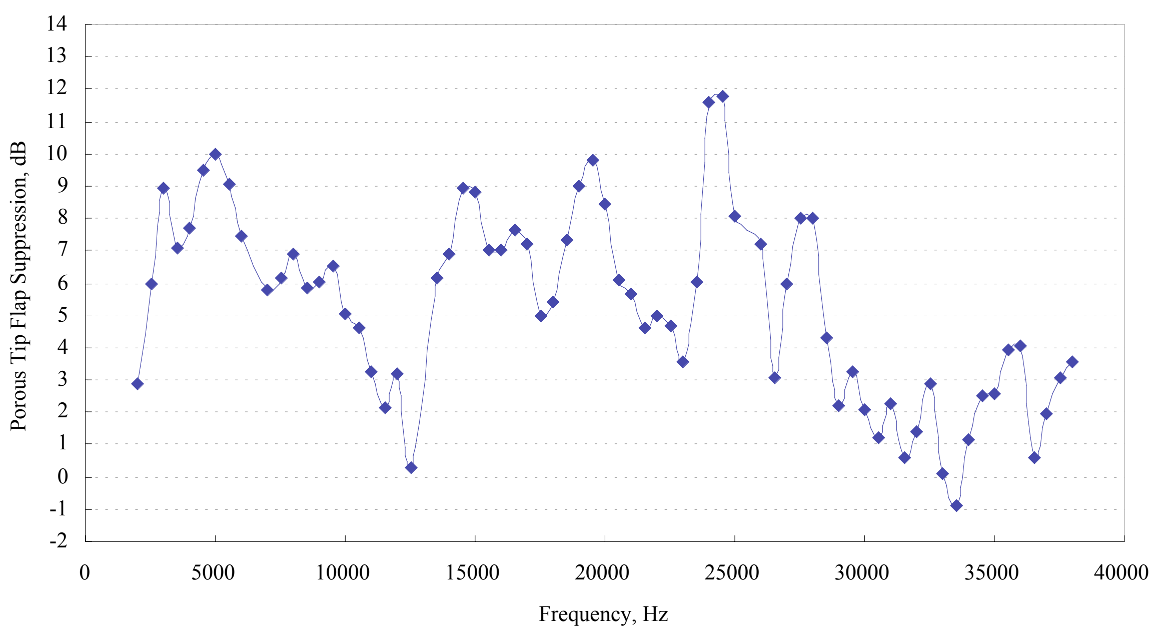
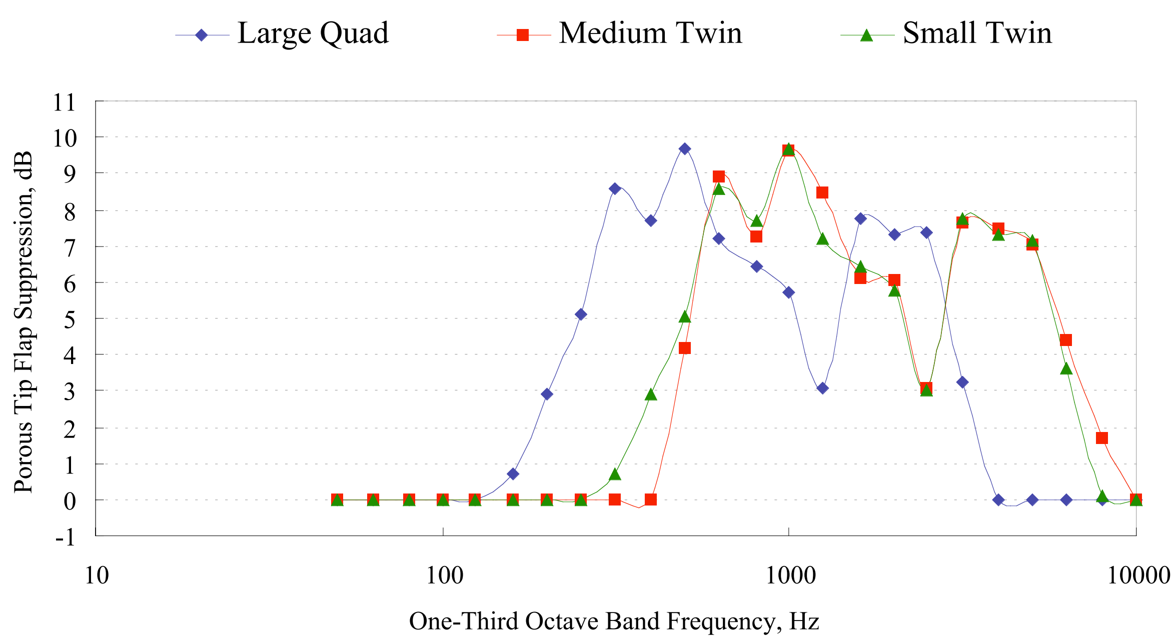
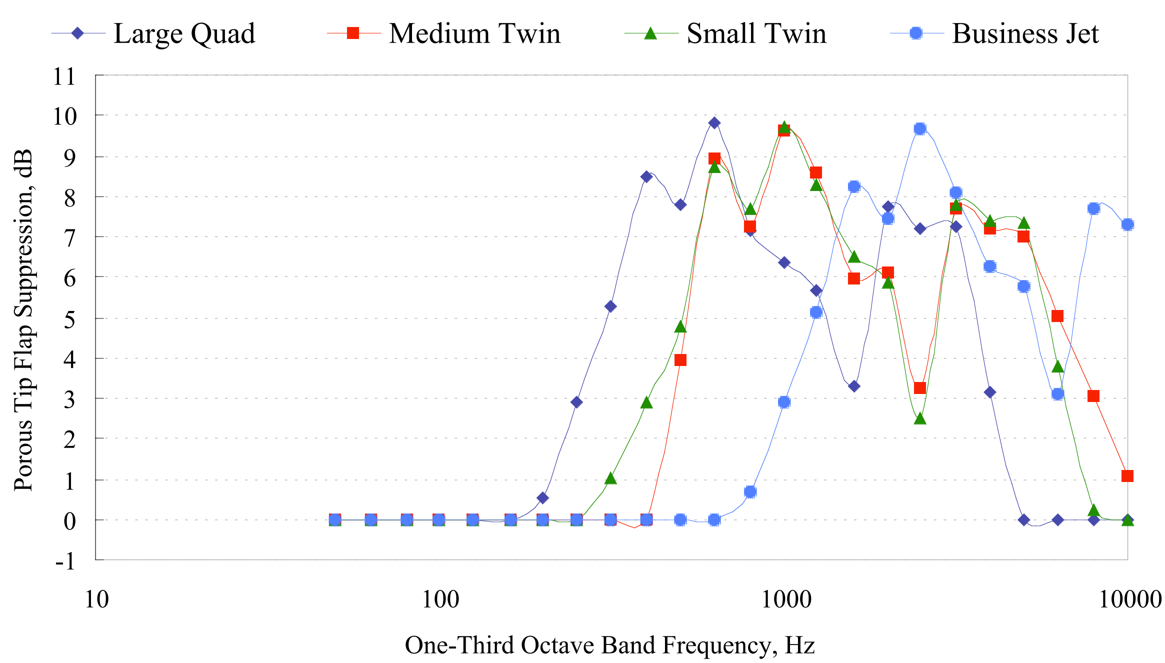



**Figure 3.2 Porous Flap Tip Suppression from NASA Ames Model Scale Test**




**(a) Inboard Flaps**




**(b) Outboard Flaps**

**Figure 3.3 Porous Tip Flap Suppression Adjusted to Full Scale from NASA Ames Model Scale Tests**


**Figure 3.4 Schematic of Slat with Slat Cove Filler**

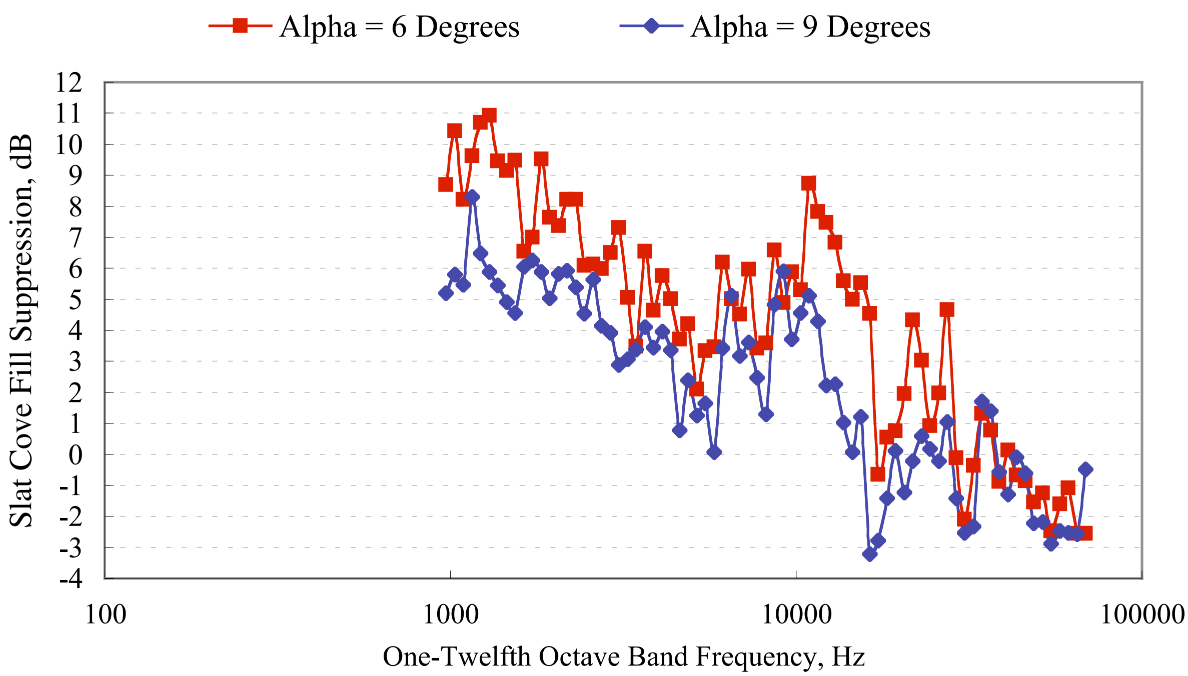
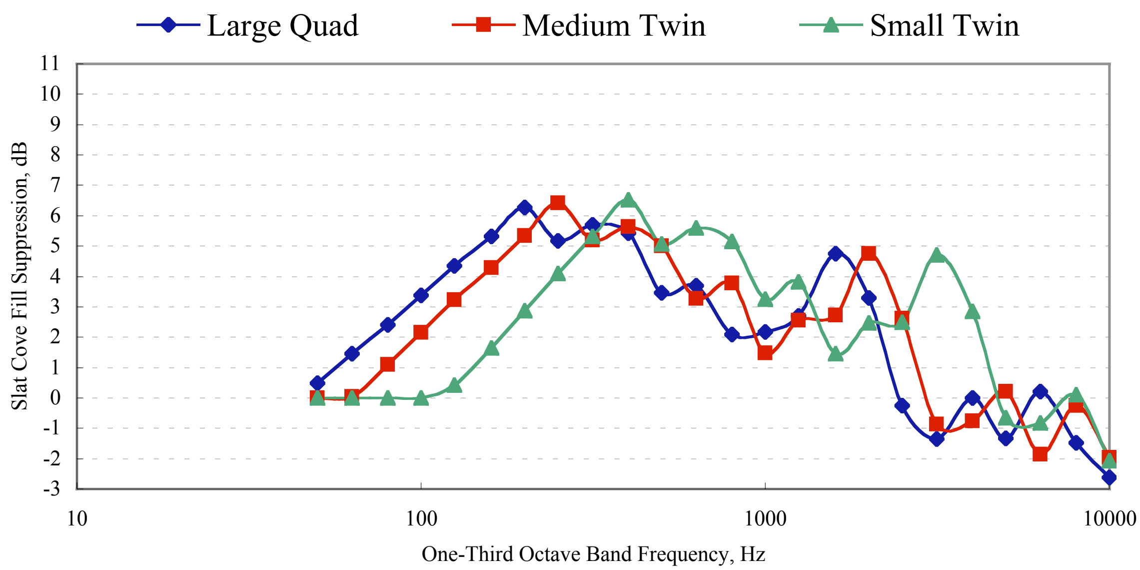
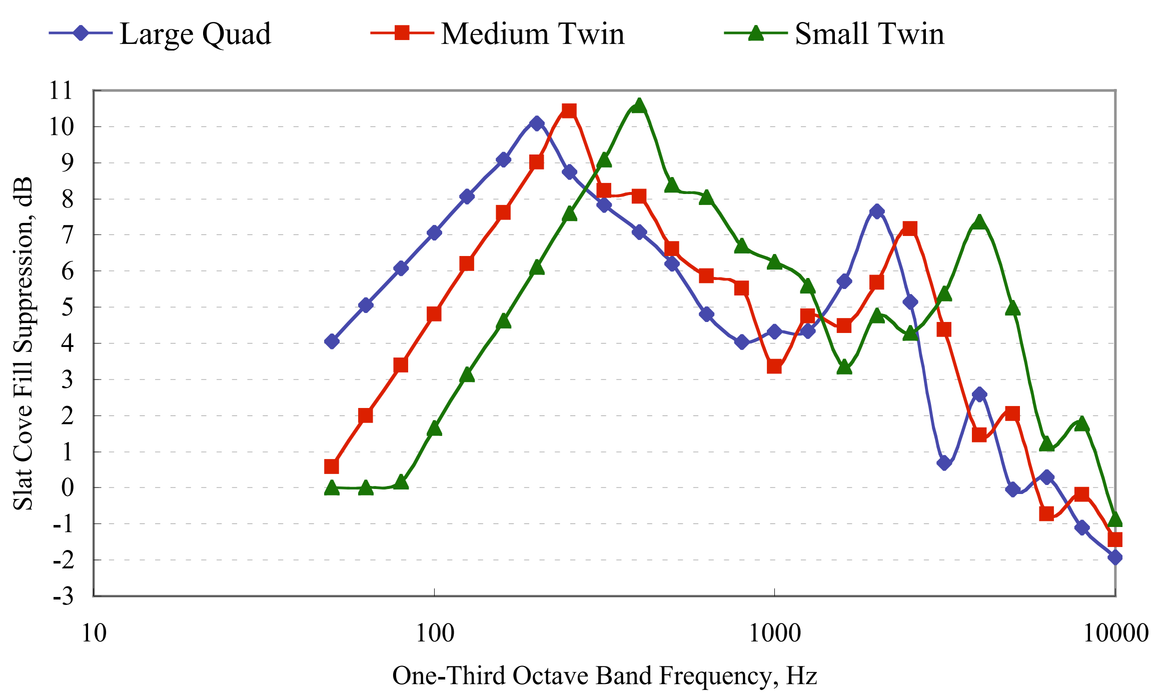



**Figure 3.5. Slat Cove Fill Suppression from NASA Langley LTPT Model Scale Tests**




**(a) Angle of Attack = 6 Degrees**




**(b) Angle of Attack = 9 Degrees**

**Figure 3.6 Full-Scale Slat Cove Fill Slat Suppression Adjusted to Full Scale from Langley PTPT Model Scale Test**

## 4.0 Engine Noise Reduction Technology Descriptions and Analysis Data

### 4.1 Introduction

The Engine Noise Reduction element of the AST Noise Reduction Program was led by the NASA Glenn Research Center and was closely coordinated with the Nacelle Aeroacoustics element led by the NASA Langley Research Center. Together, these two elements were responsible for developing technologies to reduce engine noise for current and future turbofan engines. Their importance is attested to by the fact that they accounted for approximately 75 percent of the total program resources. A small group of people from NASA and industry started to plan the program in 1992 and established the "1992 Technology" baseline that has been used to measure the program progress. This group also established the overall strategy for the technical milestones by defining a long-term, eight year plan. Initially, emphasis was placed on developing technologies for anticipated new engines with higher bypass ratios. Soon after the start of the program, GE certified the GE-90 engine with a bypass ratio of ~9. P&W developed Ultra-High Bypass (UHB) technologies through their Advanced Ducted Propulsor (ADP) concept that had a bypass ratio of ~13. However, there was concern that it would be many years before enough of these engines entered the fleet to make a significant impact on community noise, so technology development for lower bypass ratio engines was added to the plan. Since the drag and weight penalties for higher bypass ratio engines were too severe for business jet applications, addressing a larger range of bypass ratios also provided a well balanced program aimed at helping both the current and future fleet of commercial aircraft.

### 4.2 Baseline Engine Noise Determinations

Baseline engine noise models were established at the beginning of the AST Program to measure program progress. However, the originally selected engines represented fleet averages for each aircraft class. Since the effectiveness of a noise reduction technology depends on the engine cycle, these fleet averaged engine noise levels were eventually replaced by company specific engine cycles with equivalent engine noise levels. GEAE, P&W, Honeywell, and Rolls Royce each selected engine cycles that represented their respective 1992 engine technology. Each company then furnished to NASA one-third octave band spectra for each engine noise source component. NASA subsequently used these component spectra to determine engine baseline component noise levels and total baseline engine noise levels.

Among the companies, engine components noise sources nomenclature is not standardized, but for this evaluation study we adopted the following component terminology:

| | | |
|---|---|---|
| Fan Inlet Noise | or | Inlet |
| Fan Exhaust Noise | or | Aft fan |
| Combustor Noise | or | Core |
| Turbine Noise | or | Turbine |
| Jet Exhaust Noise | or | Jet. |

These subcomponent descriptions will be used interchangeably through the following sections.

## 4.3 Engine Noise Suppression Technology

The engine technology noise reduction concepts and levels below were used by NASA for the evaluation of the total engine noise for the large quad, the medium twin, the small twin, and business jet aircraft. These technologies include work contributed by NASA, Industry, and University researchers. It should be especially noted that the technology concepts used as part of the final evaluation are those concepts that were (by working group consensus) determined to be tested to technology levels of 5/6, i.e., see Table 2.1. The descriptions of some of the technology concepts are presented briefly to familiarize the reader with the concept that was evaluated. Further details of the technology concepts, testing, and data analyses are contained in the many references listed in the AST bibliography published under a separate cover.

## 4.4 Advanced Liner Technology Concepts

The advanced liner noise reduction technology as defined by NASA included several technologies that utilized nacelle geometry and treatment. For inlet noise reduction, NASA found that the best technology combination resulted from using a scarf inlet together with maximum treatable acoustic liner area that included inlet lip treatment. In scarf inlet technology concept, the inlet geometry is designed such that the lower lip extends beyond the upper lip to provide a shielding effect (shown in views of Figure 4.1). Thus, it reduces the fan inlet noise by redirecting the acoustic energy away from an observer on the ground. The advanced liner suppressions used by NASA in the evaluation were the best results obtained from a Boeing Nacelle Aeroacoustic System Technology Assessment (Reference 4). In this study, Boeing investigated several passive liners, adaptive liners, and active noise control techniques. Additionally, it was found eliminating seams in the liner not only increased liner area but also reduced inlet flow distortions caused from the wall discontinuities. Table 4.1 shows the final noise reduction suppression as determined by NASA analysis of the supplied data. These data are used as input in the final total aircraft evaluations in Section 5. For the three larger classes of aircraft, reasonable levels of reduction are indicated for the approach and cutback points. This rolled up inlet technology was not expected to have a predictable effect at the sideline point. Additionally, in the evaluation of the business jet that has a longer aft nacelle, lining was also used with success (reduction of aft radiated fan noise) for that aircraft configuration.

## 4.5 Herschel-Quincke (HQ) Tubes Technology Concept

NASA evaluated the HQ noise reduction technology (Figure 4.2) to reduce fan inlet generated noise. HQ tubes are passive devices that suppress tone noise through the use of tubes tuned to specific frequencies. By adjusting HQ tube lengths, the peak frequency at which the maximum suppression will occur can be adjusted. Honeywell tested this concept successfully as part of the Engine Validation of Noise Reduction Concepts (EVNRC) test program (Reference 5). Virginia Tech University tested three HQ tube configurations statically on a JT15D engine inlet. The configurations included a single array of 20 tubes, a single array of 16 tubes, and a double array with 20 and 16 tubes. The double array provided the best noise reduction because they were tuned to two different close frequencies that together provided a broadband noise reduction effect. Figure 4.3 shows the measured noise suppression achieved with the double array of HQ tubes. Table 4.2 shows the peak frequency used by NASA for the evaluation of the large quad, the medium twin, and the small twin aircraft with GEAE engines. These data were used as input to predict the total aircraft noise reduction levels in Section 5.

### 4.6 Active Noise Control (ANC) Technology Concept

NASA evaluated results from ANC to further reduce fan inlet generated noise. ANC is considered an option for enhancing or replacing inlet acoustic treatment. This is important because the larger diameter higher bypass ratio engines have shorter inlet lengths. Accommodating liner or HQ tube technology is difficult for shorter inlets. During the AST program ANC was primarily pursued for reducing fan tones. Active noise control for tones is achieved by generating a sound that is exactly out of phase with the targeted tone noise source. At least two companies pursued active noise control with widely varying results. The data used by NASA are from a component model test that was performed in the 9 by 15 Tunnel at NASA GRC using a 22-inch diameter ADP low speed fan model in a nacelle. The final analysis indicated that active noise control could reduce the inlet fan noise spectra by 1.5 dB at the approach as shown in Table 4.3. However, application of this technology concept also resulted in an increase in noise at the cutback point. Because ANC never achieved a consensus TRL of 5/6, no suppression from this concept was applied for the fan noise with the exception of the application of the P&W ADP on the 747-400 aircraft as explained in Section 2.3.

### 4.7 Fan with Swept Stators Technology Concept

A fan with swept stators noise reduction technology concept is shown in Figure 4.4. In this particular concept shown, the stator blades are radial at the hub and swept aft outward. The application of the technology concept reduces the inlet and aft fan noise levels by minimizing the wake interaction between the fan and the stator. The NASA predicted levels indicate that the swept stators reduce the noise level at the approach measurement point, but have little effect at the cutback measurement point (where inlet noise is minimum anyway). The swept stators prediction also showed appreciable reduction of the aft fan noise levels at all three certification points as indicated in Table 4.4. Results from NASA GRC analyses of the 1999 swept stator tests with a high-speed fan yielded the best-predicted swept stator suppression levels. These levels were subsequently used in the final evaluations of total aircraft noise in Section 5.

### 4.8 Forward Swept Fan with Swept and Leaned Stators

The swept and lean stator technology concept adds a radial lean to the backward swept technology concept above. As for the above technology, the idea is to further minimize the wake interactions between the fan rotor and stator blades. The stator assembly radial lean is clearly shown in Figure 4.5. With this technology concept of the swept and leaned stator blades, NASA combined a forward swept fan technology. The forward swept fan technology retards the on-set of high-speed rotor multiple pure tones. Evaluation of the forward swept fan concept combined with the swept and leaned stator assembly was performed by both GEAE/Allison and Honeywell Engines. The best predicted suppression levels resulted from use of the Honeywell test based on the high-speed swept fan tests performed in the NASA Glenn Research Center 9 by 15 wind tunnel. This test rig had swept and leaned stators that were optimized for noise reduction. Figure

4.6 shows the model test rig. The NASA GRC evaluations of the swept and leaned stator design are given in Table 4.5. The predictions showed that forward swept fan combined with the swept and leaned stator design significantly reduces the inlet and aft fan noise levels at the sideline and cutback certification points.

### 4.9 Chevrons/Tabs Technology Concepts

New engine nozzle technology concepts were designed and tested that reduce the fully expanded jet velocity by either mixing engine core flow with fan flow only, engine fan flow with ambient flow only, or both flows simultaneously. The results from this technology development effort tended to fall into two broad categories: tabs and chevrons. Tabs are severe protrusions into the flow at the nozzle exit plane. Chevrons are also protrusions at the nozzle exit, but of much less severity than tabs. The aggressive mixing produced by the tabs greatly reduce low-frequency noise, but with a penalty of tab-induced high-frequency noise. Chevrons, which provide a more balanced approach to mixing, reduce low-frequency noise without significant chevron-induced high-frequency noise. While most of the nozzle work was performed at model scale, both static engine tests and flight tests (EVNRC Test, Reference 9) performed by Honeywell assured that this technology achieved a TRL of 6.

The chevron technology data used by NASA for the evaluation of the large transports used results that were supplied by GEAE. Their data results yield the greatest noise reduction. The engine was configured with 12 chevrons on the core nozzle and 24 chevrons on the fan nozzle as shown in Figure 4.7. The Figure 4.8 plot shows the one-third octave band suppression spectra used for the fan and core chevron configuration evaluation. The chevron benefits are most significant during takeoff where the jet velocities are the highest. For approach they have a very minimal effect.

