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ENGINE EXHAUST NOISE DURING GROUND OPERATION OF THE XB-70 AIRPLANE

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16. Abstract

XB-70 engine noise was measured from 90° to 160° from the airplane heading at a radius of 500 feet (152 meters). Overall sound pressure levels, perceived noise levels, and normalized spectra are presented for jet exhaust velocities up to 3300 feet/second (1006 meters/second), various engine spacings, and various numbers of adjacent engines operating.

The direction of propagation of maximum noise levels moved from 135° to 120° as either the jet velocity was increased or the number of adjacent engines operating was increased. As the distance between two operating engines became greater, the overall sound pressure level increased as the angle between the microphone position and the exhaust axis decreased.

The overall sound pressure level agreed best with the SAE prediction levels at an angle of 120° for exhaust velocities between 1500 feet/second (457 meters/second) and 3000 feet/second (914 meters/second). The SAE method adequately estimated the noise spectrum of the XB-70 airplane for subsonic exhaust flow and underestimated the high-frequency spectral levels for supersonic flow.

Some shielding of the high frequencies was observed when two or more adjacent engines were operating in supersonic exhaust flow conditions. The noise spectrum shape was independent of jet exhaust velocity for the XB-70 engines with supersonic flow.

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INTRODUCTION

The continued increase in size and power of commercial aircraft engines is causing considerable concern about the noise environment in the vicinity of major airports. This concern has manifested itself in the form of government noise regulations for all new civilian subsonic transport and subsonic turbojet powered airplanes, and there will be additional noise regulations for future supersonic transport aircraft. To meet these requirements, design engineers need to be able to predict the noise generated by a particular airplane and engine configuration. The current prediction method (ref. 1) is based upon empirical data obtained from noise measurements of present-day transport aircraft and upon several fundamental assumptions such as the following: (1) The angle of maximum noise propagation is 45° from the jet exhaust. (2) The normalized noise spectrum is the same for all standard exhaust nozzles. (3) Strouhal number is the appropriate scaling parameter throughout the range of jet velocity. The predicted noise levels, as obtained from reference 1, are then corrected for atmospheric transmission losses, by using the values provided in reference 2.

To determine if the noise prediction method of reference 1, with its inherent assumptions, could be extended for use with large turbojet engines typical of future large jet transports, ground tests were made to measure the noise produced by the engines on the XB-70 airplane. In addition, with its large turbojet engines mounted side by side, the XB-70 airplane presented the opportunity to observe the effect of engine spacing on the radiated noise. The tests were conducted at Edwards Air Force Base, Calif., with the airplanes on a thrust measuring platform. The tests were directed by the NASA Flight Research Center with participation by the U. S. Air Force, North American Rockwell Corporation, General Electric Company, and The Boeing Company.

This paper presents exhaust noise measurements made around the XB-70 airplane at a radius of 500 feet (152 meters). Results of the inlet noise measurements made at a radius of 240 feet (73 meters) were presented in reference 3. Measurements of XB-70 takeoff, landing, and flyby noise were included in reference 4.

SYMBOLS

AB-1 minimum afterburner power setting

AB-2, AB-3, AB-4	stages of afterburner between minimum and maximum afterburner power settings
AB-5	maximum afterburner power setting
a_o	speed of sound in the atmosphere, feet/second (meters/second)
d	diameter of exhaust nozzle, feet (meters)
f	frequency, hertz
f_n	geometric mean frequency of octave band, hertz
N	number of engines operating
OASPL	overall sound pressure level (20 to 11,000 hertz), decibels (ref. 0.00002 N/m^2)
$OASPL_{av}$	space-averaged overall sound pressure level from 90° to 160°, from the airplane heading, decibels (ref. 0.00002 N/m^2)
OBSPL	octave band sound pressure level, decibels (ref. 0.00002 N/m^2)
PNL	perceived noise level, PNdB
SN	Strouhal number
V_c	speed of sound in the jet exhaust at nozzle exit, feet/second (meters/second)
V_R	velocity of jet exhaust at the plane of the exhaust nozzle relative to ambient air, feet/second (meters/second)

TEST AIRPLANE

The large, supersonic XB-70 airplane (fig. 1) is powered by six YJ93-GE-3 engines installed in the aft part of the fuselage. The engines are afterburning turbojets installed side by side on approximately 5-foot (1.5-meter) centers. They are identified, 1 to 6, as illustrated in figure 2. The engine exhaust nozzle is a convergent-divergent type with a variable nozzle, and the exhaust flow became supersonic at approximately 93-percent rpm for the ambient conditions during the test.

The engine inlets consist of two large, variable-throat ducts, each of which supplies air to three engines. The engines are each in the 30,000-pound (133,000-newton) thrust category for full afterburner operation. At military power (maximum power without afterburner), each installed engine is rated at approximately 20,000 pounds (89,000 newtons) of thrust. The centerline of the engines is approximately 11 feet (3.4 meters) above the ground. Engine performance details were given in reference 5.

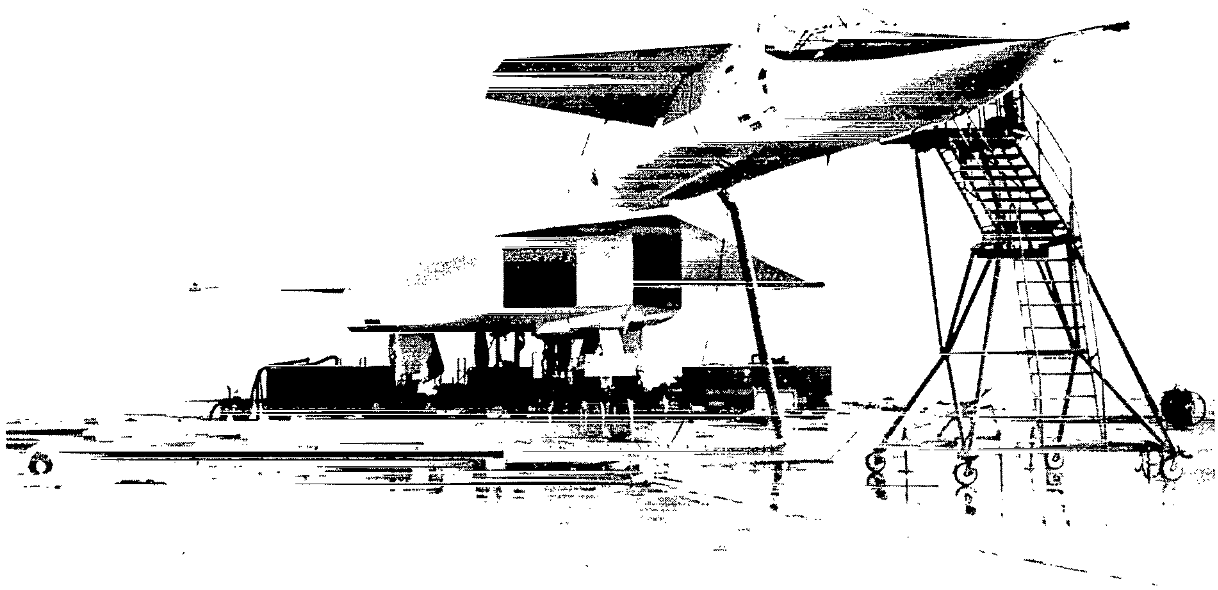

Figure 1. XB-70 airplane on the thrust measuring platform.

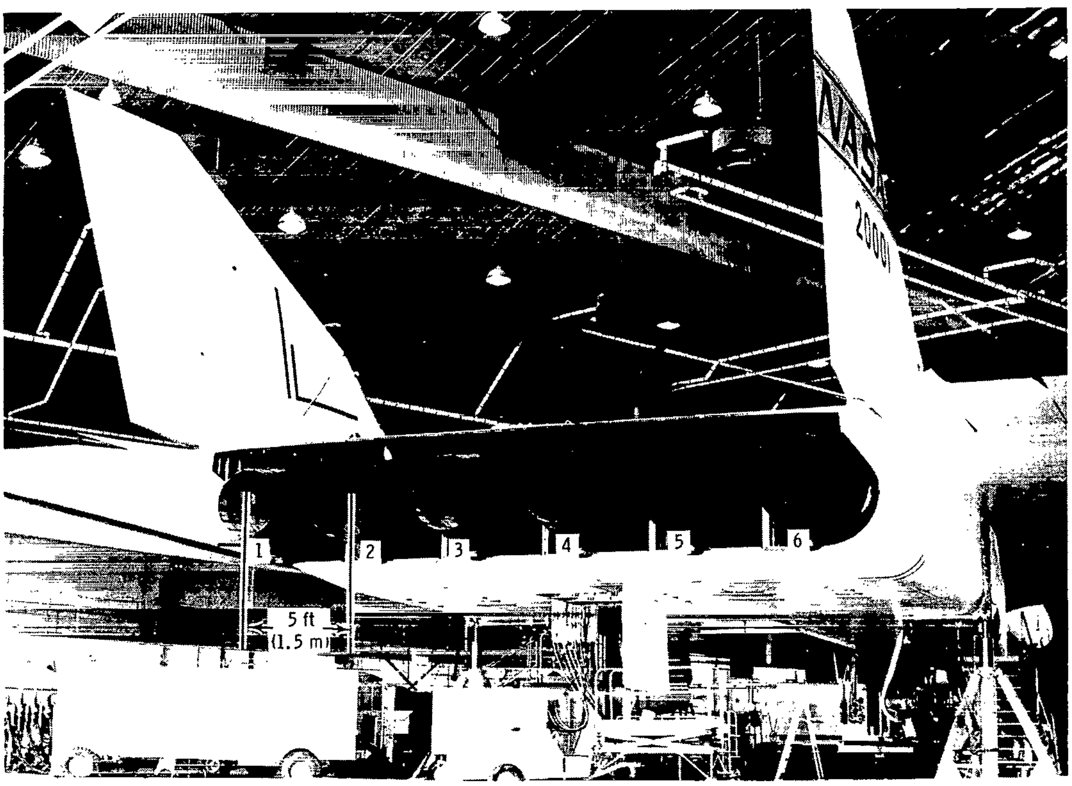

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Figure 2. Photograph of engines installed in the XB-70 airplane, with engine numbering system indicated.

TEST AREA AND INSTRUMENTATION

Test Area

The XB-70 airplane was positioned on the thrust measuring platform (fig. 1) so that the exhaust from the engines was directed horizontally over an area that was barren except for a few sagebrush. Figure 3 is a photograph of the area in which the microphones were positioned to measure the exhaust noise.

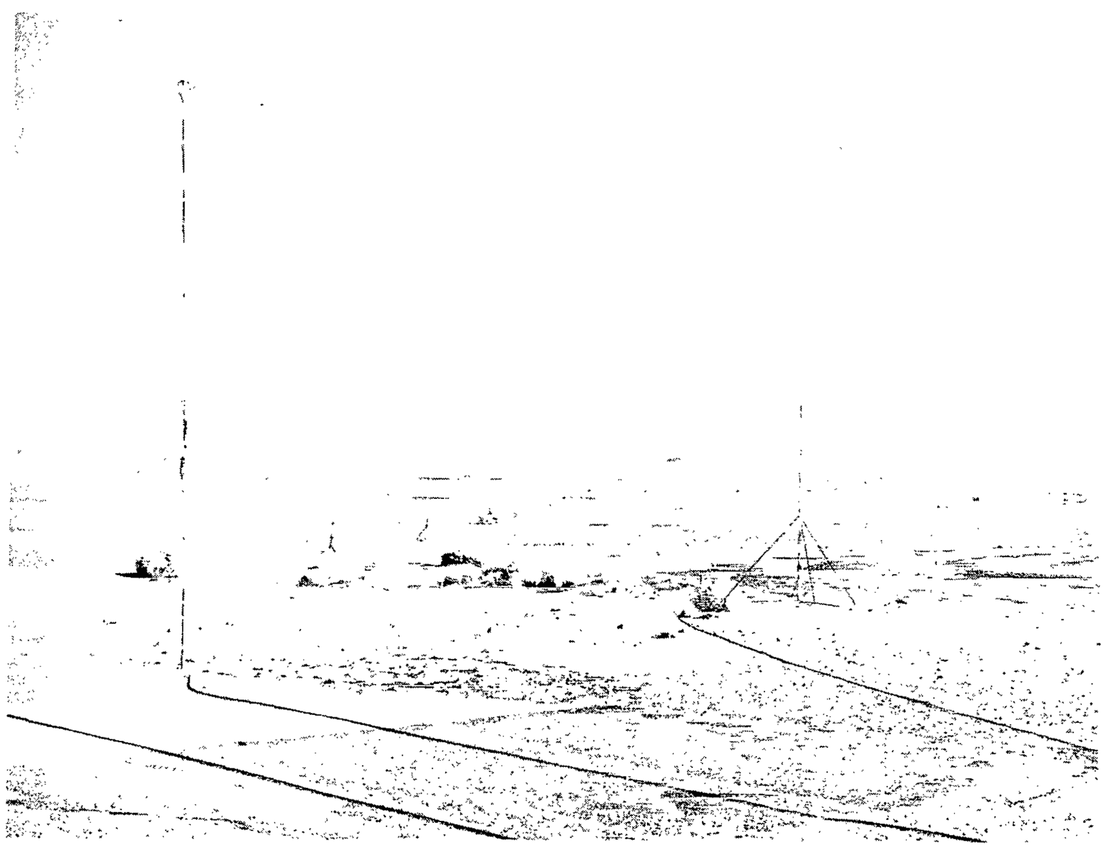


Figure 3. Area in which microphones were positioned.

Instrumentation

Data-acquisition system. — Microphones were positioned in the exhaust quadrant of the XB-70 airplane, as illustrated in figure 4. These microphones were placed on a 500-foot (152-meter) radius with its center at the intersection of the airplane centerline and the plane of the exhaust nozzles. The airplane heading is defined as 0°, and the microphones were positioned at 10° intervals from 90° to 160°. No microphones were closer to the exhaust than the 160° position because they would have been in the exhaust flow. All microphones were approximately 50 inches (1.27 meters) above the ground.

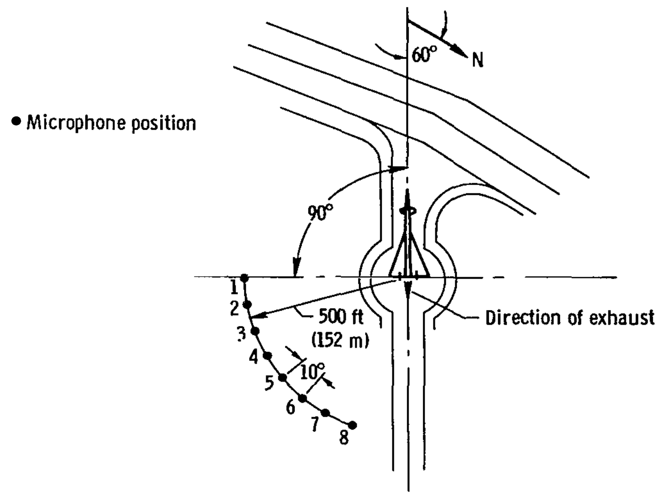


Figure 4. Microphone positions in relation to XB-70 airplane.

A block diagram of the acoustic data-acquisition system is presented in figure 5. Each microphone was connected to an oscillator detector circuit by a low-impedance coaxial cable to form a tuned radio frequency circuit. The output of each detector circuit was amplified and recorded on a magnetic-tape recorder. Time of day from a time-code receiver was also recorded to enable correlation with the engine data recorded onboard the airplane.

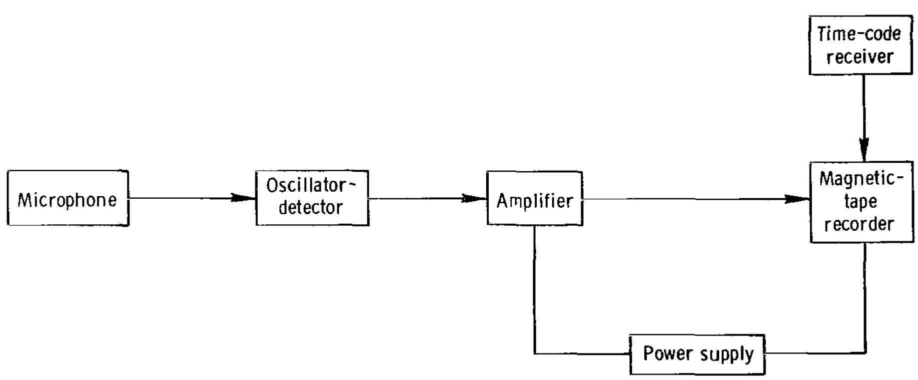


Figure 5. Block diagram of microphone station and recording station.

