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DURING TAKEOFF AND INITIAL CLIMB**

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

An analytical study was made to illustrate the manner in which engine design, sizing, and operation affect the airport and community jet-noise environment of a representative fixed-wing supersonic commercial transport. Both afterburning turbojet and duct-burning turbofan engines were considered. Neither engine type was assumed to have noise suppressors.

The numerical results pertain only to the selected airplane characteristics and method of computing engine noise. Nevertheless, the data show how the selection of noise constraints can lead to the need for larger engines than those corresponding to maximum payload capacity. Furthermore, the necessary engine sizes can exceed those required to meet other operational constraints, such as takeoff distance or engine-out climb ability.

INTRODUCTION

Excessive noise in and near airports has become an increasingly significant problem with the development of commercial jet airplanes. The higher thrust levels and gross weights associated with the supersonic transport (SST) will tend to aggravate the problem unless particular attention is paid to the type and size of engines selected, the mode of engine operation, and the airplane takeoff and initial climb procedures. The problem is further complicated by the requirement that the design and operation of the airplane for noise abatement should not adversely affect its profitability to the operator.

The effects of airplane performance, climb path, and engine size and design on jet noise during takeoff and initial climb were examined for a typical fixed-wing SST design. The relation between jet-noise reduction and payload was also investigated. Both afterburning turbojet and duct-burning turbofan engines were considered.

Jet noise can be a problem both at the airport, where it affects ground crews and boarding passengers, and during early low-altitude stages of climb, when it affects the surrounding community. An acceptable noise environment, which is not well defined at

this time, should account for the number of times the sound is heard, the duration of each sound, and the maximum sound level (ref. 1). Currently, the maximum noise level at two precise locations is specified in an attempt to define an acceptable noise environment (ref. 2). For airport noise at the start of takeoff roll, a point at the angle of maximum noise level on a sideline 1500 feet from the airplane centerline is considered. For community noise, a point on the ground directly beneath the flight path at a distance of 3 statute miles from initial brake release is considered; at this point the thrust has been reduced for a rate of climb of 500 feet per minute. The Federal Aviation Agency (FAA) suggests (ref. 2) that perceived noise levels should be no greater than 116 perceived noise decibels (PNdB) at takeoff and 105 PNdB at 3 miles. It is recognized that the specification of only two noise checkpoints somewhat oversimplifies the problem of describing the total noise environment. Nevertheless, these were the checkpoints set forth by the FAA for the noise goals to be met in the United States supersonic transport design competition. In spite of any shortcomings which may exist in the definition of checkpoints and goals, their selection has provided a basis on which to make noise comparisons in a relatively simple manner with a minimum of data at two specific points.

Various devices are occasionally considered for suppressing the noise of the jet. However, the effects of such suppression devices are ignored in the data presented herein in order to better emphasize the influence of the primary engine parameters.

SYMBOLS

C_D	drag coefficient
C_L	lift coefficient
D	drag, lb
F	net thrust, lb
L	lift, lb
V	velocity, knots or ft/sec
W	gross weight, lb
α	angle of attack, deg
γ	path angle, deg

Subscripts:

j	jet
max	maximum

METHOD OF NOISE CALCULATION

Procedures followed in this study for calculating the approximate levels of jet noise are outlined by the Society of Automotive Engineers in references 3 and 4. The calculations are for noise produced by the jet exhaust and do not include the noise generated by the fan or the compressor. During takeoff and climb, when a high thrust level is required, exhaust noise is usually high enough to mask compressor and fan noise, and this procedure gives a good estimate of the overall maximum engine-noise level. However, at very low thrust settings, exhaust noise is much lower, and compressor and fan noise also must be considered. The landing approach noise problem is not considered herein, but at the low thrust levels encountered during this phase of the mission, the major noise contributions are made by the compressor and/or fan rather than the jet. Suppression at these low thrust levels is not likely to result in changes to engine size, which is the primary concern of this report.

The calculation procedures of references 3 and 4 are based on the premise that the maximum overall sound pressure level for a hot jet is a function of the density, area, and relative velocity of the jet. Empirically obtained data indicate that, of these factors, the jet velocity is by far the most significant, as would be expected from a consideration of Lighthill's theory on the acoustic power developed by a hot jet (ref. 5). The maximum overall sound pressure level is corrected to a sound pressure level for each individual octave by means of an octave-band noise spectrum for a standard nozzle. These octave-band sound pressure levels are for a distance 200 feet from the engine centerline at a 45° angle from the jet axis, at which angle the noise is a maximum for a standard circular nozzle. These octave-band sound pressure levels are then corrected for distances beyond 200 feet by application of the inverse-square spherical spreading law. Other effects, such as atmospheric absorption, extra ground attenuation, and multiple engines, are applied to each individual octave sound pressure level. The octave sound pressure levels are then weighted in such a manner that increased emphasis is placed on frequency bands that are most annoying to the human ear. These weighted octave values of noise are subsequently summed and manipulated to include an adjustment for the maximum octave noise level. This resultant value is then converted to a perceived noise level measured in PNdB. The perceived noise level in PNdB thus calculated is approximately equal numerically to the sound pressure level in decibels of a reference sound of equal annoyance to the human ear when the reference sound is a band of random noise, 1 octave in width, centered on a frequency of 1000 cycles per second (ref. 4).

The procedures for calculating jet noise outlined by the Society of Automotive Engineers and followed in this report result only in estimates of the level of annoyance that will result for a given set of conditions. Because of the tentative and subjective nature of

the available noise data (ref. 3), more refined calculation procedures cannot be justified at the present time. These procedures for estimating jet noise are in general use in the aircraft industry in the United States and are believed to be the best available analytical method for use in a study of this type.

AIRPLANE AND FLIGHT-PROFILE CHARACTERISTICS

Airplane Characteristics

The airplane considered in this analysis was a Mach 2.7 fixed-delta-wing configuration with a takeoff gross weight of 500 000 pounds. A single fixed-size airframe with a 231-passenger seating capacity (i. e., at 200 lb per passenger, a 46 200-lb seat-limited payload) was used throughout the study. As perturbations were made in the engine characteristics, the maximum allowable payload was calculated for a range of 4000 statute miles (the nominal SST design range specified in ref. 2). In all cases considered, the flight path was chosen so that the sonic boom overpressure on the ground never exceeded 2.5 pounds per square foot, the maximum allowable overpressure specified by the FAA (ref. 2) for over-ocean transonic climb and acceleration. Mach 2.7 cruise was begun at the altitude that maximized the product of airplane lift-drag ratio and engine specific impulse (for optimum cruise performance). The initial cruise altitude meeting this criterion was approximately 63 000 feet for the majority of cases considered in this study. The initial cruise sonic boom was typically about 2.0 pounds per square foot, although the FAA-specified goal was 1.7 pounds per square foot at the start of cruise for an inter-continental version of the transport. The cruise sonic boom goal was ignored in this study.

