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Modification of the Ames 40- by 80-Foot Wind Tunnel for Component Acoustic Testing for the Second Generation Supersonic Transport

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Abstract

The development of a large-scale anechoic test facility where large models of engine/airframe/high-lift systems can be tested for both improved noise reduction and minimum performance degradation is described. The facility development is part of the effort to investigate economically viable methods of reducing second generation high speed civil transport noise during takeoff and climb-out that is now under way in the United States. This new capability will be achieved through acoustic modifications of NASA's second largest subsonic wind tunnel—the 40- by 80-Foot Wind Tunnel at the NASA Ames Research Center. Three major items are addressed in the design of this large anechoic and quiet wind tunnel: a new deep (42 inch (107 cm)) test section liner, expansion of the wind tunnel drive operating envelope at low rpm to reduce background noise, and other promising methods of improving signal-to-noise levels of inflow microphones. Current testing plans supporting the U.S. high speed civil transport program are also outlined.

Introduction

Environmental constraints will be a major factor in the design and operability of the second generation High Speed Civil Transport (HSCT). These new aircraft will travel long distances at supersonic speeds, provide the latest technology in passenger comforts, and still be competitive with an ever improving subsonic passenger fleet. The HSCT must also meet tough environmental noise and emission requirements.

Meeting the low noise exposure requirements in and around civil airports during takeoff and climb-out is one of the toughest HSCT environmental challenges. The supersonic exhaust velocities required for cruise efficiencies of HSCT engines dominate the radiated noise levels when operated in an unsuppressed mode on takeoff. If left unsupressed, the radiated noise levels exceed current Federal Aviation Administration Stage III noise rules by about 20 dBA for a typical HSCT.

A major goal of the present U.S. research and development program is to lower these radiated noise levels to be compatible with the subsonic transport fleet. Radiated noise reduction must be done without incurring excessive aircraft performance penalties that would lessen the economic competitiveness of the overall HSCT design. In concept, all of the proposed methods of reducing takeoff noise do so by augmenting the airflow to the engines. Additional air (bypass) is accelerated and mixed with the primary jet exhaust to lower the resulting jet velocities, which lowers the radiated jet noise. There are several engine flow augmentation designs under consideration. Some of the most promising augment the primary engine airflow substantially. This additional airflow must be considered in the integrated design of the aircraft because it may adversely affect takeoff performance. Conversely, if the high-lift systems block the augmented air to the engine, increases in takeoff noise may occur.

These technical aeroacoustic problems are critical to the success of the second generation HSCT. In response to the need to lessen the risk associated with radiated HSCT noise, the United States has embarked on a ground-based comprehensive scale model aeroacoustic testing program using large- and small-scale models. A substantial part of this program involves upgrading the 40- by 80-Foot Wind Tunnel (40 × 80) at NASA Ames Research Center to be able to make key aeroacoustic measurements through the turn of the century on proposed HSCT propulsion systems during takeoff and climb-out. United States industry and NASA have planned small- and large-scale engine testing as well as integrated high-lift engine aeroacoustic testing in the acoustically modified 40 × 80. The very large size and excellent speed characteristics of the 40 × 80 make it an ideal facility to reduce the risks in the HSCT technology program.

This paper reviews the existing and planned testing capabilities of the 40 × 80, including its current aeroacoustic characteristics. The planned aeroacoustic modifications are then reviewed and assessed against anticipated HSCT testing requirements. Finally, integrated acoustic technology testing is proposed that helps reduce the risk of failing to meet HSCT noise and performance goals.

The 40 × 80 as a part of the National Full-Scale Aerodynamics Complex

The 40 × 80, shown in figure 1, was constructed during the latter stages of World War II and became operational in 1944. It has a long and positive history of research and development testing for some of the world's most promising aircraft and components (about 600 test programs to date). Its large size made it an ideal wind tunnel in which to test fighter aircraft, lifting-body configurations, advanced rotorcraft, and large-scale supersonic transport models. It is often used as a large-scale component test facility to evaluate engine-airframe integration, with live aircraft engines. It has long been the world's largest and fastest wind tunnel and since the early 1970s has been used successfully for aeroacoustic testing, including the evaluation of noise suppression methods for the first generation supersonic transport.

In the early 1980s, the 40 × 80 was expanded into the National Full-Scale Aerodynamic Complex (NFAC) (figs. 2 and 3). The expansion included the repowering of the main fan drive system, a new flow-through 80- by 120-foot test section with a system of turning vanes and louvers to allow the independent use of the fan drive system for each test section, and the installation of sound absorbing materials in both test sections to enable acoustic investigations during aerodynamic testing. The new drive system was carefully designed to take maximum advantage of new acoustic technology and to reduce the drive system noise to extremely low levels. The original 40 × 80 single-return circuit was structurally modified to increase the test section speed from 200 to 300 knots, making it an ideal tunnel to investigate landing and takeoff/climb-out phases of flight for all types of aircraft. The maximum tunnel velocity of 100 knots in the new 80- by 120-foot leg makes it an ideal facility for research of rotorcraft and vertical/short takeoff and landing aircraft testing in transitioning flight.

NFAC 40 × 80 Flow Characteristics

An extensive program of scale model testing was conducted in support of the 1980 design of the expanded NFAC facility. Scale model testing was used to measure the performance of alternative design concepts for turning vanes, diffusers, fan drive, air exchangers, duct wall treatment, silencers, and other components. Upon completion of the 1980 upgrade, a series of detailed calibrations was made of the circuit mechanical and aerodynamic components with emphasis on each test section's flow quality. The flow quality in both test sections met or exceeded all the design specifications with a few minor exceptions. Olson et al. (ref. 1) and Zell and Flack (ref. 2) describe the specifications and performance of the complete 40 × 80 circuit and list numerous papers published on the scale model tests. A summary of the 40 × 80 test section flow measurements is reviewed in this section.

The maximum continuous velocity in the 40 × 80 test section is 300 knots with 5 percent air exchange. (The top speed before the 1980 repowering of the fan drive was 200 knots.) The velocity and dynamic pressure distribution over the test section cross section met the design goal of ±0.5 percent variation around the mean as illustrated in figure 4. The deviation is half that value within the test section center volume approximately 20 feet high and 40 feet wide. The velocity and dynamic pressure distributions are fairly insensitive to airspeed.

The average pitch and yaw flow angularity across the test section varies less than ±0.5 degrees. The average upwash is approximately –0.35 degrees. Figure 5 shows the axial turbulence distribution in the 40 × 80 test section and some spot checks of cross-stream turbulence. The ensemble-averaged, root-mean-square axial turbulence is generally below 0.5 percent of the mean axial velocity. The cross-stream turbulence at the centerline was 0.6 percent of the mean axial velocity. These levels of turbulence are achieved without benefit of antiturbulence devices in the circuit such as screens or honeycomb.

The total temperature distribution across the 40 × 80 test section is affected by the heat of compression from the fan drive system, the testing of live jet engines, and the amount of air exchange (fig. 6). With no air exchange, the total temperature is uniform across the duct. With the maximum air exchange of 10 percent and no jet engines, the total temperature is 8°F warmer on the left side of the test section than on the right side looking upstream. This worst case temperature gradient is caused by the cooling air entering the inside of the tunnel circuit at the air exchange door just past the first turn. The cool air gradually forces the warmer air to the outside of the circuit and out the air exhaust at the southwest corner of vane set 7 (ref. 3). Periods of one to two hours operating at maximum power are required before the gradient is established. The testing of live jet engines raises the total temperature of the circuit sooner with a similar temperature gradient.

Figure 7 shows boundary-layer dynamic pressure profiles in the 40 × 80 test section measured with fixed pressure rakes. The 40 × 80 boundary layer is 10 inches (25.4 cm) thick 36 feet (11.0 m) upstream of the turntable center. (The turntable center is the usual location of the wind tunnel models.) A 6 inch (15.2 cm) high acoustic lining creates a step in the wall height 11 feet (3.35 m) ahead of that rake position. The lining also has a 40 percent open perforated sheet plus structural ribbing on the backside of the perforated sheet on the floor to accept working floor loads creating a boundary layer that is thicker than it would be without the current acoustic lining and thicker on the floor than on the walls of the tunnel. Thirteen feet (3.96 m) upstream of the turntable center, the boundary layer grows to a height of 18 inches (45.7 cm). The other contributing factor to the boundary-layer growth is the long distance over which the air flows in the test section. The existing test section is 85 feet (25.9 m) long from the end of the inlet contraction to the start of the diffuser.

NFAC 40 × 80 Circuit Acoustic Features

The fan drive was completely replaced during the 1980 modification to the 40 × 80. One of the primary motivations was to reduce community and test section noise (ref. 4). The fan speed was reduced from the original 280 rpm to the current 180 rpm. This had a strong effect on fan noise reductions since, for a given fan, the noise varies approximately as fan speed to the 5th power. By itself, reducing fan speed from 280 to 180 rpm would theoretically reduce fan noise by approximately 17 dB. However, to increase the fan power without changing the fan diameter required an increase in the number of fan blades from 6 to 15 for each of the six fans; thus, some of the acoustic improvement due to tip speed reduction was negated by an increase in the number of fan blades. Figure 8 is a photo of the fan drive showing six 40-foot diameter fans.

The acoustic performance of the original fans was further improved by the elimination of the large motor support struts that were upstream of each rotor. The unsteady blade loads induced by the strut wakes were strong noise sources. The current fans, illustrated in figure 9, have rotors upstream of the motor support struts and stators. The nose-cone support struts upstream of the rotors, visible in figure 8, are sufficiently small to have little impact on the rotor inflow. This is not to say that the inflow is smooth; the diffuser boundary layers and corner vane wakes create a nonuniform inflow to the fans. However, sharp flow distortions, which have a strong effect on fan noise, have been avoided. The final fan-design task was to choose the proper number of rotor and stator blades for minimum acoustic mode radiation caused by rotor/stator interaction (refs. 4 and 5). This was achieved by choosing 15 rotor blades and 23 stator blades.

Figure 10 shows the fan sound power spectrum measured before and after the fan drive modifications. The sound power was obtained by converting sound pressure levels in the west leg to sound power levels based on measurements of a calibrated noise source in the fan section (ref. 6). At equal test section speeds, the new fans generate 12 dB less overall sound power than the original fans. In addition, the strong low frequency blade-passage tones at 28 and 56 Hz were transformed into weaker tones at 45 and 90 Hz. The maximum electrical power consumption of the new fans at top test section airspeed is approximately 106 MW compared to 30 MW for the original fans. Comparing top speed operations, the new fans radiate 5 dB less sound power than the original fans despite the 250 percent increase in total power of the system.

At fan power levels less than 34 MW, it is possible to control test section velocity using both variable fan blade pitch and variable fan speed. Although not originally conceived as an operational control, the variable rpm feature can be used to minimize the noise generated by the fan drive as illustrated in figure 11. For test section velocities below 100 knots, noise reductions ranging from 10 to 20 dB can be achieved by operating at low fan speed and high blade pitch. Unfortunately, low rpm operations at levels approaching 34 MW are not routine. Electrical control system and safety limits currently restrict the operational envelope. At airspeeds above 200 knots, the fans must be operated at 180 rpm. The planned modification to the fan drive control system expands the range for low rpm operation.

Vane set 6, the variable geometry vane set directly downstream of the fans, is acoustically treated as shown in figure 12. The primary purpose of the treatment is to attenuate the exhaust noise from the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center. The vane design is based on the work of Soderman (ref. 7). The vane treatment is fairly short in the streamwise direction, and the vanes block only 33 percent of the duct. Nevertheless, the measured peak noise reduction of the vane set is 20 dB at 250 Hz as illustrated in figure 13. In the 40 × 80 mode of operation, vane set 6 attenuates the downstream propagation of fan noise into the test section. The resulting noise reduction in the test section is not dramatic because the upstream fan noise radiation is similar to the downstream radiation. Thus, blocking one noise path would at best result in a 3 dB noise reduction. Low noise in the 40 × 80 test section is primarily achieved by low drive fan tip speeds of less than or equal to 377 ft/sec (180 rpm).

Test Section Acoustics

The 40 × 80 test section walls, exclusive of the floor, are currently lined with a 6 inch (15.2 cm) deep sound absorbent lining (ref. 8) composed of fiberglass bats wrapped in fiberglass cloth and covered with a 40 percent open area perforated steel plate (1/8 inch (0.032 mm) diameter holes) as shown in figure 14. The floor lining is similar, but contains a 1.5 inch (3.8 cm) thick steel grating for support of personnel and equipment, with a 4.5 inch (11.4 cm) thick fiberglass layer below the grating. The grating is supported every 2 feet (0.61 m) cross stream and every 10 feet (3.05 m) streamwise by structural members attached to the original floor. The acoustic lining can be penetrated for attachment of struts and other hardware to the steel walls of the wind tunnel if necessary.

The flow resistivity of the 6 inch (15.2 cm) and 4.5 inch (11.4 cm) thick 3 lb/ft^3 fiberglass is between 23,600 and 27,000 mks rayls/m. The flow resistance of the 9.5 oz/yd^2 fiberglass cloth is approximately 13 mks rayls. A significant part of the lining design is based on acoustic lining performance data and predictions described in ref. 9. The sound absorption of the lining shown in figure 15 is good above 300 Hz—as might be expected from a 6 inch (15.2 cm) thick lining. The sound absorption of the floor is degraded by the reduction in lining thickness and the addition of the support grating. Overall, the current liner has proven to be effective above 500 Hz. Thus the lining is adequate for absorbing many types of mid- to high-frequency noise from small models, but is inadequate for absorbing low-frequency noise from larger models such as low-frequency jet noise from medium-scale HSCT engines.

The measured background noise of the "empty" test section is illustrated in figure 16 for an airspeed of 191 knots (ref. 10). Third-octave and narrow-band data are plotted. The third-octave band sound levels were between 90 and 100 dB for that condition. At this airspeed, the dominant noise source is believed to be the wind-induced dipole noise at the microphone and strut, except for the lower harmonics of fan blade-passage noise. (The blade-passage frequency is 45 Hz for 180 rpm fan speed.) Below 120 knots airspeed, the fan noise is dominant over most of the spectrum. The test section noise varied approximately as airspeed to the 6th power, except below 120 knots, where the noise levels depended on the fan operating conditions of variable speed and variable fan pitch.

The test section noise is 5 to 10 dB quieter, at equal airspeeds, than it was before the 1980 NFAC modification. More important, the minimum level of inflow background noise is reasonably close to the background noise of other wind tunnels used for acoustic research throughout the world. Figure 17 shows the 40 × 80 background noise at 800 Hz compared with published data from the Ames 7- by 10-Foot Wind Tunnel No. 1 (ref. 11), the Langley 14- by 22-Foot Wind Tunnel (ref. 12), the Deutsch–Niederlandischer Windkanal (DNW) (ref. 12), and the Royal Aeronautical Establishment 1.5-m Wind Tunnel (ref. 13). Except for the Langley wind tunnel, the comparison shows a remarkable similarity in the noise magnitudes and variation with airspeed. The Langley 14- by 22-Foot Wind Tunnel background noise is dominated by a noisy fan, which may have tip stall (ref. 14). The other wind tunnels appear to all have a similar type of background noise at this airspeed; that is, wind-induced dipole noise in the test section, most likely from the microphone and support strut. Thus, most of the data in figure 17 appear to be a measure of microphone and strut noise and not wind tunnel drive noise. Reductions in the background noise of those facilities require improvements in the microphone nose-cone design and microphone strut design—something that is being pursued by many researchers.