**Table 4.1 Advanced Liner Suppression for Larger Aircraft, EPNdB**

| | Inlet |
|---|---|
| Approach | 2.3 |
| Sideline | N/A |
| Cutback | 4.0 |

**Table 4.2 HQ Tubes One-Third Octave Band Peak Frequencies, Hz**

| | Inlet |
|---|---|
| Large Quad | 3150 |
| Medium Twin | 3150 |
| Small Twin | 2500 |

**Table 4.3 Noise Reductions from Active Noise Control, EPNdB**
**(Not used in the final analysis)**

| | Inlet | Aft fan |
|---|---|---|
| Approach | 1.5 | 0 |
| Sideline | N/A | N/A |
| Cutback | -0.2 | 0 |

### Table 4.4 Noise Reductions from Fan with Swept Stators, EPNdB

| | Inlet | Aft fan |
|---|---|---|
| Approach | 1.4 | 0.3 |
| Sideline | -0.4 | 2.3 |
| Cutback | 0.0 | 1.4 |

### Table 4.5 Noise Reductions from Forward Swept Fan with Swept and Leaned Stators, EPNdB

| | Inlet | Aft fan |
|---|---|---|
| Approach | N/A | N/A |
| Sideline | 2.5 | 2.5 |
| Cutback | 2.5 | 2.5 |

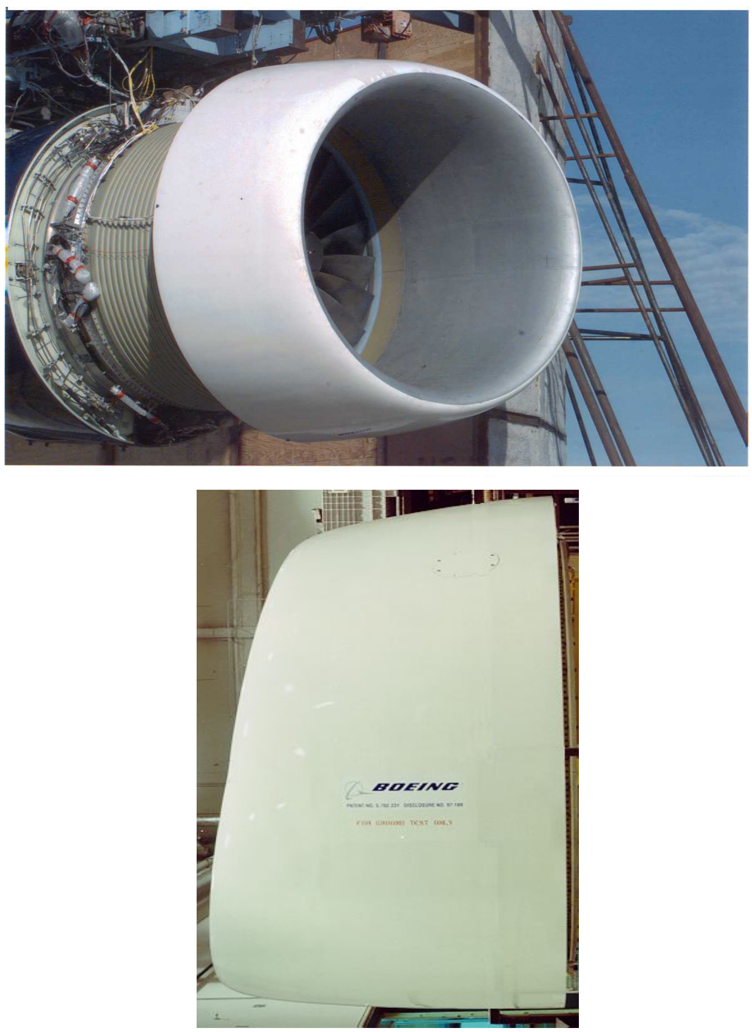


**Figure 4.1 Scarf Inlet Shown on the P&W 4098 Engine**

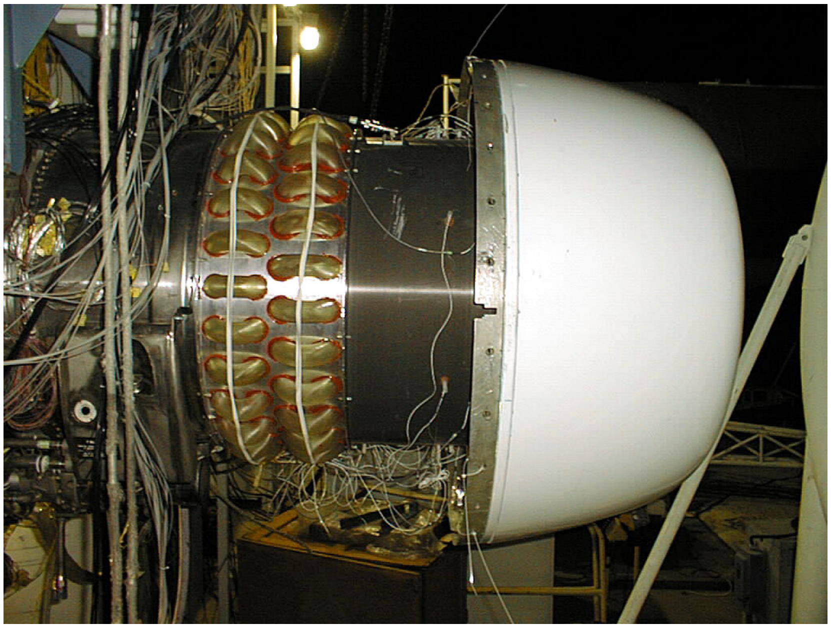


**Figure 4.2 Honeywell EVNRC Herschel-Quincke Tubes**

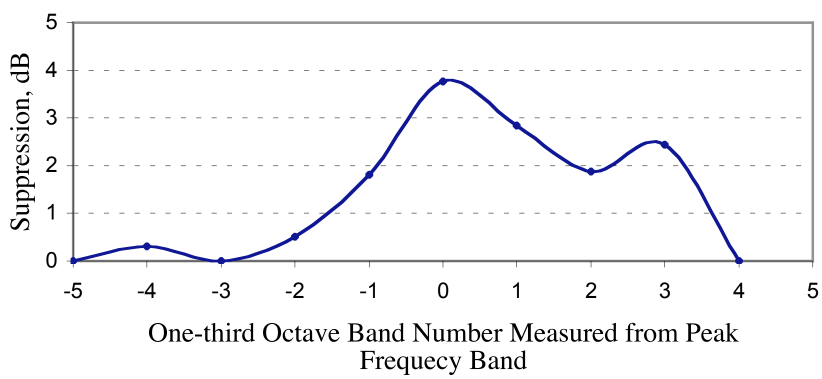



**Figure 4.3 HQ Tube Suppression Spectrum for the 20 + 16 Tube Configuration**

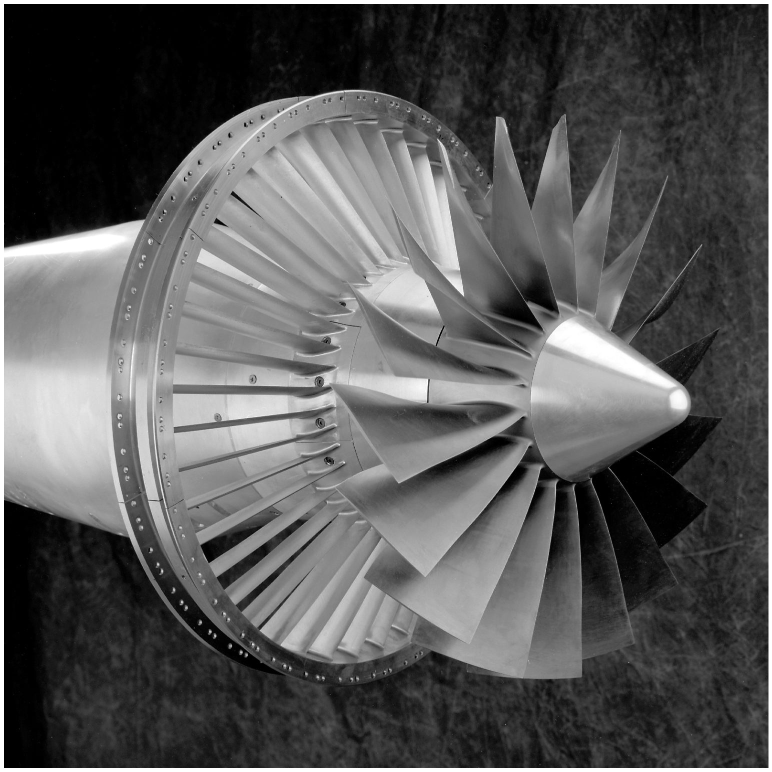


**Figure 4.4 Fan with Swept Stators**

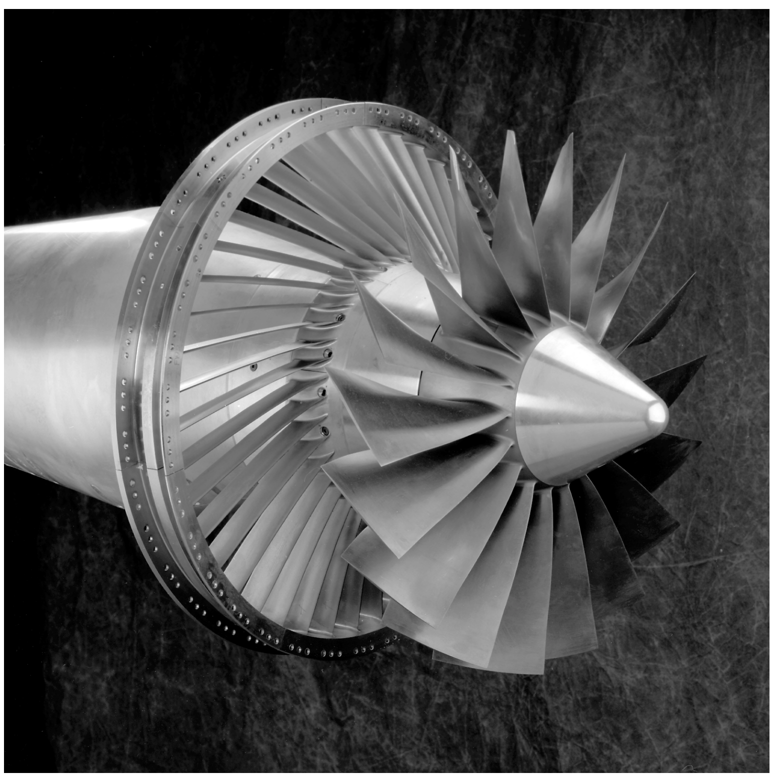


**Figure 4.5 Fan with Swept and Leaned Stators**

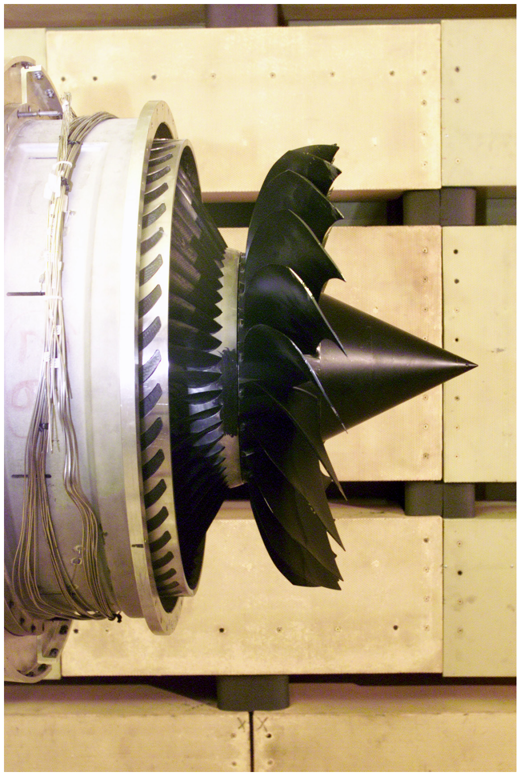


**Figure 4.6 Forward Swept Fan with Swept and Leaned Stators**

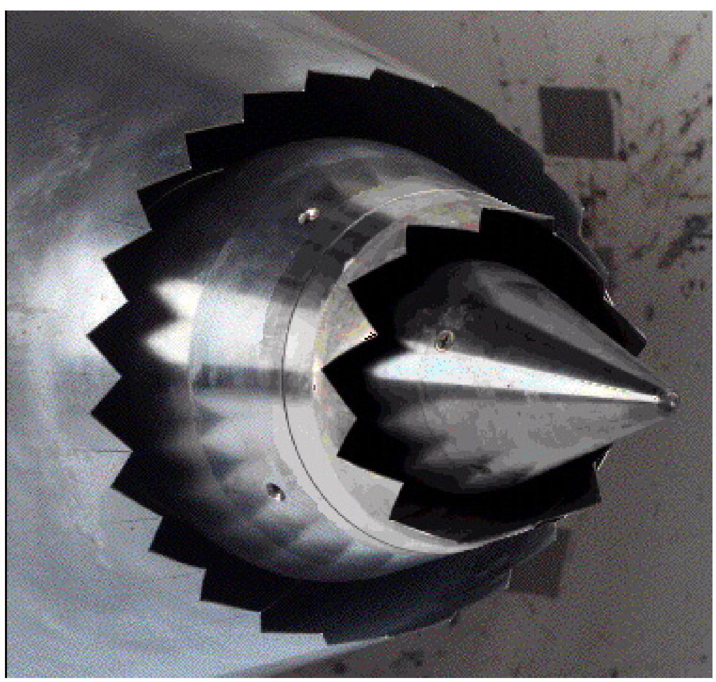


**Figure 4.7 GEAE Fan/Core Chevrons**

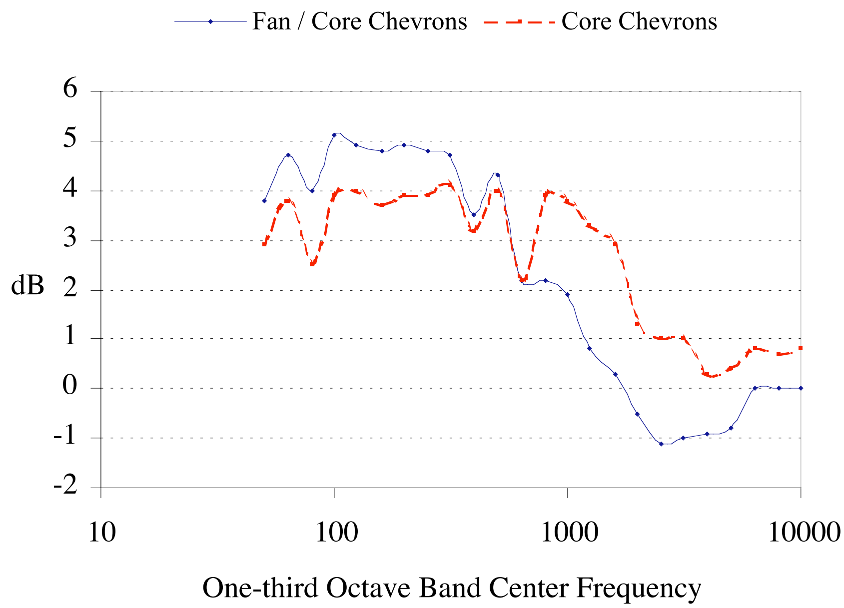



**Figure 4.8 GEAE Fan/Core Chevron Suppression Spectra**

## 5.0 Engine/Airframe Noise Reduction Evaluations

### 5.1 Introduction

NASA combined the airframe and engine noise reduction technology levels as applied to each of the four classes of aircraft at each of the three certification points. This entails flying each appropriate combination of engine and airframe noise technology at the correct operating conditions for each of the certifications points (Table 3.2) and predicting the resulting noise reduction levels. The difference between these predicted levels and the baseline levels is the achieved noise reduction for those technologies at each of the certification points. The cumulative total noise reduction from all three certification points is then presented as the AST technology progress achieved.

The technology evaluations presented are based upon the data that were supplied by NASA, Industry, and University researchers. Only the noise reduction technology results that have been agreed upon as advancing to a technology readiness level of 5/6 are utilized. The technology concepts used are from the list in Table 2.1.

The order of presentation of the aircraft noise reduction evaluations in the remainder of this section of the paper is as follows:

Large Quad Aircraft with P&W Engines
Large Quad Aircraft with GEAE Engines
Medium Twin with GEAE Engines
Small Twin with GEAE Engines

Business Jet with Honeywell Engines
Business Jet with Rolls-Royce Engines

## 5.2 Large Quad Evaluation with Pratt and Whitney Engines

### 5.2.1 Reference Engine Description

Pratt & Whitney (P&W) selected the 4056 engine cycle as the 1992 technology reference engine for the Large Quad system noise evaluations. The P&W 4056 engine has a static sea-level thrust rating of 56,000 pounds, a bypass ratio of approximately 5, and powers the Boeing 747-400. Table 5.2.1 lists relevant cycle information for the P&W 1992 technology reference engine at approach, sideline, and cutback operating conditions.

### 5.2.2 Advanced Engine Description

The P&W Advanced Ducted Propulsor (ADP) was selected as the advanced engine for the Large Quad system noise evaluations. The ADP engine was scaled to produce a static sea-level thrust equivalent to the thrust of the reference engine. Physically, the ADP fan diameter is approximately 40% larger than the 1992 technology engine, has 20 fewer blades, and has 44 fewer exit guide vanes. The bypass ratio of the ADP at full power is approximately 15, which is roughly 3 times that of the 1992 technology engine. The increased bypass ratio reduces the mixed jet velocity by approximately 26%. Table 5.2.2 lists cycle data for the ADP engine at the approach, sideline, and cutback operating conditions.

### 5.2.3 Engine Source Noise Levels

Pratt & Whitney provided NASA with received one-third octave band time histories for the P&W 4056 and the ADP engines at the approach, sideline, and cutback operating conditions. The engine noise sources include fan inlet, aft fan, combustor, turbine, and jet. The jet noise component incorporates both the core and bypass jet noise.

The results of the NASA analysis of the 1992 Technology and the ADP engines for the component engine noise levels, airframe noise levels, and aircraft noise levels are plotted in Figures 5.2.1, 5.2.3, and 5.2.5 at approach, sideline, and cutback, respectively. The ADP cycle provides significant jet noise reduction by lowering the core and bypass jet velocities and fan noise reduction by reducing the fan tip speeds. On a cumulative basis, the ADP cycle provides 18.9 EPNdB noise reduction toward the AST final goal of 30 EPNdB.

### 5.2.4 Airframe Source Noise Levels

The Boeing 747-400 was selected as the representative airframe for the Large Quad. The takeoff weight was 850,000 pounds and a landing weight was 652,000 pounds. One-third octave band source spectra were obtained from Boeing for each airframe subcomponent at approach, sideline, and cutback operating conditions. The airframe noise sources include inboard flaps, outboard flaps, aileron, slat, main gear, and nose gear. The source spectra were propagated to the measurement points using the NASA Aircraft Noise Prediction Program (ANOPP) level

L03/02/17. The received mean-square-pressure time histories were interpolated to yield levels corresponding to the engine data reception times. The engine and airframe mean-square-pressures were then added to yield the aircraft noise level. The component airframe noise levels are plotted in Figures 5.2.2, 5.2.4, and 5.2.6.

### 5.2.5 Fan Noise Reduction

The ADP engine was evaluated with the following fan noise reduction technologies:

1. Swept and leaned cut-off Fan Exit Guide Vanes (FEGV)
2. Swept and leaned cut-on fan FEGV
3. Swept and leaned cut-on fan FEGV with Active Noise Control (ANC)
4. Radial cut-on FEGV
5. Radial cut-on FEGV with ANC

The ADP engine was evaluated with the following nacelle noise reduction technologies:

1. Scarf inlet
2. 25% liner improvement
3. Scarf inlet with 25% liner improvement

Pratt & Whitney provided to NASA the suppression levels for the technologies described above. The results of NASA's evaluation of these technologies are summarized in Tables 5.2.3 to 5.2.10. These tables show the reduction in inlet and aft fan noise, engine noise, and aircraft noise. Of the five fan configurations, the swept and leaned cut-on FEGV with ANC (Table 5.2.5) provided the best inlet and aft fan suppression. The cut-on configuration without ANC increases the inlet and aft fan noise levels under certain conditions as indicated by the negative noise levels in Tables 5.2.4 and 5.2.6. Of the three nacelle configurations, the scarf inlet with 25% liner improvement provided the best inlet suppression as shown in Table 5.2.10.

### 5.2.6 Jet Noise Reduction

Core nozzle tabs were tested on the ADP engine as a means of jet noise suppression. Pratt & Whitney obtained the noise suppression for a core nozzle tab design tested in NASA's NATR facility as part of the Separate Flow Nozzle Test (SFNT) program (Reference 6). Details concerning Pratt & Whitney's tab noise benefit analysis can be found in Reference 7. The result of the evaluation by NASA of the ADP with core nozzle tabs is provided in Table 5.2.11. Note that the tabs provide no appreciable noise reduction at the three measurement points. Numerous studies have shown that the suppression from tabs (or chevrons) diminishes as the jet velocity is reduced. Since the core and bypass jet velocities are relatively low in the ADP cycle, the core nozzle tabs were ineffective for further reduction of the jet noise.

### 5.2.7 Airframe Noise Reduction

The 747-400 airframe was evaluated with the following noise reduction technologies:

1. Porous flap edges
2. Slat cove filler

Details concerning the model test, data reduction, and component suppression spectra are provided in Section 3 of this report. NASA's evaluations of the porous flaps and slat cover filler on the 747-400/ADP aircraft system indicates that component noise reduction on the order of 2 to 3 EPNdB was achieved from these technologies as indicated in Tables 5.2.12 and 5.2.13. The inboard and outboard flaps are strong noise sources on the 747-400/ADP aircraft system, especially at approach. The porous flaps reduced the aircraft noise 1.0 EPNdB at approach as shown in Table 5.2.12. Modest aircraft noise reductions are also obtained from porous flaps at the sideline and cutback operating conditions. Although the component noise reduction of the slat cove filler was between 2 and 3 EPNdB, the slat cove filler did not provide appreciable aircraft noise suppression, as indicated in Table 5.2.13, because the slat is a relatively weak noise source on the 747-400/ADP aircraft system.

### 5.2.8 Combined Engine and Airframe Noise Reduction Evaluation

Tables 5.2.14, 5.2.15, and 5.2.16 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Boeing 747-400/P&W ADP aircraft system. An examination of these tables reveals that different combinations of technologies were used at approach, sideline, and cutback. Within the guidelines of the AST program, combining the "best" technologies to achieve the most noise reduction is acceptable. The results are plotted to show the EPNL reductions for each of the approach, sideline, and cutback operating conditions.

Figures 5.2.1 and 5.2.2 show that the inlet, aft fan, inboard flaps, outboard flaps, and main gear were the most influential noise sources at the approach power setting. The engine technologies chosen by NASA to reduce the ADP noise at approach were the swept/leaned fan with cut-on FEGV and ANC and the scarf inlet with 25% liner improvement. Table 5.2.14 shows that this combination of engine technologies reduced aircraft noise by 1.5 EPNdB. The application of porous flaps and slat cove filler to the airframe reduced the aircraft noise by1.1 EPNdB, as indicated in Table 5.2.15. With multiple noise sources contributing to the aircraft noise, the greatest noise reduction is achieved by simultaneously reducing the significant noise sources. Table 5.2.16 shows that combining the above engine and airframe noise reduction technologies reduced the aircraft noise level by 3.3 EPNdB.

Aft fan noise has the greatest influence on the aircraft noise at the sideline operating condition. The ADP aft fan noise level is at least 5 EPNdB greater than the other engine and airframe noise sources as shown in Figures 5.2.3 and 5.2.4. Accordingly, the swept/leaned fan with cut-on FEGV and ANC was selected as the best fan noise reduction for the ADP because it had the greatest impact on reducing the aft fan source. Table 5.2.14 shows that the swept/leaned fan with cut-on FEGV and ANC combined with the scarf inlet plus 25% liner improvement and core nozzle tabs reduced the aircraft noise level by 2.1 EPNdB. Although the airframe noise sources were weak contributors to the aircraft noise level at sideline, reducing the flap and slat noise did achieve a modest reduction in the aircraft noise. Table 5.2.15 shows that the porous flaps and slat cove filler reduced the aircraft noise level by 0.4 EPNdB. Table 5.2.16 shows that combining the engine and airframe noise reduction technologies reduced the aircraft noise level by 2.8 EPNdB.

Aft fan noise also had the greatest influence on the aircraft noise at cutback operating condition as shown in Figures 5.2.5 and 5.2.6. With reduced engine power at the cutback point, inlet noise and outboard flap noise also contributed to the aircraft noise level. The noise reduction technologies applied at the sideline point were also applied at cutback. The aircraft noise level was reduced by 1.7 EPNdB, as indicated in Table 5.2.14, by combining the swept/leaned fan with cut-on FEGV and ANC, the scarf inlet plus 25% liner improvement, and the core nozzle tabs. Combining the porous flaps and slat cove filler reduce the aircraft noise level by 0.6 EPNdB as indicated in Table 5.2.15. Finally, combining the engine and airframe noise reduction technologies reduces the cutback aircraft noise level by 2.7 EPNdB as indicated in Table 5.2.16.

Table 5.2.17 summarizes the results of the NASA evaluations of the AST technologies applied to the Boeing 747-400 powered by the P&W ADP engines. A cumulative noise reduction of 31.7 EPNdB is achieved with 18.9 EPNdB coming from cycle benefit, 8.8 EPNdB noise reduction coming from the engine and airframe noise reduction technologies, and 4 EPNdB noise reduction coming from flight operation. Figure 5.2.7 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. The cumulative reduction surpasses the final goal of 30 EPNdB.

**Table 5.2.1 Pratt & Whitney 1992 Technology Engine Cycle Data for the Large Quad Aircraft**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 14300 | 44400 | 28100 |
| Fan Diameter, in | 93.6 | 93.6 | 93.6 |
| Fan Blade Number | 38 | 38 | 38 |
| OGV Number | 84 | 84 | 84 |
| BPR | 5.8 | 4.8 | 5.5 |
| BPF, Hz | 1520 | 2270 | 1900 |
| Core Jet Velocity, fps | 760 | 1610 | 1140 |
| Mixed Jet Velocity, fps | 720 | 1190 | 960 |

**Table 5.2.2 Pratt & Whitney ADP Engine Cycle Data for the Large Quad Aircraft**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 14300 | 44400 | 28100 |
| Fan Diameter, in | 130 | 130 | 130 |
| Fan Blade Number | 18 | 18 | 18 |
| OGV Number | 40 | 40 | 40 |
| BPR | 17.1 | 12.8 | 15.4 |
| BPF, Hz | 340 | 480 | 420 |
| Core Jet Velocity, fps | 460 | 1020 | 750 |
| Mixed Jet Velocity, fps | 530 | 840 | 710 |

**Table 5.2.3 EPNL Noise Reduction on 747-400 with ADP Engines from Swept/Leaned Cut-off FEGV**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 3.3 | 3.3 | 2.7 | 1.0 |
| Sideline | 1.6 | 2.0 | 1.2 | 0.9 |
| Cutback | 1.2 | 1.7 | 1.1 | 0.9 |

**Table 5.2.4 EPNL Noise Reduction on 747-400 with ADP Engines from Swept/Leaned Cut-on FEGV**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.9 | 2.8 | 2.3 | 0.9 |
| Sideline | 1.5 | 1.8 | 0.9 | 0.7 |
| Cutback | 0.3 | -2.5 | -2.3 | -1.9 |

* Negative values indicate an increase in noise level

**Table 5.2.5 EPNL Noise Reduction on 747-400 with ADP Engines from Swept/Leaned Cut-on FEGV with ANC**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 3.7 | 3.3 | 2.9 | 1.1 |
| Sideline | 2.0 | 3.0 | 1.7 | 1.3 |
| Cutback | 1.5 | 2.0 | 1.3 | 1.0 |

**Table 5.2.6 EPNL Noise Reduction on 747-400 with ADP Engines from Radial Cut-on FEGV**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.4 | -0.5 | -0.1 | 0.0 |
| Sideline | 0.0 | -3.2 | -2.7 | -2.4 |
| Cutback | -0.9 | -5.7 | -4.8 | -4.3 |

* Negative values indicate an increase in noise level

**Table 5.2.7 EPNL Noise Reduction on 747-400 with ADP Engines from Radial Cut-on FEGV with ANC**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.4 | 1.1 | 1.1 | 0.5 |
| Sideline | 0.7 | 1.3 | 0.8 | 0.6 |
| Cutback | 0.7 | 0.7 | 0.5 | 0.4 |

**Table 5.2.8 EPNL Noise Reduction on 747-400 with ADP Engines from 25% Liner Improvement**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.8 | 1.0 | 0.8 | 0.4 |
| Sideline | 0.8 | 1.0 | 0.7 | 0.6 |
| Cutback | 0.8 | 1.0 | 0.8 | 0.6 |

**Table 5.2.9 EPNL Noise Reduction on 747-400 with ADP Engines from Scarf Inlet**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.3 | 0.0 | 0.9 | 0.4 |
| Sideline | 2.4 | 0.0 | 0.3 | 0.3 |
| Cutback | 2.3 | 0.0 | 0.3 | 0.3 |

**Table 5.2.10 EPNL Noise Reduction on 747-400 with ADP Engines from Scarf Inlet Plus 25% Liner Improvement**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 3.1 | 1.0 | 1.6 | 0.7 |
| Sideline | 3.2 | 1.0 | 1.0 | 0.8 |
| Cutback | 3.2 | 1.0 | 1.1 | 0.8 |

**Table 5.2.11 EPNL Noise Reduction on 747-400 with ADP Engines from Core Nozzle Tabs**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 |
| Sideline | 0.6 | 0.1 | 0.1 |
| Cutback | 0.6 | 0.0 | 0.0 |

**Table 5.2.12 EPNL Noise Reduction on 747-400 with ADP Engines from Porous Flaps**

| | Inboard | Outboard | Airframe | Aircraft |
|---|---|---|---|---|
| Approach | 3.1 | 3.7 | 2.4 | 1.0 |
| Sideline | 3.9 | 4.5 | 2.4 | 0.3 |
| Cutback | 3.6 | 4.5 | 3.0 | 0.5 |

**Table 5.2.13 EPNL Noise Reduction on 747-400 with ADP Engines from Slat Cove Filler**

| | Slat | Airframe | Aircraft |
|---|---|---|---|
| Approach | 2.2 | 0.2 | 0.1 |
| Sideline | 3.2 | 0.6 | 0.1 |
| Cutback | 2.6 | 0.5 | 0.1 |

**Table 5.2.14 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Boeing 747-400 with P&W ADP Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement | 1.5 |
| Sideline | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement<br>Core Nozzle Tabs | 2.1 |
| Cutback | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement<br>Core Nozzle Tabs | 1.7 |

**Table 5.2.15 Aircraft Noise Reduction from Combined Airframe Technologies Applied to the Boeing 747-400 with P&W ADP Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps<br>Slat Cove Filler | 1.1 |
| Sideline | Porous Flaps<br>Slat Cove Filler | 0.4 |
| Cutback | Porous Flaps<br>Slat Cove Filler | 0.6 |

### Table 5.2.16 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Boeing 747-400 with P&W ADP Engines

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement<br>Porous Flaps<br>Slat Cove Filler | 3.3 |
| Sideline | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement<br>Core Nozzle Tabs<br>Porous Flaps<br>Slat Cove Filler | 2.8 |
| Cutback | Swept/Leaned Fan with Cut-on FEGV and ANC<br>Scarf Inlet with 25% Liner Improvement<br>Core Nozzle Tabs<br>Porous Flaps<br>Slat Cove Filler | 2.7 |

### Table 5.2.17 Summary of NASA's Noise Reduction Evaluations for the Boeing 747-400/P&W ADP Aircraft System

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 4.4 | 3.3 | 2.0 | 9.7 |
| Sideline | 8.4 | 2.8 | 0.0 | 11.2 |
| Cutback | 6.1 | 2.7 | 2.0 | 10.8 |
| Total | 18.9 | 8.8 | 4.0 | 31.7 |

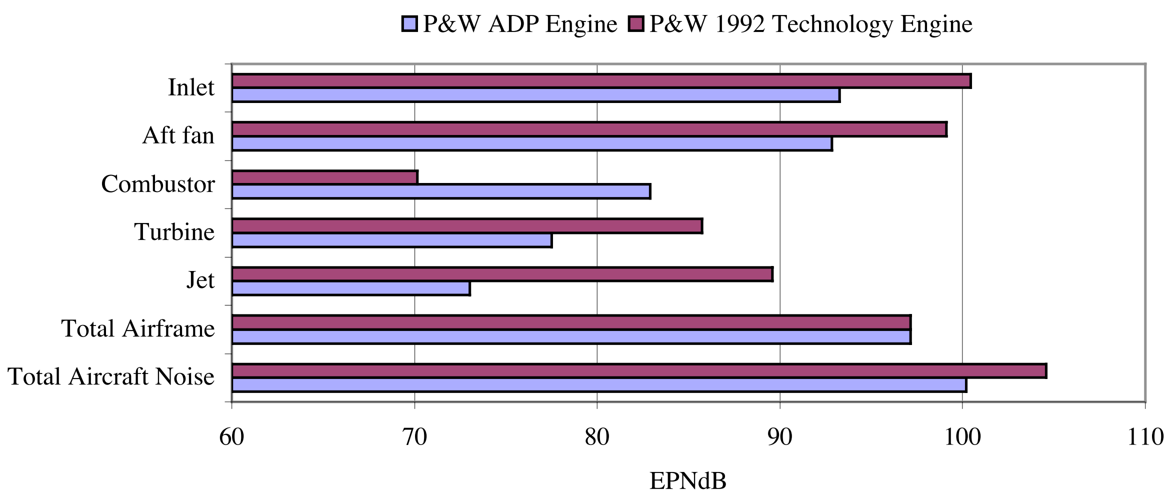



**Figure 5.2.1 Comparison of the Approach Noise Levels for the Boeing 747-400 with Pratt & Whitney 1992 Technology Engines and ADP Engines**

