Suppression of Turbofan and Turbojet Engine Generated Noise

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SUPPRESSION OF TURBOFAN AND TURBOJET ENGINE GENERATED NOISE

BY

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A Research Report Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in Environmental Systems Management

FLORIDA TECHNOLOGICAL UNIVERSITY

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ABSTRACT

Every advance in the transformation of heat energy into mechanical energy has involved a noise problem, and in general it increases with the power production. The jet airplane is a good example: the large-scale turbulence of the exhaust gases in the jet forms an unusually intense source of sound the control of which is quite difficult. The additionally generated fan noises add characteristic fan tones which are particularly noticeable on landing approaches. The human ear is the vulnerable receiver of these noises, and the problem becomes one of deciding how much jet engine noise reduction is required for the comfort or safety of the receiver, and then to devise ways to achieve it.
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SUMMARY

Noise is a by-product of aircraft propulsion, and there is no way now to completely eliminate it without also eliminating the thrust required to drive the airplane itself. The noise of the gas turbine engine has, however, been steadily reduced as the use of this engine in subsonic commercial air transportation has grown. The noise of the initial transports with turbojet engines was characterized by the roar of the jet exhaust. Jet suppressors were developed and installed, but while increasing engine operating costs, they provided only small noise reductions.

The introduction of low-bypass ratio turbofan engines reduced exhaust noise but added characteristic fan tones which are especially noticeable during landing approaches. Recently developed technology for acoustically treating fan ducts has made it possible to suppress much of the objectionable fan tones with the result that jet exhaust noise is once again prominent at high engine power settings. However, the acoustical modification of engine nacelles for currently operating aircraft is quite expensive and is helpful only in reducing landing noise.

Research programs have provided the fan design and acoustic treatment technology for reducing fan noise in high-bypass ratio turbofan engines. Also, the high-bypass ratio engine provides both good fuel economy and low jet exhaust noise levels. Reduced fan noise and jet
noise characteristics have resulted in favorable public reaction to the new wide-bodied aircraft which use high-bypass engines.
THE INDUSTRY

In 1970, the thirty-seven United States scheduled airlines operated nearly 15,000 flights daily over 390,000 miles of regulated airlanes within the United States itself. Nearly 300,000 airline employees and 525 local and regional airports were involved with the air movement of nearly 180 million passengers. Over the past decade, these airlines have trebled the number of passengers carried, doubled their work force and achieved an annual revenue of $15 billion.

Since World War II, the airlines have passed through five equipment cycles in terms of the aircraft used in providing their service. They are now entering the sixth—the use of wide-body subsonic jet aircraft, powered by turbofan engines.

The 1970 commercial aircraft fleet consisted of 2,415 passenger and cargo aircraft powered by four different classifications of engines: piston, turboprop, turbojet, and turbofan. Only 18 percent of this fleet (444 aircraft) was powered by piston or turboprop engines, and accounted for only three percent of the capacity flown, according to the FAA (1).

Turbojet engines, introduced into commercial service in 1958, permitted a substantial improvement in aircraft carrying capacity and speed over the old piston engine-powered aircraft. About ten percent, or 244 aircraft, were powered by pure turbojet engines such as the Pratt & Whitney Aircraft JT3C, JT4A, and JT12, the General Electric CJ805-3 and the Rolls-Royce Avon engines. These aircraft accounted for
12 percent of the capacity flown. These engines have compressor stages to boost the pressure of the air entering the engine inlet, a combustion section where fuel is injected and the fuel and air mixture is burned, and a turbine section which drives the compressors and accessories. The thrust output of the engine is derived from the residual energy of the burned gases in the form of a high velocity exhaust. In the pure turbojet engine, all of the air entering the engine inlet passes through the combustor and turbines.

The bulk of the 1970 fleet, 1,727 aircraft, were powered by low-bypass turbofan engines such as the Pratt & Whitney JT3D and JT8D, the General Electric CJ805-23, and the Rolls-Royce Spey. While turbofan powered aircraft account for 72 percent of the domestic fleet, they are responsible for 85 percent of the capacity flown, as based on FAA (1) figures.

Turbofan engines are essentially a modification of pure turbojet engines to reduce overall fuel consumption. These engines differ from turbojet engines in that some of the air entering the inlet bypasses the engine combustion system and rejoins the burned gases at the exhaust tailpipe. This is accomplished by adding larger diameter (fan) stages in the front of the compressor, or in the case of the General Electric CJ805-23 discussed by Dodge (2), adding a compression stage as an extension of the turbine blading. The airflow split between the bypass air and the air entering the combustion system is customarily termed the bypass ratio. Turbofan engines having a ratio less than 2:1 are classified as low-bypass ratio engines. Those engines having higher than a 2:1 ratio are classified as high-bypass ratio engines.
In 1970, the Boeing 747 aircraft, powered by Pratt & Whitney Aircraft JT9D turbofan engines, was introduced into service. These engines discussed by Yaffee (3) are a new generation of high-bypass turbofans, with reduced noise and smoke emission characteristics, and more efficiency in fuel consumption per seat-mile flown than predecessor engines.

Presently being introduced into service are other wide-bodied aircraft such as the DC-10-10 and -30 series powered by the General Electric CF6-6D and -50A, respectively, the Pratt & Whitney JT9D-25 for the DC-10-20 model, and the L1011 powered by the Rolls-Royce RB-211-22B high-bypass turbofan. As expressed by Yaffee (3), General Electric (4), and Orchard (5), these powerplants are among the quietest to date, considering that the thrust is in the order of 50,000 pounds.

The FAA (6) projections into 1975 indicate that the number of pure turbojet-powered aircraft will be reduced by more than 50 percent through retirement or resale to foreign air carriers, and that by 1980 these aircraft will no longer be in the domestic inventory. The 1980 projection also states that the domestic fleet will consist of 3,100 aircraft, comprising 56 percent low-bypass turbofan-powered aircraft, 36 percent high-bypass turbofan-powered aircraft, and eight percent by the newest and one of the oldest types of aircraft, SST's and turboprop-driven. Approximately one-third of the high-bypass ratio turbofan aircraft will be powered by a more advanced series of turbofan engines.

The high-bypass second and third generation turbofan-powered aircraft whose powerplants incorporate improved noise and smoke
emission characteristics will account for over 60 percent of the flown capacity while holding total aircraft movements to a minimum. As in the 1970's, the 1980's are expected to produce continuing improvement in the noise emission characteristics of aircraft powerplants, through the introduction of even more advanced turbofan engines.
ENGINE NOISE GENERATION

Noise Generated by Turbulent Jet Mixing

Jet exhaust noise is characterized by the roaring sound which is particularly apparent during take-offs. The source of this noise is the severe turbulence generated outside the engine in the region where the high velocity exhaust stream mixes with the surrounding undisturbed air. Near the exhaust nozzle where the jet velocity is high, small eddy-size turbulence is generated, producing relatively high frequency random noise. Continuing downstream from the nozzle, lower frequency noise is produced by the larger eddy-size turbulence. The level of this noise is related primarily to the velocity of the exhaust gas stream relative to the surrounding air.