Current 40 × 80 HSCT Testing Methods

Simulating free air flight conditions at full scale is the primary objective of most wind tunnel testing. Matching flight Reynolds number, Mach number, and geometry (including structural deformations) and maintaining low free-stream turbulence levels are normally required to guarantee aerodynamic similarity. Simulating full-scale far-field acoustic radiation using wind tunnels also requires that the wind tunnel does not disturb the radiative acoustic field; i.e., the wind tunnel boundaries or walls do not reflect acoustic waves back into the radiating acoustic field. This latter requirement is achieved by two different approaches: aeroacoustic testing in open jet and aeroacoustic testing in treated closed jet wind tunnels.

The open-jet wind tunnel surrounded by an acoustically absorbent (anechoic) chamber is the most prevalent type of aeroacoustic wind tunnel. Some excellent open-jet anechoic test facilities have been built and used in aeroacoustic research throughout the world (refs. 12–15). The major advantages of open-jet facilities are the quality of the anechoic chamber surrounding the open jet and the very low self-noise from microphones measuring the far-field radiated noise outside the uniform airflow stream. However, the open-jet anechoic wind tunnel is not a quantitative simulation of the radiative acoustic field in many situations. When tunnel flow velocities become large, the open-jet tunnel is beset by two problems: a difficult aerodynamic flow problem of successfully capturing a basically unstable open jet and the difficulties of measuring the radiative acoustics through a shear layer. The first problem has been addressed and alleviated by using clever ejection-type collectors. Speeds of 155 knots have been successfully obtained in the DNW wind tunnel in the open-jet configuration. Additional gains in tunnel speed may be possible but are difficult to achieve with this general concept because of the interaction of the chamber entrained flow with the primary jet. Acoustic scattering of radiated noise through the large shear layer also limits this concept at high tunnel velocities (ref. 16). It becomes more difficult to correctly assess the characteristics of the radiative acoustic field of the aircraft or aircraft component being tested.

The acoustically treated closed test section wind tunnel offers distinct benefits over open-jet test sections for testing at high forward velocities and large scale. Problems of measuring noise through larger shear layers are apparently eliminated when acoustic measurements are taken directly in the moving airstream. Open-jet stability and flow problems are avoided, and testing velocities are limited only by the wind tunnel speed capabilities. However, the requirement to make acoustic measurements in the acoustic far field in an anechoic space is more difficult to achieve in a closed test section wind tunnel. The obvious solution is to make the test section very large and to treat the walls of the test section with acoustic treatment in such a way as to minimize tunnel flow interactions. Simply put, this is the concept of the proposed acoustically modified 40 × 80. Of course, there are advantages and disadvantages of the proposed concept. The authors tend to view the open versus closed test section acoustic choice as complementary solutions—each having its special use to solve aero-acoustic problems. For HSCT, where takeoff and climb-out are anticipated to occur at 200 knots or greater and where large scale will be needed to demonstrate sufficient reduction in program risk, making the 40 × 80 a large-scale closed test section anechoic facility is a logical choice.

Acoustic and aerodynamic testing for the HSCT have begun in the 40 × 80 in its current shallow liner configuration. A microphone traverse system has been installed (fig. 18) to survey laterally and longitudinally around the model being tested. One of the first research test objectives was to acoustically calibrate the 40 × 80 and compare these calibrations with several good open-jet facilities. A 1/8-scale pure unsuppressed jet with a conical nozzle has been acoustically tested over a full range of pressure ratios. This same jet testing rig has been tested in other smaller anechoic open-jet facilities. The comparison is helping develop calibration and testing procedures for both types of facilities.

As mentioned previously, a disadvantage of testing in a closed test section anechoic wind tunnel is that acoustic measurements must be made in the wind tunnel airstream. Unsteady pressures associated with flow over classical microphone nose cones have created apparent background noise levels that can be as high as the event being measured. The problem is strongly dependent upon the velocity over the nose cone. The apparent background noise increases dramatically with speed. To mitigate this problem, new low noise inflow nose cones were developed (ref. 17) and are being used to measure inflow noise for HSCT testing. As shown in figure 19, the special nose cones effectively reduce microphone self-noise, especially high-frequency pure tones associated with the boundary-layer induced resonance of these devices.

One of the major purposes of the current HSCT testing is to develop testing procedures that can be used later on larger HSCT models. Larger models, perhaps even full-scale engines, may be tested in the 40 × 80 as part of an HSCT technology risk reduction program. Making acoustic measurements on the large models in the radiative far field will be difficult at best, if not impossible. At the present time, near- and far-field measurements are being made on smaller models in the 40 × 80 to help develop extrapolation methods for the larger scale models.

Integration of the engine, engine suppressers, and high-lift devices is important to the HSCT program from both the performance and acoustic perspectives. The HSCT engines will move very large amounts of air in close proximity to the wing/flap assemblies. The flaps and wing must be designed to utilize this altered airflow to maintain good lift-to-drag ratios on takeoff and climb-out. At the same time, the engine must generate sufficient takeoff thrust at low noise levels. Good flow into the engine and suppressers at all inlets must be assured. Finally, there may be certain acoustic shielding benefits to certain engine/airframe designs that need to be assessed. Many of these factors will be evaluated in a high-lift engine aeroacoustic test in the 40 × 80. This 1/8-scale model will look at the integration of takeoff aerodynamics, acoustics, and installed engine performance.

Planned 40 × 80 Acoustic Modifications

The 40 × 80 acoustic modification project is supported by several NASA/industry aeronautical programs and has won the endorsement of many NASA oversight committees. The large scale and high speed capability of the acoustically enhanced 40 × 80 will help reduce the noise and performance technology risks associated with program development.

Several acoustic designs for the NFAC were considered before arriving at the planned concept (ref. 18). Usability and cost of the modifications were considered for each design. The extensive 1980 modification to the fan drive system ensured relatively low background noise levels. All of the proposed modifications were relatively inexpensive for a tunnel of this size, making the 40 × 80 modification the most cost-effective solution that satisfied most of the stated needs. However, some specific requirements for low-frequency rotorcraft testing could not be accommodated.

The planned 40 × 80 acoustic modification is described in three major tasks. The first is the installation of a new anechoic liner for the 40 × 80 test section. The second is the modification of the main fan drive control system to utilize its low rpm (low noise) operations. The third is to lower the effective test section background noise through additional background noise reduction methods. The first two tasks are illustrated in figure 20.

Anechoic Liner for 40 × 80 Test Section

Creating an anechoic space inside a hard-walled closed test section wind tunnel is a difficult challenge. A nearly anechoic space is required from 100 to 20,000 Hz to support both large- and medium-scale acoustic research and development. The low-frequency requirement requires a wedge or bulk treatment of large depth while the high-frequency requirement demands a fairly open porous (low acoustic impedance) surface. In addition, high wind tunnel velocities require a low drag interface surface that can withstand 300 knots (M = 0.45) and still yield acceptable acoustic performance.

The preliminary design for the 40 × 80 anechoic liner is sketched in figure 20. The interior dimensions of the existing 40 × 80 have been maintained by choosing a design which utilizes the existing ring-girder structure by relocating the pressure shell and its support structure from the inside to the outside of the ring girders. An isometric diagram of the test section modifications is shown in figure 21. This novel design creates a new cavity approximately 42 inches (107 cm) deep over 90 percent of the test section allowing for extensive acoustic treatment. The location of the existing test section aerodynamic surface does not change in this new design. Therefore, all of the other aerodynamic sections of the circuit (contraction cone, diffuser, etc.) are usable and do not require extensive modifications to maintain or improve flow quality of the wind tunnel. Another major advantage of utilizing the existing ring girder for the design is that the tie-ins for the major support of the wind tunnel do not need major modifications—they are quite capable of supporting the aerodynamic and structural loads of the new design. The lack of major structural change to the girder design and the similarity of the flow circuit design also help reduce the overall cost of the proposed modifications—a very important requirement in today's competitive market.

At least four deep-liner concepts were considered to fill the new deep cavity which is created by moving the test section walls to the outside of the ring girders. As shown in figure 22, they are: a single-layer bulk liner, a multi-layer bulk liner, a "classical wedge" system, and a "poor man's wedge" system. The concept of a poor man's wedge is sketched in figure 22. It consists of vertically spaced bulk acoustic material separated by layers of air (or very low impedance material like steel wool). The single uniform deep layer of low density bulk material is perhaps the least expensive method of achieving good anechoic properties. However, the material is quite light and requires a secondary structure to support it which degrades its near-anechoic properties. Its absorptive properties were also not quite as good as the wedge system at low frequencies. The multilayer bulk material treatment design was also considered and eliminated because its design did not match the acoustic performance of the wedge system at low frequencies.

The classical wedge and the poor man's wedge designs were both evaluated in a simple low-frequency test program (ref. 19). The classical wedge system is used in most anechoic chamber designs and needs little explanation. It yielded almost perfect performance (absorption coefficient > 0.99) at the lower frequencies of interest as shown in figure 23. As shown in figure 23, the performance of the poor man's wedge approaches that of the classical wedge design at low and mid frequencies. However, the promise of achieving large cost savings by using the poor man's wedge system was tempered somewhat by the problem of finding a good practical material to act as the low impedance layer between the acoustically absorptive layers and by the problem of adding the structure needed to support the vertical layers. In the final evaluation, the classical wedge system yielded the best performance at a reasonable cost.

Choosing a porous interface between the wind tunnel test section and the deep acoustic liner is another engineering compromise. The interface material must allow sound waves to pass through the interface with little energy reflected back to the interior of the test section and, at the same time, contain the free airstream velocity in the wind tunnel test section. Through experimental testing, an interface material that approached the acoustic impedance of air was found that accomplished this goal. At the present time, the 40 × 80 test section interface design consists of a 68 percent open porous plate backed by a fine mesh screen. This design is a complex trade-off between acoustic and aerodynamic performance, structural suitability, ease of manufacture, and cost.

Because the wind tunnel interface is very porous, pressure gradients at the interface could cause air to flow through the interface, i.e., areas of lower pressure would cause air to flow into the deep wedge cavity while areas of higher pressure would cause the air to flow to the free stream. This type of secondary flow must be avoided because it causes a general degradation of tunnel performance, directly affects the local aerodynamic flow field, and thickens the test section boundary layer. To avoid these secondary flows, the test section liner design is divided into a large number of 4 foot (1.22 m) square compartments which are sealed on the five sides which are not facing the flow (fig. 24). Over any one compartment, static pressure is fairly constant at the wind tunnel interface even with typical models mounted in representative test locations. The resulting "egg crate" design is integrated into the 40 × 80 test section as an efficient orthotropic structural solution which is very rigid and easy to standardize.

Preliminary testing over a range of design options has shown the design concept to be workable with excellent acoustics and good flow. A minimum coefficient of absorption of 0.9 has been specified under a no-flow condition from 80 to 20,000 Hz. Over most of the low to medium frequencies, coefficients of absorption of 0.99 have been realized to date. Although the design team is confident that the wind tunnel interface and acoustic cavity systems will work as designed, a full-scale coupon test is planned in the existing 40 × 80 for final design validation. An 8 foot (2.44 m) wide by 22 foot (6.7 m) long portion of the tunnel has been removed and replaced with a deep cavity (fig. 25). The cavity is compartmentalized into 4 × 4 foot (1.22 m) sections and will be covered with the newly designed interface and tested to the full 300 knot airspeed capability of the 40 × 80.

Low rpm (Low Noise) 40 × 80 Operations

The repowering of the 40 × 80 fan drive in the early 1980s not only increased the top test section velocity of the 40 × 80 from 200 to 300 knots, it also significantly lowered the radiated noise of the fans. This reduction (see fig. 10) was achieved by good acoustic design, low rpm/low fan tip speed operation, variable pitch control of the fan blades, and variable rpm.

The purpose of the variable rpm drive is to bring the wind tunnel fan speed up to electrical line frequency 60 Hz (180 rpm). The variable speed control limits the power that the fan drive will accept to less than 34 MW during this process. A 34 MW limit corresponds to about 200 knots in the 40 × 80 test section. If fan rpm is reduced to lower noise levels, blade pitch of the main drive fans must be increased to maintain constant test section velocity. Fortunately, the blades are designed for little or no blade stall over the full operating range of the fan drive up to 52 degrees angle of pitch. Thus, no matter what operating rpm of the fan drive is chosen, the fan drive will not experience increased vibration and noise associated with blade stall.

The wind tunnel drive fan control cannot currently utilize the full 34 MW low rpm capability of the 40 × 80. At low fan drive rpm and high fan blade pitch, electrical loading in the control circuits and operational safety limit the power available to the drive system as shown in figure 26. Maximum power to the fan drive is effectively constrained as a function of fan drive rpm and blade pitch in the ranges ideal for controlling low background noise.

The planned aeroacoustic modification to the 40 × 80 will open these low power limits by increasing the capability of the fan drive control system through interpole shunting of the motor drive control system. This will increase the delivered power to the six main fan motors allowing them to run at lower tip speeds for the same wind tunnel velocities. A plot of this improved fan drive power capability as a function of fan rpm is also shown in figure 26.

The benefits of lower rpm capability are greatest at lower airspeeds where the effective test section noise is lowest and low inflow microphone self-noise does not dominate the background noise measurements. The improved low rpm capability is plotted as a function of test section velocity in figure 27. At velocities less than 200 knots, significant decreases in fan drive rpm and corresponding tip speed are shown. At 60 knots the fan drive can be operated at 40 rpm with 52 degrees of blade pitch and a corresponding tip speed of 84 ft/sec (25.6 m/sec). This substantially lowers the wind tunnel background noise from the present "quiet" drive speed of 180 rpm and corresponding tip speed of 377 ft/sec (114.8 m/sec). At 120 knots, 90 rpm generates a tip speed of 188 ft/sec (57.3 m/sec) and is predicted to reduce fan drive sound power by 10 dB (see fig. 11). At 160 knots, 135 rpm generates a tip speed of 283 ft/sec (86.2 m/sec) and is predicted to reduce fan drive sound power by 5 dB.

The cost of modifying the 40 × 80 control system to add the interpole shunting capability is minimal, making interpole shunting a very cost-effective noise reduction device at the lower test section velocities. Adding interpole shunting also makes the entire fan drive operation more robust and reliable. During normal startup procedures, when low rpm operation is used to bring the drive motors up to line frequency (60 Hz), interpole shunting reduces the possibility of electrical problems in the 40 × 80 drive control.