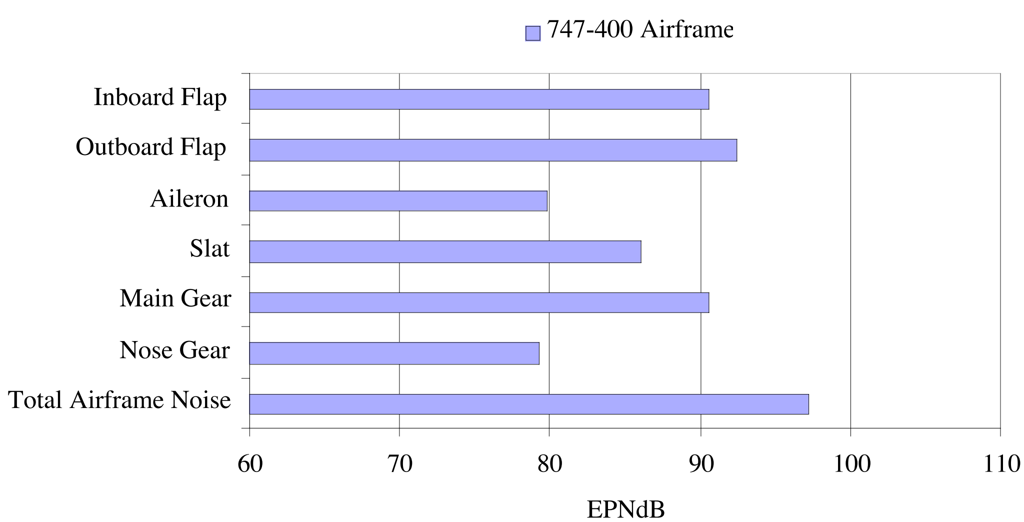



**Figure 5.2.2 Approach Airframe Noise Levels for the 747-400**

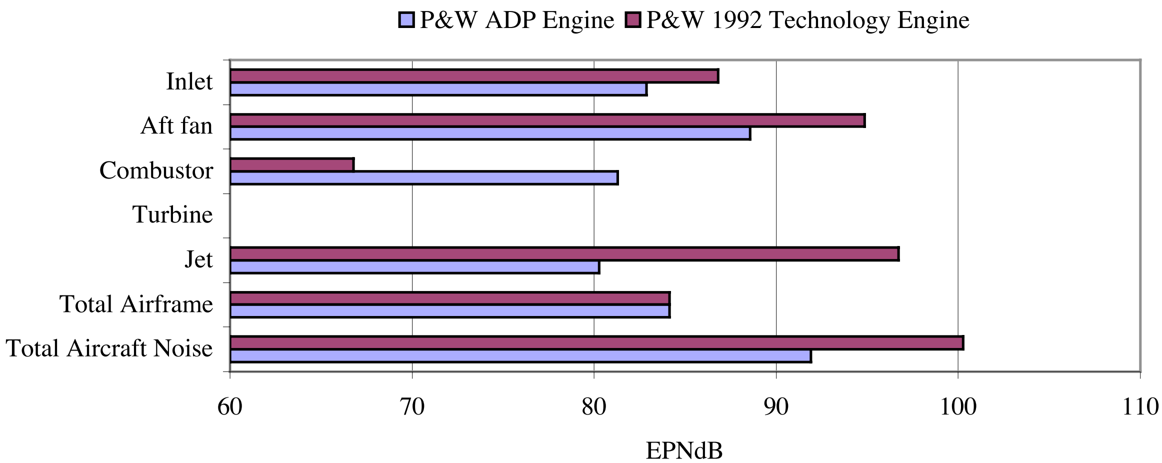



**Figure 5.2.3 Comparison of the Sideline Noise Levels for the Boeing 747-400 with Pratt & Whitney 1992 Technology Engines and ADP Engines**

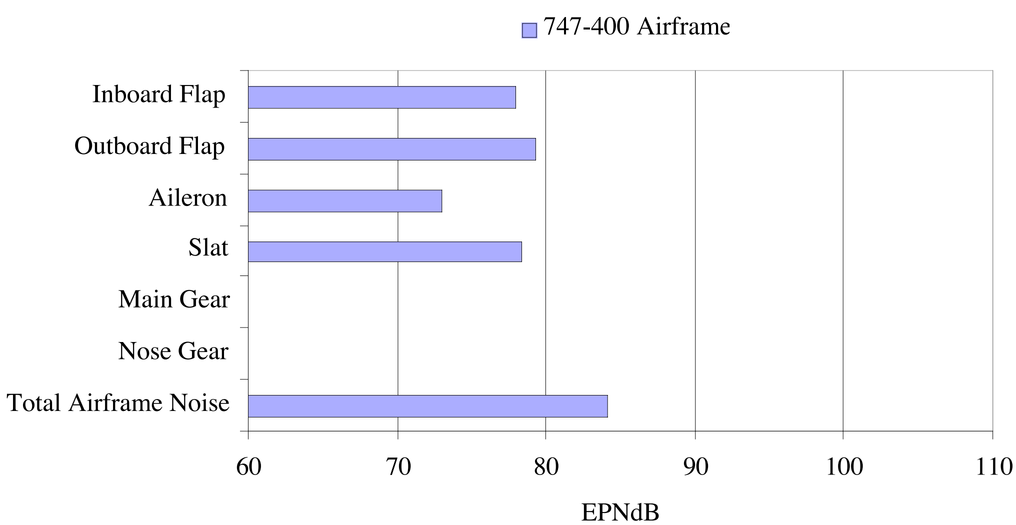



**Figure 5.2.4 Sideline Airframe Noise Levels for the Boeing 747-400**

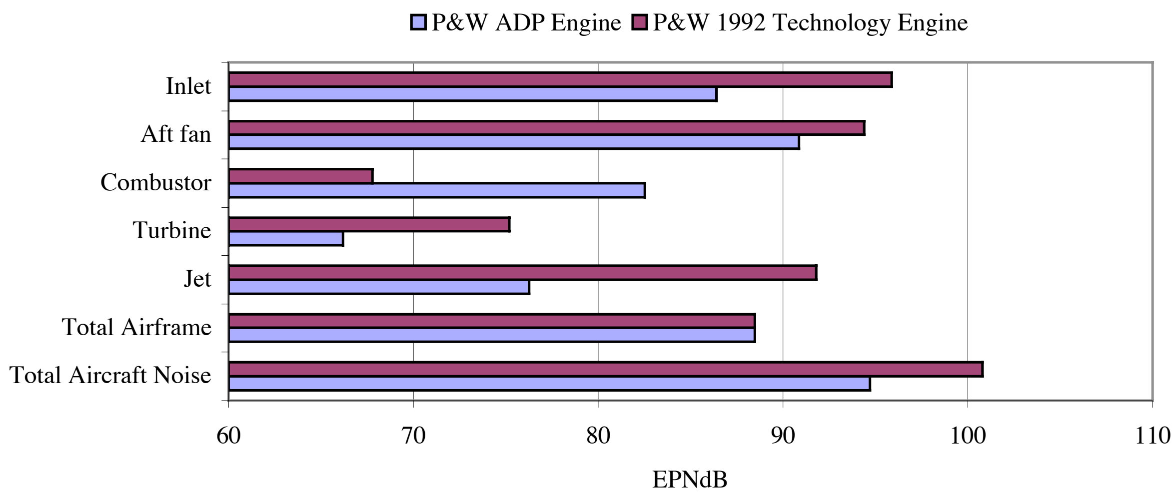



**Figure 5.2.5 Comparison of the Cutback Noise Levels for the Boeing 747-400 with Pratt & Whitney 1992 Technology Engines and ADP Engines**

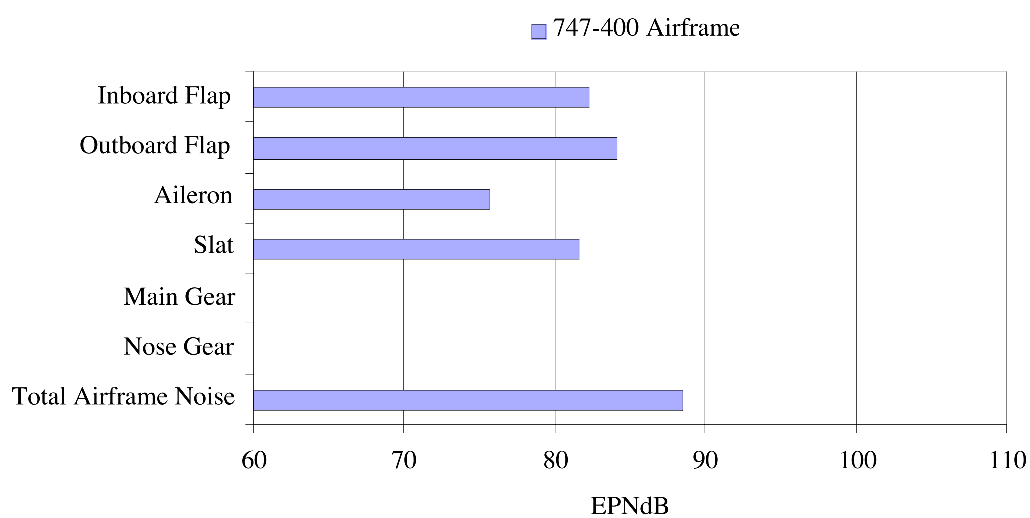



**Figure 5.2.6 Cutback Airframe Noise Levels for the Boeing 747-400**

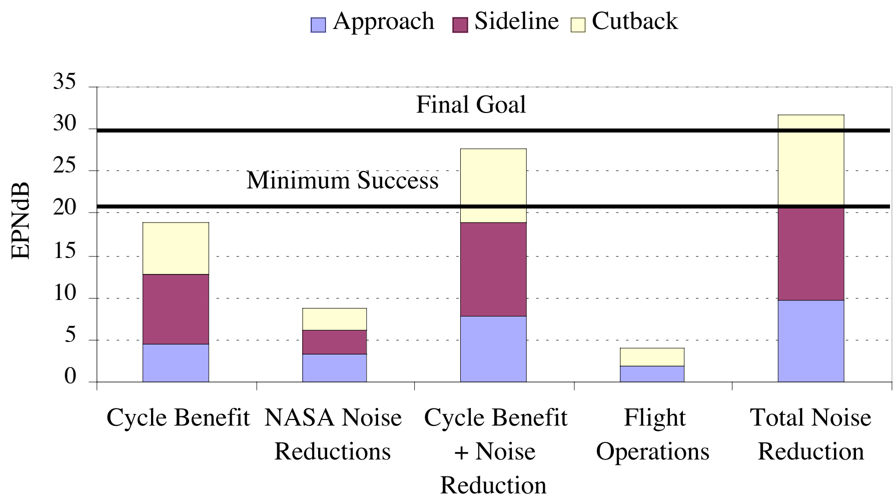



**Figure 5.2.7 Cumulative Noise Reduction for the Boeing 747-400 with P&W ADP Engines**

## 5.3 Large Quad Evaluation with GEAE Engines

### 5.3.1 Reference Engine Description

General Electric Aircraft Engines (GEAE) selected the CF6-80C2 engine as the 1992 technology engine for the Large Quad aircraft noise evaluations. The CF6-80C2 series of engines powers the Boeing 747-200, 747-300, and the 747-400 aircraft. This version of the CF6-80C2 engine for the 747-400 aircraft has 58,000 pounds of static sea level thrust and a bypass ratio of approximately 5.0. Table 5.3.1 lists the cycle parameters for the reference engine at approach, sideline, and cutback operating conditions.

### 5.3.2 Advanced Engine Description

GEAE developed a high bypass ratio (HBPR) engine based on the GE90 cycle for the Large Quad noise evaluations. The HBPR engine was scaled to produce a static sea level thrust equivalent to the reference engine. The HBPR fan is approximately 7% larger than the reference engine, has 16 fewer blades, and has 26 fewer exit guide vanes. The bypass ratio at full power is approximately 8.4. Increasing the bypass ratio reduced the mixed jet velocity by 10% to 15%. Table 5.3.2 lists cycle parameters for the HBPR engine at the approach, sideline, and cutback operating conditions.

### 5.3.3 Engine Source Noise Levels

GEAE provided NASA with two sets of noise data for the 1992 technology engine and two sets of noise data for the HBPR engine. One data set consisted of the one-third octave band received time histories of each engine noise component. These data included propagation effects such as atmospheric absorption, spherical spreading, ground reflections, and source motion effects. The second data set consisted of the one-third octave band spectra at the source. This data set was free-field and lossless but did include changes in the source spectra due to motion effects. The GEAE engine noise sources include the fan inlet, aft fan, combustor, and jet. Turbine noise for this engine (cut-off turbine design) is included in the aft fan source. The jet noise component incorporates the noise generated by the core and bypass jet flows.

NASA evaluated both sets of data during the AST program. While small differences in component noise levels between the source data and the propagated data sets were observed, the two data sets generated nearly identical results. Most of the differences in noise levels can be attributed to the different ground reflection models used by GEAE and NASA. The free-field lossless data were used to produce the results in this report because it facilitated the addition of the airframe noise sources. Using the free-field lossless data eliminated the need to interpolate the airframe noise at the three operating conditions and enabled the same propagation models to be used for the engine and airframe noise sources.

The results of the NASA analysis of the 1992 Technology and the HBPR engines for the component engine noise levels, airframe noise level, and aircraft noise level are plotted in Figures 5.3.1, 5.3.3, and 5.3.5 at the approach, sideline, and cutback operating conditions. Note from Figure 5.3.7 showing the cumulative noise reduction that the HBPR cycle provides significant jet noise reduction by lowering the core and bypass jet velocities and significant fan noise reduction by reducing the fan tip speeds. On a cumulative basis, the HBPR cycle provides 10.6 EPNdB noise reduction toward the AST final goal of 30 EPNdB.

### 5.3.4 Airframe Source Noise Levels

The Boeing 747-400 was selected as the representative airframe for the Large Quad. The takeoff weight was 850,000 pounds and a landing weight was 652,000 pounds. One-third octave band source spectra were obtained from Boeing for each airframe subcomponent at approach, sideline, and cutback operating condition. The airframe noise sources include inboard flaps, outboard flaps, aileron, slat, main gear, and nose gear. The source spectra were propagated to the measurement points using the NASA Aircraft Noise Prediction Program (ANOPP) level L03/02/17. The component airframe noise levels are plotted in Figures 5.3.2, 5.3.4, and 5.3.6.

### 5.3.5 Fan Noise Reduction

The HBPR engine was evaluated with the following fan noise reduction technologies:

1. Advanced liners
2. Herschel-Quincke (HQ) tubes
3. Swept stators
4. Forward swept fan
5. Active Noise Control (ANC) (not used in the final analysis)

Details concerning the fan noise suppression can be found in Section 4. Tables 5.3.3 through 5.3.7 list the acoustic benefit of the fan noise reduction technologies. No single technology provided the best noise reduction at all three operating conditions. The advanced liners and HQ tubes performed well at approach and cutback but provided no noise reduction at sideline. The swept stators performed well at approach while the forward swept fan performed best at sideline and cutback. Active noise control provided minimal noise reduction at approach and no noise reduction at sideline or cutback. ANC was not used in the final analysis.

### 5.3.6 Jet Noise Reduction

The HBPR engine was evaluated with the following jet noise reduction technologies:

1. 12 chevrons on the core nozzle
2. 12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

Chevrons on the core and bypass nozzles provided slightly better suppression than chevrons on the core nozzle alone. Therefore, only the results of the core and bypass chevron configuration are provided in this report. The chevron noise reduction spectrum was provided to NASA by GEAE. The result of NASA's evaluation of the HBPR engine with fan/core chevrons is provided in Table 5.3.8. Note that the best noise reduction is achieved at the sideline operating condition where the reduction in jet velocities has the greatest impact.

### 5.3.7 Airframe Noise Reduction

The 747-400 airframe was evaluated with the following noise reduction technologies

1. Porous flap edges
2. Slat cove filler

Details concerning the model test, data reduction, and component suppression spectra are provided in Section 3 of this report. NASA's evaluations of the porous flaps and slat cover filler on the 747-400/GEAE HBPR aircraft system indicates that component noise reduction on the order of 2 to 4.5 EPNdB was achieved from these technologies as indicated in Tables 5.3.9 and 5.3.10. The inboard and outboard flaps are strong noise sources on the 747-400/GEAE HBPR aircraft system, especially at approach. The porous flaps reduced the aircraft noise by 1.0 EPNdB at approach as shown in Table 5.3.9. Modest aircraft noise reductions are also obtained from porous flaps at the cutback operating conditions. Although the component noise reduction of the slat cove filler was between 2 and 3 EPNdB, as indicated in Table 5.3.10, the slat cove filler did not provide appreciable aircraft noise suppression because the slat is a relatively weak noise source on the 747-400/GEAE HBPR aircraft system.

### 5.3.8 Combined Engine and Airframe Noise Reduction Evaluation

Tables 5.3.11, 5.3.12, and 5.3.13 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Boeing 747-400 powered by GEAE HBPR engines. An examination of these tables reveals that different combinations of technologies were used at approach, sideline, and cutback. Within the guidelines of the AST program, combining the "best" technologies to achieve the greatest noise reduction was acceptable. The results are plotted to show the EPNL reductions for each of the approach, sideline, and cutback operating conditions.

Figures 5.3.1 and 5.3.2 indicate that at the at approach operating condition, the inlet, aft fan, inboard flap, outboard flap, and main gear were each strong contributors to the noise of the 747-400/GEAE HBPR aircraft system. The engine technologies chosen by NASA to reduce the approach engine noise were the advanced liners, HQ tubes and swept stators. Table 5.3.11 shows that the combined engine technologies reduced the aircraft noise by 0.6 EPNdB. It is interesting to note that the most significant noise source at the approach operating condition was due to the outboard flaps. Combining the porous flaps and the slat cove filler reduced the aircraft noise by 1.1 EPNdB as indicated in Table 5.3.12. With multiple noise sources contributing to the aircraft noise, the greatest noise reduction is achieved by simultaneously reducing the significant noise sources. Table 5.3.13 shows that combining the engine and airframe noise reduction technologies reduced the aircraft approach noise level by 2.0 EPNdB.

When HQ tubes are installed in the inlet, small sections of the liner must be removed. How much degradation this would have on the suppression of the advanced liners was unknown. It was NASA's determination that the amount of liner removed would be small and the impact on the liner suppression would be minimal. Therefore, no degradation in the advanced liner suppression was incorporated into the NASA evaluations.

As indicated in Figures 5.3.3 and 5.3.4, jet noise followed by aft fan and combustor noise were the strongest contributors to the aircraft noise at the sideline operating condition. The fan/core chevrons provided a 2.2 EPNdB jet noise reduction as indicted in Table 5.3 8. In general, the fan noise reduction technologies provided little suppression at sideline. The swept stators and the forward swept fan were the only two technologies that provided suppression of the aft fan. The engine technologies chosen by NASA to reduce the engine noise at sideline were the forward swept fan and the fan/core chevrons. Table 5.3.11 shows that the combined engine technologies reduced the aircraft noise by 2.1 EPNdB. The airframe noise sources are relatively unimportant at the sideline operating condition, and therefore the airframe noise reduction technologies have minimal impact on the aircraft noise. As indicated in Table 5.3.12, the porous flaps and slat cove filler reduced the aircraft noise by only 0.1 EPNdB. Combining the engine and airframe noise reduction technologies reduced the aircraft sideline noise by 2.2 EPNdB, as indicated in Table 5.3.13.

Referring to Figures 5.3.5 and 5.3.6, note that inlet, aft fan, and jet noise are the most significant noise sources at the cutback operating condition for the 747-400/GEAE HBPR aircraft system. NASA selected the advanced liners, the forward swept fan, HQ tubes, and fan/core chevrons to reduce the engine noise at the cutback operating condition. Table 5.3.11 shows that combining engine technologies listed above yielded a 1.6 EPNdB reduction in aircraft noise. While the cutback operating condition is dominated by engine noise sources, noise from the flaps and slats do contribute to the aircraft noise. NASA's evaluation of the porous flaps and the slat cove filler on the 747-400/GEAE HBPR aircraft system is provided as shown in Table 5.3.12. The analysis indicated that 0.6 EPNdB reduction in aircraft noise could be achieved. NASA's evaluation of the combining engine and airframe noise reduction technologies discussed above is provided in

Table 5.3.13. Combining the engine and airframe technologies yielded a 2.5 EPNdB reduction in aircraft noise.

Table 5.3.14 summarizes the results of the NASA evaluations of the AST technologies applied to the 747-400/GEAE HBPR aircraft system. A cumulative reduction of 21.3 EPNdB was achieved with 10.6 EPNdB from cycle benefit, a 6.7 EPNdB reduction from the engine and airframe noise reduction technologies, and a 4 EPNdB reduction from flight operation. Figure 5.3.7 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. The cumulative aircraft noise reduction slightly exceeds the minimum success goal of 21 EPNdB.

**Table 5.3.1 GEAE 1992 Technology Engine Cycle Data for the Large Quad Aircraft**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 13500 | 45500 | 27500 |
| Fan Diameter, in | 93 | 93 | 93 |
| Fan Blade Number | 38 | 38 | 38 |
| OGV Number | 80 | 80 | 80 |
| BPR | 6.5 | 5.0 | 5.7 |
| BPF, Hz | 1424 | 2151 | 1819 |
| Core Jet Velocity, fps | 711 | 1493 | 1088 |
| Mixed Jet Velocity, fps | 708 | 1179 | 959 |

**Table 5.3.2 GEAE HBPR Engine Cycle Data for the Large Quad Aircraft**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 13500 | 45500 | 27500 |
| Fan Diameter, in | 100 | 100 | 100 |
| Fan Blade Number | 22 | 22 | 22 |
| OGV Number | 54 | 54 | 54 |
| BPR | 10.7 | 8.4 | 9.3 |
| BPF, Hz | 651 | 1021 | 855 |
| Core Jet Velocity, fps | 679 | 1443 | 1035 |
| Mixed Jet Velocity, fps | 622 | 1023 | 837 |

**Table 5.3.3 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Advanced Liners**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.3 | N/A | 0.7 | 0.3 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 4.1 | N/A0 | 0.5 | 0.3 |

**Table 5.3.4 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from HQ Tubes**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.1 | N/A | 0.7 | 0.3 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 0.4 | N/A | 0.1 | 0.1 |

**Table 5.3.5 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Swept Stators**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.4 | 0.3 | 0.6 | 0.3 |
| Sideline | 0.0 | 1.4 | 0.4 | 0.4 |
| Cutback | -0.4 | 2.3 | 0.8 | 0.7 |

**Table 5.3.6 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Forward Swept Fan**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 | 0.0 |
| Sideline | 2.6 | 2.5 | 0.8 | 0.7 |
| Cutback | 2.5 | 2.5 | 1.4 | 1.0 |

**Table 5.3.7 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Active Noise Control**
**(not used in the final analysis)**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.5 | N/A | 0.5 | 0.2 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | -0.2 | N/A | 0.0 | 0.0 |

**Table 5.3.8 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Fan/Core Chevrons**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 |
| Sideline | 2.2 | 1.2 | 1.2 |
| Cutback | 1.0 | 0.3 | 0.3 |

**Table 5.3.9 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Porous Flap Edges**

| | Inboard | Outboard | Airframe | Aircraft |
|---|---|---|---|---|
| Approach | 3.1 | 3.7 | 2.3 | 1.0 |
| Sideline | 3.9 | 4.5 | 2.4 | 0.1 |
| Cutback | 3.6 | 4.6 | 3.0 | 0.5 |

**Table 5.3.10 EPNL Noise Reduction on Boeing 747-400 with HBPR Engines from Slat Cove Filler**

| | Slat | Airframe | Aircraft |
|---|---|---|---|
| Approach | 2.2 | 0.2 | 0.1 |
| Sideline | 3.2 | 0.6 | 0.0 |
| Cutback | 2.6 | 0.5 | 0.1 |

**Table 5.3.11 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Boeing 747-400 with GEAE HBPR Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners<br>HQ Tubes<br>Swept Stators | 0.6 |
| Sideline | Forward Swept Fan<br>Fan/Core Chevrons | 2.1 |
| Cutback | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons | 1.6 |

**Table 5.3.12 Aircraft Noise Reduction from Combined Airframe Technologies Applied to the Boeing 747-400 with GEAE HBPR Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps<br>Slat Cove Filler | 1.1 |
| Sideline | Porous Flaps<br>Slat Cove Filler | 0.1 |
| Cutback | Porous Flaps<br>Slat Cove Filler | 0.6 |

**Table 5.3.13 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Boeing 747-400 with GEAE HBPR Engines**

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners<br>HQ Tubes<br>Swept Stators<br>Porous Flaps<br>Slat Cove Filler | 2.0 |
| Sideline | Forward Swept Fan<br>Fan/Core Chevrons<br>Porous Flaps<br>Slat Cove Filler | 2.2 |
| Cutback | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons<br>Porous Flaps<br>Slat Cove Filler | 2.5 |

**Table 5.3.14 Summary of NASA's Noise Reduction Evaluations for the Boeing 747-400/GEAE HBPR Aircraft System**

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 4.8 | 2.0 | 2.0 | 8.8 |
| Sideline | 2.9 | 2.2 | 0.0 | 5.1 |
| Cutback | 2.9 | 2.5 | 2.0 | 7.4 |
| Total | 10.6 | 6.7 | 4.0 | 21.3 |

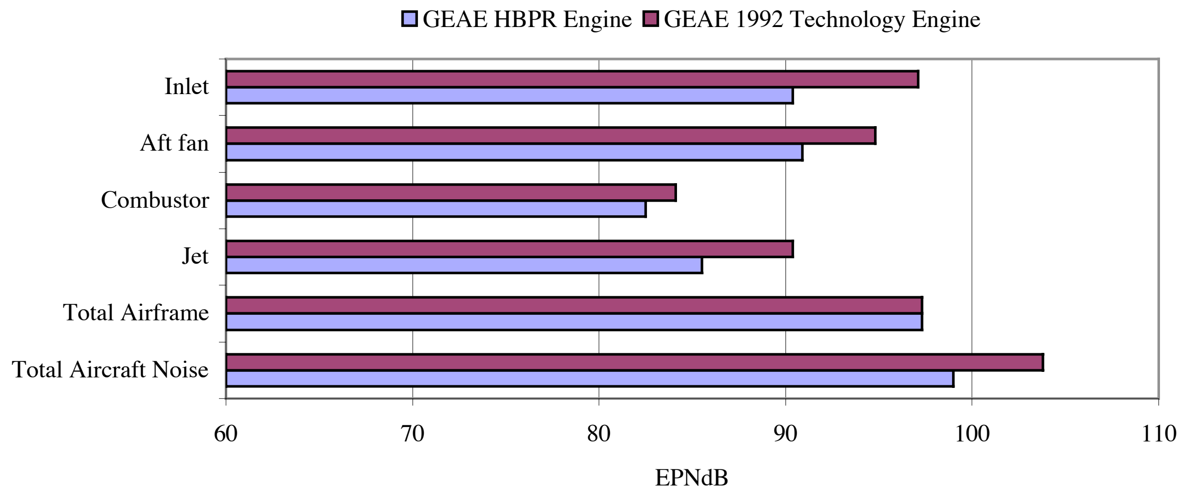



**Figure 5.3.1 Comparison of the Approach Noise Levels for the Boeing 747-400 with GEAE 1992 Technology Engines and HBPR Engines**

