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JET AIRCRAFT ENGINE NOISE REDUCTION

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Abstract

Aircraft flyover noise is a serious problem to literally millions of people, and the federal government is doing something about it. Through NASA and the FAA, advanced technology is being aggressively developed, as described herein, to identify and minimize noise sources in aircraft engines, and to absorb noises which cannot otherwise be eliminated. The economic impact resulting from reducing engine noise levels will also be presented and the challenge posed to reducing this economic impact by further improvement in engine noise reduction technology will be discussed.

Introduction

The problem of aircraft noise needs no introduction because most people have experienced it at one time or another in the vicinity of major airports. In concert with the FAA, the NASA is deeply involved in solving this problem by developing new noise reduction technology that will quiet future airplanes and have a minimum impact on airplane economics.

The material that is to be reviewed in this paper can provide only an overview of the complex matrix of problems involved in aircraft noise reduction. First will be presented a discussion of the major noise sources, the noise generation mechanisms involved, and what can be done to reduce or suppress the noise generated. Following this, an indication of the current performance and economic penalties involved in achieving aircraft noise reduction will be discussed. And finally an indication of the importance of advanced technology in reducing the cost of aircraft noise reduction will be shown.

Noise Sources

A cross section of a typical turbofan engine, the type which has been commonly used in transport aircraft since the introduction of the B-707 and DC-8, is shown in Fig. 1. The engine thrust results from the high exhaust velocities developed in both the core and fan jet streams. These high jet velocities are among the primary sources of engine noise. The jet noise is caused by the highly turbulent mixing which occurs between these high velocity streams and the surrounding air. A second important source of noise is called machinery noise and it is radiated from the interior of the engine, as shown in the figure by the fan (which propagates out the fan inlet and discharge ducts), the compressor, the turbine and possibly the combustor.

Jet noise. - Jet noise is a major and frequently dominant contributor to overall engine noise. The amount of noise generated is strongly related to the jet velocity, as shown in Fig. 2 (from ref. 1) for several kinds of data. The jet noise is presented in terms of the overall sound pressure level (OASPL) which has been corrected for density and area differences by the term 10 log (ρ_J^2 A). Superimposed is an SAE correlation curve which is commonly used for hot jets at velocities above 1000 feet per second. Obviously a reduction in jet velocity yields a major reduction in jet noise. By exploiting this relationship (low jet velocity produces low jet noise), major noise reductions have already been achieved in the new engines powering the DC-10, B-747, and L-1011 wide-body jets. Further jet noise reductions are possible, particularly for the core jet, but there is a practical limit. As jet velocity is reduced, more air must be pumped in order to maintain constant thrust. This requires a larger fan and results in a heavier engine as well as an increase in nacelle drag. Accordingly, one must make a judgment of the jet noise reduction in light of the attendant penalties.

One "fix" which has been used to reduce jet noise is the concept of breaking up a large single jet into many small ones. Sound pressure level (SPL) is shown in Fig. 3 (from ref. 1) as a function of frequency for a J-75 engine operating statically with a large single exhaust nozzle and also one formed of 37 round tubes. The noise reduction is impressive, particularly below 1200 Hz, but such noise improvement is achieved at the cost of reductions in thrust on the order of 5 percent, and significant increases in nozzle weight. Also, the effectiveness of such multi-tube jet noise suppressors diminishes as jet velocity decreases, and as a result they are less effective for use on engines of conventional take-off-and-landing type aircraft. It is likely that further reductions in jet noise without commensurate performance penalties will be difficult to accomplish.