The major sources of all aerodynamic noise for a modern turbojet/turbofan engine are shown in Figure 1. What are considered jet noise consists of two parts: (1) noise generated by turbulence within the engine and emerging from the nozzle, and, (2) noise generated by the turbulent mixing of the jet. Physical processes involved in the jet mixing noises are first identified as pressure fluctuations associated with unsteady momentum transport: through compressibility they produce pulsations in the medium [dilatation theory as discussed in the article by Ribner (7)]. These dilatations generate a basic noise pattern of a mildly ellipsoidal nature. The final pattern evolves into a heart-shape owing to the dominating effects of convection of the
sources by the mean flow and refraction of the sound by the velocity and temperature gradients.

To present a "popular" picture of the noise generation process we might idealize the actual irregular eddying flow that we call turbulence: the turbulent regions of a jet are approximated as a random assortment of tiny sub-jets imbedded in and carried along by the main jet flow as in Figure 2. The configuration is shown to be unsteady. Upon the collision of two such sub-jets, the impact or stagnation region is compressed. As the jets then give way--by contact from other jets--the impact region rebounds. These compression and rebound actions cause emission of sound waves.

The pattern of jet noise as shown in Figure 3, with contours of equal intensity, evolves from development of the quadrupole theory as summarized by Hooker (8). A quadrupole noise source consists of four sources symmetrically arranged around the origin, each individual source being 180 degrees out of phase with its immediate neighbor. The pressure fluctuations from such an arrangement mutually cancel one another along the X-X and Y-Y axes, and the maximum noise is radiated in directions 45 degrees from the axes, as shown in Figure 4, and will evolve into the pattern as in Figure 5. Quadrupole sources of noise will be generated where vorticity is generated by shear forces, such as in the mixing region at the periphery of a jet.

When a high speed jet issues from a nozzle into the surrounding ambient air, some of the latter is picked up at the periphery of the jet by viscous action, is dragged along with it, and a mixing process takes
place. In the mixing region, a severe gradient of velocity exists normal to the jet, and due to the viscosity of the air, this gradient produces vortices and shear forces, which, in turn, produce quadrupole noise sources with their X-X axis along the direction of the jet. The process for both subsonic and supersonic jets is illustrated in Figure 6.

Townsend (9) explains that up to the end of the potential core, the noise generated per unit length of the jet remains constant, but once the potential core has ended, then mixing of equal and opposite vortices takes place, mutually cancelling one another, and the noise generated falls off extremely rapidly with distance downstream. Tests by Keast and Maidanik (10) confirmed these near-field properties. The supersonic jet has similar properties, except that the potential core is much longer.

The typical quadrupole field shows maximum noise intensity at 45 degrees to the jet axis in the rear arc. The noise to the side and forward of the engine is a mixture of the forward quadrupole field from the jet, and the monopole field from the engine intakes, together with the machinery noise from the compressors.

**Compressor/Fan Noise**

The jet noise dominates in most phases of turbojet operation. However, in the throttle-back landing approach the compressor whine from the inlet dominates in the forward hemisphere (Figure 7).

Fan noise, on the other hand, dominates over the jet noise in most phases of turbofan operation (Figure 8). On take-off the jet noise pre-empts only a certain conical zone to the rear; the fan whine
dominates everywhere else. Throttling back from the landing approach reduces the fan noise very slightly, but completely silences the jet noise in comparison. Thus, a turbofan engine makes almost as much noise on approach as on take-off.

Sound propagated forward through the inlet duct may have a spectrum as in Figure 9. Except for the lack of fan duct noise radiation, the turbojet engine has the same general compressor noise characteristics as the turbofan engine.

The relative importance of the three types of noise shown in Figure 9 depends on the type of engine and the measures for noise reduction that have been taken. Although multiple-tone noise has been noted on engines now in use, it has become a problem principally on the new-generation high-bypass-ratio engines, which have reduced discrete-frequency noise generation.

Copeland, Crigler, and Dibble (11) found that discrete-frequency noise occurs for both an isolated rotor and, more largely, for a rotor used with a stator. For the latter case, the sound generation follows the reasoning based on Figure 10. The stator blades leave a wake behind them with a velocity lower than the mean velocity of flow. When the rotor blade passes through the wake, a lift change arises. Such a lift change fluctuation occurs at each encounter between rotor and stator blade, resulting in a pressure pattern that rotates with a speed that depends on the number of rotor and stator blades and on the rotor speed.
Broadband noise was explained by Maestrello and McDaid (12) as resulting from blade lift fluctuations. Here the random discarding of vortices at the trailing edge of the rotor, as well as from oncoming turbulence, is responsible for the lift fluctuations. They assumed multiple-tone noise to be generated by a mechanism that is of secondary importance unless the relative tip speed of the rotor is supersonic. At such a speed a shock wave is formed at the leading edge of each blade. As the shock waves propagate through the inlet, the multiple-tone character of the sound is emphasized.

The level of fan noise is determined primarily by the number of fan blades and the speed at which they pass through the air around them. The higher the speed of the fan or the greater the number of blades, the higher the pitch of sound produced. This constitutes the "blade-passing frequency" which is so objectionable to the public. The frequency can be reduced, making it less irritating to the ear, by lowering the speed of the fan or reducing the number of blades. Doing that, however, also adversely affects the pressure ratio of the engine. That, in turn, affects thrust, which the industry does not want to sacrifice, if possible.

In a study of inlet noises, Copeland (13) found obvious results were the increase in noise levels with increasing rotor tip speeds. Increasing the tip speed for a given rotor was associated with an increase in blade loading. Increasing this loading for a constant tip speed had the effect of increasing the noise pressure level.
It should be observed that, in contrast to the high-bypass engine, which moves air at a lower velocity through the jet exhaust, the low-bypass engine compresses the air and forces it through to produce more compressor "whine".
ENVIRONMENTAL EFFECTS OF NOISE

Human Responses to Noise

Noise is difficult to picture, describe, or define, but it has become an environmental hazard. Some serious health effects have been correlated with prolonged exposure to noise. The medical opinion is that noise levels above 85 dBA over an extended period of time pose a serious threat to human hearing and the rest of the body. Besides obvious hearing effects on the ears, the heart, blood vessels, hormone output by glands, acid secretion by the stomach, and the ability of the eyes to focus can be adversely affected by sudden exposure to noise, as reported in Congressional hearings (14).

The young adult with normal hearing can perceive frequencies from about 20 to 20,000 Hz. However, the ear is not equally sensitive to all frequencies, being more sensitive to the frequencies from 1,000 to 4,000 Hz. Figure 11 depicts functions of frequency and dB, relating them to thresholds of perceived sounds.

Subjective responses such as Perceived Noise Level (PNdB); Effective Perceived Noise Level (EPNdB); Noise Exposure Forecast (NEF) and so on are terms not generally understood by the general public. Sound pressure converted to decibels (dB) is the scale most commonly used for public consumption. Bradbury (15) explains that power is most commonly measured on a scale with one-trillionth of a watt as the zero point, the most common reference point for the sound pressure scale is 0.0002 of one microbar. At this level, a whisper may be heard by young
healthy ears and thus 0.0002 microbar represents the zero decibel level on the sound pressure scale. Figure 12 shows the relationships between sound pressures and dB, and the relative energy necessary to proceed from step to step. The important thing to remember about the decibel scale is that it is not directly numerical, but logarithmic. For the average reader, there is a subjective approximation that an increase of ten dB would be judged, on the average, to make a sound twice as loud. The dB(A) is simply the A-weighted sound level resulting from a weighting of the sound signal that gives greater emphasis to components in the mid-frequency region, and less emphasis to components at lower and higher frequencies.

