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INVESTIGATION OF JET-ENGINE NOISE REDUCTION BY SCREENS LOCATED TRANSVERSELY ACROSS THE JET

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SUMMARY

An investigation of screens placed transversely across the jet as a noise-reduction device was conducted on a full-scale turbojet engine to determine the effect on the sound field of screen mesh, wire diameter, and screen location. The investigation showed that the screens, when properly placed, lower the noise level in the area downstream of the jet exit and increase it upstream. The power level radiated by the engine can be lowered more than 7.5 decibels and, since the sound field is nearly circular, is essentially nondirectional. The maximum sound pressure level for an engine-screen combination can be made about 12 decibels less than that of the engine alone. The screen position is critical, and in certain positions very undesirable resonance noises are obtained.

The back pressure of a properly located screen on the engine is negligible and permits operation at rated engine conditions. The thrust loss of the system is prohibitively large for flight installation, but the system offers considerable promise as a low-cost, portable, ground run-up noise-reduction device.

INTRODUCTION

The reduction of noise generation by jet engines has been the subject of considerable research (refs. 1 to 4), but as yet no noise-reduction device has been found that is effective in all respects and can be applied directly to the engine. For particular applications such as test cells, known acoustic techniques can be applied that greatly reduce the sound level leaving the test cell. The lack of any generalized technique for the reduction of jet noise suggests that, at present, it may be more effective to treat separately each noise problem, that is, airports, aircraft carriers, test cells, and so forth, and attempt to alleviate the most troublesome aspects of each.

A recent investigation with a 1-inch-diameter air jet (ref. 4) has shown that a considerable reduction in sound pressure[1] at an angle of 40° from the jet axis (downstream) can be achieved by means of screens mounted normal to the jet flow near the jet exit. Since most of the total acoustic power generated by a jet engine is radiated rearward, considerable noise reduction in the most critical direction (approximately 30° to 40° from the jet axis) may be possible. The results of reference 4 show that the screen, when properly placed, reduced the lower-frequency components of the noise more than the higher-frequency components. This device therefore offers considerable promise for jet-engine noise reduction since the greatest portion of the energy is at the low frequencies. At present, however, the frequency distribution of jet-engine noise cannot be predicted from air jet data, and any effects of the screens on the sound spectrum can only be determined from a full-scale engine investigation. It is evident that screens might prove useful for jet-engine noise reduction in certain specific applications such as engine ground run-up or carrier catapult launching of aircraft and may provide sufficient sound reduction without additional muffling equipment. In addition, the possible elimination of the low-frequency portion of the sound spectrum would greatly reduce the cost of muffling for either ground run-up or test cells if additional sound reduction is necessary. Furthermore, the screens offer a means of noise reduction which may possibly be lightweight, small, and easily portable.

The investigation reported herein was conducted at the NACA Lewis laboratory on a full-scale engine in order to determine the effect on the sound field of screen size and location.

APPARATUS AND PROCEDURE

The engine and screens used in this investigation were mounted on a thrust stand as shown in figure 1. The area where the stand is located is unobstructed rearward and to the sides for over 1/2 mile. The nearest reflecting surface other than the control room was located approximately 600 feet in front of the thrust stand. The reflective effects from the control room should be extremely small at all the measuring stations shown in figure 2, because no measuring stations are close to the building and because of the small size of the building and the angle at which it is located. Measurements of the over-all sound pressure level were made approximately 5 feet above ground level at 15° intervals from the jet axis and at 100 and 200 feet from the jet exit as shown in figure 2.

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[1] The meaning of the acoustic terms in this report can be found in many texts. For purposes of standardization the nomenclature (sound pressure, sound pressure level, power level, and spectrum level) used herein is that of reference 5.

Sound-pressure-level measurements were made with a General Radio Company Type 1551-A Sound-Level Meter. The frequency spectrum was measured on the 200-foot radius at azimuth angles of 30°, 90°, and 180° (fig. 2) simultaneously with the over-all field survey. Each set of measurements required approximately 9 minutes. The frequency distributions were measured with an automatic audio-frequency analyzer and recorder (Bruël and Kjaer Audio Frequency Recorder Type 2311 and Condenser Microphone Type 4111). The frequency range of this system is from 35 to 18,000 cps and is divided into 27 one-third octave bands. The spectrum recorder and related equipment were mounted in a specially adapted, insulated, panel truck. Before each test both the sound-level meter and the frequency-recorder system were calibrated with a General Radio Company Type 1552-A Sound-Level Calibrator.

The jet engine used in this investigation was an axial-flow engine with a rated sea-level static thrust of 5000 pounds at rated engine speed (7950 rpm) and rated tail-pipe temperature (1275° F). Under these conditions the total- to static-pressure ratio across the nozzle exit was approximately 1.7. For all the tests the engine was operated at rated conditions, and for each screen size and position the engine air flow, thrust, and fuel flow as well as the sound data were measured.

The screens used in the investigation were mounted in a special three-pronged holder (fig. 1). This holder was attached to the bedplate of the thrust stand and permitted measurement of the net thrust of the engine-screen combination. The screens were bolted between two rolled angle sections of approximately 44-inch inside diameter. In addition, each screen wire was welded to the face of the downstream section. The screen position downstream of the jet exit was adjustable in 3-inch increments from approximately 0 to 60 inches. The screen sizes investigated are given in table I.

The test procedure for each screen configuration was begun with the screen placed as close as possible to the jet exit, and then the tail-pipe temperature and engine speed were checked. If the screen blockage was sufficient to cause rated tail-pipe temperature at less than rated engine speed, the screen was moved downstream (3 in.) to the next position and the engine operation rechecked. In general, the engine could be operated at rated conditions for screen positions 6 or more inches downstream of the jet exit.

The total acoustic power generated by a jet engine is radiated in all directions. This acoustic power can be calculated from the measured sound pressure levels by the following procedure. For purposes of calculation the engine is assumed to be surrounded by a spherical control surface through which passes all the radiated power (fig. 3). The origin of the spherical surface is located at the center of the engine exit. Since the sound-pressure-level measurements are made at a height closely corresponding to that of the engine, the radius of the sphere corresponds to the measuring-station radii of figure 2, that is, 100 or 200 feet. The following two assumptions can be made about the sound field:

(1) The ground plane acts as a perfect reflector.

(2) The sound field is symmetric about the jet axis.

Unpublished data have shown both of these assumptions to be reasonably correct. Measurements of reflection from both the concrete and the hard-packed grassy surface around the engine have shown little absorption. The rotational symmetry of a jet sound field has been verified with a 4-inch air jet. Because of the preceding assumptions and since measurements are made every 15° about the jet exit (fig. 2), the sound pressure level is used as a constant over a 15° interval with its midpoint at the measuring station. Such a zone of constant sound pressure level is illustrated in figure 3. The sound power W_s passing through a zone of area S can be calculated by means of the following equation:

$$W_s = \frac{372}{\rho c} S \times 10^{-14} \text{ antilog} \left(\frac{\text{SPL}}{10}\right), \text{ watts}$$

where

SPL sound pressure level, db (re 2×10^{-4} dyne/sq cm)

ρ density of ambient air, g/cu cm

c speed of sound in ambient air, cm/sec

S area, sq ft

The total acoustic power W radiated by the engine is the summation of the power passing through each zone of area S associated with a particular measuring station, that is, $W = \Sigma W_s$. The power level PWL of the source is defined as

$$\text{PWL} = 10 \log_{10} \left(\frac{W}{W_0}\right), \text{ db}$$

where W_0 is a reference power of 10^{-13} watt. The values of PWL calculated from the 100- or 200-foot-radius measurements agree within 1 decibel for each test condition.

RESULTS AND DISCUSSION

Total acoustic power. - The total acoustic power radiated by the engine both with and without screens is shown in figure 4 where the power level is plotted as a function of screen position for all the screens investigated. The power levels are the averages of values calculated for the 100- and 200-foot radii. The power levels for the engine with screens generally fall below the power level of the engine alone. In most cases the minimum power level was obtained with the screen located at a point 6 to 17 inches downstream of the jet exit. Screen C, however, gave nearly uniform power levels for all screen positions as far downstream as 27 inches from the jet exit; in fact, the minimum sound power level occurred at that point. The somewhat oscillatory nature of the curves was due to resonance noises which varied in strength as a function of screen position, as will be discussed in the section Sound spectra. Figure 4 indicates that a properly located screen can reduce the sound power level 7.5 decibels or more compared with the engine alone.

It has been shown (ref. 1) that jet-engine noise generation at take-off conditions results principally from the turbulent mixing of the jet with the surrounding medium. The total acoustic power generated by such mixing increases directly with jet area and a high power (near 8) of the exit jet velocity (refs. 1, 6, and 7). Obviously, reducing the jet velocity should produce large noise reductions. The noise-reduction effect of the screen largely results from the reduction of velocities in the jet downstream of the screen. A measure of the effective velocity downstream of the screen can be obtained by dividing the net thrust of the engine-screen combination by the engine mass flow.

In figure 5 the minimum sound power level[2] is plotted as a function of effective velocity for all the screens investigated. A single curve may be drawn through these data, but these results are valid only for the particular conditions investigated. If the jet-exit conditions are changed (i.e., velocity and density), other curves might be obtained. For engineering purposes these data are probably sufficiently accurate, since all jet engines (at rated conditions) operate at fairly similar values of jet velocity and density.

Therefore, to a first approximation, the minimum sound power level associated with an engine-screen combination is dependent only on the effective velocity downstream of the screen. The screen mesh and solidity appear to affect the correlation through their influence on effective velocity only.