Fan noise. - Fan noise competes with jet noise for the dominant role in the overall engine noise picture. Data from fans and engines (shaded symbols) have been combined to produce the shaded noise bands in Fig. 4. Here are shown maximum perceived noise level (PNdB) for 90, 000 pounds take-off thrust plotted against fan pressure ratio. Fan noise level is seen to increase with fan pressure ratio for the three classes of fan configuration indicated. Also shown in the figure are the pressure ratio ranges found appropriate for STOL, CTOL, and AST types of aircraft. These acronyms refer to "short take-off-and-landing", "conventional take-off-and-landing" and "advanced supersonic transport" aircraft, respectively. It can be seen that fan noise will be a problem for supersonic aircraft because of the high fan pressure ratio required, but it will also be a problem for STOL aircraft, even though the fan pressure ratio and therefore its noise will be lower, because of planned operations from extremely small airports in downtown areas where allowable noise levels will be extremely low.

Two of the most significant mechanisms which generate fan noise are illustrated in Fig. 5. Looking at the tip of a fan assembly (upper sketch), one sees a row of rotor blades moving to the left past a set of stationary stator blades. As the incoming air flows over a rotor blade the air near the blade surfaces is slowed down by friction, producing a low velocity wake behind the blade (shaded areas). These wakes, shown relative to the moving rotor, then intermittently pass over each of the stator blades, changing momentarily the angle of attack. Thus each stator blade will experience an oscillating lift, and for each change in lift will create a vortex downstream. The creation of such vortices is believed at least partly responsible for the dominant fan noise source in subsonic compressors and fans. The higher noise levels shown in Fig. 4 with two-stage fans are due to the additional wake-interaction noise of the second stage.

The second important noise generation mechanism produces a large number of discrete tone noises called multiple pure tone (MPT) noise. To get more pressure out of a single stage fan and thus a lighter engine, designers have increased the tip speed of the fan rotor blades well into the supersonic regime. At supersonic speeds, shock waves are formed at the leading edge of each rotor blade. A family of such waves is shown in Fig. 5, propagating upstream toward the inlet of the nacelle. Because of slight blade variations due to manufacturing tolerances, these waves are not all parallel. Some waves coalesce and reinforce one another to produce strong pressure waves which, along with harmonics, are heard as a family of pure tones. Such multiple pure tone noise (MPT) can be both intense and irritating and is often called buzz-saw noise. The increase in noise in going from the low speed to the high speed single stage fans in Fig. 4 is primarily due to this mechanism.

One method of decreasing fan noise, which has been used successfully in newer engines, is illustrated in Fig. 6 (from ref. 1). In this figure the noise level is presented in terms of perceived noise which has been tone corrected (PNLT). As the stator row is moved downstream away from the rotor blades, the noise level is significantly reduced. This is as one would intuitively expect, since the wakes from the rotor will mix with adjacent undisturbed air and be reduced in intensity (velocity defect) before striking the stators. As usual, there is a counterbalancing penalty, for as the spacing is increased, the engine becomes longer and heavier.

Another concept under study for reducing wake-produced noise is the use of leaned stators. With this concept, shortly to be demonstrated in several experiments, the stator blades are leaned away from the radial position. Thus each rotor blade wake, which procedes toward the stator in the form of a more-or-less radial sheet, does not encounter the entire span of the stator blade at the same instant. One can think of the leaned stator blade as progressively slicing through this wake sheet, first at one end and then progressively to the opposite end, producing only local small vortices and hopefully lower noise. If successful, this concept may allow the spacing to again be reduced resulting in a still quiet but lighter engine.

Noise Suppression

The discussion thus far has dealt with a few of the many concepts for reducing noise generation. The noise levels desired by society, however, are lower than can presently be achieved by reduction in the source noise generation. Accordingly, intensive efforts are devoted to learning how best to absorb some of the residual noise. This absorption is accomplished with the forms and arrangements of acoustic "treatment" shown in Fig. 7. Although these arrangements are intended primarily for fan noise suppression, the same principles can be employed for suppression of other internal noise sources such as the compressor, turbine, and combustor if they become significant contributors. All available surfaces of the air flow passages within the engine and nacelle are formed of porous or perforated materials with closed backing cavities underlying. The design of such system is based upon a highly sophisticated application of Helmholtz resonator theory. One may envision a noise (pressure) wave having a momentary pressure higher than the pressure in the backing cavity, causing flow through the porous face sheet into the cavity. The face sheet orifice and cavity combination will form jets which alternately flow into and out of the cavity in response to the rising and falling acoustic pressure in the duct. Acoustic energy is removed in the process by turbulent jet dissipation and viscous interaction with the walls of the orifice and cavity.