A reserve fuel allowance was used in this study and included (1) an additional amount of fuel equal to 7 percent of the mission fuel, (2) fuel for a 300-statute-mile cruise to an alternate airport at the supersonic cruise altitude and Mach number, and (3) fuel for a 30-minute subsonic hold at Mach 0.6 at an altitude of 15 000 feet. Included as part of the mission fuel was fuel for a 10-minute taxi prior to takeoff and a 5-minute taxi after landing, as well as fuel for a 4-minute departure air maneuver and a 5-minute destination air maneuver, both at Mach 0.41 and an altitude of 5000 feet.

The assumed low-speed aerodynamic data for takeoff and initial climb are presented in the form of a lift-drag polar in figure 1. The airplane studied had a takeoff wing loading (i. e., gross weight divided by wing planform area) of 59 pounds per square foot. A maximum takeoff angle of attack of 13° (as limited by dragging the tail on the ground) was assumed, and the lift coefficient C_L at lift-off was thereby limited to a maximum of 0.59. The lift-off velocity was maintained at 165 knots throughout the study. At lift-off, the lift-

drag ratio L/D , as shown in figure 1, was approximately 5.3. The maximum L/D of 13.5 was obtained at a C_L of 0.15, which corresponds to an angle of attack of slightly more than 3° . The higher lift-drag ratios were not achieved until after lift-off, when higher velocities allowed lower angles of attack.

Altitude and Velocity Trade-Offs

At the start of takeoff roll, the noise is measured at 1500 feet from the airplane centerline and is, therefore, a function only of the engine design and mode of operation. However, community noise is measured 3 miles from brake release, and altitude and throttle setting at this point are functions of both the engine and the selected flight path. Two possible types of initial flight path are indicated in figure 2 for equal amounts of takeoff thrust. One type of flight path, for example, results from a climb at the maximum rate (with, generally, no increase in speed) in order to be at the maximum altitude at the 3-mile point; this maximizes the attenuation due to extra-distance spherical spreading, as previously discussed. Another, and perhaps more acceptable flight path, is obtained by accelerating to a higher velocity and lower altitude at the 3-mile point, with the result that less thrust is required to obtain the specified climb rate of 500 feet per minute after reaching the 3-mile point.

For the same distance from the noise source, a lower thrust setting results in a lower perceived noise level. Hence, to obtain the minimum community-noise level, there is a trade-off involved between higher altitudes with lower flight speeds at higher thrust levels and lower altitudes with higher flight speeds at lower thrust levels. The latter procedure, in which altitude was sacrificed for acceleration, is more realistic from a performance standpoint because a greater speed margin is obtained for maneuvers or gusty conditions.

Expending a given amount of takeoff power to obtain a higher 3-mile velocity at the expense of altitude can reduce the thrust required for the 500-foot-per-minute climb. A higher velocity permits the airplane to fly at a lower lift coefficient which, from figure 1, corresponds to a higher lift-drag ratio and, hence, a lower drag. In other words, the drag, as shown in figure 3, at 260 knots and 1100 feet altitude is about one-half the drag at 165 knots and 2400 feet. Since

$$F = \frac{D + W \sin \gamma}{\cos \alpha}$$

where α and γ are as shown in figure 3 and W is assumed to be constant at essentially the takeoff value, the thrust required for the 500-foot-per-minute climb at 3 miles

decreases with velocity as shown in figure 3. This characteristic is generally found in highly swept delta configurations of this type.

AFTERBURNING TURBOJET ENGINES

Design Characteristics and Modes of Operation

The turbojet engines used in this analysis had a design turbine-inlet temperature of 2200° F with a design compressor-pressure ratio of 10. The maximum afterburner temperature was 3000° F. Part power operation with afterburning was obtained by retaining the design turbine-inlet temperature and reducing the afterburner temperature. Without any afterburning, it was necessary to reduce the turbine-inlet temperature to reduce power. Two modes of compressor operation were considered when turbine-inlet temperatures were reduced below the design value. One involved operation on the full-power operating line on the compressor map (mode A, fig. 4(a)), while the other involved operation with constant corrected airflow at the compressor face (mode B, fig. 4(a)). Flexibility in the establishment of a part power operating line was made possible by the use of a variable-area primary exhaust nozzle, which is a necessity with this type of engine. Mode B part power operation at reduced turbine-inlet temperatures requires that exhaust nozzle area be increased as turbine-inlet temperature is reduced with engine shaft speed held almost constant. Mode A part power operation at reduced turbine-inlet temperatures was achieved with much smaller changes in primary exhaust nozzle area and significant reductions in engine shaft speed. Mode B operation resulted in a smaller exit jet velocity and a greater exit mass flow than mode A operation for a given part power thrust setting, as shown in figure 4(b).

Takeoff Noise

Takeoff noise varies with thrust setting, mode of part power operation, and engine size. Engine size is indicated by the magnitude of the sea-level static airflow (lb/sec). The calculated 1500-foot sideline noise is shown for both modes of part power operation in figure 5 for four 675-pound-per-second engines. Since jet noise is much more sensitive to exit velocity than to gas mass flow and exit velocity is smaller at a given part power thrust level with mode B operation (fig. 4(b)), mode B operation results in a greater noise reduction. For the maximum afterburning takeoff at 70 200 pounds thrust per engine, the 1500-foot sideline perceived noise at the start of takeoff roll is 123.9 PNdB, when the effects of ground attenuation and engine masking are considered. Figure 5 shows that the

116-PNdB goal can be met with mode A part power operation if the thrust is reduced to 56.5 percent of the maximum afterburning thrust. Mode B part power operation is more favorable because the noise goal can be met with 62.0 percent, instead of 56.5 percent, of maximum thrust.