The relation given by the results of figure 5 shows that sound power generated by the engine-screen combination is a function of the effective velocity raised to a low power (approximately 1.7). Also shown on the

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[2] The minimum power level refers to the particular screen position that radiates the smallest acoustic power as determined from figure 4.

figure is a curve which shows the sound power level that would be expected from a jet with an area equal to the tail-pipe area and issuing into the atmosphere at the effective velocity (eighth-power law). The rather large difference between the two curves results from either or both of two factors: (1) noise generated upstream of the screen, and (2) noise generated by the screen. References 4 and 8 have shown that the major portion of the jet noise originates in a region at least several jet diameters downstream of the jet exit. Therefore, the amount of noise generated between the jet exit and the screen apparently is fairly small. The principal factor in changing the velocity exponent would therefore appear to be the screen-generated noise.

Possibly, reducing the screen noise generation by using properly shaped airfoil sections instead of wires (e.g., ref. 9) would improve the effectiveness of the screens.

A close inspection of the data of figure 5 shows that both screens E and F produce equal sound power levels even though the effective velocity associated with screen F is somewhat less than that associated with screen E. Any further decreases in effective velocity might not produce further decreases in minimum sound power level. Certainly some minimum value would be expected, since the screen resistance spreads the jet and hence bends it outward. As screen resistance is increased, the quantity of gas bent parallel to the screen increases. In fact, at a solidity of unity all the gas would be turned outward at nearly undiminished velocity. This condition would probably result in as much noise as that caused by the unobstructed jet. There is, therefore, some optimum screen resistance which reduces the jet velocity without bending the flow to the extent that a large portion of the flow is parallel to the screen.

It is evident from figure 5 that the fine-mesh screens (C, D, E, and F) give much more noise reduction than the coarse-mesh screens (A and B). Furthermore, the lower-solidity screen (screen A) gives less noise reduction than the screen with the same mesh but higher solidity.

Sound spectra. - The spectrum of the sound radiated from the combination of the engine and screen C is shown in figure 6, where the spectrum level is plotted as a function of frequency for several screen positions. The data shown were obtained at the 200-foot radius at azimuth angles of 30° (fig. 6(a)) and 180° (fig. 6(b)) and are typical of all the screens investigated. Also shown in the figures, as a reference, is the sound spectrum of the engine alone.

For an azimuth angle of 30°, screen C shows a definite reduction of sound level from that of the engine alone at frequencies less than 2000 cps except when a strong resonant condition was obtained at approximately 350 cps. All the screens investigated produced resonance noises when located aft of the initial resonance position. The general trend (fig. 6) indicates increasing resonance strength with increasing distance downstream. However, the resonance strength oscillates somewhat from point to point, increasing then decreasing in a manner such that maximum resonance intensities are obtained only at certain critical positions (fig. 4). At these positions the peaks show increasing energy with increasing distance downstream, and between the peak values the resonance decreases to a minimum.

The strength of the resonance at several positions was such that considerable fatigue damage occurred to the screens, and it was necessary to terminate the tests at less than the full distance available. This was particularly true of screens E and F, which suffered considerable wire breakage as soon as a strong resonance appeared. From a structural standpoint, the larger-diameter wire screens (0.250 in. or greater) did not deteriorate appreciably, and only a few wires were found to be broken at the conclusion of the tests.

At an azimuth angle of 180° (fig. 6(b)) nearly all the spectra with screens are somewhat above the spectrum for the engine alone. The trend of the curves with increasing distance downstream of the jet exit is, in general, quite inconsistent except for the increasing strength of the resonance at a frequency of approximately 350 cps. The spectra show an increase in the sound energy at the higher frequencies (above 200 cps) as compared with the engine alone. Changes in frequency distribution of this nature are extremely difficult to evaluate from the standpoint of human response. If the spectra of the engine alone and the engine with screens (27-in. position) are compared with the usual Fletcher loudness-level curves for the ear (ref. 10), it can be shown that spectrum shift does not appreciably increase the apparent loudness. This results from the rather flat response of the human ear at high intensities. At lower sound intensities, that is, greater distances from the source than 200 feet, it might be expected that the shift in sound energy to the higher frequencies would result in an increase in the apparent loudness (ref. 10). However, the effect of sound absorption (both meteorological and terrain), which increases with increasing frequency, would probably offset the shift in frequency distribution. In general, however, it is extremely difficult to extrapolate to large distances from a sound source, since the effects of wind, temperature gradient, and terrain are extremely large.

The effect of screen size, that is, mesh and wire diameter, on the frequency spectrum is shown in figure 7, where the spectrum level is plotted as a function of frequency for all the screens investigated. The particular point chosen for comparison is the position at which the minimum power level was obtained (as determined from fig. 4). The spectrum of the engine without screens is also shown for comparison. The minimum power condition was chosen because it is the position at which the screen would be placed for practical applications. The results obtained at the 200-foot radius at azimuth angles of 30° and 180° are shown in figures

7(a) and (b), respectively. At an azimuth angle of 30° the spectrum levels with screens are, in general, less than for the engine without screens. There does not appear to be any appreciable shift or change in the shape of spectrum distribution due to the screens except for an increase in the relative amount of energy at frequencies above 3000 cps. This effect, however, would not appear to be significant, since most of the sound energy exists in the low-frequency region (less than 300 cps). A comparison of these curves with the Fletcher curves (ref. 10) shows no increase in apparent loudness resulting from the altered distribution. At an azimuth angle of 180° the spectra for the engine with screens appear quite flat over a considerable frequency range, that is, 40 to 2000 cps. This result should not be objectionable for the reasons given previously in discussing figure 6(b).

At an azimuth angle of 90° the sound pressure level and the frequency spectrum of the engine alone and the engine with screens (at the screen position for minimum sound power) are nearly the same.

In general, therefore, it may be concluded that, from the standpoint of human response, the shapes of the sound spectra radiated by the engine both with and without screens are not greatly different. However, for acoustic muffling, there may be some differences between the engine alone and with screens as illustrated in figure 8. In this figure the percentage of the total energy in each frequency band is presented for the engine alone and for the engine with screen C at the minimum-power-level position. Results are shown for azimuth angles of 30°, 90°, and 180°. Considerable differences exist in the distribution of the sound intensity with and without screens. At the 30° position most of the energy for the engine with screen C occurs at frequencies below 100 cps with a large decrease in energy between 70 and 200 cps as compared with the engine alone. There is also somewhat of an increase in the energy at frequencies above 1000 cps. At the 90° position there are no large changes in the energy distribution. At the 180° position the energy decreases considerably at frequencies below 400 cps and increases considerably above 1000 cps. It appears, therefore, that a larger percentage of the total energy (engine with screens) exists at higher frequencies (above 1000 cps). There is still, however, a considerable amount of low-frequency energy (below 100 cps). The principal reduction in the sound energy occurs between 100 and 500 cps.

Directional effects. - The directional effects of the screens as a function of screen position are illustrated by the polar diagrams of the sound fields at the 200-foot radius for screen C (fig. 9). Also shown on the figure for purposes of comparison is the polar diagram of the sound field for the engine without screens. The over-all effect of the screen, without regard to position, is to lower the sound pressure level downstream of the jet exit and raise it upstream as compared with the engine alone. The effect of increasing screen distance from the tail pipe is rather small in the rear quadrants but quite marked in the front quadrant where the sound pressure level increases quite rapidly. This result agrees with the general trend of increasing power level with increasing distance of the screen from the exit as previously discussed (fig. 4). It is interesting to note, however, that the increase in power level results largely from increasing sound pressure levels in front of the engine.

The effect of the screen on the sound field is quite marked (fig. 9). At the 15-inch position there is a reduction in sound pressure level of approximately 14 decibels at an azimuth angle of 30° as compared with that of the engine alone. Moreover, a comparison of the highest sound pressure level of the engine-screen combination (15-in. position) with that of the engine alone shows a decrease of 12 decibels. This decrease in maximum noise level is extremely desirable since it ameliorates the directional effects of the engine noise to a great degree.

The polar diagrams of the sound fields for each screen size are shown in figure 10 for the 200-foot radius at the minimum-power-level condition, that is, the screen position giving the smallest radiated total acoustic power.

The results for screens C and D are shown in figure 10(a) along with a reference sound polar diagram of the engine without screens. The sound polar diagrams for screens E and F are shown in figure 10(b). These figures indicate that there are no really significant differences in the sound fields of screens C to F. There is some asymmetry in the rear quadrants due to wind, and this condition was noted throughout the investigation. After passing through the screen, the jet was strongly affected by the prevailing wind even though all the tests were conducted at wind velocities less than 10 feet per second. Even at these low wind velocities the jet appeared to be dissipated and blown away very rapidly. This was probably caused by the large decrease in jet velocity and jet energy due to passage through the screens.

For all four screens the sound pressure levels in the downstream quadrants are much less (approximately 12 db at 30°) than for the engine alone; there is somewhat of an increase in front of the engine (about 7 db at 160°). In any case, the maximum sound pressure level with screens (approximately 112 db at an azimuth angle of 160°) shows a considerable decrease over that of the engine alone (approximately 123 db at an azimuth angle of 30°). There is a slight tendency for the sound pressure levels to decrease with increasing screen mesh as might be expected from the results shown in figure 4. However, the effect is small with respect to the directionality pattern.

The results obtained with screens A and B are shown in figure 10(c). Screen B gives somewhat of a reduction in the sound pressure levels in the rear quadrants as compared with the engine alone but is not nearly so effective as screens C to F. Even though the screen solidity is approximately the same, the effective velocity and the power levels (fig. 5) are much larger. Screen A has a solidity of approximately one-half that of the other screens; this decreased solidity results in considerably higher sound pressure levels in the rear quadrants than occurred with the other screens. In the region ahead of the engine the lower-solidity screen shows smaller increases in the sound pressure levels than do the other screens, and, in fact, the results approach those for the engine alone.

Thrust of engine-screen combination. - As might be expected, the drag of the screen was large; hence, the loss in thrust of the engine-screen combination was also large. The following table lists the values of thrust obtained with the various screens for the condition of minimum sound power level. Also shown are the results for the engine alone.