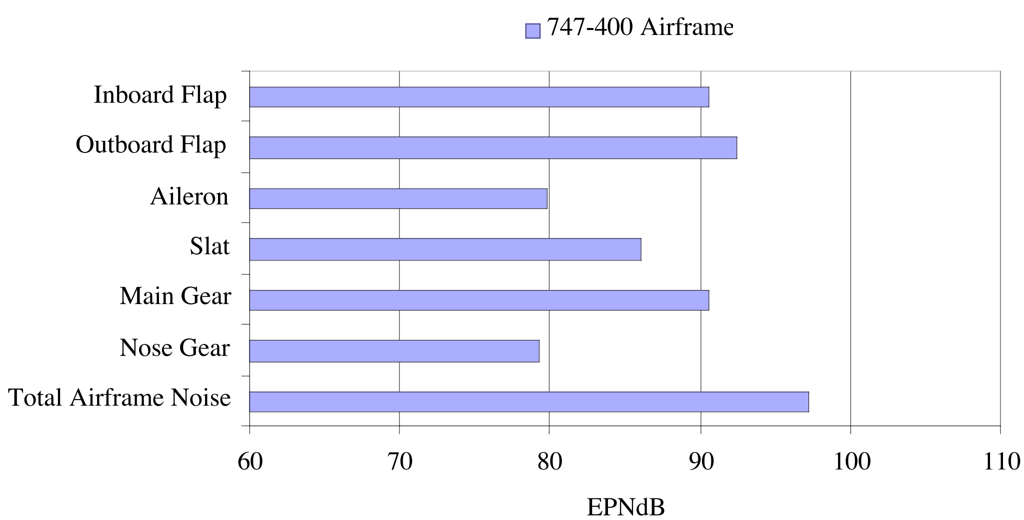



**Figure 5.3.2 Approach Airframe Noise Levels for the Boeing 747-400**

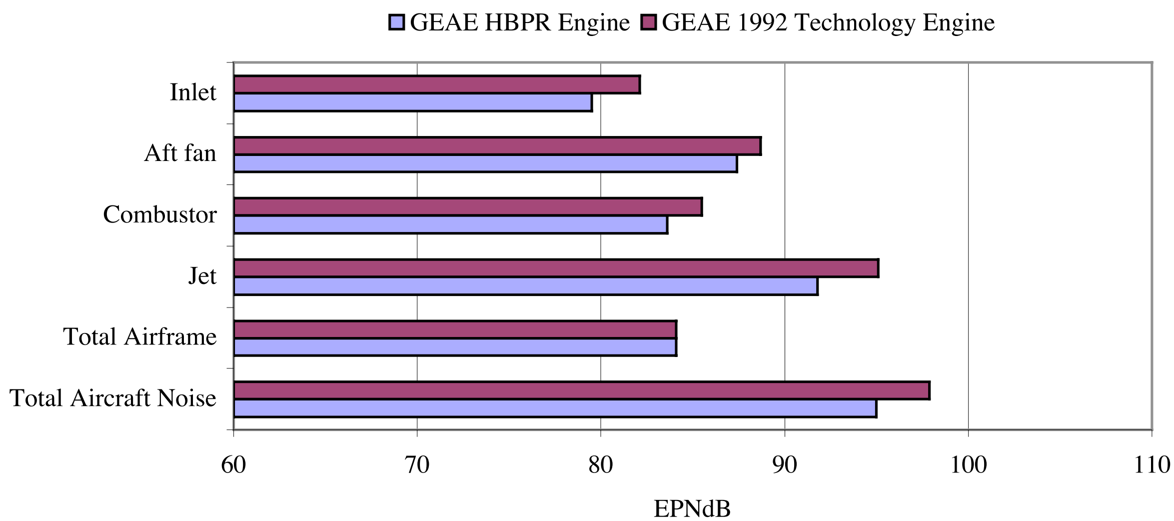



**Figure 5.3.3 Comparison of the Sideline Noise Levels for the Boeing 747-400 with GEAE 1992 Technology Engines and HBPR Engines**

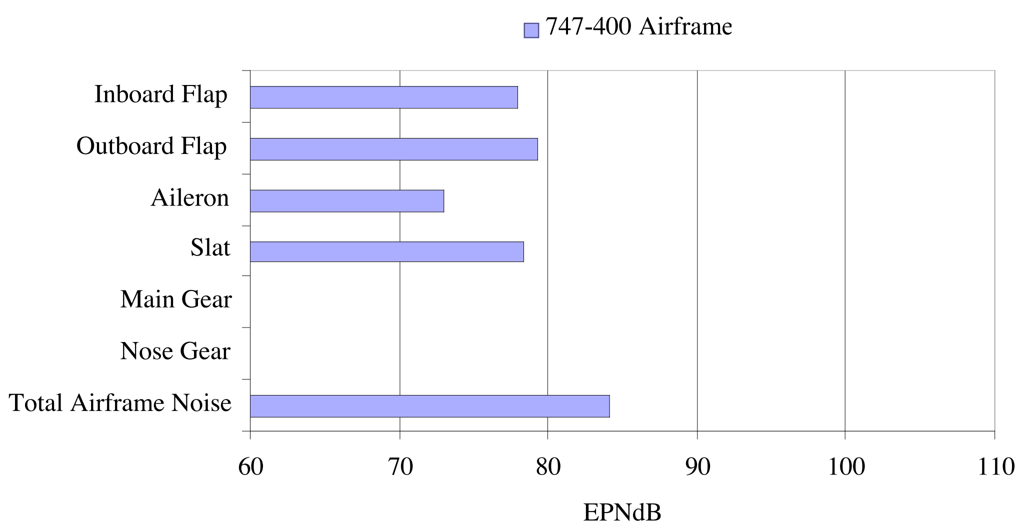



**Figure 5.3.4 Sideline Airframe Noise Levels for the Boeing 747-400**

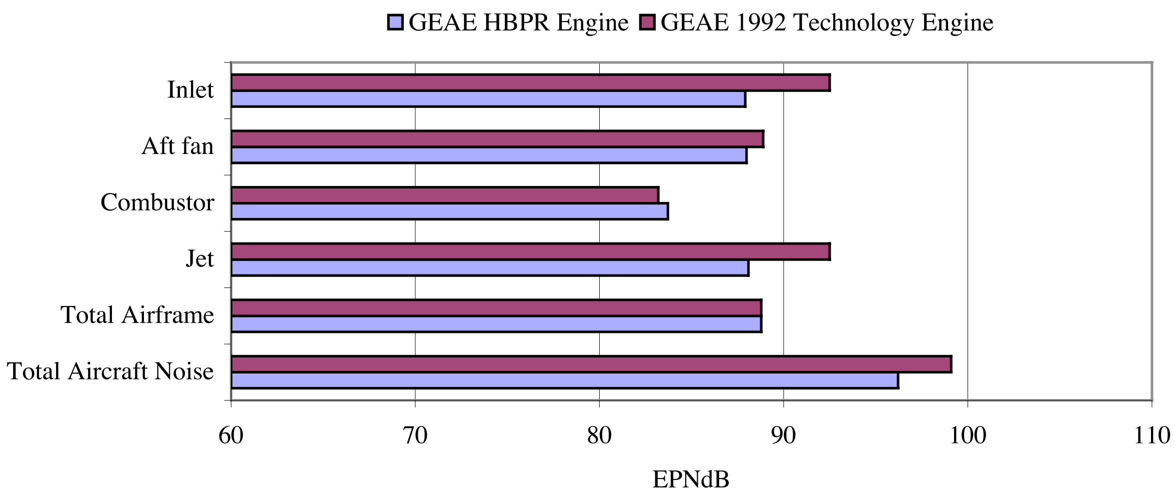



**Figure 5.3.5 Comparison of the Cutback Noise Levels for the Boeing 747-400 with GEAE 1992 Technology Engines and HBPR Engines**

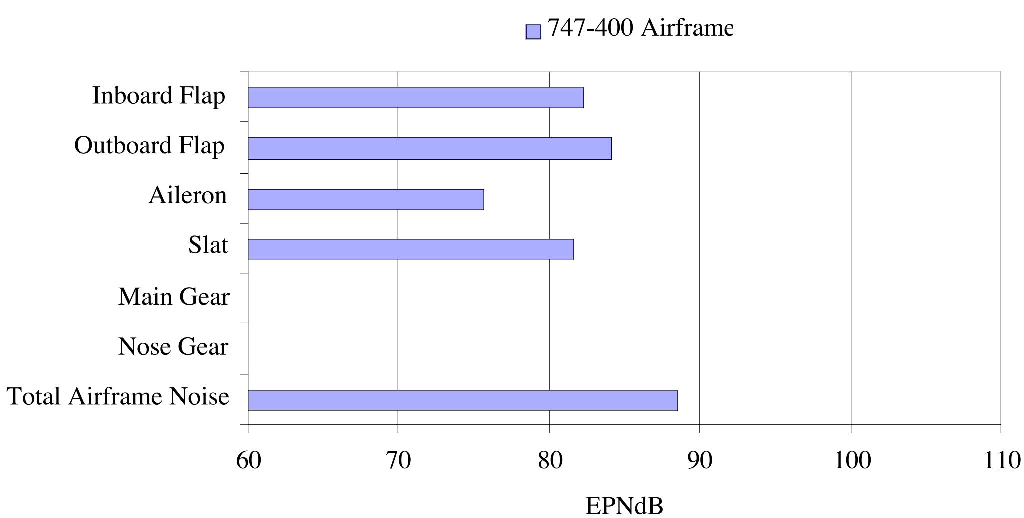



**Figure 5.3.6 Cutback Airframe Noise Levels for the Boeing 747-400**

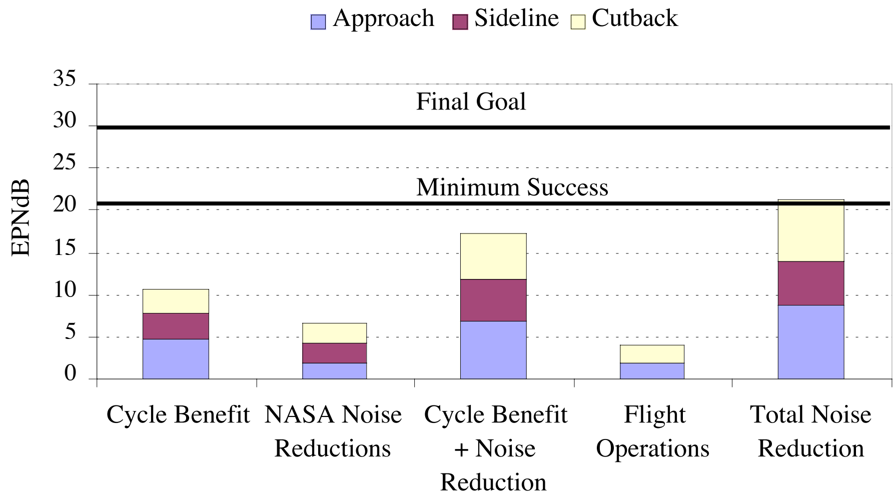



**Figure 5.3.7 Cumulative Noise Reduction for the Boeing 747-400 with GEAE HBPR Engines**

## 5.4 Medium Twin Evaluation with GEAE Engines

### 5.4.1 Reference Engine Description

General Electric Aircraft Engines (GEAE) selected the CF6-80C2 engine as the 1992 technology engine for the Medium Twin noise evaluations. The CF6-80C2 series of engines powers the Boeing 767-300. This version of the CF6-80C2 engine for the 767-300 aircraft has 60,000 pounds of static sea level thrust and a bypass ratio of approximately 5.0. Table 5.4.1 lists the cycle parameters for the reference engine at approach, sideline, and cutback operating conditions.

### 5.4.2 Advanced Engine Description

GEAE developed a high bypass ratio (HBPR) engine based on the GE90 cycle for the Medium Twin noise evaluations. The HBPR engine was scaled to produce a static sea level thrust equivalent to the reference engine. The HBPR fan has 16 fewer blades and 26 fewer exit guide vanes than the fan of the reference engine. Additionally, the diameter of the HBPR fan is 10% larger with a bypass ratio at full power of approximately 8.3. Increasing the bypass ratio reduced the mixed jet velocity by 10% to 15%. Table 5.4.2 lists cycle parameters for the HBPR engine at the approach, sideline, and cutback operating conditions.

### 5.4.3 Engine Source Noise Levels

GEAE provided NASA with two sets of noise data for the 1992 technology engine and two sets of noise data for the HBPR engine. One data set consisted of the one-third octave band received time histories of each engine noise component. These data included propagation effects such as atmospheric absorption, spherical spreading, ground reflections, and source motion effects. The second data consisted of the one-third octave band spectra at the source. This data set was free-field and lossless but did include changes in the source spectra due to motion effects. The GEAE engine noise sources include the fan inlet, aft fan, combustor, and jet. Turbine noise for this engine (cut-off turbine design) is included in the aft fan noise source. The jet noise component incorporates the noise generated by the core and bypass jet flows.

NASA evaluated both sets of data during the AST program. While small differences in component noise levels between the source data and the propagated data were observed, the two data sets generated analogous results. Most of the differences in noise levels can be attributed to the different ground reflection models used by GEAE and NASA. The free-field lossless data were used to produce the results in this report because it facilitated the addition of the airframe noise sources. Using the free-field lossless data eliminated the need to interpolate the airframe noise at the three operating conditions and enabled the same propagation models to be used for the engine and airframe noise sources.

The results of the NASA analysis of the 1992 Technology and the HBPR engines for the component engine noise levels, airframe noise level, and aircraft noise level are plotted in Figures 5.4.1, 5.4.3, and 5.4.5 at the approach, sideline, and cutback operating conditions. Note from Figure 5.4.7 showing the cumulative noise reduction that the HBPR cycle provides significant jet noise reduction by lowering the core and bypass jet velocities and significant fan noise reduction by reducing the fan tip speeds. On a cumulative basis, the HBPR cycle provides a 9.0 EPNdB noise reduction toward the AST final goal of 30 EPNdB.

### 5.4.4 Airframe Source Noise Levels

The Boeing 767-300 was selected as the representative airframe for the Medium Twin. The takeoff weight was 400,000 pounds and a landing weight was 320,000 pounds. One-third octave band source spectra were obtained from Boeing for each airframe subcomponent at approach, sideline, and cutback operating condition. The airframe noise sources include inboard flaps, outboard flaps, aileron, slat, main gear, and nose gear. The source spectra were propagated to the measurement points using the NASA Aircraft Noise Prediction Program (ANOPP) level L03/02/17. The component airframe noise levels are plotted in Figures 5.4.2, 5.4.4, and 5.4.6.

### 5.4.5 Fan Noise Reduction

The HBPR engine was evaluated with the following fan noise reduction technologies:

1. Advanced liners
2. Herschel-Quincke (HQ) tubes
3. Swept stators
4. Forward swept fan
5. Active Noise Control (ANC) (not used in the final analysis)

Details concerning the fan noise suppression can be found in Section 3. Tables 5.4.3 through 5.4.7 list the acoustic benefits of the fan noise reduction technologies. No single technology provided the best noise reduction at all three operating conditions. The advanced liners and HQ tubes performed well at approach and cutback but provided no noise reduction at sideline. The swept stators performed well at approach while the forward swept fan performed best at sideline and cutback. Active noise control provided minimal noise reduction at approach and no noise reduction at sideline or cutback. ANC was not used in the final analysis.

### 5.4.6 Jet Noise Reduction

The HBPR engine was evaluated with the following jet noise reduction technologies:

1. 12 chevrons on the core nozzle
2. 12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

Chevrons on the core and bypass nozzles provided slightly better suppression than chevrons on the core nozzle alone. Therefore, only the result of the core and bypass chevrons configuration is provided in this report. The chevron noise reduction spectrum was provided to NASA by GEAE. The result of NASA's evaluation of the HBPR engine with fan/core chevrons is provided in Table 5.4.8. Note that the best noise reduction is achieved at the sideline operating condition where the reduction in jet velocities has the greatest impact.

### 5.4.7 Airframe Noise Reduction

The 767-300 airframe was evaluated with the following noise reduction technologies:

1. Porous flap edges
2. Slat cove filler

Details concerning the model test, data reduction, and suppression spectra are provided in Section 4 of this report. NASA's evaluations of the porous flaps and slat cover filler on the 767-300/GEAE HBPR aircraft system indicates that component noise reduction on the order of 0.1 to 0.4 EPNdB was achieved from these technologies as indicated in Tables 5.4.9 and 5.4.10. While the inboard flaps and slats are important noise sources on the 767-300/HBPR aircraft system during approach, inlet and aft fan are the dominate noise sources and therefore the component airframe noise reduction is not as significant as might be expected. At approach, the porous flaps reduced the aircraft noise by 0.4 EPNdB as shown in Table 5.4.9. Aircraft noise suppression from the porous flaps at sideline and cutback was negligible. The slat cove filler provides no appreciable suppression of the aircraft noise at approach, sideline, or cutback as shown in Table 5.4.10.

### 5.4.8 Combined Engine and Airframe Noise Reduction Evaluation

Tables 5.4.11, 5.4.12, and 5.4.13 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Boeing 767-300 powered by GEAE HBPR engines. An examination of these tables reveals that different combinations of technologies were used at approach, sideline, and cutback. Within the guidelines of the AST program, combining the "best" technologies to achieve the most noise reduction was acceptable.

The results are plotted to show the EPNL reductions for each of the approach, sideline, and cutback operating conditions.

Figures 5.4.1 and 5.4.2 indicate that at the approach operating condition, the inlet, aft fan, inboard flap, slat, and main gear were each strong contributors to the noise of the 767-300/GEAE HBPR aircraft system. The engine technologies chosen by NASA to reduce the approach engine noise were the advanced liners, HQ tubes, and swept stators. Table 5.4.11 shows that combining these engine technologies reduced aircraft noise by 1.1 EPNdB. Fan/core chevrons were ineffective at reducing the jet noise at approach and were therefore not included in the list of engine noise reduction technologies. Combining the porous flaps and the slat cove filler reduced the aircraft noise by 0.6 EPNdB as indicated in Table 5.4.12. With multiple noise sources contributing significantly to the aircraft noise, the greatest noise reduction is achieved by simultaneously reducing the major noise sources. Table 5.4.13 shows that combining the engine and airframe noise reduction technologies reduced the approach aircraft noise level 1.9 EPNdB at the approach operating condition.

During the evaluations, concerns were raised about combining the HQ tubes with the advanced liner. When HQ tubes are installed in the inlet, some of the liner must be removed. How much degradation this would have on the suppression of the advanced liners was unknown. It was NASA's determination that the amount of liner removed would be small and the impact on the liner suppression would be minimal. Therefore, no degradation in the advanced liner suppression was incorporated into the NASA evaluations.

At the sideline operating condition, jet noise, aft fan, and combustor noise were the strongest contributors to the aircraft noise, as indicated in Figure 5.4.3. The fan/core chevrons provided a 1.2 EPNdB noise reduction as indicted in Table 5.4 8. In general, the fan noise reduction technologies provided little suppression at sideline. Of the five fan noise reduction technologies evaluated, only the swept stators and the forward swept fan provided suppression of the aft fan. The engine technologies chosen by NASA to reduce the engine noise at sideline were the forward swept fan and fan/core chevrons. Table 5.4.11 shows that the combined engine technologies reduced sideline aircraft noise by 2.1 EPNdB. The airframe noise sources are relatively unimportant at sideline, and therefore the airframe noise reduction technologies have minimal impact on the aircraft noise. As indicated in Table 5.4.12, the porous flaps and slat cove filler did not reduce the sideline aircraft noise. Combining the engine and airframe noise reduction technologies reduced the sideline aircraft noise by 2.2 EPNdB, as indicated in Table 5.4.13.

As shown in Figure 5.4.5, jet mixing, aft fan, and inlet noise were the most significant sources for the 767-300/GEAE HBPR aircraft system at the cutback operating condition. NASA selected the advanced liners, the HQ tubes, and the forward swept fan and fan/core chevrons to reduce the engine noise at cutback. Table 5.4.11 shows that the combined engine technologies yielded a 2.2 EPNdB noise reduction. The airframe noise sources are relatively unimportant at cutback, and therefore the airframe noise reduction technologies have minimal impact on the aircraft noise. As shown in Table 5.4.12, combining the porous flaps and the slat cove filler resulted in a 0.1 EPNdB noise reduction. Table 5.4.13 shows that combining the engine and airframe noise reduction technologies achieved a 2.3 EPNdB reduction in aircraft noise.

Table 5.4.14 summarizes the results of the NASA evaluations of the AST technologies applied to the 767-300/GEAE HBPR aircraft system. A cumulative reduction of 19.4 EPNdB was achieved with 9.0 EPNdB from cycle benefit, a 6.4 EPNdB reduction from the engine and airframe noise reduction technologies, and a 4 EPNdB reduction from flight operation. Figure 5.4.7 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. The cumulative aircraft noise reduction falls just slightly below the minimum success goal of 21 EPNdB.

One may wonder why the 747-400/GEAE HBPR aircraft system (described in Section 5.3) met the minimum success goal while the 767-300/GEAE HBPR aircraft system did not, especially since both aircraft are powered by similar power plants and utilize identical noise reduction technologies. The benefits from the noise reduction technologies for the two aircraft, according to the NASA evaluations, are nearly the same. The difference between the two aircraft occurs in the cycle benefit provided by the HBPR engines. The HBPR engine for the Medium Twin achieved 1.6 EPNdB less cycle benefit than the HBPR engine for the Large Quad.

**Table 5.4.1. GEAE 1992 Technology Engine Cycle Data for the Medium Twin**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 13000 | 48500 | 33000 |
| Fan Diameter, in | 93 | 93 | 93 |
| Fan Blade Number | 38 | 38 | 38 |
| OGV Number | 80 | 80 | 80 |
| BPR | 6.5 | 4.9 | 5.5 |
| BPF, Hz | 1391 | 2206 | 1951 |
| Core Jet Velocity, fps | 682 | 1550 | 1197 |
| Mixed Jet Velocity, fps | 682 | 1198 | 1019 |

**Table 5.4.2. GEAE HBPR Engine Cycle Data for the Medium Twin**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 13000 | 48500 | 33000 |
| Fan Diameter, in | 102 | 102 | 102 |
| Fan Blade Number | 22 | 22 | 22 |
| OGV Number | 54 | 54 | 54 |
| BPR | 10.8 | 8.3 | 9.0 |
| BPF, Hz | 613 | 1005 | 878 |
| Core Jet Velocity, fps | 635 | 1445 | 1109 |
| Mixed Jet Velocity, fps | 589 | 1018 | 871 |

**Table 5.4.3 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Advanced Liners**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.3 | N/A | 0.8 | 0.5 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 4.1 | N/A | 0.4 | 0.4 |

**Table 5.4.4 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from HQ Tubes**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.5 | N/A | 0.8 | 0.5 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 0.4 | N/A | 0.0 | 0.0 |

**Table 5.4.5 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Swept Stators**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.4 | 0.3 | 0.7 | 0.5 |
| Sideline | 0.0 | 1.4 | 0.5 | 0.5 |
| Cutback | -0.4 | 2.3 | 0.8 | 0.8 |

**Table 5.4.6 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Forward Swept Fan**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 | 0.0 |
| Sideline | 2.6 | 2.6 | 0.9 | 0.8 |
| Cutback | 2.6 | 2.5 | 1.4 | 1.3 |

**Table 5.4.7 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Active Noise Control**

**(not used in the final analysis)**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.5 | 0.0 | 0.5 | 0.4 |
| Sideline | 0.0 | 0.0 | 0.0 | 0.0 |
| Cutback | -0.2 | 0.0 | 0.0 | 0.0 |

**Table 5.4.8 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Fan/Core Chevrons**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 |
| Sideline | 2.2 | 1.3 | 1.2 |
| Cutback | 1.1 | 0.4 | 0.4 |

**Table 5.4.9 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Porous Flaps**

| | Inboard | Outboard | Total Airframe | Aircraft |
|---|---|---|---|---|
| Approach | 3.3 | 3.9 | 1.0 | 0.4 |
| Sideline | 1.4 | 3.1 | 0.5 | 0.0 |
| Cutback | 1.2 | 2.8 | 0.4 | 0.0 |

**Table 5.4.10 EPNL Noise Reduction on Boeing 767-300 with HBPR Engines from Slat Cove Filler**

| | Slat | Total Airframe | Aircraft |
|---|---|---|---|
| Approach | 2.4 | 0.6 | 0.2 |
| Sideline | 3.3 | 2.0 | 0.0 |
| Cutback | 3.7 | 2.1 | 0.1 |

**Table 5.4.11 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Boeing 767-300 with GEAE HBPR Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners<br>HQ Tubes<br>Swept Stators | 1.1 |
| Sideline | Forward Swept Fan<br>Fan/Core Chevrons | 2.1 |
| Cutback | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons | 2.2 |

**Table 5.4.12 Aircraft Noise Reduction from Combined Airframe Technologies Applied to the Boeing 767-300 with GEAE HBPR Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps<br>Slat Cove Filler | 0.6 |
| Sideline | Porous Flaps<br>Slat Cove Filler | 0.0 |
| Cutback | Porous Flaps<br>Slat Cove Filler | 0.1 |

**Table 5.4.13 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Boeing 767-300 with GEAE HBPR Engines**

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners | |
| | HQ Tubes | 1.9 |
| | Swept Stators | |
| | Porous Flaps | |
| | Slat Cove Filler | |
| Sideline | Forward Swept Fan | |
| | Fan/Core Chevrons | 2.2 |
| | Porous Flaps | |
| | Slat Cove Filler | |
| Cutback | Advanced Inlet Liners | |
| | HQ Tubes | 2.3 |
| | Forward Swept Fan | |
| | Fan/Core Chevrons | |
| | Porous Flaps | |
| | Slat Cove Filler | |

**Table 5.4.14 Summary of NASA's Noise Reduction Evaluations for the Boeing 767-300/GEAE HBPR Aircraft System**

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 4.0 | 1.9 | 2.0 | 7.9 |
| Sideline | 3.8 | 2.2 | 0.0 | 6.0 |
| Cutback | 1.2 | 2.3 | 2.0 | 5.5 |
| Total | 9.0 | 6.4 | 4.0 | 19.4 |