Even brief exposures to high level discrete frequencies and upper broadband frequencies as emitted in the vicinity of airports is cause for alarm, and is reason for possible physical harm. Progressive loss of hearing in the upper frequencies is the result, and it is a loss that can never be regained. As brought out by the Public Health Service (16), surveys have shown that residents living close to an airport and subject to the noise from frequent engine run-up operations on jet aircraft are showing high frequency hearing losses.

Noise Exposure Forecasts in the Community

Public concern about noise is beginning to be translated into action; for example, the noise argument against the supersonic transport and establishing the federal EPA Office of Noise Abatement and Control. The Environmental Protection Act requires that the environmental impact --including noise effects--be assessed before proceeding on federally
funded construction projects. Upon contemplating a large project, therefore, communities requiring federal financial assistance must actively assess possible community effects from noise, particularly as involves airport constructions.

A great deal of work has gone into the development of criteria for airport planning and of techniques for correlating human annoyance with such factors as the sound level, the signal duration, how many flyovers occur, and what time of day they occur. One type of result is shown in Figure 13 which describes the projected 1975 operations at O'Hare International Airport, Chicago. Outside contour 30, land is said to be normally acceptable for residential housing, but hospitals, schools, and churches may require special construction to shield against aircraft noise. Noise exposure forecasts for a typical single runway appear as in Figure 14.

While coordinated efforts to further reduce engine generated noises will continue with the FAA, NASA, and the industry, Franken and Page (17) say that one of the more appealing approaches to the community noise problem is land use planning--establishing land use patterns that separate the most objectionable aircraft noises from noise sensitive areas.

Over the years a great deal has been done to protect airport neighbors from aircraft noise exposure, and many programs are underway to accelerate this effort. However, there does not appear to be quick and simple solutions to the problem. Noise certifications by the FAA will be a big step in the right direction, and it will result in the gradual introduction of quieter aircraft during the 1970's.
IMPROVEMENTS ACCOMPLISHED OR UNDER CONSIDERATION

Exhaust Noise Suppression

The first generation of jet transports were powered by turbojet engines where exhaust noise was predominant due to the high exhaust gas stream velocities associated with this engine. The two basic techniques for reducing this type of noise involve: (1) changing the characteristics of the mixing of the high velocity hot exhaust gases with the surrounding air; and (2) reducing the relative velocity of the jet. As thrust from the engine is directly related to the exhaust velocity, the second approach can only be utilized on engines already in service by an operating procedure to be discussed at a later time in this paper. Therefore, noise reduction efforts have been concentrated on the first method. Exhaust noise suppressors, consisting of multitubed or lobed type nozzles, as in Figure 15, were developed for use on the commercial fleet to suppress jet exhaust roar. These suppressors brought about significant weight and drag penalties but they did produce modest noise reductions during take-off.

Since noise is largely a subjective phenomenon, a noise suppressor, in order to adequately fulfill its objective, must not merely reduce the physical quantity--sound pressure--but must provide a marked degree of noise reduction as interpreted by a major cross section of the listening public. Coles, Mihaloew and Swan (18) conclude that while the costs of suppressor R & D have been great, these may well be insignificant in comparison with the increment of the operational costs directly attributable to the reduction of noise. These operational
costs appear as: (1) reductions in engine efficiency, and (2) increases in airplane weight and in drag and structural complexity--resulting in increases in fuel consumption, flight time, maintenance and runway requirements, and reduction in payload or range. It is thus essential for economic operation that the internal and external aerodynamic losses attendant upon the installation of noise suppression devices to the aircraft be kept to a minimum.

In a continuing study of a configuration to reduce the noise of turbojet engines, experimenters have investigated lobe-type, slotted, corrugated, multitube, toothed, ejector, and multiorifice nozzle designs in an effort to break up the high-velocity jet flow and accelerate the mixing of the jet with the surrounding air. In tests for the eight-lobed suppressor nozzle configuration, Schmeer, Salters, and Cassetti (19) found that the static thrust showed loss in take-off power of approximately 3.5 percent. Part of this loss was regained by the addition of an ejector. Acoustic measurements for ground operation showed reductions of up to five dB in sound pressure level and three dB in total radiated acoustic power at high engine power conditions for this nozzle configuration (Figure 16).

The slot nozzle exposes a large part of the jet to the secondary air by virtue of its large perimeter. The noise suppressing capabilities of a slot nozzle are confined primarily to changes in the directivity and frequency of the noise. The sound power reduction was only in the order of three dB. Coles (20) confirmed that maximum noise reduction occurs at a spacing-to-width ratio of approximately 1.5 to
2.0, because of interference characteristics between nozzles. He was further able to predict from turbulence data of a circular nozzle and a single long slot nozzle, and later verify by experiment, that the noise output of the slot is one-half that of the circular nozzle.

With the advent of the turbofan engine, wherein exhaust suppressors are not used on present installations, emphasis on suppressor design and test has diminished. Dramatic improvements are not readily envisioned. Instead, modified combinations of known techniques will probably be explored, such as, alteration of the mixing patterns, including use of injectors, the use of lined absorbers, and the concept of shielding by the wing as discussed by Ribner (7).

Noise Reduction From Turbofan Engines

Jet exhaust noise levels were reduced appreciably with the introduction of the turbofan engine. Compared to turbojet engines, the turbofan engine has higher airflows and thus can produce a given thrust with lower exhaust velocities. The first generation turbofan engines have approximately 25 percent lower exhaust gas velocities than turbojet engines. As the level of exhaust noise is related to about the eighth power of the relative exhaust gas velocity, significant reductions in jet exhaust noise were achieved. Jet exhaust suppressors on the turbofan engine does not bring further significant reductions because the benefits from a suppressor decrease as jet velocity is decreased. At the jet velocities associated with the turbofan engine, types of suppressors developed to date would provide only a small reduction in jet exhaust noise with no significant
reduction in overall noise. Consequently, jet suppressors have not been used on airplanes powered by turbofan engines.

With reduced levels of jet exhaust noise, the noise from the turbofan engine is dominated by the shrill whine of fan blade passing noise. Although a similar type of noise is generated by turbojet engine compressors, it is not as apparent, since it is partially masked by the sound of the jet exhaust. In the turbofan engine this noise propagates both forward from the inlet and rearward from the fan discharge ducts, whereas the inlet is the only source of this noise in turbojet engines.

After extensive research, a theory was advanced at Pratt & Whitney Aircraft by Tyler and Sofrin (21) which relates the generation of the discrete fan blade passing noise to the number of blades and vanes in the fan section of the engine. In the light of this concept, original production JT3D engines were modified to incorporate more desirable numbers of fan blades and vanes, and the axial spacing of the fan blade and vane rows was optimized for minimum noise generation. Subsequent first generation turbofan engines such as the Pratt & Whitney Aircraft JT8D made use of the theory to control the generation of fan noise to the extent practicable. According to Dodge (2) the General Electric CJ805-23 turbofan engine was designed without inlet guide vanes, so that fan noise was considerably reduced.

With the advent of the second generation high-bypass ratio turbofan engine, it became possible to take advantage of preceding research on fan noise. New high-bypass ratio turbofan engines have been developed for commercial service to power the "wide-body" aircraft as
the Boeing 747, the McDonnell-Douglas DC-10, the Lockheed L-1011, and proposed foreign aircraft. Because these large engines produce well over twice as much thrust as the largest commercial powerplants in previous service, there was concern that noise levels would escalate. Contrariwise, these new powerplants are significantly less noisy than earlier smaller engines.