Screen	Thrust of engine-screen combination, lb	Sound power level, PWL, db
A	3734	166.0
B	3080	165.2
C	2218	162.2
D	2186	162.4
E	2201	160.8
F	1613	160.9
None	5023	168.3

In general, the table shows a trend of decreasing thrust with decreasing sound power level as previously discussed (fig. 5).

SUMMARY OF RESULTS

As part of a program for the study of jet noise and means for its suppression, the sound field around an engine equipped with screens located transversely across the jet has been investigated and the following results obtained:

1. Screens located close to the jet exit lowered the sound power level radiated by the engine by as much as 7.5 decibels.

2. The sound fields of the engine-screen combination with the screen properly located showed that the noise level downstream of the engine was reduced by as much as 12 to 14 decibels with an increase of about 7 decibels in the front quadrant. The resultant sound field had no strong directional characteristics as exist with the engine alone.

3. The fine-mesh screens (i.e., 1, 2, 3, and 4 mesh) are much more effective noise suppressors than the larger-mesh (2-in. wire spacing) screens.

4. The screen position downstream of the jet exit is critical. At less than 6 inches from the jet exit, a back pressure on the engine was obtained and at further than 12 inches downstream certain screens produced resonant noises. The resonance sound powers were of sufficient strength to seriously damage the fine-mesh screens. In this respect, the large-mesh, large-diameter wire screens were much less critical.

5. The sound spectra radiated by the engine-screen combinations are different from that radiated by the engine alone. In general, there is a shift of energy from the middle frequencies (100 to 500 cps) to the higher frequencies (above 1000 cps). There is still considerable energy at low frequencies (less than 100 cps). The nature of these shifts is such that they would not be easily detectable by the human ear.

CONCLUDING REMARKS

Although the screens are effective noise suppressors, a considerable portion of the noise from an engine-screen combination is generated by the screen itself. The effectiveness of screens might be considerably increased by substituting properly shaped airfoils for wires.

From an over-all standpoint, the 1-mesh, 0.250-inch-diameter wire screen appeared to give the best compromise among noncritical resonance operation, structural integrity, and noise reduction. This screen produced no resonance as far as 27 inches downstream of the jet exit, caused a decrease in power level of approximately 6 decibels, and suffered little or no wire damage.

The loss in thrust with the screen in place is prohibitively large for a flight installation, but the system offers considerable promise as a low-cost, portable, noise-reduction device for use during ground run-up of engines either for airport or aircraft carrier operation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 14, 1955

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TABLE I. - SCREEN DIMENSIONS

Screen	Mesh (number of wires per in.)	Screen size		
		Center-to-center wire distance, in.	Wire diameter, in.	Solidity, $\frac{\text{Blocked area}}{\text{Total area}}$
A	1/2	2.0	0.250	0.234
B	1/2	2.0	.500	.437
C	1	1.0	.250	.437
D	2	.50	.125	.437
E	3	.333	.080	.422
F	4	.250	.063	.441

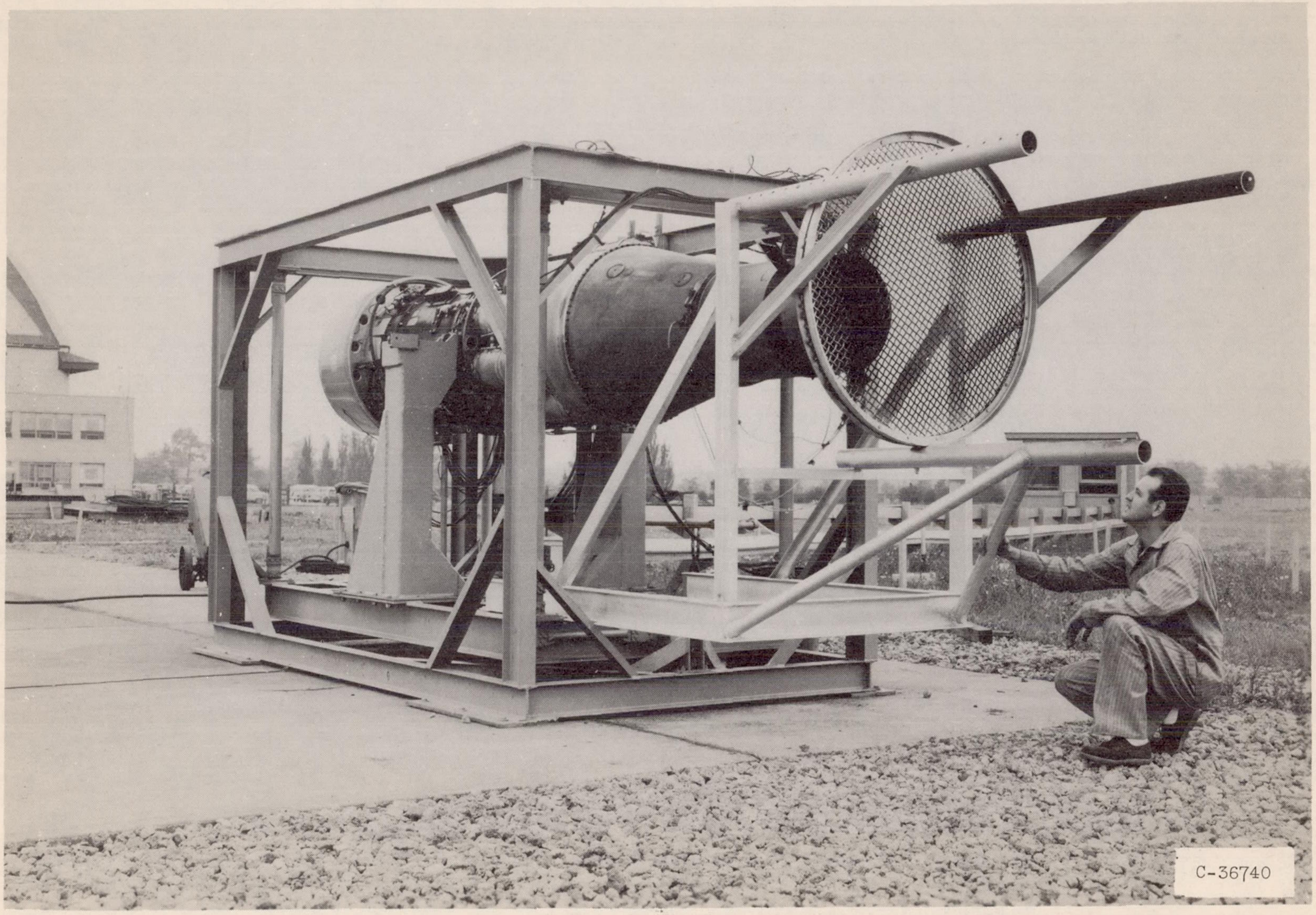


Figure 1. - Thrust stand showing screen mount.

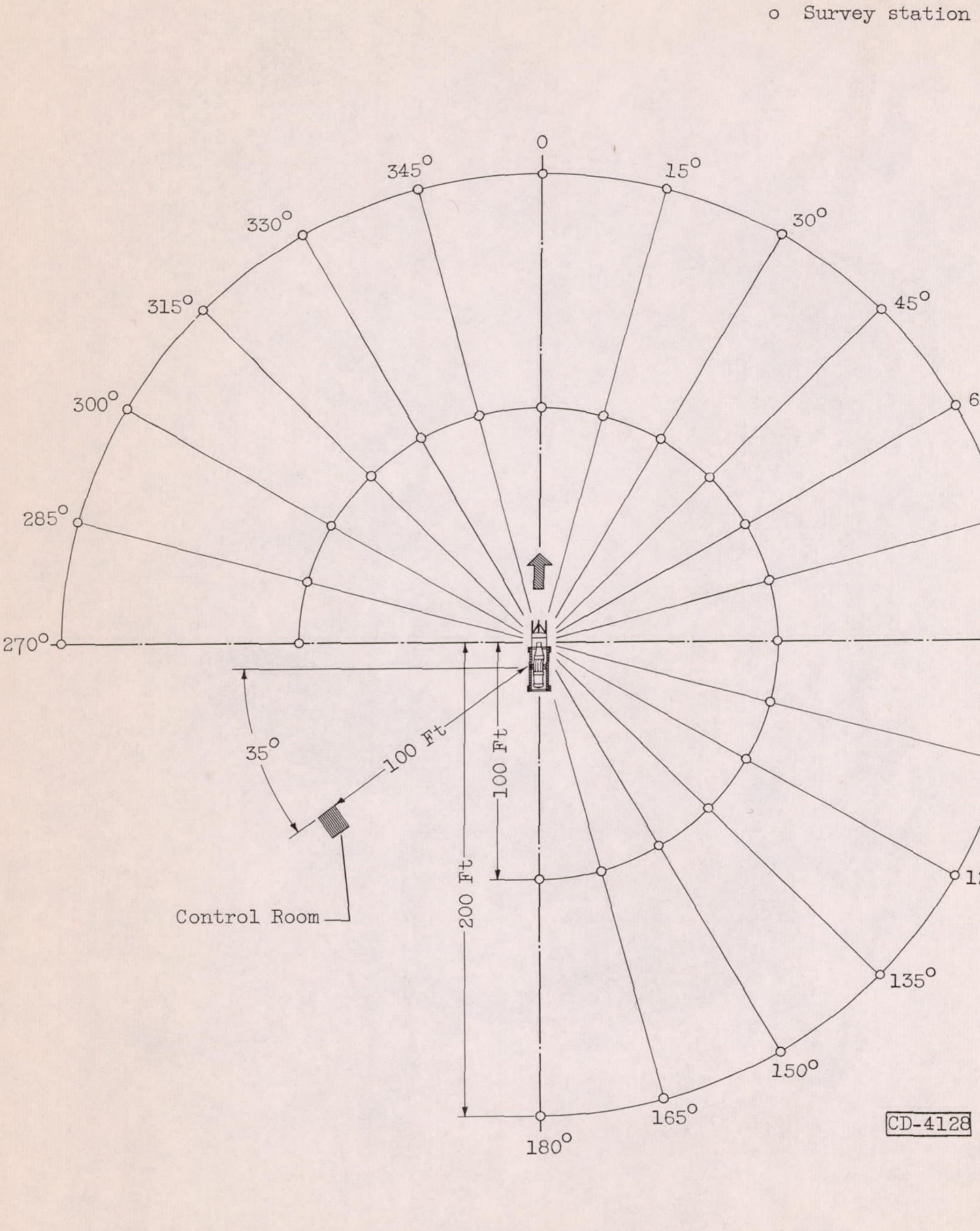


Figure 2. - Location of survey stations in sound field around engine thrust stand.

