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FLIGHT VELOCITY EFFECTS ON EXHAUST NOISE OF A WEDGE NOZZLE INSTALLED ON AN UNDERWING NACELLE ON AN F-106 AIRPLANE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1976

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3361		

4. Title and Subtitle	5. Report Date
FLIGHT VELOCITY EFFECTS ON EXHAUST NOISE OF A WEDGE NOZZLE INSTALLED ON AN UNDERWING NACELLE ON AN F-106 AIRPLANE	February 1976
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Richard R. Burley	E-8548
	10. Work Unit No.
9. Performing Organization Name and Address	505-04
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

It is important to know whether the relatively high takeoff speeds of supersonic transport aircraft will change the exhaust noise levels of nozzles from those measured at static conditions. To gain some insight into this question, a modified F-106B aircraft was used to conduct flyover and static tests on a wedge nozzle. Flight velocity had an adverse effect on exhaust noise when compared with static results at the same relative jet velocity but a beneficial effect when compared with static results at the same absolute jet velocity. The wedge nozzle, which has a two-dimensional wedge surface rather than an axisymmetric plug surface, had a higher peak flyover noise level than the plug nozzle.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Flight velocity effects; Exhaust noise; Nozzle thrust; Propulsion systems; Two-dimensional nozzle	Unclassified - unlimited STAR Category 07 (rev.)

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	30	$3.75

* For sale by the National Technical Information Service, Springfield, Virginia 22161

FLIGHT VELOCITY EFFECTS ON EXHAUST NOISE OF A WEDGE NOZZLE INSTALLED ON AN UNDERWING NACELLE ON AN F-106 AIRPLANE

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SUMMARY

It is important to know whether the relatively high takeoff speeds of supersonic transport aircraft will change the noise levels of exhaust nozzles from those measured at static conditions. To gain some insight into this question, flyover and static tests were conducted on a wedge nozzle. This nozzle is similar to a plug nozzle but has a two-dimensional wedge surface rather than an axisymmetric plug surface. The acoustic and thrust characteristics of the wedge nozzle were compared to those of a plug nozzle. For the tests, an F-106B aircraft was modified to carry two underwing nacelles, each containing a calibrated J85-GE-13 turbojet engine. Data were taken over a range of J85 power settings that resulted in absolute jet velocities from about 420 to 640 meters per second at static conditions and from about 574 to 714 meters per second at flyover conditions (corresponding to relative jet velocities from 440 to 536 m/sec). The flyovers were conducted at an altitude of 91 meters and a Mach number of 0.4.

The adjusted flyover and static conditions of the wedge nozzle were compared at the acoustic angle that resulted in peak flyover noise. Flight velocity had an adverse effect on the exhaust noise by 3 PNdB when compared with static results at the same relative jet velocity but a beneficial effect of 5 PNdB when compared with static results at the same absolute jet velocity. The peak flyover noise level of the wedge nozzle was about 3 PNdB greater than that of the plug nozzle at an absolute jet velocity of 670 meters per second because it has considerably more middle- and high-frequency noise than the plug nozzle.

INTRODUCTION

During takeoff of advanced supersonic transport aircraft, the dominant noise source is the high-velocity jet issuing from the exhaust nozzle. Until recently, investigations of acoustic characteristics of both unsuppressed and suppressed exhaust nozzles generally had been done at static conditions (cf., refs. 1 to 3). However, the takeoff speed of these aircraft can be as high as Mach 0.35 when maximum sideline noise is reached. Thus, an important question is whether flight speed affects the noise of exhaust nozzles.

To gain some insight into this question, a series of flyover and static tests are being conducted on both unsuppressed and suppressed exhaust nozzles. Some preliminary results have been published in references 4 and 5. Results for a wide variety of suppressor configurations have shown that flight speed can adversely affect the noise of some suppressor configurations (refs. 6 to 9). An investigation of three basic types of unsuppressed nozzles (a plug nozzle, a variable-flap ejector nozzle, and an auxiliary-inlet ejector nozzle) has shown that flight speed can have a beneficial effect on the noise of an auxiliary-inlet ejector nozzle (ref. 10).

Another interesting basic type of unsuppressed nozzle is a wedge nozzle. This nozzle is similar to a plug nozzle but has a two-dimensional wedge surface rather than an axisymmetric plug surface. The wedge nozzle has the potential of achieving aerodynamic performance comparable to that of a plug nozzle and also of providing alternative solutions to the mechanical and cooling problems of a plug nozzle (refs. 11 and 12). The nozzle of reference 11 was also tested with a multispoke primary to determine its internal performance as a noise suppressor. The addition of 14 spokes reduced its performance by 4.5 percentage points (from 94 percent to 91.5 percent) at takeoff conditions (ref. 13). The basic wedge nozzle itself, however, might be quieter than a plug nozzle since its two-dimensional wedge could affect the directivity and frequency of the noise.

The present investigation was conducted to determine whether flight velocity affects the noise and thrust of a wedge nozzle. A secondary objective was to compare the wedge nozzle acoustic and thrust characteristics with those of the plug nozzle of reference 10 (which was used as a baseline or reference nozzle for suppressor tests). Also investigated was the effect of changing the orientation of the two-dimensional wedge from vertical to horizontal at static conditions.

For the tests, an F-106B aircraft was modified to carry podded engines mounted near the aft lower surface of the wing, with the exhaust nozzles extending beyond the wing trailing edge. The primary jet exhaust was provided by a calibrated J85-GE-13 turbojet engine. The flyovers were conducted at an altitude of 91 meters and a Mach number of 0.4. Acoustic measurements were taken from a ground station directly beneath the flightpath. For static tests, the acoustic measurements were made at a radial distance of 30.48 meters from the nozzle. Data were taken over a range of J85 engine power settings from part throttle to military power (maximum dry). This gave a range of absolute jet velocities from about 574 to 714 meters per second for flyover conditions (corresponding to relative jet velocities from 440 to 536 m/sec) and from 420 to 640 meters per second at static conditions.

SYMBOLS

A_8	primary-nozzle-exit effective flow area (hot), cm^2
D	nozzle drag, kN
F	nozzle gross thrust, kN
F_{ip}	ideal thrust of primary jet, kN
M_0	flight Mach number
P_8	total pressure at primary nozzle exit, kN/m^2
p_0	ambient static pressure, kN/m^2
R_p	direct-ray distance between exhaust nozzle and microphone (fig. 12(b)), m
T_8	total temperature at primary nozzle exit, K
T_s	total temperature of secondary air, K
V_a	aircraft flight velocity, m/sec
V_j	ideal absolute jet velocity, m/sec
V_r	relative jet velocity, $V_j - V_a$, m/sec
W_s	secondary weight flow, kg/sec
W_8	weight flow at primary nozzle exit, kg/sec
Y	coordinate of wedge surface (fig. 5(b)), m
θ	angle between direct ray and jet centerline (fig. 12(b)), deg
$\omega\sqrt{\tau}$	corrected secondary weight flow ratio, $W_s/W_8 \sqrt{T_s/T_8}$

APPARATUS AND PROCEDURE

Test Facility

An F-106B aircraft modified to carry two underwing nacelles was used for the flyover and static tests. The aircraft is shown in flight in figure 1 with nozzles that had previously been tested. A schematic view of the nacelle-engine installation is shown in figure 2. The 63.5-centimeter-diameter nacelles were located at approximately 32 percent semispan, with the exhaust nozzles extending beyond the wing trailing edge. Since the nozzle would interfere with normal elevon movement, a section of the elevon immediately above each nacelle was cut out and rigidly fixed to the wing. Each nacelle contained a calibrated J85-GE-13 afterburning turbojet engine. The nacelles had normal shock inlets with blunted cowl lips for the flyover tests. Secondary air to cool the engine was supplied from the inlet and was controlled at the periphery of the compressor face by a calibrated rotary secondary flow valve. For the static tests, the blunted cowl lips were replaced with a bellmouth as shown in figure 3. The suppressor nozzle shown in this figure was one that had previously been tested.

Each nacelle was attached to the wing by two links normal to the nacelle axis; the axial force was measured by a load cell attached to the wing as shown in figure 2. An accelerometer in the nacelle allowed the load cell to be compensated for acceleration. The axial force transmitted to the compensated load cell can be divided into two components: (1) nacelle drag forward of the research nozzle, referred to as the tare force; and (2) research-nozzle gross thrust minus drag. Gross thrust minus drag was determined by adding the tare force to the compensated load-cell reading. The tare force was zero for static tests (ref. 10). For flyover tests, the tare force was the sum of the ram drag and the skin friction drag on the nacelle and strut (ref. 10).

Wedge Nozzle

The wedge nozzle, installed on the aircraft with the wedge in its horizontal position, is shown in figure 4. It was also tested with the wedge in its vertical position, but only at static conditions. The dimensions of the nozzle are given in figure 5. The nozzle consisted of a 10° half-angle centerbody, sideplates that were swept at $25^{\circ}30'$, a primary flap, and an outer shroud. Coordinates for the contour of the forward portion of the wedge are given in table I. The primary flap had a maximum angle of 10° at the plan view centerline that washed out to 0° at the sides of the wedge (fig. 5(b)). The outer shroud was simulated in its retracted position for efficient operation at the low pressure ratios of takeoff conditions. Further details of this nozzle design, along with its installed performance over the Mach number range 0.7 to 1.10, are given in reference 12.

