# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3516

## SUMMARY EVALUATION OF TOOTHED-NOZZLE ATTACHMENTS AS A JET-NOISE-SUPPRESSION DEVICE

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## SUMMARY

Toothed attachments to a full-scale turbojet nozzle were investigated for possible jet-noise reduction and thrust penalty. The attachments caused slight reductions in total sound power that are insignificant when evaluated in terms of engine thrust losses and aircraft payload penalty. At the reduced thrust levels obtained with the toothed nozzles, corresponding sound power reductions could be realized by throttling the standard turbojet engine.

Sound pressure levels were reduced behind the engine but were increased elsewhere. A typical resident in the airport neighborhood would hear increased loudness in the middle frequencies; however, the resulting over-all auditory effect is considered to be negligible.



## INTRODUCTION

The generation of jet noise has been, in part, attributed to turbulent mixing in the intense velocity gradient at the jet boundary. It was suggested that thickening of the mixing zone between the jet and the surrounding atmosphere would reduce shear and possibly reduce noise. One proposal for the thickening of the mixing zone involved the use of serrations or teeth attached to the lip of the jet nozzle.

Tests with small air jets incorporating nozzle teeth were conducted in England and are reported in reference 1. These tests indicated that the teeth caused a moderate reduction in maximum sound pressure level at subsonic pressure ratios and larger reductions at choked pressure ratios. Some preliminary full-scale research is reported in references 2 and 3. During the tests of reference 2, the engine was mounted under the wing and adjacent to the tail boom of a cargo airplane.

For the tests reported herein, the engine was removed from the airplane and installed in a free-field thrust stand with no sound reflecting

surface near the jet. Reference 2 presents only sound pressure levels; this paper also presents spectrum, total sound power, and thrust data. The present report summarizes the performance of the toothed inserts as a jet-noise-suppression device.

## APPARATUS AND PROCEDURE

The engine used in these tests was an axial-flow turbojet engine with a sea-level rated thrust of 5000 pounds. The nozzle pressure ratio was such that the nozzle was nearly choked under static conditions at standard inlet temperature. The tests simulate the noise generated during take-off and climbing flight speeds. From the standpoint of a ground observer, these are the flight conditions of acoustic concern. The tests were made with two nozzle modifications: a 6- and a 12-toothed attachment. Figure 1 shows the thrust-stand installation with the 12-toothed nozzle attached to the tail pipe. Toothed-nozzle design details are given in reference 2. 3645

In order to maintain rated turbine-outlet temperature at rated engine speed, it was necessary to increase tail-pipe area when the teeth attachments were installed.

Engine instrumentation was routed to a control room located 100 feet from the thrust stand at an azimuth angle of 240°. Figure 2 shows the orientation of the engine, control room, and sound survey stations. Engine thrust, fuel flow, mass flow, and turbine-outlet temperature were recorded in order to correlate engine performance with noise production.

Measurements of sound pressure levels were made at 15° intervals in a 270° sector around the engine. No sound pressure measurements were taken in the quadrant where the control room was located. For purposes of total-sound-power calculation, the sound pressures in the two forward 90° quadrants were assumed to be symmetrical. The sound pressure levels were observed on a General Radio Company Type 1551-A Sound-Level Meter located 200 feet from the jet nozzle. The frequency distribution of sound pressure was measured at stations 30°, 90°, and 180° from the jet axis at a distance of 200 feet from the nozzle. The frequency data were taken with a Brüel and Kjaer Audio Frequency Recorder Type 2311. The frequency range for this instrument is from 35 to 18,000 cps and is divided into 27 one-third octave bands. The spectrum recorder was transported in an acoustically insulated panel truck. Prior to each run the General Radio Company and the Brüel and Kjaer meter-microphone circuits were calibrated with a General Radio Company Type 1552-A Sound-Level Calibrator and Type 1307-A Transistor Oscillator.

The decibel unit is used herein to represent sound pressure level, spectrum level, and total power level. Complete definitions and formulas

for these acoustic terms are presented in reference 4. Sound pressure level, based on a reference of 0.0002 dyne per square centimeter, is indicated by the sound-level meter which responds simultaneously to all frequencies from 20 to 10,000 cps. Spectrum level is the sound pressure level in a finite band width (one-third octave) corrected to a unit frequency. Total power level involves a hemispherical integration of sound pressure and represents all the sound power issuing from a sound source. Power level is based on a reference of $10^{-13}$ watt. The following specific example will indicate the relative magnitudes of these decibel terms. A turbojet engine with 5000-pound thrust, which produced a maximum sound pressure of 122 decibels at 200 feet from the nozzle, created a maximum single-frequency-spectrum level of 100 decibels at 200 feet and a corresponding total power level of 168.3 decibels. A power level of 168.3 decibels is equivalent to 6.76 kilowatts.





## RESULTS AND DISCUSSION

### Sound Pressure Measurements

The sound pressure level at rated engine speed for the standard nozzle and the 6- and 12-toothed nozzle inserts is presented in figure 3. All the sound pressure data reported herein were obtained at a distance of 200 feet from the nozzle. The 6-toothed configuration caused a 6-decibel reduction in maximum sound pressure level, whereas the 12-toothed configuration caused a 3-decibel reduction. However, the 6-toothed nozzle produced greater sound pressures forward and abeam of the engine; the 12-toothed nozzle produced slightly higher sound levels abeam of the engine.