The acoustic data-acquisition system was calibrated in the laboratory over a frequency range from 20 to 11,000 hertz before and after the tests. The system was acoustically calibrated for level and linearity on the day of the tests.

Weather data were measured at a weather station about 2 miles (3200 meters) from the test site and at another station approximately 800 feet (244 meters) to the left of the airplane. The weather instrumentation near the airplane measured temperature, wind direction, and velocity at 6 feet (1.8 meters) and 50 feet (15.2 meters) above the ground. Only the temperature data collected at 6 feet (1.8 meters) were used because the temperature at the two heights differed at the most by 0.5° F (0.3° C).

Data-reduction system. – A block diagram of the data-reduction system used to analyze the noise is shown in figure 6. A magnetic-tape playback unit recovered the data signal which was routed to an octave band analyzer. Parallel analog outputs of octave band data were amplified and recorded on strip-chart recorders. An effective averaging time of 10 seconds was used in analyzing the acoustic data.

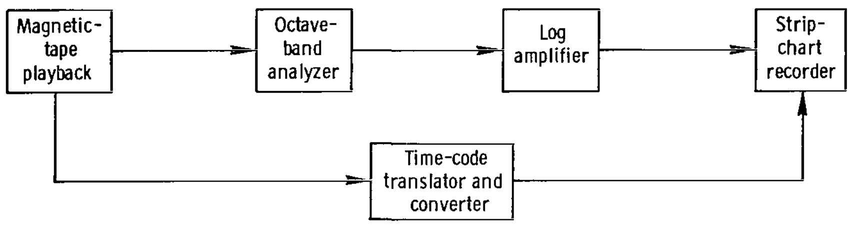


Figure 6. Block diagram of data-reduction system.

The noise analysis system was electrically calibrated, and the energy acceptance of each filter in the octave band analyzer was determined.

Data accuracy. – The reduced acoustic data were corrected for data-acquisition- and data-reduction-system response, angle of sound impingement on the microphone diaphragm, and background noise. The noise-reduction system was an averaging system, and the measured sound levels are considered to be accurate to ±1 dB.

The weather data were averaged over 15-minute intervals. The associated accuracies of the weather data are estimated to be ±1 lb/ft^2 (±48 N/m^2) for the atmospheric pressure, ±1° F (±0.6° C) for the temperature, ±5 percent for the relative humidity, ±2 knots for wind speed, and ±20° for wind direction.

TEST PROCEDURES

Before engine start on the day of the tests, ambient noise levels were recorded for each microphone position. After the engines were started, the pilot announced over the radio that power was set when the airplane's instrumentation indicated stable engine operation for a given test point. During this same period, the engine operation parameters were recorded onboard the airplane, and the total thrust was measured by the thrust measuring platform. The runs were 2 minutes long except when the afterburner was in operation; then the runs were approximately 1 minute. Acoustic data were recorded for 1 minute during the last part of every run. Runs were extended or repeated when necessary to complete the data acquisition.

Engine operating data for all test points in this report are specified as percent rpm, military power, and five stages of afterburner with AB-1 as minimum afterburner and AB-5 as maximum afterburner. Average specific engine operating conditions are detailed as velocity of the jet, area of the exit nozzle, weight flow of the exhaust, and temperature of the expanded jet. These quantities were computed from the onboard data by using the gas generator method discussed in reference 6. Run numbers were assigned to provide an orderly presentation of the data.

RESULTS AND DISCUSSION

The tests discussed in this report were designed to evaluate the effects of various parameters such as engine power setting (i.e., jet velocity), number of adjacent engines operating, and the relative spacing of the engines in operation on the radiated engine exhaust noise. The test conditions for each data run are presented in table 1,

TABLE 1. SUMMARY OF ENGINE DATA

Run	Engines operating	Engine operating condition	V_R, (a)		Exit nozzle area, (a)		Weight flow of exhaust, (a)		Temperature of expanded jet, (a)	
			ft/sec	m/sec	ft^2	m^2	lb/sec	kg/sec	°R	°K
1	1	80% rpm	950	289	7.5	0.70	190	86	1060	589
2	1	90% rpm	1510	460	7.2	.67	246	112	1240	689
3	2	93% rpm	1680	512	6.9	.64	260	118	1280	711
4	1	97% rpm	2070	631	7.0	.65	280	127	1430	794
5	1	100% rpm	2380	725	6.7	.62	285	129	1560	867
6	1	Military	2470	753	6.7	.62	283	128	1610	894
7	2	Military	2470	753	6.2	.58	285	129	1590	883
8	2	Military	2480	756	6.2	.58	284	129	1590	883
9	1	AB-2	2800	853	7.2	.67	286	130	2140	1189
10	2	AB-3	2950	899	7.0	.65	288	131	2340	1300
11	1	AB-4	3010	917	7.7	.72	287	130	2520	1400
12	1	AB-5	3250	991	8.2	.76	288	131	3000	1667
13	2	AB-5	3260	994	7.9	.73	289	131	2930	1628
14	1,2	80% rpm	890	271	7.4	.69	184	83	1080	600
15	1,2	90% rpm	1430	436	7.1	.66	240	109	1230	683
16	1,2	97% rpm	2000	610	6.8	.63	272	123	1410	783
17	1,2	Military	2440	744	6.3	.59	276	125	1610	894
18	1,2	Military	2460	750	6.3	.59	277	126	1620	900
19	1,2	AB-1	2680	817	6.6	.61	280	127	1990	1105
20	1,2	AB-1	2690	820	6.6	.61	278	126	1980	1100
21	1,2	AB-2	2780	847	6.9	.64	280	127	2180	1211
22	1,2	AB-3	2870	875	7.1	.66	281	127	2340	1300
23	1,2	AB-4	3010	917	7.4	.69	281	127	2590	1439
24	1,2	AB-5	3210	978	8.0	.74	283	128	3010	1672
25	1,2	AB-5	3230	985	8.0	.74	281	127	2990	1661
26	1,2,3	80% rpm	870	265	7.3	.68	182	83	1100	611
27	1,2,3	90% rpm	1450	442	7.1	.66	230	104	1270	706
28	1,2,3	97% rpm	1980	604	6.8	.63	255	116	1450	806
29	1,2,3	Military	2390	728	6.8	.63	260	118	1650	917
30	1,2,3	AB-1	2640	804	6.6	.61	262	119	2030	1128
31	1,2,3	AB-5	3140	957	8.0	.74	266	121	3030	1683
32	All	80% rpm	920	280	7.5	.70	184	83	1100	611
33	All	85% rpm	1160	354	7.4	.69	209	95	1140	633
34	All	90% rpm	1490	454	7.2	.67	231	105	1260	700
35	All	97% rpm	1990	607	7.0	.65	255	116	1440	800
36	All	Military	2400	732	6.5	.60	260	118	1650	917
37	All	AB-1	2650	808	7.1	.66	265	120	2210	1228
38	All	AB-2	2760	841	7.1	.66	265	120	2210	1228
39	All	AB-3	2850	869	7.3	.68	266	121	2390	1328
40	All	AB-4	2990	911	7.6	.71	267	121	2670	1483
41	All	AB-5	3140	957	8.2	.76	269	122	3010	1672
42	1,4	80% rpm	900	274	7.5	.70	194	88	1060	589
43	1,4	90% rpm	1500	457	7.1	.66	254	115	1200	667
44	1,4	97% rpm	2040	622	6.8	.63	285	129	1360	756
45	1,4	Military	2470	753	6.3	.59	288	131	1560	867
46	1,4	AB-1	2720	829	6.8	.63	289	131	1930	1072
47	1,4	AB-5	3300	1006	8.2	.76	293	133	2980	1656
48	1,6	80% rpm	900	274	7.5	.70	191	87	1050	583
49	1,6	90% rpm	1470	448	7.2	.67	248	112	1230	683
50	1,6	97% rpm	2030	619	7.0	.65	280	127	1390	772
51	1,6	Military	2490	759	6.4	.60	284	129	1600	889
52	1,6	AB-1	2720	829	6.9	.64	286	130	1950	1083
53	1,6	AB-5	3280	1000	8.2	.76	289	131	2980	1656

[a]Values presented are the average per engine, based on the number of engines operating.

and the weather data for the tests are summarized in table 2. The direction of maximum sound level and the effect of high jet velocities on the overall sound pressure level (OASPL) in any given direction are of fundamental interest. The effect of engine combinations and spacing on the OASPL is also evaluated. Where appropriate, theoretical predictions of OASPL are compared with the measured OASPL as a function of jet velocity.

TABLE 2. – WEATHER CONDITIONS

Runs	Atmospheric pressure,		Temperature,		Relative humidity, percent	Wind			
						6 ft (1.8 m) above ground,		50 ft (15.2 m) above ground,	
	lb/ft^2	N/m^2	F°	C°		Velocity, knots	Direction,* deg	Velocity, knots	Direction,* deg
1 to 13	1972	94,420	26	-3.4	78	2	180	-	--
14 to 25	1977	94,660	26	-3.4	73	3	220	6	60
26 to 31	1976	94,610	25	-4.0	77	3	270	6	50
32 to 41	1974	94,520	25	-4.0	78	3	270	5	70
42 to 47	1973	94,470	25	-4.0	78	2	220	3	90
48 to 53	1974	94,520	25	-4.0	78	1	180	3	90

*Direction from north from which wind was blowing.

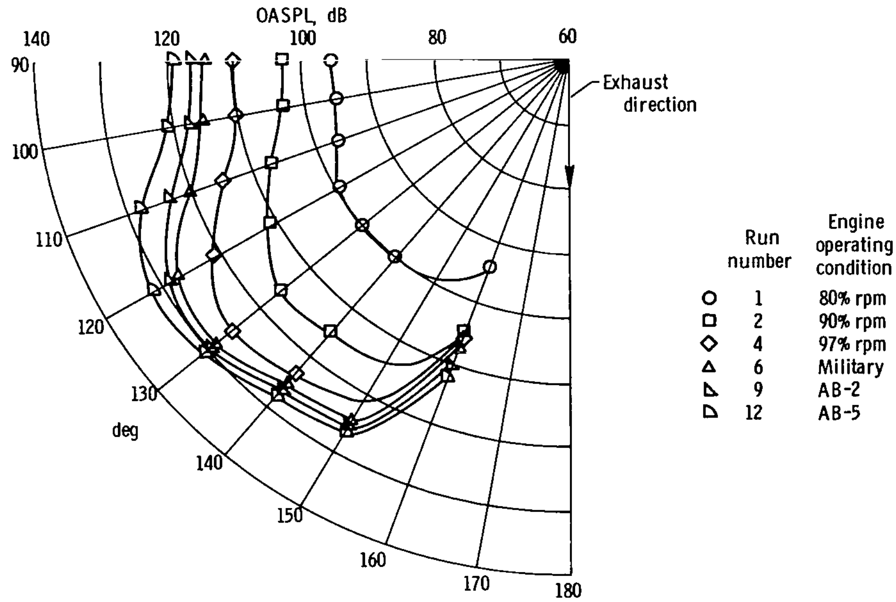
To compare the spectra for different operating conditions, the octave band sound pressure levels (OBSPL) are plotted versus Strouhal number and versus a modified Strouhal number. Comparisons with other experimental data are made where appropriate.

The measured noise levels are presented in terms of sound pressure levels (SPL) without corrections to the data for atmospheric absorption except where specifically noted.

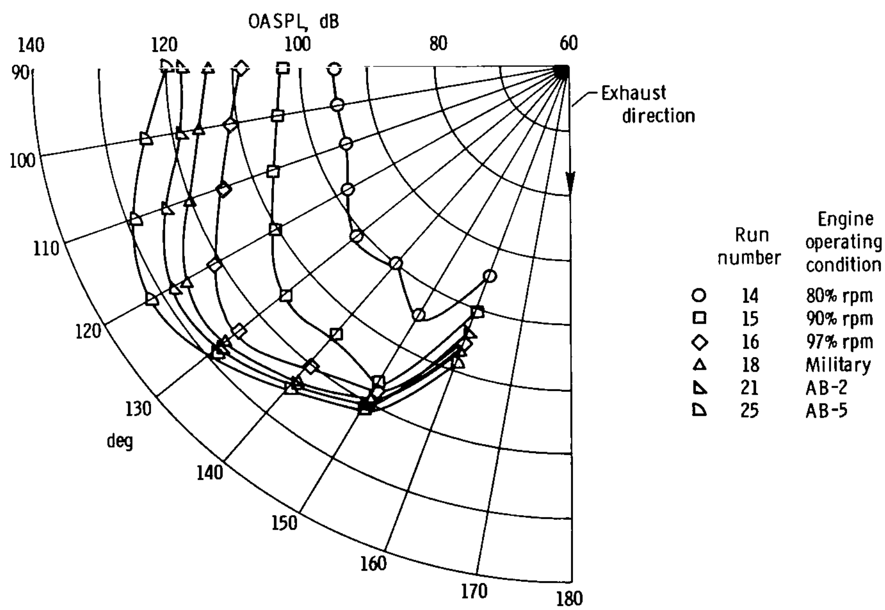
Overall Noise Levels

Effect of engine power on propagation direction. – The contours at 500 feet (152 meters) for selected engine power settings are presented in figures 7(a) to 7(f). The contours show that as the engine power and associated jet exhaust velocity V_R were increased, the SPL increased and the direction of propagation of the maximum SPL shifted away from the exhaust axis. The maximum SPL during full afterburner was at 120° for all engine combinations. The change in the direction of the maximum SPL is believed to be caused by the increasing exhaust velocity and temperature.

At engine power settings below 97 percent, the angle of maximum sound propagation agrees well with the SAE-predicted angle of approximately 135° for one engine, six engines, or two widely spaced engines (figs. 7(a) and 7(d) to 7(f)). For other engine combinations at low power settings, the angle of maximum sound propagation is 150°.

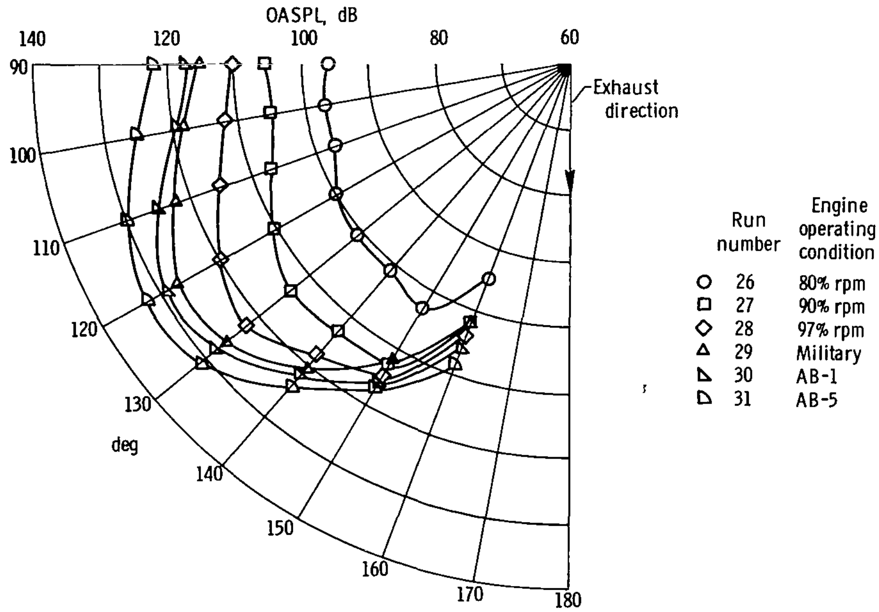


(a) Engine 1.