Although there is still much to be learned, the concept works quite well and has been used extensively in recent commercial engines, as well as the NASA Quiet

Engine. But again the gains are balanced by performance losses and increased weight as shown in Fig. 8 based on data from Ref. 2. Here it is seen that noise may be reduced progressively by adding more and more treated area in the forms of duct inlet rings and splitter rings in the exhaust ducts. But it is also seen that the direct operating costs of the airplane are progressively increased at an ever steepening rate.

Quiet Engine Results

The objective of the NASA Quiet Engine program (ref. 3) was to develop engine noise reduction technology and to demonstrate the lowest engine noise levels that could be obtained when all the noise reduction technology available was incorporated into an engine design. The engine was designed and built for NASA by the General Electric Company. It was designed to produce 22, 000 pounds of thrust at sea level static conditions. A cross section of the engine is shown in Fig. 7. An acoustically-treated nacelle was built for the Quiet Engine by The Boeing Company and a photograph of the engine and nacelle combination is shown installed in the NASA Lewis engine acoustic test facility in Fig. 9. The acoustic treatment included three inlet splitter-rings and one fan-duct splitter ring which had acoustic treatment on both sides. In addition, acoustic treatment was placed on both the inner and outer walls of the fan inlet duct, the fan discharge duct, and the core exhaust duct.

The noise reduction results achieved by this Quiet Engine and nacelle are translated most meaningfully in Fig. 10 taken from Ref. 4. The figure shows the areas on the ground wherein the noise level would be greater than 90 EPNdB during landing and takeoff of a DC-8 type aircraft. (The term EPNdB is the noise unit the Federal Aviation Agency (FAA) uses to regulate aircraft noise and it is found by taking the perceived noise and modifying it for duration and tone content.) With the engines currently installed in the DC-8, which were developed ten years ago without regard for noise, 65, 800 acres would be exposed to noise greater than 90 EPNdB. This is about the noise level beside a very busy freeway. If the airport were surrounded by city dwellers, on the order of 800, 000 people could be annoyed. With the new Quiet Engine and nacelle using duct treatment only, the area decreases to 2670 acres. The further addition of treated inlet rings and exhaust splitters reduces the acreage to 930, of which most of the 90 EPNdB "footprint" is on the unpopulated airport property.

In addition to the Quiet Engine program which is intended for guiding new engine developments, NASA in conjunction with the FAA, has just embarked upon a retrofit program intended to determine the most practical engine or nacelle modifications to quiet the existing installations in the DC-8, 707, 727, 737, and DC-9 airplanes. This program should produce major relief in community noise in the 1975-80 time period before any completely new quiet engine can reach the marketplace.

Cost of Noise Reduction

The dramatic improvement illustrated by the Quiet Engine and nacelle made possible with the technology existing three years ago was not achieved without engine performance and therefore airplane economic penalties. Thrust was reduced by 4-5 percent, and each flight nacelle built to incorporate these features would be perhaps 500 pounds heavier than an untreated nacelle.

In the preceding discussion, for each gain made in reducing noise, performance and/or weight penalties were incurred with an impact on economics. If we are to proceed using current technology to the noise levels represented by the Quiet Engine and even further as we would like, direct operating costs (DOC) will become higher than the airline industry can absorb without substantial increases in ticket price. Thus, most of the burden must ultimately be borne by the traveling public in the form of increased ticket price.