No direct jet-velocity or thrust measurements were taken during the tests reported in reference 2. However, it was necessary to use an oversize exit area, and consequently the engine pressure ratio and jet velocity were lower than the normal rated values.

Because the jet velocity was low, the sound pressure levels obtained for the standard engine in reference 2 were somewhat lower than those presented herein. When the engine was transferred to the thrust stand, more uniform fuel distribution, an improved inlet cowling, and a tail pipe were provided; the combination caused increases in jet velocity and sound pressure levels.

### Frequency Spectrum

The spectrum analyzer was used to obtain sound pressures in one-third octave band widths at three azimuth locations. The corresponding

sound spectrum levels are shown in figure 4 for the 30°, 90°, and 180° stations. At an azimuth angle of 30° the toothed nozzles, in general, produced lower spectrum levels than the standard engine. At the higher spectrum levels, which correspond to frequencies from 40 to 200 cps, the 6-toothed nozzle shows the greater attenuation. In order to determine the significant noise frequencies at the 200-foot radius, cumulative sound intensity is shown in figure 5. The cumulative sound intensity at a given frequency is defined as the sum of all the spectrum levels below the given frequency. The ordinate in figure 5 is the dimensionless ratio of cumulative intensity to total intensity. At the 30° azimuth (fig. 5(a)), 75 percent of the sound intensity occurs at frequencies below 200 cps for the 6-toothed device and below 135 cps for the 12-toothed nozzle. The remaining 25 percent represents only 1 decibel. Figure 4(a), with the significant frequencies considered to be below 200 and 135 cps, respectively, indicates that the 6-toothed nozzle produces spectrum levels approximately 5 decibels below those of the standard nozzle while the reduction with the 12-toothed nozzle is somewhat less.

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At the 90° azimuth, figure 5(b) shows that all spectrum levels corresponding to frequencies below 1000 cps for the 6-toothed nozzle and 2000 cps for the 12-toothed nozzle must be considered. The corresponding spectrum-level plot (fig. 4(b)) shows that at frequencies less than 2000 cps the toothed nozzles, in general, produced higher spectrum levels than the standard nozzle.

At the 180° azimuth (fig. 5(c)), the significant spectrum levels occur at frequencies below 1000 cps for the 6-toothed nozzle and 400 cps for the 12-toothed nozzle. The corresponding spectrum levels (fig. 4(c)) indicate that the standard and 12-toothed nozzle average out at about equal levels, but the 6-toothed nozzle shows higher spectrum levels over nearly the entire range of critical frequencies.

An inspection of the sound spectrum levels shows that the sound levels at an azimuth angle of 30° are reduced by the addition of teeth inserts, but that the sound is, in general, increased abeam and ahead of the engine. This result agrees with the over-all sound-pressure-level variation in figure 3.

## Total Sound Power and Engine Thrust

The following table lists the measured total-sound-power levels and thrust variation for the toothed-nozzle configurations.

| Nozzle configuration | Total sound power, db | Thrust loss, percent |
|---|---|---|
| Standard | 168.3 | 0 |
| 6-Toothed | 166.7 | 2.5 |
| 12-Toothed | 166.0 | 6.0 |

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At rated engine speed and rated turbine-outlet temperature, the 6- and 12-toothed nozzles caused thrust losses of approximately $2\frac{1}{2}$ and 6 percent, respectively. These losses represent $2\frac{1}{2}$- and 6-percent increases in specific fuel consumption. If a jet transport cruising at 500 miles per hour on a 3000-mile flight is considered, increases in fuel load of $2\frac{1}{2}$ or 6 percent could reduce payload by 8 or 18 percent, respectively.

Figure 6 presents total sound power levels for the toothed nozzles as well as several familiar engine and afterburner sound power levels which are shown for comparison purposes. All the sound power data for the various tail-pipe configurations were obtained with the same engine. Sound power is presented in terms of both watts and decibels. The abscissa of figure 6 is the Lighthill parameter

$$\frac{\rho_0 A V^8}{a_0^5}$$

where

$\rho_0$ ambient-air density

A nozzle-exit area

V jet velocity

$a_0$ ambient acoustic velocity

The theoretical work of reference 5 indicates that for subsonic pressure ratios the total sound power should be proportional to this parameter. With the exception of the afterburner, effective jet velocity for use in the calculation of the Lighthill parameter was determined from engine thrust and mass-flow measurements. The toothed-nozzle and afterburner data were obtained at rated engine speed and exhaust temperature. Afterburner sound power level was determined from the data in reference 6.

Transition from rated engine operation to maximum-thrust afterburner operation resulted in a 9-decibel increase from approximately 168 to 177 decibels. Throttling from rated engine speed to 80 percent of rated speed resulted in an 11-decibel decrease. In contrast with these significant sound power variations, the toothed nozzles caused less than 2.5-decibels sound power attenuation.