Plug Nozzle

The plug nozzle is shown in figure 6. It consisted of a 10° half-angle conical plug body, a primary flap with a 14° trailing edge, and an outer shroud that was simulated in its retracted position. Further details of this nozzle design are given in reference 14; acoustic and thrust results for flyover conditions are presented in reference 10.

Instrumentation

An onboard digital data system was used to record pressures, temperatures, and load-cell output on magnetic tape (further details of this system are given in ref. 15). A flight-calibrated test boom located on the aircraft nose was used to determine free-stream static and total pressure, aircraft angle of attack, and yaw angle. Aircraft speed was obtained from a calibrated Machmeter, the output of which was sampled and recorded six times in 11.5 seconds by the onboard digital data system.

Aircraft altitude and position were determined with the aid of a camera located adjacent to the microphone. The camera recorded a picture of the aircraft as it passed overhead; at the same time a 14-kilohertz signal was recorded on the tape (further details are given in ref. 8).

Engine airflow was determined by using the calibration results of reference 16 along with measurements of engine speed and total pressure and temperature at the compressor face. Fuel flows were obtained from calibrated flowmeters. Total temperature T_8, total pressure P_8, and effective flow area A_8 at the primary nozzle exit were obtained by using the values of engine airflow and fuel flow, the measured values of total pressure and temperature at the turbine discharge, and the afterburner pressure drop calibration results of reference 16. Calibration results of the secondary-flow-valve pressure drop and position were used to determine secondary airflow.

Total pressure and temperature of the secondary air were obtained from the probes shown in figure 7. The probes were located at 0°, 90°, 180°, and 270°. The thermocouples were Chromel/Alumel and had radiation shields.

The noise measuring instrumentation is shown in the block diagram of figure 8. The microphone was ceramic and 2.54 centimeters in diameter with a frequency response that was flat to within ±2 decibels for grazing incidence over the frequency range used. The output of the microphone was recorded on a two-channel direct-recording tape recorder. The entire system was calibrated in the field before and after each test with a conventional tone calibrator. The tape recorder was calibrated for linearity with a "pink" noise generator (constant energy per octave).

The flyover signal, recorded on magnetic tape, was played back through a 1/3-octave-band analyzer, and the sound pressure level (SPL) output was then reduced to digital form (fig. 8(b)). The averaging time used for data reduction was 0.1 second. The digital results were recorded on tape.

The static signal recorded on magnetic tape was played back through a 1/3-octave-band analyzer, and the sound pressure level output was automatically plotted (fig. 8(c)). The averaging time used during data reduction was 1/8 second. The plotted results were converted into digital form and recorded on tape.

Meteorological conditions in terms of dry-bulb and dewpoint temperatures, wind speed and direction, and barometric pressure were recorded periodically throughout the test. Testing was done only when wind speeds were less than 5.14 meters per second.

Procedure

The microphone stations for the acoustic measurements at static conditions are shown in figure 9. A portable microphone was positioned 1.22 meters above the concrete surface and was oriented to receive the acoustic pressure waves at normal incidence (fig. 9(a)). The resulting spectra were adjusted to what would be obtained had the microphone been oriented to receive the acoustic pressure waves at grazing incidence. As shown later, this was the microphone orientation when recording the flyover signal. The microphone was fitted with a wind screen that caused no loss of signal. The acoustic measurements were made at a radial distance of 30.48 meters from the nozzle exit in increments of 10° over a 90° sector (fig. 9(b)). During the measurements, the main engine (J75) was at idle power. The J85 engine in the nacelle containing the research nozzle was operated over a range of power settings with the cooling air on when needed, and the J85 engine in the other nacelle was shut off.

Background noise level for the static tests was determined with both J85 engines off, the J75 engine at idle power, and external cooling air on. It was necessary to supply air from an external source to cool the J85 engine when it was operating at military power setting. The air was supplied from an air start cart located on the far side of the aircraft (fig. 10). The supply line went from the start cart to the J85 engine, and the air was directed around the engine through a nozzle (fig. 3). The J75 engine had to be operating when static data were taken because it supplied the electrical power for the onboard digital data system.

The frequency spectrum for the background noise (with J75 at idle power and external cooling air on) is shown in figure 11 at an acoustic angle of 40°. The acoustic angle of 40° is where the effect of flight velocity was examined. The spectrum had a peak value of 85 decibels at a frequency of 250 hertz. The lowest sound pressure levels of interest for the wedge nozzle are about 100 decibels (as shown in the section Acoustic Characteristics). Thus, the background noise level is sufficiently low that it does not interfere with the noise from the wedge nozzle.

Acoustic measurements of the flyover noise were made from a ground station under the flightpath. The microphone setup is shown in figure 12(a). The microphone was positioned 1.22 meters above the concrete surface. It was fitted with a wind screen that caused no loss of signal and was oriented to receive the acoustic pressure waves at grazing incidence.

As the aircraft travels along its flightpath, the direct-ray distance from the nozzle to the microphone R_p continuously changes (fig. 12(b)). The angle between the direct ray and the jet exit centerline, referred to as the acoustic angle θ, also changes. The relation between R_p and θ shown in figure 12(b) assumes that the aircraft flies directly over the microphone at an altitude of exactly 91 meters (ref. 10 discusses the reasons for selecting this altitude). But since this may not always be the case, provisions were made to adjust the recorded sound pressure level to those conditions (details are given in ref. 8).

While the noise data were being recorded during the flyover, the main engine of the aircraft was at idle power. The J85 engine in the nacelle that contained the research nozzle was operated at military and part power settings. The J85 engine in the other nacelle was shut off and allowed to windmill.

Background noise level during flyover was determined with the main engine at idle power and both J85 engines shut off and allowed to windmill. The results are shown in figure 13. Figure 13(a) presents the change in perceived noise level with acoustic angle. Background noise level reached a peak value of 98 PNdB at an angle of 110° and decreased to a value of 91 PNdB at an acoustic angle of 40° (the acoustic angle where the peak noise level of the wedge nozzle occurred). Figure 13(b) presents the 1/3-octave frequency spectrum at the acoustic angle of 40°. The spectrum is fairly flat at a level of about 67 decibels between frequencies of 125 and 3200 hertz and is lower than this at the other frequencies. The lowest perceived noise level of interest for the wedge nozzle is 113 PNdB; the lowest spectral level of interest is 86 decibels. Thus, the background noise level is sufficiently low that it does not interfere with the noise from the wedge nozzle.

RESULTS AND DISCUSSION

Acoustic Characteristics

Flight velocity effects. - The approach to investigating whether flight velocity affects the noise of the wedge nozzle was to adjust the measured flyover and static spectra to comparable conditions of 30.48 meters from the nozzle in the free field and on a standard day. The Doppler shift of frequency, which was accounted for in the flyover spectra, caused a maximum frequency shift of one 1/3-octave band. Details of the adjustments are given in reference 10. The static spectra used herein were obtained with the two-dimensional wedge oriented vertically in order to be consistent with the flyover results obtained with the wedge oriented horizontally. The adjusted flyover and static spectra then were compared at a constant relative jet velocity of 536 meters per second and also at a constant absolute jet velocity of 670 meters per second for the acoustic angle that resulted in peak flyover noise. A relative jet velocity of 536 meters per second in flight corresponds to an absolute jet velocity of 670 meters per second, which, in turn, corresponds to military power setting on the J85 engine. Significant differences between the adjusted spectra were attributed to flight velocity.

In making the comparison, the greatest emphasis should be placed on the data at frequencies between 160 and 5000 hertz. At frequencies below 160 hertz, the short integration time, the narrowness of the frequency bands, and the rapidly changing conditions of the flyover combine to give results that are less reliable. At frequencies above 5000 hertz, the acoustic signal received at the ground station quite possibly is below the noise floor of the recording equipment (ref. 17). In addition, the atmospheric absorption coefficients are very large at these high frequencies and multiply the noise floor to unrealistically high noise levels when the data are adjusted to 30.48 meters. In the figures the flyover spectra from 160 to 5000 hertz are shown by the solid lines and those from 50 to 160 and 5000 to 10 000 hertz are shown by the dashed lines.

The flyover and static spectra are compared at the same relative jet velocity and also at the same absolute jet velocity in figure 14. When the comparison is made at the same relative jet velocity, the flyover 1/3-octave spectrum peaks at a much higher frequency (1000 Hz) than does the static spectrum (400 Hz). Also, the flyover spectrum is lower than the static spectrum from frequencies of 160 to 630 hertz but higher from frequencies of 800 to 5000 hertz. These differences resulted in overall sound pressure levels (OASPL) that were essentially the same for the flyover as for the static condition but a perceived noise level (PNL) that was about 3 PNdB higher for the flyover than for the static condition. It suggests that flight velocity had a slightly adverse effect on the noise of the wedge nozzle.