Noise level improvements were not accidental. Noise suppression features of the new generation of commercial high-bypass ratio powerplants include the use of only one fan stage, with no inlet guide vanes forward of the fan, and fan exit guide vanes spaced well aft. The acoustically optimum numbers of blades and exit guide vanes are used. These features reduce the loudness of the tones from the fan. Sound absorbing linings are used in the inlet and discharge ducts to further suppress fan noise. Significantly lower levels of jet exhaust noise are produced as a result of the low jet velocity of the high-bypass ratio cycle.

The turbofan engine, from the very principle of its design, produced less exhaust noise than a conventional jet of the same power. A turbofan engine has its main exhaust stream surrounded by a "ring" of much lower velocity air expelled by the fan. The fan air serves to cushion the main exhaust stream, thereby reducing the overall shearing effect. At the same time, the fan stream added to the engine's total exhaust, increasing the total thrust produced.

In the high-bypass turbofan, most of the air bypasses the main jet, or "core engine", as in Figure 17, and is exhausted by the fan
(which is fairly large in diameter compared to the basic engine dimensions). Since the velocity of the fan exhaust is much lower than that from the core engine, the high-bypass design, in effect, lowers the overall exhaust velocity required to produce a given thrust level. This means less shearing, and less noise.

Bypassed air, then, circumvents the combustion chamber and turbine and rejoins the hot gas stream in the tailpipe; the jet temperature is therefore lower than that of the turbojet engine of the same thrust, and consequently the velocity is also lower and the mass flow, and jet diameter, correspondingly higher.

While the fan has been getting primary attention, efforts in sound reduction are being made on all parts of the engine package. Examples are: noise research on low-pressure turbines; acoustic treatment of the core jet nozzles to suppress noise going out the exhaust; application of high-temperature honeycomb acoustic treatment, similar in acoustic principle to that used in the fan frame, to the core engine. Typical areas of acoustic treatment are as shown in Figures 18 and 19, with Figure 20 graphically portraying benefits achieved as a relation of frequency and sound pressure level.

Noise Reduction From Operational Procedures

The EPA enthusiasts (22) say that further reductions in community noise exposure are (and can be) obtained by the use of revised aircraft operating procedures. These procedures include routing aircraft away from noise-critical areas, thrust reductions following take-off, and dispersion of departure routes. Routing procedures, such as making turns away
from densely populated areas, are used on both departures and landing approaches. Coastal airports take advantage of these procedures to route traffic over the water as quickly as safety of flight will permit. These procedures are also aided by using preferential runways to direct traffic away from noise sensitive areas and by optimizing aircraft climb-out procedures.

A strong factor in subjective response to aircraft noise is the frequency of over-flights. This factor has been minimized during take-off operations by dispersing departure routes, avoiding the concentration of all flights over a specific populated area.

An additional factor which has contributed to the control of aircraft noise is the use of noise monitoring systems at airports as brought out in the Congressional hearings (14). Initial systems were set up by the Port of New York Authority at Kennedy Airport, where take-off noise levels near the airport community boundaries were limited to 112 PNdB. By the use of monitoring microphones, violations of this criteria can be detected, and the offending aircraft notified. The airport operator can enforce the criteria by threatening an airline having excessive violations with the loss of the right to airport access. This system provides the incentive for airlines to reduce power when passing over the communities near the airport. Similar noise monitoring systems are now in operation at many of the major airports in the world.

The procedure for Washington National Airport features retention of maximum take-off power until the airplanes reach 3,000 feet, as a substitute for the current (1972) noise abatement procedure which
involves a power reduction at about 400 feet followed by a 500-fpm climb rate until the airplane reached 3,000 feet.

The basic concept envisioned by the FAA (6) is to reduce the high noise level area on the ground by getting the airplane higher quicker. The new procedure has little noise reduction effect at close-in measuring points, but it has significant effect as distances increase from the end of the runway. FAA officials estimate a 15 PNdB reduction at seven to eight miles from the end of the runway with this new procedure.

The program does not require pilots to follow the new profile, but cooperation has been reportedly good. Following the profile completely requires maintaining 10 knots above V2, a take-off safety speed, which varies with aircraft. This can produce deck angles of up to 20 degrees, and some pilots have been reluctant to comply as a result.

The techniques of using preferential runways and making turns during climbout are aimed at shifting the noisiest parts of the noise pattern away from the residential areas. Techniques of low speed climbout and power reductions soon after take-off capitalize on the powerful effect of decreased thrust, with altitude playing an important role. Airline pilots object to all but the use of preferential runways on the ground that they reduce the margin of safety to unacceptable levels.

**Current Research Efforts**

A wide variety of programs sponsored both by private industry and by the Government have been underway to research various facets of
the engine noise problem. Some of these programs could result in near-term benefits to the public and others are directed towards longer-term knowledge which may improve engine design for the future.

According to Yaffee (23), recent NASA funded programs with Boeing and McDonnell-Douglas to demonstrate the effects of acoustically treated inlets and fan ducts on the 707 and DC-8 aircraft powered by JT3D engines benefit the public in two possible ways. Results of these tests and other concurrent industry-sponsored tests advanced acoustical treatment technology in time to be exploited by the high-bypass ratio installations now going into service. These tests also provided factual data on the effects of treated nacelles in flight and performance characteristics as well as noise suppression for specific models of 707 and DC-8 aircraft. These data are available to help assess the cost and possible noise reduction benefits from retrofit of the types of four-engine aircraft used for the test. Since the sound pressure levels in the inlet duct of commercial turbofan engine aircraft can easily exceed 170 dB, the effectiveness of sound absorbent linings at the intake can be appreciated, even though weight and expense are added as penalties.

Based on studies by Powell and Van Houten (24), one of the most common duct lining concepts for use in jet engines consists of a thin sheet of absorbing material supported by a honeycomb structure, which is backed by an impervious sheet of aluminum. The absorbing material is most commonly a felted or woven metal cloth, or fiberglass reinforced epoxy or polyimid, or other similar material. This structure forms a resonant absorber on the order of one inch thick.
Zorumski (25) says that a practical method for reducing noise from turbofan engines is to install "broad-band resonators" inside the engine nacelles. Because of considerations of weight, safety, and endurance, these resonators are usually made of thin porous sheets of material (either metallic or fiberglass-plastic) which are fastened to a honeycomb wall structure. The cavities behind the porous sheet are usually about one-quarter wavelength deep, since this depth gives good absorbing qualities. In general, Zorumski continues, the greater the exposed area of porous material, the more the sound is absorbed, so that engine designers must look for ways to alter the engine geometry to increase this area. Of course, this increase must be accomplished without upsetting the basic flow field within the engine, which presumably has already been optimized on a performance basis.

Tests on variable geometry choked inlet flows by Chestnut and Clark (26) showed that pure tones radiating from an axial-flow compressor can be reduced by choking in the inlet. Also, Cawthorn, Morris, and Hayes (27) investigated the possible method of reducing compressor noise heard on the ground in front of the airplane during an approach by choking the inlet and thus creating a small region of supersonic flow. Theoretically, the sound cannot propagate forward through this choked flow region and thus cannot exit from the mouth of the inlet.