Additional Background Noise Reduction Methods

As aircraft and their propulsive systems become quieter to meet more stringent environmental constraints, the ability to measure these lower noise levels becomes more of a challenge. Wind tunnel drive fan noise, microphone self-noise, and the noise radiating from the test section walls all contribute to the problem, depending upon the test section velocity. Earlier in the 40 × 80 aeroacoustic modification project, bulk acoustic treatment was planned for the walls at the corners of the wind tunnel downstream of the test section, before the flow enters the fan drive. The purpose of this inexpensive treatment was to block the sound from entering the test section from the downstream direction. However, after some in situ testing, it was found that the bulk acoustic treatment was effective only at low frequencies, where, for most 40 × 80 acoustic problems of interest, low fan drive rpm could ensure good signal-to-noise levels. Consequently, the acoustical treatment of the tunnel walls at the downstream turning vanes was removed from the project.

At lower noise levels, sounds radiating from the test section liner and support struts also become factors that can limit inflow signal-to-noise levels. Good wind tunnel and support strut design reduce these unwanted noise sources. Regions of separated flow must be avoided on the microphone as well as the model support struts. The surfaces exposed to the flow must be relatively smooth to keep the size of the boundary layers small to reduce test section boundary-layer noise and test section drag. This requirement is somewhat at odds with the criterion that the tunnel walls be transparent to acoustic waves. Transparent walls are not perfectly smooth and can generate sizable boundary layers. Nevertheless, by specifying an acoustic impedance of about 10 mks rayls for the liner design with a 68 percent open porous plate liner, a reasonable trade-off has been achieved between boundary-layer size and test section absorbtivity.

Perhaps the most promising technology to emerge to help solve the signal-to-noise measurement problems of closed-walled wind tunnels is the use of acoustic arrays. A set of calibrated microphones are mounted in the flow and arranged in predetermined positions. Data gathered on this microphone set is electronically processed as a single sensor. Array processing helps improve signal-to-noise ratios, reduces correlated but unwanted background noise, and steers an effective receptor beam to look only at noise sources of interest. A simple array of this type is shown in figure 28 mounted on an aerodynamic surface in the 40 × 80. Through off-line signal processing, it also is possible to steer the array to look at various components of noise emanating from the model being tested. Of course, this technology also has its limitations. To get large signal-to-noise ratios and narrow beam widths, many microphones are necessary. Their placement is also frequency dependent if optimum signal-to-noise levels are to be achieved. This necessitates large amounts of data retrieval and storage and requires the use of sophisticated signal processing techniques. Nevertheless, signal-to-noise level improvements of up to 30 dB and beyond are ultimately possible. Because of such large potential improvements, much of the effort to improve test section signal-to-noise levels is focused on developing the application of this promising technology to the inflow measurement of radiated sound.

Planned HSCT Component Testing

One of the objectives of the planned HSCT 40 × 80 aeroacoustic testing is to quantify the noise and performance of the isolated engine and the engine installed beneath the wing of the aircraft during takeoff conditions. This testing should be done at as large a scale as possible and under simulated takeoff conditions to help minimize developmental risk. As described earlier, the first steps are currently under way. Closed test section calibrations and comparisons with open-jet wind tunnels are in progress. A 1/8-scale circular jet has been tested up to 200 knots airspeed in the existing 40 × 80 and compared with data acquired in open-jet facilities at lower airspeeds. Testing and correlation procedures are being developed that increase the confidence in the measured data. For the smaller models, both near- and far-field acoustic measurements are possible in the 40 × 80. The performance and noise installation effects of small models are also currently being evaluated.

Larger scale testing is planned after the 40 × 80 acoustic modification is completed. The deep new liner will improve the absorptive properties of the test section over the entire frequency range and will make the 40 × 80 one of the best anechoic closed test section (and hence higher speed) acoustic wind tunnels in the world. Being nearly anechoic at low frequencies (80 Hz) allows acoustic testing at larger scale to help reduce technology risk. An extensive program of isolated engine testing at 1/2 geometric scale is currently being planned for the acoustically modified 40 × 80. As sketched in figure 29, the larger model engines will be a good size for 40 × 80 testing. Near-field acoustic measurements will be made similar to those made on the 1/8-scale testing. Far-field measurements will be somewhat constrained at this larger scale. However, the near-field/far-field techniques developed at smaller scale in this testing program will be used to help extrapolate selected acoustic data to the acoustic far field.

A second phase of high-lift engine aeroacoustic testing is also planned after the acoustic modification to the 40 × 80 is complete. The higher quality anechoic space will allow accurate assessments of the trade-offs between takeoff performance and noise. The influence of the high-lift system on engine noise radiation as well as the influence of engine inlet and exhaust flows on high lift designs will be assessed.

Concluding Remarks

The planned modifications of the NASA Ames Research Center 40- by 80-Foot Wind Tunnel (40 × 80) for future aeroacoustic testing to support the second generation high speed civil transport research program have been described. When completed, the modified 40 × 80 will be the world's largest closed test section anechoic wind tunnel and will have a test section velocity capability of 300 knots. The acoustically modified 40 × 80 will help address takeoff noise and performance trade-offs of proposed HSCT acoustic technology and thereby help reduce program risk. The acoustically modified 40 × 80 will also be a unique asset in the development of other new aircraft where environmental noise problems are an important design constraint.

Final design of the acoustic modification to the 40 × 80 has just been completed. The modification program has been supported by extensive component testing to help reduce facility development risk to acceptable levels. The tunnel modification will begin in the fall of 1995 and be completed by the spring of 1997. During this construction period, the 80 × 120 leg of the tunnel will remain operational for all but four months. Early in 1997, the 40 × 80 will become operational and ready for both acoustic and large-scale performance testing.

It is anticipated that the 40 × 80 will play an important role for aeroacoustic testing of many aircraft and their components. It will offer a new way of assessing, on the ground, the aeroacoustic performance of the next generation of aircraft. Its large-scale and high-speed capabilities are complementary to many other excellent smaller facilities throughout the world. Aeroacoustic data gathered in these facilities together with data gathered at larger scale and at higher speed in the 40 × 80 will advance understanding and help reduce the development risks to new quiet aircraft/engine designs.

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Figure 1. NASA Ames 40- by 80-Foot Wind Tunnel (before 1980 conversion to National Full-Scale Aerodynamic Complex (NFAC)).

Figure 2. Aerial view of the National Full-Scale Aerodynamic Complex (NFAC) at NASA Ames Research Center.

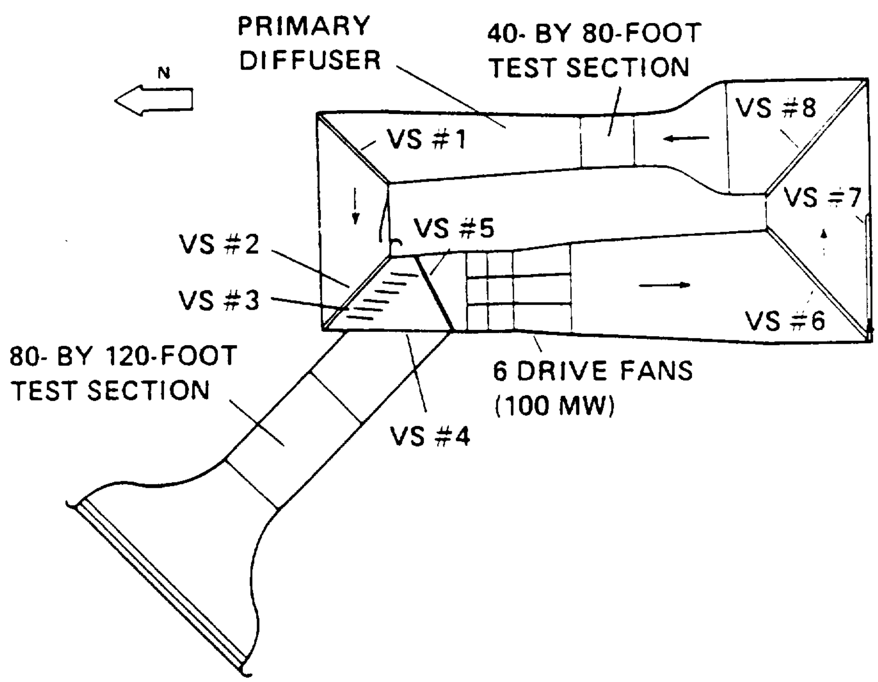
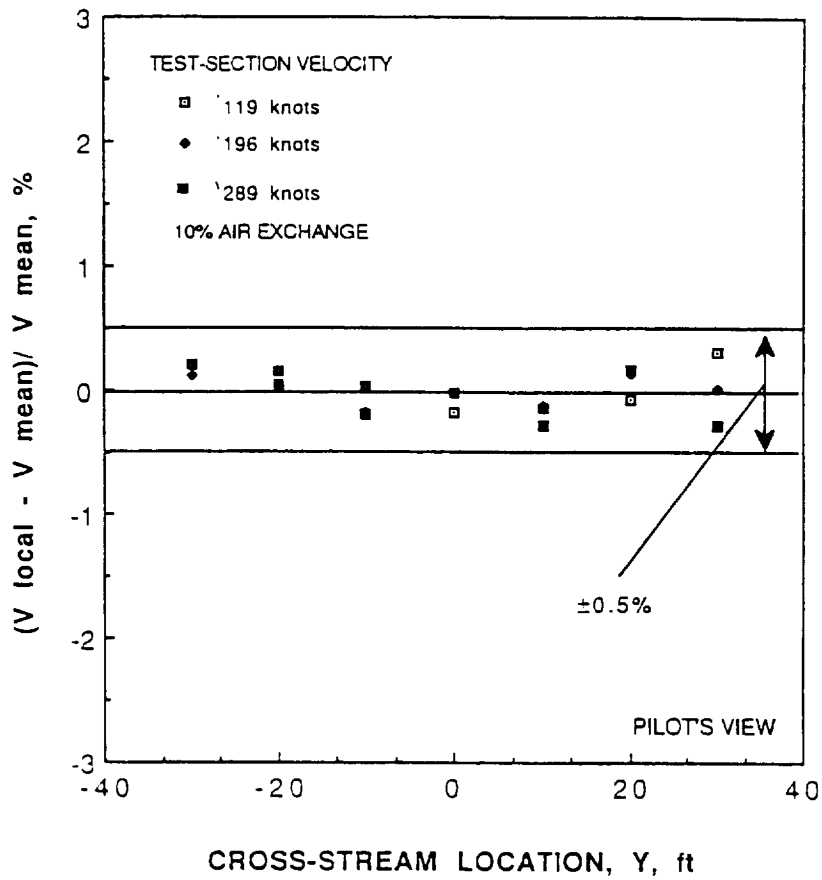
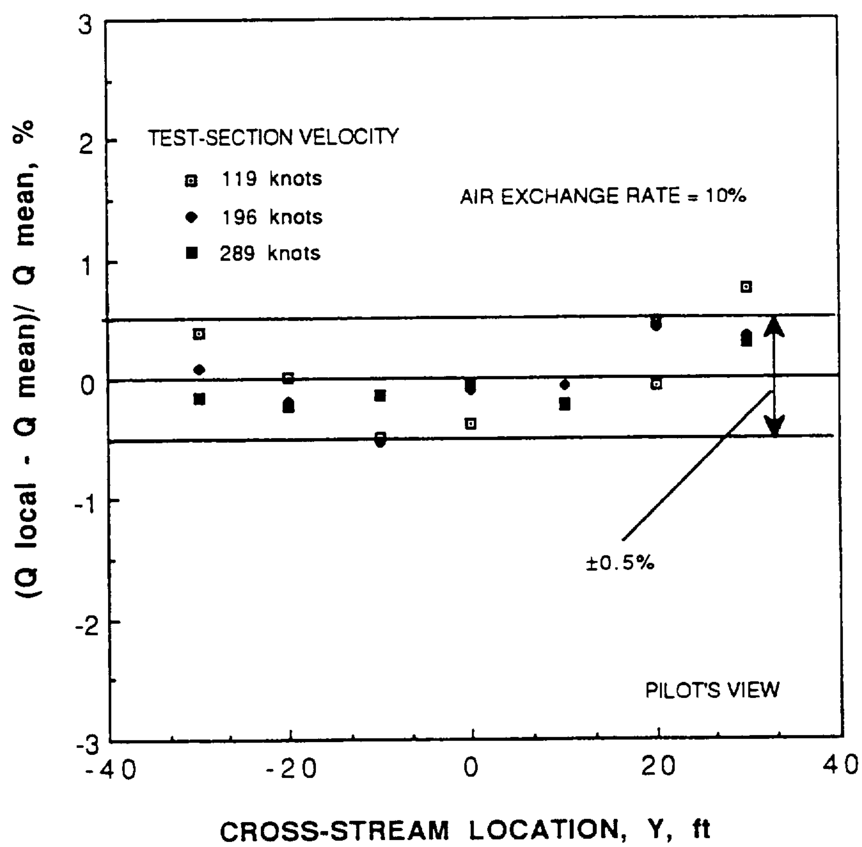


Figure 3. Plan view of NFAC which illustrates the 40- by 80-Foot and 80- by 120-Foot Wind Tunnel circuits (vanes set for 40 × 80 operation).



(a) Velocity distribution.

Figure 4. Velocity and dynamic pressure distributions in the test section for low, medium, and high test section velocities. The air exchange rate for all three cases is 10 percent.



(b) Dynamic pressure distribution.

Figure 4. Concluded.