When the comparison is made at the same absolute jet velocity, there is again a large difference in the frequencies at which the flyover and static spectra peak. Also the flyover spectrum is lower than the static spectrum over most of the frequency range of interest. This resulted in an OASPL that was 4 decibels lower and a PNL that was 5 PNdB lower for the flyover than for the static condition. It suggests that flight velocity had a beneficial effect on the noise of the wedge nozzle when the comparison was made on the basis of the same absolute jet velocity.

The dip in figure 14 in the static spectra at about 1400 hertz is where the first cancellation frequency would be expected to occur. The method for adjusting to free field probably undercorrects for this (ref. 10 gives the method for correcting to free field).

Another indication of flight velocity effect was obtained by comparing the flyover and static results in terms of the variation in perceived noise level with acoustic angle. Figure 15 compares the results for a typical flyover at an altitude of 91 meters to static results extrapolated from the 30.48-meter radius at which the data were taken to the 91-meter sideline. The results are shown for the same relative jet velocity (536 m/sec) and for the same absolute jet velocity (670 m/sec). When the results are compared at the same relative jet velocity, the effect of flight velocity is to increase the peak noise level and shift it closer to the jet axis. The static noise level reached a peak of

118 PNdB at an acoustic angle of 50° from the jet axis. The flyover noise level, however, reached a peak of 120 PNdB at an acoustic angle of 40°. At acoustic angles between 50° and 90°, the flyover noise level was essentially the same as the static noise level.

When the results are compared at the same absolute jet velocity, the effect of flight velocity is to reduce the peak noise level but again shift it closer to the jet axis. The static noise level reached a peak of about 126 PNdB at an acoustic angle of 50° (compared to the flyover peak of 120 PNdB at 40°). There was no significant difference between flyover and static noise levels at acoustic angles of less than 30°.

Comparison with plug nozzle at flyover. - As mentioned in the INTRODUCTION, the wedge nozzle might be quieter than a plug nozzle since it has a two-dimensional wedge surface rather than an axisymmetric plug surface. The dominant noise sources of the wedge nozzle might be different from those of the plug nozzle. This could alter the level, directivity, and frequency of the wedge nozzle noise compared to that from a plug nozzle.

Figure 16 compares the noise results of the wedge nozzle at flyover conditions with those of the plug nozzle of reference 10. Figure 16(a) presents the comparison in terms of the variation in perceived noise level with acoustic angle at an absolute jet velocity of 670 meters per second, which corresponds to a relative jet velocity of 536 meters per second. The peak noise level for both nozzles occurred at approximately the same acoustic angle of 40°. But the wedge nozzle was noisier in flight by about 3 PNdB than the plug nozzle at acoustic angles where the exhaust noise dominates (i.e., at angles less than 55°). At higher acoustic angles (from 55° to 90°), there was no significant difference in the noise between the two nozzles.

Figure 16(b) gives the comparison in terms of the 1/3-octave-band frequency spectra. There is a significant difference between the spectrum of the wedge nozzle and that of the plug nozzle. The wedge nozzle has considerably more middle- and high-frequency noise than the plug nozzle (from 500 to 5000 Hz). This difference, especially in the frequencies that are most annoying to the ear (3150 to 4000 Hz), accounts for the wedge nozzle being noisier in flyover than the plug nozzle.

Figure 16(c) presents the comparison in terms of the change in peak perceived noise level with changes in absolute jet velocity at a constant flight velocity. The peak perceived noise level of the wedge nozzle remains a constant 3 PNdB above that of the plug nozzle over the range of absolute jet velocities from about 574 to 714 meters per second. This suggests that the additional noise sources associated with the wedge nozzle are affected in the same manner in flyover by changes in absolute jet velocity as are the noise sources associated with the plug nozzle. This, as will now be shown, is not the case at static conditions.

Comparison with plug nozzle at static conditions. - Figure 17 compares the noise of the wedge nozzle at static conditions with that of the plug nozzle. Also shown is the effect on the noise of the wedge nozzle at static conditions of changing the orientation of the two-dimensional wedge. Figure 17(a) shows the results in terms of the variation in perceived noise level with acoustic angle. The orientation of the two-dimensional wedge had a considerable effect on the noise level of the wedge nozzle over the entire range of acoustic angles investigated. A maximum reduction of 4 PNdB was achieved, at an absolute jet velocity of 670 meters per second, by changing the orientation of the wedge from vertical to horizontal. The reduction occurred at an acoustic angle of about 50° from the jet axis, which is the location of the peak noise level for the wedge when oriented vertically as well as horizontally.

With the wedge oriented horizontally, the noise level of the wedge nozzle was lower than that of the plug nozzle for acoustic angles where the exhaust noise dominates (i.e., at angles less than 55°). At higher acoustic angles, there was no marked difference in the noise between the two nozzles.

Even with the wedge oriented horizontally, however, it is not clear that the wedge nozzle would be quieter than the plug nozzle when the results are extrapolated from the 91-meter sideline to the 648-meter sideline (the sideline measurement location prescribed by FAR 36). The peak noise level of the wedge nozzle was about 2 PNdB lower than that of the plug nozzle at a jet velocity of 536 meters per second and at the 91-meter sideline. However, the peak noise level of the wedge nozzle occurred further away from the jet axis (50°) than it did for the plug nozzle (40°). As a result, the peak noise level of the plug nozzle traveled further to reach the 648-meter sideline and, consequently, was attenuated more than the peak noise level of the wedge nozzle - about 2 decibels more because of inverse-square effect. Thus, the peak noise level received at the sideline might be about the same for the two nozzles.

Figure 17(b) presents the results in terms of the 1/3-octave frequency spectrum at the 91-meter sideline. The orientation of the two-dimensional wedge had a significant effect on the spectrum level of the wedge nozzle but did not affect the frequency where the spectrum peaked. Changing the wedge orientation from vertical to horizontal reduced the spectrum level over most of the frequency range (from 200 to 10 000 Hz). The spectra still peaked at the same frequency of 400 hertz.

The spectrum levels of the wedge nozzle can differ significantly when the wedge orientation is changed. With the wedge oriented vertically, its spectrum level generally was above that of the plug nozzle from frequencies of about 1600 to 10 000 hertz. With the wedge oriented horizontally, its spectrum level generally was below that of the plug nozzle from frequencies of about 250 to 4000 hertz. The spectra of both nozzles, however, peaked at the same frequency of 400 hertz.

Figure 17(c) shows the effect of absolute jet velocity on peak perceived noise level. The reduction in peak perceived noise level with reduced jet velocity was independent of the orientation of the two-dimensional wedge. When oriented vertically, the wedge nozzle was 4 PNdB noisier over the entire range of jet velocities investigated than when oriented horizontally.

The reduction in peak perceived noise level with reduced jet velocity is less for the wedge nozzle than for the plug nozzle. This again suggests that the noise sources dominating the exhaust jet of the wedge nozzle are different from those dominating the exhaust jet of the plug nozzle.

This result (that the peak noise level of the wedge nozzle is less dependent on jet velocity than that of the plug nozzle at static conditions) is different from the result at flyover conditions. At flyover conditions (as mentioned in connection with fig. 16(c)), the peak noise level of the wedge nozzle had the same dependence on relative jet velocity as that of the plug nozzle. A full explanation of this difference between static and flyover results is not yet known. However, the slope of the plug nozzle was essentially the same at static conditions as at flyover conditions at the higher values of absolute jet velocity, while the slope of the wedge nozzle was different (cf. figs. 16(c) and 17(c)). This suggests a relative change in the strength of the noise sources associated with the wedge nozzle compared to those associated with the plug nozzle.

Thrust Characteristics

In addition to acoustic characteristics, thrust characteristics also are important. Thrust performance is presented in figure 18 in terms of nozzle gross thrust coefficient as a function of exhaust nozzle pressure ratio. Figure 18(a) presents the thrust coefficient at static conditions. The thrust coefficient of the wedge nozzle was essentially the same as that of the plug nozzle over the entire range of pressure ratios investigated. At a pressure ratio of 1.95 (V_j = 536 m/sec), the thrust coefficient of the wedge nozzle was about 0.985. Figure 18(b) presents the thrust coefficient at flyover conditions. The thrust coefficient of the wedge nozzle was essentially the same as that of the plug nozzle over the pressure ratio range from about 2 to 2.5. At a pressure ratio of 2.5 (V_j = 670 m/sec), the thrust coefficient of the wedge nozzle was about 0.965.

SUMMARY OF RESULTS

A series of flyover and static tests were conducted on a wedge nozzle to investigate flight velocity effects. A secondary objective was to compare the wedge nozzle acoustic and thrust characteristics with those of a plug nozzle. Also investigated at static conditions was the effect of changing the orientation of the two-dimensional wedge from vertical to horizontal. The results can be summarized as follows:

1. Flight velocity had an adverse effect of about 3 PNdB when the adjusted flyover and static conditions at the acoustic angle that resulted in peak flyover noise were

compared at the same relative jet velocity but a beneficial effect of about 5 PNdB when they were compared at the same absolute jet velocity.