A trade then becomes obvious between the number of people annoyed by aircraft noise and the annoyance imposed on the traveling public by higher ticket price. This trade is illustrated in Fig. 11 which shows the number of people exposed to 90 EPNdB per takeoff as a function of ticket price. Here the reference point is the new wide body aircraft such as the B-747, DC-10, and L-1011, which already include significant noise reduction technology. In order to simplify the estimation of change in ticket price, the assumption is made here that increases in DOC are directly related to ticket price. It is evident that with current technology, large reductions in annoyance below that of current aircraft, will result in significant increases in ticket price for the air traveler. However, continued vigorous technology development should produce large reductions in annoyance without any increase in ticket price, as indicated by the arrow in the figure. The shaded advanced technology line is the estimated improvement in noise reduction technology that will be available in the early 1980's.

Thus far the thrust of our efforts has been to learn <u>how</u> to reduce noise and thus community annoyance. Work in the future will be directed not only to further reduction in noise but also towards developing noise reduction technology that will have less of an economic impact on airplane operations. Through the application of advanced research it is believed and expected that we can move into the region shown by the shaded area in Fig. 11. Such progress should allow a much improved noise environment with prices that the traveler can accept.

Conclusions

Significant progress has been made in the development of new engine noise reduction technology as evidenced by the Quiet Engine Program. The prospect for reducing the noise levels of future aircraft below that of the new wide body jets is good. However, a significant penalty in the form of increased cost to the traveler will be expected as new airplane noise levels are gradually reduced. Continued efforts in the noise reduction technology area should allow for not only much lower aircraft noise levels, but with correspondingly reduced cost to the traveler.

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4. Statement of David Cochran, General Electric Co., to the Sub-committee on Advanced Research and Technology of the Committee on Science and Astronautics, U. S. House of Representatives, Jan. 19, 1972.

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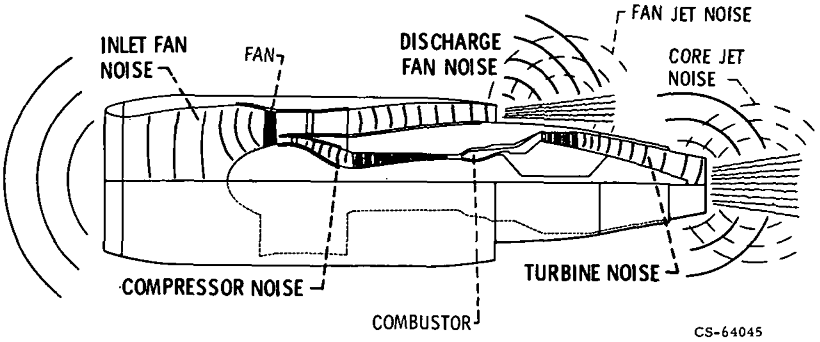

Figure 1. - Turbofan noise sources.

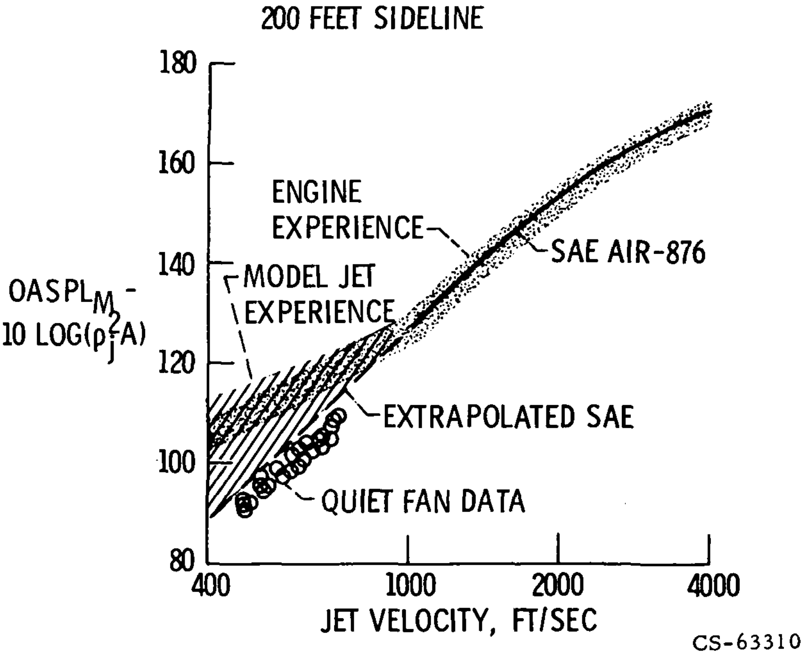

Figure 2. - Effect of jet velocity on jet noise.