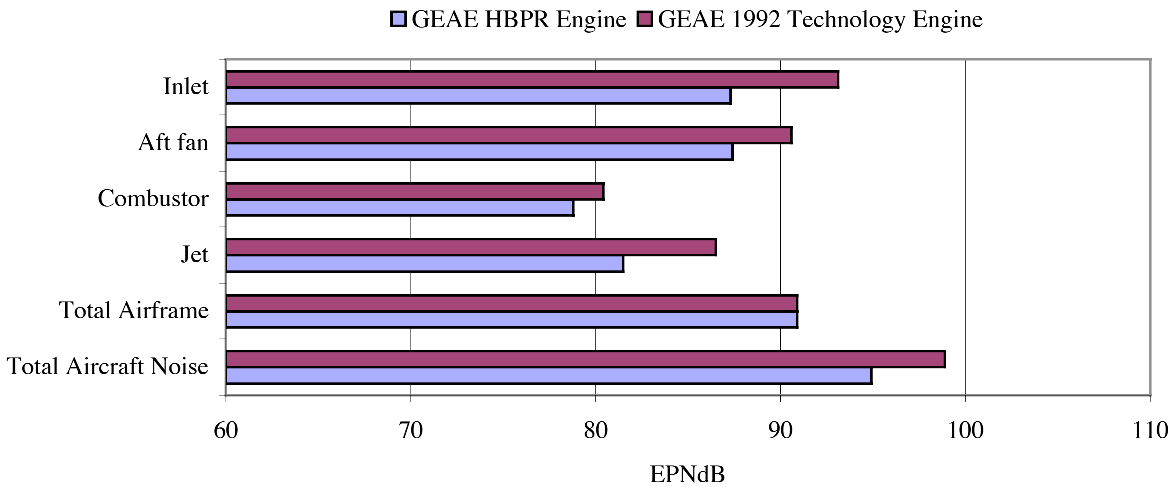



**Figure 5.4.1 Approach Noise Levels for the Boeing 767-300 with GEAE 1992 Technology Engines and HBPR Engines**

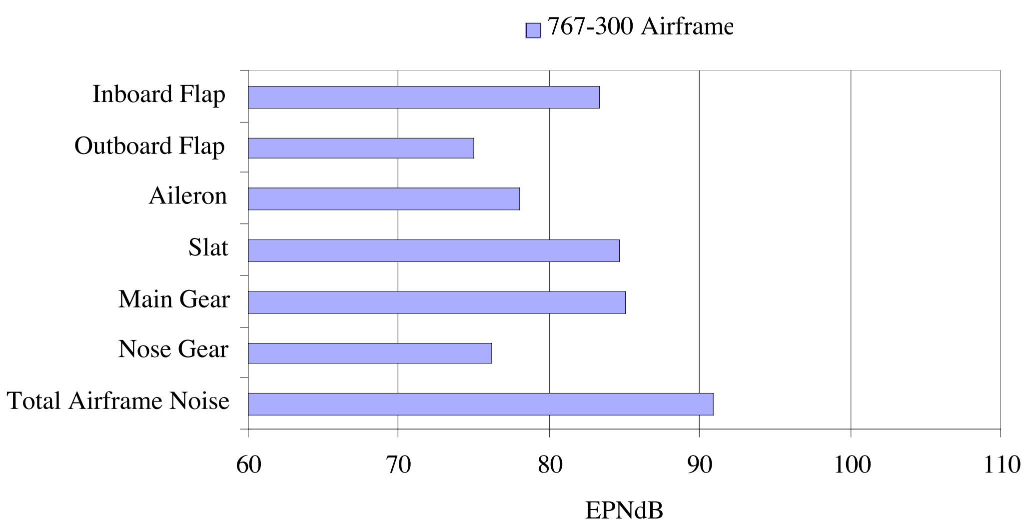



**Figure 5.4.2 Approach Airframe Noise Levels for the Boeing 767-300**

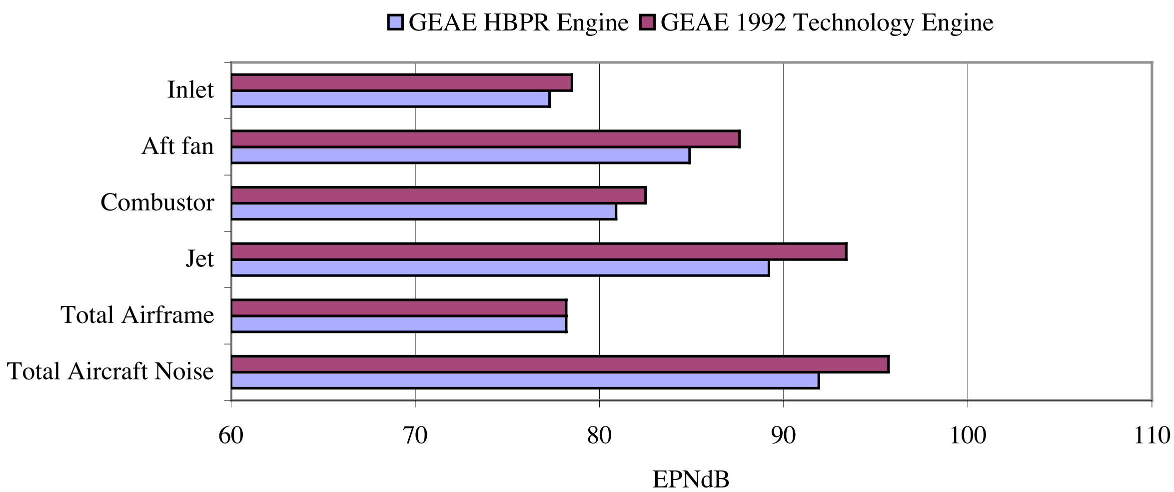



**Figure 5.4.3 Sideline Noise Levels for the Boeing 767-300 with GEAE 1992 Technology Engines and HBPR Engines**

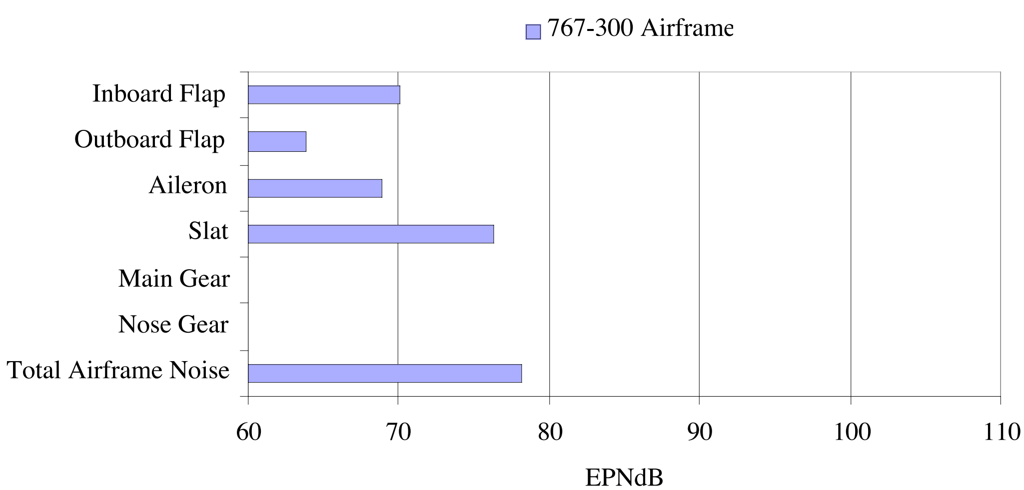



**Figure 5.4.4 Sideline Airframe Noise Levels for the Boeing 767-300**

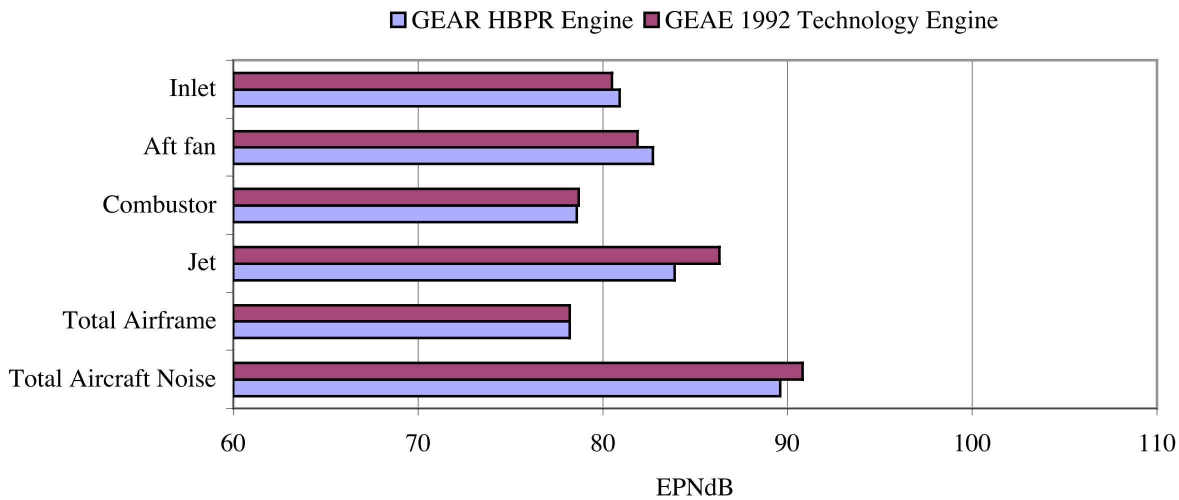



**Figure 5.4.5 Cutback Noise Levels for the Boeing 767-300 with GEAE 1992 Technology Engines and HBPR Engines**

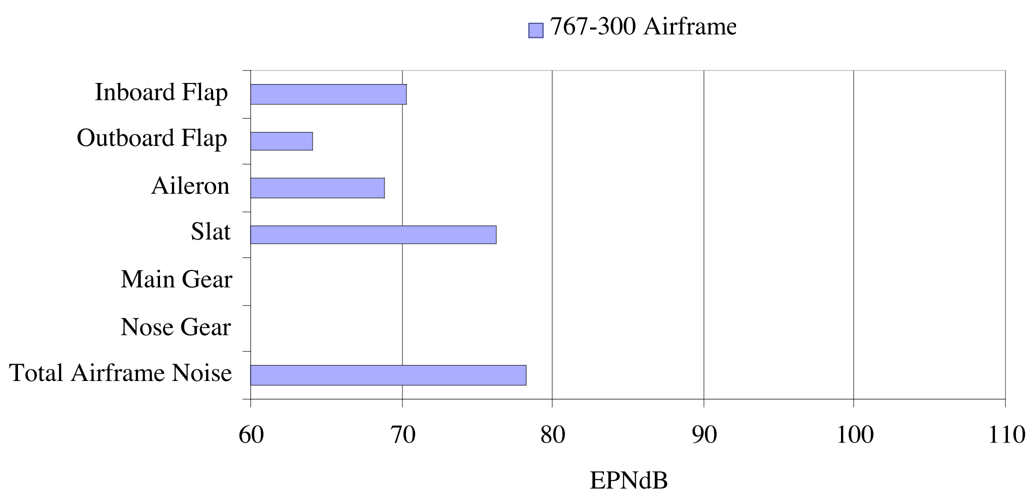



**Figure 5.4.6 Cutback Airframe Noise Levels for the Boeing 767-300**

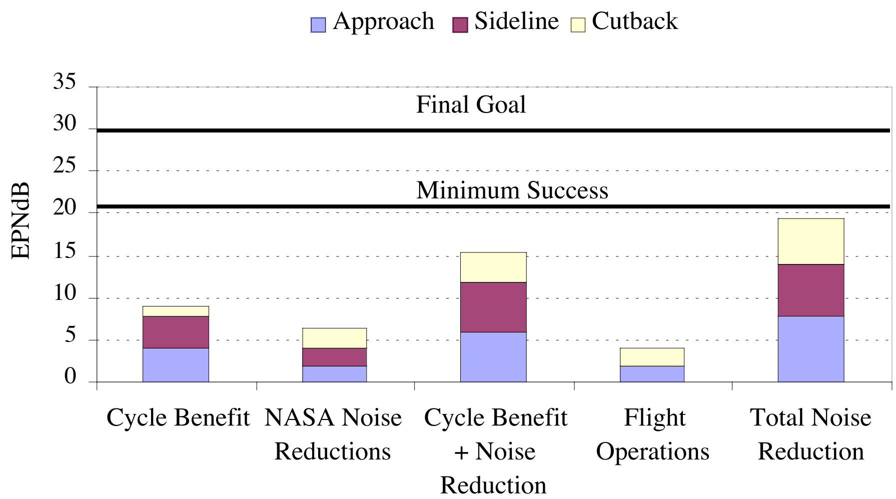



**Figure 5.4.7 Cumulative Noise Reduction for the Boeing 767-300 with GEAE HBPR Engines**

## 5.5 Small Twin Evaluation with GEAE Engines

### 5.5.1 Reference Engine Description

General Electric Aircraft Engines (GEAE) selected the CFM56 engine as the 1992 technology engine for the Small Twin aircraft noise evaluations. The version of the CFM56 engine for the 737-300 aircraft has 22,000 pounds of static sea level thrust and a bypass ratio of approximately 5.0. Table 5.5.1 lists the cycle data for the approach, sideline, and cutback operating conditions for the Small Twin.

### 5.5.2 Advanced Engine Description

The GEAE advanced engine for the Small Twin is based on the GE90 cycle. The HBPR engine was scaled to produce a static sea level thrust equivalent to the 1992 technology engine. The HBPR fan has approximately the same fan diameter as the reference engine, has 16 fewer blades, and has 26 fewer exit guide vanes. Increasing the bypass ratio to 8.3 reduces the mixed jet velocity by 10% to 15%. Table 5.5.2 lists cycle data for the approach, sideline, and cutback operating conditions.

### 5.5.3 Engine Source Noise Levels

GEAE provided NASA with two sets of data for 1992 reference engine and the advanced HBPR engine. One set of data was provided at the measurement points that included all forward flight and propagation effects. The other set of data was provided at the noise source. The second data set did not include propagation effects but did include forward flight corrections. One-third octave-band spectra were provided for the fan inlet, aft fan, combustor, and jet at the approach, sideline, and cutback points. The jet noise component represents both the core and bypass jet noise.

NASA evaluated both sets of data during the AST program. While small differences in component noise levels between the source data and the propagated data were observed, the two data sets generated analogous results. Most of the differences in noise levels can be attributed to the different ground reflection models used by GEAE and NASA. The free-field lossless data was used to produce the results in this report because it facilitated the addition of the airframe noise sources. Using the free-field lossless data eliminated the need to interpolate the airframe noise at the three operating conditions and enabled the same propagating models to be used for the engine and airframe noise sources.

The results of the NASA analysis of the 1992 Technology and the HBPR engines for the component engine noise levels, airframe noise level, and aircraft noise level are plotted in Figures 5.5.1, 5.5.3, and 5.5.5 at approach, sideline, and cutback, respectively. Note that the HBPR cycle provides significant jet noise reduction by lowering the core and bypass jet velocities and fan noise reduction by reducing the fan tip speeds. On a cumulative basis, the HBPR cycle provides11.4 EPNdB noise reduction toward the AST final goal of 30 EPNdB. Figure 5.5.7 shows the cumulative noise reduction for the HBPR engine on the 737-300 aircraft.

### 5.5.4 Airframe Source Noise Levels

The Boeing 737-300 was selected as the representative airframe for the Small Twin. The takeoff weight was 138,500 pounds and a landing weight was 115,500 pounds. One-third octave band source spectra were obtained from Boeing for each airframe subcomponent at approach, sideline, and cutback operating conditions. The airframe noise sources include inboard flaps, outboard flaps, aileron, slat, main gear, and nose gear. The source spectra were propagated to the measurement points using the NASA Aircraft Noise Prediction Program (ANOPP) level L03/02/17. The component airframe noise levels are plotted in Figures 5.5.2, 5.5.4, and 5.5.6.

### 5.5.5 Fan Noise Reduction

The HBPR engine was evaluated with the following jet noise reduction technologies:

1. Advanced liners
2. Herschel-Quincke (HQ) tubes
3. Swept stators
4. Forward swept fan
5. Active noise control (ANC) (not used in the final analysis)

Details concerning the fan noise suppression can be found in Section 3 of this report. Tables 5.5.3 through 5.5.7 list the acoustic benefit of the fan noise reduction technologies. No single technology provided best noise reduction at all three measurement points. The advanced liners and HQ tubes performed well at approach and cutback but provided no noise reduction at sideline. The advanced liners and HQ tubes were not used in the aft fan. The swept stators performed well at approach while the forward swept fan performed best at sideline and cutback.

Active noise control provided minimal noise reduction at approach and no noise reduction at sideline or cutback. ANC was not used in the final analysis.

### 5.5.6 Jet Noise Reduction

The HBPR engine was evaluated with the following jet noise reduction technologies:

1. 12 chevrons on the core nozzle
2. 12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

Chevrons on the core and bypass nozzles provided slightly better suppression than chevron on the core nozzle alone. Therefore, only the results of the core and bypass chevron configuration are provided in this report. The chevron noise reduction spectrum was provided to NASA by GEAE. The result of NASA's evaluation of the HBPR engine with fan/core chevrons is provided in Table 5.5.8. Note that the best noise reduction is achieved at the sideline operating condition where the reduction in jet velocities has the greatest impact.

### 5.5.7 Airframe Noise Reduction

The 737-300 airframe was evaluated with the following noise reduction technologies:

1. Porous flap edges
2. Slat cove filler

Details concerning the model test, data reduction, and suppression spectra were presented in Section 3. NASA's evaluations of the porous flaps and slat cover filler on the 737-300/HBPR aircraft indicate that significant source noise reduction is achieved from these technologies as shown in Tables 5.5.9 and 5.5.10. The inboard flaps, outboard flaps, and slats are strongest airframe noise sources on the Boeing 737-300/HBPR aircraft system at approach. The porous flaps reduced the approach aircraft noise by 0.9 EPNdB as shown in Table 5.5.9. Suppression of the aircraft noise from the porous flaps at sideline and cutback was negligible. The slat cove filler alone provides little suppression of the aircraft noise as shown in Table 5.5.10, because there are other noise sources of greater source strength.

### 5.5.8 Combined Engine and Airframe Noise Reduction Evaluation

Tables 5.5.11, 5.5.12, and 5.5.13 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Boeing 737-300 powered by GEAE HBPR engines. Examining these tables reveals that different combinations of technologies were used at approach, sideline, and cutback. Within the guidelines of the AST program, combining the "best" technologies to achieve the most noise reduction was acceptable.

The approach noise for the Boeing 737-300/GEAE HBPR aircraft system is characterized by a mixture of engine and airframe noise sources. Figures 5.5.1 and 5.5.2 indicate that the inlet, aft fan, inboard flaps, outboard flaps, and slat noise sources were strong contributors to the approach noise. The engine technologies chosen by NASA to reduce the approach engine noise were the advanced liners, HQ tubes, and swept stators. Table 5.5.11 shows that combining these engine technologies reduced the aircraft noise by 0.6 EPNdB. Fan/core chevrons were ineffective at reducing the jet noise at approach and were therefore not included in the list of engine noise reduction technologies. Combining the porous flaps and the slat cove filler reduced the aircraft noise by 1.0 EPNdB as indicated in Table 5.5.12. With multiple noise sources contributing to the aircraft noise, the greatest noise reduction is achieved by simultaneously reducing the significant noise sources. Table 5.5.13 shows that combining the engine and airframe noise reduction technologies reduced the aircraft approach noise level by 1.8 EPNdB.

When HQ tubes are installed in the inlet, some of the liner must be removed. How much degradation this would have on the suppression of the advanced liners was unknown. It was NASA's determination that the amount of liner removed would be small and the impact on the liner suppression would be minimal. Therefore, no degradation in the advanced liner suppression was incorporated into the NASA evaluations.

Jet noise was by far the strongest contributor to the aircraft noise at sideline as indicated in Figure 5.5.3. Fan/core chevrons provided significant jet noise reduction at the sideline as indicted in Table 5.5 8. In general, the fan noise reduction technologies provided little suppression at sideline noise because of the relatively low fan noise levels relative to the jet noise. The engine technologies chosen by NASA to reduce the engine noise at sideline were the forward swept fan and chevrons. Table 5.5.11 shows that the combined engine technologies reduced sideline aircraft noise by1.9 EPNdB. The airframe noise sources are relatively unimportant at sideline, and therefore the airframe noise reduction technologies have minimal impact on the aircraft noise. As indicated in Table 5.5.12, the porous flaps and slat cove filler produced no predictable noise reduction. Combining the engine and airframe noise reduction technologies reduced the sideline aircraft noise by 2.0 EPNdB as indicated in Table 5.5.13.

At the cutback operating condition, inlet, aft fan, and jet noise were the most significant sources for the Boeing 737-300/GEAE HBPR aircraft system as indicated in Figure 5.5.5. NASA selected the advanced liners, the HQ tubes, and the forward swept fan and fan/core chevrons to reduce the engine noise at cutback. Table 5.5.11 shows that combined engine technologies yielded a 2.0 EPNdB noise reduction. The airframe noise sources are relatively unimportant at cutback, and therefore the airframe noise reduction technologies have minimal impact on the aircraft noise. Combining the porous flaps and the slat cove filler resulted in a 0.1 EPNdB noise reduction. Table 5.5.13 shows that combining the engine and airframe noise reduction technologies achieved a 2.2 EPNdB reduction in aircraft cutback noise.

Table 5.5.14 summarizes the results of the NASA evaluations of the AST technologies applied to the 737-300/GEAE HBPR aircraft system. A cumulative aircraft noise reduction of 21.4 EPNdB was achieved with 11.4 EPNdB from cycle benefit, a 6.0 EPNdB reduction from the engine and airframe noise reduction technologies, and a 4 EPNdB reduction from flight operation. Figure 5.5.7 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. The cumulative reduction met the minimum success goal of 21 EPNdB.

**Table 5.5.1. GEAE 1992 Technology Engine Cycle Data for the Small Twin**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 5500 | 17500 | 12500 |
| Fan Diameter, in | 60 | 60 | 60 |
| Fan Blade Number | 38 | 38 | 38 |
| OGV Number | 80 | 80 | 80 |
| BPR | 5.6 | 4.9 | 5.1 |
| BPF, Hz | 2050 | 3066 | 2766 |
| Core Jet Velocity, fps | 847 | 1268 | 1144 |
| Mixed Jet Velocity, fps | 673 | 1118 | 968 |

**Table 5.5.2. GEAE HBPR Engine Cycle Data for the Small Twin**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 5500 | 17500 | 12500 |
| Fan Diameter, in | 60 | 60 | 60 |
| Fan Blade Number | 22 | 22 | 22 |
| OGV Number | 54 | 54 | 54 |
| BPR | 10.5 | 8.3 | 8.9 |
| BPF, Hz | 1082 | 1681 | 1491 |
| Core Jet Velocity, fps | 785 | 1220 | 1082 |
| Mixed Jet Velocity, fps | 614 | 1016 | 879 |

**Table 5.5.3 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Advanced Liners**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 2.3 | N/A | 0.6 | 0.3 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 4.1 | N/A | 0.4 | 0.4 |

**Table 5.5.4 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from HQ Tubes**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.7 | N/A | 0.5 | 0.2 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | 0.6 | N/A | 0.1 | 0.1 |

**Table 5.5.5 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Swept Stators**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.4 | 0.3 | 0.6 | 0.3 |
| Sideline | 0.0 | 1.4 | 0.3 | 0.2 |
| Cutback | -0.4 | 2.3 | 0.7 | 0.6 |

**Table 5.5.6 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Forward Swept Fan**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 | 0.0 |
| Sideline | 2.6 | 2.6 | 0.5 | 0.4 |
| Cutback | 2.6 | 2.6 | 1.1 | 1.0 |

**Table 5.5.7 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Active Noise Control**
**(not used in the final analysis)**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.5 | N/A | 0.4 | 0.2 |
| Sideline | 0.0 | N/A | 0.0 | 0.0 |
| Cutback | -0.2 | N/A | 0.0 | 0.0 |

**Table 5.5.8 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Fan/Core Chevrons**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 |
| Sideline | 2.1 | 1.4 | 1.3 |
| Cutback | 1.3 | 0.6 | 0.5 |

**Table 5.5.9 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Porous Flaps**

| | Inboard | Outboard | Airframe | Aircraft |
|---|---|---|---|---|
| Approach | 2.5 | 2.5 | 1.6 | 0.9 |
| Sideline | 2.5 | 2.6 | 0.3 | 0.0 |
| Cutback | 2.4 | 2.8 | 0.3 | 0.0 |

**Table 5.5.10 EPNL Noise Reduction on Boeing 737-300 with HBPR Engines from Slat Cove Filler**

| | Slat | Airframe | Aircraft |
|---|---|---|---|
| Approach | 2.9 | 0.5 | 0.2 |
| Sideline | 3.0 | 2.4 | 0.0 |
| Cutback | 3.3 | 2.6 | 0.1 |

**Table 5.5.11 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Boeing 737-300 with GEAE HBPR Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners<br>HQ Tubes<br>Swept Stators | 0.6 |
| Sideline | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons | 1.9 |
| Cutback | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons | 2.0 |

**Table 5.5.12 Aircraft Noise Reduction from Combined Airframe Technologies Applied to the Boeing 737-300 with GEAE HBPR Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps<br>Slat Cove Filler | 1.0 |
| Sideline | Porous Flaps<br>Slat Cove Filler | 0.0 |
| Cutback | Porous Flaps<br>Slat Cove Filler | 0.1 |

**Table 5.5.13 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Boeing 737-300 with GEAE HBPR Engines**

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Advanced Inlet Liners<br>HQ Tubes<br>Swept Stators<br>Porous Flaps<br>Slat Cove Filler | 1.8 |
| Sideline | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons<br>Porous Flaps<br>Slat Cove Filler | 2.0 |
| Cutback | Advanced Inlet Liners<br>HQ Tubes<br>Forward Swept Fan<br>Fan/Core Chevrons<br>Porous Flaps<br>Slat Cove Filler | 2.2 |

**Table 5.5.14 Summary of NASA's Noise Reduction Evaluations for the Boeing 737-300/GEAE HBPR Aircraft System**

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 7.4 | 1.8 | 2.0 | 11.2 |
| Sideline | 3.5 | 2.0 | 0.0 | 5.5 |
| Cutback | 0.5 | 2.2 | 2.0 | 4.7 |
| Total | 11.4 | 6.0 | 4.0 | 21.4 |