2. Another indication of flight velocity effect was obtained by comparing the noise results at the acoustic angles that gave peak noise levels for flyover and static conditions. When these results were compared at the same relative jet velocity, flight velocity increased the peak noise level by about 2 PNdB. When they were compared at the same absolute jet velocity, flight velocity decreased the peak noise level by about 6 6 PNdB. For both comparisons, the effect of flight velocity was to shift the peak noise level closer to the jet axis (from 50° to 40°).

3. The peak flyover noise level of the wedge nozzle was about 3 PNdB greater than that of the plug nozzle at a relative jet velocity of 536 meters per second. The wedge nozzle has considerably more middle- and high-frequency noise than the plug nozzle.

4. The rate of change in peak perceived noise level with absolute jet velocity was the same for the wedge and plug nozzles at flyover conditions. It was less for the wedge nozzle than the plug nozzle at static conditions.

5. At static conditions, a 4-PNdB noise reduction could be achieved by changing the orientation of the two-dimensional wedge from vertical to horizontal at an absolute jet velocity V_j of 536 meters per second. The noise level of the wedge nozzle then was lower than that of the plug nozzle at acoustic angles of less than 55° to the jet axis.

6. At static conditions, the nozzle gross thrust coefficient of the wedge nozzle was 0.985 at a nozzle pressure ratio of 1.95 (V_j = 536 m/sec), which is the same as that of the plug nozzle. At flyover conditions, the nozzle gross thrust coefficient of the wedge nozzle was 0.965 at a pressure ratio of 2.5 (V_j = 670 m/sec), which again is the same as that of the plug nozzle.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 26, 1975,
505-04.

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17. Little, John W.; Miller, Robert F.; Oncley, Paul B.; and Panko, Raymond E.: Studies of Atmospheric Attenuation of Noise. NASA Acoustically Treated Nacelle Program, NASA SP-220, 1969, pp. 125-135.

TABLE I. - COORDINATES OF WEDGE SURFACE UPSTREAM

OF PRIMARY NOZZLE EXIT[a]

Station measured from primary nozzle exit, S, cm	Coordinate of wedge surface, symmetrical about horizontal centerline,[b] Y, cm	Station measured from primary nozzle exit, S, cm	Coordinate of wedge surface, symmetrical about horizontal centerline,[b] Y, cm
0	15.11	25.40	9.98
2.69	15.49	27.94	8.74
3.81	15.67	30.48	7.39
5.08	15.80	31.12	7.04
6.35	15.85	31.85	6.63
7.62	15.82	32.38	6.22
8.89	15.72	33.02	5.79
10.16	15.49	33.66	5.31
11.43	15.19	34.29	4.78
12.70	14.81	34.92	4.17
15.24	14.02	35.56	3.48
17.78	13.11	36.20	2.67
20.32	12.14	36.83	1.32
22.86	11.10	37.03	0

[a]See fig. 5(b).

[b]Coordinates are faired smoothly.

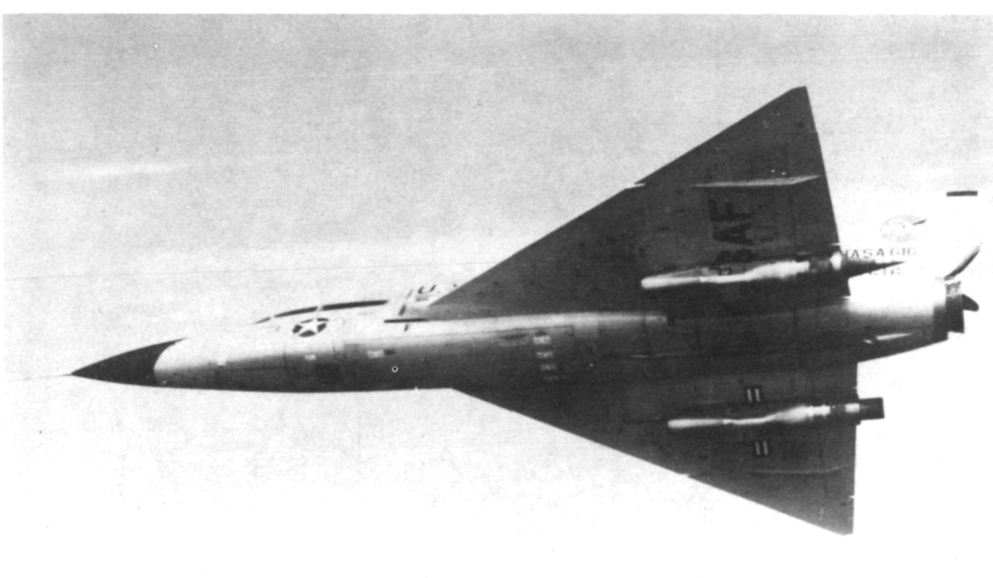

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Figure 1. - Modified F-106B aircraft in flight.

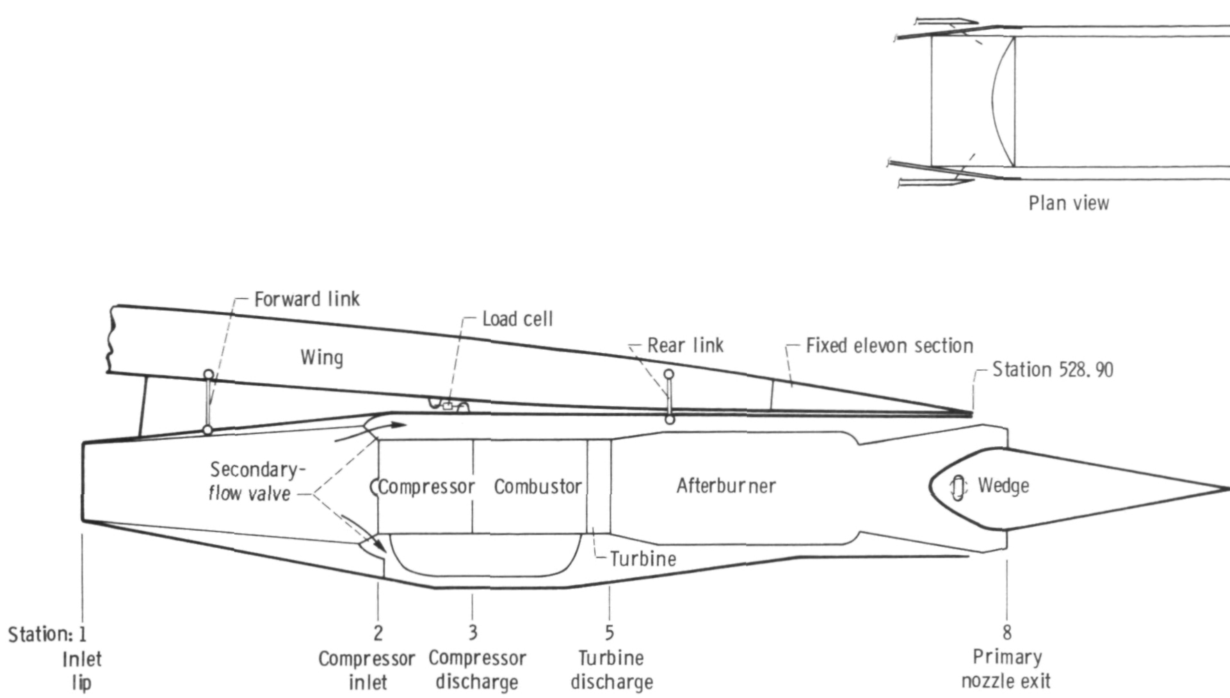
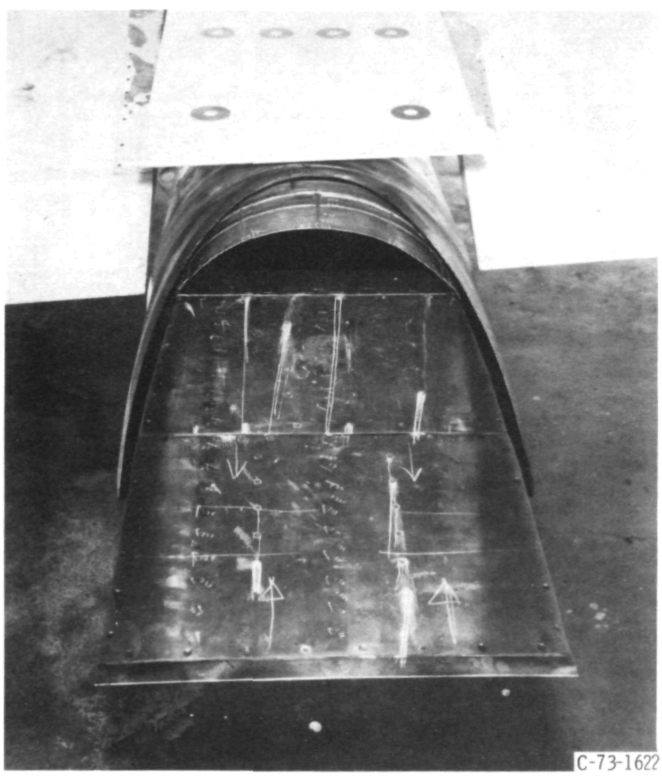


Figure 2. - Schematic of nacelle-engine installation.