The curve, which has a slope of 9 decibels per decade, was drawn through the standard-engine and afterburner data. Because the toothed-nozzle data fall within 1 decibel of the curve, it is apparent that equivalent thrust and sound-power reductions would be realized simply by throttling the engine. However, at the same thrust and noise levels the throttled engine would exhibit lower fuel consumption than the toothed configuration. 3645

## Auditory Effects

Only the 6-toothed nozzle is considered in the following discussion, since it exhibits higher thrust than the 12-toothed nozzle. The auditory effect of the toothed-nozzle installation will depend on the relative position of the engine and observer. Clearly, if the observer were stationed 200 feet from the engine on the 30° azimuth, the toothed nozzle would be 8 decibels quieter than the standard nozzle. Conversely, an observer stationed ahead or abeam of the engine would hear higher noise levels. Since the total sound power level was reduced only $1\frac{1}{2}$ decibels when the 6-toothed nozzle was installed, one might expect the integrated net acoustic effect to be insignificant. As shown in reference 2, a theoretical analysis indicates that an aircraft passing over the observer at 200 feet would create the same maximum sound pressure level with either the toothed-nozzle or standard configuration.

If a typical resident in an airport neighborhood who is located 3/4-mile slant distance from the take-off flight path is considered, the resultant spectrum levels will be those shown in figure 7. The spectrum levels were computed from the data obtained at 200 feet by assuming an inverse square relation between sound level and distance. The distance to the fixed observer is, of course, increased to $1\frac{1}{2}$ miles when the observer is subjected to noise from the 30° jet azimuth.

Contours of equal loudness level (ref. 7) are also shown in figure 7. At a loudness level of 100 phons, the frequency response of the ear is nearly flat; however, at the lower levels the ear is more sensitive to the midfrequencies. The figure shows that the toothed nozzle, which increases the noise at the midfrequencies, produces maximum loudness levels at an azimuth angle of 90° that are as high as those of the standard nozzle at 30°.

At a distance of 3/4 mile there may be greater atmospheric attenuation of the high-frequency noise; however, the high loudness levels occur at frequencies below 1600 cps where atmospheric attenuation is negligible.

## CONCLUDING REMARKS

The toothed attachments caused slight reductions in total sound power which became insignificant when evaluated in terms of engine thrust losses and aircraft payload penalty. Equivalent sound power reductions and corresponding thrusts could be obtained by throttling the standard turbojet engine. The throttled turbojet would demonstrate lower specific fuel consumption than the toothed configuration.

The nozzle attachments reduced the maximum sound pressure level, which occurred in the rear sector, but increased the levels in other sectors.

The low-frequency components of jet noise are the most bothersome to aircraft ground crews; however, residents in the airport neighborhood are also annoyed by the middle frequencies. Since the toothed nozzle increases the noise at the middle frequencies, installation of this device would not be expected to reduce public objection to jet noise.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 6, 1955

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7. Rosenblith, Walter A., et al.: Handbook of Acoustic Noise Control. Vol. II. Noise and Man. WADC Tech. Rep. 52-204, Aero. Medical Lab., Wright-Patterson Air Force Base, June 1953. (Contract No. AF 33(038)-20572, RDO No. 695-63.)

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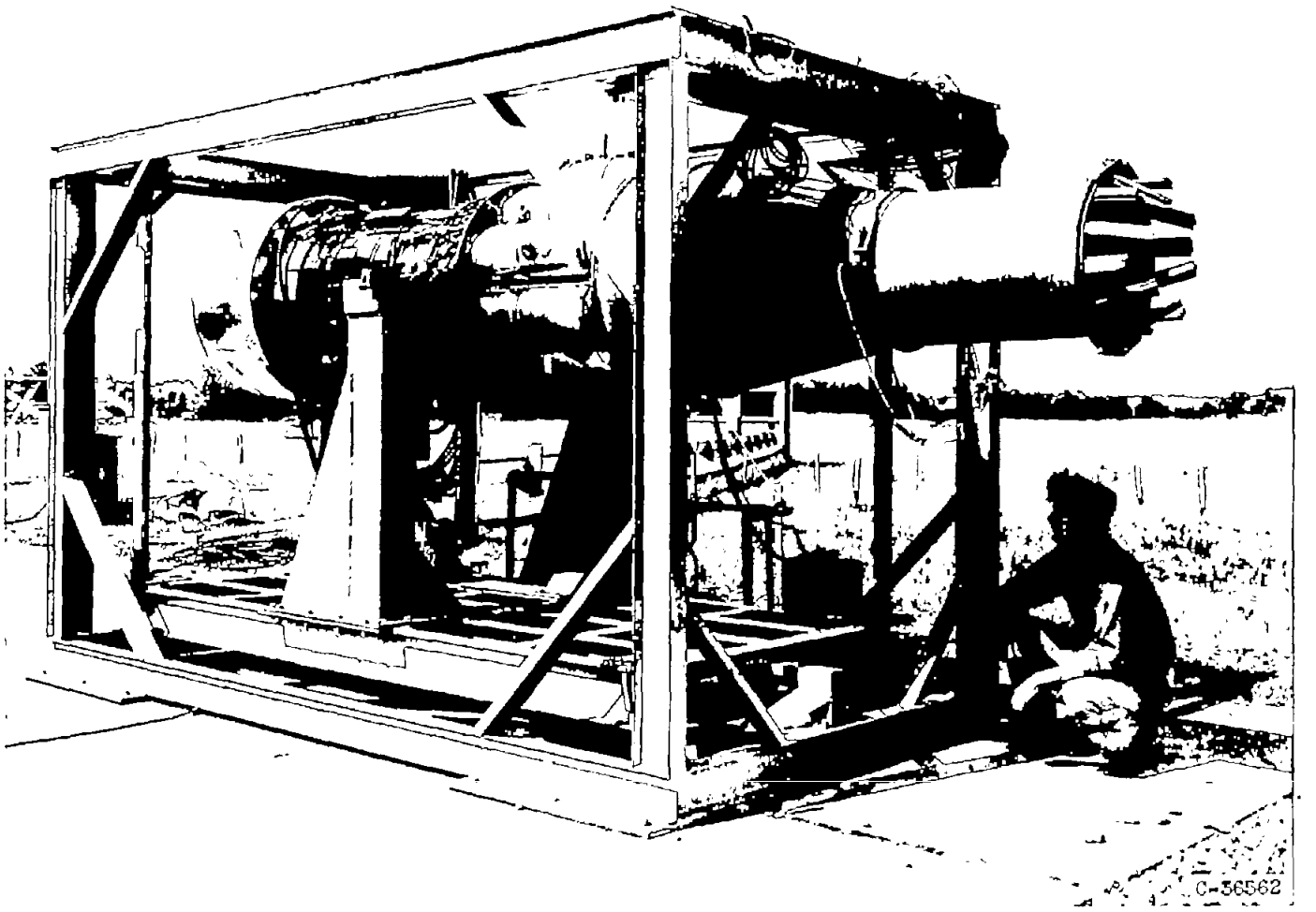