Noise at 3-Mile Point

The 3-mile noise varies with all the conditions that affect takeoff noise and with the mode of climb to the 3-mile point. After the power cutback at the 3-mile point, the trade-off between altitude and velocity for minimum noise results in an altitude of 700 feet and a velocity of 220 knots for a takeoff at 56.5 percent of maximum thrust. This 56.5-percent thrust setting was required to meet the takeoff noise goal with mode A operation (fig. 5). Figure 6 shows how the altitude at 3 miles, the thrust after power reduction for climb at 500 feet per minute, and the community noise vary as the 3-mile-point airspeed is varied after takeoff at 56.5 percent of maximum thrust. It can be seen from figure 6 that the 3-mile noise goal cannot be met with mode A operation of a 675-pound-per-second engine. When mode B operation is used with this size engine, however, noise levels below both FAA goals can be attained. Figure 5 shows that at this level of takeoff thrust, the 1500-foot sideline noise at the start of roll was 113.2 PNdB, almost 3 PNdB below the goal. Figure 6 shows that, at the 3-mile point, a noise level of 100.5 PNdB was obtained, which was more than 4 PNdB below the goal. The 3-mile noise goal can be met with mode B operation at a velocity as low as 187 knots at a somewhat higher thrust setting than that which produced the minimum noise level of 100.5 PNdB.

Engine Sizing

To meet the noise goals with mode A operation, more takeoff thrust is required to reduce the 3-mile noise through a higher altitude and/or a greater airspeed. A small reduction in jet velocity and a much larger increase in engine airflow are required to increase the thrust at takeoff without increasing the sideline noise, since jet noise is much more sensitive to exit velocity than to gas mass flow. Hence, for mode A operation, a larger engine is required to meet both noise goals, while, for mode B operation, the reverse of the preceding argument would indicate that a smaller engine could be used. For example, with mode B operation, the perceived noise levels at the two checkpoints can be raised to the limits of the FAA goals by increasing the exit velocity and decreasing the airflow. However, the exact amount of these changes can be found only after completing a series of iterative calculations that consider the effect of takeoff thrust on 3-mile air-

speed and/or altitude. Figure 7(a), which uses takeoff sideline noise and 3-mile community noise as the coordinates with engine size and takeoff thrust setting as parameters, summarizes the results of a series of such iterative calculations for mode B part power operation. It is shown in figure 7(a) that a 575-pound-per-second-engine size meets both noise goals when the engines are throttled back during takeoff. In this study to determine the engine size requirement, the 3-mile altitude and velocity were allowed to vary in such a manner as to minimize noise. Figure 7(b) shows that a 3-mile altitude of 750 feet, achieved with the 575-pound-per-second engine, satisfies the noise goals. The corresponding 3-mile velocity (not shown) is 211 knots.

Lift-off distance, of course, is affected by takeoff throttle setting as well as engine size, as indicated in figure 7(c). Lower throttle settings and smaller engine sizes increase the distance required for lift-off, but for the range of engine sizes and throttle settings considered, this distance was always within acceptable limits (i. e., not greater than distances required for existing subsonic commercial intercontinental jet airliners). For the 575-pound-per-second-engine at the throttle setting that permits the attainment of both FAA noise goals, the required lift-off distance is about 4300 feet, well within acceptable limits.

For the range of engine sizes considered, only a minimal amount of afterburning was required for cruise at the payload-optimum altitude. The initial cruise sonic boom for the airplanes of this study was typically about 2.0 pounds per square foot, but the FAA goal of 1.7 pounds per square foot could have been obtained with all the engine sizes considered by initiating cruise at a higher altitude. Although meeting the cruise sonic boom goal would not affect engine sizing, payload would suffer as a result of additional fuel consumption.

The airplane should have enough thrust margin to be able to maintain a 3-percent climb gradient immediately after takeoff at lift-off velocity (165 knots) in case of some unforeseen event such as loss of an engine. All of the engine sizes considered could meet this requirement on a hot (standard temperature $+15^{\circ}$ C) day after landing gear retraction, provided the throttle setting of the three remaining engines is increased.

Payload

The engine size contours of figure 7(a) may be replaced by contours of constant payload if a relation between engine size and weight can be determined and changes in the weight of fuel required to accomplish the design mission are taken into account. Smaller engines are necessarily lighter, and payload, therefore, increases as engine size decreases if there is not a commensurate increase in the weight of fuel required to accom-

plish the mission. For the range of engine sizes investigated (475 to 675 lb/sec), the engine weight reduction accomplished by a size reduction was always greater than the increase in fuel weight. In determining the change in engine weight for a given variation in design airflow, engine weight was assumed to be proportional to airflow raised to the 1.3 power, a representative value for this type of engine. The base weight of one installed 575-pound-per-second engine was assumed to be 15 950 pounds. The installed weight includes the weight of inlet, nacelle, nozzle, thrust reverser, and accessories, in addition to the weight of the bare engine.

A payload of 35 500 pounds can be carried over the 4000-mile design range by the 575-pound-per-second engines that meet the noise goals. This payload is only 77 percent of the seat-limited payload of 46 200 pounds (fig. 7(d)). A comparison of figures 7(a) and (d) indicates that the payload obtained with the smallest engine considered (475 lb/sec) is much higher at 96 percent of the seat-limited payload, in spite of the fact that the total fuel required (including reserves) increases by more than 2 percent (about 5300 lb). With the 475-pound-per-second engine, performance is adequate, but the noise goals are not met. For example, figure 7(d) shows that with takeoff thrust at 86 percent of maximum in order to observe the 105 PNdB noise goal at 3 miles, the noise at takeoff would be 121.6 PNdB, almost 6 PNdB above the goal. Other assumptions regarding engine weight would have changed the payload plot of figure 7(d). For example, if the airflow scaling exponent were assumed to be 1.0 instead of 1.3, reduction of the engine size from 575 to 475 pounds per second would permit a payload increase of only 15 percent instead of 25 percent.

DUCT-BURNING TURBOFAN ENGINES

Design Characteristics

The duct-burning turbofan engines considered in this analysis were designed for a 2300^o F turbine-inlet temperature during the takeoff and climb-acceleration phases of flight, with a reduction to 2200^o F during cruise. Maximum allowable duct-burner temperature was considered to be 3100^o F. The overall design compressor-pressure ratio was 11.9, with a design fan pressure ratio of 2.7 and a bypass ratio of 1.3. The latter two design parameters were allowed to vary to determine their effect on noise. Unlike the afterburning turbojet engines discussed in the preceding section, the duct-burning turbofan engines considered herein have fixed-geometry primary exhaust nozzles. The fixed primary nozzle implies that the part power mode of operation obtained when the turbine-inlet temperature is reduced below its design value must satisfy conditions traced by the full-power operating line on the compressor map.