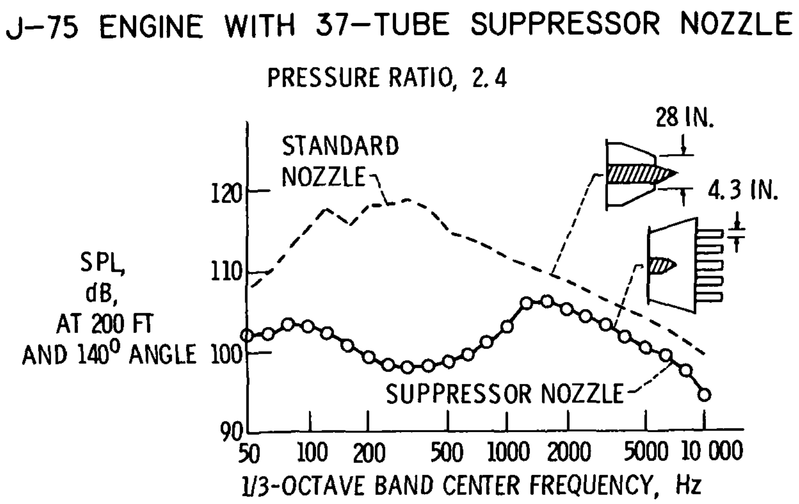

Figure 3. - Noise reduction with multi-tube nozzles.

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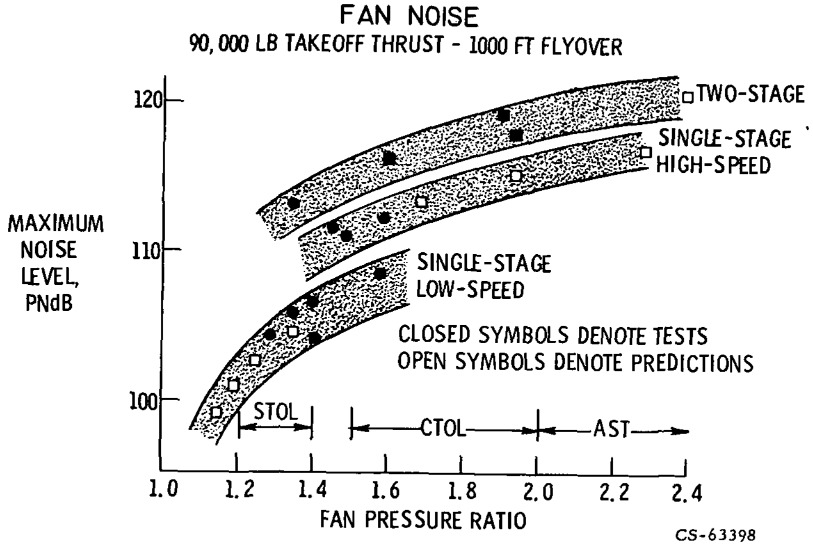
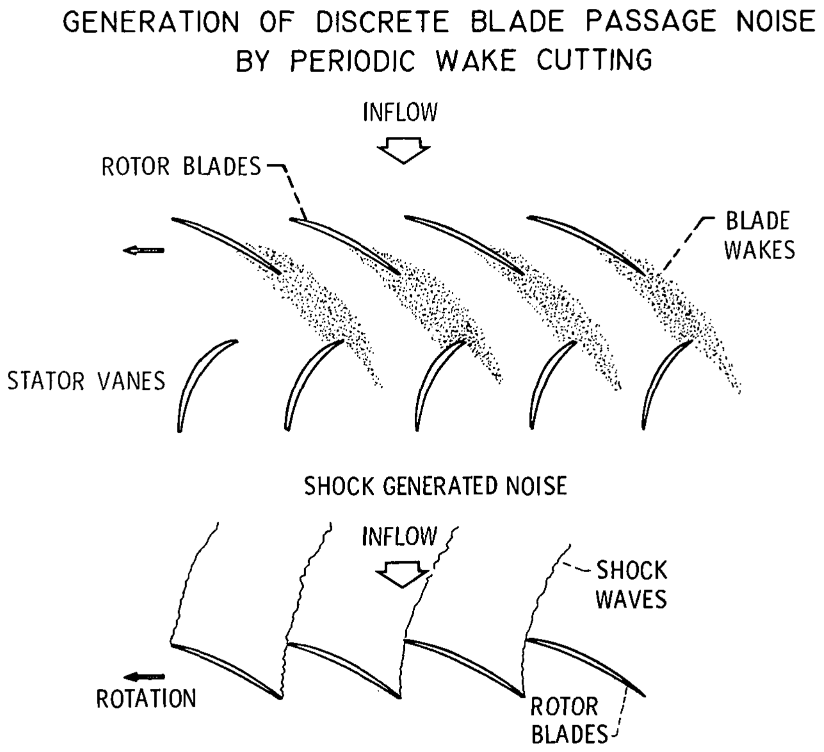