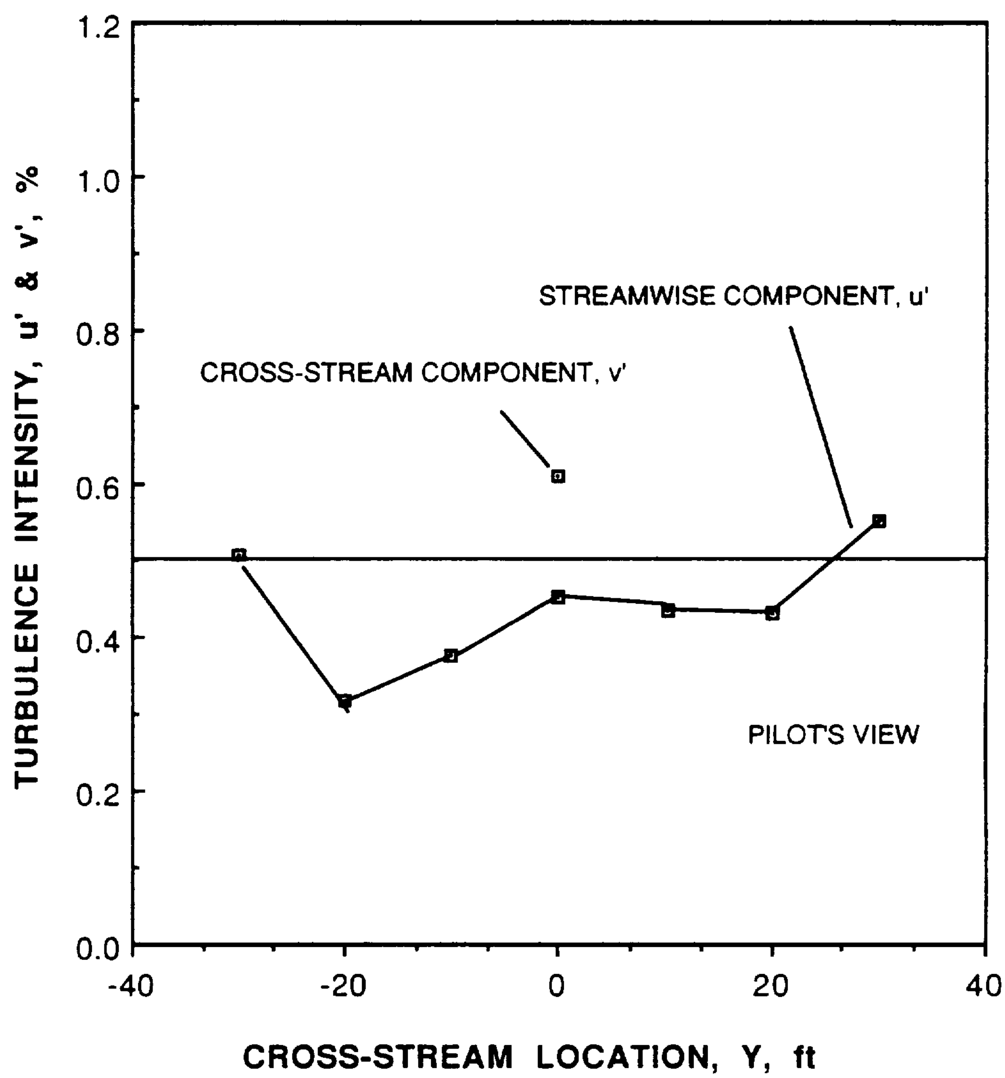


Figure 5. Test section turbulence at an air exchange rate of 10 percent.

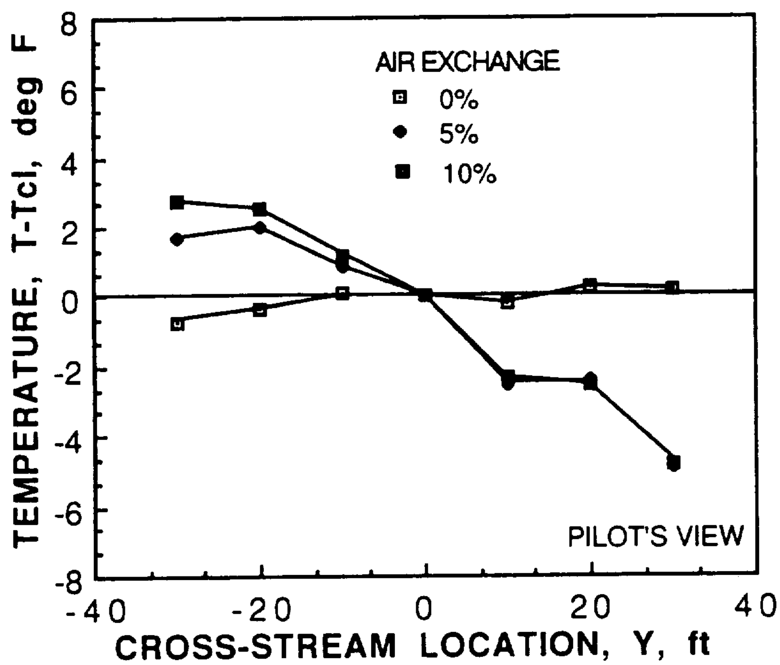


Figure 6. Effect of air exchange rate on test section total temperature distributions.

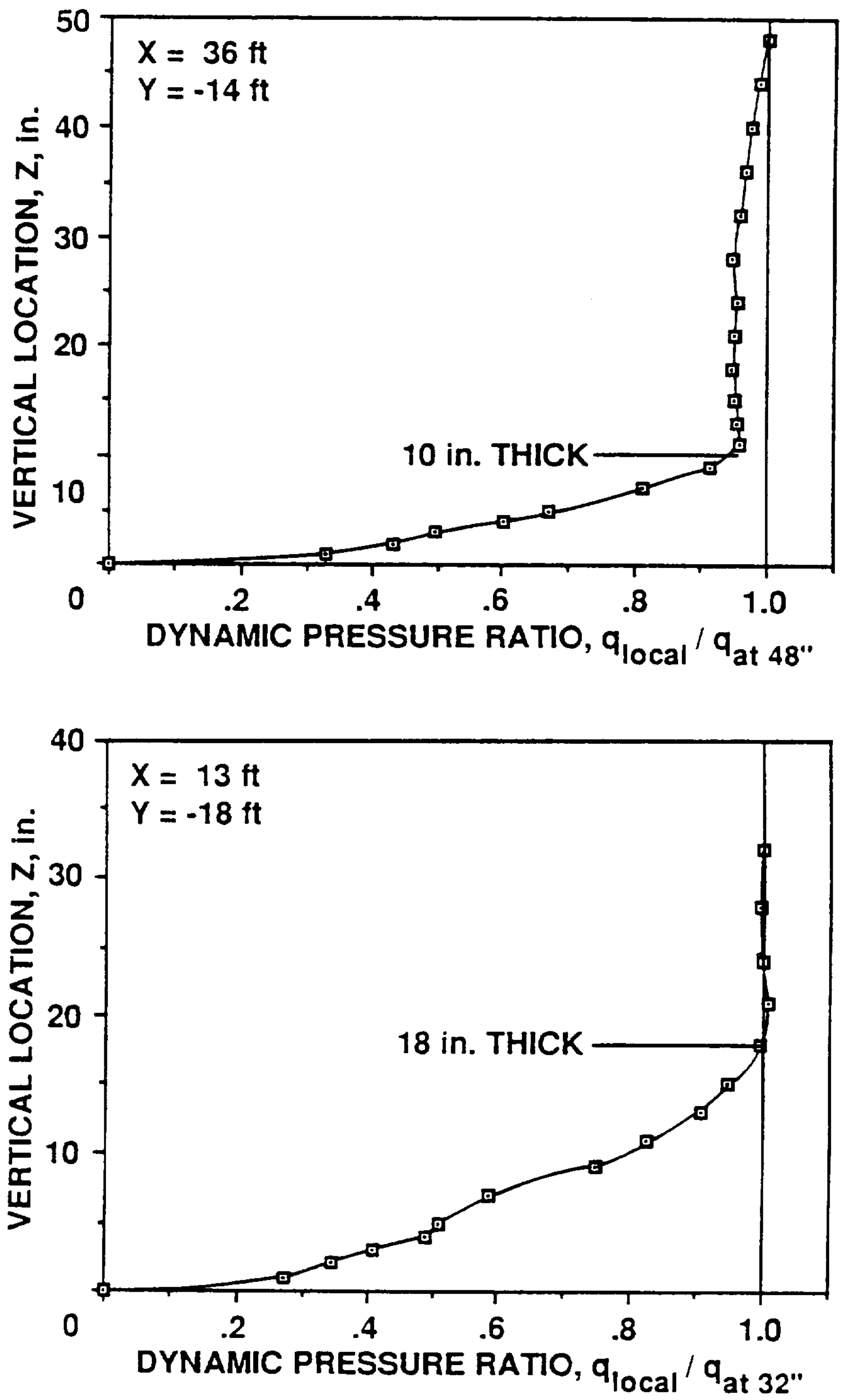


Figure 7. Dynamic pressure profiles from fixed rakes on the test section floor.

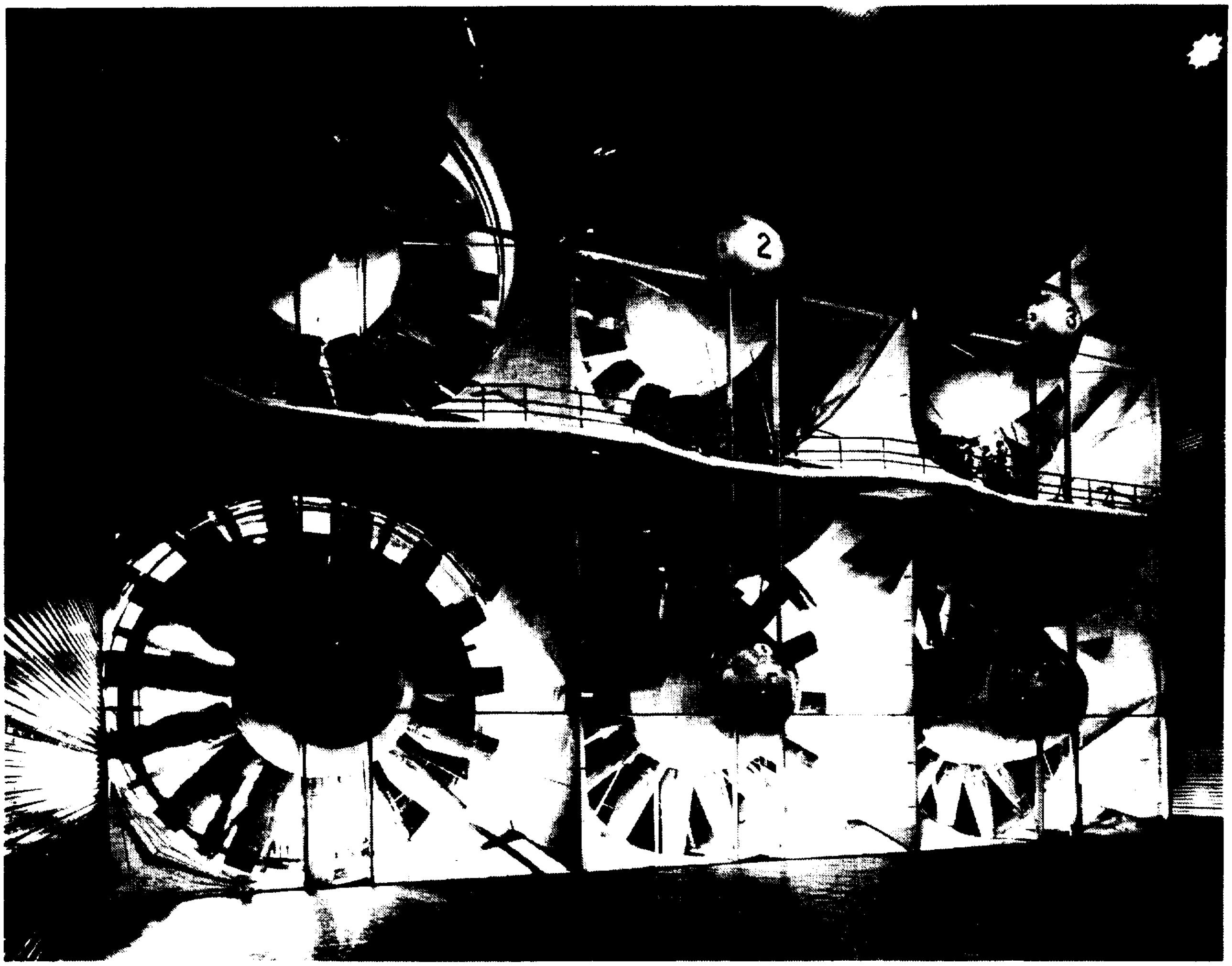


Figure 8. NFAC fan drive.

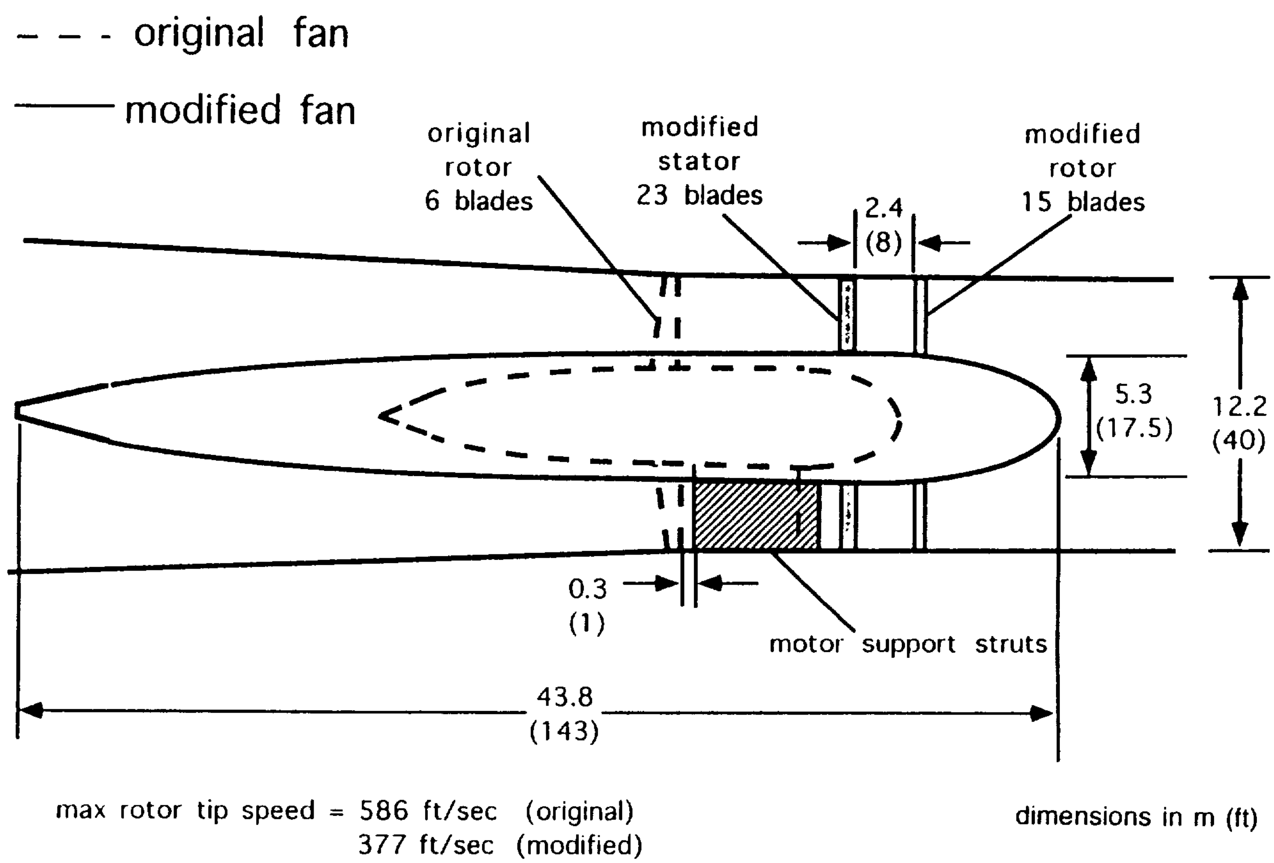


Figure 9. Drive fan geometry before and after the 1983 modifications.