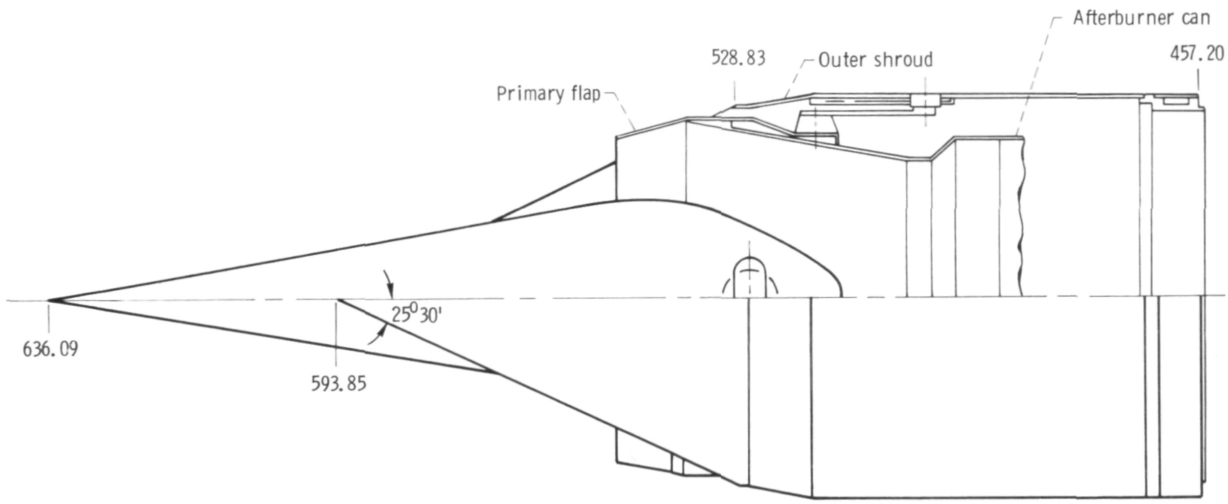
Figure 3. - Nacelle modification for static tests.

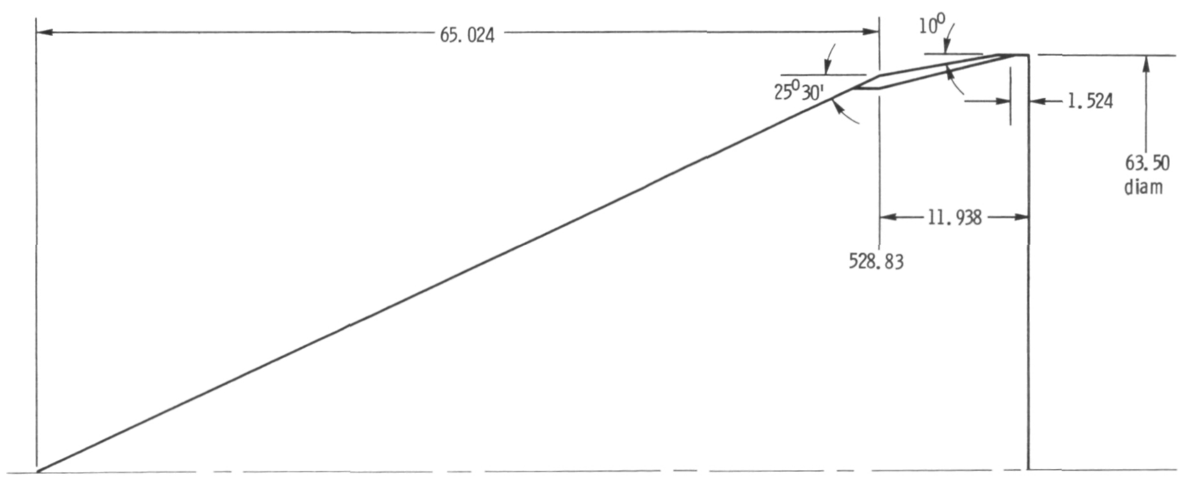
(a) Three-quarter aft view.



(b) Three-quarter top view.

Figure 4. - Wedge nozzle mounted horizontally.

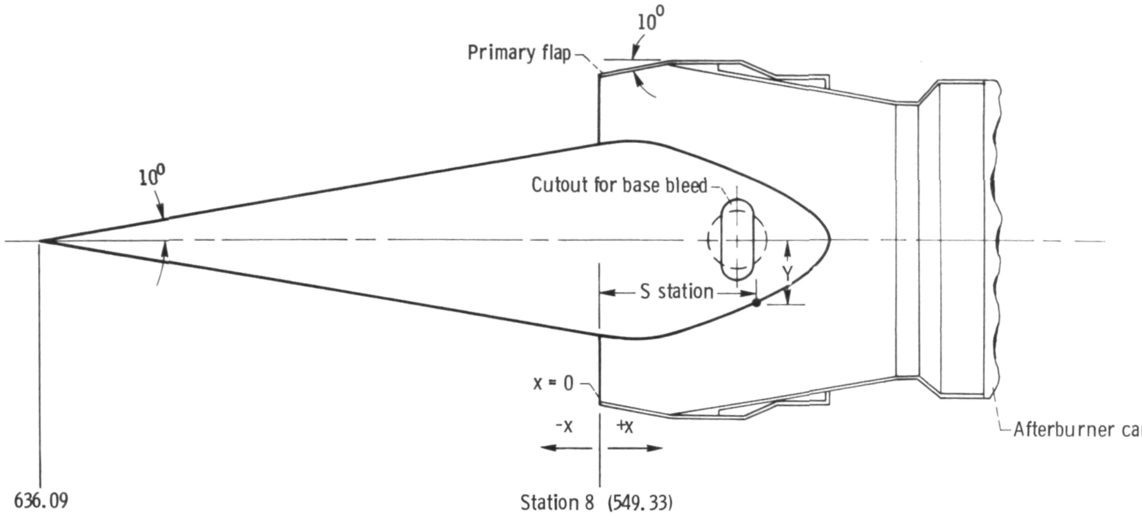




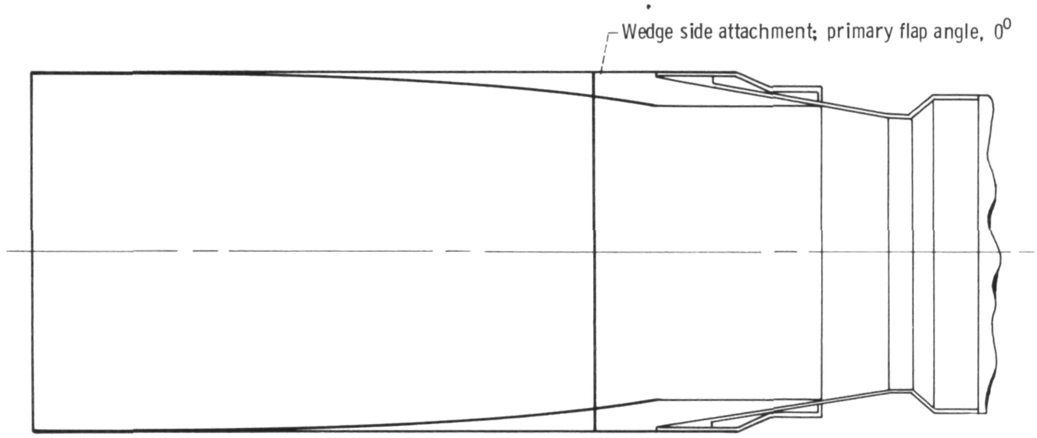
Details of outer shroud

(a) Outer shroud with sideplates.

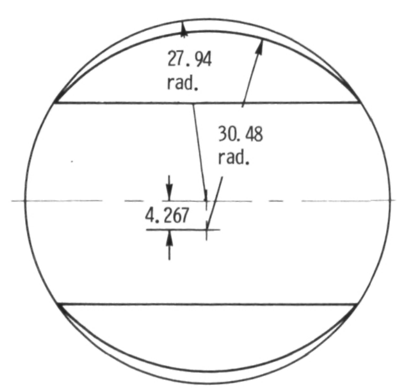
Figure 5. - Wedge nozzle dimensions. (Dimensions are in centimeters.)