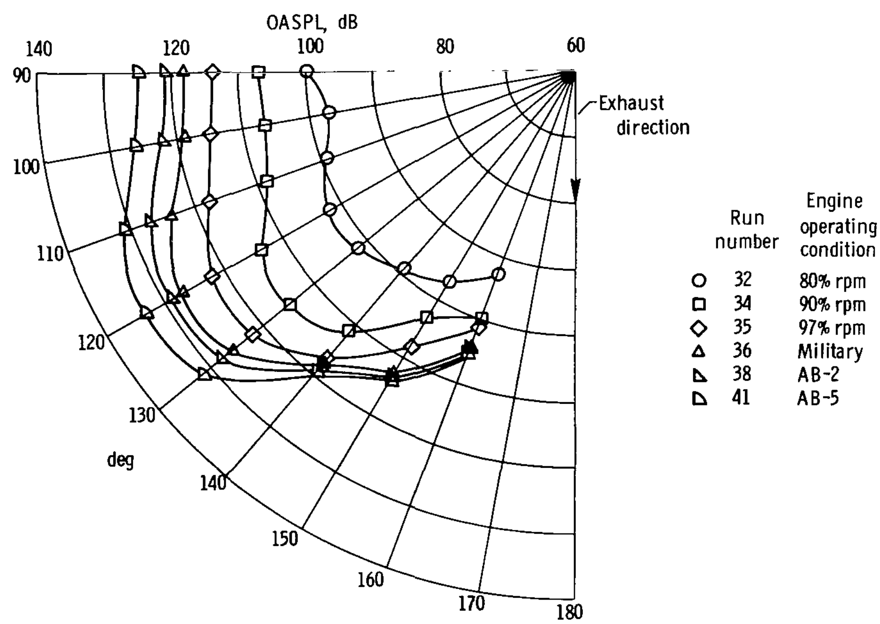


(b) Engines 1 and 2.

Figure 7. Overall sound pressure level contours for various power settings at 500 feet (152 meters).

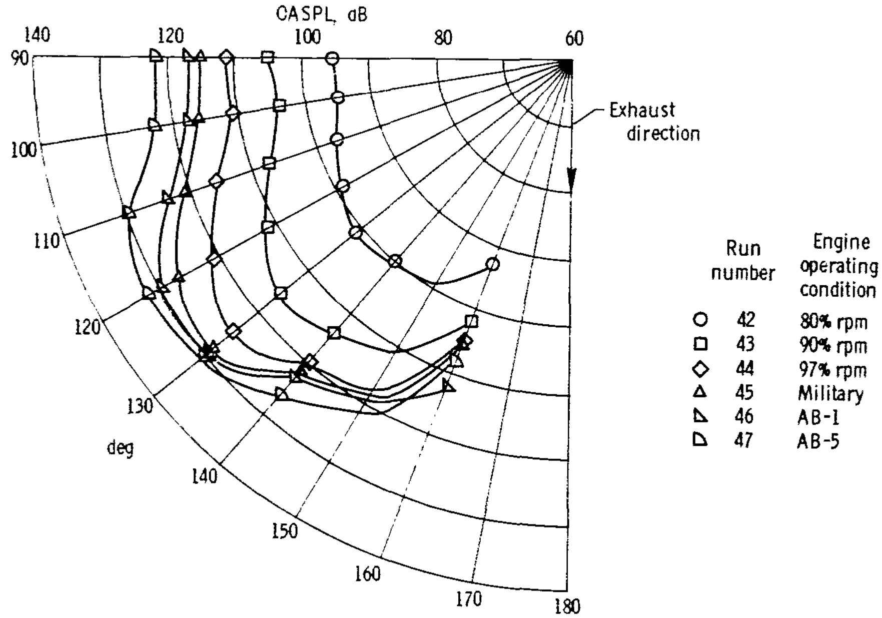


(c) Engines 1, 2, and 3.

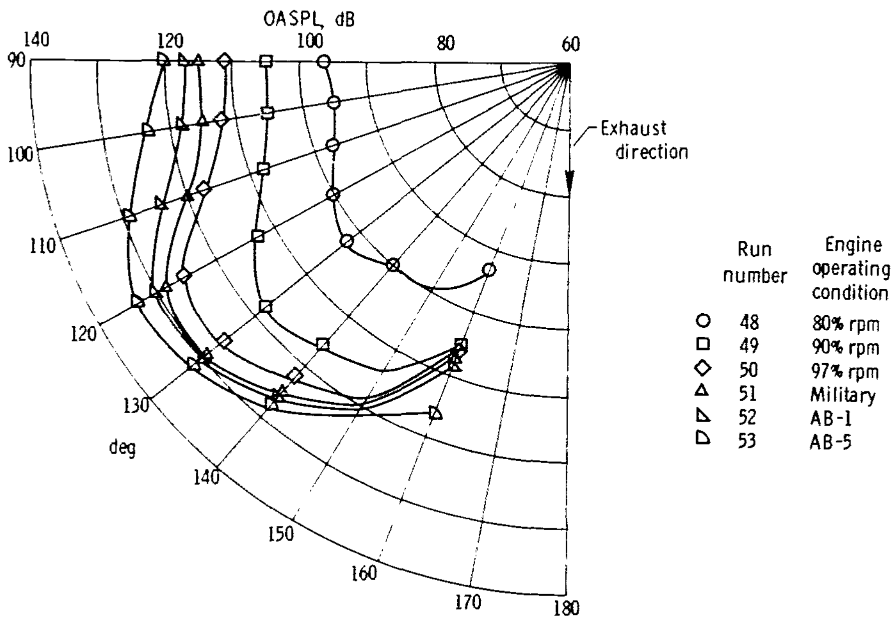


(d) Engines 1, 2, 3, 4, 5, and 6.

Figure 7. Continued.



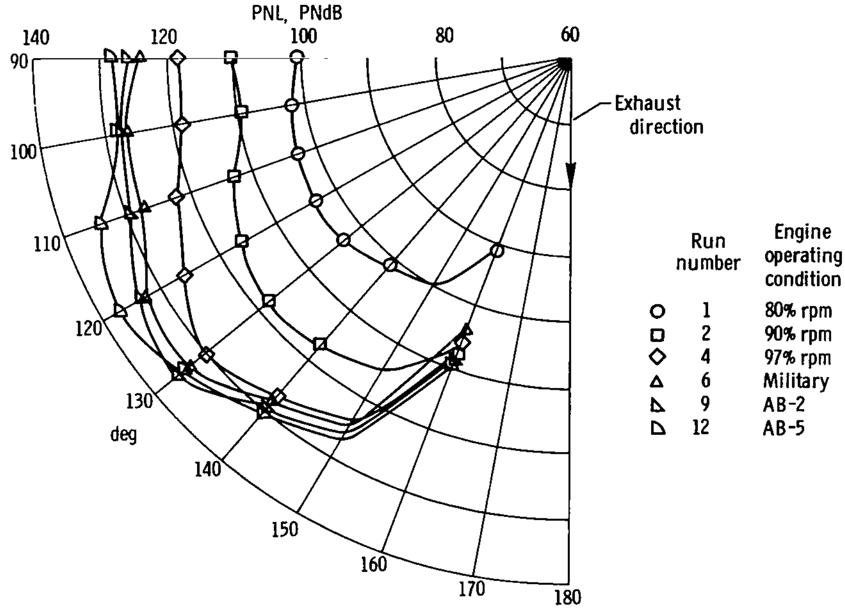
(e) Engines 1 and 4.



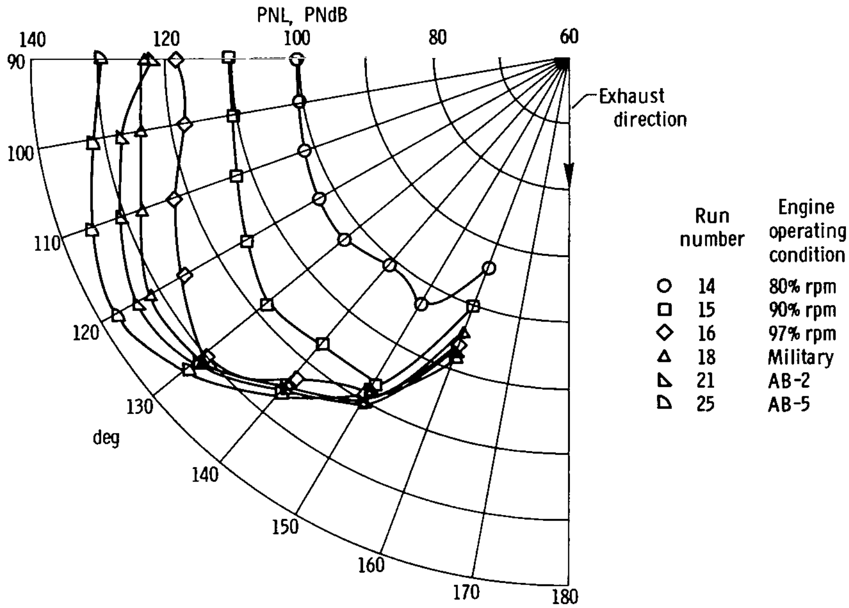
(f) Engines 1 and 6.

Figure 7. Concluded.

Effect of engine power on perceived noise levels. — Presented in figures 8(a) to 8(f) are the data from figure 7 shown in terms of perceived noise level (PNL).

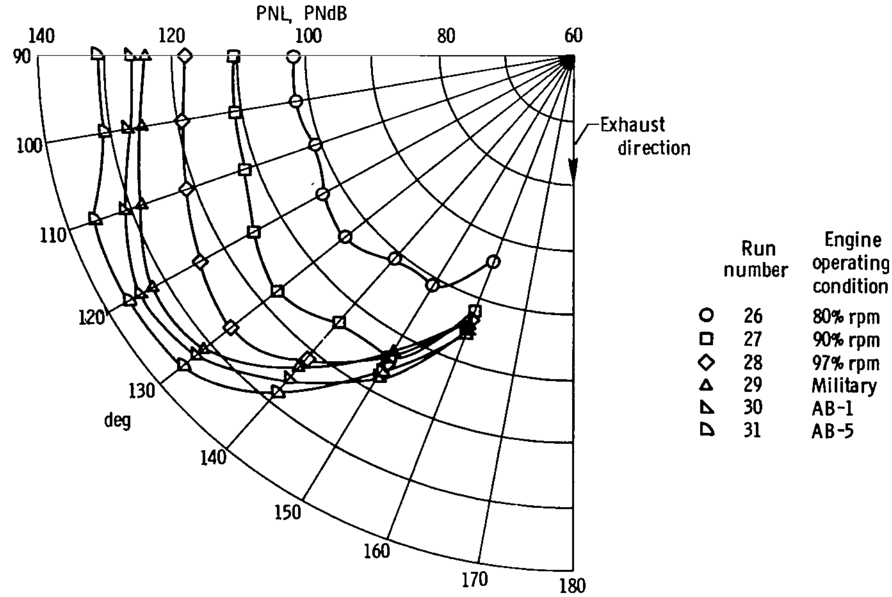


(a) Engine 1.

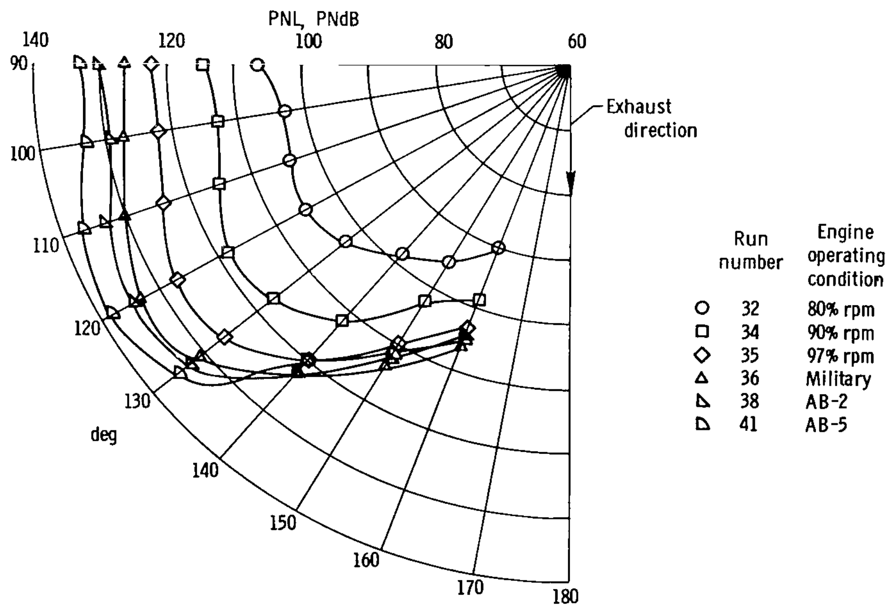


(b) Engines 1 and 2.

Figure 8. Perceived noise level contours for various power settings at 500 feet (152 meters).

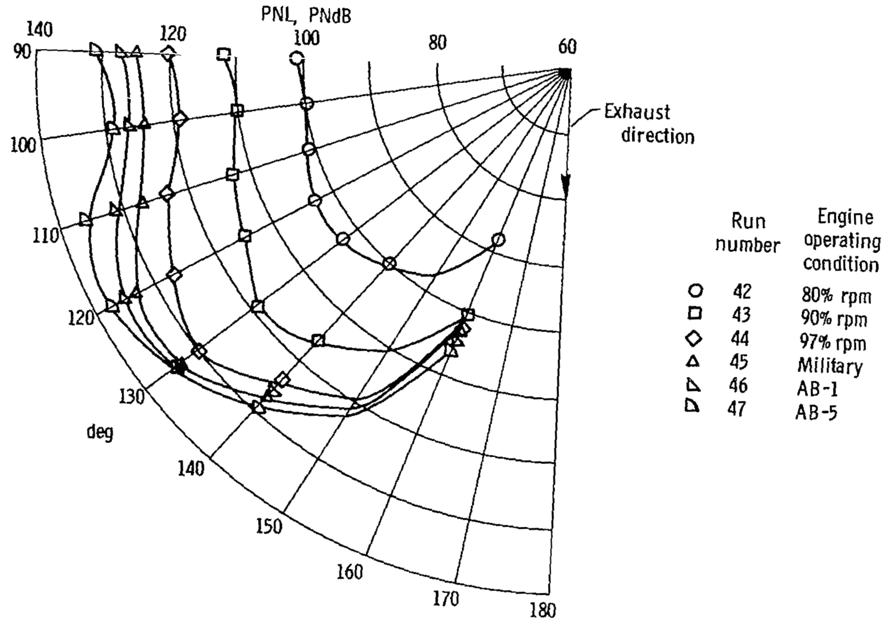


(c) Engines 1, 2, and 3.

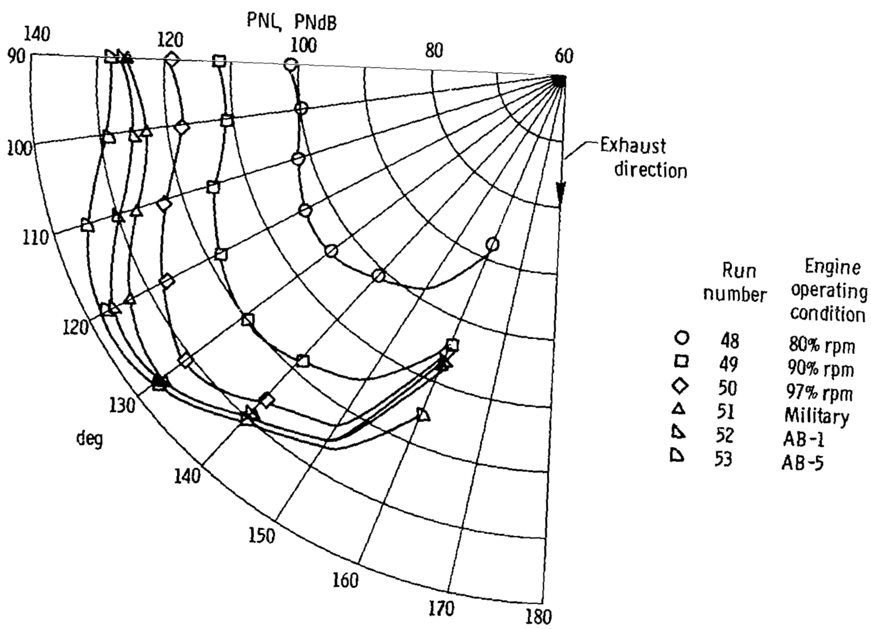


(d) Engines 1, 2, 3, 4, 5, and 6.