Figure 1. - Thrust stand with 12-toothed-nozzle installation.

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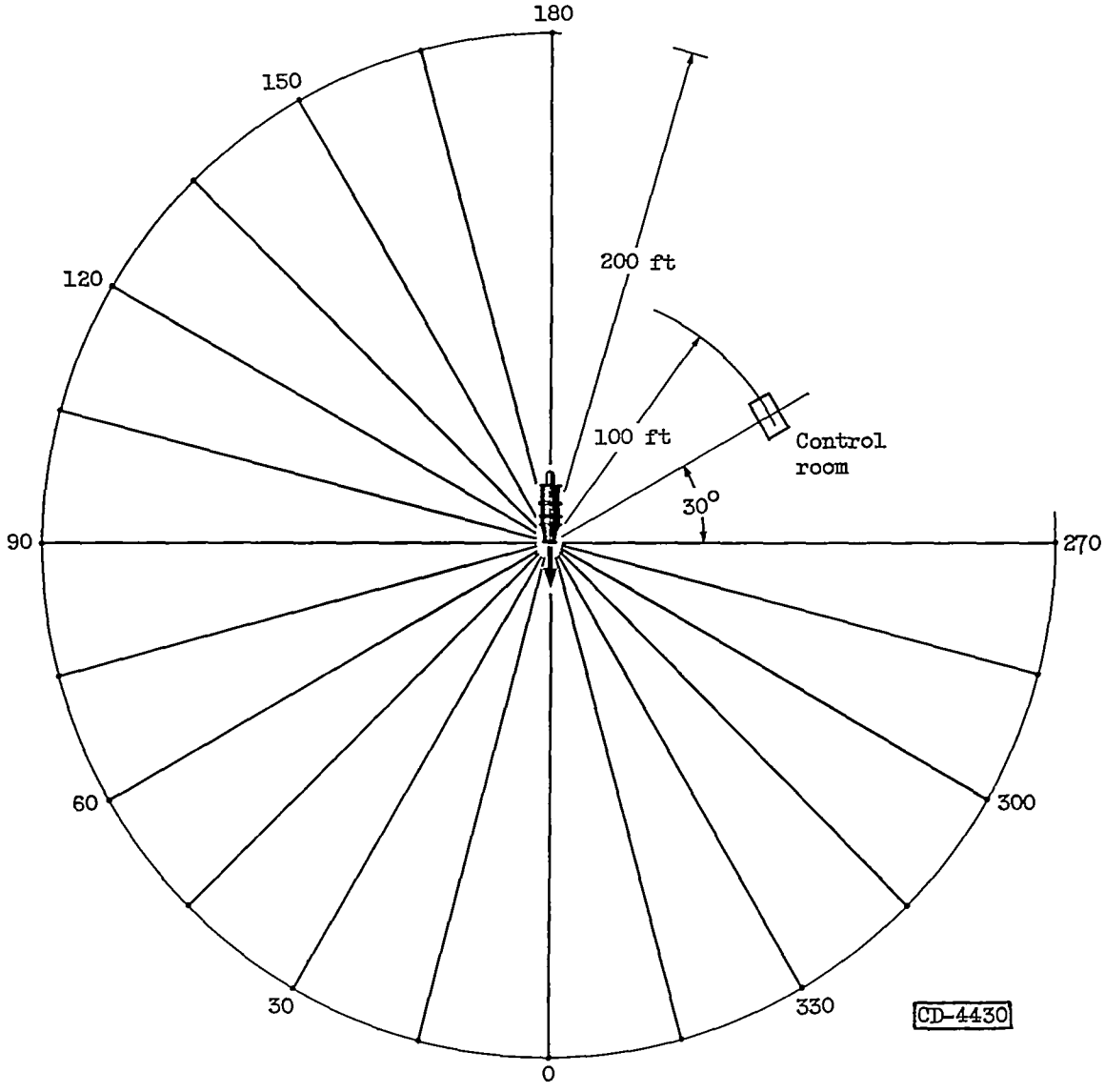


Figure 2. - Location of survey stations and control room in jet sound field.