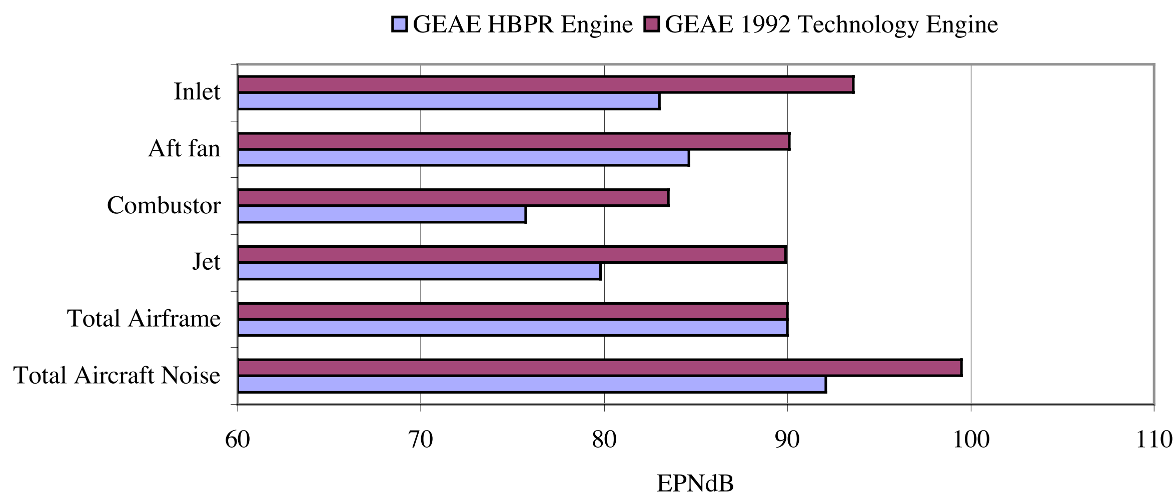



**Figure 5.5.1 Approach Noise Levels for the Boeing 737-300 with GEAE 1992 Technology Engines and HBPR Engines**

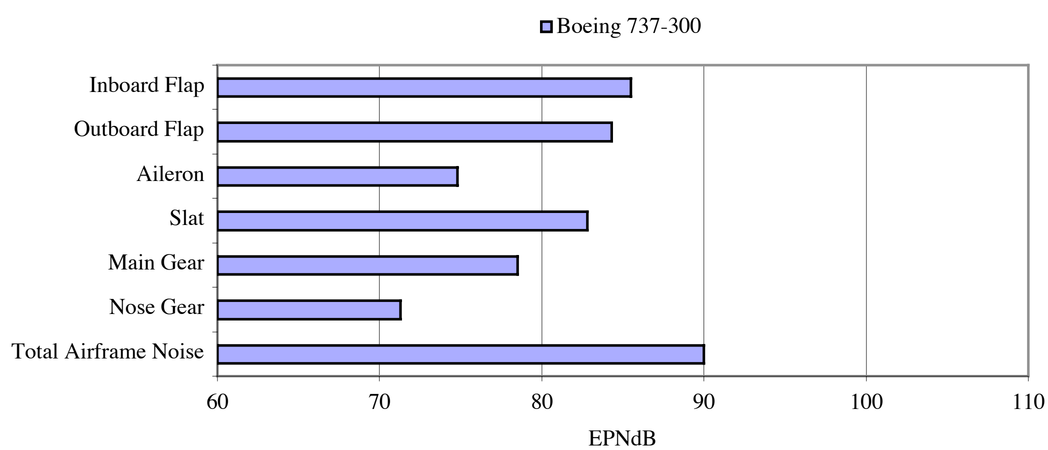



**Figure 5.5.2 Approach Airframe Noise Levels for the Boeing 737-300**

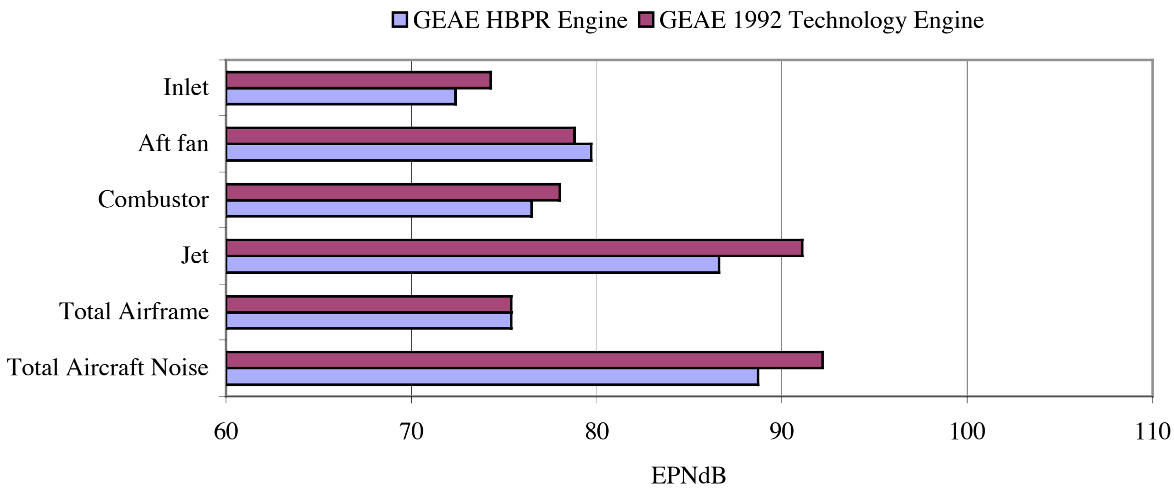



**Figure 5.5.3 Sideline Noise Levels for the Boeing 737-300 with GEAE 1992 Technology Engines and HBPR Engines**

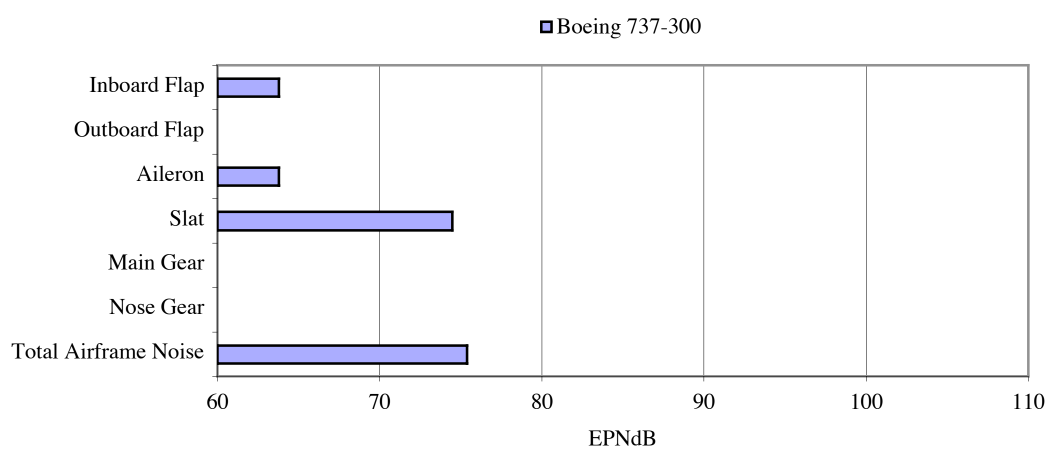



**Figure 5.5.4 Sideline Airframe Noise Levels for the Boeing 737-300**

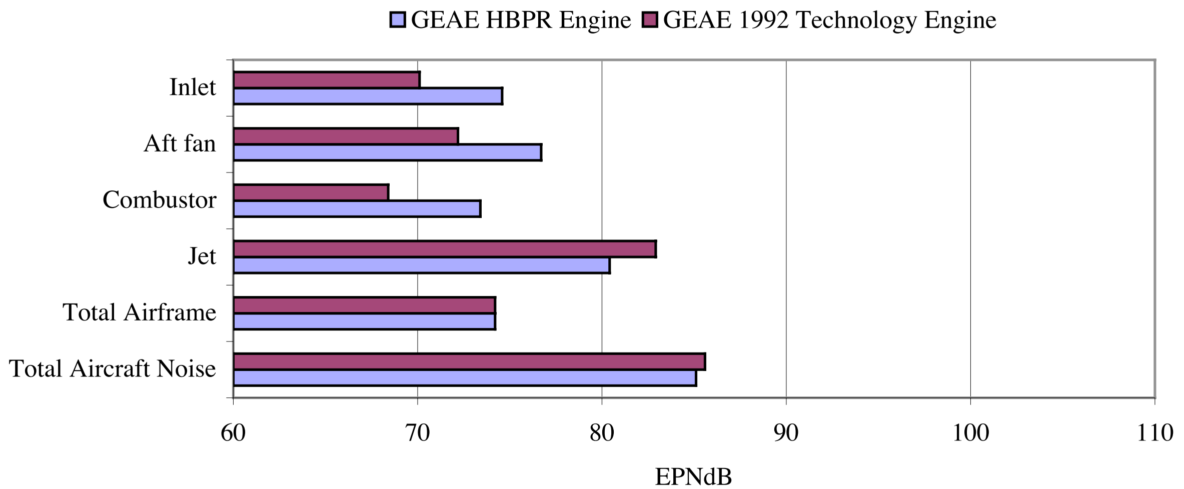



**Figure 5.5.5 Cutback Noise Levels for the Boeing 737-300 with GEAE 1992 Technology Engines and HBPR Engines**

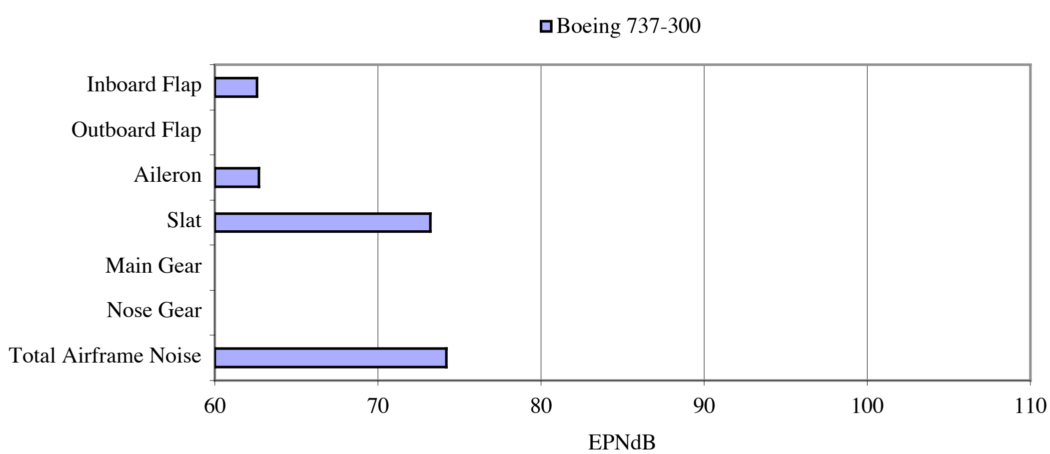



**Figure 5.5.6 Cutback Airframe Noise Levels for the Boeing 737-300**

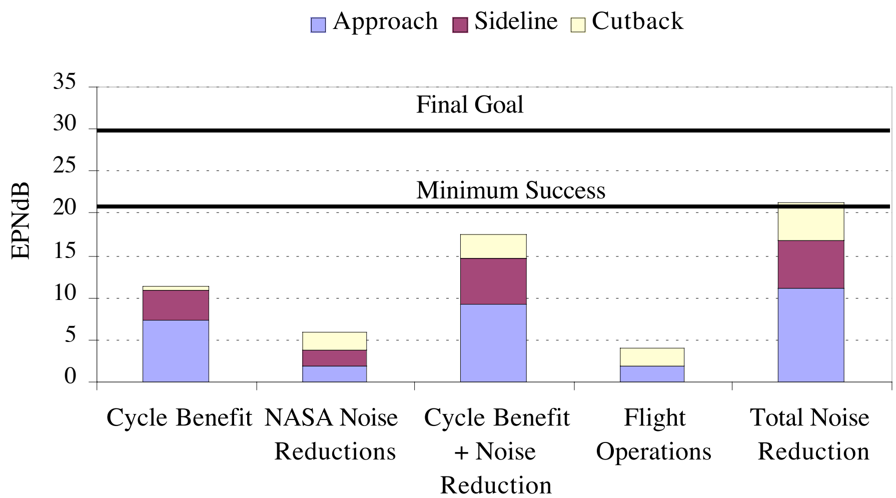



**Figure 5.5.7 Cumulative Noise Reduction for the Boeing 737-300 with GEAE HBPR Engines**

## 5.6 Business Jet Evaluation with Honeywell Engines

### 5.6.1 Reference Engine Description

The 1992 technology engine selected by Honeywell Engines and Systems (Honeywell) for the Business Jet system noise studies is based on the architecture and cycle of the TFE731-5 engine, which powers the Hawker 800 aircraft. The reference engine cycle was adjusted slightly to match the 1992 fleet average Business Jets EPNL noise levels defined in Reference 1. The Honeywell 1992 technology reference engine has a sea level static takeoff thrust of 4,300 pounds and a bypass ratio of approximately 3.5. Table 5.6.1 lists the cycle data for the approach, sideline, and cutback operating conditions.

### 5.6.2 Advanced Engine Description

Honeywell provided NASA with two high bypass ratio engine cycles, one with a bypass ratio of 5.4 and the other with a bypass ratio of 7.3. Bypass ratios are quoted at takeoff power (i.e., sideline operating condition). NASA selected the 7.3 bypass ratio engine for its noise reduction evaluation. The advanced engine, identified in this report as the Honeywell HBPR engine, has an equivalent static sea level thrust as the reference engine. The HBPR fan was designed with the same number of fan blades and exit guide vanes as the reference engine. However, the diameter of the HBPR fan was increased 27%, thus increasing the bypass ratio. Increased bypass ratio reduces the mixed jet velocity by approximately 25% at each certification point. Table 5.6.2 lists cycle data for the approach, sideline, and cutback operating conditions.

### 5.6.3 Engine Source Noise Levels

Honeywell provided NASA with received noise spectra at the approach, sideline, and cutback operating conditions. The engine noise sources include fan inlet, aft fan, combustor, turbine, and jet. The jet noise component represents both the core and bypass nozzles.

NASA's evaluation of the component engine noise levels, airframe noise level, and aircraft noise level are plotted in Figures 5.6.1, 5.6.3, and 5.6.5 at the approach, sideline, and cutback operating conditions, respectively. The HBPR cycle provides significant jet and fan noise reduction by reducing the fan tip speeds and lowering the core and primary jet velocities. The cycle benefit provided a cumulative 15.4 EPNdB toward the minimum success goal of 21 EPNdB. This is shown in Figure 5.6.7 that illustrates the cumulative noise reduction for the Business Jet.

### 5.6.4 Airframe Source Noise Levels

The approach airframe subcomponent noise levels were predicted using the Boeing airframe prediction model (Reference 3). The Boeing airframe model, however, was not calibrated for takeoff conditions. Therefore, the sideline and cutback airframe component levels were predicted using the ANOPP Fink model (Reference 8). The details of the input data used are described in Section 3 of this report. The predicted subcomponent airframe noise and total airframe noise levels for each certification point are plotted in Figures 5.6.2, 5.6.4, and 5.6.6.

### 5.6.5 Fan Noise Reduction

The Honeywell HBPR engine was evaluated with the following fan noise reduction technologies:

1. Scarf inlet with a single degree of freedom inlet liner
2. Herschel-Quincke (HQ) tubes
3. GE High-Speed Fan with swept and leaned stators
4. Aft duct treatment

NASA utilized the noise reduction data supplied by Honeywell from the Engine Validation of Noise Reduction Concepts (EVNRC) tests (Reference 9) and other AST participants. The results of NASA's evaluations are shown in Tables 5.6.3 through 5.6.6. These tables show the impact of the individual technologies on the noise sources, the engine, and the aircraft. The predictions made at each certification point assumed that the inlet (and its radiated noise) is shielded by the wing.

The inlet component noise levels are appreciably reduced by the scarf inlet with inlet treatment, as indicated in Table 5.6.3. However, this technology did not reduce the aircraft noise level because of the effect of wing shielding. The inlet noise of the Honeywell HBPR cycle is much lower than the other engine and airframe sources as shown in Figures 5.6.1, 5.6.3, and 5.6.5. Consequently, the scarf inlet with inlet treatment does not have a measurable effect on reducing the Business Jet aircraft noise because of aircraft configuration effects.

NASA's evaluation of the Herschel-Quincke (HQ) Tubes on the Honeywell HBPR cycle is listed in Table 5.6.4. NASA used the HQ tube suppression results from a single array of 20 tubes obtained by Honeywell during the EVNRC program. The HQ tubes are installed in the inlet but not in the aft duct. As in the case of the scarf inlet, the HQ tubes did not reduce the aircraft system noise. Because of the relatively low levels of the inlet noise component, NASA did not pursue additional evaluations with a double tube array configuration.

The suppression from the GE High-Speed Fan with wide-chord rotor and swept and leaned stators was scaled appropriately and applied to the Honeywell HBPR cycle. The High-Speed Fan utilizes a 24-blade rotor with eighty (80) 35-degree swept and leaned stator vanes. This technology provided significant inlet and aft fan noise suppression as well as aircraft noise suppression at the approach and cutback as indicted in Table 5.6.5. The GE High-Speed Fan was used by NASA as a technology evaluated on the final Business Jet configuration.

The result of NASA's evaluations of a single degree-of-freedom linear liner applied to the aft fan component of the HBPR cycle is listed in Table 5.6.6. Significant noise reduction was obtained during approach and cutback. The aft fan duct suppression is included NASA's final business jet configuration.

### 5.6.6 Jet Noise Reduction

The Honeywell HBPR engine was evaluated with the following jet noise reduction technologies:

1. Mixer nozzle
2. Separate flow nozzle with chevrons
3. Variable area nozzle

The results of NASA's evaluations of these technologies are shown in Tables 5.6.7 through 5.6.9.

Honeywell measured the mixer nozzle suppression, during the EVNRC program. The mixer nozzle reduces the effective jet velocity by increasing the mixing of the core and bypass flows. Although modest suppression is obtained at sideline and cutback, as indicated in Table 5.6.7, this technology is not used in NASA's final business jet configuration because the separate flow nozzle with chevrons provides better jet noise suppression.

Honeywell tested a separate flow nozzle with chevrons on the TFE731-60 engine during the EVNRC program. Chevrons were applied to the core and bypass nozzles. The results of NASA's evaluation of this technology on the HBPR cycle are listed in Table 5.6.8. Note that jet noise was not further suppressed at approach because of the low jet velocity at this operating condition. At the higher jet velocity conditions for the sideline and cutback, the chevrons provided better aircraft noise reductions. NASA used the separate flow nozzle with fan/core chevrons as a technology evaluated on the final Business Jet configuration.

The Variable-Area Exhaust Nozzle reduces jet noise and aft fan noise by altering the bypass ratio. The results of NASA's evaluations of this technology on the HBPR cycle are listed in Table 5.6.9. This technology also increased the aft fan noise and aircraft noise during approach and cutback. NASA did not use this technology as part of the best technology.

### 5.6.7 Airframe Noise Reduction

The Business Jet has fewer airframe control surfaces than the larger commercial transports and therefore has fewer airframe noise sources. This was discussed earlier in Section 3 of this report and, consequently, airframe noise is only significant during approach. The airframe configuration adopted for this study does not have ailerons or inboard flaps. The Business Jet airframe also has a much simpler landing gear configuration than the large commercial transports. Hence, NASA selected only one airframe noise reduction technology for evaluation on the Business Jet. This is the porous flap edge technology.

The result of NASA's evaluations is shown in Table 5.6.10. This technology contributed noticeably to the approach noise for the component, airframe, and aircraft noise reduction.

### 5.6.8 Combined Engine and Airframe Noise Reduction Evaluation

Tables 5.6.11, 5.6.12, and 5.6.13 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Business Jet powered by Honeywell HBPR engines. NASA configured the HBPR engines with the GE High-Speed fan, aft fan duct treatment, and the separate flow nozzle with fan/core chevrons. The airframe noise reduction technology included porous flaps. These technologies were employed at the approach, sideline and cutback operating conditions.

The approach noise of the Business Jet configured with Honeywell HBPR engines is dominated by aft fan noise and outboard flap noise as indicated in Figures 5.6.1 and 5.6.2. The combined engine noise reduction technologies reduced the aircraft EPNL by 1.3 EPNdB as shown in Table 5.6.11. Most of the engine suppression can be attributed to the GE High-Speed Fan. The porous flaps reduced the aircraft EPNL by 0.4 EPNdB as shown in Table 5.6.12. Combining the engine and airframe technologies reduced the aircraft EPNL at approach by 1.9 EPNdB as indicated in Table 5.6.13.

The sideline noise is dominated by jet noise followed closely by combustor noise and aft fan noise as indicated in Figure 5.6.3. The combined engine technologies reduced the aircraft noise by 1.1 EPNdB as indicated in Table 5.6.11. Since airframe noise is not significant for the Business Jet during takeoff, the combined airframe technologies did not provide any noise reduction at the sideline operating condition as shown in Table 5.6.12. Accordingly, all of the 1.1 EPNdB aircraft noise reduction indicated in Table 5.6.13 was obtained from the engine noise reductions technologies.

The cutback noise is dominated by aft fan noise, combustor noise, and jet noise as indicated in Figures 5.6.5. . The combined engine technologies reduced the aircraft noise by 1.2 EPNdB as indicated in Table 5.6.11. As in the sideline analysis, airframe noise is not very significant for the Business Jet during takeoff. Consequently, the combined airframe technologies provide only a 0.1 EPNdB noise reduction. Combining the engine and airframe technologies reduced the aircraft EPNL at approach by 1.3 EPNdB as indicated in Table 5.6.13.

Table 5.6.14 summarizes the results of the NASA evaluations of the AST technologies applied to the Business Jet powered by Honeywell HBPR engines. A cumulative reduction of 23.7 EPNdB was achieved with 15.4 EPNdB from cycle benefit, a 4.3 EPNdB reduction from the engine and airframe noise reduction technologies, and a 4 EPNdB reduction from flight operation. Figure 5.6.7 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. The cumulative noise reduction met the minimum success goal of 21 EPNdB.

**Table 5.6.1. Honeywell 1992 Technology Engine Cycle Data for the Business Jet**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 1190 | 3558 | 2166 |
| Fan Diameter, in | 29 | 29 | 29 |
| Fan Blade Number | 30 | 30 | 30 |
| OGV Number | 61 | 61 | 61 |
| BPR | 5.0 | 3.6 | 4.1 |
| BPF, Hz | 3417 | 4918 | 4325 |
| Core Jet Velocity, fps | 782 | 1528 | 1164 |
| Mixed Jet Velocity, fps* | 689 | 1108 | 912 |

* Mass-averaged core and bypass expanded jet velocities

**Table 5.6.2. Honeywell HBPR Engine Cycle Data for the Business Jet**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 1190 | 3558 | 2166 |
| Fan Diameter, in | 37 | 37 | 37 |
| Fan Blade Number | 30 | 30 | 30 |
| OGV Number | 61 | 61 | 61 |
| BPR | 9.8 | 7.3 | 8.3 |
| BPF, Hz | 2165 | 3128 | 2748 |
| Core Jet Velocity, fps | 648 | 1266 | 965 |
| Mixed Jet Velocity, fps* | 533 | 829 | 693 |

**Table 5.6.3 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Scarf Inlet and Inlet Liner**

| | Inlet | Engine | Aircraft |
|---|---|---|---|
| Approach | 2.9 | 0.1 | 0.0 |
| Sideline | 4.8 | 0.0 | 0.0 |
| Cutback | 3.5 | 0.0 | 0.0 |

**Table 5.6.4 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Herschel-Quincke Tubes**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.4 | 0.0 | 0.0 | 0.0 |
| Sideline | -2.2 | 0.0 | 0.0 | 0.0 |
| Cutback | 2.8 | 0.0 | 0.0 | 0.0 |

**Table 5.6.5 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from High Speed Fan**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 4.8 | 4.7 | 1.9 | 1.0 |
| Sideline | 0.8 | 0.7 | 0.2 | 0.2 |
| Cutback | 6.2 | 4.5 | 0.8 | 0.7 |

**Table 5.6.6 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Aft Fan Duct Treatment**

| | Aft fan | Engine | Aircraft |
|---|---|---|---|
| Approach | 2.4 | 1.0 | 0.6 |
| Sideline | 0.7 | 0.2 | 0.2 |
| Cutback | 2.9 | 0.5 | 0.4 |

**Table 5.6.7 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Mixer Nozzle**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.2 | 0.1 | 0.0 |
| Sideline | 0.7 | 0.4 | 0.4 |
| Cutback | 0.6 | 0.4 | 0.4 |

**Table 5.6.8 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Separate Flow Nozzle with Chevrons**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | 0.0 | 0.0 | 0.0 |
| Sideline | 1.5 | 0.8 | 0.7 |
| Cutback | 0.9 | 0.4 | 0.3 |

**Table 5.6.9 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Variable Area Nozzle**

| | Jet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 0.1 | -1.7 | -0.7 | -0.4 |
| Sideline | 0.1 | 1.1 | 0.3 | 0.3 |
| Cutback | 0.3 | -0.8 | -0.5 | -0.5 |

**Table 5.6.10 EPNL Noise Reduction on Business Jet with Honeywell HBPR Engines from Porous Flaps**

| | Outboard | Airframe | Aircraft |
|---|---|---|---|
| Approach | 3.0 | 1.5 | 0.4 |
| Sideline | 1.8 | 1.0 | 0.0 |
| Cutback | 1.8 | 1.0 | 0.2 |

**Table 5.6.11 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Business Jet with Honeywell HBPR Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons | 1.3 |
| Sideline | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons | 1.1 |
| Cutback | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons | 1.2 |

**Table 5.6.12 Aircraft Noise Reduction from Combined Airframe Technologies Applied to the Business Jet with Honeywell HBPR Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps | 0.4 |
| Sideline | Porous Flaps | 0.0 |
| Cutback | Porous Flaps | 0.1 |

**Table 5.6.13 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Business Jet with Honeywell HBPR Engines**

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons<br>Porous Flaps | 1.9 |
| Sideline | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons<br>Porous Flaps | 1.1 |
| Cutback | High Speed Fan<br>Aft Fan Duct Treatment<br>Separate Flow Nozzle with Fan/Core Chevrons<br>Porous Flaps | 1.3 |

**Table 5.6.14 Summary of NASA's Noise Reduction Evaluations for the Business Jet with Honeywell HBPR Engines**

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 3.1 | 1.9 | 2.0 | 7.0 |
| Sideline | 7.4 | 1.1 | 0.0 | 8.5 |
| Cutback | 4.9 | 1.3 | 2.0 | 8.2 |
| Total | 15.4 | 4.3 | 4.0 | 23.7 |