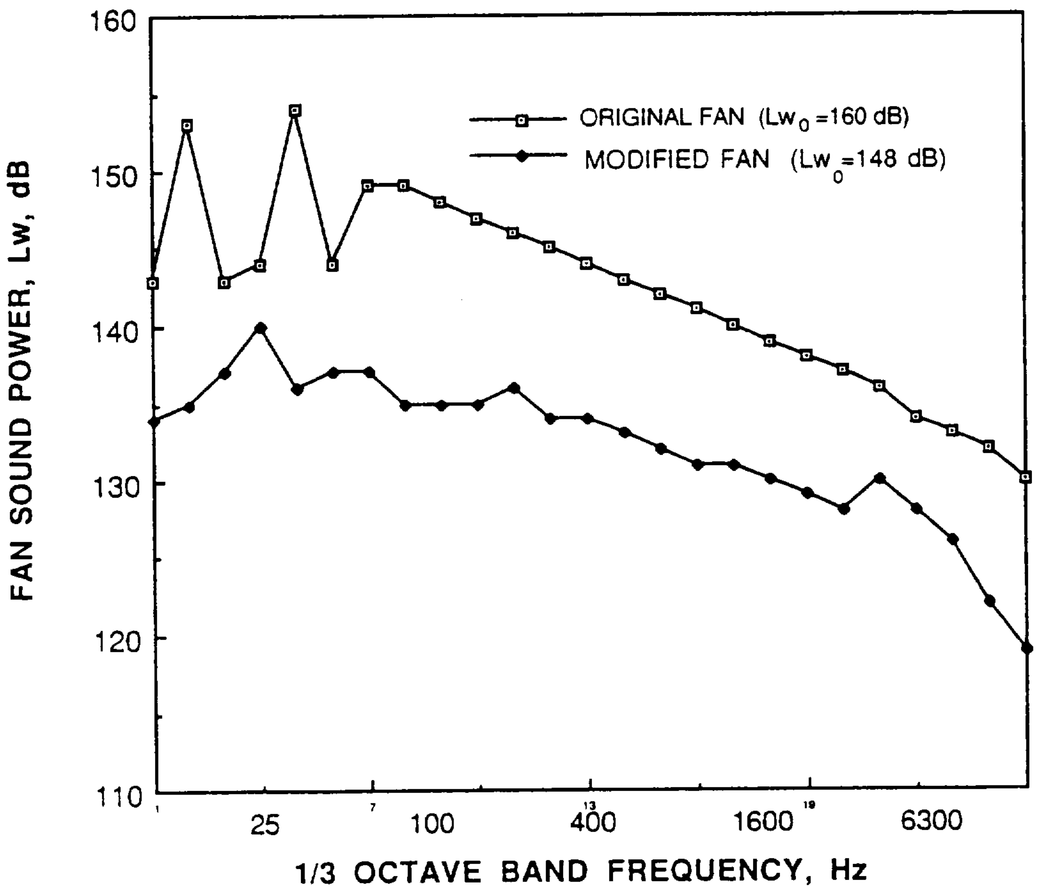


Figure 10. Fan sound power spectra measured before and after the fan drive modification.

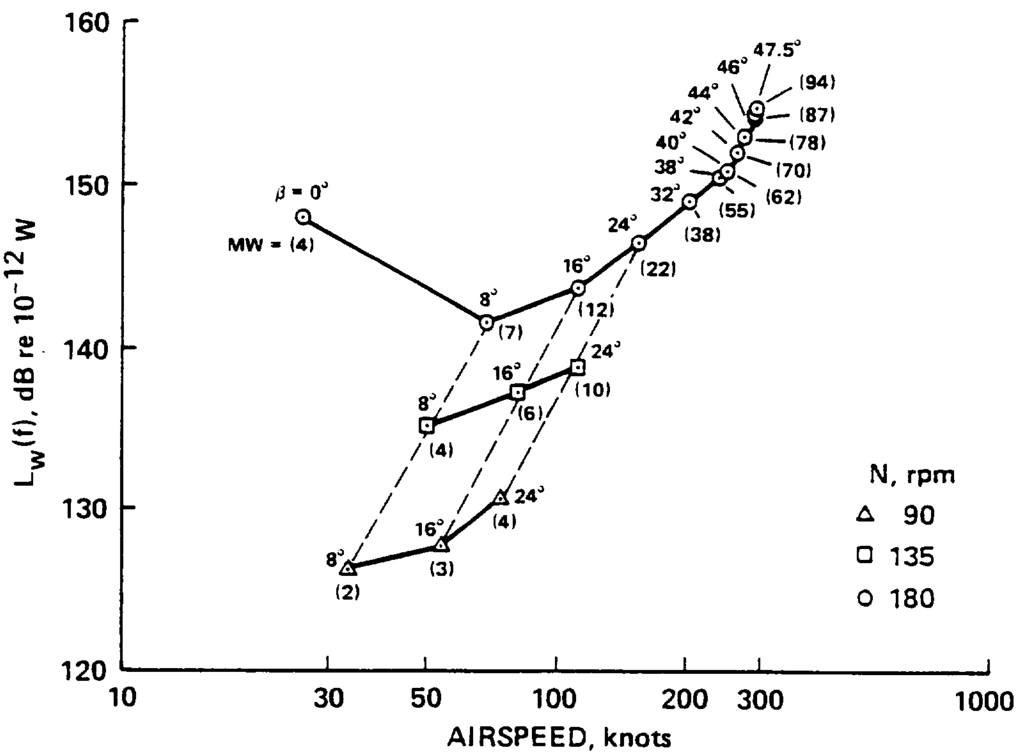


Figure 11. Fan sound power variation with test section airspeed. Blade pitch angle (β) and fan drive electrical consumption (MW) are noted.

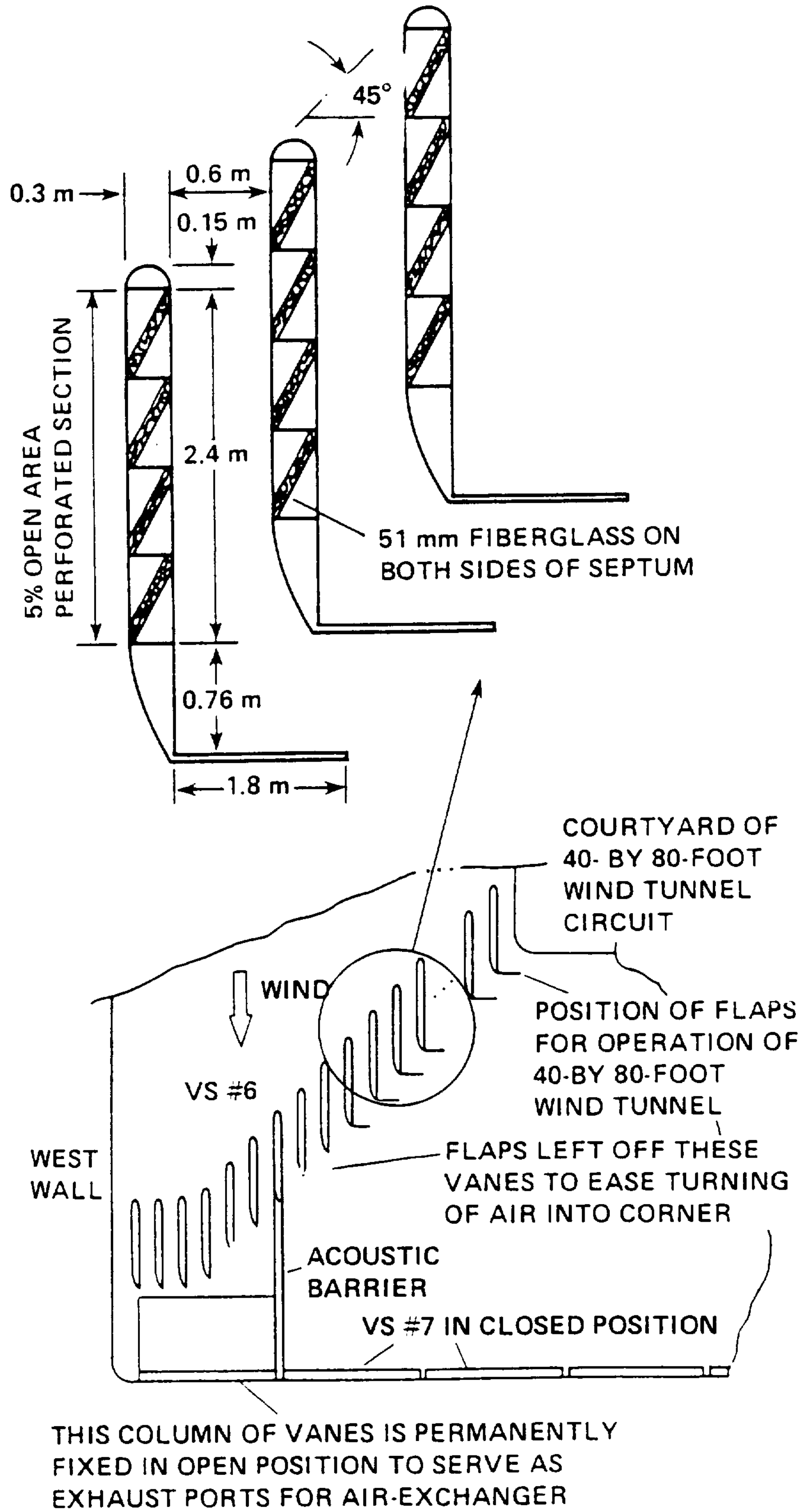


Figure 12. The acoustically treated vane set 6 downstream of the drive fans.

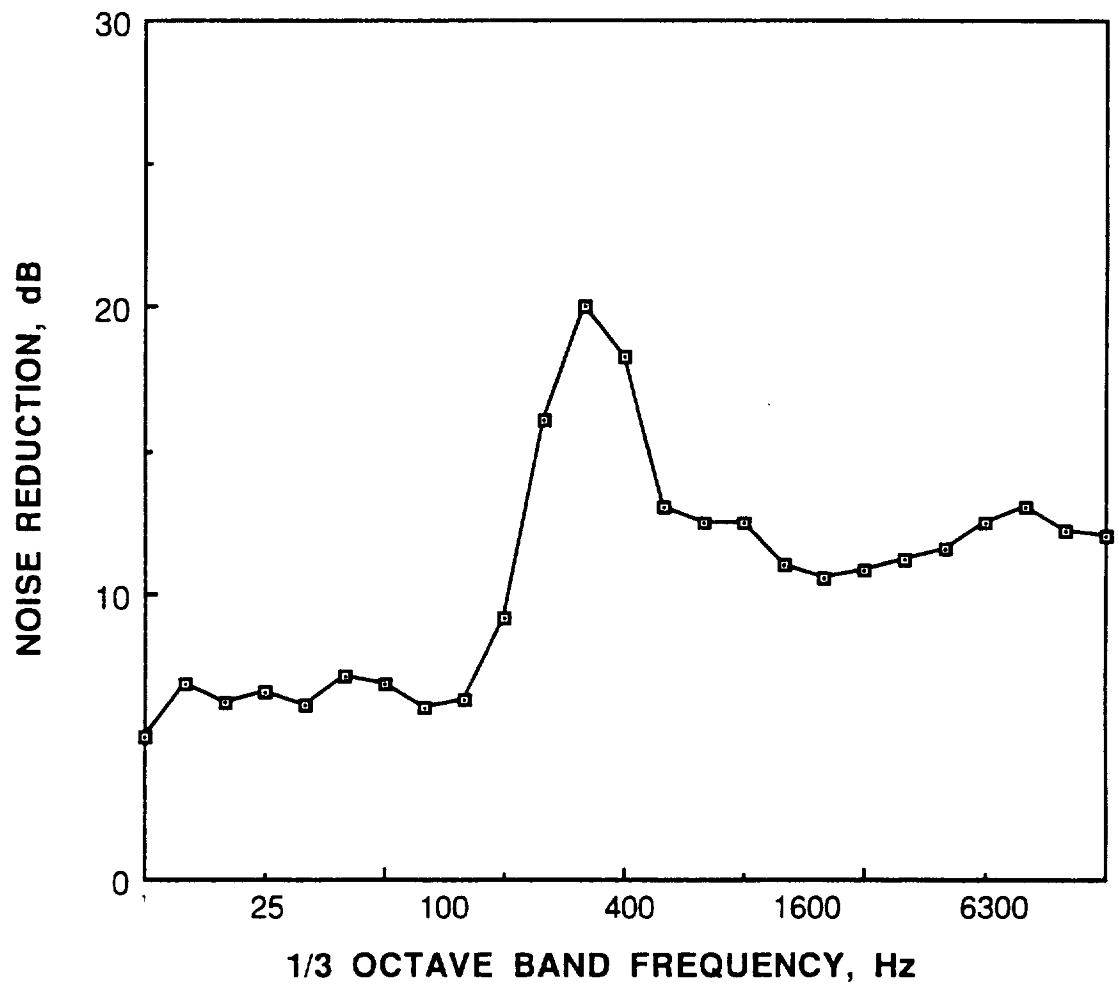


Figure 13. Noise reduction of vane set 6 as measured upstream and downstream of the vane set; 175 rpm fan speed, 0 degree fan blade pitch angle.

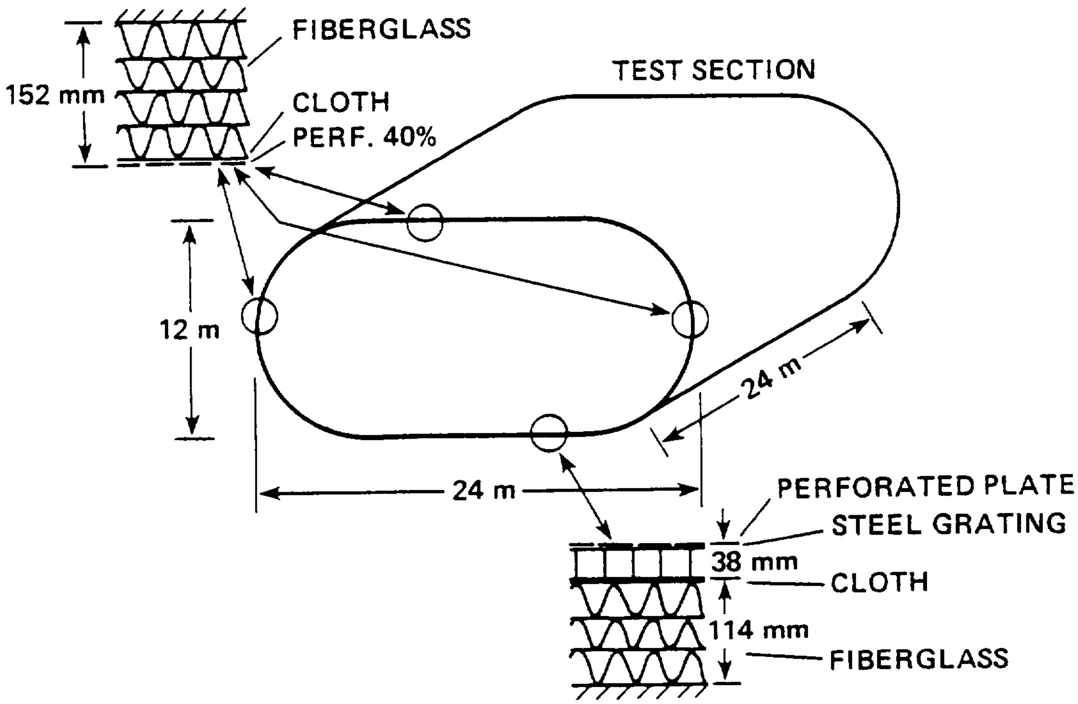


Figure 14. Existing 40 × 80 test section acoustic wall lining.