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CD-2 back

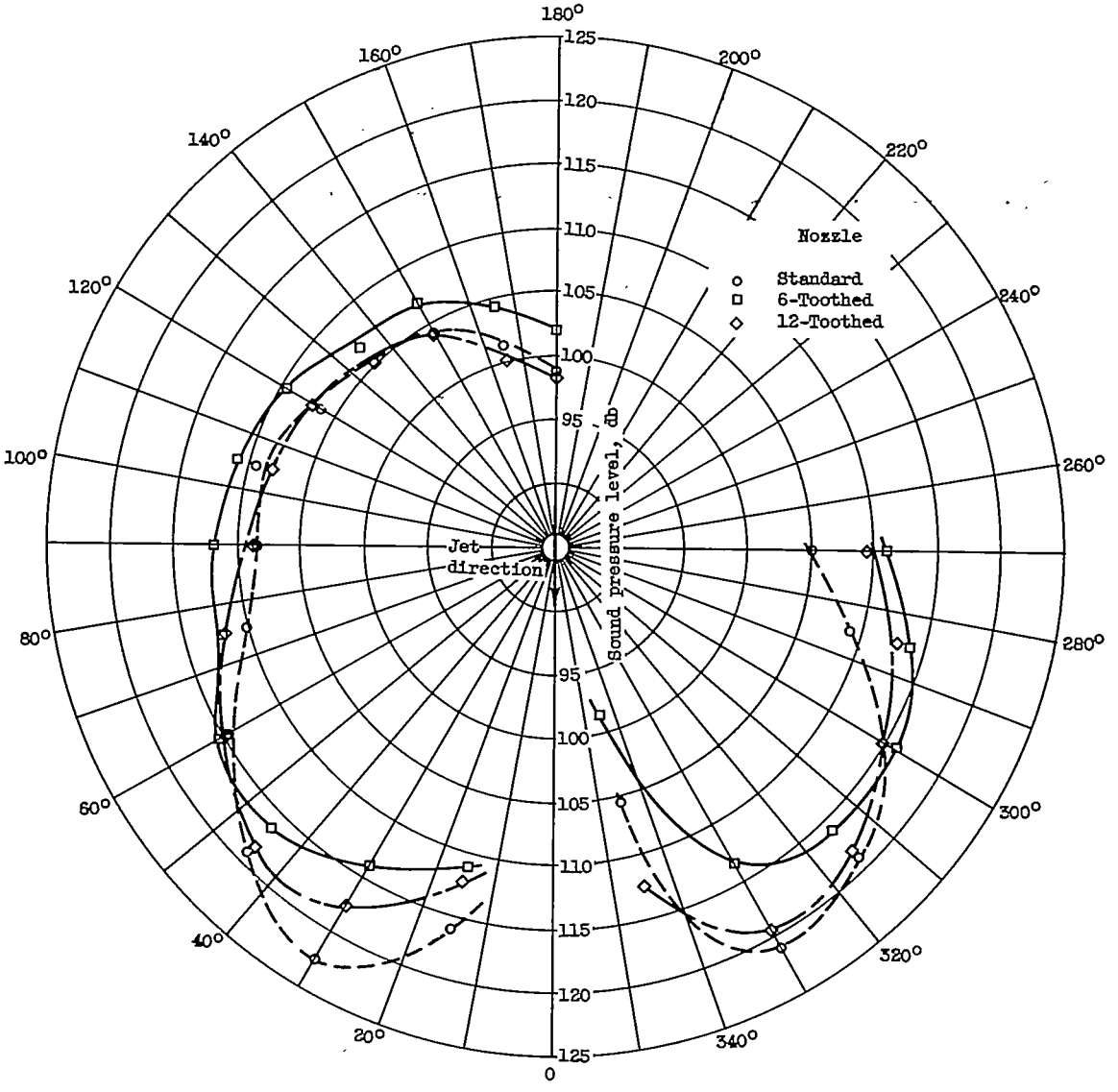