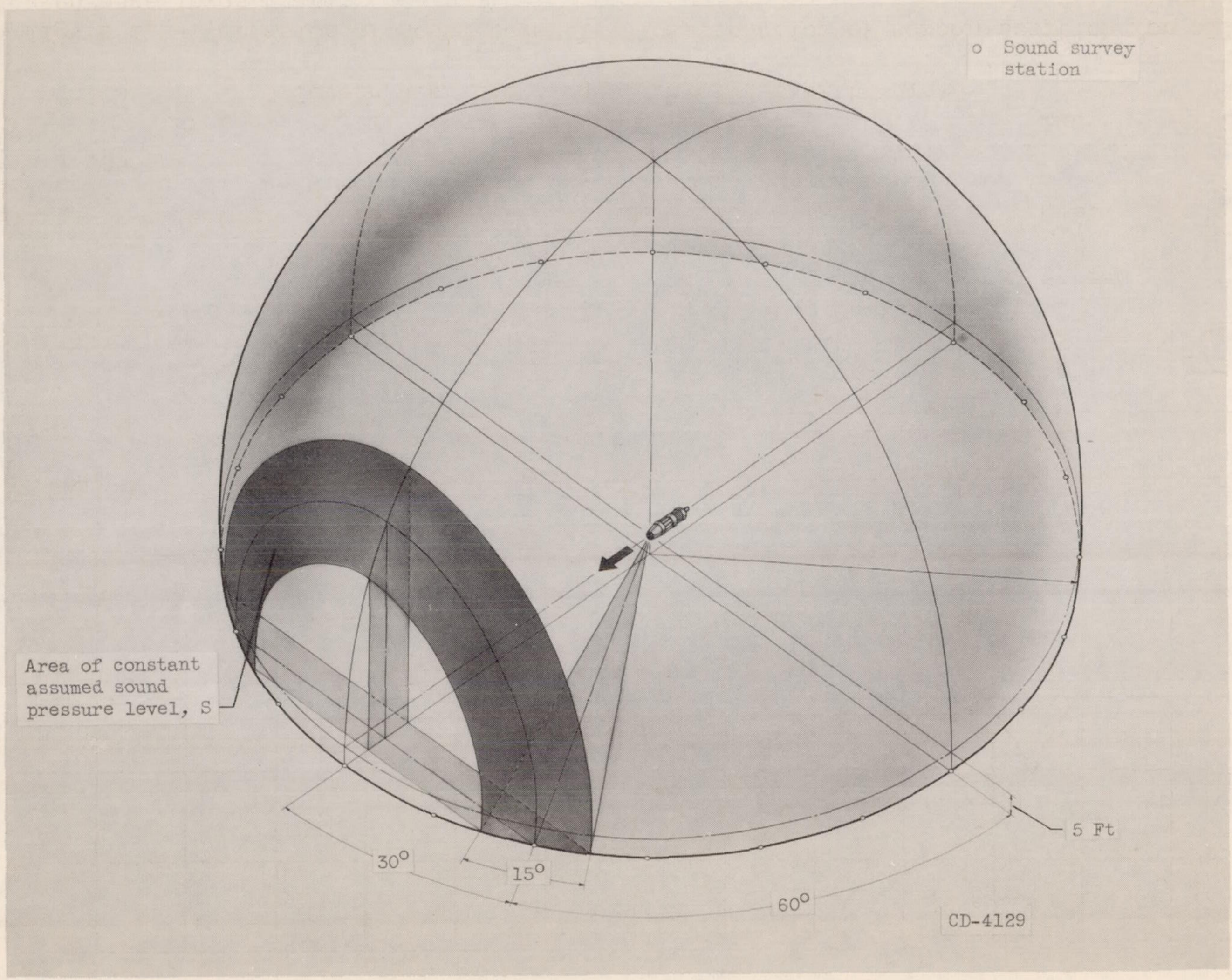


Figure 3. - Sketch illustrating surface used for calculation of sound power level radiated by engine.

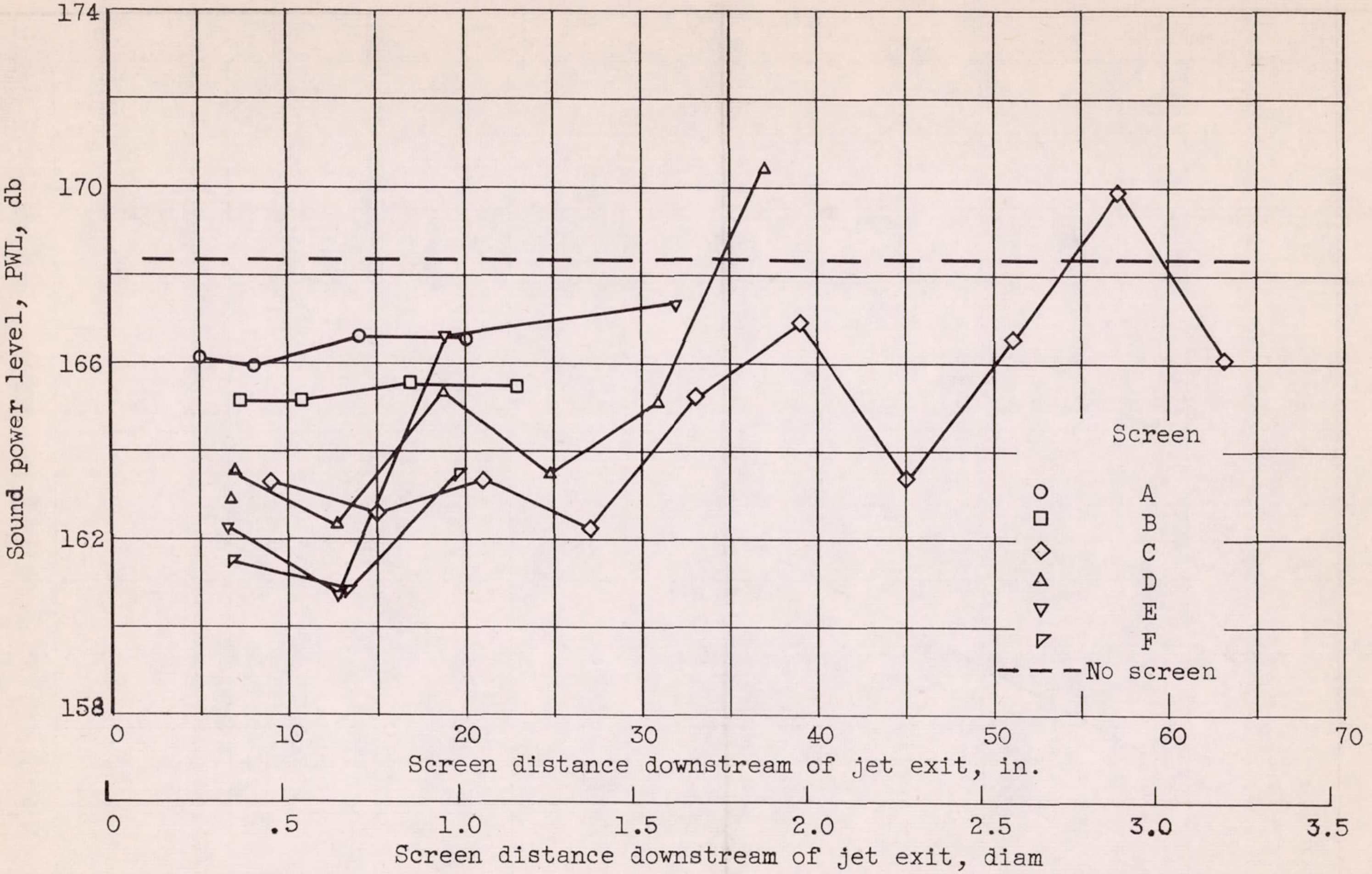


Figure 4. - Variation of sound power level as function of screen position for all screens investigated.