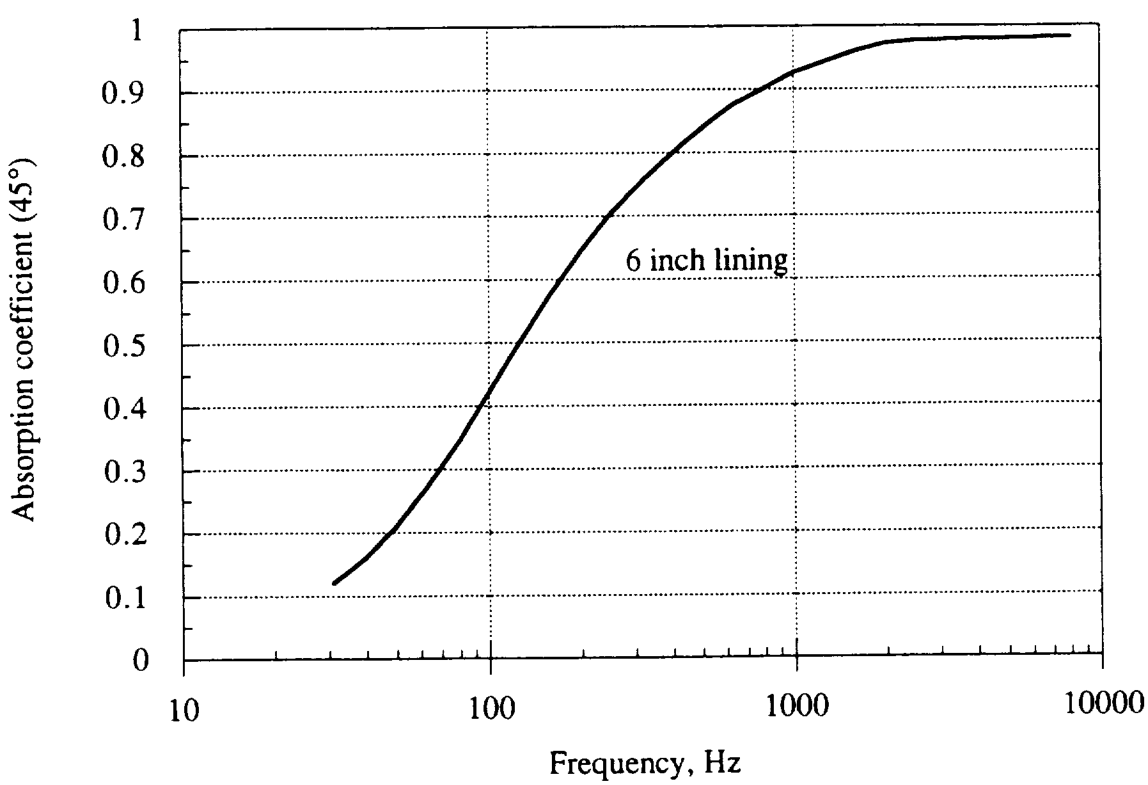
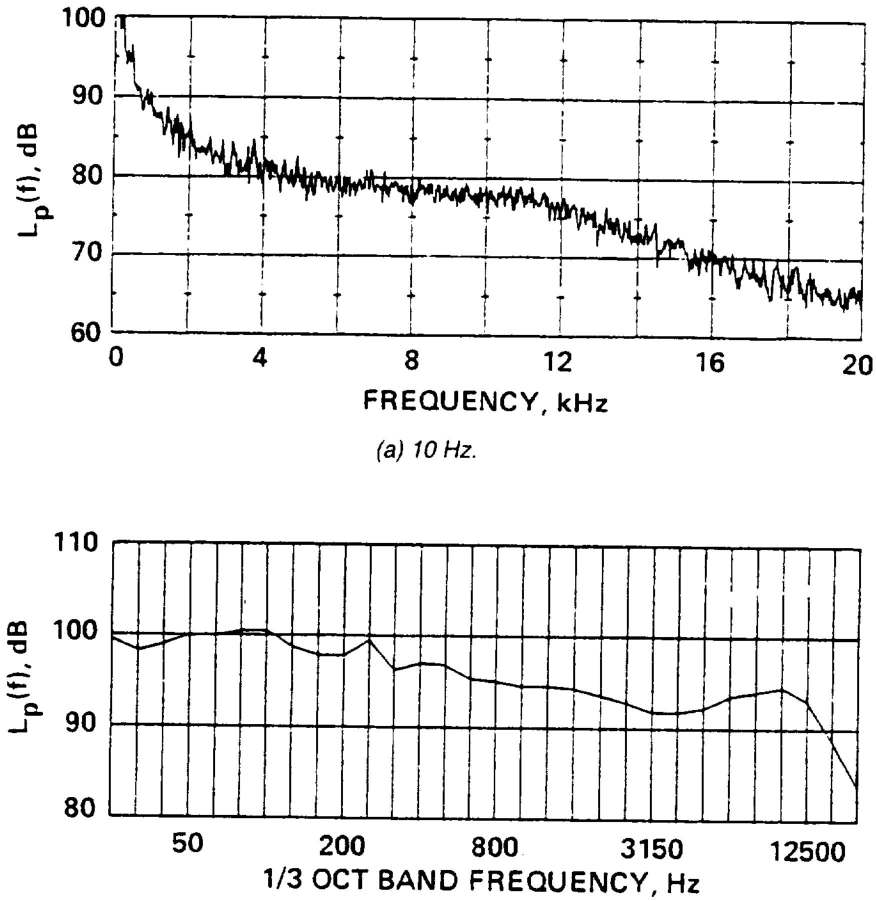


Figure 15. Predicted sound absorption coefficients of test section wall lining; 15.2 cm thick, 45 degree incidence.



(a) 10 Hz.

(b) One-third octave.

Figure 16. Test section background noise measured in narrow-band and third-octave spectra; U = 191 knots, 180 rpm fan speed, 32 degree fan blade pitch.

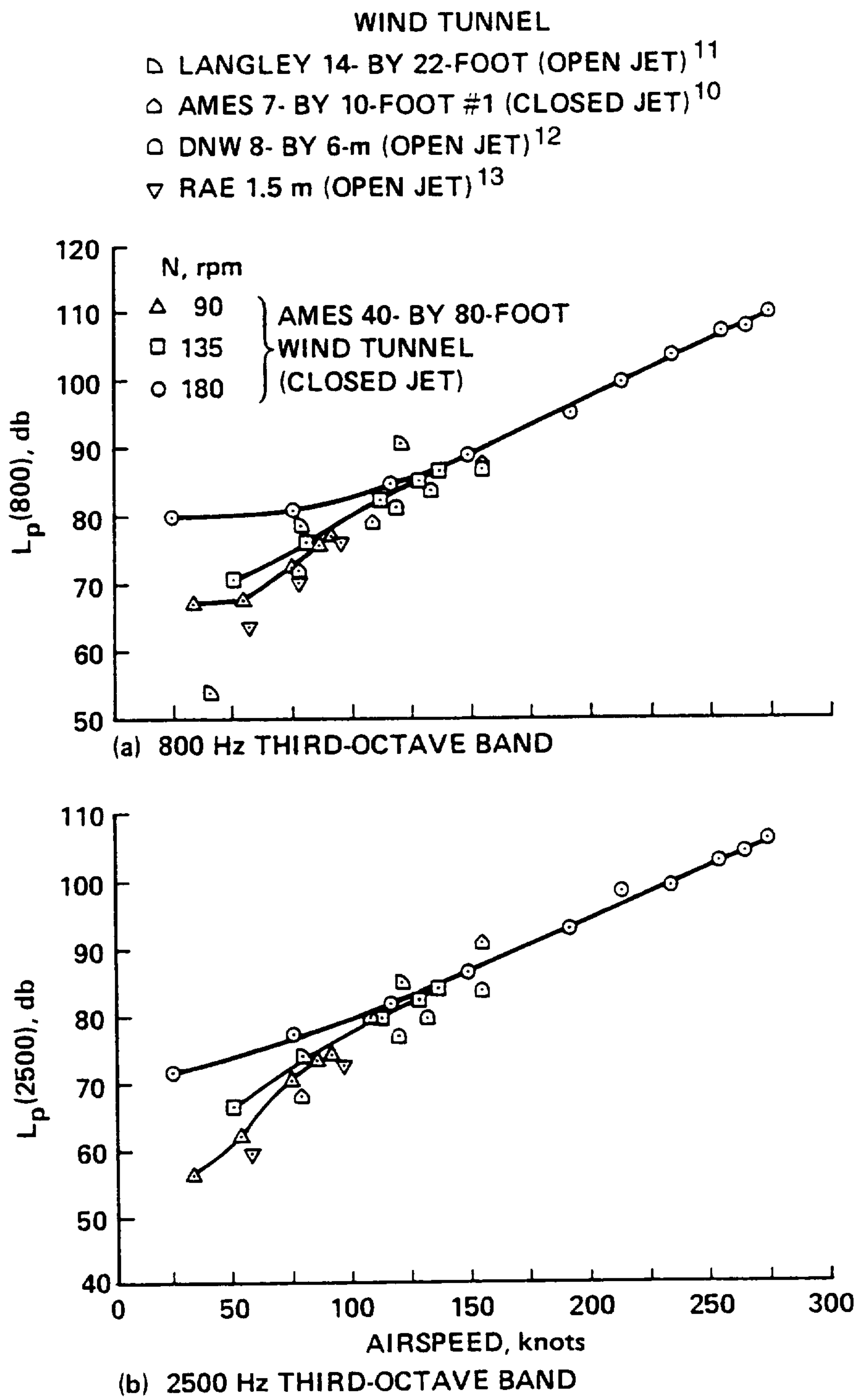


Figure 17. A comparison of inflow background noise vs. airspeed from five wind tunnels.

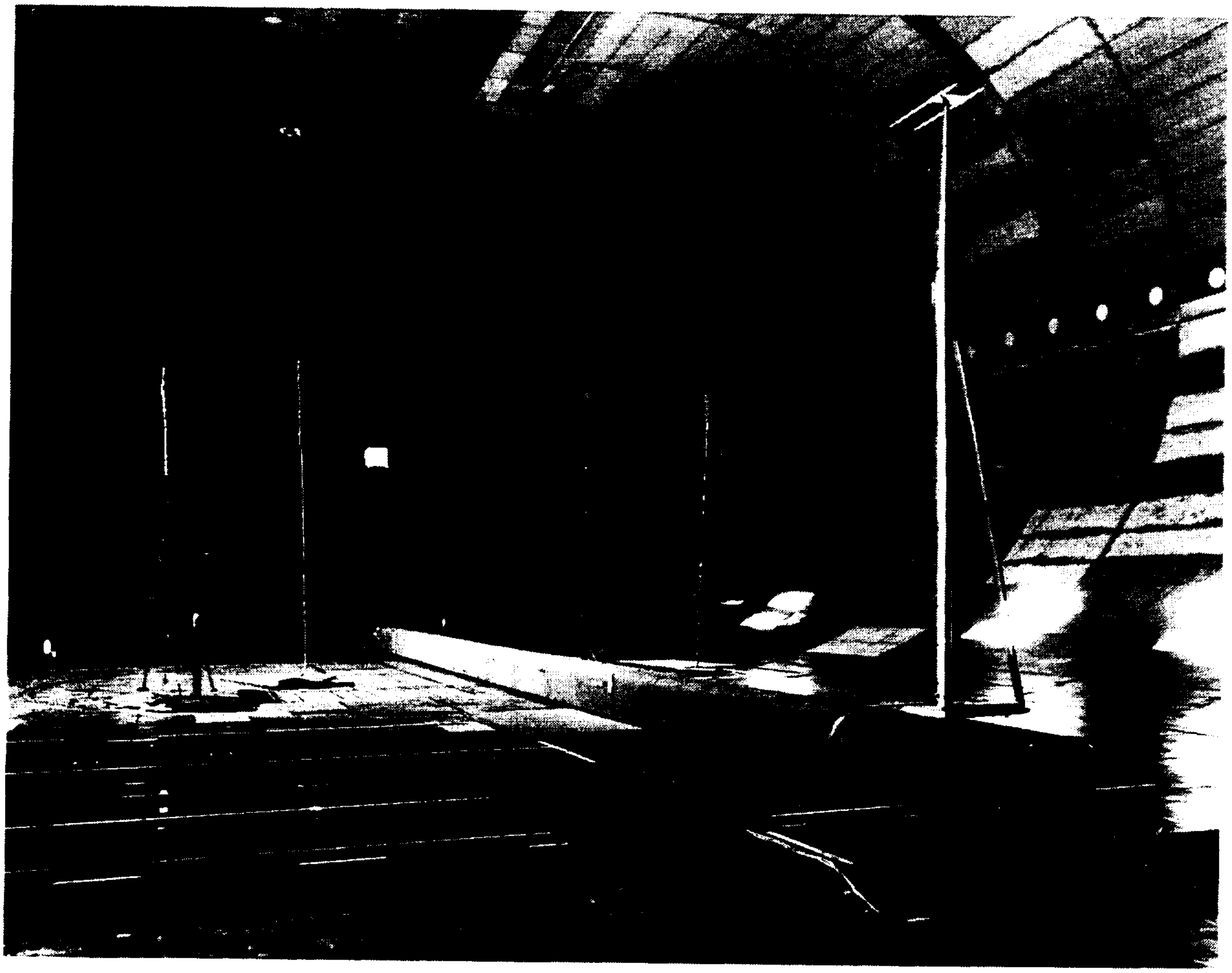


Figure 18. Acoustic survey apparatus with dual-microphone sensors installed in the test section during static calibration.