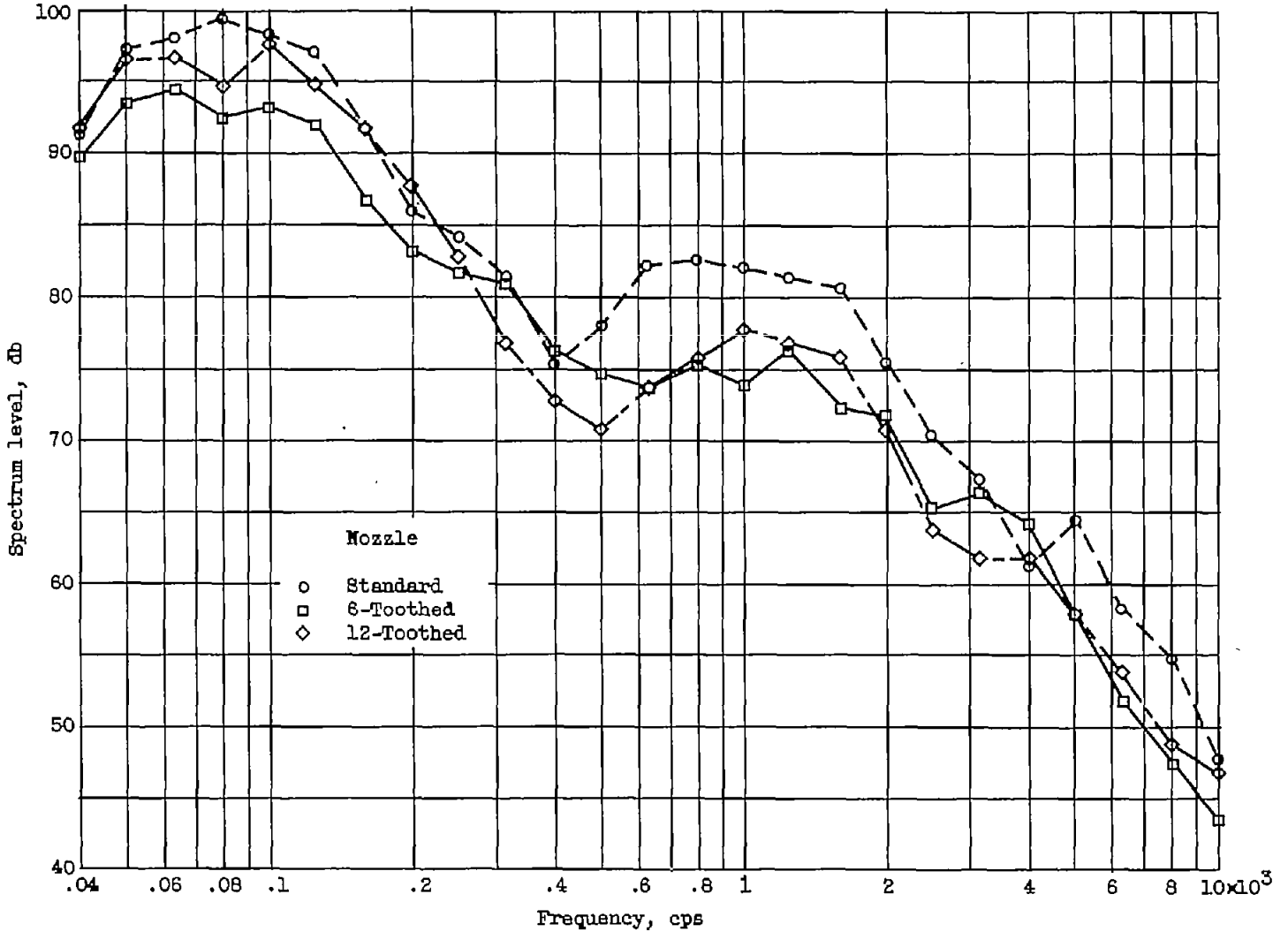
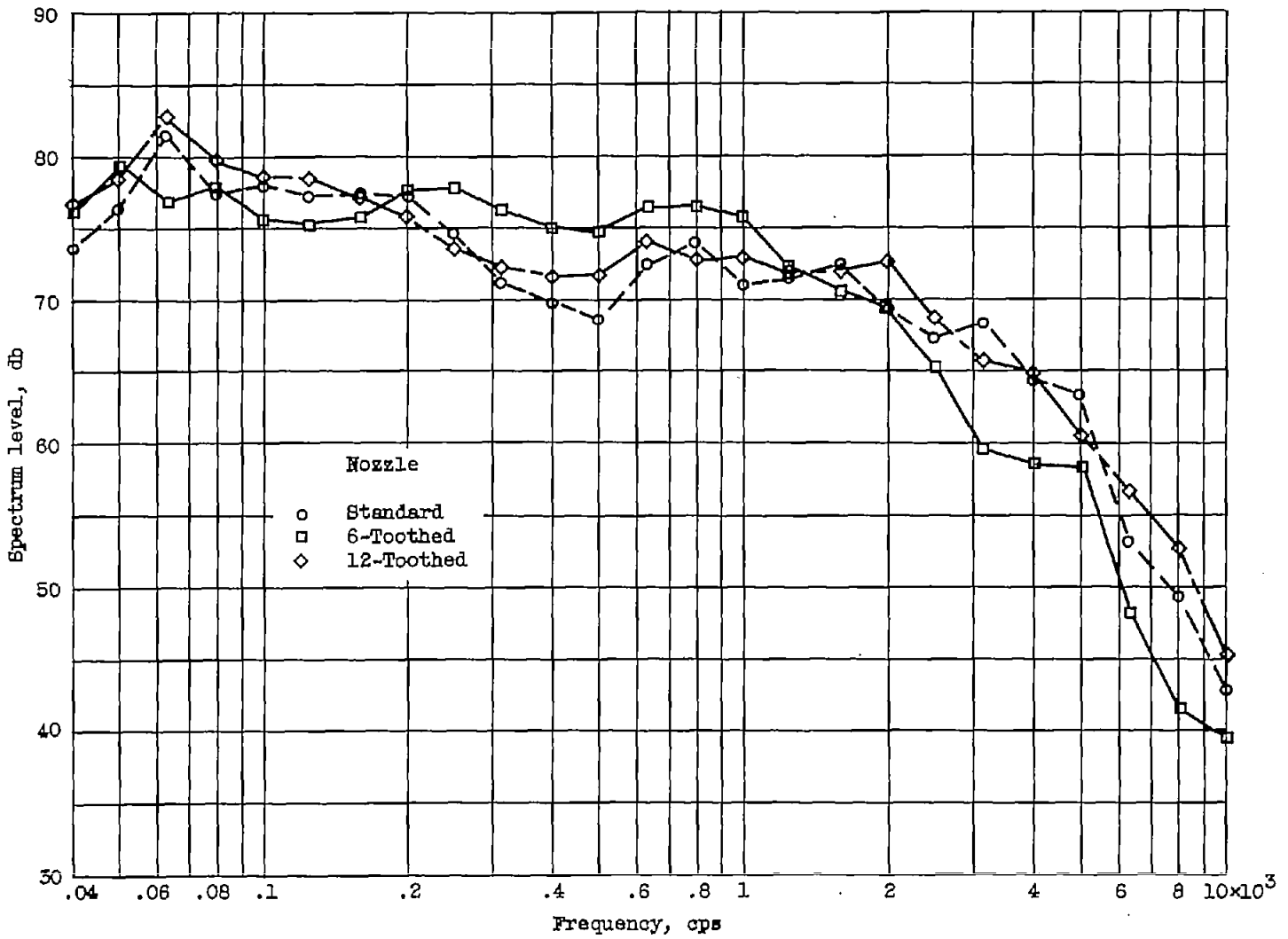