Figure 4. - Fan noise levels.


GENERATION OF DISCRETE BLADE PASSAGE NOISE BY PERIODIC WAKE CUTTING

SHOCK GENERATED NOISE

Figure 5. - Two mechanisms producing fan noise.

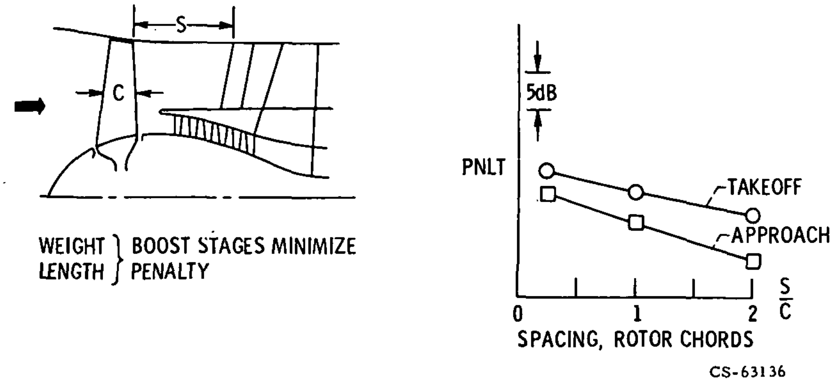


Figure 6. - Effect of rotor-stator spacing on fan noise.

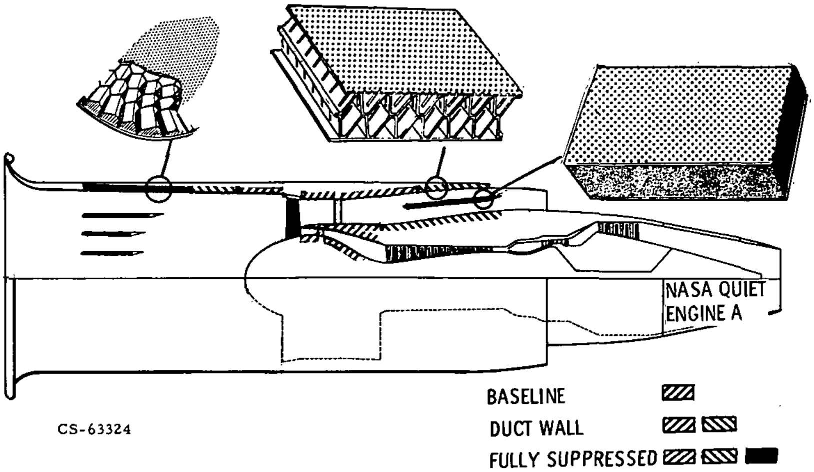


Figure 7. - Sound suppression by acoustic treatment.