Takeoff Noise

For both the afterburning turbojet and the duct-burning turbofan engines, takeoff noise varies with mode of part power operation. It has been shown that turbojet engine noise can be minimized at unaugmented thrust settings by scheduling combustor fuel flow and exhaust nozzle primary area. For the turbofan with a fixed primary exhaust nozzle, noise can be minimized at augmented thrust settings by scheduling combustor fuel flow and duct-burner fuel flow. For a particular set of engine design parameters, there is probably some combination of primary and duct-burner temperature that maximizes the takeoff thrust for a given level of sideline noise. Figure 8 indicates that for 650-pound-per-second engines operating at the relatively high levels of thrust required for lift-off and with a 1.3 bypass ratio and a 2.7 fan pressure ratio, thrust depends primarily on the level of sideline noise generated and is insensitive to the combination of primary and duct-burner temperatures that produce it. Sideline noise levels are presented in figure 9 as a function of thrust and range from 119.3 PNdB at maximum power down to about 109 PNdB at 60 percent of full power. Figure 9 shows that the engines would have to be throttled back to 81.5 percent of maximum design power to meet the 116 PNdB takeoff noise goal. At the lower thrust levels which are encountered after the power cutback at 3 miles, in contrast to the situation at lift-off, there is a combination of primary and duct-burner temperatures that minimizes noise.

Engine Sizing

A turbofan engine size can be found which allows the airplane to satisfy both the sideline noise goal and the 3-mile noise goal. Shown in figure 10(a) are the results of such a study for engines with a design bypass ratio of 1.3 and a design fan pressure ratio of 2.7. The airplane was accelerated after takeoff so as to minimize noise at the 3-mile point. Figure 10(a) indicates that a 650-pound-per-second engine with a takeoff thrust setting of 81.5 percent of the maximum available is required to meet both FAA noise goals. Smaller engines violated one or both of the goals. In addition, for the aerodynamic assumptions of the present study, engines smaller than 650 pounds per second must be ruled out because of inadequate engine-out second segment climb performance (3-percent climb gradient at lift-off velocity with landing gear retracted on a hot day).

Payload

Larger engines necessitate additional engine weight at the expense of payload, even though there is a reduction in the fuel weight requirement with larger engines. This fact

is illustrated by figure 10(b), which is essentially the same as figure 10(a) except that the lines representing constant engine size were replaced by the payload contours. A payload of 45 000 pounds can be carried with the 650-pound-per-second engines that meet the noise goals. This payload is 97.5 percent of the seat-limited payload of 46 200 pounds. The weight of an installed 650-pound-per-second engine was assumed to be 14 150 pounds. In addition to the weight of the bare engine, the installed weight includes the weight of inlet, nacelle, nozzle, thrust reverser, and accessories. Engine weights were calculated for different engine sizes by assuming an airflow scaling exponent of 1.1, a value representative of the duct-burning turbofan engine. Other assumptions regarding the value of the scaling exponent would, of course, change the values assigned to the payload contours.

Figure 11 shows how the payload is expected to vary with changes in design bypass ratio if the engines are resized as necessary to meet both FAA noise goals. The design fan pressure ratio was fixed at 2.7. Figure 11 shows that the 1.3 bypass ratio used in the previous figures yields the maximum payload (97.5 percent of the seat-limited payload). As bypass ratio was varied, engine performance and weight varied. Performance affects payload through fuel load, both useful and reserve. The fuel load variation with bypass ratio, however, was small.

Variation in engine weight accounted for practically all the variation in payload. Engine weight increased with size and decreased with increasing bypass ratio over the range of bypass ratios considered, but the size effect predominated. Larger engine sizes are required both above and below a bypass ratio of 1.3, as shown in figure 11. Bypass ratios higher than 1.3 require larger engines to provide adequate takeoff thrust so that reasonable altitudes and velocities may be obtained at the 3-mile point. At bypass ratios greater than 1.3, with maximum duct burning, the main stream jet velocity is lower than the duct stream velocity, which then becomes the predominant noise source. Duct-burner temperature cannot be raised without a significant increase in noise level; it is desirable, therefore, to increase engine size (airflow) as bypass ratio is increased and, at the same time, decrease somewhat the duct-burner temperature. This procedure tends to equalize the noise contribution of the two streams and minimize the total perceived noise level for a given amount of thrust.

At bypass ratios lower than 1.3, the noise characteristics of the duct-burning turbofan begin to approach those of the afterburning turbojet. As bypass ratio is reduced, the outer turbine driving the fan is unloaded, and thus the primary jet velocity is increased if turbine-inlet temperature is held constant. Higher primary jet velocities, however, create higher noise levels. To avoid this occurrence, it is necessary to reduce the primary burner temperature so that the primary jet velocity is reduced to a level somewhat below the duct stream velocity. Since the reduction in turbine-inlet temperature reduces the thrust, it is necessary to increase the engine size to obtain enough thrust at takeoff to gain altitude and speed sufficient for satisfactory 3-mile noise levels.

Other analyses have shown that a fan pressure ratio of 2.7 is optimum for a bypass ratio of 1.3. Actually, however, to get the true picture of the effect bypass ratio has on payload, the design fan pressure ratio should be reoptimized for different bypass ratios. This was done for the maximum bypass ratio considered in figure 11 (i. e. , a bypass ratio of 2.75). Figure 12(a) shows that, as fan pressure ratio is reduced from the value of 2.7 considered in the preceding bypass-ratio optimization, the payload increases from a level of 82.8 percent to a maximum of 92.5 percent of the seat-limited payload when a fan pressure ratio of 2.3 is reached. Although the engine size required to meet the noise goals continues to decrease down to a fan pressure ratio of 2.15 (fig. 12(b)), reductions below the optimum of 2.3 cause increases in wave drag, specific fuel consumption, and engine weight per unit airflow that negate any engine weight saving that might otherwise accrue from a reduced airflow.

From this limited investigation of the effects of bypass ratio and fan pressure ratio on the takeoff noise environment and the design-range payload, it appears that a payload as high as 97.5 percent of the seat-limited payload is attainable with duct-burning turbofan engines that satisfy both takeoff noise goals. The engines are characterized by a design bypass ratio of 1.3 and a design fan pressure ratio of 2.7. A more complete optimization would not change these results significantly.