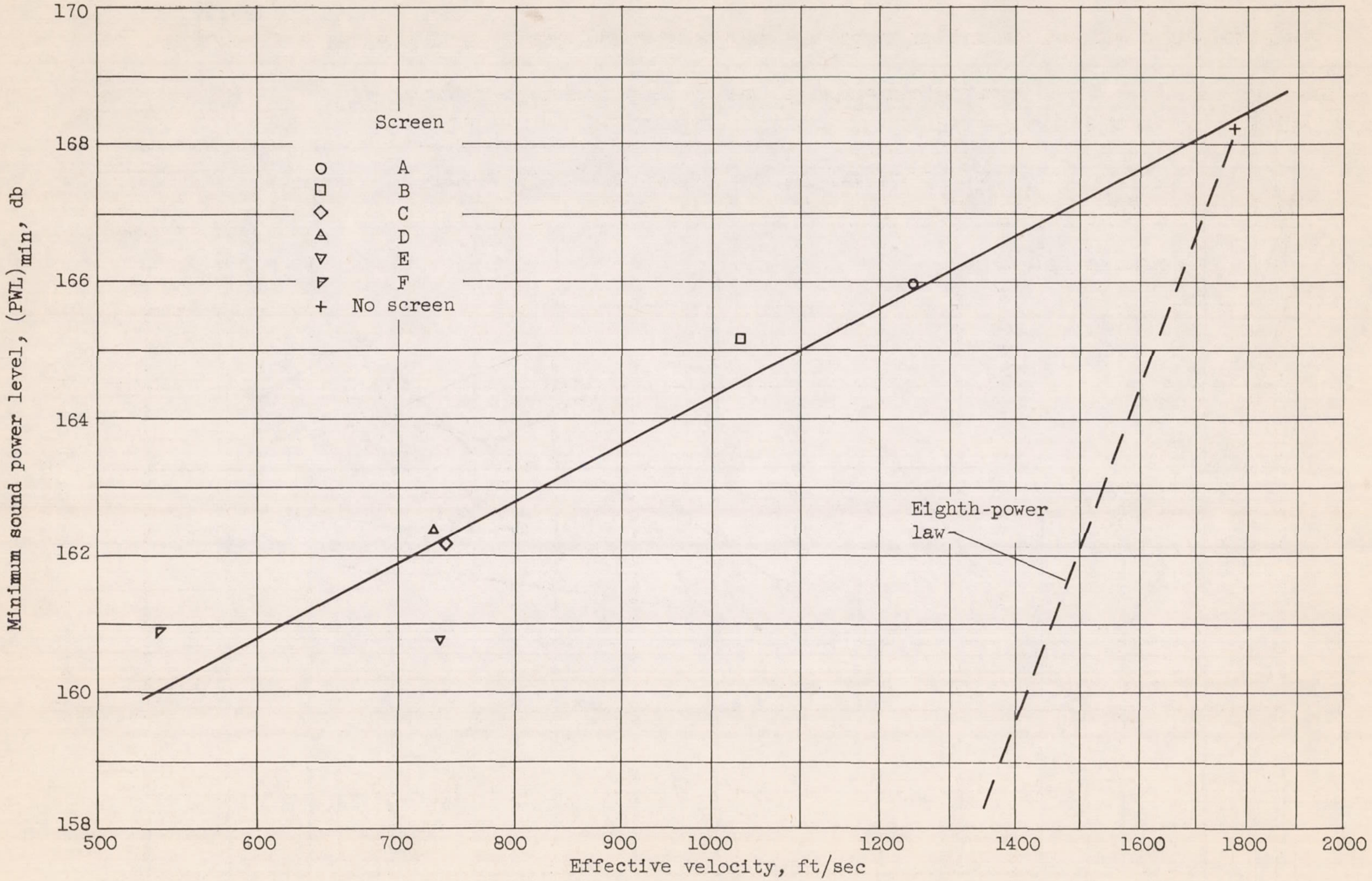
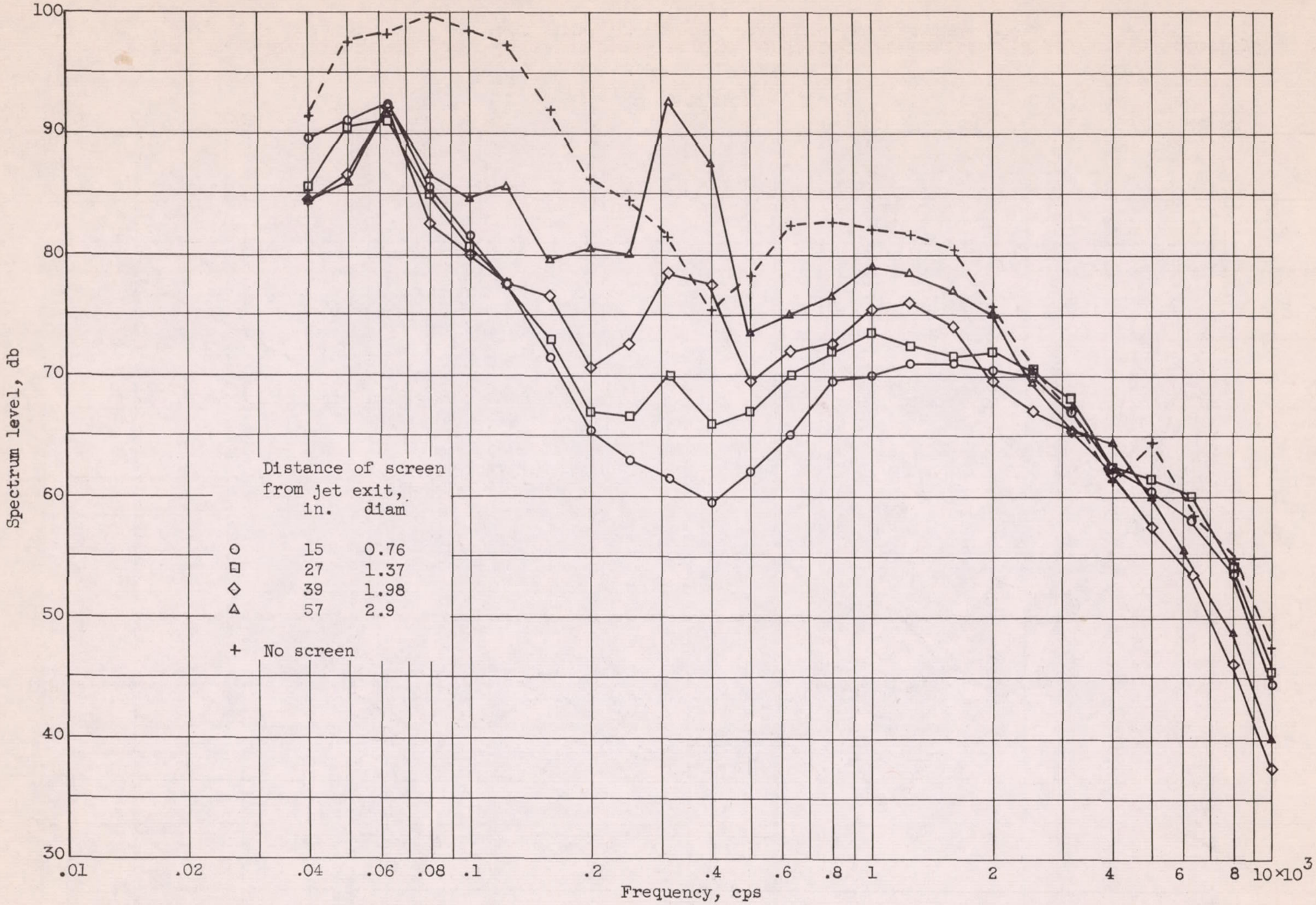
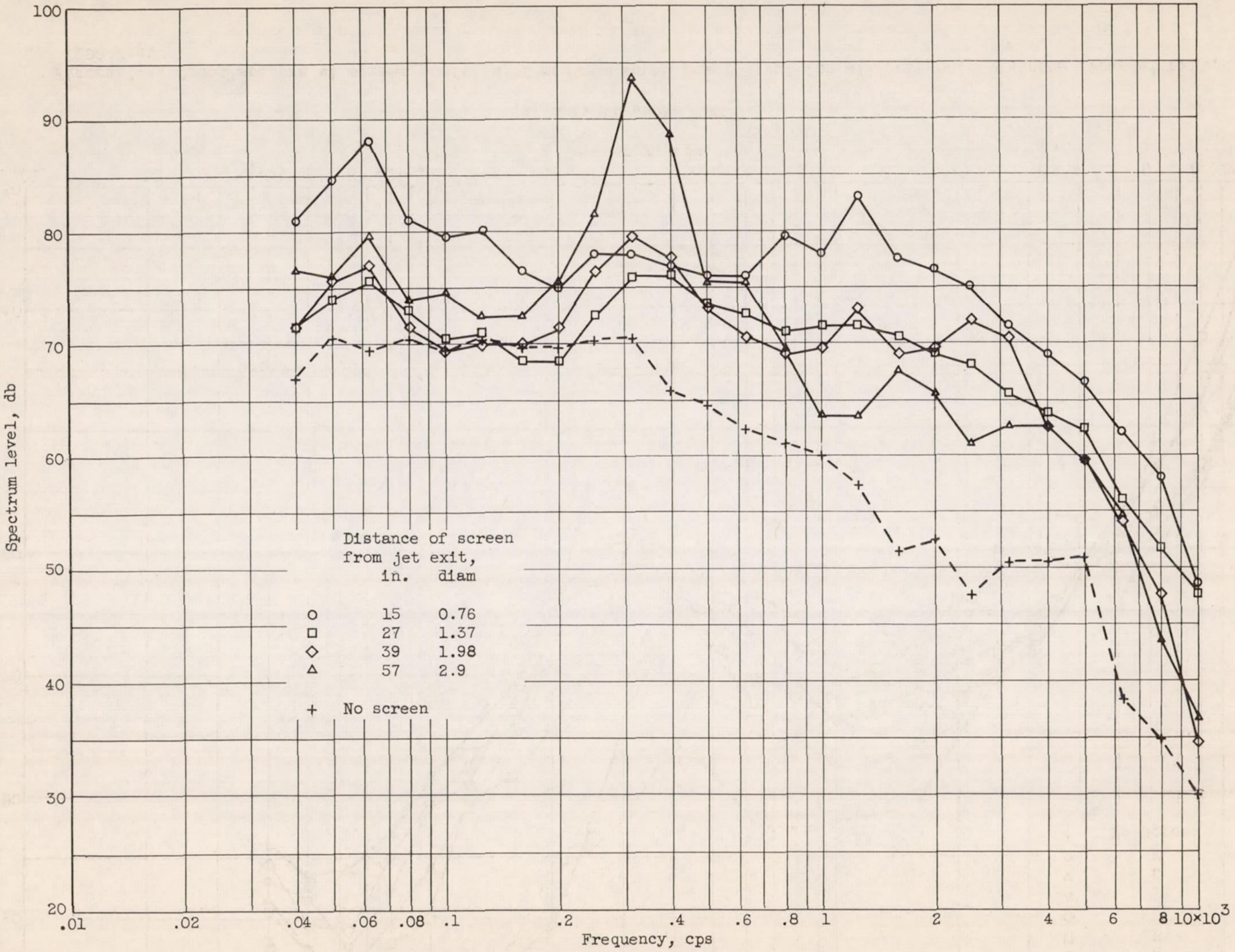


Figure 5. - Minimum sound power level at rated engine conditions as function of effective velocity.