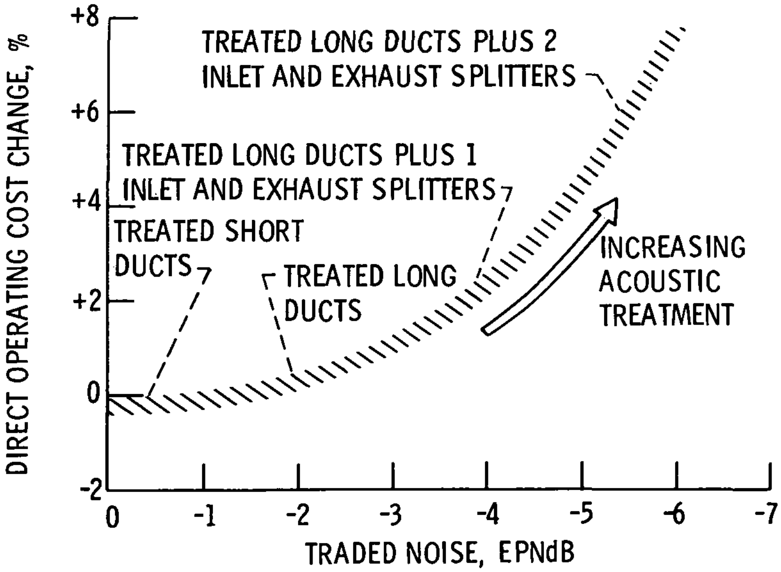


Figure 8. - The cost of noise suppression.