Figure 8. Continued.



(e) Engines 1 and 4.

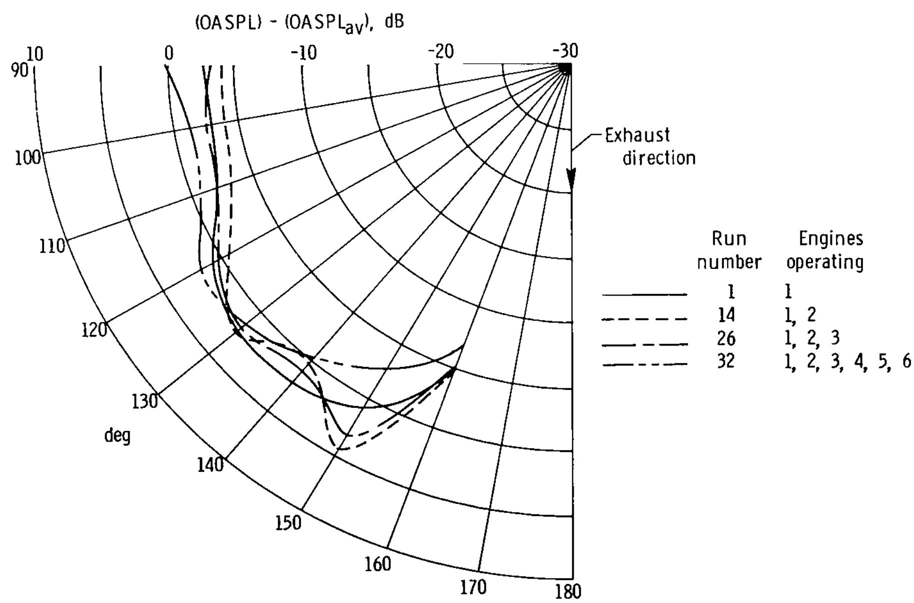


(f) Engines 1 and 6.

Figure 8. Concluded.

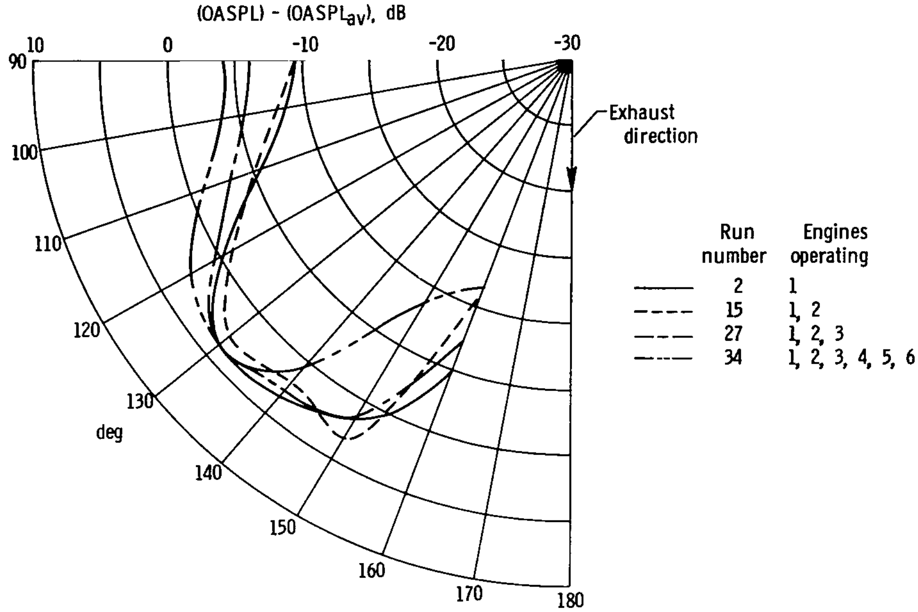
Perceived noise level is a measure of human response, as defined in reference 7. The PNL contours exhibit the same characteristics as the OASPL contours in that the maximum PNL shifted away from the exhaust axis as the engine power was increased. At distances other than 500 feet (152 meters), the PNL contours may not exhibit the same characteristics as the OASPL contours because of a change in the frequency spectrum due to ground and atmospheric absorption.

Effect of number of engines operating on propagation direction. – The effect of increasing the number of adjacent engines operating on the direction of OASPL propagation is shown in figures 9(a) to 9(f). To compare the data for different sound pressure levels, the contours are plotted as (OASPL) - ($OASPL_{av}$), where $OASPL_{av}$ is the average OASPL of all the microphones for a specific run. At the lower power settings (figs. 9(a) and 9(b)), the direction of propagation was pronounced at 150° for certain combinations of engines operating. The direction of the secondary high level shifted from approximately 130° to 120° as the number of engines operating was increased. The direction of propagation for higher power settings (figs. 9(c) to 9(f)) shows a definite shift away from the exhaust direction as the number of engines operating was increased. Contours for engines 1 and 4 and engines 1 and 6 operating are not shown because of the similarity to the contours for engines 1 and 2 operating.

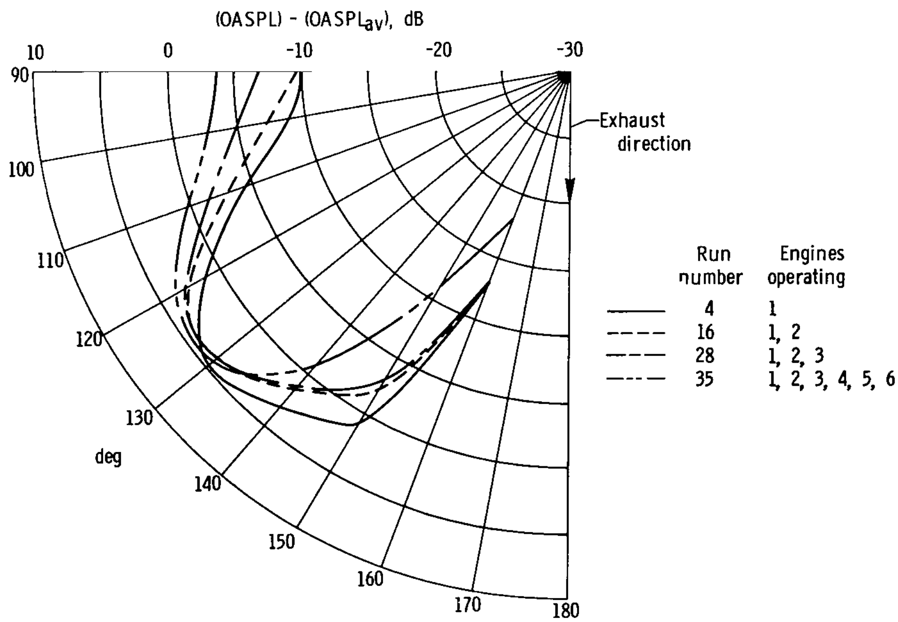


(a) Engine operating condition, 80 percent rpm.

Figure 9. Change in direction of sound propagation due to number of engines operating at approximately constant jet exhaust velocity.

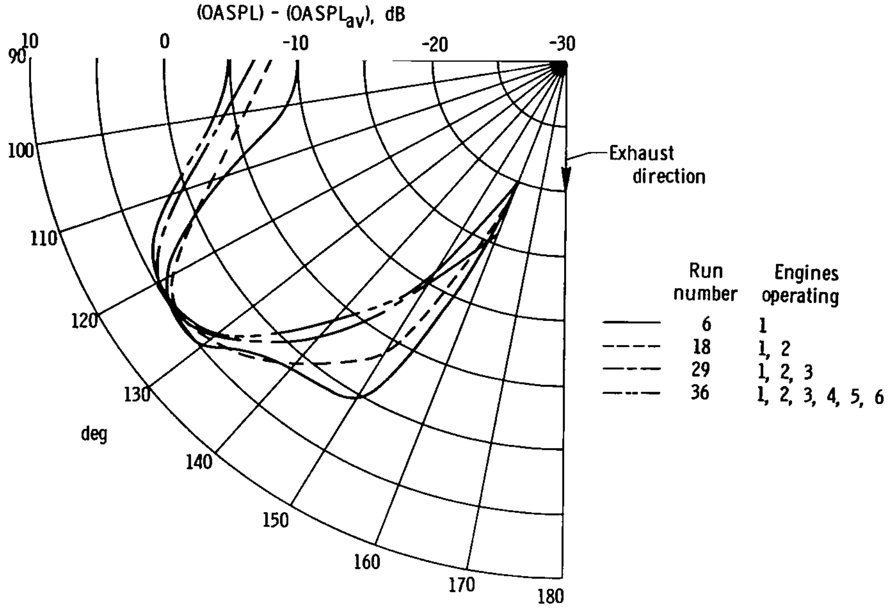


(b) Engine operating condition, 90 percent rpm.

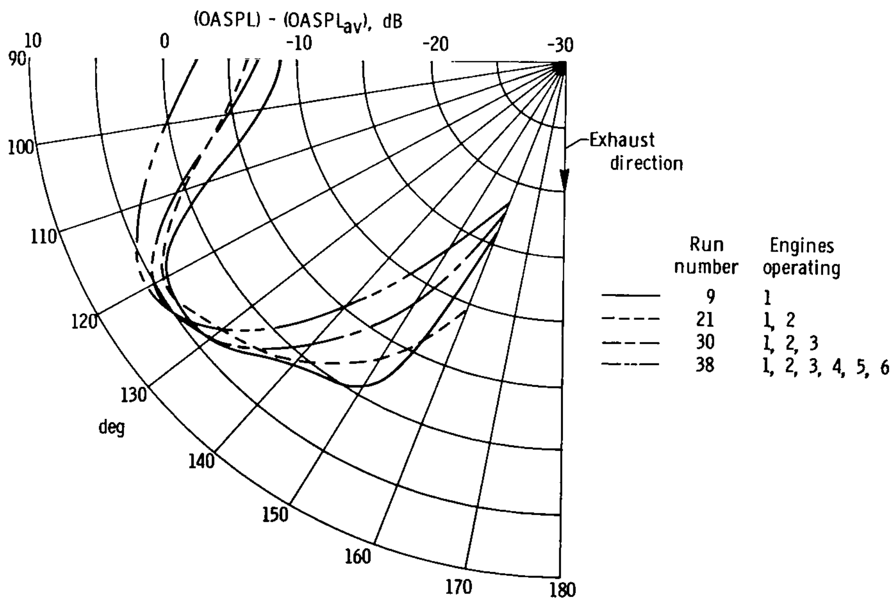


(c) Engine operating condition, 97 percent rpm.

Figure 9. Continued.

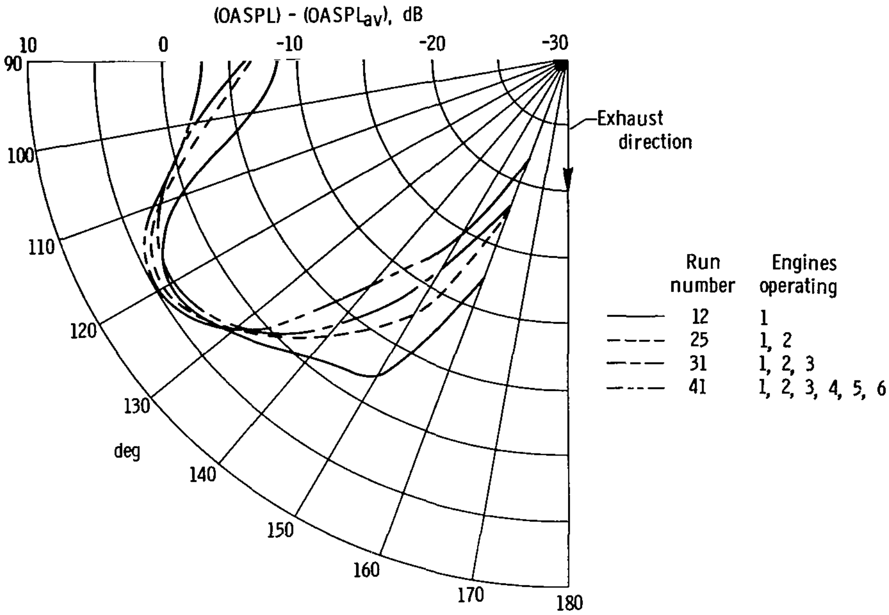


(d) Engine operating condition, military.



(e) Engine operating condition, minimum afterburner.

Figure 9. Continued.



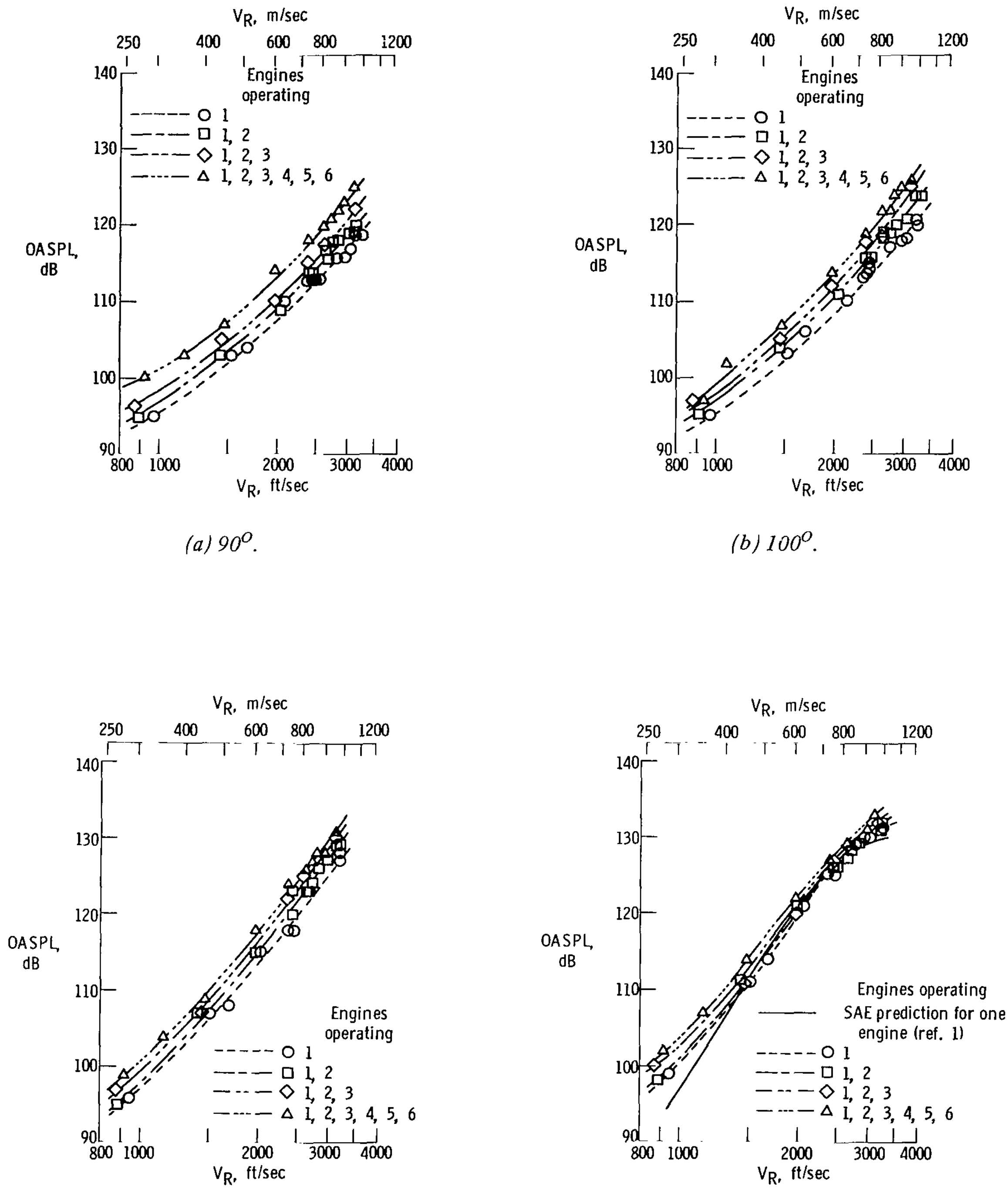
(f) Engine operating condition, maximum afterburner.

Figure 9. Concluded.