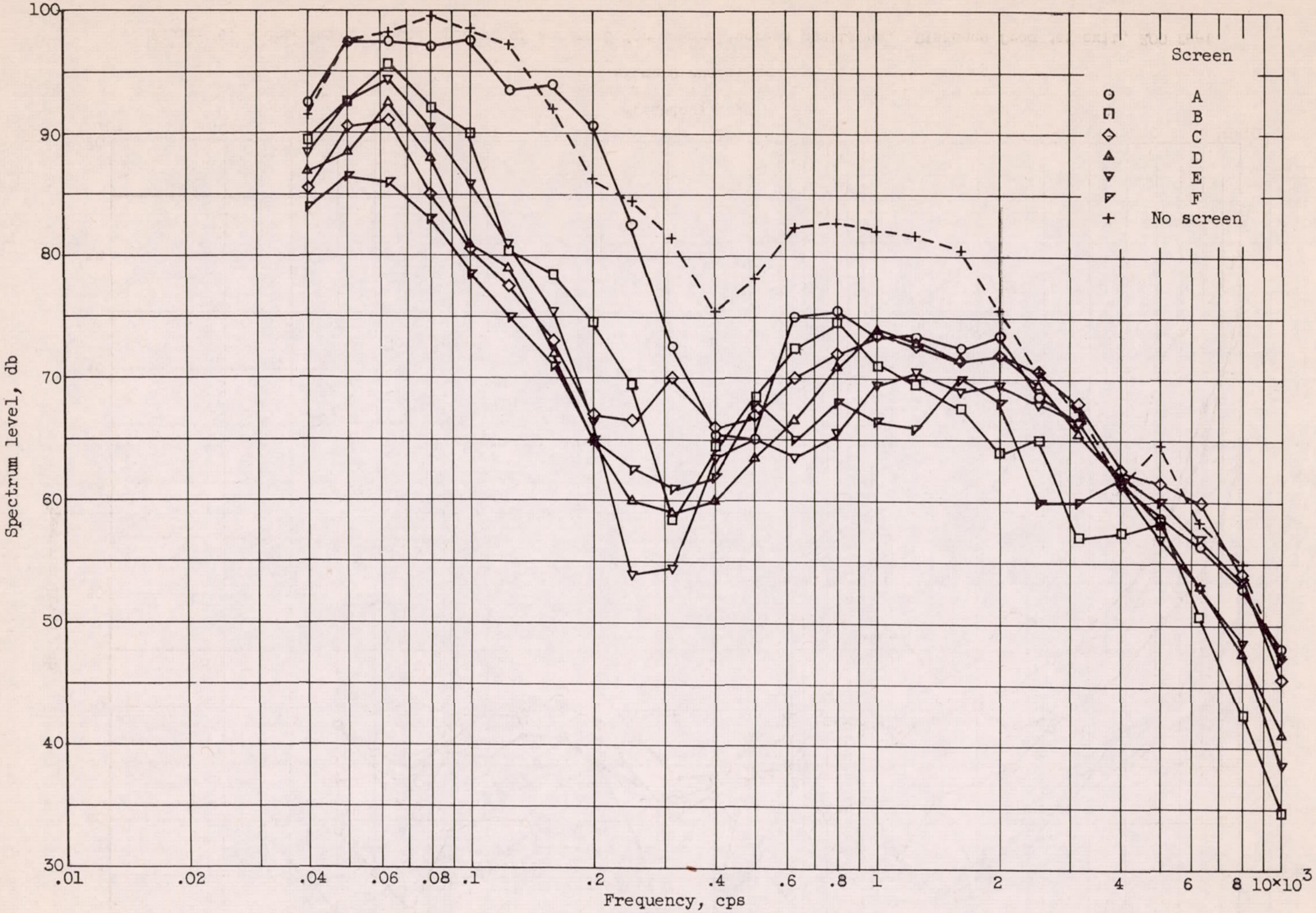
(a) Azimuth angle, 30°.

Figure 6. - Sound spectra of screen C for several screen positions. Distance from jet exit, 200 feet.



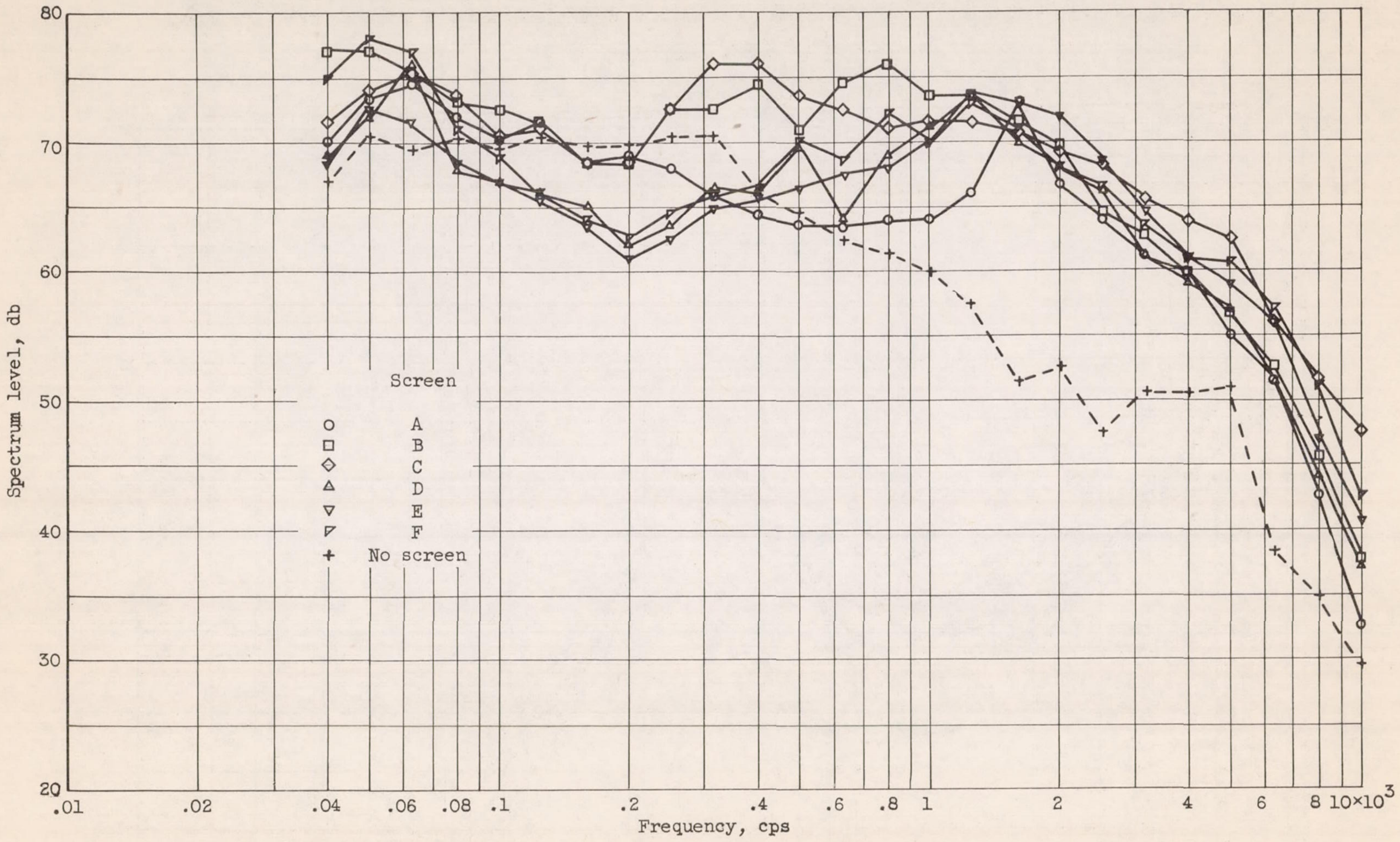
(b) Azimuth angle, 180°.

Figure 6. - Concluded. Sound spectra of screen C for several screen positions. Distance from jet exit, 200 feet.



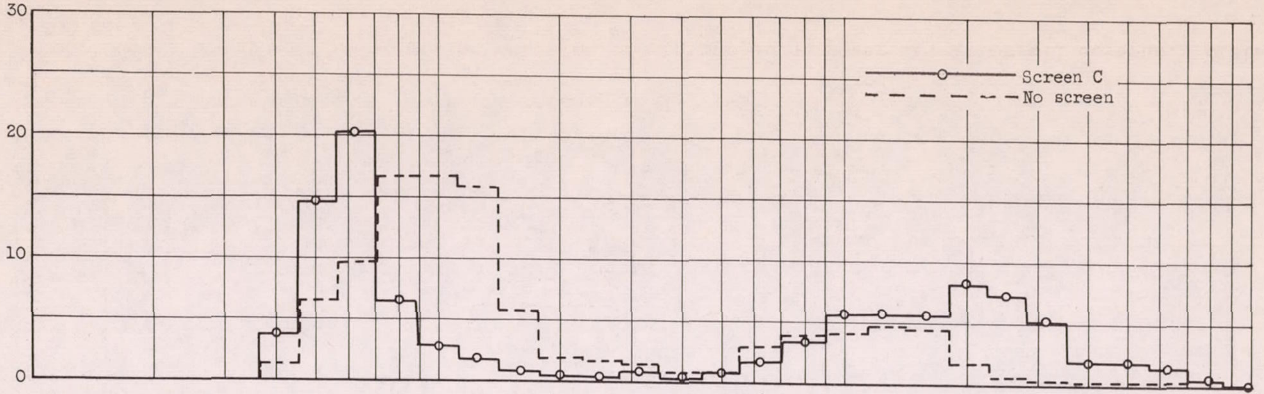
(a) Azimuth angle, 30°.