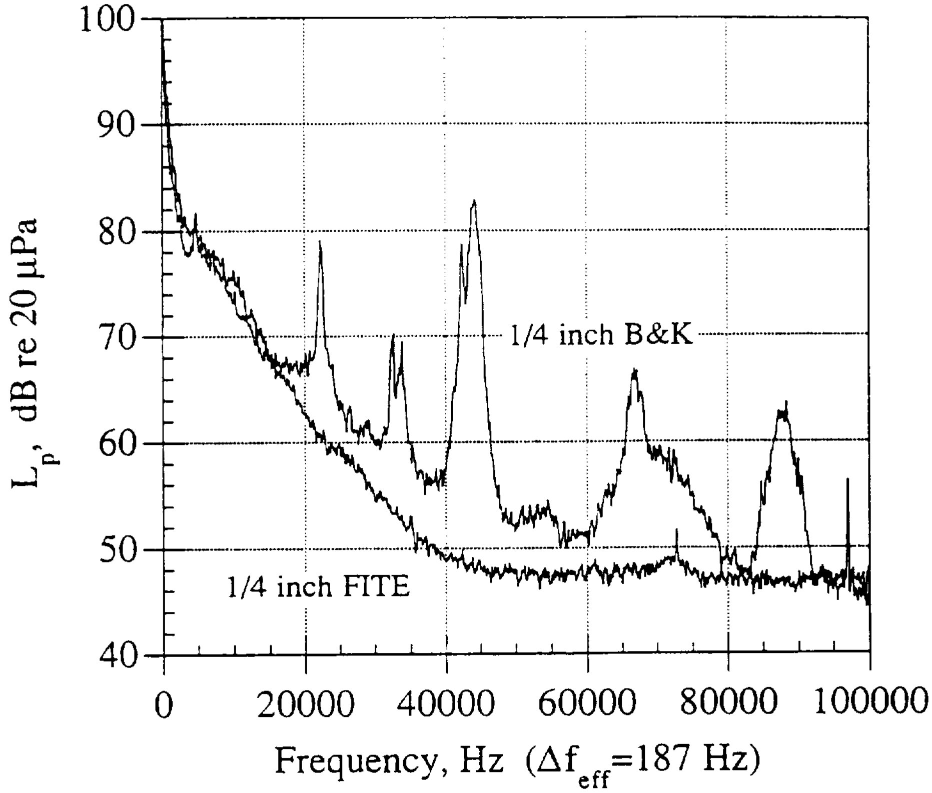


Figure 19. High-frequency tones at 160 knots reduced by the Ames flow-induced tone eliminator microphone nose cone.

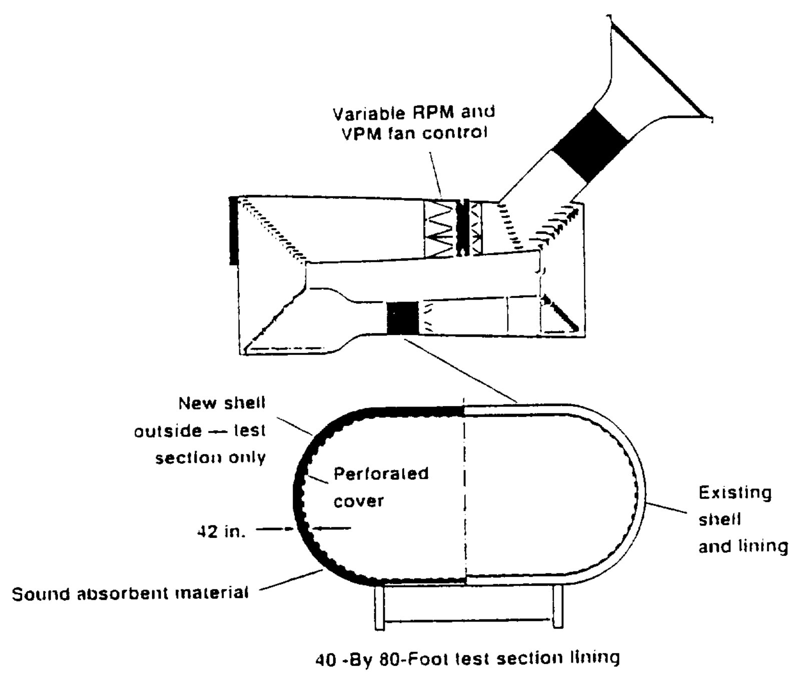


Figure 20. A sketch of the planned acoustic modifications to the 40 × 80.

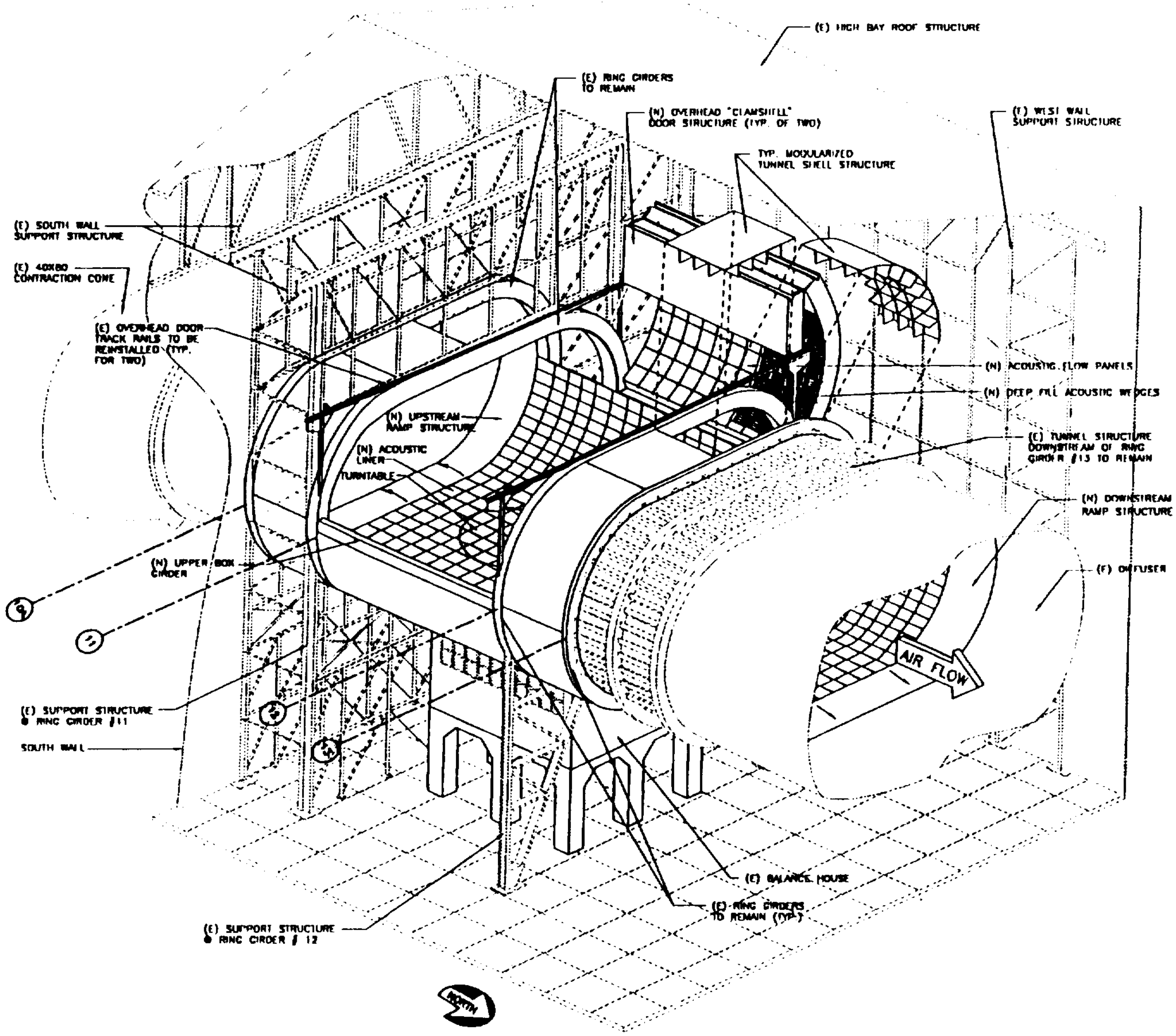


Figure 21. An isometric sketch of the new acoustic liner for the 40 × 80 test section.

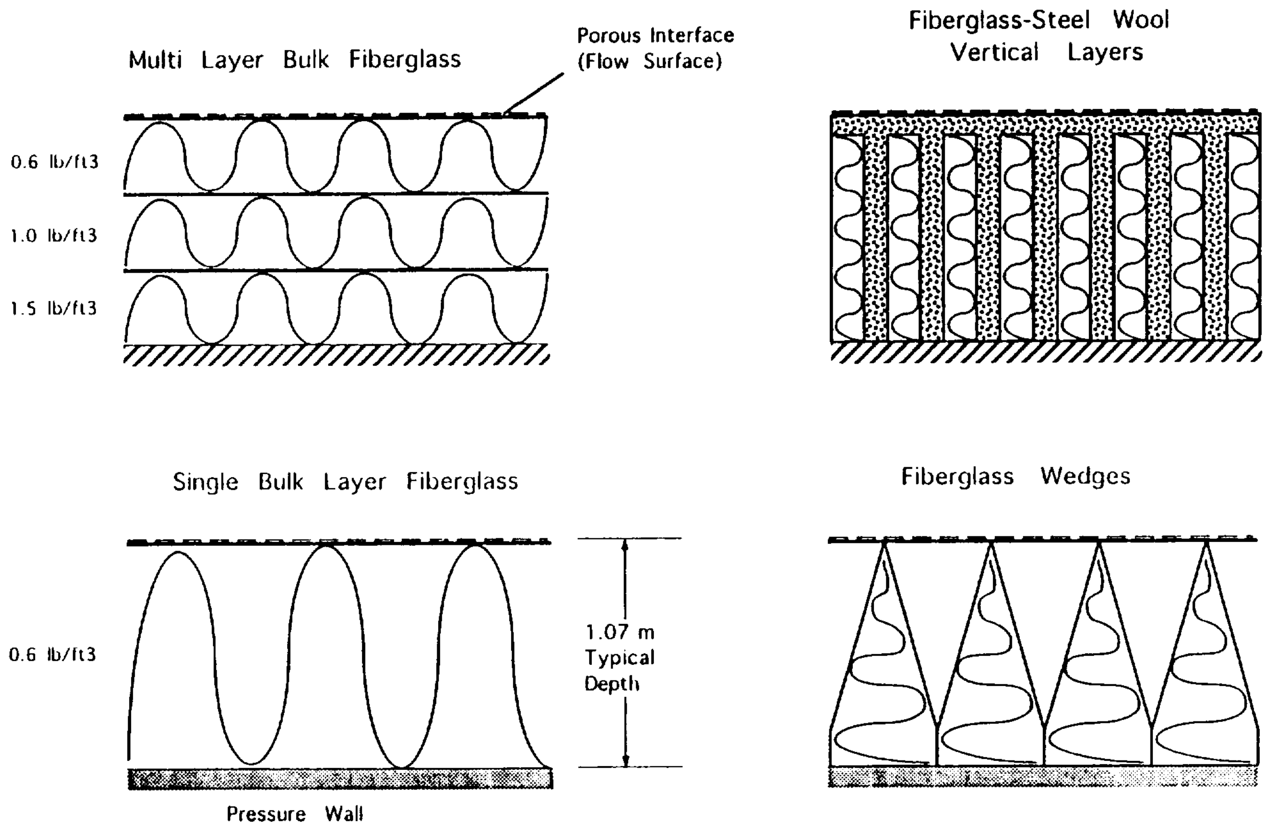


Figure 22. Four candidate design concepts for the 40 × 80 deep wall lining.

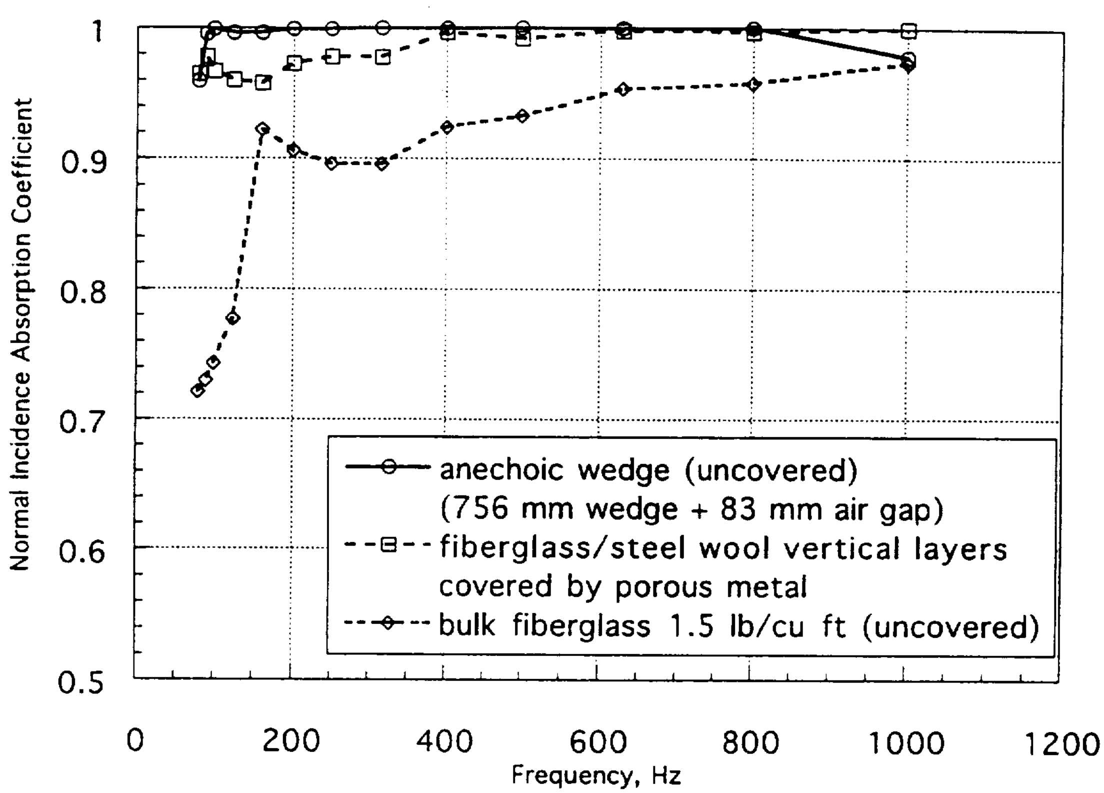


Figure 23. Sound absorption comparison of a multilayer bulk absorber, classical wedge, and poor man's wedge liner designs.