Effect of jet velocity on OASPL.– The OASPL data as a function of jet velocity for various combinations of engines operating are shown in figures 10(a) to 10(h) for angular positions of 90° to 160° from the airplane heading. Figures 10(a) to 10(d) show an increase in noise level at ؟0°, 100°, 110°, and 120°, as adjacent engines are added; however, the magnitude of the increase is less at each succeeding position from 90° to 120°. At 130° (fig. 10(e)) there is no evident trend, and, for the higher jet velocities, the SPL at 140° and 150° (figs. 10(f) and 10(g)) decreases as additional engines are operated. The microphone at 160° (fig. 10(h)) was in the flow of the exhaust gages and probably accounts for the large amount of scatter in the data.

The maximum measured noise levels (fig. 7) are compared with the SAE-predicted maximum levels for one engine at power settings above 90 percent in figures 10(d) and 10(e). The SAE method assumes that the angle of maximum noise emission is 135° from the aircraft heading and predicts the OASPL for a sideline distance of 200 feet (61 meters). The predicted noise levels shown in figures 10(d) and 10(e) were corrected for spherical spreading to the same distance as the measured data. Predicted levels for more than one engine can be made by adding $5 \log_{10} N$, where N is the number of engines operating.

The predicted level for one engine operating is in reasonable agreement with the measured SPL for one engine at an angle of 120° (fig. 10(d)) and exhaust velocities between 1500 feet/second (457 meters/second) and 3000 feet/second (914 meters/second). At 130° (fig. 10(e)) the agreement between the OASPL and the predicted OASPL is not as good as at 120°, which may be due to the change in direction of propagation of maximum OASPL, as shown in figure 9.



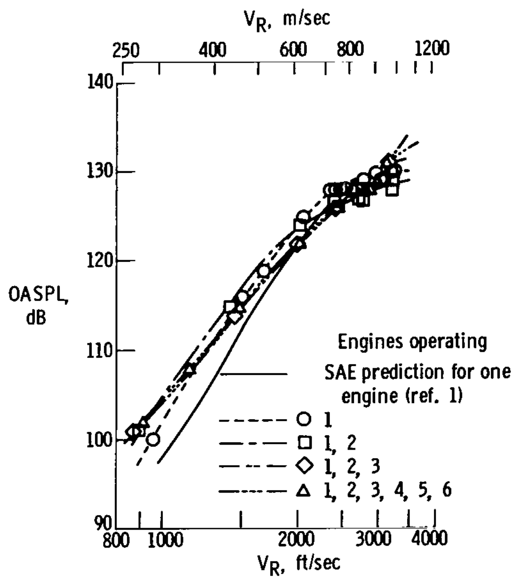
(a) 90°.

(b) 100°.

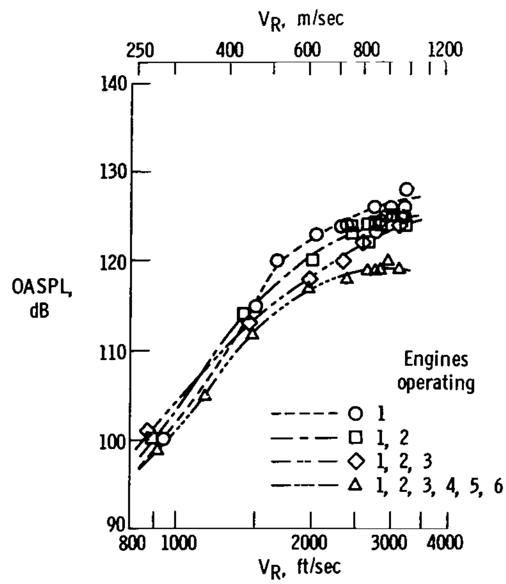
(c) 110°.

(d) 120°.

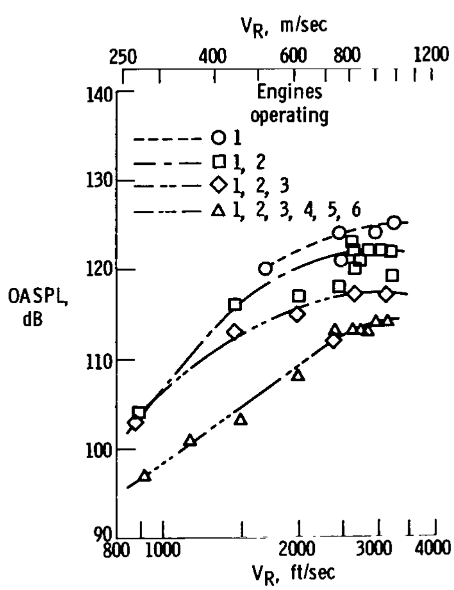
Figure 10. Change in overall sound pressure level, due to number of engines operating, at angular positions of 90° to 160° from the airplane heading and a radius of 500 feet (152 meters).



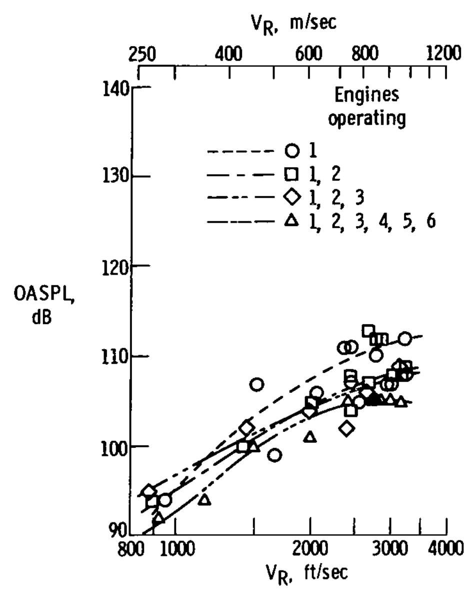
(e) 130°.



(f) 140°.



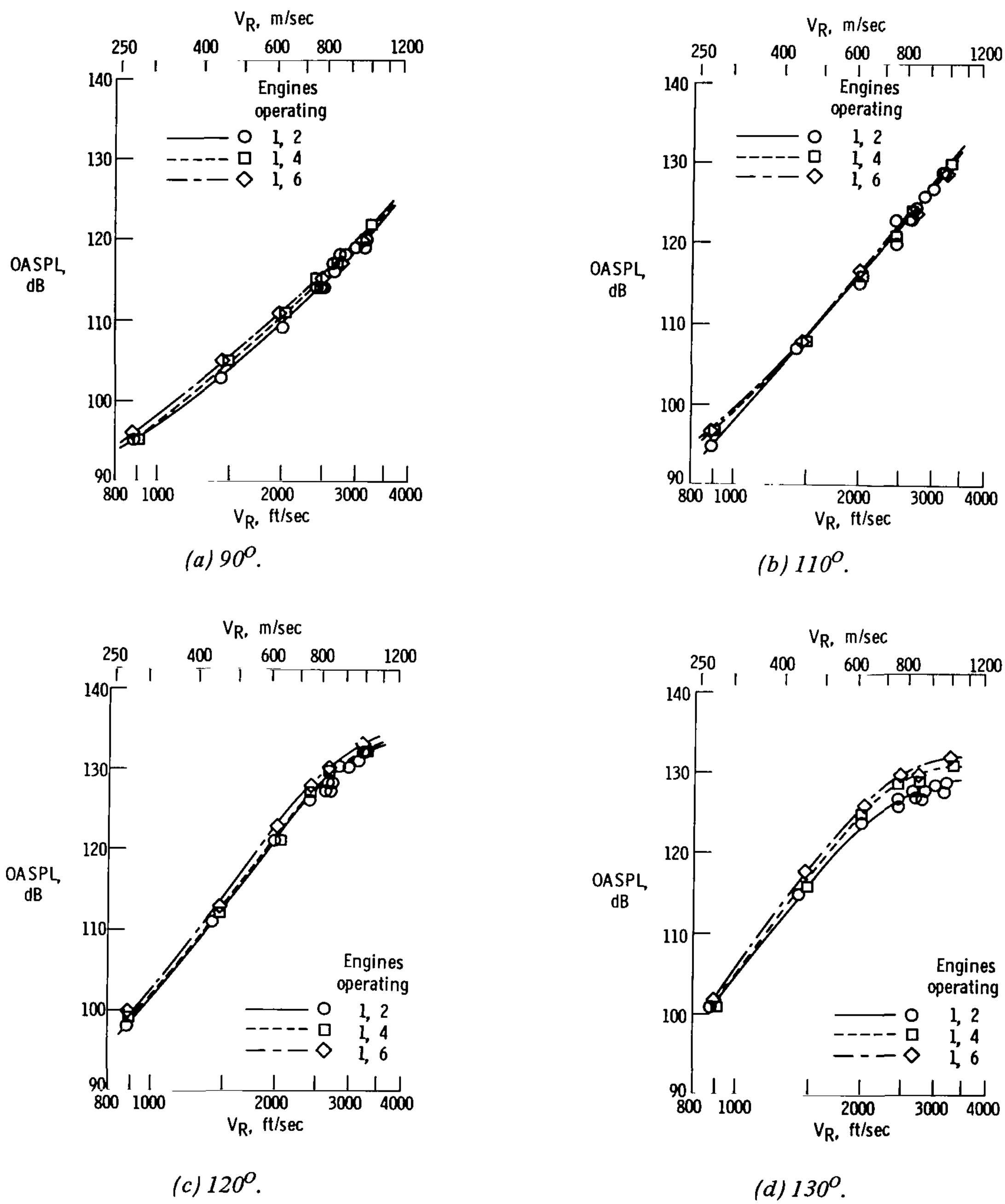
(g) 150°.



(h) 160°.

Figure 10. Concluded.

Effect of engine spacing. – The effect of engine spacing on the OASPL is shown in figures 11(a) to 11(e) for center-to-center engine spacing of approximately 5, 15, and 25 feet (1.5, 4.6, and 7.6 meters). The noise level is either negligibly affected or generally increases slightly as the engines are spaced farther apart, particularly for the larger exhaust velocities at the 130° and 140° positions.



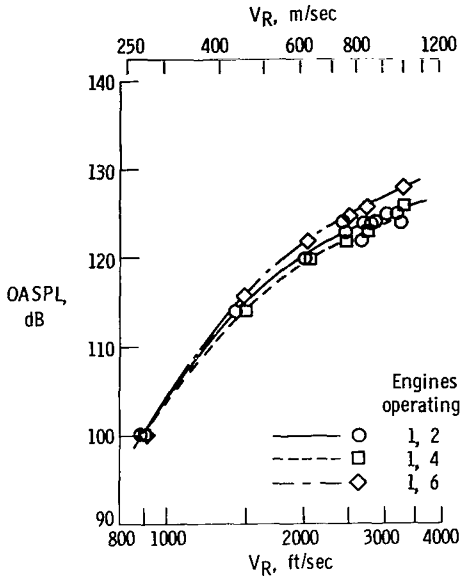
(a) 90°.

(b) 110°.

(c) 120°.

(d) 130°.

Figure 11. Effect of engine spacing on overall sound pressure level at various angular positions to the airplane heading.



(e) 140°.

Figure 11. Concluded.

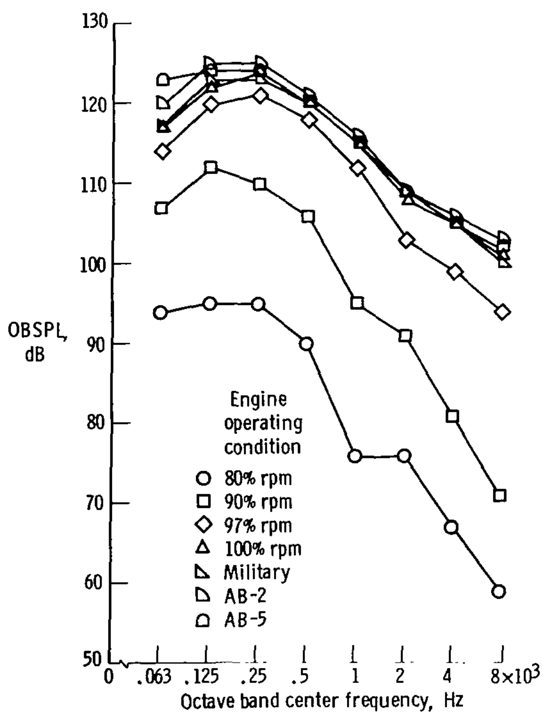


Figure 12. Variation of octave band sound pressure levels for different engine operating conditions. One engine at 500 feet (152 meters) and direction of 130°.

Octave Band Spectrum

The basic spectral characteristics of the exhaust noise generated by one XB-70 engine for various engine power settings are illustrated in figure 12. The data were obtained at a distance of 500 feet (152 meters) and an angle of 130° from the aircraft heading. In this form the data do not permit direct comparison of the spectra for different engine power settings; however, previous investigators (refs. 8 and 9) showed that spectra for different jet velocities and exit areas can be directly compared if the octave band sound pressure levels are referenced to the OASPL and the frequencies nondimensionalized. The nondimensional frequency is the Strouhal number which is defined as follows:

$$SN = \frac{fd}{V_R}$$

where f is the frequency, d is the diameter of the jet exhaust at the nozzle exit, and V_R is the velocity of the jet exhaust. Strouhal number can be used to nondimensionalize spectra for both subsonic and supersonic exhaust velocities (ref. 1). The XB-70 exhaust becomes supersonic for power settings above 93 percent rpm.

Subsonic-flow octave band spectrum levels. – The octave band spectra as a function of Strouhal number are shown in figures 13(a) to 13(c) at angles of 90°, 120°, and 140° for various spatial distances between operating engines. It is apparent that the spectrum shape varies with angular position about the airplane; however, no discernible trends of the effect of engine spacing on the spectrum are evident.