Figure 7. - Sound spectra at screen position of minimum sound power level for all screens. Distance from jet exit, 200 feet.

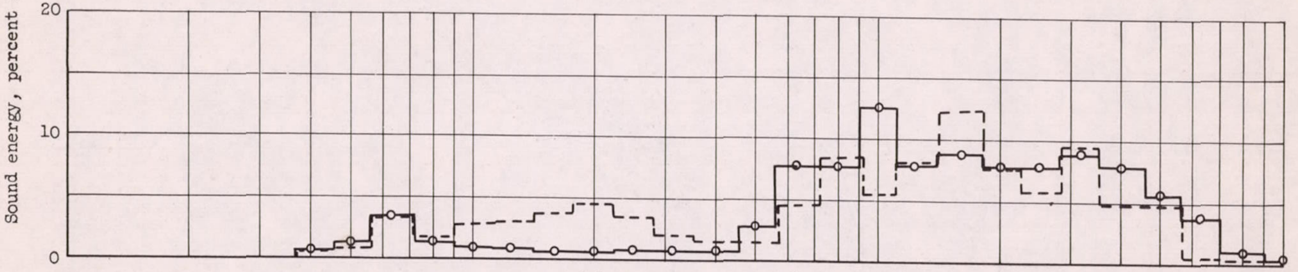


(b) Azimuth angle, 180°.

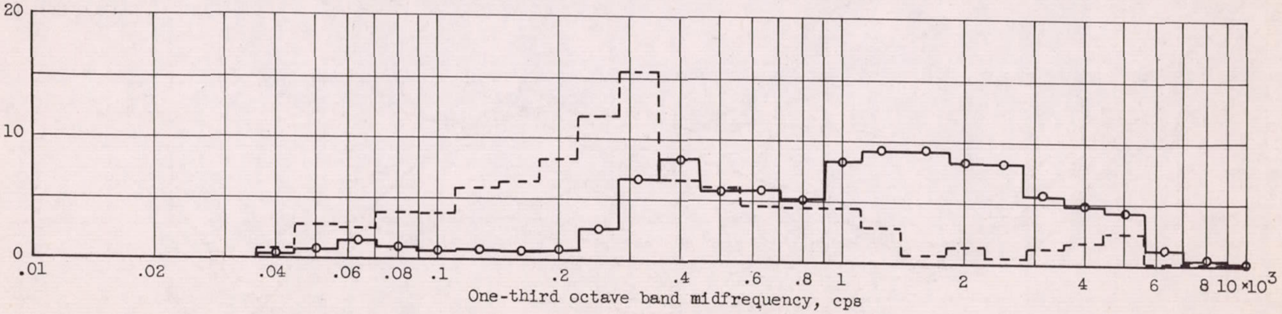
Figure 7. - Concluded. Sound spectra at screen position of minimum sound power level for all screens. Distance from jet exit, 200 feet.



(a) Azimuth angle, 30°.



(b) Azimuth angle, 90°.



(c) Azimuth angle, 180°.

Figure 8. - Percentage of total sound energy in each one-third octave band for three points in sound field. Screen at minimum-power-level position.

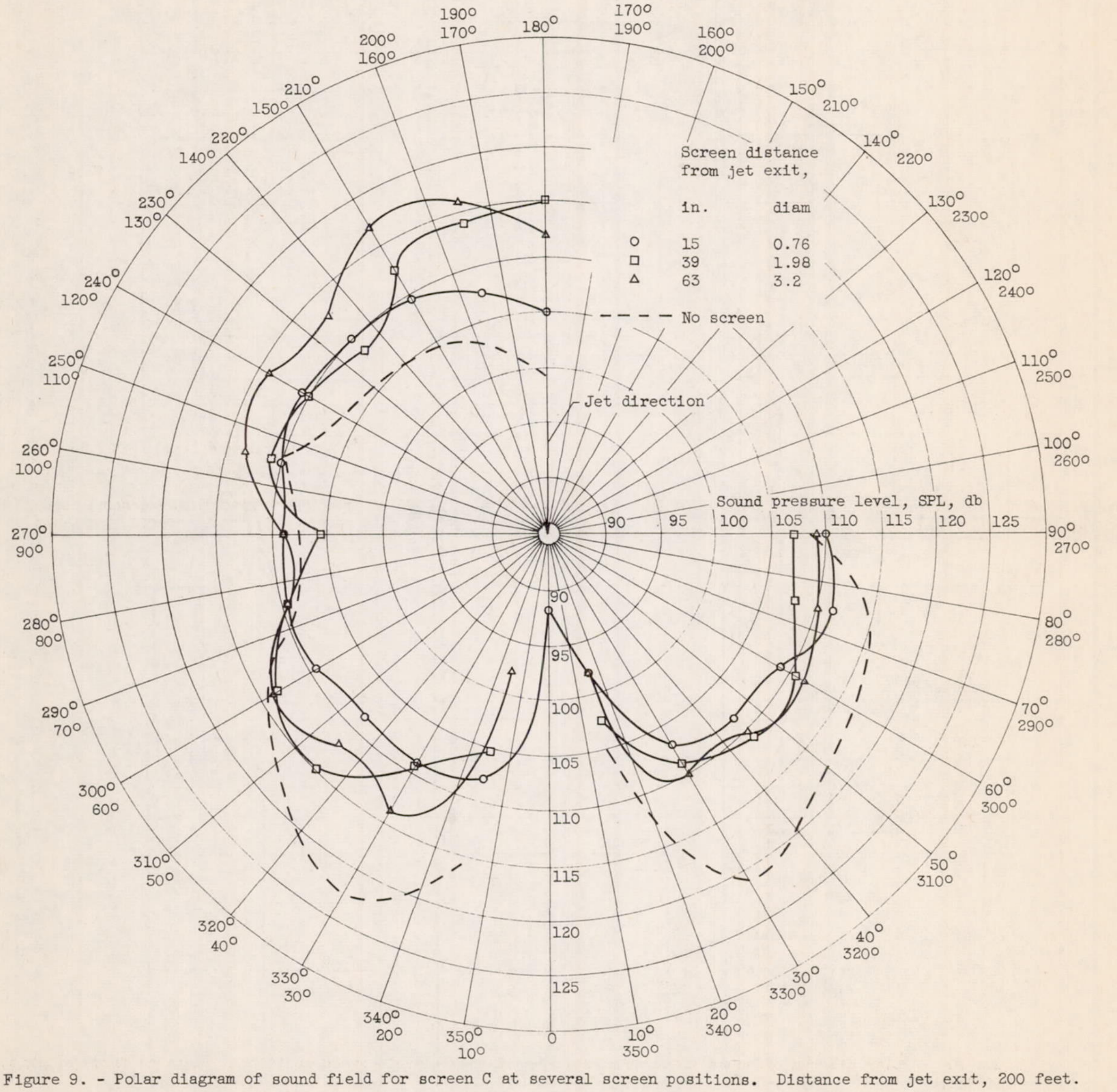
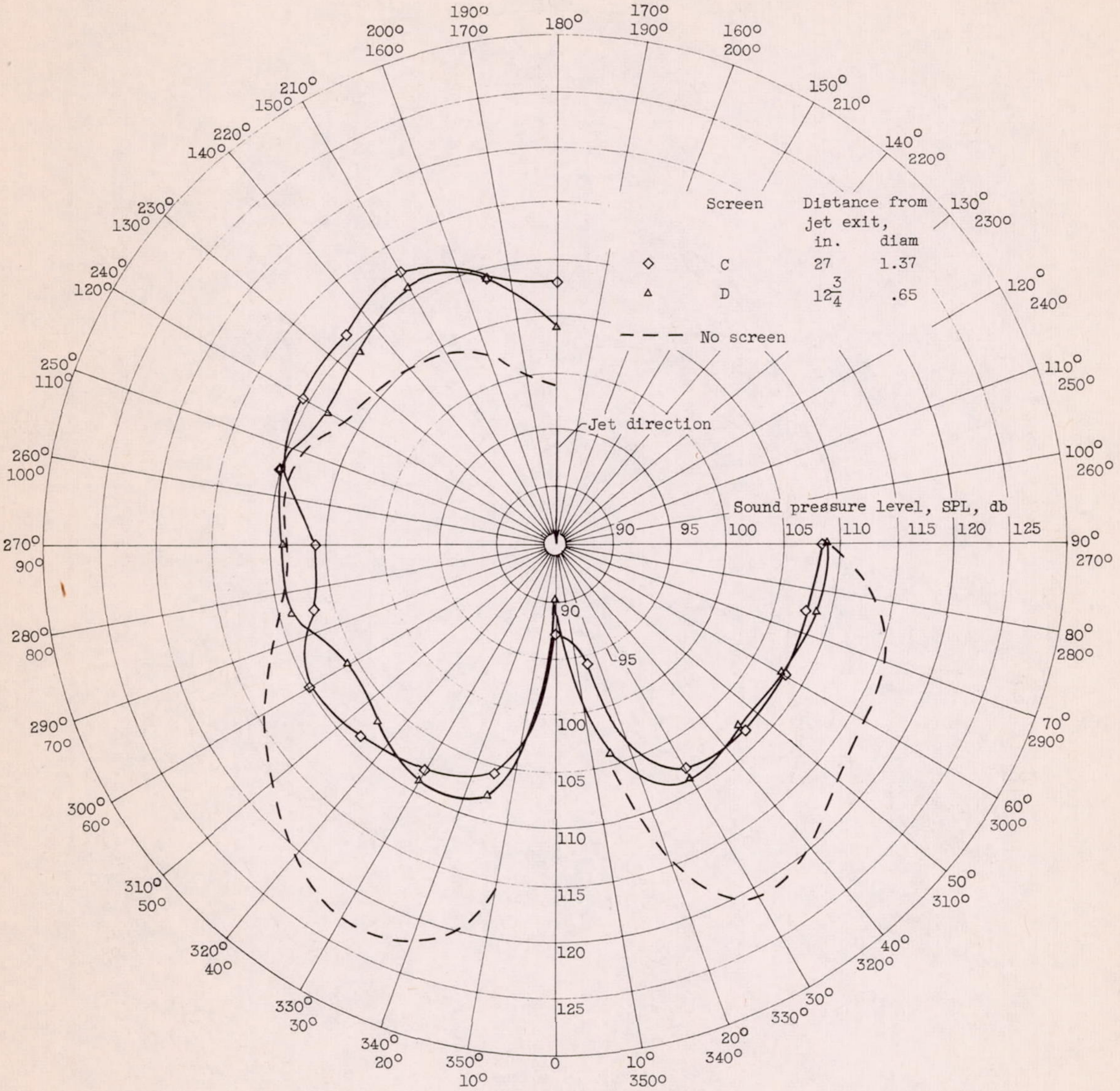
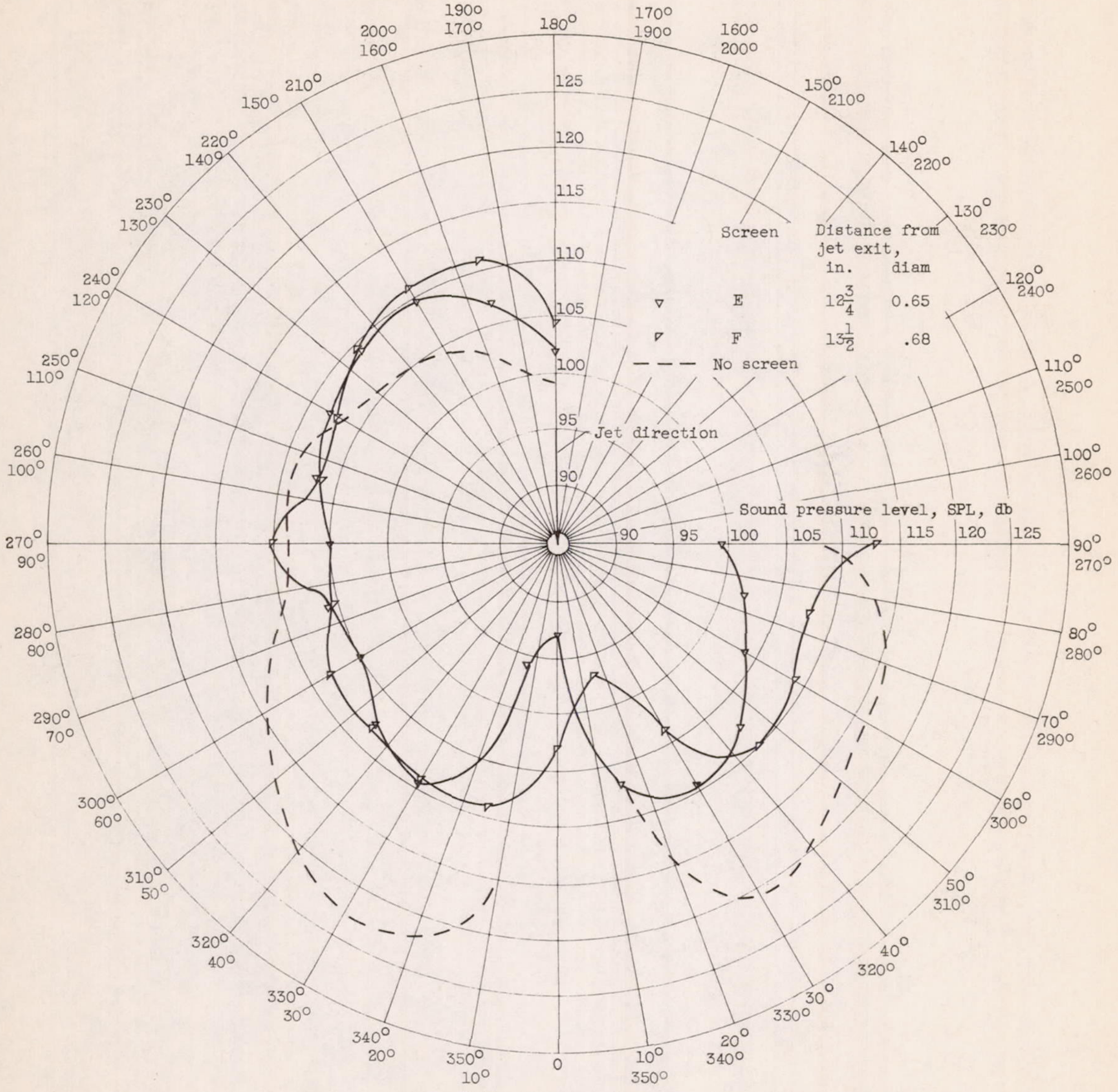