The use of other means of nearly passive techniques in alleviating jet engine noise, such as by the injection of water and solid particles, has been suggested; experimental investigations have been made of water injection into jet exhausts. The results have not
indicated sufficient noise reduction for the amount of injectant required.

An interesting technique reported on by Manson, Lieberman, and Burge (28), concerned the use of foam injection for jet noise suppression. Injected foam broke up into flakes, which absorbed sound energy by resonance in the foam, or served as scatterers; hence, the more effective absorption of high frequency sounds. Much of the basic work on the use of foam injections was conducted on small, cold jets, but yielded results which could be applicable to engine jets. When foam was injected into the cold nitrogen jet, the perceived noise level was decreased. The decrease was highest for high noise emission levels and for high frequencies. This finding was in agreement with the hypothesis that foam acts as a resonating energy absorber whose absorption capability is most pronounced in the audible high frequency range (one to 10 kHz).

Use of a single fan stage and limiting the tip speeds are effective. In addition, the total perceived noise can be reduced by properly tuned acoustic lining in the fan ducts. Noise studies made by Crigler and Copeland (29) showed that the interaction tones specifically can be kept down by adequate axial spacing of the rows of rotors and stators (about two chords) and by selecting the difference in number between rotor and stator blades so that most of the interaction modes will decay. Graphical results of rotor-stator spacing effects and of effects based on number of blades are shown in Figures 21 and 22. Results of these studies were to have an important bearing on the "Quiet Engine" developments, to be discussed later.
With a three-spool arrangement (Figure 23), another noise reduction feature becomes possible in the form of a variable final nozzle which can be used to slow down the fan and the low-pressure shaft system (including the fan turbine) while maintaining constant thrust. Closing the nozzle alters the pressure ratio across the turbines, and because the turbine stages will behave almost as though the flow through them is choked, the bulk of this change will be felt by the final, low-pressure stages. The net effect is a reduction in both fan noise and turbine-generated noise.

The Rolls-Royce/Snecma M45H engine core (Figure 24) was selected for an ultra-quiet engine that would utilize a fixed-pitch front fan or a variable-pitch front fan in various versions. The variable-pitch version is now the RB.410 engine. Coleman (30) says this engine is below FAA noise requirements in sideline, 1,500 foot flyover and approach modes. Basic design has called for soundproofing the fan duct, using Nomex honeycomb that is plated with stainless steel perforated with small holes to reduce forward noise. Even without such insulation, an acceptable noise footprint of 5.4 square miles has been achieved.

As detailed by their Aircraft Engine Group (31), the General Electric Company pioneered the high-bypass turbofan design during the competition for the power plant for the USAF C-5. In addition to its prime design objective of high thrust and improved specific fuel consumption over the present generation of turbofans, the TF-39 high-bypass turbofan resulted in a tertiary benefit of much lower sound levels than present turbofans - despite the fact that the engine is nearly twice as powerful. The high-bypass turbofan is basically a
low-sound design because 80 percent of the thrust comes from the fan that produces a larger, slower jet velocity than today's turbofans that have a smaller, higher velocity exhaust. Thus the TF-39, with no sound treatment, offered an immediate improvement on noise level.

From this point, the GE CF6 design was studied and modifications of turbomachinery design of the fan made even further acoustic improvements. For example, no inlet guide vanes resulted in a 4 dB reduction, and changed spacing and the ratio of fan rotor blades to stator blades gave an additional 6-7 dB reduction.

According to Yaffee (23), the NASA Quiet Engine "A" has been installed in an experimental quiet nacelle developed under a contract by the Boeing Company. First results from acoustic tests at the Lewis Research Center showed the nacelle cut engine noise an additional 9-11 EPNdB to 89 EPNdB on approach and 7-8 EPNdB to 90 EPNdB on take-off for a four-engine transport such as the Boeing 707 or McDonnell-Douglas DC-8. With the General Electric engine outside of the nacelle, Lewis engineers measured 97 EPNdB take-off noise and 98 EPNdB approach noise. Comparable GE figures were 98 EPNdB for take-off and 100 EPNdB on approach. Three-ring inlet and inside of the nacelle are extensively treated with polymide noise absorptive materials. The nacelle also has a splitter ring in the fan exhaust duct.

In the early part of the Quiet Engine Program a rather wide range of engine configurations was examined. A set of design constraints (Table 1) was selected within which engines were designed in more detail under contract by Allison Division of General Motors
Corporation (Contract NAS 3-10496), Pratt & Whitney Division of United Aircraft Corporation (Contract NAS 3-10497) and the General Electric Company (Contract NAS 3-11166).

In discussing the program, Dramer, et al (32) confirmed that screening of various engine layout designs resulted in a conclusion that a quiet engine should have a bypass ratio in the range of 5 to 6. The cruise thrust was set at 4,900 pounds; the corresponding take-off thrust for such an engine, about 22,000 pounds. This compared with thrust ratings of such current aircraft as the Boeing 707 and the McDonnell-Douglas DC-8. The fan was specified to be mounted in a shaft by itself with no compressor stages so that changes in fan configuration and speed could be achieved with the least impact on the rest of the engine.

In order to minimize the noise associated with the single-stage fan, inlet guide vanes were ruled out and the spacing between rotor and stator blade rows was specified to be at least 2 rotor chords. It was desired to have the flow subsonic over the blades in order to eliminate the noise associated with supersonic relative velocities, the so-called "shock noise" or "buzz-saw noise". In order to achieve subsonic relative flow, the tip speed at take-off could be a maximum of about 1,000 ft/sec. These engines operate so that the tip speed at take-off is about 10 percent lower than the value at the cruise condition. Thus, the take-off tip-speed limit of 1,000 ft/sec corresponds to a cruise tip speed of 1,100 ft/sec.

In order to achieve an overall compression ratio of 18 with
a fan pressure ratio of 1.5, the pressure ratio required of the compressor is 12. Both two-spool and three-spool engines were considered. They differ in that the main compressor is made up of one or two rotors.

Turbine temperature at cruise and take-off are important because they set the jet noise level. The design turbine temperature must be 1,775 degrees F or lower in order to assure adequately low jet noise levels. This design-turbine-temperature limit of 1,775 degrees F corresponds to a take-off turbine temperature of 2,000 degrees F.

The engine designed by Allison is a three-spool engine as shown in Figure 25. The single-stage fan develops a pressure ratio of 1.5 at cruise and has a diameter of 74 inches. The tip speed at take-off is 1,020 ft/sec. The fan blade has a chord at the tip of 6.2 inches and an aspect ratio of 3. The fan is driven by a five-stage turbine, offset somewhat from the gas generator turbine in order to obtain higher tip speed at a given rotational speed. The overall compression ratio of 24 is achieved with a 16:1 compressor consisting of two rotors having eight stages and pressure ratios of 4. Each rotor is driven by a single-stage turbine. Noise performance is summarized as 104 PNdB at take-off power, 1,000-ft altitude, and 105 PNdB at approach power, 325-ft altitude. Further reductions of 10 PNdB are expected with the use of acoustically lined nacelles. The data is an estimation procedure by Allison based on an empirical correlation on several fan parameters, the most important of which takes into account the blade spacing, loading, and the presence of upstream blade rows, if any.
The Pratt & Whitney engine designed within the constraints is shown in Figure 26. The single-stage fan has a take-off tip speed of 1,000 ft/sec and develops a pressure ratio at cruise of 1.6. The rotor blade has a rather long chord of 7 inches at the tip and an aspect ratio of 2.2. The fan diameter is 68.9 inches. The engine has two spools. The single-rotor compressor develops a pressure ratio of 12.5 and has five stages of variable stators. The compressor is driven by a two-stage high-pressure turbine. The first stator, first rotor, and second stator are air-cooled. Noise performance summary showed expected 106 PNdB at take-off power, 1,000-ft altitude, and 104 PNdB at approach power, 325-ft altitude. Again, a further 10 PNdB reduction was anticipated by the use of acoustically lined nacelles.