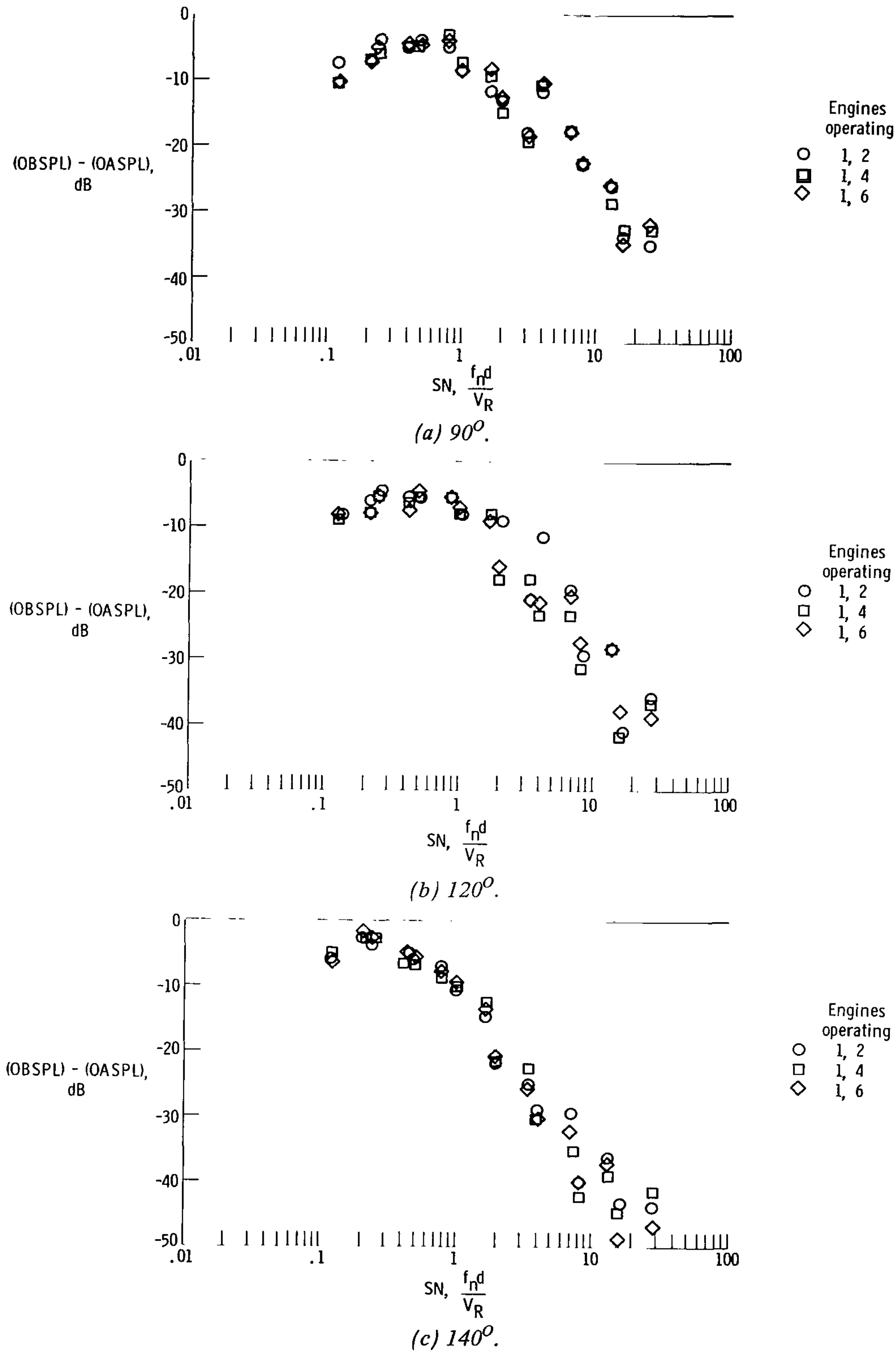
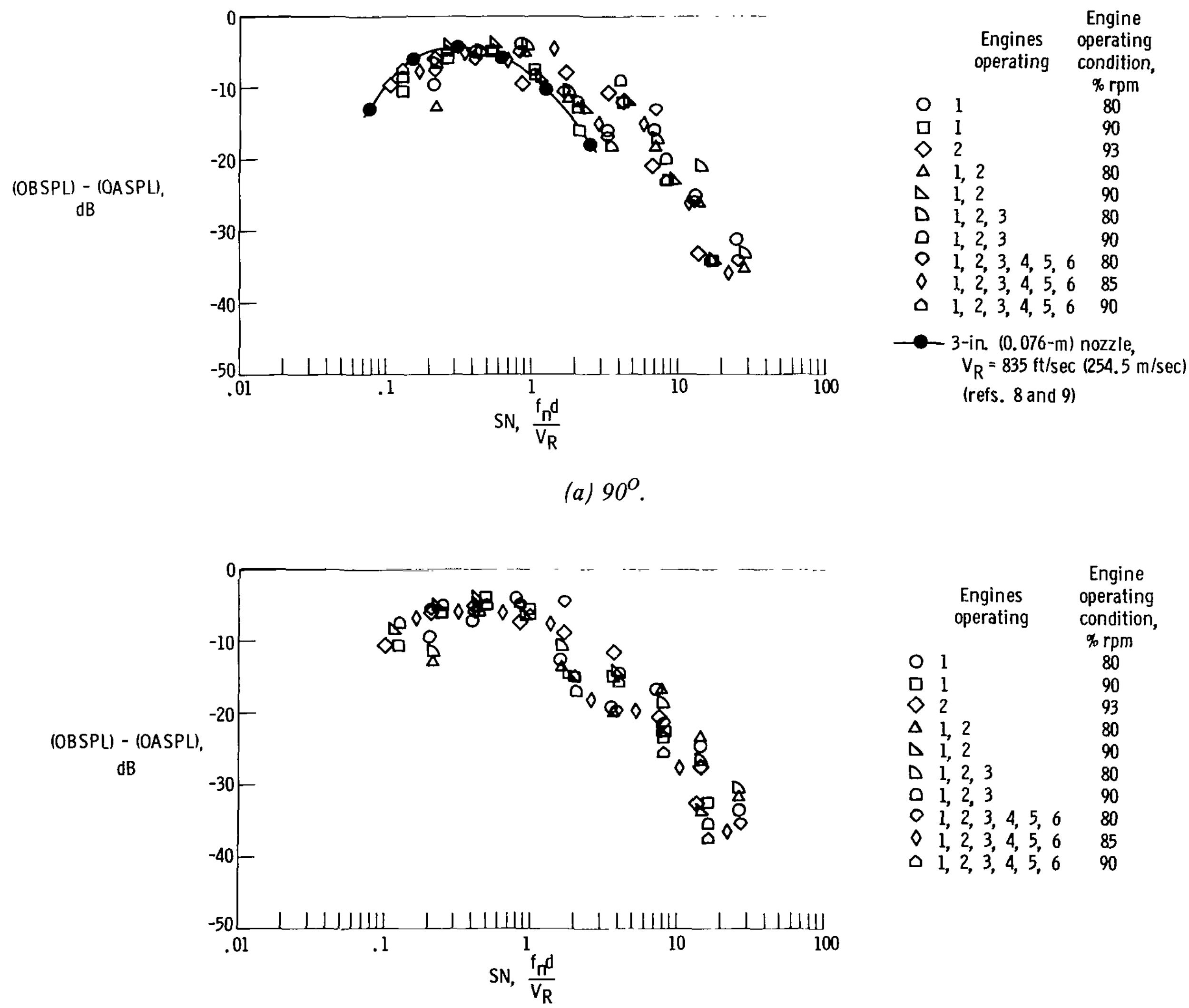


Figure 13. Octave band spectrum as function of Strouhal number at 500 feet (152 meters) for different engine spacing when V_R was subsonic.

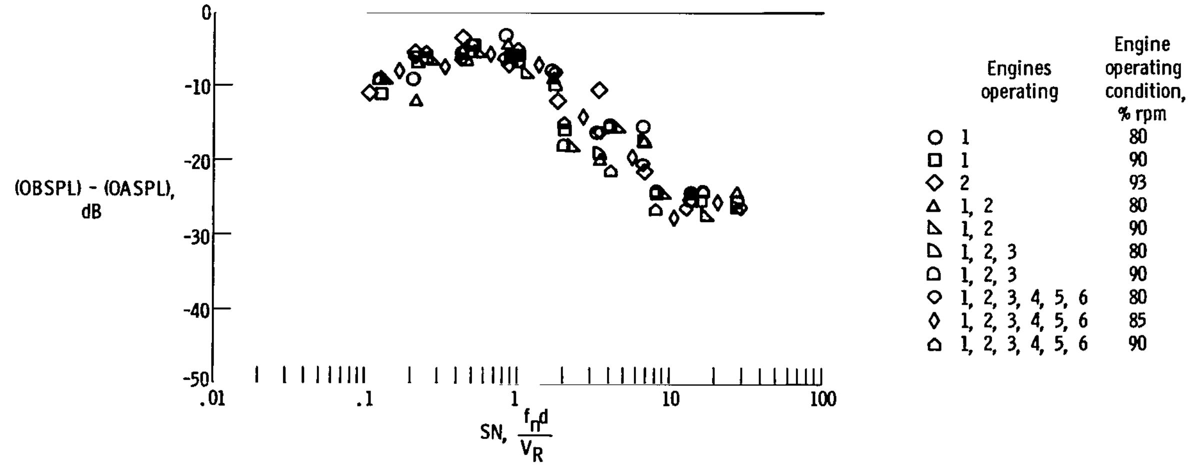
Presented in figures 14(a) to 14(h) are the octave band spectra as a function of Strouhal number for angles of 90° to 160° and one, two, three, and six adjacent engines operating. Several observations can be made about these spectra. First, there is no apparent change in the spectra shape, in the plane of the measurements, for any angle as the number of engines operating was increased. Second, the spectra peak shifts from a Strouhal number of about 0.8 at 90° to a Strouhal number of about 0.25 at 160°, and the octave band levels at the higher Strouhal number are less at an angle of 160° than at 90°. These last two effects are not unexpected, because the results of reference 10 showed that high-frequency noise is generated near the jet exit plane but low-frequency noise is generated several exhaust diameters downstream of the jet exit. This distribution of sound sources accounts for the relative dominance of the low frequencies in the spectra for angular positions near the jet axis.



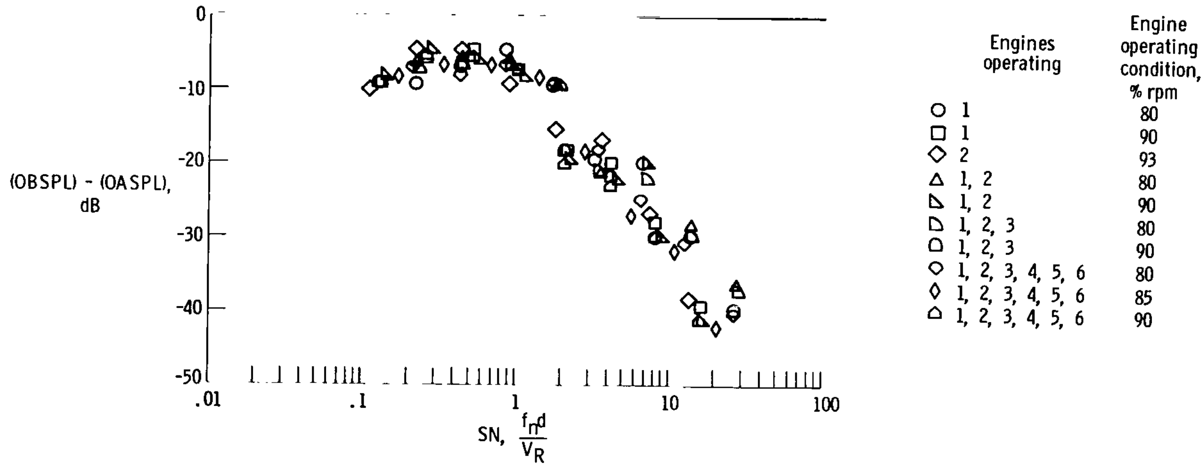
(a) 90°.

(b) 100°.

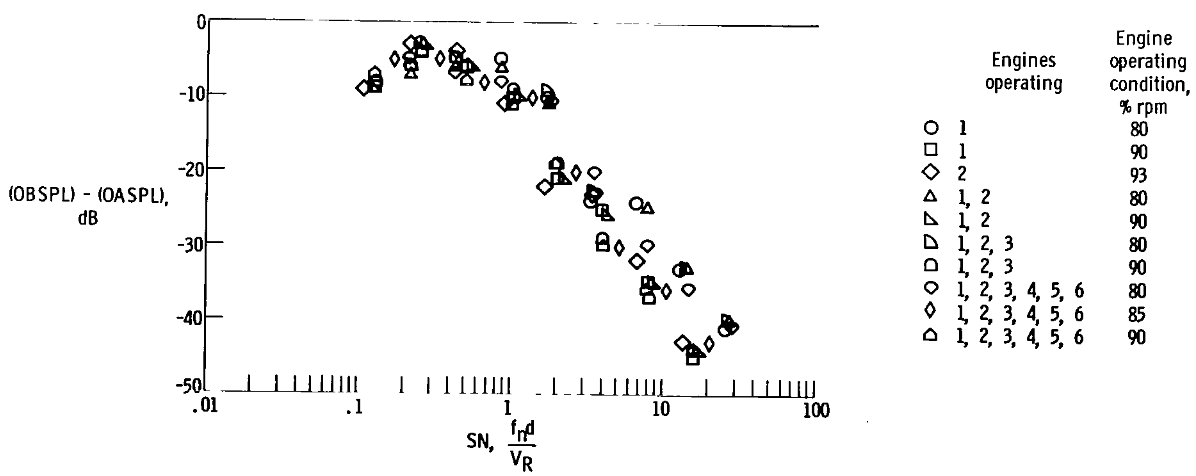
Figure 14. Octave band spectrum as function of Strouhal number at 500 feet (152 meters) for one, two, three, and six engines operating when V_R was subsonic.



(c) 110°.

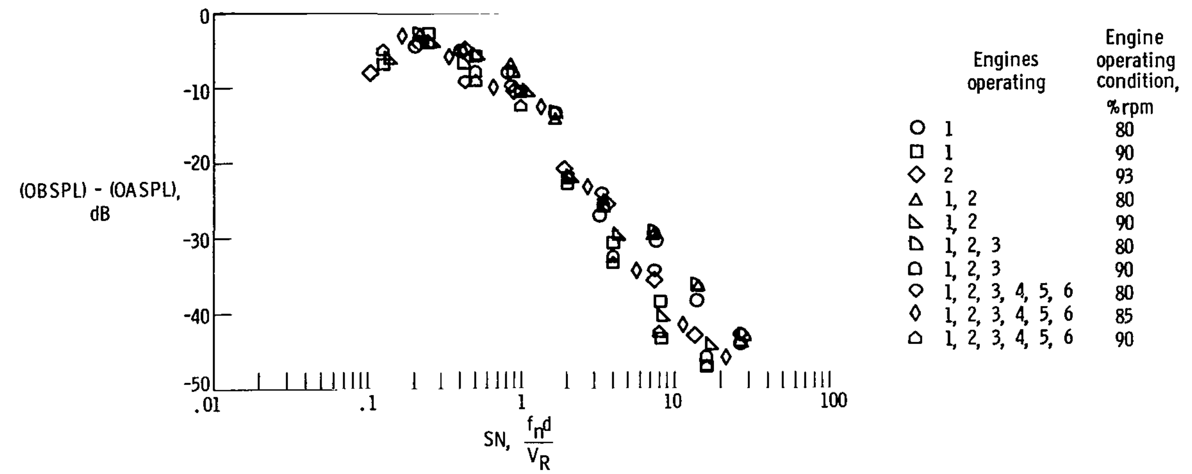


(d) 120°.

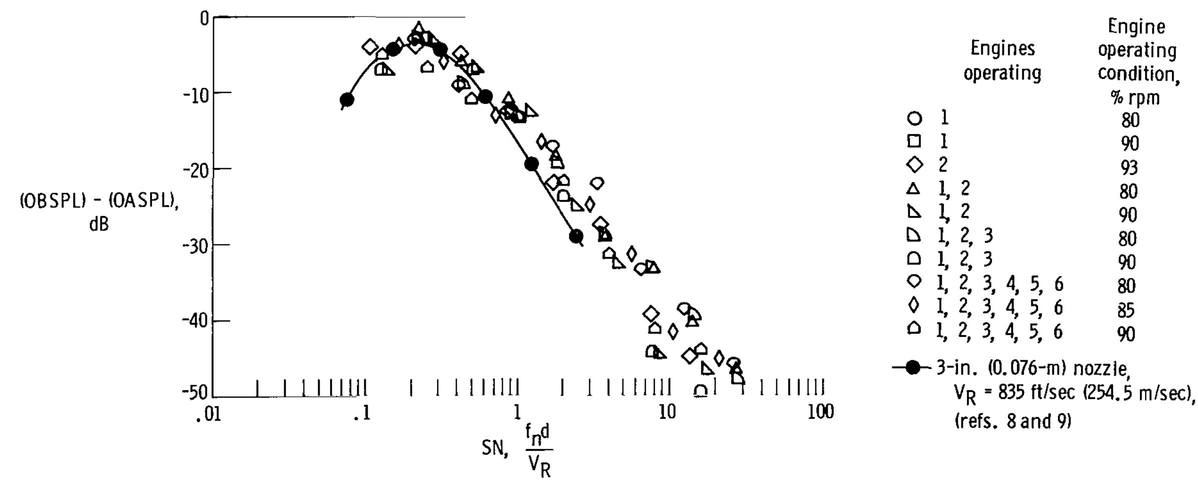


(e) 130°.

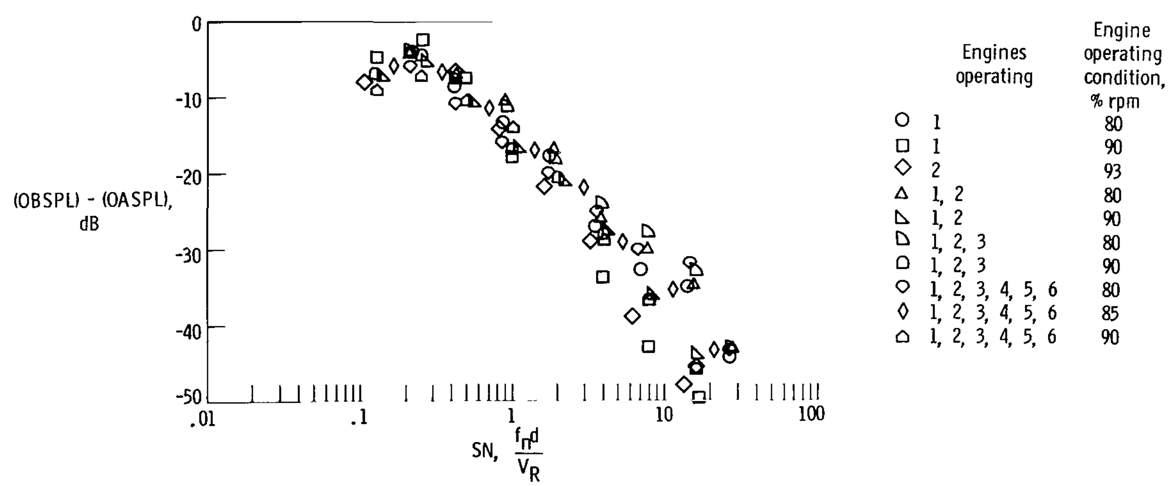
Figure 14. Continued.