SUMMARY OF RESULTS

A limited analytical study was made of the SST airport and community jet-noise problem during takeoff and initial climb. Both afterburning turbojet and duct-burning turbofan engines were considered in the fixed-delta-wing configuration chosen to illustrate the effect noise constraints may have on payload.

For the aerodynamic characteristics assumed in this study, it was necessary to accelerate during the initial climb after lift-off, rather than seek the maximum possible altitude, in order to minimize the 3-mile community noise. For the afterburning turbojet engine type, the takeoff and 3-mile noise goals set by the FAA required the use of engines larger than those that would otherwise satisfy the various performance criteria. The use of the larger engines to meet the noise goals would decrease the vehicle payload capability at the design range because of the heavier engine weight. A part-power takeoff thrust at reduced levels of turbine-inlet temperature with the afterburner off was required. A smaller engine (resulting in less payload penalty) could be used when thrust was reduced by reducing fuel flow and holding airflow constant rather than by reducing both fuel flow and airflow.

When duct-burning turbofan engines were used, a part-power thrust with the duct burner on was required to satisfy both noise goals. Both duct-burner and main-combustor fuel flows were regulated to obtain the maximum thrust for a given noise level.

For this engine type, takeoff and 3-mile noise considerations did not require that the engine size be increased above the size dictated by other performance criteria. One-engine-out capability on a hot day during second segment climb dictated the same engine size that was required to satisfy the noise goals.

With afterburning turbojet engines, the 575-pound-per-second engine was required for the 500 000-pound airplane of this study in order to meet the noise goals. With duct-burning turbofan engines, a 650-pound-per-second engine would be required. These engine sizes allow payloads of 35 500 pounds with afterburning turbojet engines and 45 000 pounds with duct-burning turbofan engines for a 4000-mile design mission.

The payload capacity was sensitive to imposed noise goals. Although the numerical results presented are applicable only to the airplane assumed herein, it is concluded that sufficiently stringent noise requirements can be the critical factor sizing the engines for commercial supersonic transports. Thus, it is of great importance that the criteria and levels of the noise parameters imposed on the engine and airframe designer accurately reflect the noise environment that will satisfy the public.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 28, 1967,
126-15-02-02-22.

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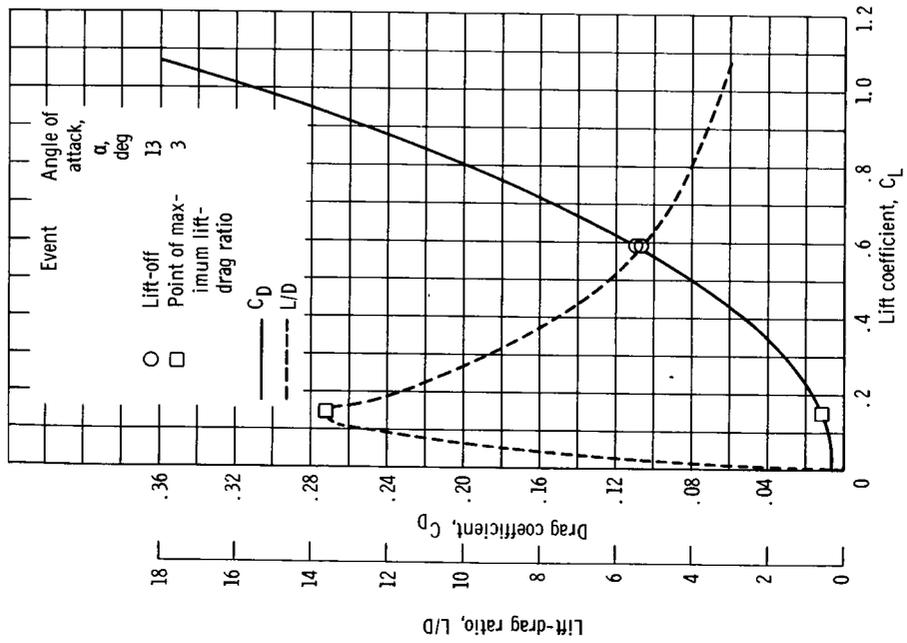


Figure 1. - Takeoff and initial climb aerodynamics.

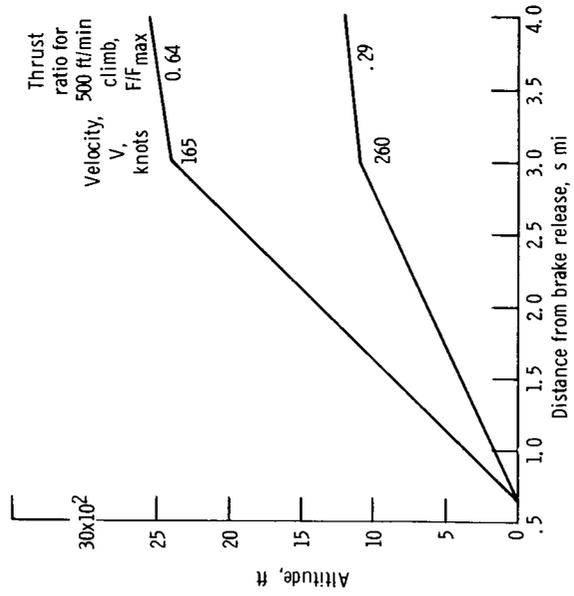


Figure 2. - Takeoff and initial climb procedure with 475-pound-per-second afterburning turbojet engines. Maximum afterburning up to 3-mile point; lift-off velocity, 165 knots.