The fan noise is still the dominant source and suppressors would benefit the ground observer. The fan noise prediction method at Pratt & Whitney is based on test data obtained with JT3D and JT9D engines. The prime correlating parameter is the rotational tip speed of the fan.

The design studies by Allison and Pratt & Whitney indicated that the combination of the high-bypass-ratio engine and moderate turbine temperatures result in marked reductions in jet noise. Estimates of the fan noise reduction possible with a low-tip-speed fan are significant but the fan remains the dominant noise source.

The NASA plans to build and test several engines of the general character just discussed.

That portion of the Quiet Engine Program contracted to GE in
mid-1969 is expected to be completed early in 1973. The contract initially called for the design, development and testing of two experimental, quiet turbofan engines and four different single-stage fans - A, B, C and X. The engines used in the program are basically a composite of GE's TF-39 and CF6 core engines derated to run at 22,000 pounds thrust plus the experimental fans and their turbines. (Figure 27).

Fans A and B are low tip-speed (1,160 fps) fans with high aerodynamic loadings to achieve the design pressure ratio of 1.5. They are driven by moderately loaded four-stage low-pressure turbines. Fan C has a high design tip-speed (1,550 fps) with moderate aerodynamic loading. Its design pressure ratio is 1.6 and it is driven by a heavily loaded two-stage turbine. Fan X was to incorporate all the best features of A, B and C.

Yaffee (23) explains that fan A proved to be aerodynamically and mechanically superior and was accepted by the Lewis Research Center as the fan for the first quiet engine. Using fan A on the derated TF-39/CF6 engine core, Lewis tests have shown that, if installed on a four-engine transport such as the Boeing 707 or McDonnell-Douglas DC-8, and without any special acoustic suppression in the nacelles, would produce noise levels of 100 EPNdB on approach compared with 119.5 EPNdB for present JT3D-powered DC-8 and 707 aircraft and 98 EPNdB on take-off (at FAR Part 36 measuring points) versus 113 EPNdB for the DC-8 and 707.

Coincident with the Quiet Engine Project, GE developed a new broadband sound absorber design as part of the engine nacelle itself. Currently being used with the CF6 family of engines, this treatment
not only enables absorption of sound over a wide range of frequencies, but also provides a surface which will not be affected by water, oil and dirt for prolonged periods of time. This new design can be fabricated from reinforced plastic and metal and has sufficient strength to serve as a structural component of the engine.

Figure 28 shows the CF6 fan configurations incorporating the several significant features which contribute directly to noise levels. The areas of shading show the wide application of acoustical absorption materials developed by GE.

**Regulatory Requirements**

The passage in 1968 by Congress of Public Law 90-411 which directed the Federal Aviation Administration to take all measures feasible to reduce the escalation of aircraft noise has resulted in rulemaking to include noise demonstration requirements as part of the aircraft certification process prior to production for sale in the United States. Rules were issued in December 1969 for the new wide-bodied aircraft and for future subsonic aircraft; others are planned for supersonic aircraft, V/STOL aircraft and for retrofit of current aircraft. In establishing noise rules, it appears necessary to evolve a meaningful demonstration procedure and to set noise limits which are economically acceptable and attainable with today's technology.

The FAA promulgated Federal Air Regulation 36 in 1969 with which to set noise limits for commercial aircraft. Used is the international Effective Perceived Noise Decibel (EPNdB) in measuring noise levels. EPNdB includes tone levels as well as duration of noise and
varies from -10 to +5 difference from dB(A) for the same sound. The FAA noise limits for take-off and landing are 108 EPNdB for aircraft with maximum load. Figure 29 shows that measurements for FAR 36 are taken 3.5 nautical miles from brake release or beginning of take-off roll, 0.35 nautical mile from the center line when the plane is halfway down the runway and underneath the plane after take-off. For landing, measurements are taken one nautical mile from touchdown and at the same side and overhead locations as in take-off. Comparable figures are also given for STOL certifications in Figure 30.

Approach and take-off noise from commercial aircraft is closely related to aircraft gross weight, because thrust requirements change due to the weight factor. Figures 31 and 32 show this relationship and the sound levels produced relative to the FAR 36 certification limits.

Proposed FAA maximum allowable noise levels to be required for certification of future aircraft require a maximum allowable 109 EPNdB one mile from the runway threshold on a 3 degree glide slope on approach, 116 EPNdB 1,500 feet either side of runway centerline, at start of take-off for sideline noise, and 105 EPNdB at 3 miles from brake release on take-off.

The EPA (22) cites that present legislation in Congress may reduce FAA's power in noise control by placing control jurisdiction under the Environmental Protection Agency. EPA would thus approve any noise standards issued by the FAA, and the EPA administrator would publish criteria on the effects of noise and then set standards for
transportation equipment, to include aircraft. The House version, however, says that EPA would only be a consultant to FAA, rather than having veto authority over FAA noise regulations.

House hearings (14) brought out that an essential is legislation reserving to the Federal Government exclusive jurisdiction, not only to promulgate noise standards, but also to enforce such standards throughout the United States. Unless there is Federal preemption in this area, the same aircraft might be subject to differing and possibly inconsistent, local, state and regional standards - an untenable situation for interstate carriers. Thus, Federal preemption is required to resolve the problem and to lead the way to a technically practical and economically tolerable program to obtain unified standards for aircraft engine noise.
BARRIERS AND COMPLICATIONS

State-of-the-Art Limitations

There is a popular concept that jet engine noise research has been neglected, and that large improvements could be achieved only if a massive program was launched to attack the technical problems. There are those who feel that if the technology which produced the miracle of space travel were directed toward solving the noise problem, such breakthroughs would be forthcoming as a matter of course. Although there have been no scientific breakthroughs in the past, the noise generation processes of jet engines have been the subject of a significant amount of research with the result that the noise levels of the new wide-bodied aircraft are measurably lower than those of the largest narrow-body jet aircraft. The several noise generation processes inherent in the jet engine are fairly well understood as a result of this research, although they are recognized as being very complex. Engine designers and manufacturers at this time do not foresee a scientific breakthrough which will make a dramatic change in the noise situation.

The very nature of the decibel, the basic unit in the measurement of sound must be understood if one is to predict the likely results of future research. The decibel unit is used because it is well suited to cover the very large range of loudness to which the ear is sensitive. A change in noise of ten decibels generally is judged as a doubling or halving of the subjective loudness of a noise.
In the physical world, however, a ten decibel reduction, which sounds half as loud, is obtained by removal of 90 percent of the original noise-producing acoustic energy. Removal of half this acoustic energy would produce only a modest three decibel reduction detectable by most people only under carefully controlled conditions. Thus, very large changes in the physical process of noise generation must be made to obtain even modest noise changes as judged by a listener. Additional research must continue in order to obtain those noise reductions possible beyond today's state-of-the-art.