(f) 140°.



(g) 150°.



(h) 160°.

Figure 14. Concluded.

To evaluate the degree of correlation that can be attained between octave band sound pressure spectrum of a model air jet and a large turbojet engine, the model air jet spectrum from references 8 and 9 is also plotted in figures 14(a) and 14(g)). The model nozzle diameter was 3 inches (0.076 meter), and the jet velocity was 835 ft/sec (254.5 m/sec). The comparison of model jet data with turbojet data indicates the need for caution in using model jet spectra to predict turbojet engine noise spectra.

The XB-70 spectrum obtained at an angle of 130° and the predicted spectrum obtained by using the SAE theory are compared in figure 15. The XB-70 data used in this comparison were for subsonic exhaust velocities only and were corrected for atmospheric absorption by using values obtained in reference 2. The SAE method adequately estimates the XB-70 spectrum for subsonic flow for single- or multi-engine operation.

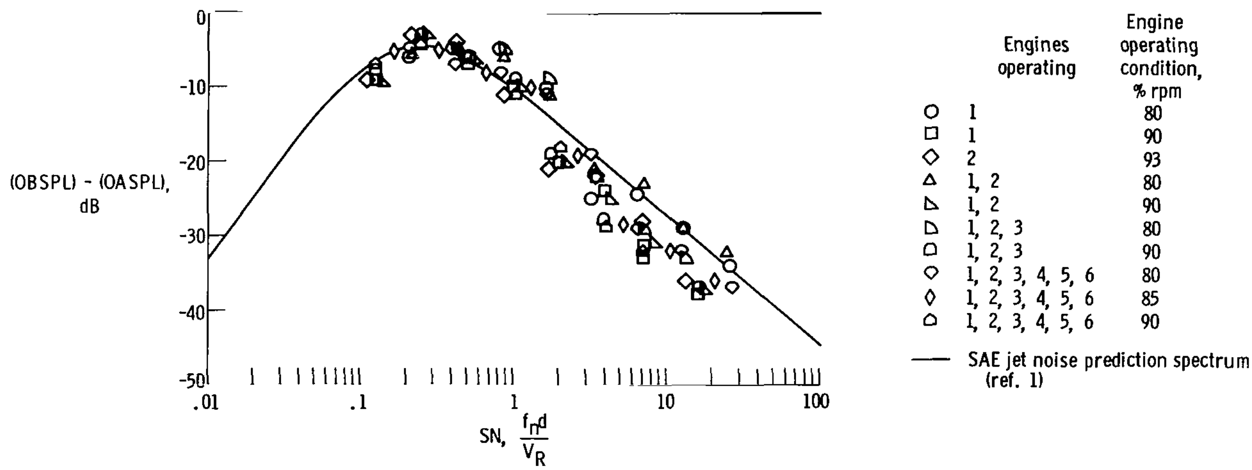


Figure 15. Comparison of octave band spectra with SAE spectrum. XB-70 data measured at 130° and corrected for atmospheric attenuation to 200-foot (61-meter) sideline distance when V_R was subsonic.

Supersonic-flow octave band spectrum levels. — Although the Strouhal number as a function of V_R was developed for subsonic flows, reference 1 indicates that the method can be used for jet nozzle pressure ratios up to 3.0; pressure ratios above 1.86 result in supersonic flow. The maximum pressure ratio of the convergent nozzle of the XB-70 engines was less than 3.0 during the tests. It should also be noted that the exit nozzle diameter varied with engine power settings for supersonic flow.

The spectrum for one engine of the XB-70 with supersonic flow is shown in terms of Strouhal number in figure 16. The Strouhal number based on V_R appears to give reasonable correlation for these data, which were measured at an angle of 130° and a radius of 500 feet (152 meters). A comparison of the spectrum of figure 16 with the spectrum of figure 14(e), which is for subsonic flow and independent of the number of engines operating, shows that the spectrum peaks coincide in both instances, but the spectrum level for the high frequencies (SN > 4) is approximately 5 dB to 10 dB higher for supersonic exhaust flow.

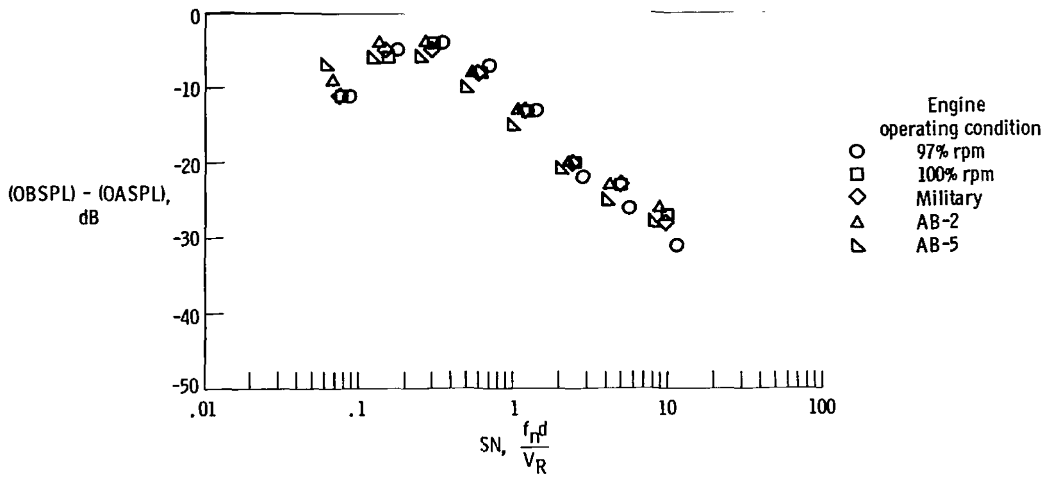


Figure 16. Comparison of octave band spectrum with Strouhal number at 500 feet (152 meters) and an angle of 130° from the airplane heading for one engine at various operating conditions when V_R was supersonic.

The data from figure 16 were corrected to a sideline distance of 200 feet (61 meters) by using atmospheric absorption values obtained from reference 2 and are compared in figure 17 with the spectrum predicted by the SAE method. The agreement is reasonable except for a Strouhal number larger than 4. The spectrum levels for $SN > 4$ are accentuated by the atmospheric corrections.

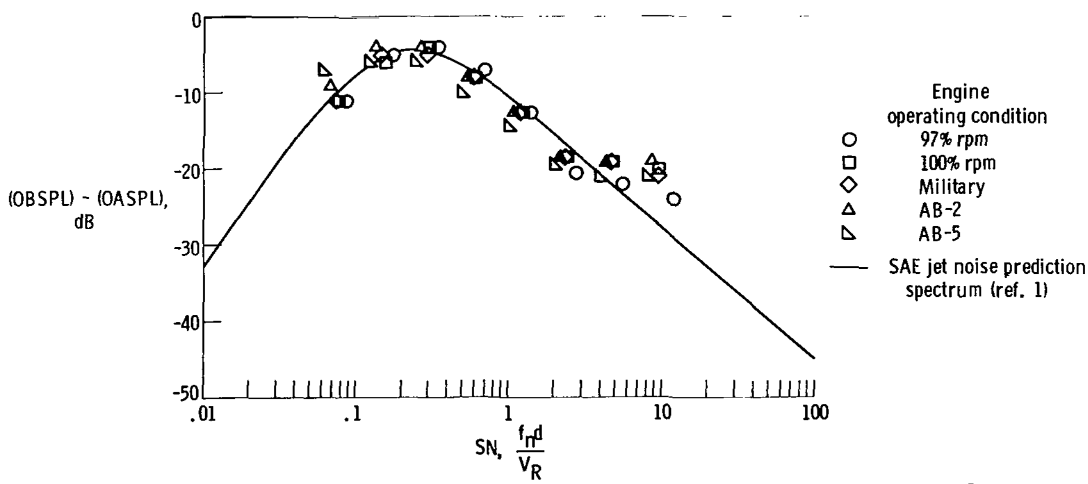
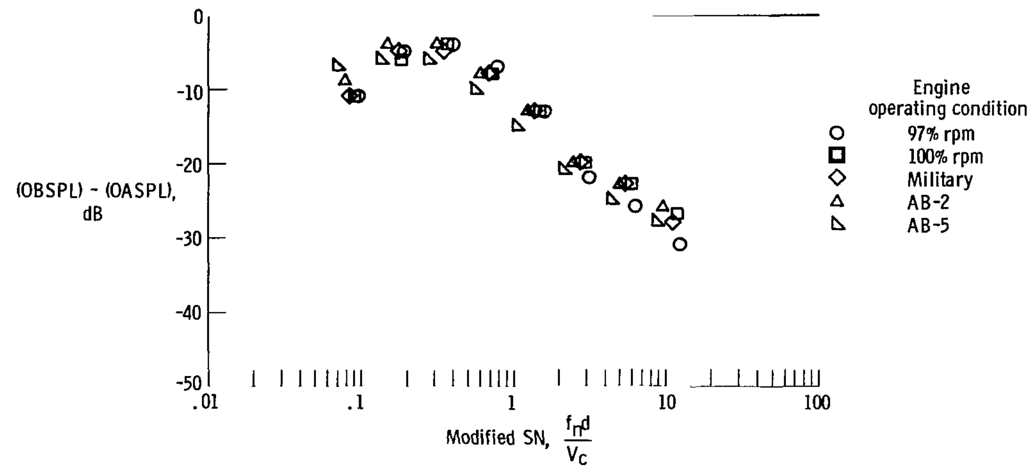
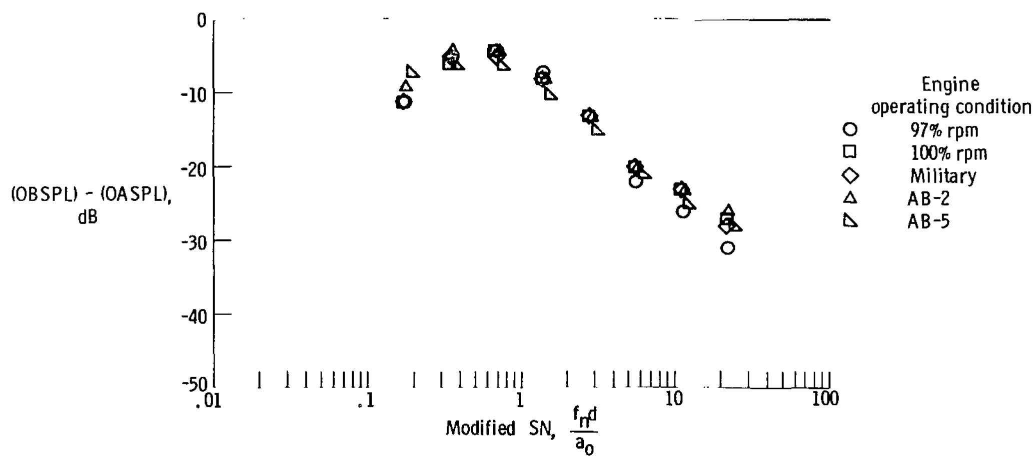


Figure 17. Comparison of octave band spectrum for one engine with SAE spectrum. XB-70 data measured at 130° and corrected for atmospheric attenuation to 200-foot (61-meter) sideline distance when V_R was supersonic.

Previous investigators (refs. 9 and 11) indicated that a modified Strouhal number based on the speed of sound would provide better correlation of data than obtained with an unmodified Strouhal number for supersonic exhaust flow. To assess such a change in relation to the XB-70 data, Strouhal number was modified by replacing V_R with V_c, the speed of sound in the jet exhaust based on the perfect gas law for air, and then with a_o, the ambient speed of sound. The data of figure 16 were evaluated in terms of the modified Strouhal number based on replacing V_R with V_c; the results are shown in figure 18(a). When V_R is replaced by a_o, the data from figure 16 appear as shown in figure 18(b). The data correlate much better when V_R is replaced by a_o (fig. 18(b)). This indicates that the spectrum shape is independent of the jet exhaust velocity for this engine with supersonic exhaust flow.



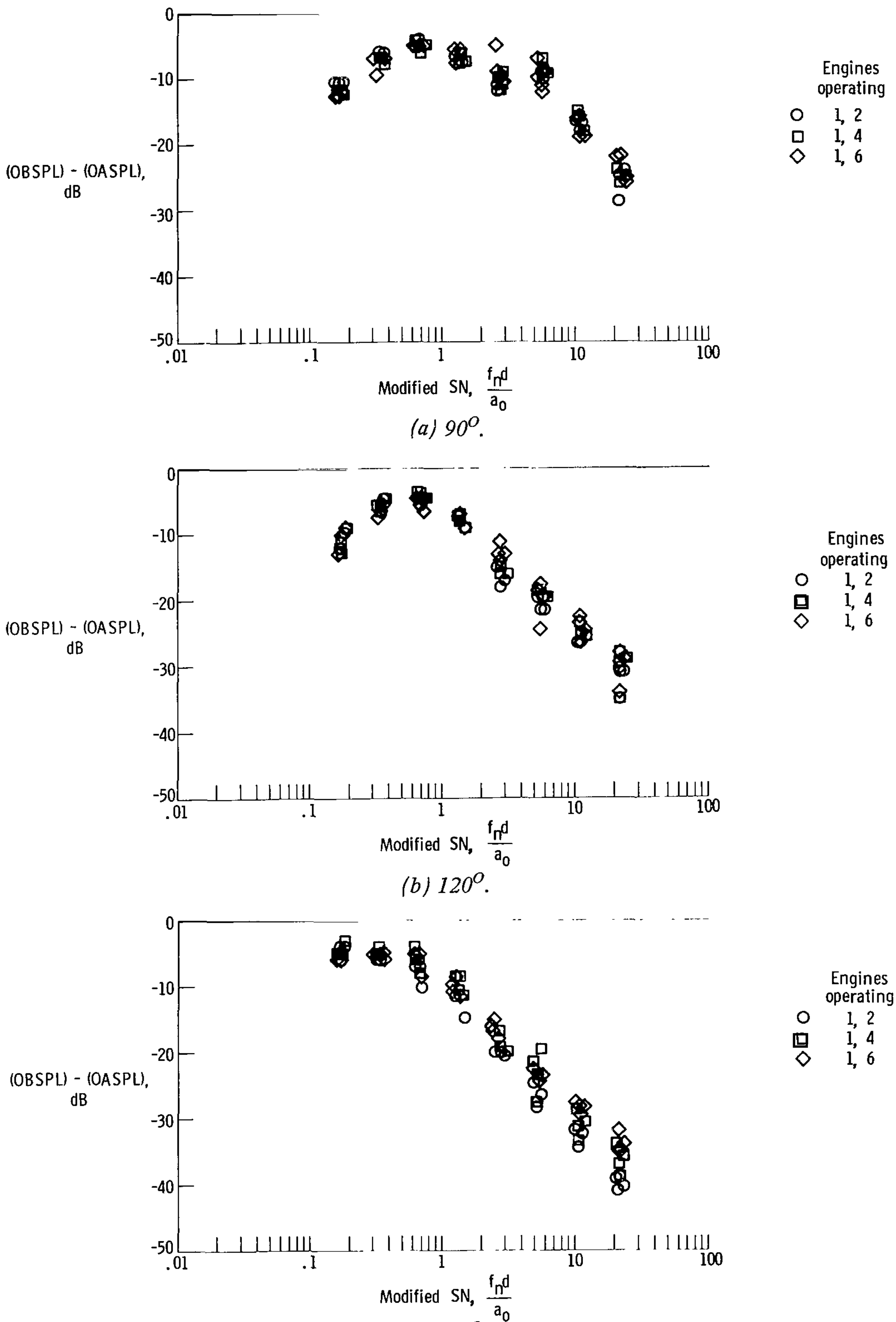
(a) Strouhal number modified by using speed of sound in the jet exhaust at nozzle exit.