Side view (see table I)



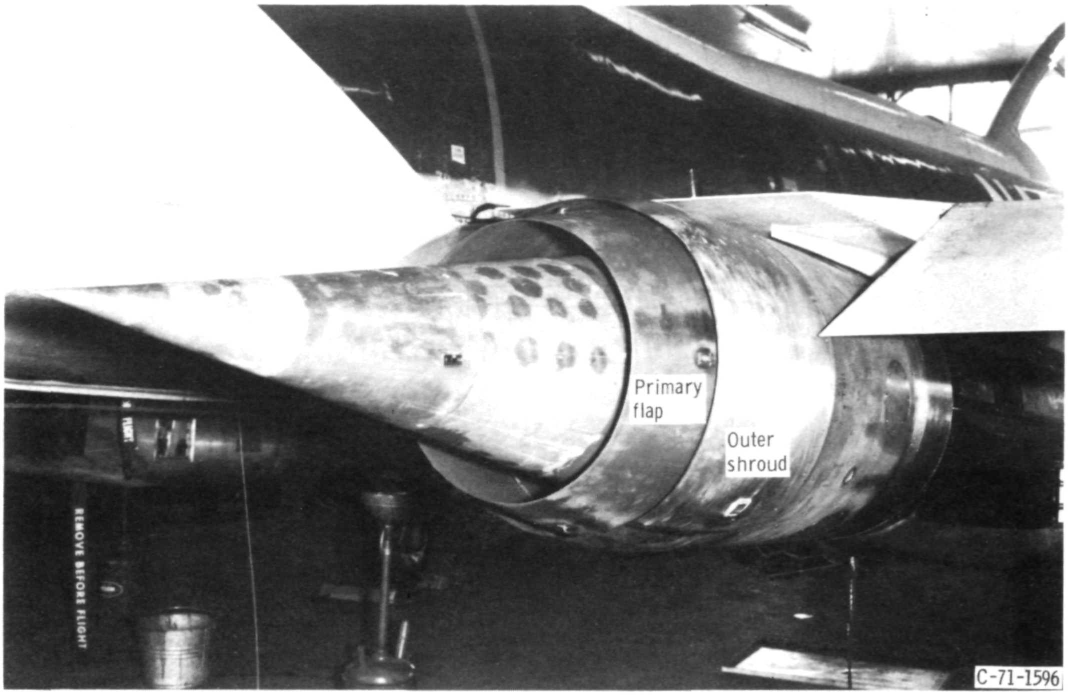
Top view



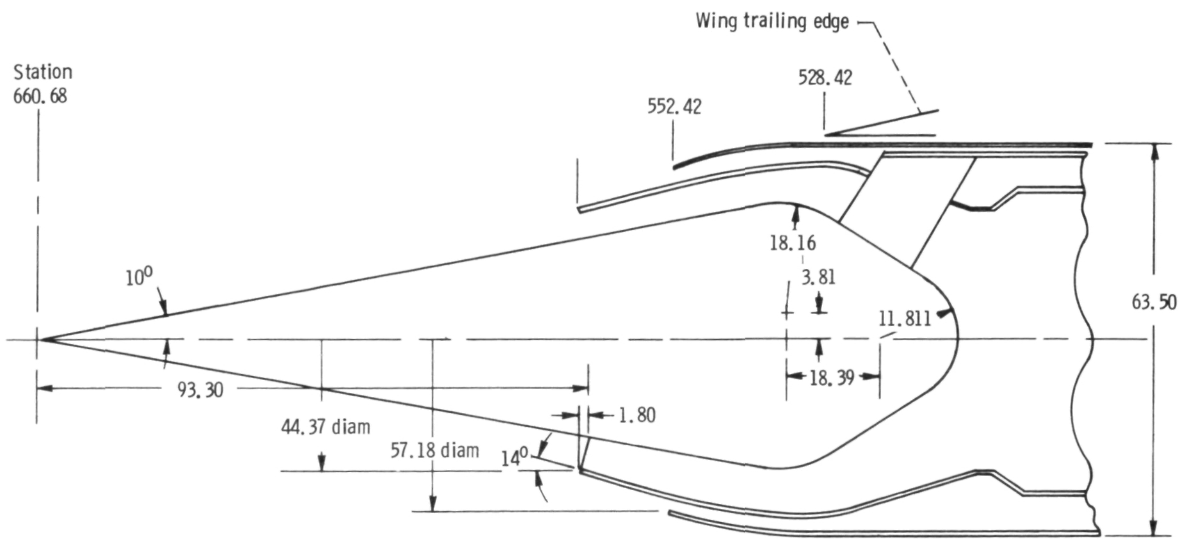
End view

(b) Primary nozzle.

Figure 5. - Concluded.



(a) Installed.



(b) Dimensional characteristics. (Dimensions are in centimeters; station numbers are based on a compressor inlet station number of 254.)

Figure 6. - Plug nozzle.

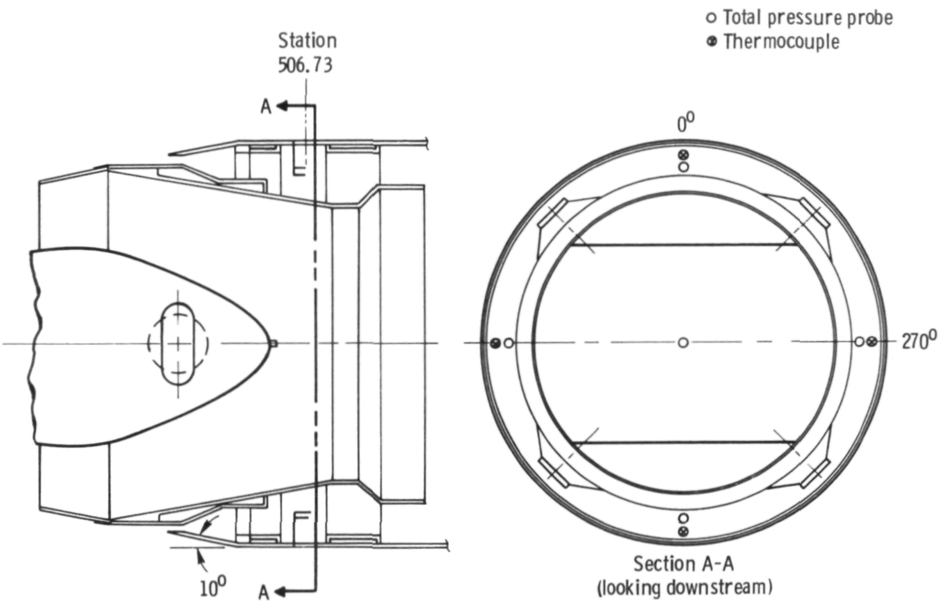
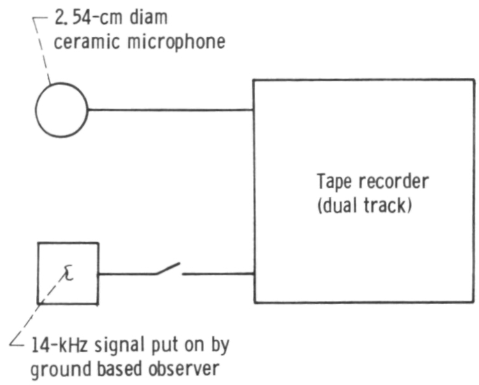
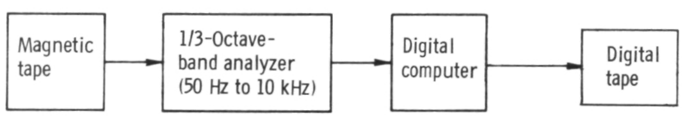


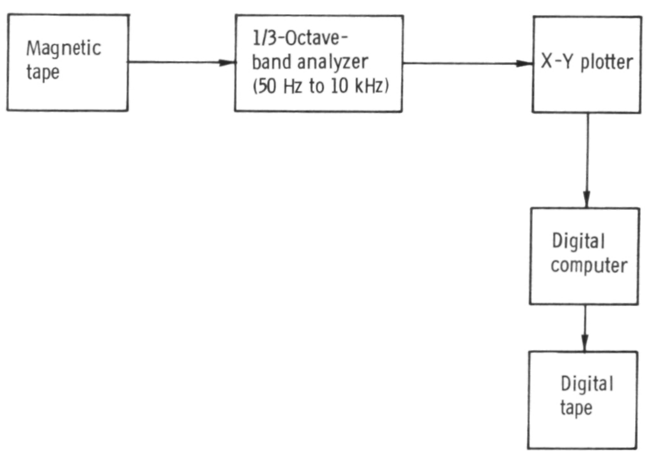
Figure 7. - Secondary-passage instrumentation. (Dimensions are in centimeters.)



(a) Recording system for both static and flyover tests.



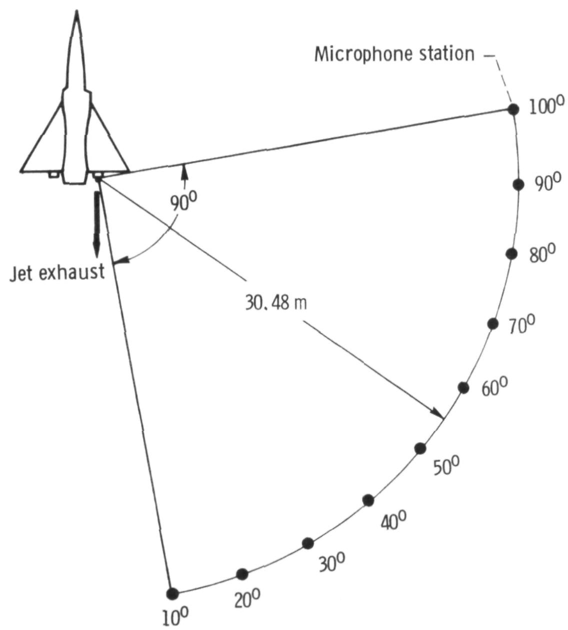
(b) Playback system for flyover test-



(c) Playback system for static tests.

Figure 8. - Schematic flow diagrams for noise recording system and data reduction for both static and flyover tests.

(a) Microphone orientation.