Figure 9. - Polar diagram of sound field for screen C at several screen positions. Distance from jet exit, 200 feet.



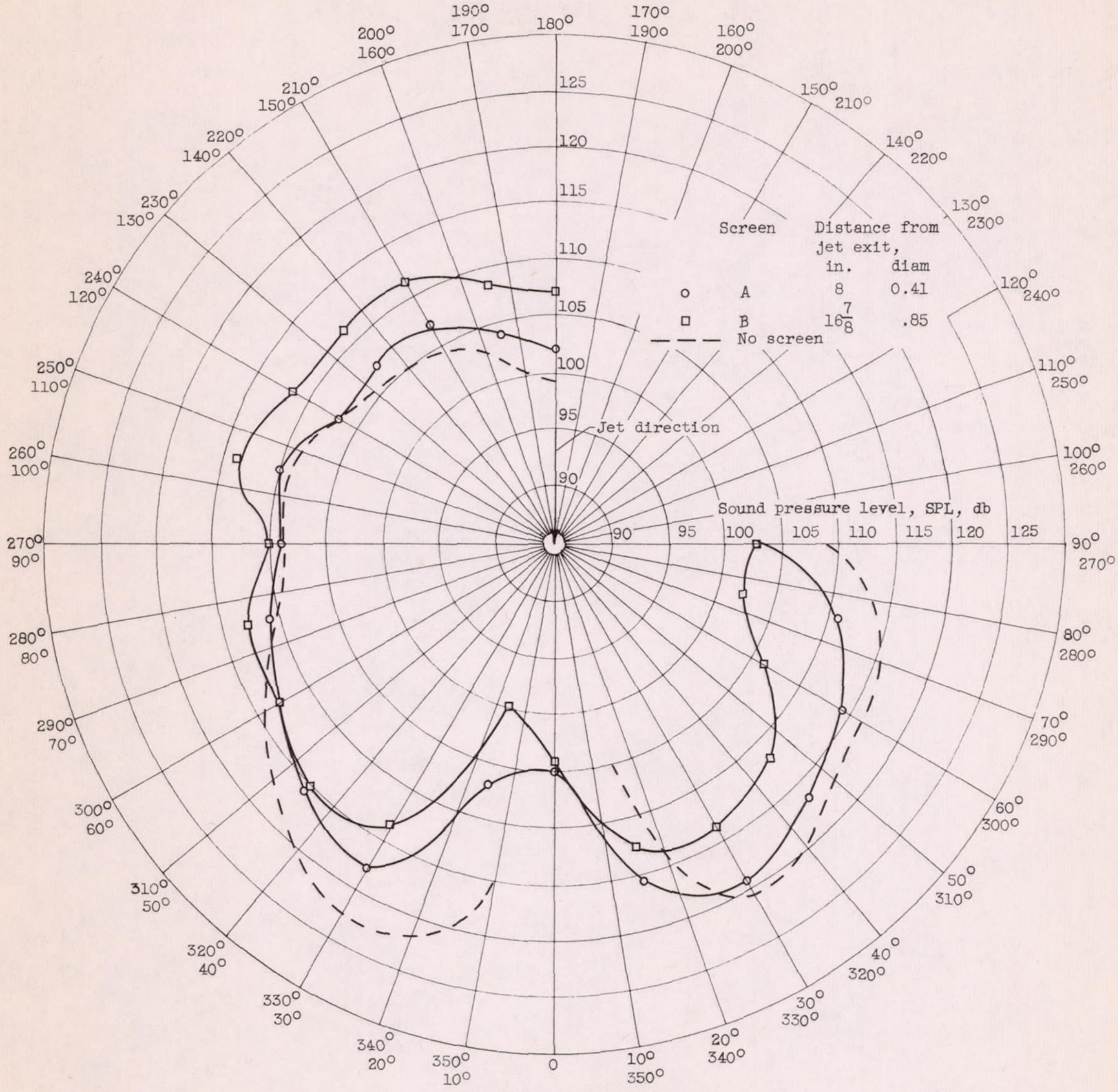
(a) Screens C and D.

Figure 10. - Polar diagram of sound field at minimum-sound-power-level screen position. Distance from jet exit, 200 feet.



(b) Screens E and F.

Figure 10. - Continued. Polar diagram of sound field at minimum-sound-power-level screen position. Distance from jet exit, 200 feet.



(c) Screens A and B.

Figure 10. - Concluded. Polar diagram of sound field at minimum-sound-power-level screen position. Distance from jet exit, 200 feet.