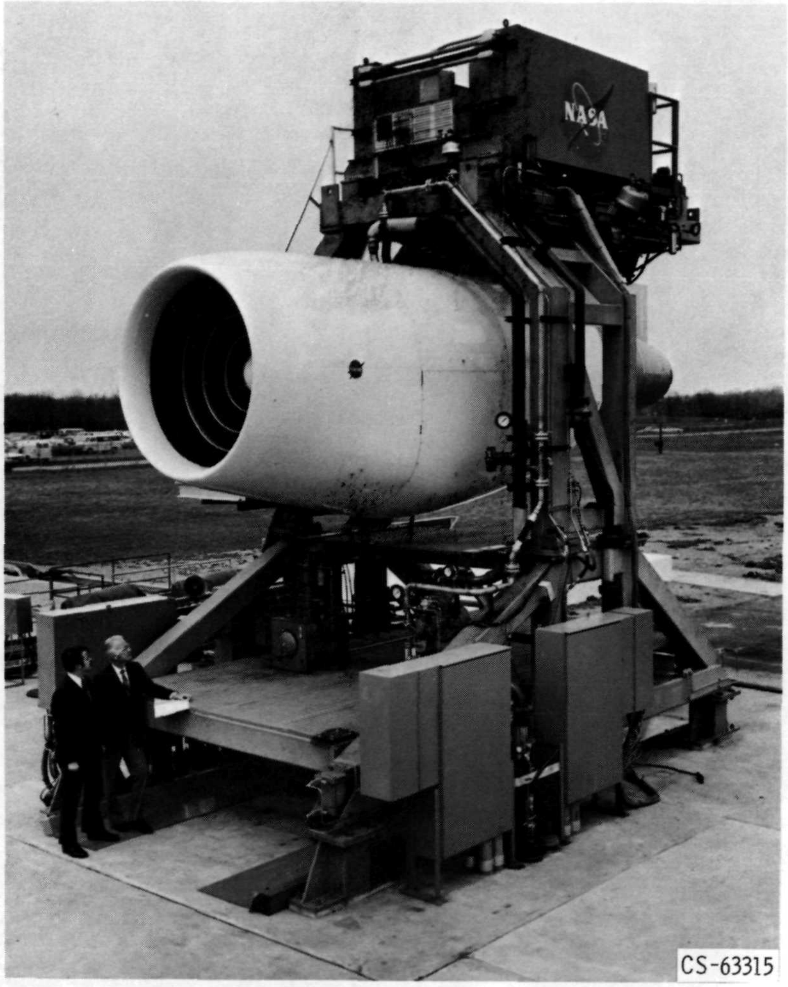


Figure 9. - NASA quiet engine number 1 in acoustic nacelle.

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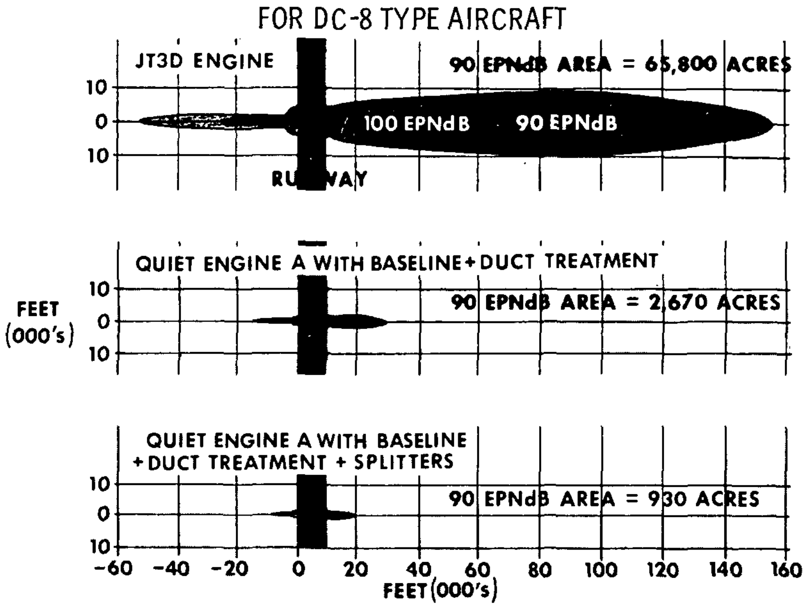

Figure 10. - Impact of quiet engine technology on community noise.

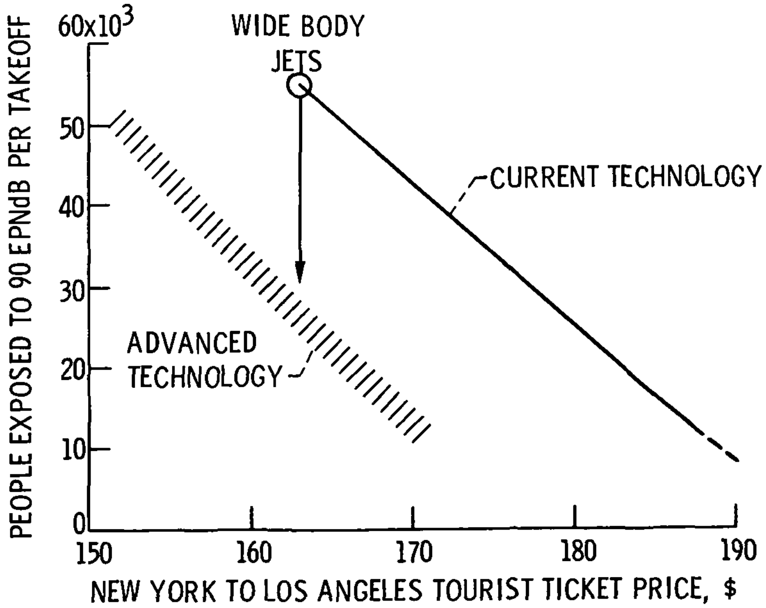

Figure 11. - Community noise relief versus cost to the traveler.