It is not suggested that the end of developments is in sight—rather we can still look forward to design skill giving us lighter and more reliable engines, to advances in aerodynamics leading to improved compressor and turbine efficiencies, to metallurgist and production engineers developing new materials and better ways of air-cooling the turbine stators and rotating blades, and to acoustical engineering advances in producing more effective sound absorbing materials spanning wider ranges of frequencies.

Aircraft noise reduction has been a major industry goal for nearly 15 years, and literally millions of dollars have been put into programs geared to understanding and eliminating the problem. Every noise reduction in a jet engine is laboriously achieved. In some cases it means a change in the design of the engine; in others, it is the addition of acoustic material to help absorb some of the engine's sound. Usually a weight, performance, and cost penalty must be paid to make an engine more quiet.
There is no reason to suspect that engine noise reductions will not continue to be made. But as suggested, it may be a painfully slow process that requires concerted effort on the part of many.

**Retrofit of Current Aircraft**

The early jet-powered commercial aircraft used turbojet engines equipped with jet suppressors. There would appear to be little in the way of noise abatement that can be done for these aircraft short of re-engining or premature retirement of these aircraft from service.

The majority (over 1,700 as of July 1, 1970) of existing jet-powered commercial aircraft are powered by low-bypass ratio turbofan engines to which the data obtained in the NASA quiet nacelle program could be pertinent. Although the quiet nacelles tested by NASA were not equipped with thrust reversers and inlet anti-icing features (FAA required) and were not developed to have the structural integrity required for long term commercial use, similar nacelles probably could be developed for flight use.

Congressional hearings (14) pointed out that although noise reduction of from about ten to 15 PNdB beneath the approach path of the aircraft at an altitude of 370 feet was obtained, only modest improvements in take-off noise were achieved, because the dominant noise source, jet rumble, is not affected by the quiet nacelles. Cost of equipping four-engine aircraft with treated nacelles has been estimated to be from $600,000 to $1,000,000 per airplane. Complete conversion of the huge fleet of fan-powered Boeing 707 and McDonnell-Douglas DC-8
aircraft (approximately 670 aircraft) would take three years after the first kits were available.

Although similar flight tests have not been completed for the Boeing 727/737 series and the McDonnel-Douglas DC-8, which are powered by JT8D low-bypass ratio turbofans, it can be calculated from ground tests that a reduction of five to seven PNdB can be achieved with treated nacelles. Essentially no reduction in take-off noise would result. Cost of this conversion has been estimated at $200,000 to $400,000 per aircraft, with about five to six years required to develop retrofit kits and outfit the existing fleet.

If, in addition to nacelle fitting, a new quiet fan were installed, cost of retrofitting a four-engined aircraft is estimated at between $1.5 million to $2 million. The cost for a three-engine airplane would be three-fourths that amount, or from $1.1 million to $1.5 million. Figure 33 is based on data provided by the Lewis Research Center, showing the estimated noise reductions that could be achieved in present transports by retrofitting their Pratt & Whitney JT3D and JT8D engines with new quiet fans and nacelles.

Estimates are that there will be 800 to 900 four-engined aircraft in the U. S. commercial fleet by the end of this decade. This would mean a total retrofit cost of from $1.2 billion to $1.8 billion. As a start in this direction, NASA has allocated $9 million in its Fiscal 1973 budget to develop the retrofit kit, the first of which would be ready in four years.

These are staggering costs that the airlines may not consider economically feasible, nor can the airlines consider replacement of
partly depreciated aircraft for the sake of engine refitting only. It is only in the relatively newer aircraft with low-bypass engines where modification trade-off might be more attractive economically than complete re-equipment. Noise versus direct operating cost trade-offs are shown in Figure 34.

It is hard to conceive that any amount of regulation can cause an already financially imperiled industry to adopt a massive change program unless possible government incentives are provided such as: low-interest loans for financing equipment changes; landing fee adjustments for aircraft meeting desired standards; accelerated write-offs of federal or state income tax reduction for airlines whose equipment meets standards. Whatever the final decision, resistance by the airline industry is predictable and will be effective.

Future Prospects

Upon looking beyond the problem of reducing noise from the current jet aircraft designs, what might we anticipate about the noise characteristics of future aircraft? Specific types of aircraft will have noise characteristics which are unique to their specific design. Of particular interest for the future are supersonic transports, subsonic transports, V/STOL aircraft, and possibly lift fans.

The FAA (6) emphasizes that the trend in subsonic powerplant design has been toward turbofan cycle engines of higher bypass ratio, and this trend is expected to continue. Several factors have influenced this trend and the effects on noise have been highly favorable. Jet exhaust noise levels have been reduced as a result of increases in
bypass ratio because of the lower jet exhaust velocity associated with higher turbine work extraction. The fan performance characteristics required for efficient operation of a high-bypass engine allow the use of single-stage designs, which are more amenable to noise suppression than are two-stage fans.

Some additional improvements in subsonic aircraft noise resulting from the more extensive application of the same type of technology incorporated in the powerplant installations for today's wide-bodied jets can be expected. It appears, however, that the introduction of the high-bypass ratio jet engines having acoustically treated nacelles represents a large improvement in engine noise suppression and that additional large reductions will probably proceed less rapidly. Because large noise reductions are unlikely, even more diligent research efforts are required to identify and produce the relatively small improvements which may nevertheless be possible.

Perhaps the greatest challenge to noise suppression will be presented by V/STOL power plants. These aircraft must have acceptably low noise levels to be allowed to operate from V/STOL ports near populated areas. Because of the short field take-off requirements, these aircraft operate with larger thrust size engines than would a conventional transport of comparable weight. Weight penalties paid for noise suppression must be kept low to efficiently achieve this high thrust-to-weight ratio. At the present time, both turbofan powerplants and propellers are being considered for V/STOL applications. Factors such as range, cruising speed and aircraft size as well as noise influence the choice of propulsion type. For many uses, turbofan power
plants are clearly superior. Propellers are competitive with turbofan propulsion for the smaller aircraft, up to about 50 passengers.

All factors which are considered effective for reducing noise from subsonic turbofan engines are also applicable to STOL turbofan powerplants or lift fans. Because of the heavily populated environment within which these aircraft are expected to operate, bypass ratios of as high as ten or more may be required to provide adequately low jet noise. Fan noise will be controlled by selection of fan design tip speed, the aerodynamic design of the fan, and the extent to which treatment can be incorporated in the nacelle. Since available methods of noise suppression result in both thrust losses and weight increases, noise requirements will have a strong influence on the economics and possibly even the feasibility of a STOL aircraft for commercial purposes. These factors will be even more critical for STOL aircraft using lift fans.

The primary noise problem of supersonic aircraft frequently is referred to as "sideline" noise because it occurs at maximum thrust operation during take-off roll and early climb before a noise abatement power cutback is made. This noise problem is unique to the supersonic transport because it is the only commercial aircraft having afterburning engines. The source of the problem is the high level of jet noise generated downstream of the jet nozzle by the turbulent mixing of the exhaust jet stream wake with ambient air. These powerplants produce high levels of jet exhaust noise on take-off because of the high exit velocity associated with engines equipped with afterburners. After-
burning powerplants create a loud, dominantly low-pitched jet rumble which carries over long distance.