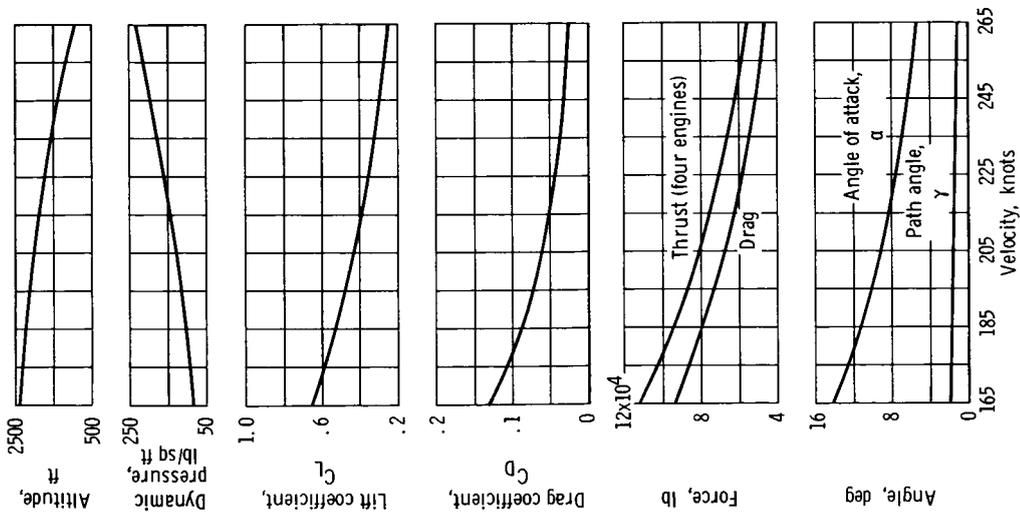
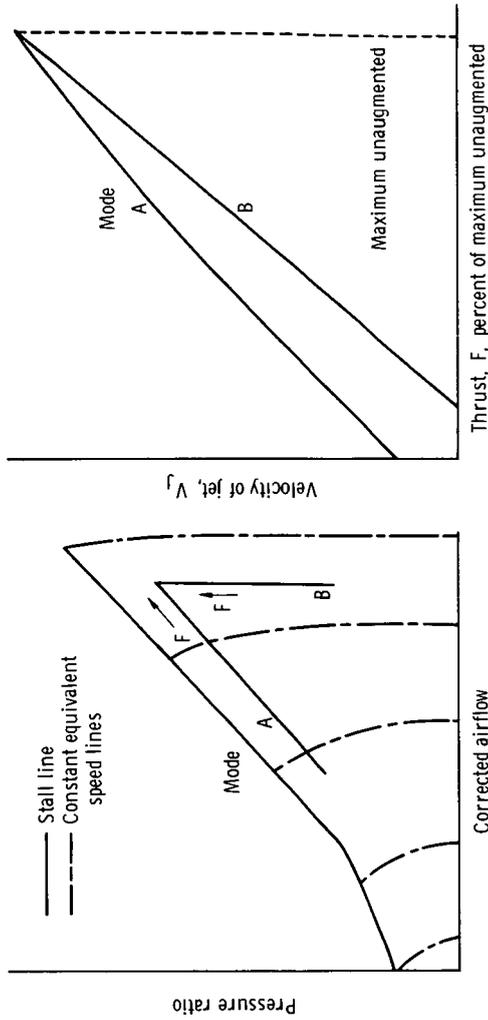


Figure 3. - Typical 500-foot-per-minute climb conditions at 3 statute miles from start of takeoff roll. Sea-level static thrust, 50 000 pounds per engine.



(a) Compressor map showing modes.
 (b) Comparison of partial power modes.
 Figure 4. - Partial power operation with afterburning turbojet engines.

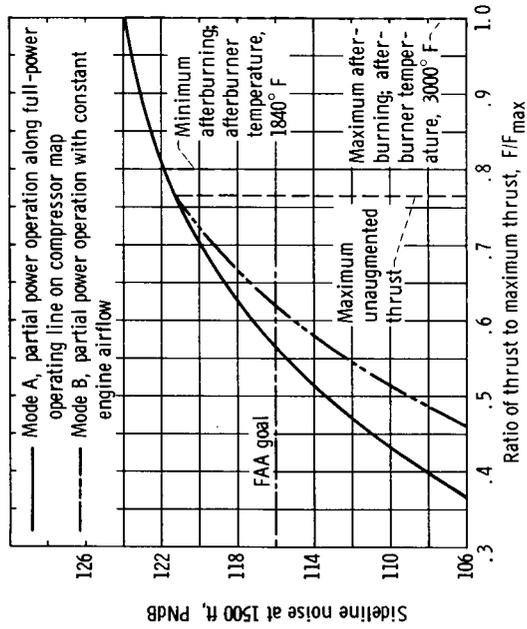


Figure 5. - Calculated noise at start of takeoff roll with four afterburning turbojet engines. Design turbine inlet temperature, 2200° F; design airflow, 675 pounds per second per engine.

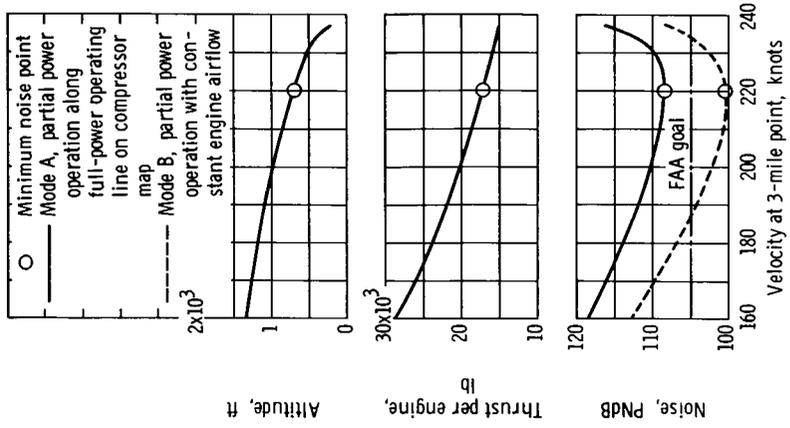
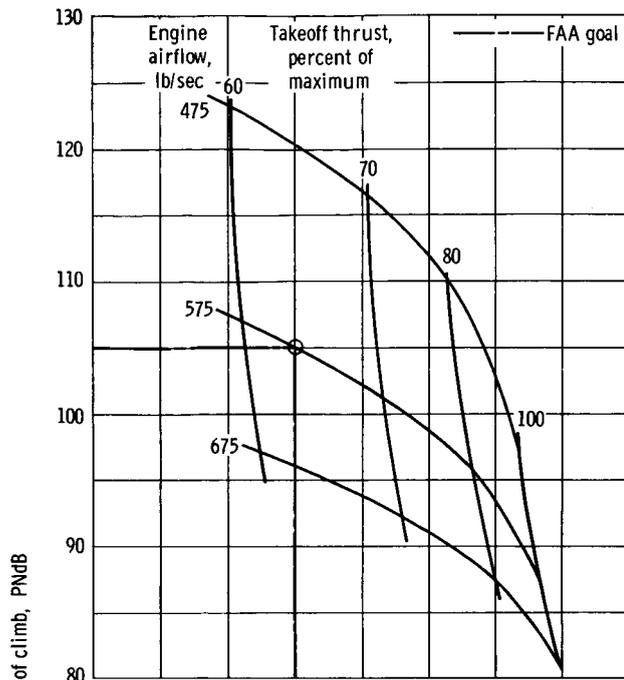
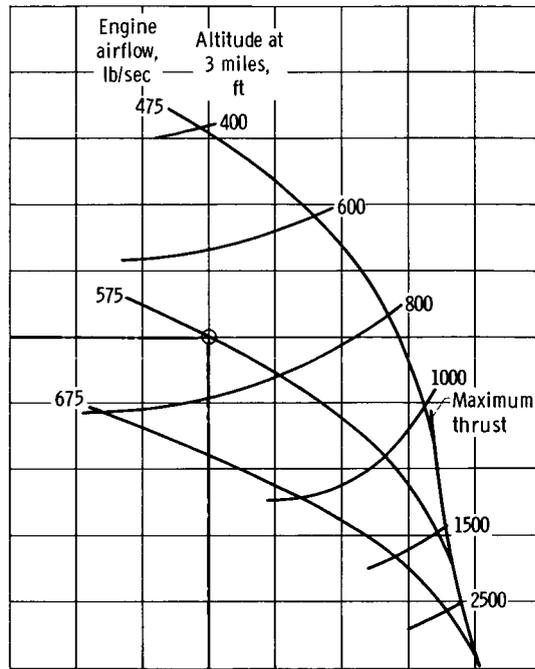