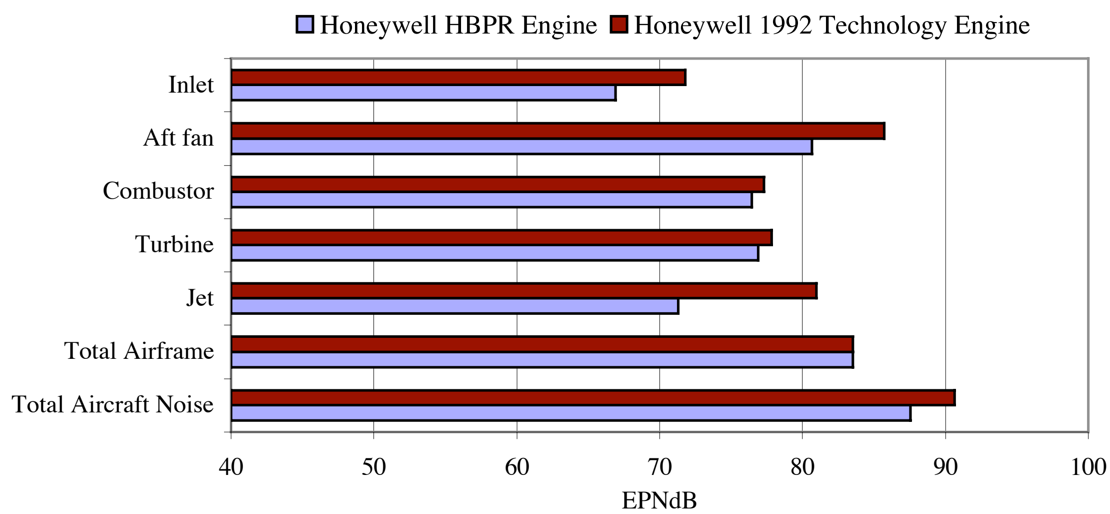



**Figure 5.6.1 Approach Noise Levels for the Business Jet with Honeywell 1992 Technology Engines and HBPR Engines**

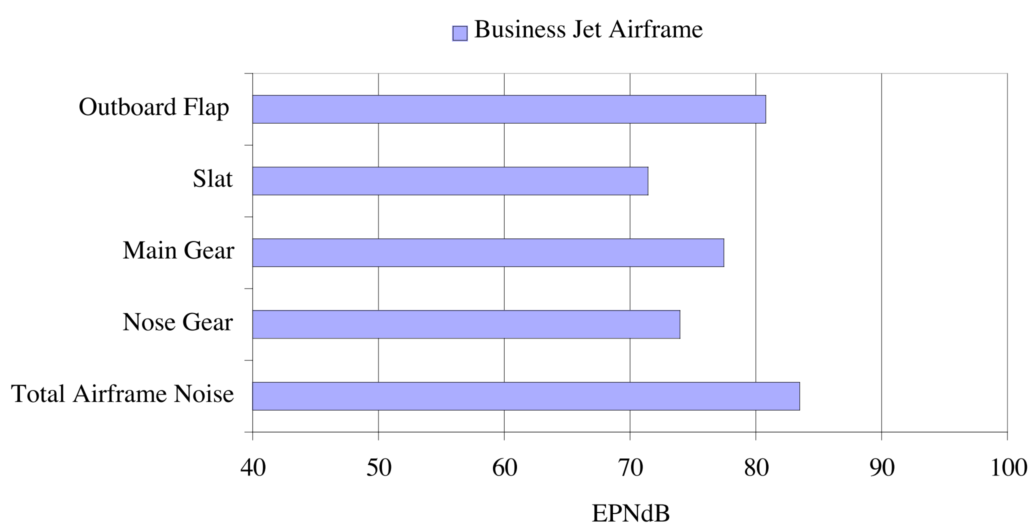



**Figure 5.6.2 Approach Airframe Noise Levels for the Business Jet**

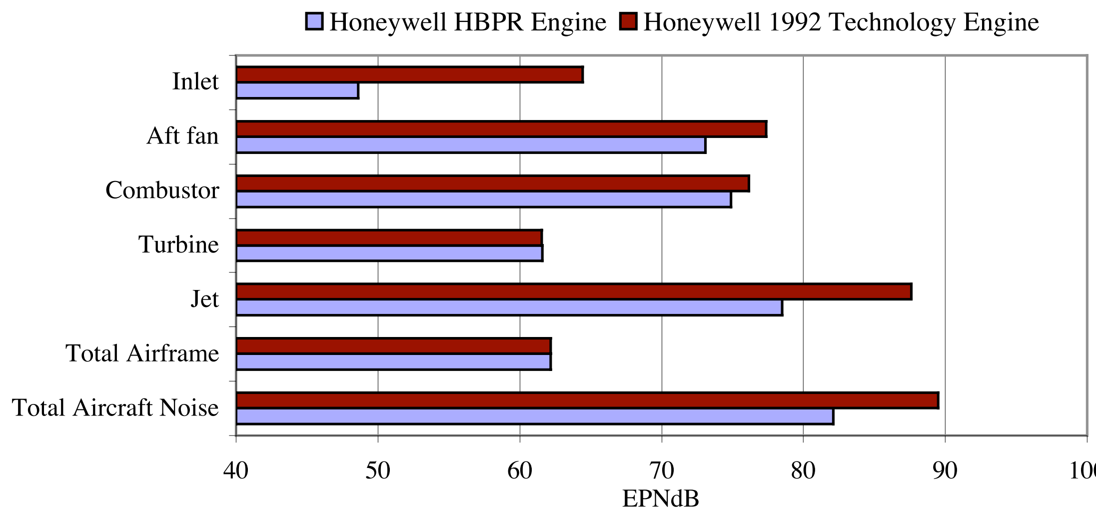



**Figure 5.6.3 Sideline Noise Levels for the Business Jet with Honeywell 1992 Technology Engines and HBPR Engines**

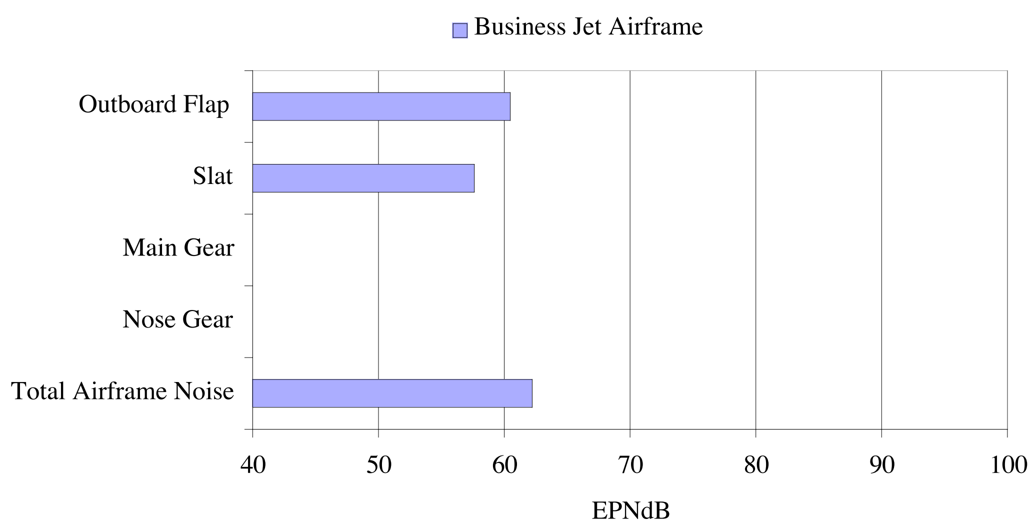



**Figure 5.6.4 Sideline Airframe Noise Levels for the Business Jet**

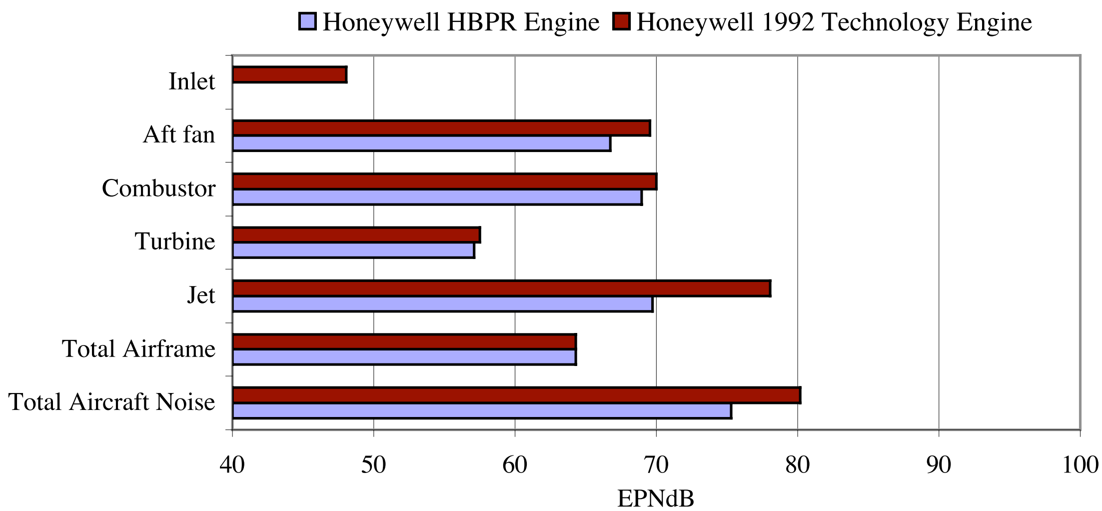



**Figure 5.6.5 Cutback Noise Levels for the Business Jet with Honeywell 1992 Technology Engines and HBPR Engines**

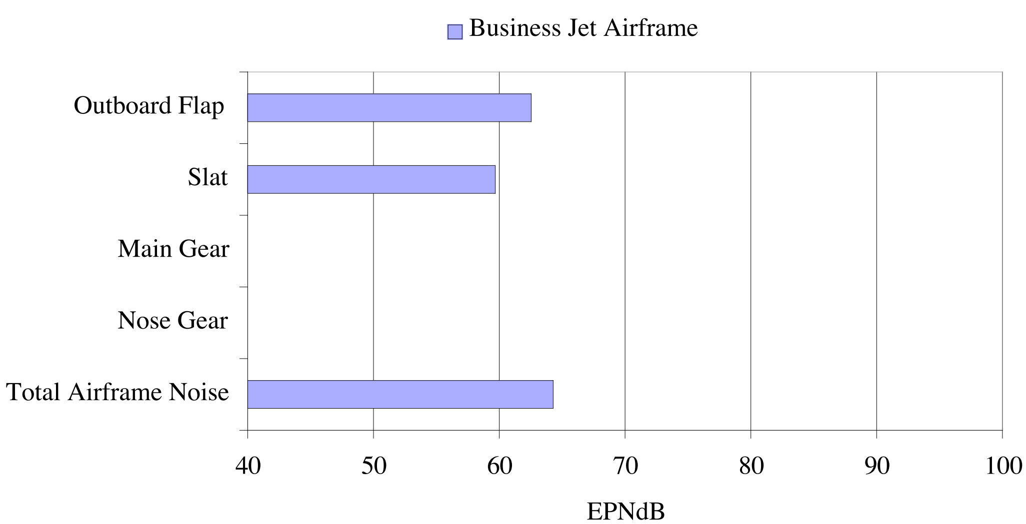



**Figure 5.6.6 Cutback Airframe Noise Levels for the Business Jet**

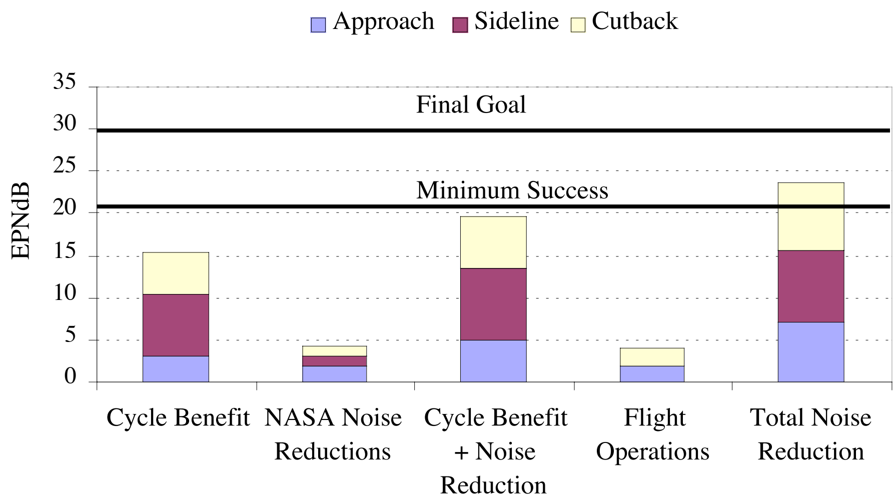



**Figure 5.6.7 Cumulative Noise Reduction for the Business Jet with Honeywell HBPR Engines**

### 5.7 Business Jet Evaluation with Rolls Royce Engines

### 5.7.1 Reference Engine Description

The reference engine selected by Rolls Royce was derived from the results of previous internal studies, scaled to a flow size which could meet the aircraft cruise thrust requirements at the fan design corrected speed. The resulting configuration would produce 5450 pounds of static thrust at sea level. The wide chord fan has a diameter of 30.3 inches and a design corrected tip speed of 1510 feet per second. The core and bypass jet flows are internally mixed by an annular mixer and then exhausted through a single nozzle. The outer bypass duct is a single degree of freedom perforate acoustic liner. The fan duct inner wall is acoustically hard. Table 5.7.1 lists cycle data for the approach, sideline, and cutback operating conditions.

### 5.7.2 Advanced Engine Description

Rolls Royce designed three reduced tip speed fans to be integrated with the baseline cycle. For each of the fan designs, the design point mass flow, pressure rise, flow split, and tip diameter were held constant. The design tip speeds were 1450 ft/sec, 1350 ft/sec, and 1250 ft/sec. Rolls Royce provided NASA with acoustic data for the 1250 ft/sec fan. This engine is identified in this report and used as the 1250 Fan.

### 5.7.3 Engine Source Noise Levels

Rolls Royce provided NASA with received source one-third-octave band noise spectra at the approach, sideline, and cutback operating conditions. The engine noise sources are the fan inlet, fan exhaust, combustor, turbine, and jet. The jet noise component incorporates both the core and bypass jet flows.

The component engine noise levels, airframe noise levels, and aircraft noise levels are plotted in Figures 5.7.1, 5.7.3, and 5.7.4 at approach, sideline, and cutback, respectively. The 1250 Fan provides significant fan noise reductions at approach and cutback. At the sideline operating condition, the aft fan noise increases slightly while the inlet noise decreases by a similar amount. The cycle benefit of the 1250 Fan provides a 1.7 EPNdB (as shown in Figure 5.7.5) cumulative noise reduction toward the final goal of 30 EPNdB.

### 5.7.4 Airframe Source Noise Levels

The airframe component noise levels for the Rolls Royce business jet were predicted by NASA using the Boeing model describe in Section 3 of this report. To make the predictions, the aircraft approach performance provided by Rolls Royce was used in conjunction with the airframe geometry established for the Honeywell business jet. The approach speed and angle of attack for the Rolls Royce and Honeywell business jets were slightly different (as noted in Section 3, Table 3.2 of this report) and therefore the component airframe noise levels are slightly different.

Airframe noise was not included in NASA's evaluation of the Rolls Royce business jet at sideline or cutback. The received airframe noise levels used in the Honeywell evaluations could not be used because the takeoff speed, angle of attack, etc. were not consistent with the Rolls Royce takeoff conditions. Ignoring airframe noise during takeoff does not significantly degrade the evaluation since airframe noise is relatively unimportant during takeoff for the business jet. Wing shielding effects are also ignored in NASA's evaluation.

### 5.7.5 Engine Noise Reduction

The Rolls Royce fan and jet noise reduction concepts were used in the NASA evaluations of the Rolls Royce business jet aircraft system. The noise reduction technologies include various combinations of swept fan outlet guide vanes (OGV), forced mixing of the core and bypass flow streams with a lobe mixer, and liner improvement.

### 5.7.6 Fan Noise Reduction

Rolls Royce introduced sweep into the fan outlet guide vanes for fan noise reduction, in addition to reducing the fan tip speed mentioned earlier. The results of NASA's analysis of the 1250 Fan with swept OGV are provided in Tables 5.7.2. Inlet approach noise, aft fan approach noise, and aft fan cutback noise were each reduced by roughly 2 EPNdB. The most significant noise reduction occurred at sideline where the aft fan noise was reduced by 5.6 EPNdB.

### 5.7.7 Jet Noise Reduction

Rolls Royce tested several mixer nozzles. Details concerning the mixer designs can be found in Reference 10. NASA evaluated the Rolls Royce optimum mixer, as this was the only configuration for which NASA received data. The optimum mixer was so named by Rolls

Royce because it achieved the best jet noise suppression. The optimum mixer had 20 lobes with a mixing length 75% of the baseline mixer. The result of the NASA evaluations of optimum mixer is provided in Table 5.7.3. The jet noise level and the total engine noise level were reduced by approximately 1 EPNdB at both the sideline and cutback operating conditions. At approach, the jet noise increased by 1.2 EPNdB. Since jet noise is not a significant noise source at approach, the aircraft noise level did not increase.

### 5.7.8 Combined Fan and Jet Noise Reduction

The swept OGV fan and the 20 lobe optimum mixer technologies were combined and the results of the NASA evaluations are provided in Table 5.7.4. Combining these technologies improves the noise reduction at all three operating conditions. The aircraft noise is reduced at approach by the use of the swept OGV fan and the takeoff noise is reduced by the use of the 20 lobe optimum mixer.

A second combination of technologies was evaluated which provided even better noise reduction. This combination used swept OGV fan, 20-lobe mixer with scalloped sidewalls, and a double degree of freedom liner in the inlet and aft ducts. The performance of the 20 lobe mixer with scalloped sidewalls was identical to the 20 lobe optimum mixer as shown in Tables 5.7.4 and 5.7.5. The addition of the double degree of freedom liner significantly improved the inlet and aft fan noise reduction at each operating condition. NASA selected the above combination of noise reduction technologies for the final business jet configuration with the Rolls Royce 1250 Fan engines.

### 5.7.9 Airframe Noise Reduction

The business jet has fewer airframe control surfaces than the larger commercial transports and therefore has fewer airframe noise sources. The airframe configuration adopted for this study does not have ailerons or inboard flaps. The business jet airframe also has a much simpler landing gear than the large commercial transports. Consequently, airframe noise is only significant during approach. NASA evaluated only one airframe noise reduction technology for the Business Jet. The technology selected is the porous flap. At approach, the porous flaps reduced the flap noise 3 EPNdB, the airframe noise 1.3 EPNdB, and the aircraft noise 0.3 EPNdB as shown in Table 5.7.6.

### 5.7.10 Combined Engine and Airframe Noise Reduction Evaluations

Tables 5.7.7, 5.7.8, and 5.7.9 show the reduction in aircraft noise resulting from the engine and airframe noise reduction technologies selected by NASA for the Business Jet powered by Rolls Royce 1250 Fan engines. NASA configured the 1250 Fan with the swept OGV fan, 20-lobe mixer with scalloped sidewalls, and a double degree of freedom liner in the inlet and aft ducts. The airframe noise reduction technology included porous flaps. The combined engine and airframe technologies produced a cumulative 3.4 EPNdB reduction in aircraft noise as shown in Table 5.7.10.

The approach noise of the Rolls Royce business jet with the 1250 Fan is dominated by turbine noise and outboard flap noise as shown in Figures 5.7.1 and 5.7.2. The magnitudes of the turbine and outboard flap noise levels establish a noise floor and therefore lessen the impact of the fan and jet noise reduction technologies. The swept OGV fan with the Double Degree of Freedom (DDOF) liner (inlet and aft duct) and the 20-lobe mixer with scalloped sidewalls reduced the aircraft noise at approach by 0.4 EPNdB as indicated in Table 5.7.7. Adding the porous flaps reduced the aircraft noise an additional 0.4 EPNdB (to 0.8 EPNdB) for approach as shown in Table 5.7.9.

Jet noise dominated the sideline and cutback noise levels of the Rolls Royce business jet configured with the 1250 Fan by a wide margin. Refer to Figures 5.7.3 and 5.7.4 for a comparison of the component noise levels at the sideline and cutback operating conditions. The jet noise component was more than 8 EPNdB higher than the next highest source (i.e. inlet noise) at sideline and 7 EPNdB higher than the next highest source (i.e. combustor noise) at cutback. Accordingly, the majority of the noise reduction during takeoff comes from the forced mixing of the core and bypass flow streams. The swept OGV fan with the DDOF liner (inlet and aft duct) and the 20-lobe mixer with scalloped sidewalls reduced the aircraft noise at sideline and cutback by 1.5 and 1.1 EPNdB, respectively, as indicated in Tables 5.7.7 and 5.7.9.

Table 5.7.10 summarizes the results of the NASA evaluations of the AST technologies applied to the Business Jet powered by the Rolls Royce 1250 Fan engine. A cumulative reduction of 9.1 EPNdB is achieved with 1.7 EPNdB from cycle benefit, a 3.4 EPNdB reduction from the engine and airframe noise reduction technologies, and a 4 EPNdB reduction from flight operation. Figure 5.7.5 shows the cumulative EPNL noise reduction achieved as compared to the NASA minimum success and final goal levels. This falls short of the minimum success goal of 21 EPNdB.

In Reference 10, Rolls Royce reports on the evaluation of a higher bypass ratio engine with fan and jet noise reduction technologies. NASA did not receive the acoustic data for this engine and consequently, similar results for evaluation of this higher bypass ratio engine are not included in this report.

**Table 5.7.1. Rolls Royce 1992 Technology Engine Cycle Data for the Business Jet Aircraft**

| | Approach | Sideline | Cutback |
|---|---|---|---|
| Net Thrust, lbf | 1200 | 3700 | 2400 |
| Fan Diameter, in | 30.3 | 30.3 | 30.3 |
| BPR | 5.2 | 4.7 | 4.9 |
| Mixed Jet Velocity, fps | 658 | 951 | 850 |

**Table 5.7.2 EPNL Noise Reduction on Business Jet with Rolls Royce 1250 Fan from Swept Fan Outlet Guide Vanes**

| | Inlet | Aft fan | Engine | Aircraft |
|---|---|---|---|---|
| Approach | 1.8 | 2.0 | 0.3 | 0.3 |
| Sideline | 0.1 | 5.6 | 0.2 | N/A |
| Cutback | 0.3 | 2.4 | 0.1 | N/A |

**Table 5.7.3 EPNL Noise Reduction on Business Jet with Rolls Royce 1250 Fan from 20 Lobe Optimum Mixer**

| | Jet | Engine | Aircraft |
|---|---|---|---|
| Approach | -1.2 | -0.1 | 0.0 |
| Sideline | 1.0 | 0.9 | N/A |
| Cutback | 0.9 | 0.8 | N/A |

**Table 5.7.4 EPNL Noise Reduction on Business Jet with Rolls Royce 1250 Fan from Swept Outlet Guide Vanes and 20 Lobe Optimum Mixer**

| | Inlet | Aft fan | Jet | Engine | Aircraft |
|---|---|---|---|---|---|
| Approach | 1.8 | 2.0 | -1.2 | 0.4 | 0.3 |
| Sideline | 0.1 | 5.6 | 1.0 | 1.1 | N/A |
| Cutback | 0.3 | 2.4 | 0.9 | 0.9 | N/A |

**Table 5.7.5 EPNL Noise Reduction on Business Jet with Rolls Royce 1250 Fan from Swept Outlet Guide Vanes, DDOF Inlet & Aft Duct Liners, and 20 Lobe Mixer Nozzle with Scalloped Sidewalls**

| | Inlet | Aft fan | Jet | Engine | Aircraft |
|---|---|---|---|---|---|
| Approach | 4.2 | 3.3 | -1.2 | 0.6 | 0.4 |
| Sideline | 4.1 | 6.5 | 1.0 | 1.5 | N/A |
| Cutback | 5.4 | 4.8 | 0.9 | 1.1 | N/A |

**Table 5.7.6 EPNL Noise Reduction on Business Jet with Rolls Royce 1250 Fan from Porous Flaps**

| | Outboard Flap | Airframe | Aircraft |
|---|---|---|---|
| Approach | 3.0 | 1.3 | 0.3 |
| Sideline | N/A | N/A | N/A |
| Cutback | N/A | N/A | N/A |

**Table 5.7.7 Aircraft Noise Reduction from Combined Engine Technologies Applied to the Business Jet with Rolls Royce 1250 Fan Engines**

| | Combined Engine Technologies | EPNdB |
|---|---|---|
| Approach | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner | 0.4 |
| Sideline | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner | 1.5 |
| Cutback | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner | 1.1 |

**Table 5.7.8 Aircraft Noise Reduction from Airframe Technologies Applied to the Business Jet with Rolls Royce 1250 Fan Engines**

| | Combined Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Porous Flaps | 0.3 |
| Sideline | N/A | N/A |
| Cutback | N/A | N/A |

**Table 5.7.9 Aircraft Noise Reduction from Combined Engine and Airframe Technologies Applied to the Business Jet with Rolls Royce 1250 Fan Engines**

| | Combined Engine and Airframe Technologies | EPNdB |
|---|---|---|
| Approach | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner<br>Porous Flaps | 0.8 |
| Sideline | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner | 1.5 |
| Cutback | Swept Outlet Guide Vanes<br>Optimized Jet Mixer with Scalloped Sidewalls<br>Double Degree of Freedom Liner | 1.1 |

**Table 5.7.10 Summary of NASA's Noise Reduction Evaluations of the Business Jet with Rolls Royce 1250 Fan Engines**

| | Cycle Benefit | Noise Reduction | Flight Ops | Total |
|---|---|---|---|---|
| Approach | 0.7 | 0.8 | 2.0 | 3.5 |
| Sideline | 0.1 | 1.5 | 0.0 | 1.6 |
| Cutback | 0.9 | 1.1 | 2.2 | 4.0 |
| Total | 1.7 | 3.4 | 4.0 | 9.1 |

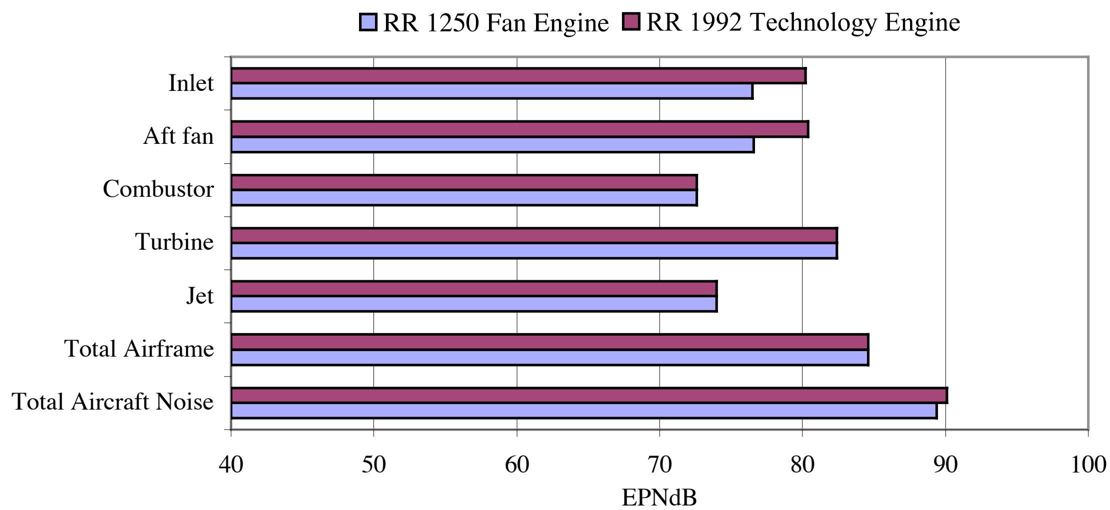



**Figure 5.7.1 Comparison of the Approach Noise Levels for the Business Jet with Rolls Royce 1992 Technology Engines and 1250 Fan Engines**

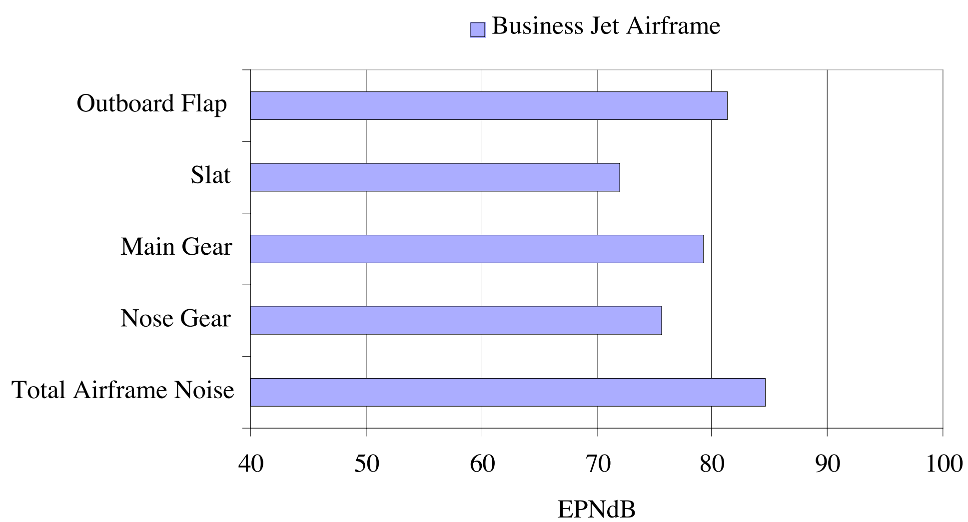



**Figure 5.7.2 Approach Airframe Noise Levels for the Rolls Royce Business Jet**

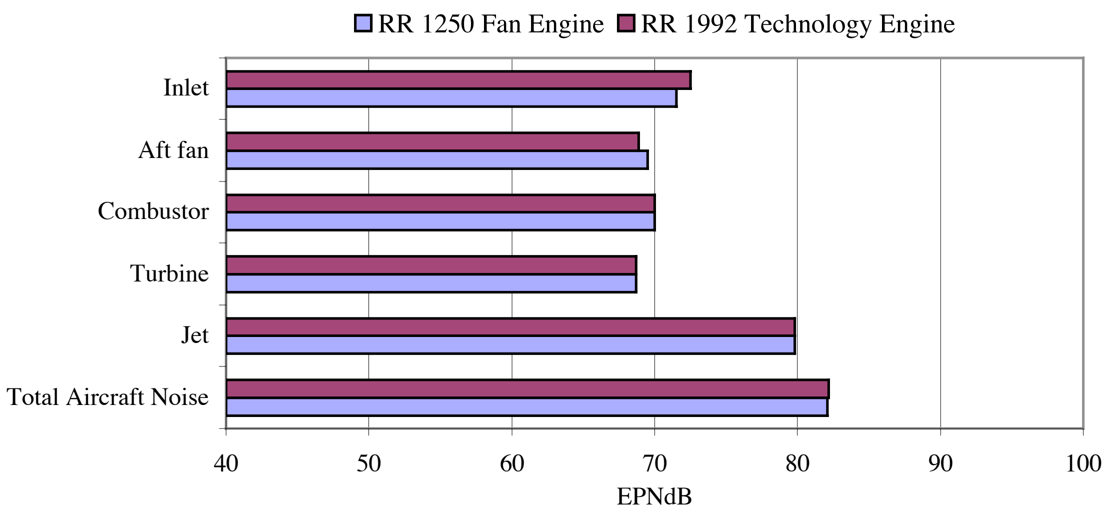



**Figure 5.7.3 Comparison of the Sideline Noise Levels for the Business Jet with Rolls Royce 1992 Technology Engines and 1250 Fan Engines**

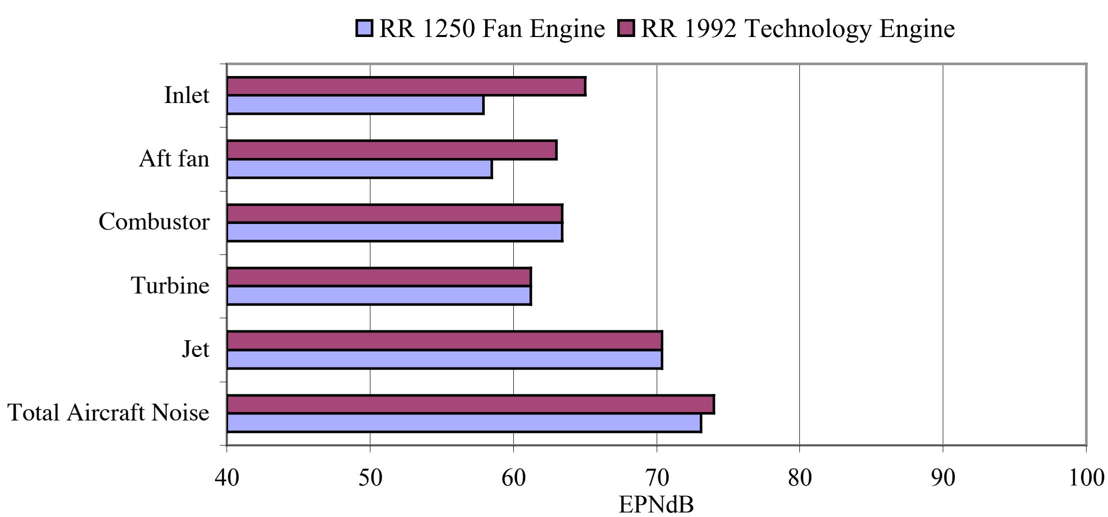



**Figure 5.7.4 Comparison of the Cutback Noise Levels for the Business Jet with Rolls Royce 1992 Technology Engines and 1250 Fan Engines**

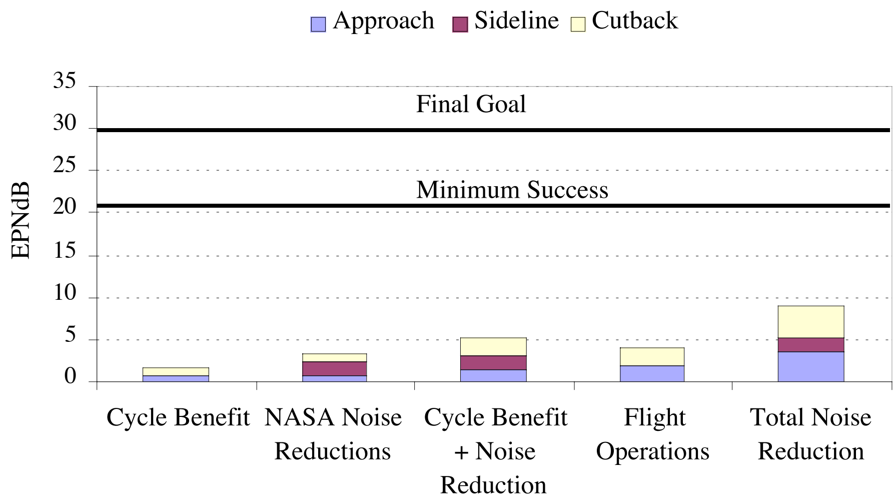



**Figure 5.7.5 Cumulative Noise Reduction for the Business Jet with Rolls Royce 1250 Fan Engine**

## 6.0 Summary of AST Noise Reduction Results

### 6.1 Introduction

In this section of the paper is presented a summary of the NASA technology evaluations and comparisons with the program goals. These evaluations and comparisons result from combining the best airframe noise reduction technologies with the best engine noise reduction technologies to predict the best total aircraft noise reduction as applied to each of the four classes of aircraft.

In Section 1 of this paper, program objectives and goals were presented. It further addressed an overview of the program research scope incorporating the participation of Government agencies, Industry, and universities. In Section 2, the methodology for establishing the program baseline aircraft classes and component noise levels was covered. The idea of using a cumulative noise goal (3 X 10 EPNdB noise reduction per certification point = 30 EPNdB cumulative) as a measure of program success was introduced. This section also contains discussions of NASA's technology readiness levels and their defined role in the evaluation procedure. This section also briefly cites the reason for inclusion of a 2 EPNdB noise reduction benefit at cutback and approach. This is the operations noise reduction benefit that results from observations from a demonstration flight test that used the NASA Aries 757 aircraft. Section 3 discusses the role of airframe noise, subcomponent definition and research, and details of the airframe component noise reduction technologies used as part of this evaluation. Section 4 similarly discusses the role of propulsion system noise, component determination research, and details of the engine noise reduction technologies used as a part of this evaluation. In Section 5, the proposed new engine cycles are combined with the best noise reduction technologies appropriate for that particular cycle. The engine noise reduction levels are then rolled up with the best airframe noise reduction levels to yield a total best aircraft noise reduction for each airframe/engine combination. As defined earlier in Section 2, the airframe/engine combinations are as follows:

Large Quad (LQ) Aircraft with P&W Engines
Large Quad (LQ) Aircraft with GEAE Engines
Medium Twin (MT) with GEAE Engines
Small Twin (ST) with GEAE Engines
Business Jet (BJ) with Honeywell Engines
Business Jet (BJ) with Rolls Royce Engines

As a reminder, the technology evaluations presented are based upon the noise reduction technology results that were supplied by NASA, Industry, and University researchers participating in the AST program. Only those noise reduction technology results that have been agreed upon by the working group as advancing to a technology readiness level of 5/6 are utilized (operations benefit being a consensus exception). Many other noise reduction technologies were studied but failed to be included for the final goal evaluation because they did not meet this criterion. These technologies will, of course, be candidates for inclusion into the noise reduction evaluations in a follow-on program. The technology concepts used are those that were listed in Table 2.1.