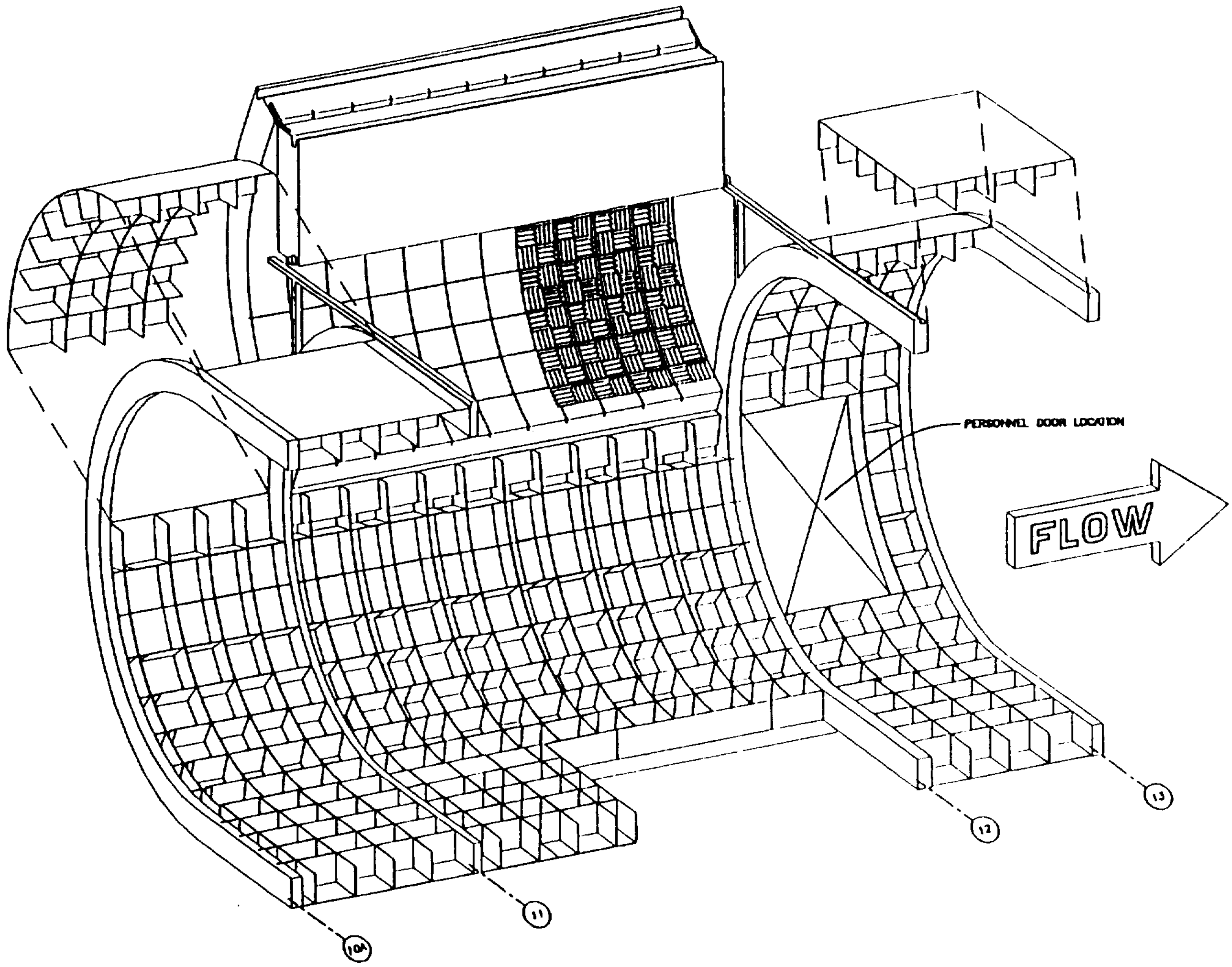


Figure 24. The 40 × 80 egg crate test section design made up of many hundred 4 × 4 foot compartments.

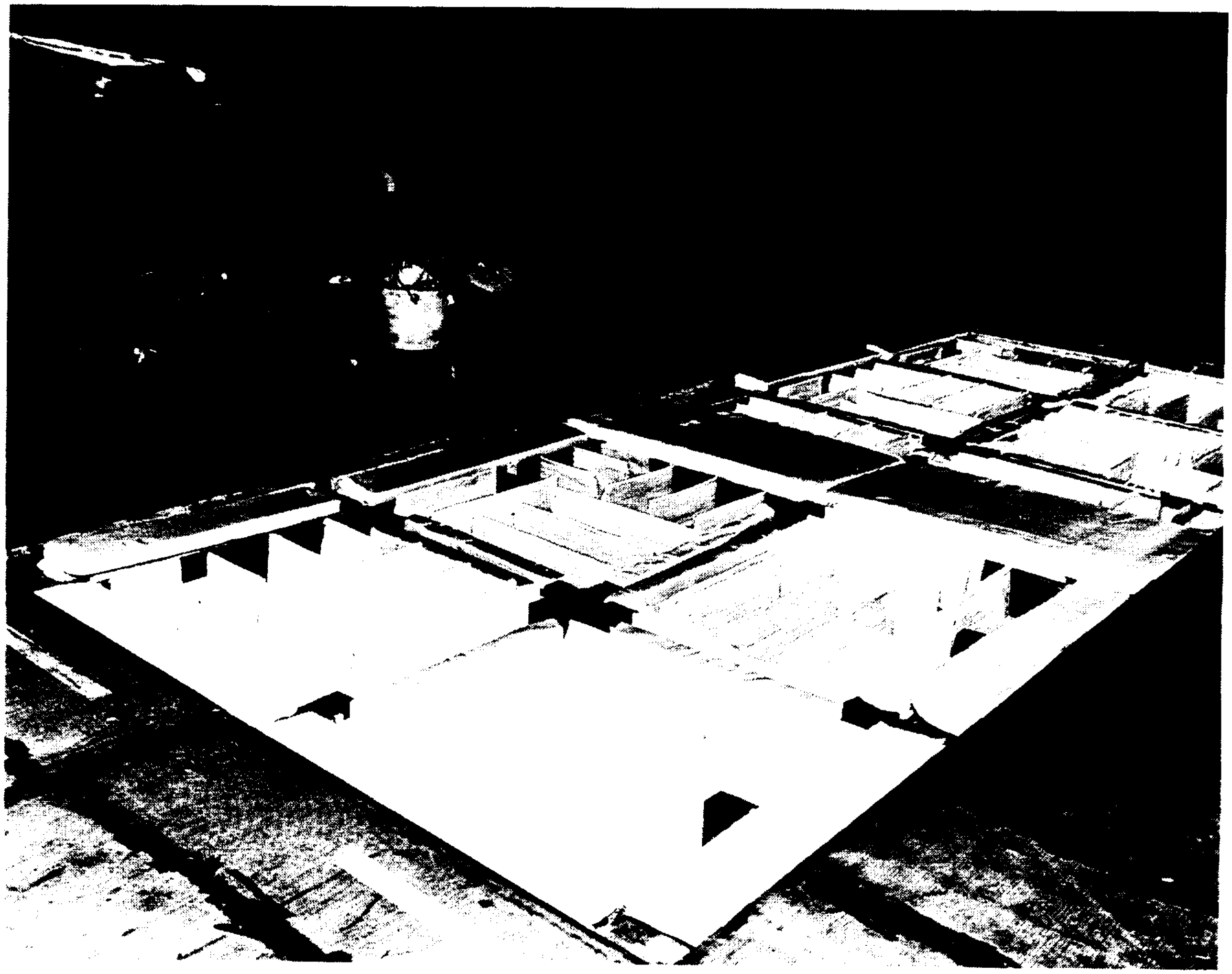


Figure 25. Deep liner test coupon installed in the test section floor. The porous cover is not shown.

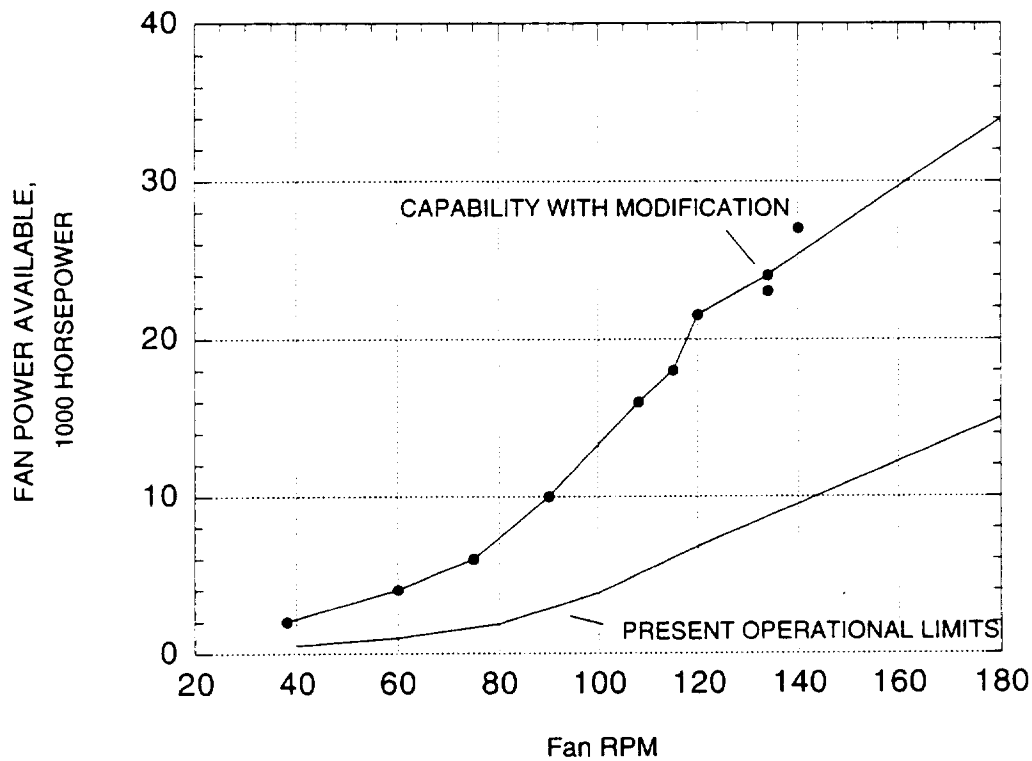


Figure 26. Maximum effective drive power available as a function of fan rpm (before and after interpole shunting).

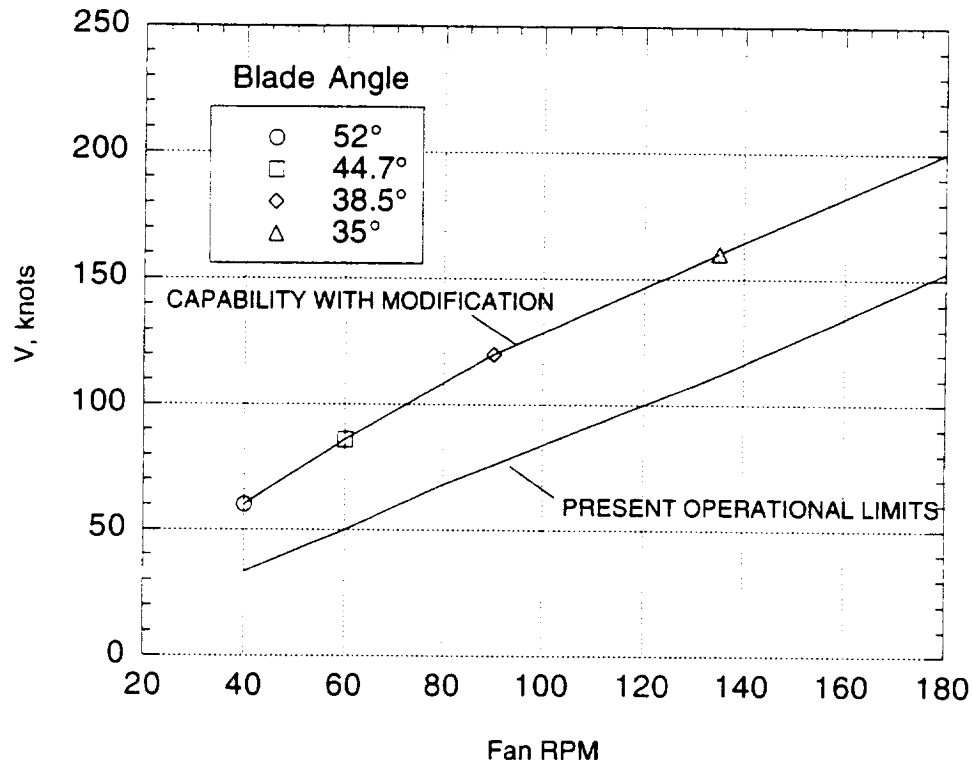


Figure 27. Maximum 40 × 80 test section velocities as a function of fan rpm (before and after interpole shunting).

Figure 28. Phased microphone array being calibrated in the 40 × 80.

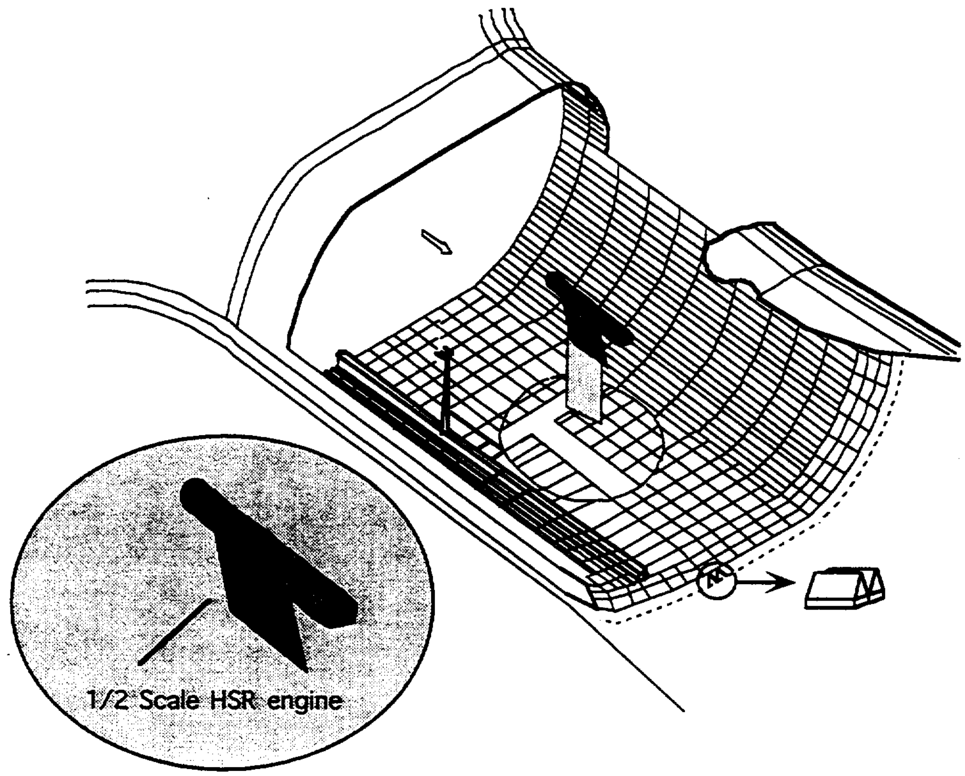


Figure 29. Proposed high-speed research large jet engine test in the modified 40 × 80.

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13. ABSTRACT *(Maximum 200 words)*

The development of a large-scale anechoic test facility where large models of engine/airframe/high-lift systems can be tested for both improved noise reduction and minimum performance degradation is described. The facility development is part of the effort to investigate economically viable methods of reducing second generation high speed civil transport noise during takeoff and climb-out that is now under way in the United States. This new capability will be achieved through acoustic modifications of NASA's second largest subsonic wind tunnel—the 40- by 80-Foot Wind Tunnel at the NASA Ames Research Center. Three major items are addressed in the design of this large anechoic and quiet wind tunnel: a new deep (42 inch (107 cm)) test section liner, expansion of the wind tunnel drive operating envelope at low rpm to reduce background noise, and other promising methods of improving signal-to-noise levels of inflow microphones. Current testing plans supporting the U.S. high speed civil transport program are also outlined.

14. SUBJECT TERMS

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