The design objectives for supersonic transport aircraft are to limit noise to no more than that produced by the largest of today's wide-bodied subsonic transports. The inherent mission requirements of the SST call for supersonic cruise, transonic acceleration and subsonic flight capability. Accordingly, a high thrust engine is required, with relatively high jet velocity compared to subsonic transport engines. As a consequence, the relatively high take-off jet velocity will produce relatively high sideline noise levels, while the relatively high take-off climb rate will reduce the area exposed to noise during climbout. The variable geometry inlet duct required for operation over the required wide range of flight speeds may be used in a choked or near-choked mode of operation to suppress inlet noise during landing.

General Electric's 70,000 pound thrust GE4, which is to power the U. S. SST, has demonstrated sound levels that would enable the SST, powered by four GE4's, to meet the new FAA limits for "community noise"—the noise the aircraft makes after take-off and during approach. However, further improvement will be necessary for the SST to comply with requirements for airport noise.
CONCLUSIONS

A point appears to have been reached where no immediate break-throughs are foreseen, and it is anticipated that further noise reductions will be achieved only in small increments, and possibly at great expense. Despite the progress made to date in reducing noise levels, aircraft will continue to be judged as noisy by those who live or work in close proximity to airports and the flight paths associated with landing and approach patterns.

It is apparent that the Federal Government must lead the way, not only to generate sensible noise control legislation and enforcement measures, but also to provide the aircraft and airline industries continued support in research endeavors.

Operating procedures appear to have been stretched to their practical limits consistent with safety, and drastic relief in this area is not anticipated. If our airport facilities are to exist and expand, more attention must be given now to the judicious use of land near airports to minimize effects of aircraft noise on the community.
Fig. 1.—Sound Radiated From a Turbofan Engine

Fig. 2.—Simplified Scheme of Sound Sources in a Turbulent Jet (Dilatation Theory) (7)
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Fig. 4.--Sources of Noise--The Quadrupole (8)

Fig. 5.--General Type Noise Pattern Evolving from Quadrupole Noise Source (8)
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Fig. 7.--Turbojet Engine Noise Sources and Distribution (7)

Fig. 8.--Turbofan Engine Noise Sources and Distribution (7)
Fig. 9.—Turbofan Engine Inlet Noise Spectrum (7)

Fig. 10.—Discrete Frequency Interaction Noise Generating Mechanism (11)
Fig. 11.—Functions of Frequency and DB, as Related to Thresholds of Perceived Sound
<table>
<thead>
<tr>
<th>dB</th>
<th>Relative energy</th>
<th>Sound pressure dyn/cm²</th>
<th>Typical examples</th>
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<td>0</td>
<td>1</td>
<td>0.0002</td>
<td>Threshold of hearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(absolute)</td>
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<tr>
<td>10</td>
<td>10</td>
<td>0.002</td>
<td>Threshold of hearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(average)</td>
</tr>
<tr>
<td>20</td>
<td>$10^2$</td>
<td>0.02</td>
<td>Quiet garden</td>
</tr>
<tr>
<td>30</td>
<td>$10^3$</td>
<td></td>
<td>Country road</td>
</tr>
<tr>
<td>40</td>
<td>$10^4$</td>
<td>0.2</td>
<td>Quiet office</td>
</tr>
<tr>
<td>50</td>
<td>$10^5$</td>
<td></td>
<td>Average office</td>
</tr>
<tr>
<td>60</td>
<td>$10^6$</td>
<td>2</td>
<td>Conversation</td>
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<tr>
<td>70</td>
<td>$10^7$</td>
<td></td>
<td>Noisy office</td>
</tr>
<tr>
<td>80</td>
<td>$10^8$</td>
<td>20</td>
<td>Engineering works</td>
</tr>
<tr>
<td>90</td>
<td>$10^9$</td>
<td></td>
<td>Noisy factory</td>
</tr>
<tr>
<td>100</td>
<td>$10^{10}$</td>
<td>200</td>
<td>Power station</td>
</tr>
<tr>
<td>110</td>
<td>$10^{11}$</td>
<td></td>
<td>Gunfire</td>
</tr>
<tr>
<td>120</td>
<td>$10^{12}$</td>
<td>2000</td>
<td>Aero engine</td>
</tr>
<tr>
<td>130</td>
<td>$10^{13}$</td>
<td></td>
<td>Jet engine</td>
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<tr>
<td>140</td>
<td>$10^{14}$</td>
<td>2000</td>
<td>Threshold of pain</td>
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- ONEWAY RUNWAY UTILIZATION
- NORMAL CLIMB GRADIENT
- NORMAL 3° GLIDE ANGLE

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CF6 Fan Designed for Low Noise Levels

The CF6 fan configuration incorporates several significant features which contribute directly to low noise levels:

1. Low Tip Speed (1305 ft/sec at take-off)—for low noise level generation.
2. No fan inlet guide vanes—eliminates inlet wake-generated noise.
3. Large axial spacing between the fan blades and the outlet guide vanes—reduces the intensity of downstream wake cutting noise.
4. Swept and canted OGV’s—reduces the strength of wake cutting.
5. High OGV to fan blade ratio—reduces duct noise transmission.

Fig. 28.--General Electric CF6 Fan Configuration Showing Extensive Use of Acoustic Absorptive Materials
SIDELINE MEASURING POINT
WHERE NOISE AFTER LIFTOFF IS GREATEST

APPROACH MEASURING POINT

0.25 N. MILES

1 N. MILE

3.5 N. MILES

THRESHOLD OF RUNWAY OR START OF TAKEOFF ROLL

Fig. 29.--Noise Measuring Points for Airplane Type Certification (6)

SIDELINE MEASURING POINT
WHERE NOISE AFTER LIFTOFF IS GREATEST

APPROACH MEASURING POINT

1000 FT.

2000 FT.

4000 FT.

THRESHOLD OF RUNWAY OR START OF TAKEOFF ROLL

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### TABLE 1. NASA QUIET ENGINE DESIGN CONSTRAINTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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<tbody>
<tr>
<td><strong>Engine</strong></td>
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<tr>
<td>Bypass ratio</td>
<td>5 to 6</td>
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<tr>
<td>Cruise thrust, lb</td>
<td>4900</td>
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<tr>
<td>Takeoff thrust, lb</td>
<td>22,000</td>
</tr>
<tr>
<td><strong>Fan</strong></td>
<td></td>
</tr>
<tr>
<td>Number of stages</td>
<td>1</td>
</tr>
<tr>
<td>Inlet guide vanes</td>
<td>none</td>
</tr>
<tr>
<td>Spacing between rotor and stators</td>
<td>2 rotor chords</td>
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<tr>
<td>Tip speed, takeoff; ft/sec</td>
<td>1000</td>
</tr>
<tr>
<td>Tip speed, cruise; ft/sec</td>
<td>1100</td>
</tr>
<tr>
<td>Pressure ratio, cruise</td>
<td>1.5 to 1.6</td>
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<tr>
<td><strong>Compressor</strong></td>
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</tr>
<tr>
<td>Rotors</td>
<td>1 or 2</td>
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<tr>
<td>Maximum pressure ratio per rotor</td>
<td>12.5</td>
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<tr>
<td><strong>Turbine</strong></td>
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<tr>
<td>Inlet temperature, takeoff; °F</td>
<td>2000</td>
</tr>
<tr>
<td>Inlet temperature, cruise; °F</td>
<td>1775</td>
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LIST OF REFERENCES