The following list is a synopsis of the total noise reduction technologies as determined to be the best suited for application to each airframe/engine combination as illustrated in Section 5. It is these technologies that were determined by NASA in Section 5 to meet the criteria set by program management with working group consensus. The noise reduction impact results presented are based upon these technologies for each airframe/engine combination.

**LQ with P&W ADP (56,000 lbs static thrust at sea level with BPR of 15) Engines**

This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies

Swept and leaned cut-on fan FEGV with Active Noise Control

**Nacelle noise** reduction technologies

Scarf inlet with 25% liner improvement

**Jet noise** reduction technologies

Core nozzle tabs

**Airframe noise** reduction technologies

Porous flap edge
Slat cove filler

**LQ with GEAE HBPR (46,000 lbs static thrust at sea level with BPR of 8.4) Engines**

This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies

Advanced liners (includes Amax + Scarf inlet + lip treatment)
Herschel-Quincke (HQ) tubes (inlet only)
Swept stators
Forward swept fan with swept stators

**Jet noise** reduction technologies
12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

**Airframe noise** reduction technologies
Porous flap edge
Slat cove filler

**MT with GEAE HBPR (60,000 lbs static thrust at sea level with BPR 8.3) Engines**
This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies
Advanced liners (includes Amax + Scarf inlet + lip treatment)
Herschel-Quincke (HQ) tubes (inlet only)
Swept stators
Forward swept fan with swept stators

**Jet noise** reduction technologies
12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

**Airframe noise** reduction technologies
Porous flap edge
Slat cove filler

**ST with GEAE HBPR (22,000 lbs static thrust at sea level with BPR 8.3) Engines**
This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies
Advanced liners (includes Amax + Scarf inlet + lip treatment)
Herschel-Quincke (HQ) tubes (inlet only)
Swept stators
Forward swept fan with swept stators

**Jet noise** reduction technologies
12 chevrons on the core nozzle and 24 chevrons on the bypass nozzle

**Airframe noise** reduction technologies
Porous flap edge
Slat cove filler

**BJ with Honeywell HBPR (4300 lbs static thrust at sea level with BPR 7.3) Engines**
This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies
GE High-Speed Fan with swept and leaned stators
Aft duct treatment

**Jet noise** reduction technologies
Separate flow nozzle with fan/core chevrons

**Airframe noise** reduction technologies
Porous Flap edge

**BJ with Rolls Royce HBPR (3700 lbs static thrust at sea level with BPR 5.0) Engines**
This engine/airframe combination was evaluated with the following technologies:

**Fan noise** reduction technologies
Reduced fan tip speed
Sweep in the fan outlet guide vanes

**Nacelle noise** reduction technologies
Double degree of freedom liner

**Jet noise** reduction technologies
Optimum mixer with 20 lobes and a mixing length 75% of the baseline mixer

**Airframe noise** reduction technologies
Porous flap edge

Table 6.1 summarizes noise reduction levels drawn from each of the detailed evaluation subsections in Section 5. It shows the results of applying the best noise reduction benefits as predicted for each of the engine/aircraft combinations listed above. It presents a breakdown of the noise reduction benefits as predicted for each of the certification points. It is further categorized showing the benefits achieved from engine cycle improvement, improvements in engine noise reduction hardware (as described above), and the benefit of adding noise reduction achieved from advanced operations. It also shows the total noise reduction for each certification point and total noise reduction for each of the engine cycle, hardware and flight operations noise reduction categories. Finally, the table shows the cumulative noise reduction benefit achieved by adding all the certification point noise reduction levels together as required to compare to the cumulative program goal of 30 EPNdB.

The Working Group agreed that the 2 EPNdB noise reduction benefit would be added at only the approach and cutback certification points. Hence, no operations benefit is shown for the sideline certification point.

The above data are displayed in bar chart format to make the interpretation of the noise reduction evaluation results easier. Each of the components shown here is the same as shown in each of the detailed evaluation subsections in Section 5.

Figures 6.1 through 6.4 are bar chart presentations of the noise reduction results contained in Table 6.1. Figures 6.1(a) and (b) show the noise reduction effects of the engine cycle change predicted for each class of aircraft. These results demonstrate what had been learned early in the AST program that engine cycle is a very strong driver of aircraft noise reduction levels. This was in general achieved by the design of engine cycles that result in larger diameter higher bypass ratio engines. Figure 6.1(a) shows the effect of the engine cycle changes for each of the three certification points for each aircraft/engine configuration. Of particular note are the large noise reduction levels demonstrated for the sideline and approach conditions. Figure 6.1(b) shows the cumulative noise reduction benefit (sum of the three certification points noise reduction levels). As illustrated in this figure by the large noise reduction level totals, the engine cycle changes remain an important parameter to reduce engine noise. As can be seen from these results, noise reduction from engine cycle changes can range from about 9 to 19 EPNdB. Noise reduction for this category will be seen to be huge compared to the other two categories. The Rolls Royce results are somewhat of an anomaly resulting from the selection by Rolls Royce of a quiet baseline engine. Hence, the application of the AST technology to the chosen engine shows very little effect, i.e., the baseline engine was quiet to begin with.

Figures 6.2(a) and (b) show the noise reduction levels achieved through the application of the best hardware noise reduction technologies. These hardware technologies include the use of advanced liners, advanced fan blade and stator design, Herschel-Quincke tubes and exhaust nozzle tabs and chevrons (on both core and bypass nozzles). Figure 6.2(a) shows the effect of the best of these hardware technologies for each of the certification points for each aircraft configuration. Figure 6.2(b) shows the cumulative noise reduction benefit. The trends from these figures suggest that the benefit of hardware noise reduction technologies increase with airframe/engine system size. An underlying factor is that the airframe/engine system that showed the greatest noise reduction also had the highest bypass ratio engine. One of the strategies of the AST program was to reduce jet noise by employing higher bypass ratio engines and then attacking the fan noise by a judicious choice of fan noise reduction and nacelle technologies.

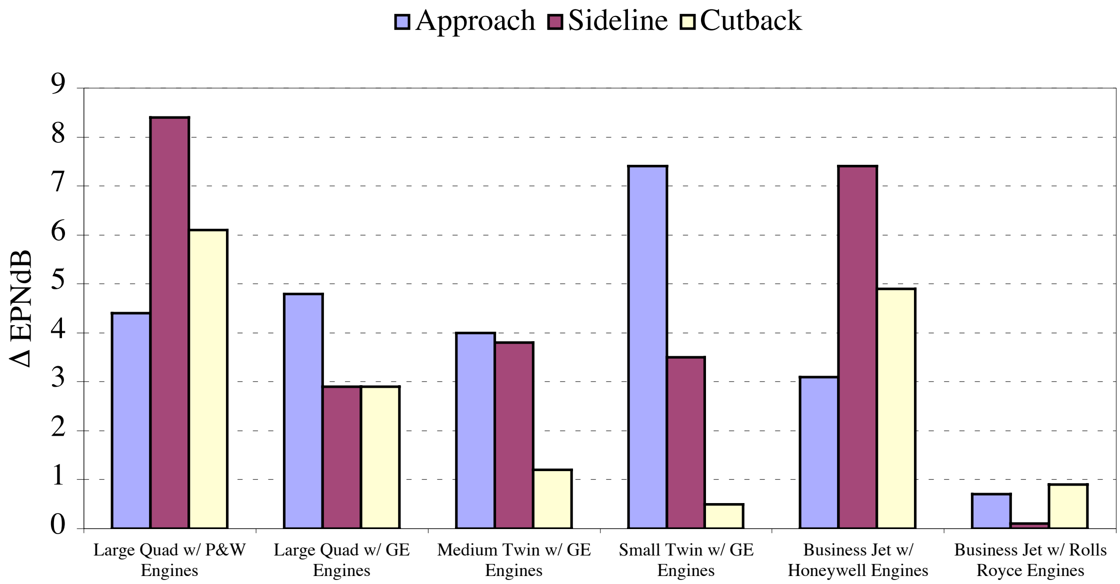
Figures 6.3(a) and (b) simply shows the effect of adding the noise reduction effects achieved from flight operations (2 EPNdB at approach and cutback points) to the hardware noise reduction technologies. Their importance is self evident in the noise reduction increases in the approach and cutback certification point totals for each aircraft configuration. If these operations noise reduction can be realized they can contribute greatly towards the total noise reduction as demonstrated in Figure 6.3(b). Also from Figure 6.3(b), it is clearly shown that the contributions from both hardware noise reduction and operations (about 7 to 13 EPNdB) lag significantly behind the noise reduction benefit resulting from engine cycle change (9 to 19 EPNdB).

Finally, Figures 6.4(a) and (b) show the cumulative totals of the noise reduction technology achieved by the AST program research for each airframe/engine combination. As illustrated by the figure, the noise reduction results achieved vary and are dependent upon the aircraft class and engine cycle applied. Figure 6.4(a) shows total noise reduction achieved by each of the aircraft configurations at each of the certification points. Figure 6.4(b) shows cumulative totals for each aircraft configuration. This latter figure also has shown the AST minimum success and program goal levels. Again the program had chosen as it metric for success to achieve a 10 EPNdB noise reduction at each certification point. Hence, the cumulative total goal becomes 30 EPNdB as indicated on the bar chart. The minimum program success goal was set at 7 EPNdB at each certification point or a cumulative noise reduction total of 21 EPNdB. As demonstrated, the large quad aircraft with the Pratt and Whitney high bypass ratio (~13) engine surpassed the program goal. Both the large quad aircraft with GEAE engines (BPR ~8) and the small twin aircraft with GEAE engines (BPR ~ 6) exceeded the minimum success goals. The medium twin aircraft class with GEAE engines (BPR ~8) fell slightly under the minimum success goal. The business jet with Honeywell engines (BPR ~6) also exceeded the minimum success program goal. The business jet with Rolls Royce engines fell short of the minimum program goal. As explained earlier in Section 5, this was a result of Rolls-Royce choice of a very quiet baseline engine at the program start.

The evaluation of the impact of noise reduction technologies upon total aircraft noise has been shown to be a very complex as well as a time-consuming task. There are few shortcuts that can be employed to quickly ascertain the impact of a developed noise reduction technology upon an airframe engine combination. As demonstrated by the plots in Figures 6.1 to 6.4 demonstrated trends are few. Noise reduction technologies do not appear to scale in a linear manner. Hence, noise reduction impact benefits must be thoroughly analyzed accounting for all noise aspect of airframe/engine combinations.

**Table 6.1 AST Noise Reduction Benefit Summary**

| Aircraft System | | Cycle Benefit | AST Noise Benefit | Flight Ops | Total AST Noise Benefit |
|---|---|---|---|---|---|
| **LQ (B 747-400) with P&W ADP Engines** | Approach | 4.4 | 3.3 | 2.0 | **9.7** |
| | Sideline | 8.4 | 2.8 | 0.0 | **11.2** |
| | Cutback | 6.1 | 2.7 | 2.0 | **10.8** |
| | Total | **18.9** | **8.8** | **4.0** | **31.7** |
| **LQ (B 747-400) with GEAE HBPR Engines** | Approach | 4.8 | 2.0 | 2.0 | **8.8** |
| | Sideline | 2.9 | 2.2 | 0.0 | **5.1** |
| | Cutback | 2.9 | 2.5 | 2.0 | **7.4** |
| | Total | **10.6** | **6.7** | **4.0** | **21.3** |
| **MT (B 767-300) with GEAE HBPR Engines** | Approach | 4.0 | 1.9 | 2.0 | **7.9** |
| | Sideline | 3.8 | 2.2 | 0.0 | **6.0** |
| | Cutback | 1.2 | 2.3 | 2.0 | **5.5** |
| | Total | **9.0** | **6.4** | **4.0** | **19.4** |
| **ST (B 737-300) with GEAE HBPR Engines** | Approach | 7.4 | 1.8 | 2.0 | **11.2** |
| | Sideline | 3.5 | 2.0 | 0.0 | **5.5** |
| | Cutback | 0.5 | 2.2 | 2.0 | **4.7** |
| | Total | **11.4** | **6.0** | **4.0** | **21.4** |
| **Business Jet with Honeywell HBPR Engines** | Approach | 3.1 | 1.9 | 2.0 | **7.0** |
| | Sideline | 7.4 | 1.1 | 0.0 | **8.5** |
| | Cutback | 4.9 | 1.3 | 2.0 | **8.2** |
| | Total | **15.4** | **4.3** | **4.0** | **23.7** |
| **Business Jet with Rolls Royce 1250 Fan Engines** | Approach | 0.7 | 0.8 | 2.0 | **3.5** |
| | Sideline | 0.1 | 1.5 | 0.0 | **1.6** |
| | Cutback | 0.9 | 1.1 | 2.2 | **4.0** |
| | Total | **1.7** | **3.4** | **4.0** | **9.1** |

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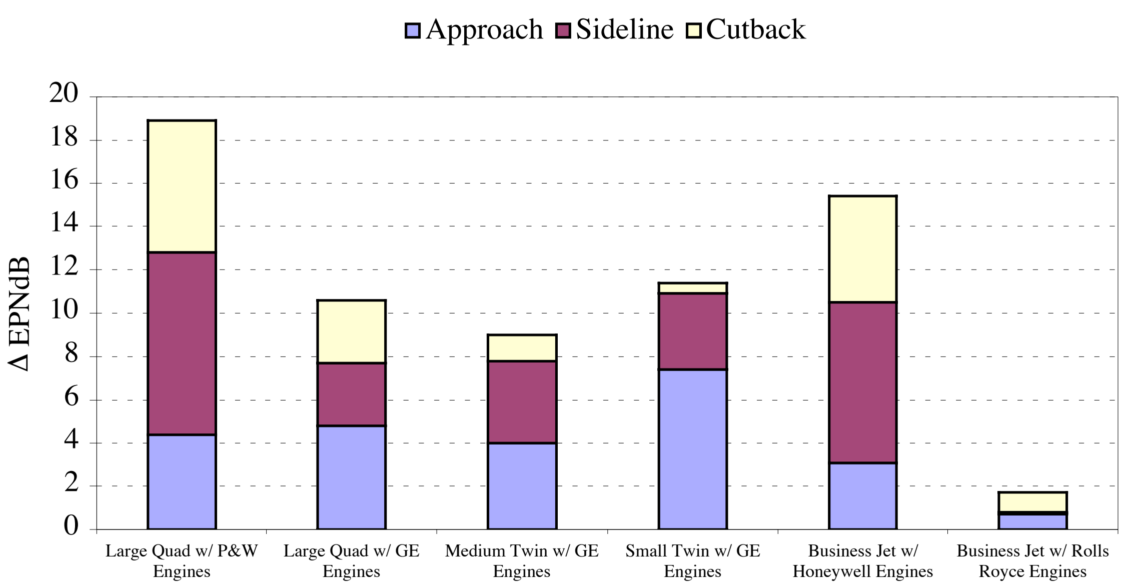


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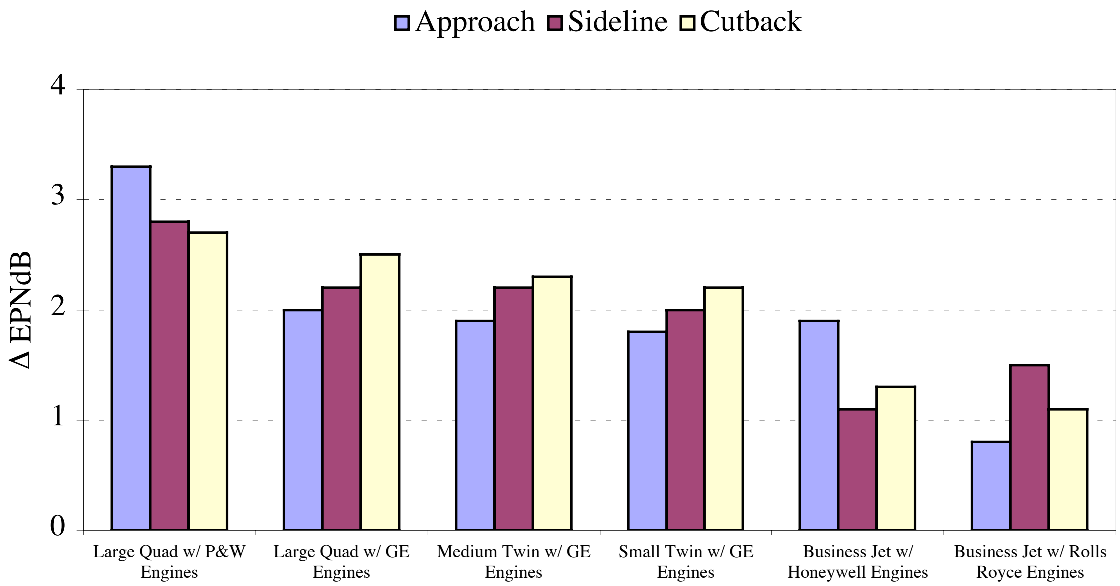
**Figure 6.1 Cycle Benefit Comparisons**

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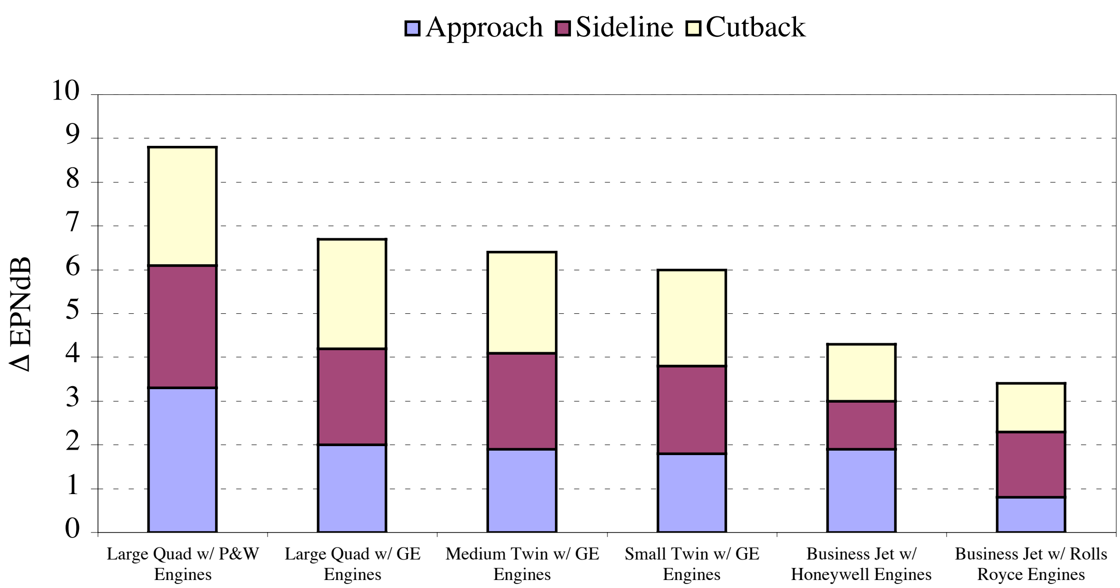


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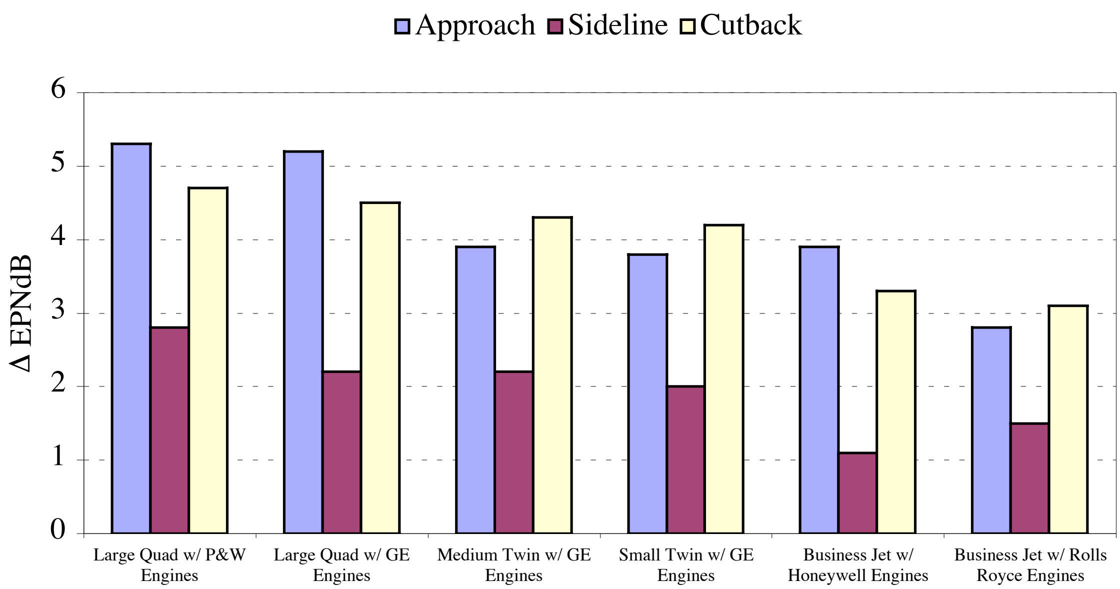
**Figure 6.2 Noise Benefit Comparisons**

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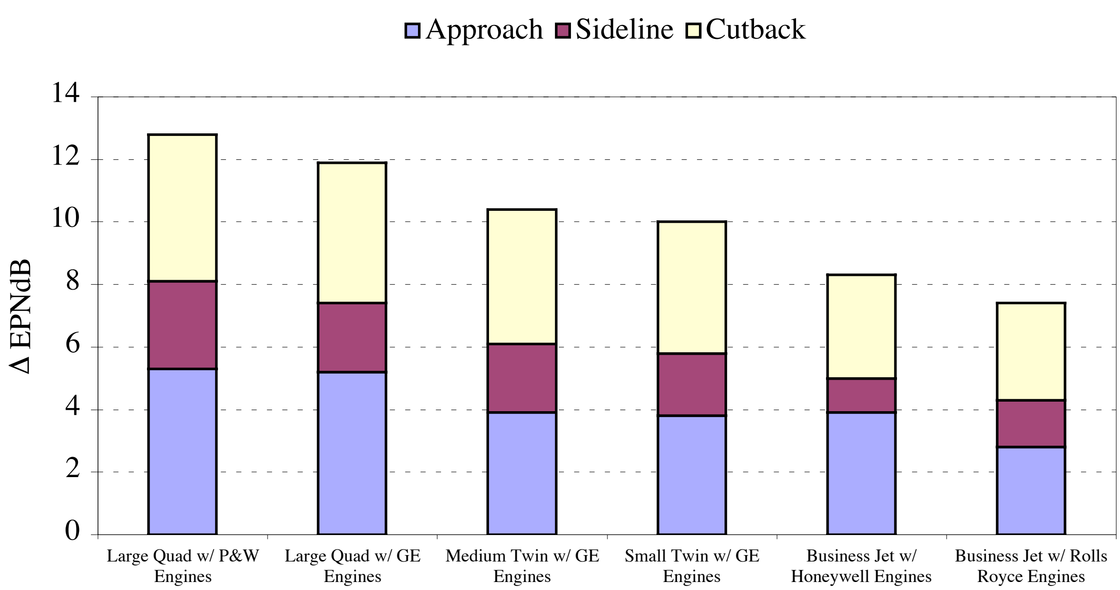


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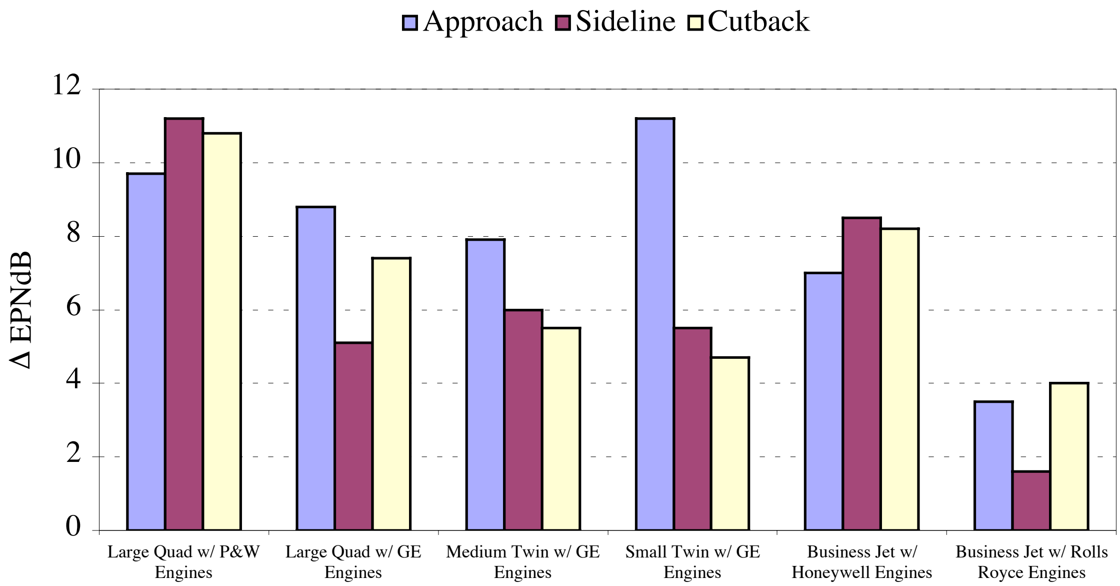
**Figure 6.3 Comparisons of Noise Benefit Plus Flight Operations**

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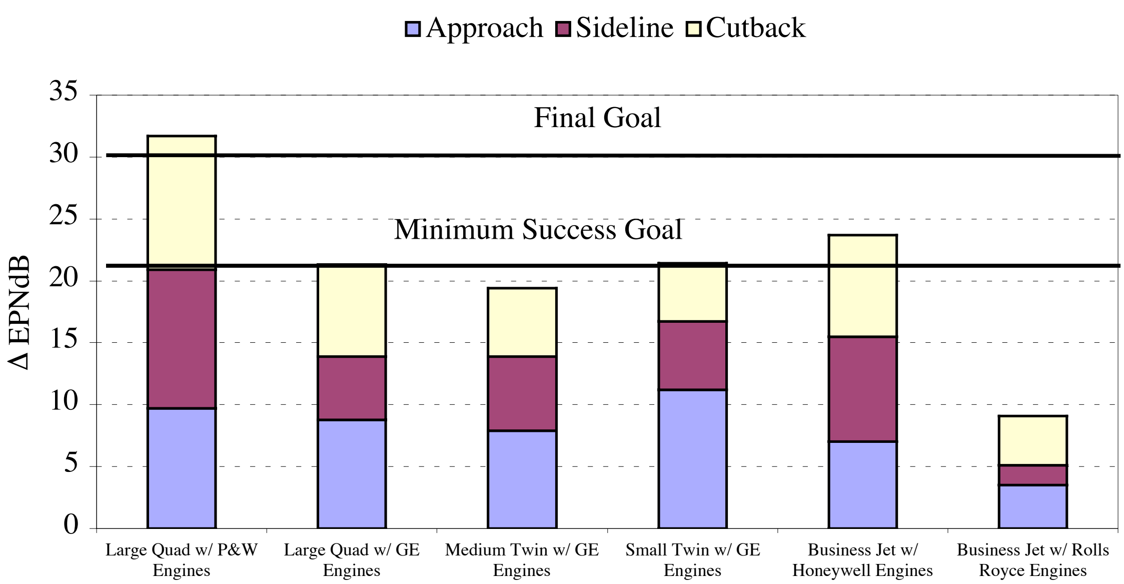


**(b)**

**Figure 6.4 Total AST Noise Reduction For Each Engine/Airframe Combination Measured Against the Program Goals**

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**14. ABSTRACT**
This report presents a detailed evaluation of the aircraft noise reduction technology concepts developed during the course of the NASA/FAA Advanced Subsonic Technology (AST) Noise Reduction Program. In 1992, NASA and the FAA initiated a cosponsored, multi-year program with the U.S. aircraft industry focused on achieving significant advances in aircraft noise reduction. The program achieved success through a systematic development and validation of noise reduction technology. Using the NASA Aircraft Noise Prediction Program, the noise reduction benefit of the technologies that reached a NASA technology readiness level of 5 or 6 were applied to each of four classes of aircraft which included a large four engine aircraft, a large twin engine aircraft, a small twin engine aircraft and a business jet. Total aircraft noise reductions resulting from the implementation of the appropriate technologies for each class of aircraft are presented and compared to the AST program goals.

**15. SUBJECT TERMS**
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