(b) Microphone location.

Figure 9. - Microphone orientation and locations for static tests.

Figure 10. - Location of external source of cooling air for static tests.

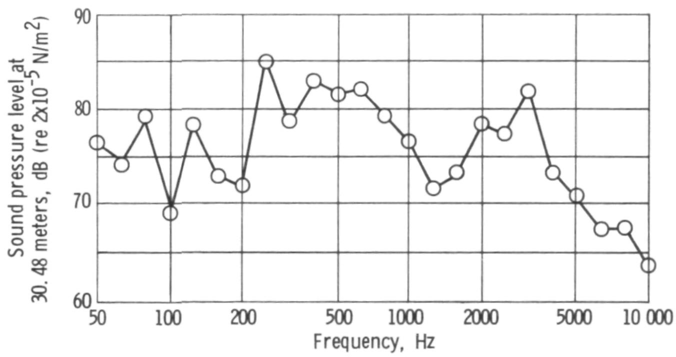
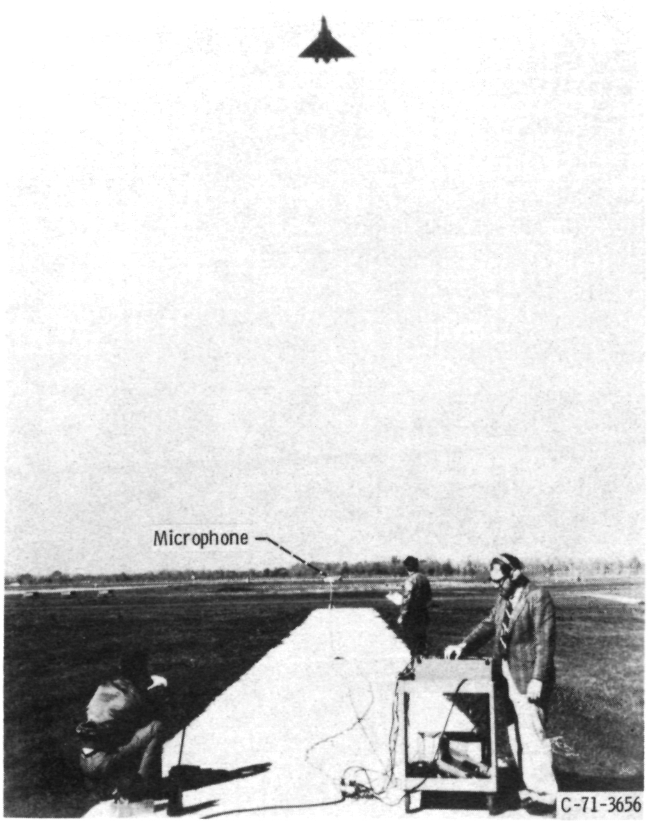
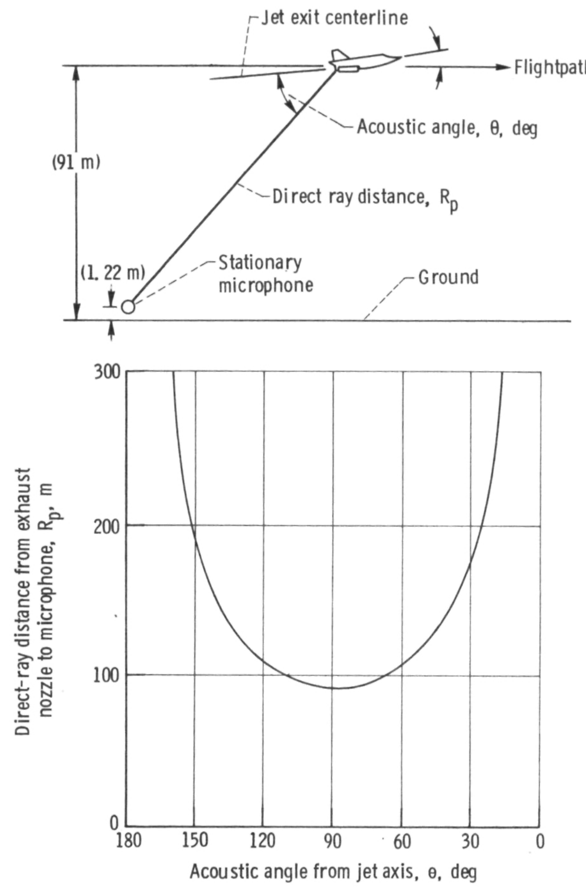


Figure 11. - One-third-octave-band static spectrum of background noise at acoustic angle of 40^0. Free-field, standard-day conditions.

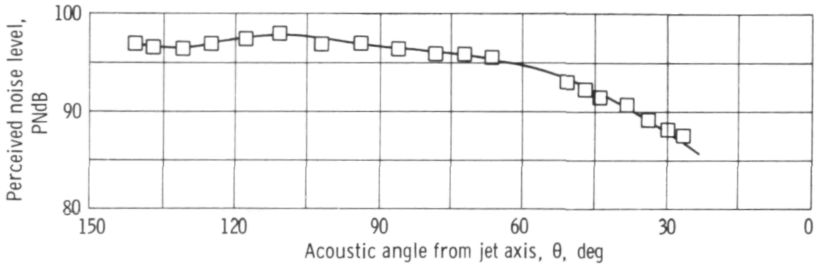


(a) Microphone orientation.

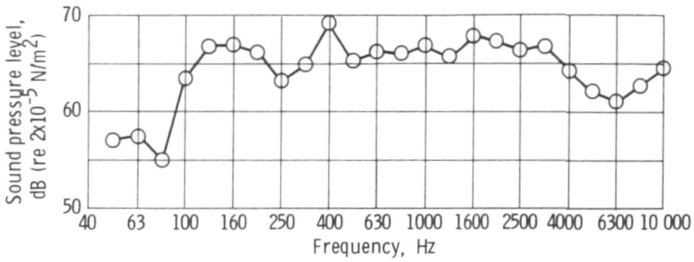


(b) Geometry.

Figure 12. - Microphone orientation and geometry for flyover tests.



(a) Perceived noise level for 91-meter altitude.



(b) One-third-octave-band spectra at 91-meter altitude and 40° acoustic angle.

Figure 13. - Background noise for flyover.

Test	Absolute jet velocity, V_j, m/sec	Relative jet velocity, V_r, m/sec	Overall sound pressure level, OASPL, dB	Perceived noise level, PNL, PNdB
● Flyover	670	536	124	135
□ Static	536	536	123	132
◇ Static	670	670	128	140

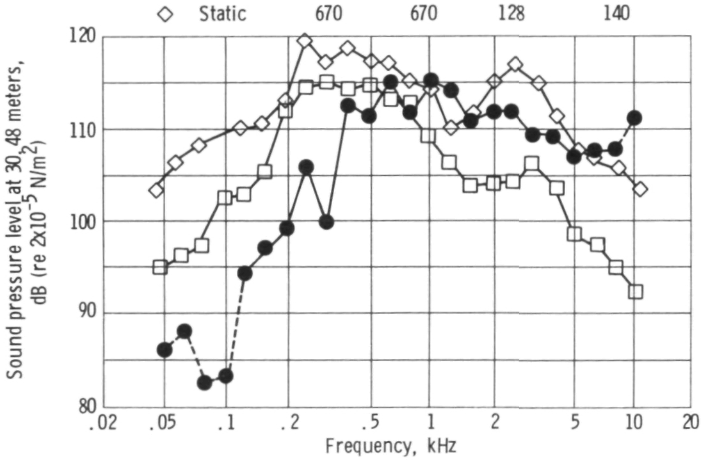


Figure 14. - Effect of flight velocity on spectra at angle of peak flyover noise, 40°. One-third-octave bands.