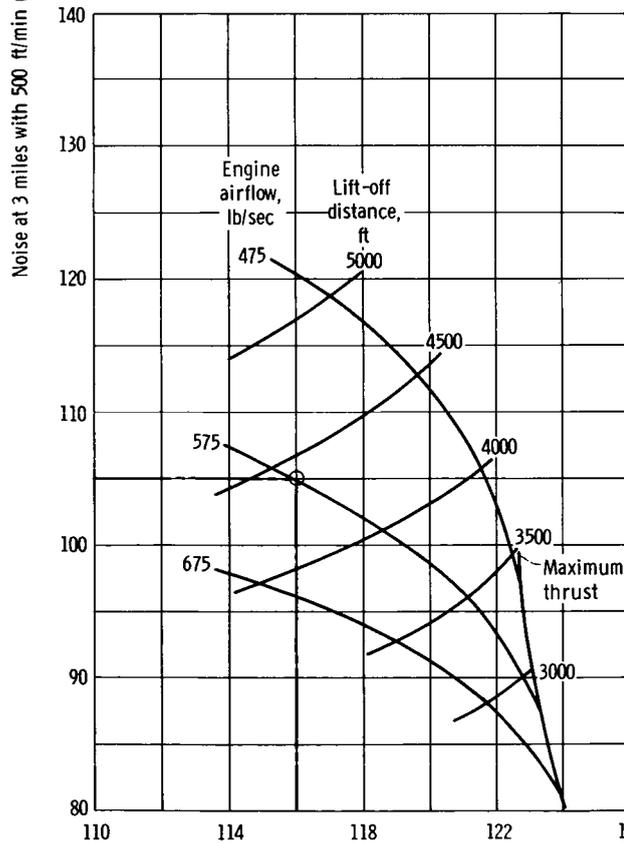
Figure 6. - Conditions at 3 statute miles from start of takeoff roll with four afterburning turbojet engines. Design airflow, 675 pounds per second per engine; thrust up to 3-mile point, 56.5 percent of maximum; power cut back for 500-foot-per-minute climb.



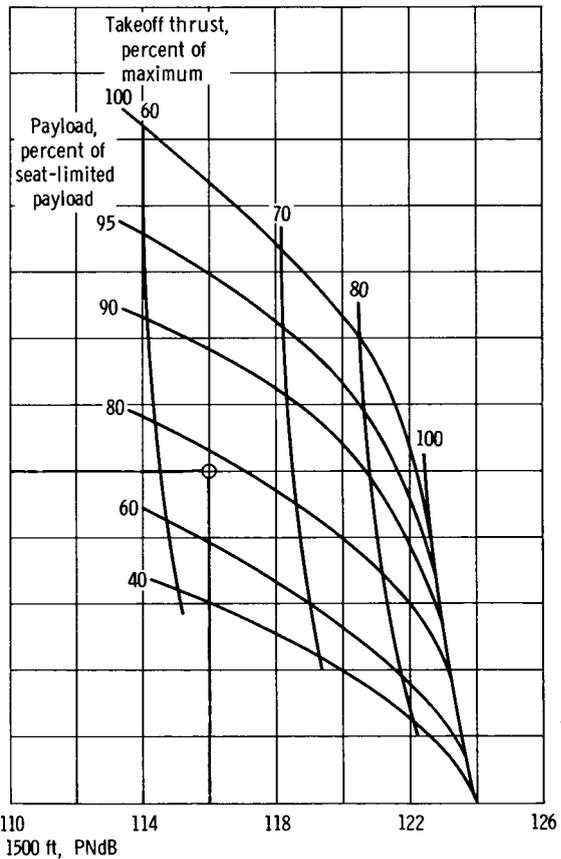
(a) Engine size.



(b) Effect on altitude at 3 miles from brake release.



(c) Lift-off distance.



(d) Payload.

Figure 7. - Effect of noise goals on airplane and engine parameters with four afterburning turbojet engines. Mode B, constant-airflow operation during partial power.

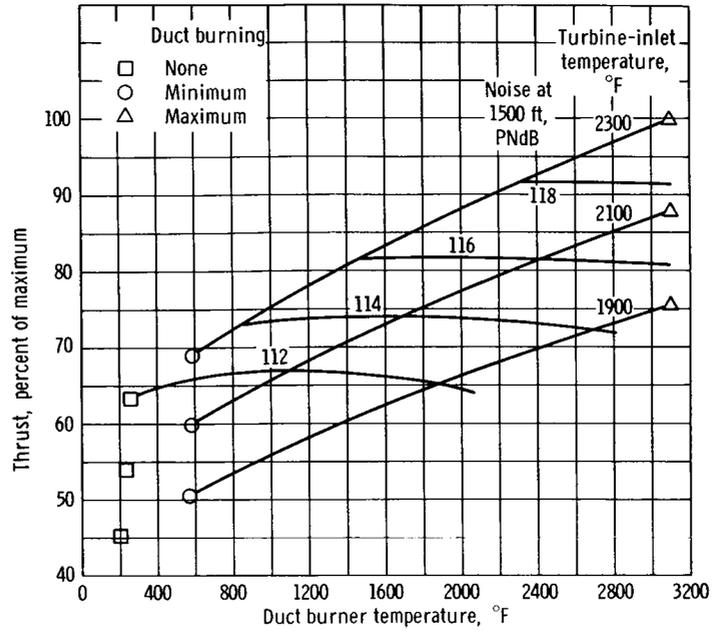


Figure 8. - Takeoff thrust and noise with four duct-burning turbofan engines. Design airflow, 650 pounds per second per engine; design bypass ratio, 1.3; design fan pressure ratio, 2.7; maximum thrust per engine, 51 970 pounds.