(b) Strouhal number modified by using ambient speed of sound.

Figure 18. Octave band spectrum as function of a modified Strouhal number at 500 feet (152 meters) and 130^o for one engine operating at various power conditions when V_R was supersonic.

The effect of engine spacing on octave band spectrum levels for two engines operating with supersonic exhaust flow is shown in figure 19 as a function of modified Strouhal number based on a_o. At 90° (fig. 19(a)) there are no discernible trends of the effect of engine spacing on the noise spectrum. However, at 120° and 140° (figs. 19(b) and 19(c)) the spectrum level (for modified SN > 2) increases as the engine spacing increases. This implies that, near the angle of maximum noise propagation, the high-frequency noise of one exhaust is shielded by the other exhaust when adjacent engines are operated.



(a) 90°.

(b) 120°.

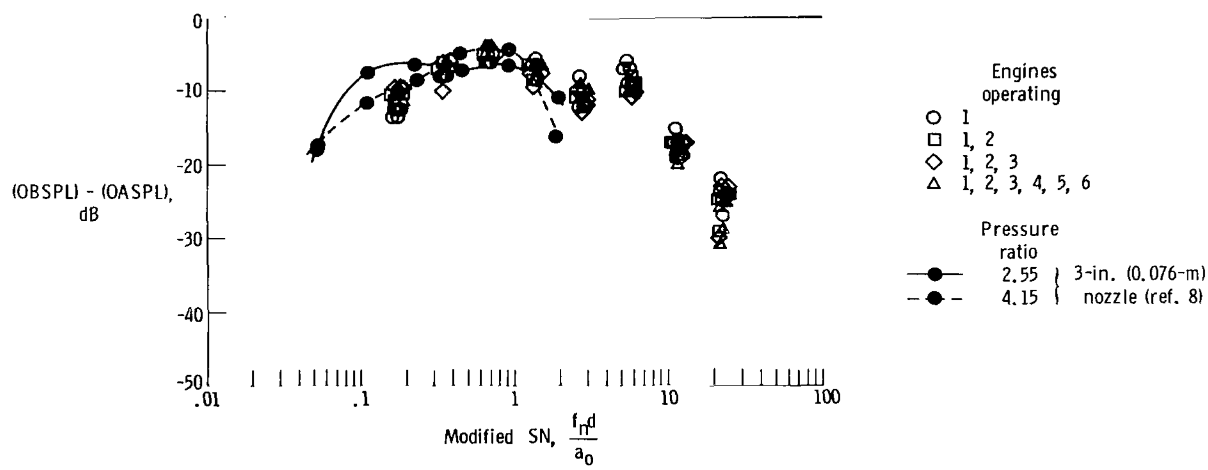
(c) 140°.

Figure 19. Octave band spectrum as function of a modified Strouhal number at 500 feet (152 meters) for different engine spacing when V_R was supersonic.

Shown in figure 20 are the octave band spectra from 90° to 150° as a function of Strouhal number (based on a_o) for supersonic exhaust flows where V_R varied from 1980 feet/second (604 meters/second) to 3260 feet/second (994 meters/second). Data are shown only for angles up to 150° because, as noted previously, the microphone at 160° was in the exhaust flow when the flow was supersonic. Trends in these spectra are similar to those observed for the subsonic spectra in that the spectrum peak occurs at a modified Strouhal number of 0.6 at 90° and at a modified Strouhal number of 0.25 at 150°. Also, the relative level of the spectrum for the higher modified Strouhal numbers is less at 150° than at 90°. Again, this probably results from the distribution of the apparent sound sources in the jet flow.

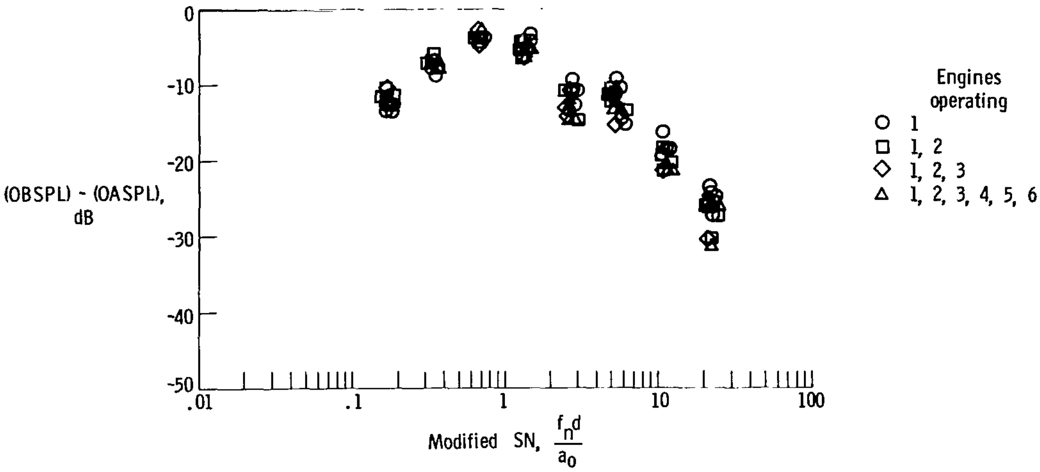
With one engine operating, the spectra levels in the high frequencies (SN > 4) tend to be higher than when two, three, or six adjacent engines were operating (figs. 20(a) to 20(f)). There are no data at 150° for one engine operating (fig. 20(g)). In the plane in which the measurements were made, it again appears that the exhaust of the near side engine shielded the high frequencies generated in the other exhaust(s) when two or more adjacent engines were operating.

For comparison, the spectra for a 3-inch (0.076-meter) nozzle at supersonic exhaust velocities (ref. 8) are plotted in figures 20(a) and 20(g). Thus, as for subsonic flow, the comparison shows the need for care in using model jet sound pressure spectra to predict large-scale turbojet engine sound pressure spectra.

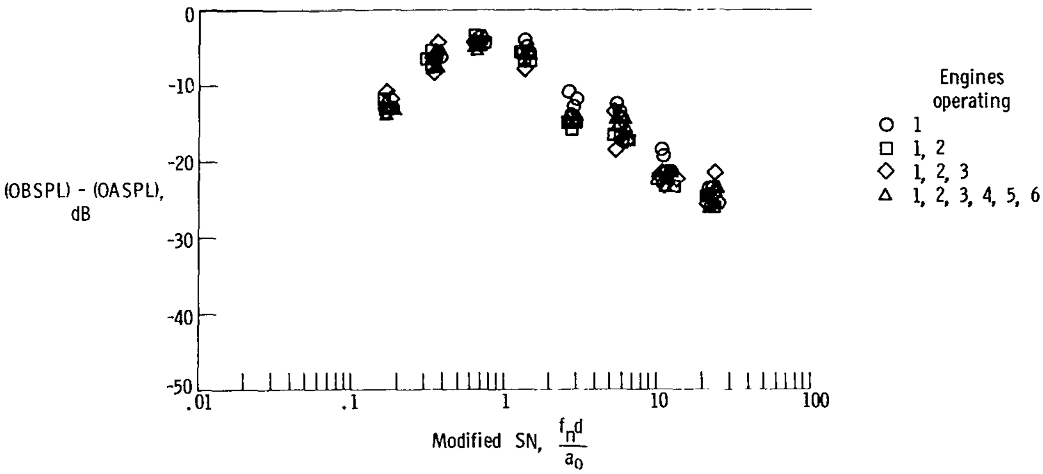


(a) 90°.

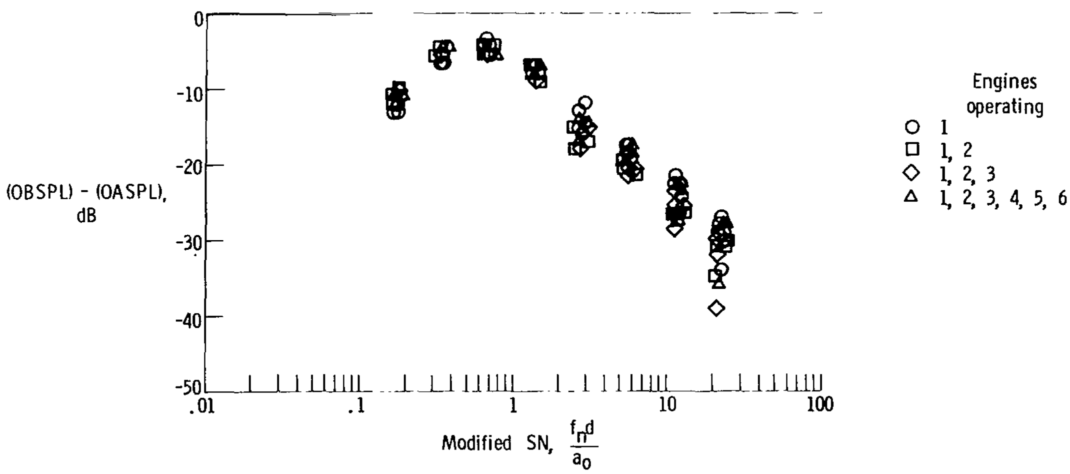
Figure 20. Octave band spectrum as function of modified Strouhal number at 500 feet (152 meters) for one, two, three, and six engines operating when V_R was supersonic.



(b) 100°.

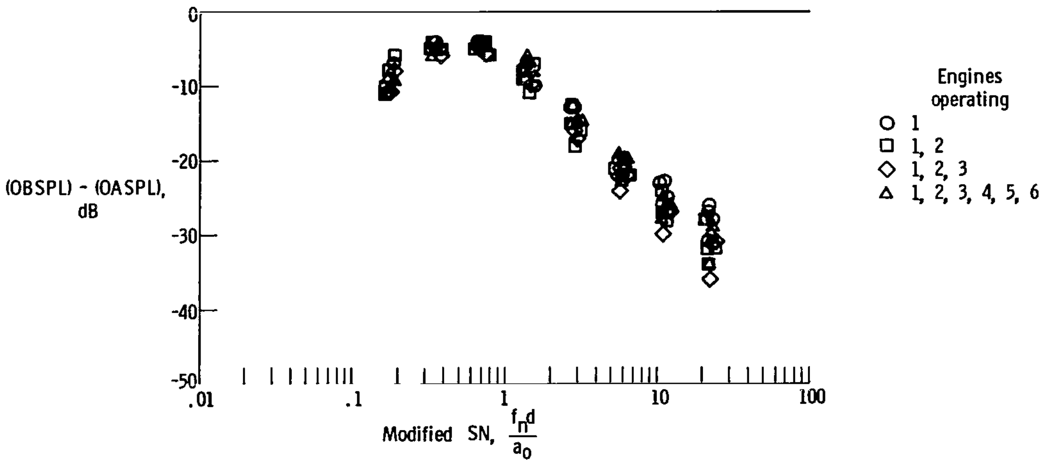


(c) 110°.

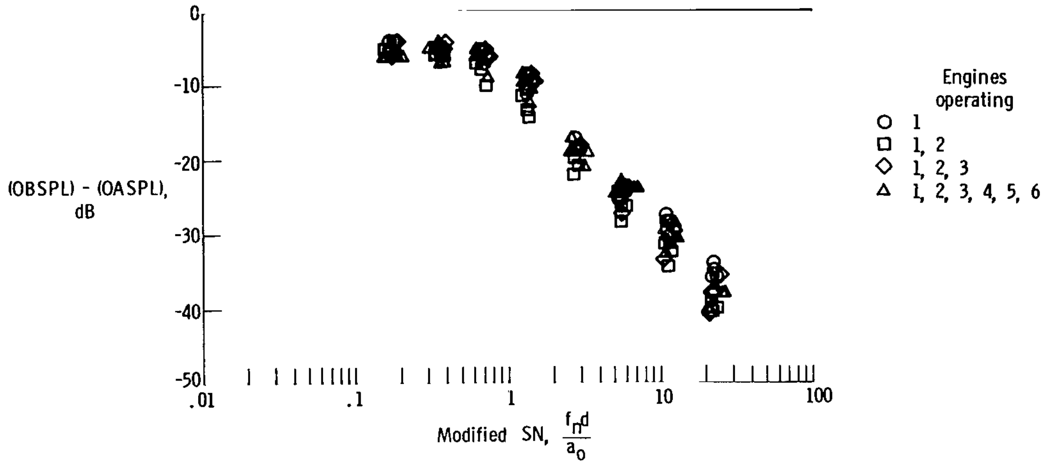


(d) 120°.

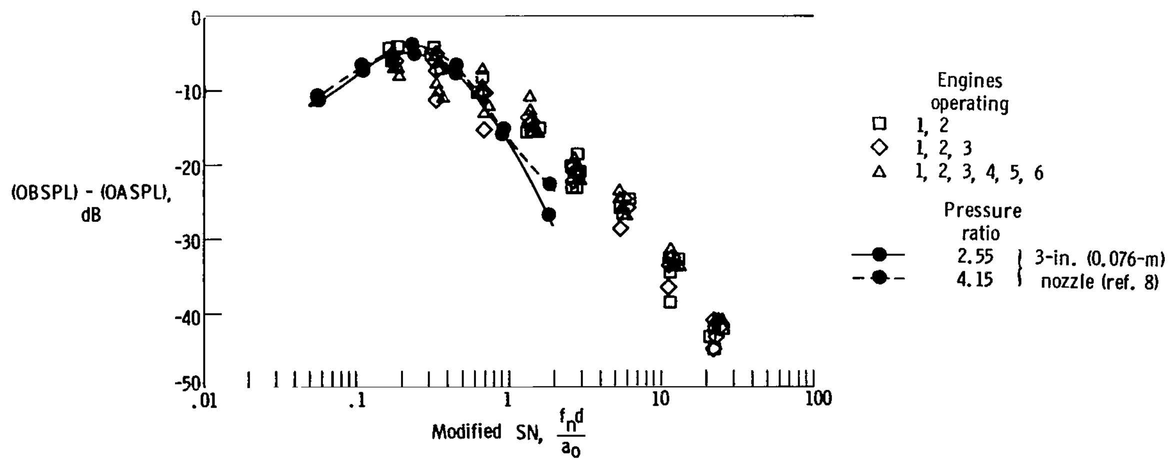
Figure 20. Continued.



(e) 130°.



(f) 140°.



(g) 150°.

Figure 20. Concluded.

CONCLUDING REMARKS

Measurements were made of engine exhaust noise during ground operation of the XB-70 airplane. These measurements were obtained in the left rear exhaust quadrant and at a radius of 500 feet (152 meters) from the intersection of the aircraft centerline and exhaust nozzle plane for various engine combinations and power settings.

The direction of propagation of maximum sound pressure level and perceived noise level was shown to move from 135° to 120° from the airplane's heading as the jet velocity increased and as the number of adjacent engines operating increased.

The measured overall sound pressure levels as a function of jet-exit velocity agreed best with the SAE-predicted levels at an angle of 120° for exhaust velocities between 1500 feet/second (457 meters/second) and 3000 feet/second (914 meters/second).

The effect of engine spacing on the overall sound pressure level at 90° was negligible, but, as the angle between the microphone position and the exhaust axis decreased, the noise level increased as the distance between engines increased, particularly for the larger exhaust velocities. Engine spacing appeared to have no effect on the spectra for subsonic exhaust flow. When two or more adjacent engines were operated in supersonic exhaust flow conditions, the exhaust flow of the near side engine shielded the high frequencies generated in the other exhaust flow(s).

The use of Strouhal number as a spectral scaling parameter appears to have limitations for estimating turbojet sound pressure level spectra from model jet spectra for both subsonic and supersonic exhaust flow. The SAE method, which is based on Strouhal number, adequately estimated the noise spectrum of the XB-70 airplane with subsonic exhaust flow for single- or multi-engine operation and underestimated the high-frequency spectral levels (Strouhal number > 4) for supersonic exhaust flow.

The best correlation of the data for different engine operating conditions with supersonic flow was obtained by using a modified Strouhal number based on the speed of sound in the atmosphere. This indicates that the noise spectrum shape was independent of the jet exhaust velocity for this engine with supersonic exhaust flow.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., September 10, 1970.

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