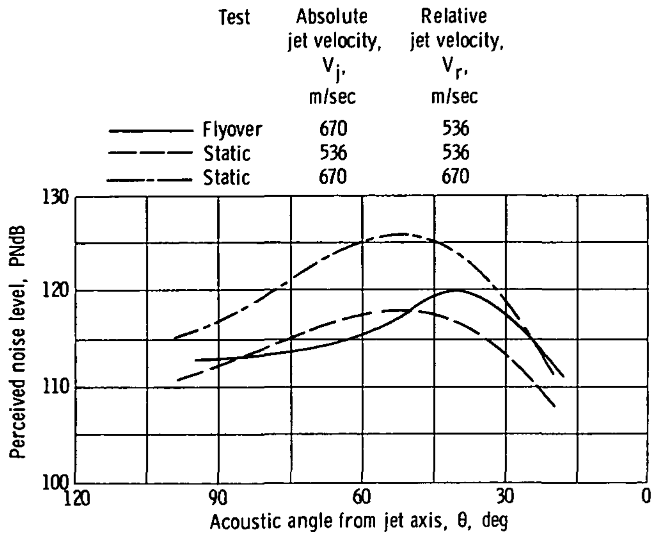
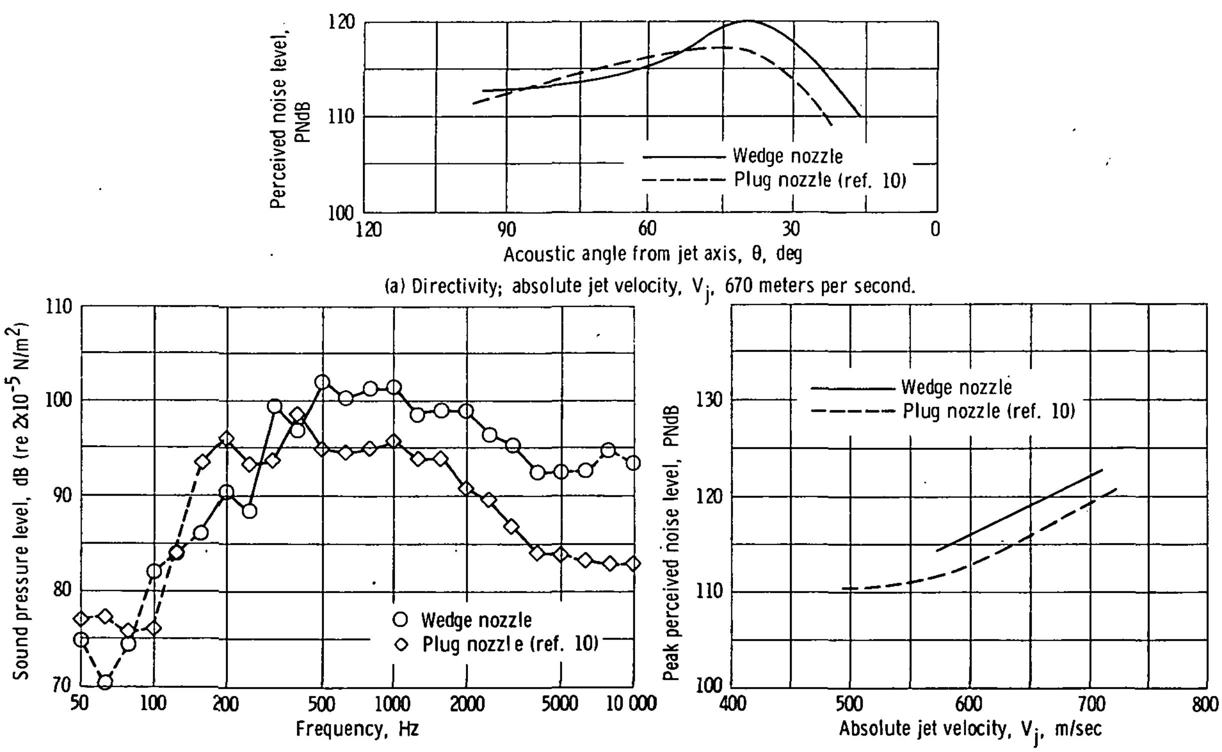


Figure 15. - Effect of flight velocity on directivity. Flyover altitude, 91 meters; sideline distance, 91 meters; free-field, standard-day conditions.

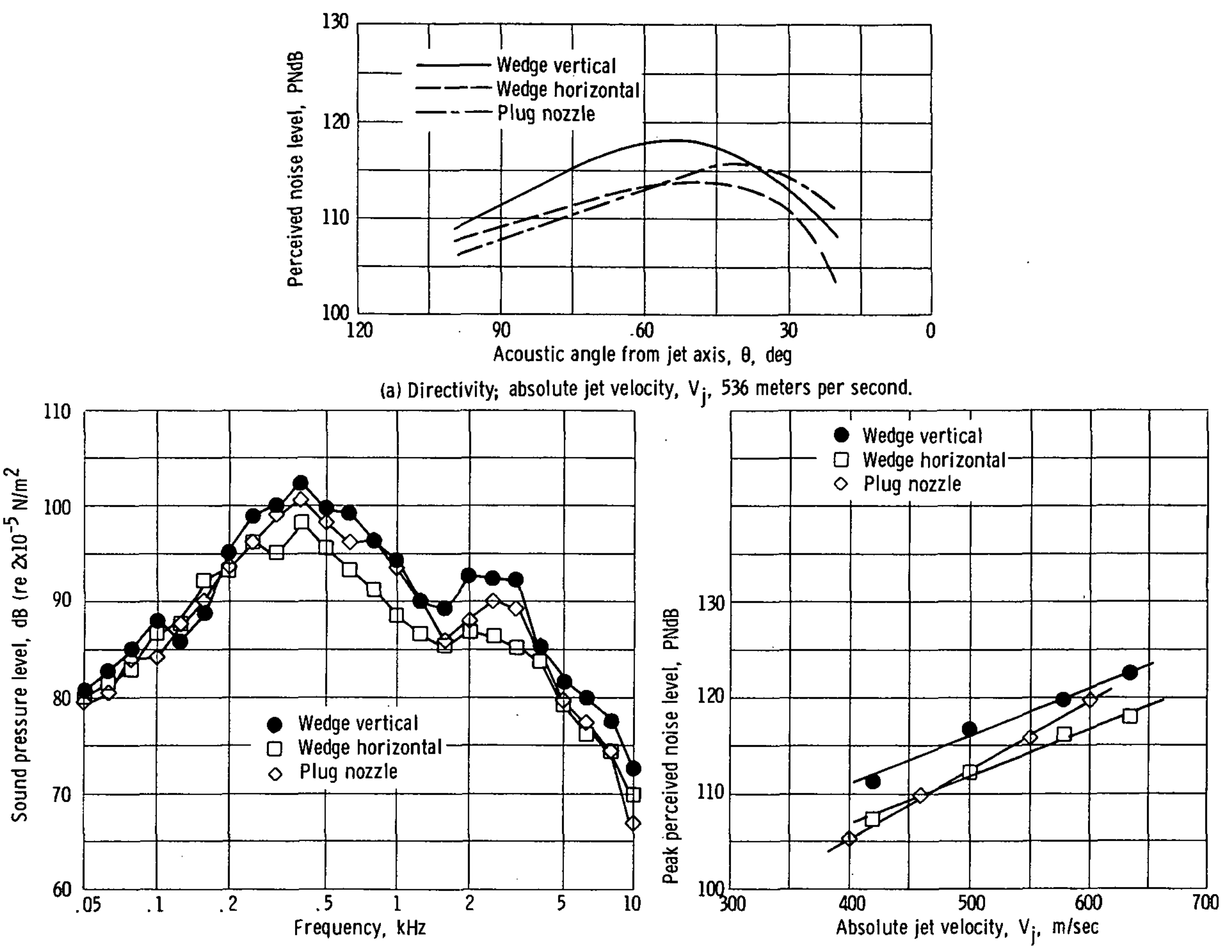


(a) Directivity; absolute jet velocity, V_j, 670 meters per second.

(b) One-third-octave band spectra at acoustic angle of 40°; absolute jet velocity, V_j, 670 meters per second.

(c) Effect of absolute jet velocity at constant flight speed.

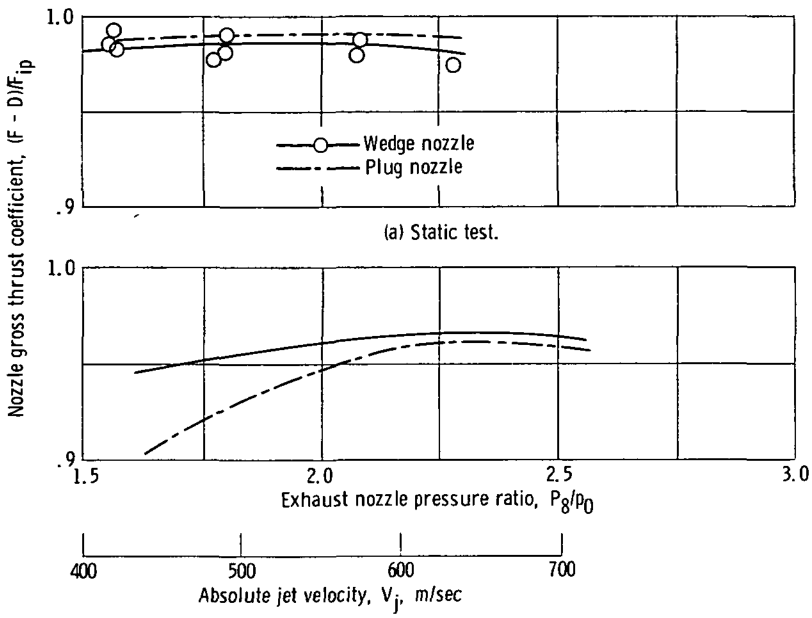
Figure 16. - Comparison of wedge and plug nozzles at flyover conditions. Flyover altitude, 91 meters; free-stream Mach number, M_0, 0.4; free-field, standard-day conditions.



(b) One-third-octave-band spectra at acoustic angle of 50°; absolute jet velocity, V_j, 536 meters per second.

(c) Effect of absolute jet velocity.

Figure 17. - Comparison of wedge and plug nozzles at static conditions. Sideline distance, 91 meters; free-field, standard-day conditions.



(b) Flyover test; flight Mach number, M_0, 0.4; corrected secondary weight flow ratio, $\omega\sqrt{\tau}$, 0.06.

Figure 18. - Thrust coefficients.

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