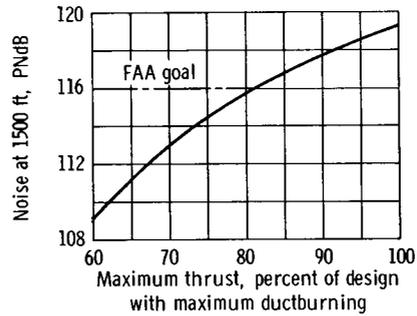


Figure 9. - Engine operation for minimum noise at start of takeoff roll with four ductburning turbofan engines.

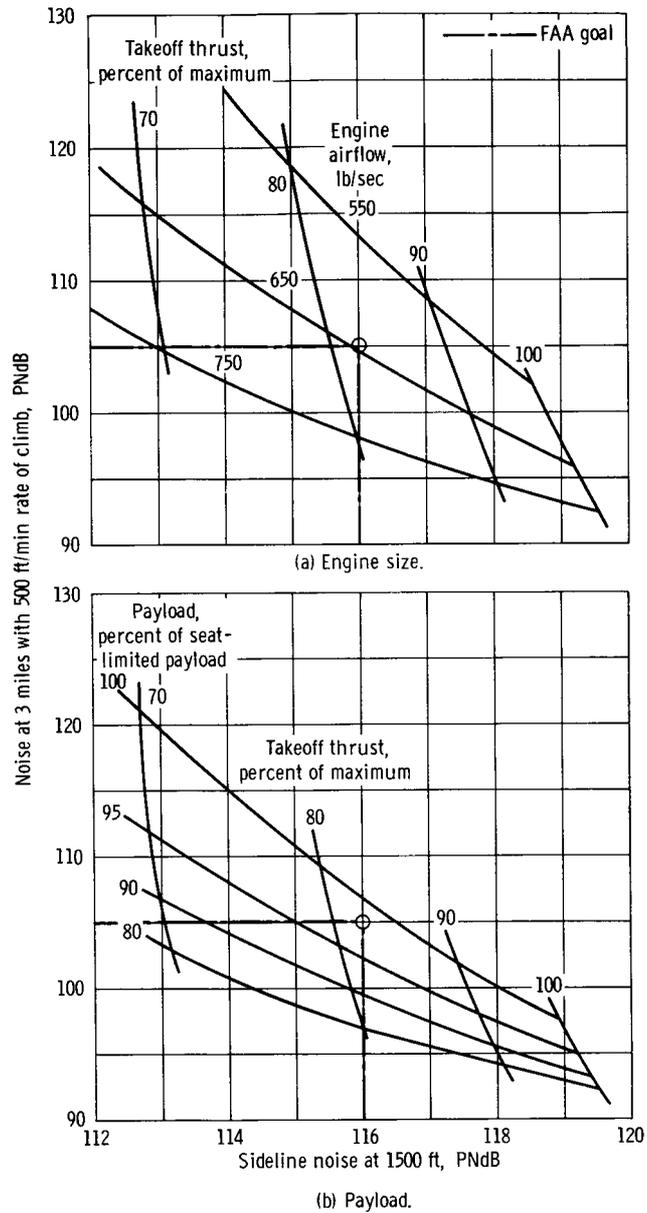
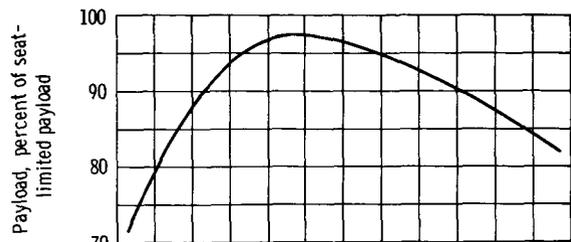
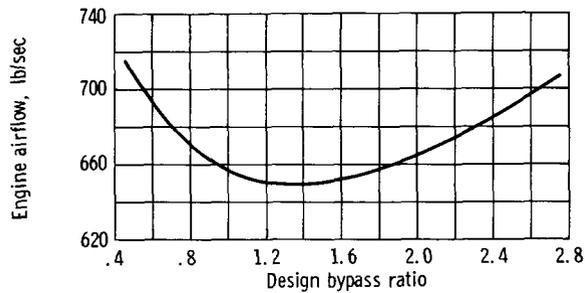


Figure 10. - Effect of noise goals on airplane and engine parameters with four ductburning turbofan engines. Design bypass ratio, 1.3; design fan pressure ratio, 2.7.

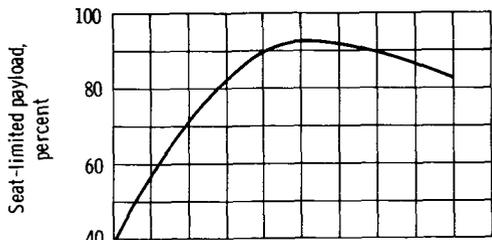


(a) Seat-limited payload.

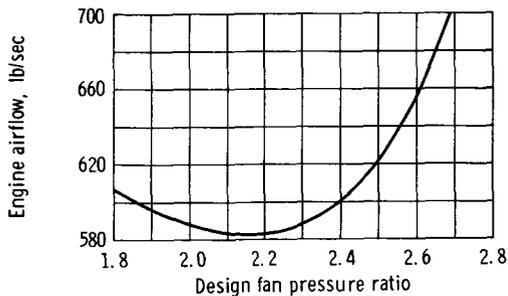


(b) Engine airflow.

Figure 11. - Effect of bypass ratio on airplane payload and engine airflow. Design fan pressure ratio, 2.7; sideline noise at takeoff, 116 perceived noise decibels; 3-mile community noise, 105 perceived noise decibels.



(a) Seat-limited payload.



(b) Engine airflow.

Figure 12. - Effect of fan pressure ratio on airplane payload and engine airflow. Design bypass ratio, 2.75; sideline noise at takeoff, 116 perceived noise decibels; 3-mile community noise, 105 perceived noise decibels.