Figure 3. - Polar diagram of sound field. Distance from nozzle, 200 feet.



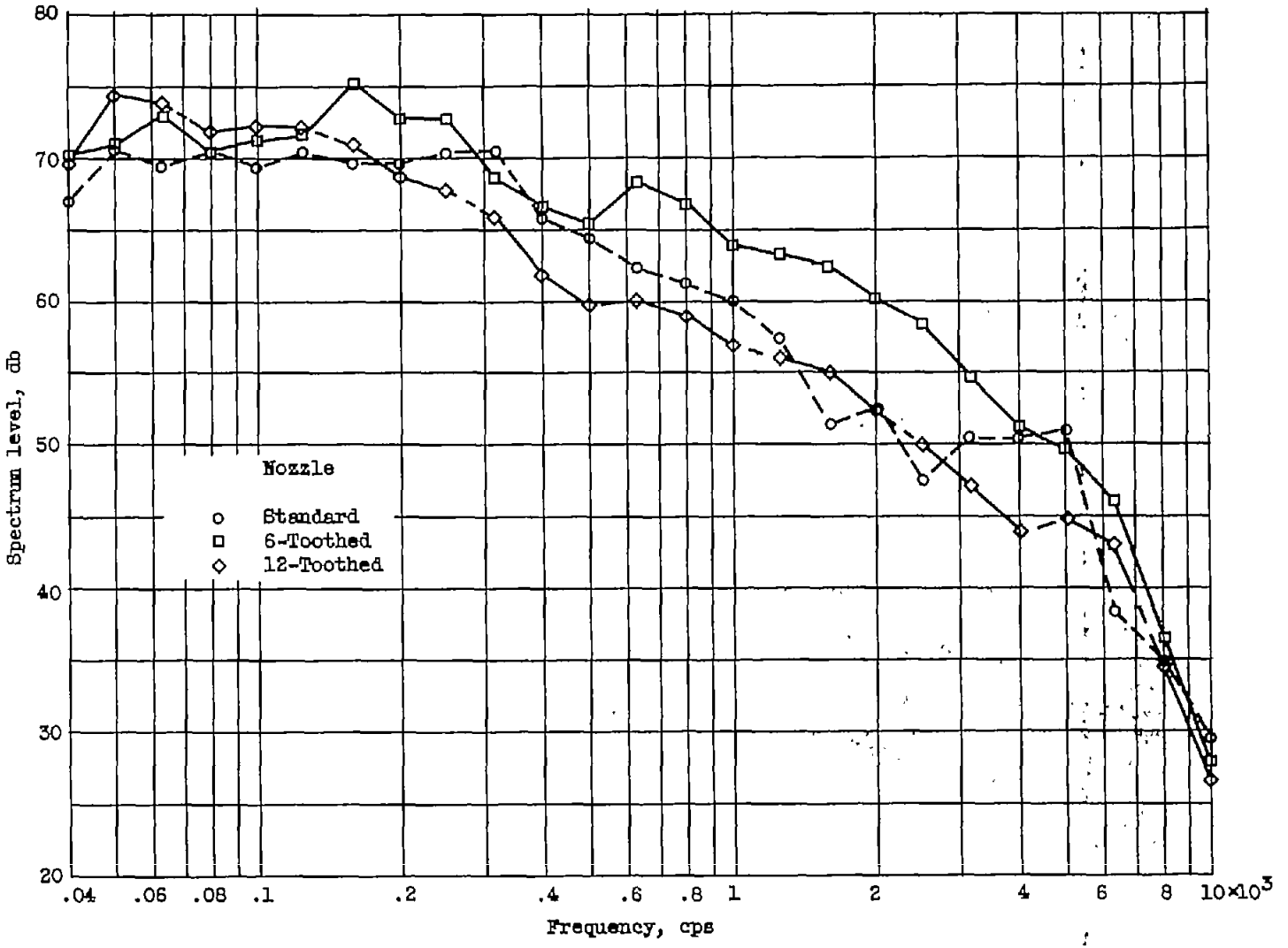

(a) Azimuth angle, 30°.

Figure 4. - Spectrum level 200 feet from nozzle.



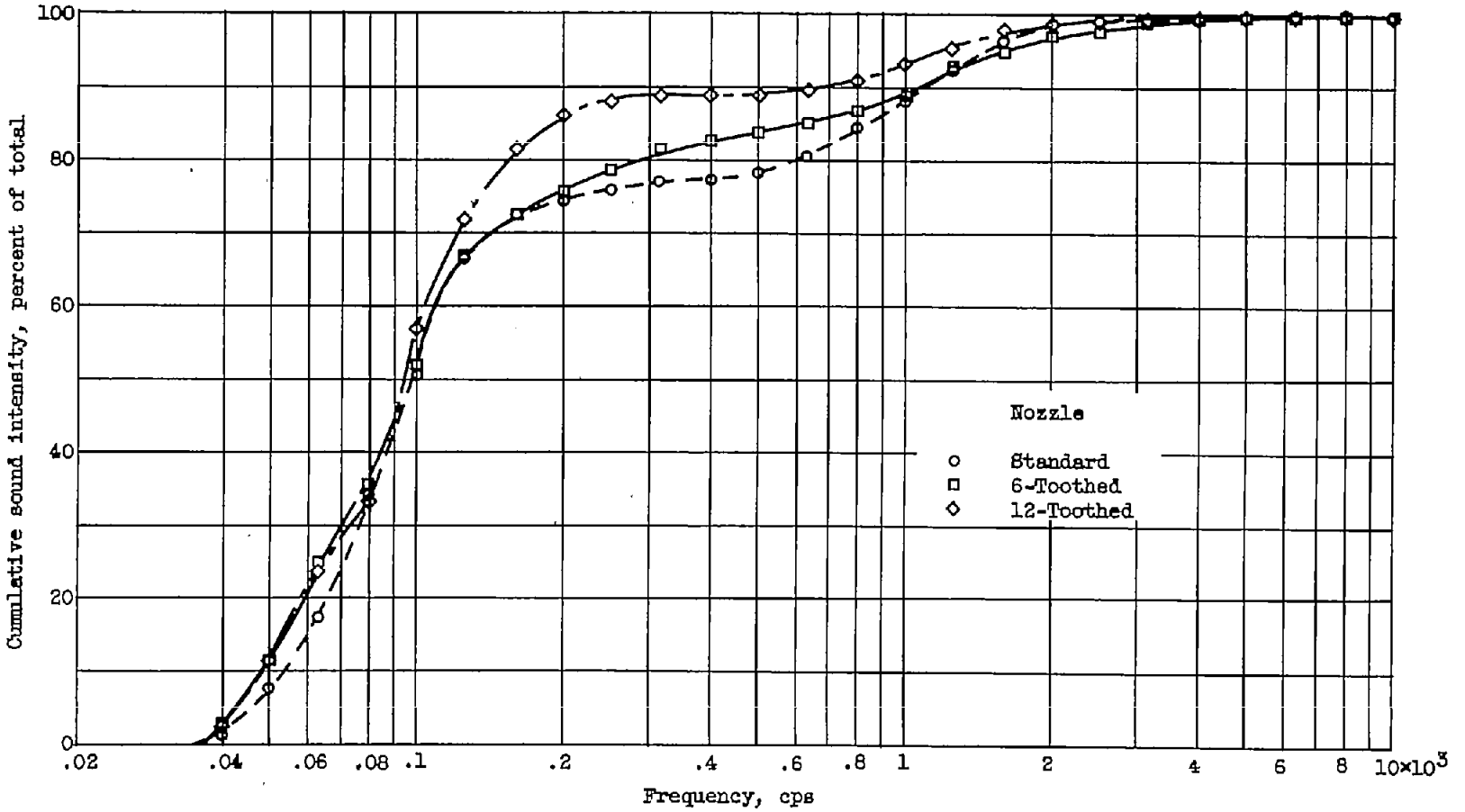

(b) Azimuth angle, 90°.

Figure 4. - Continued. Spectrum level 200 feet from nozzle.




(c) Azimuth angle, 180°.

Figure 4. - Concluded. Spectrum level 200 feet from nozzle.




(a) Azimuth angle, 30°.

Figure 5. - Spectral distribution of sound intensity.

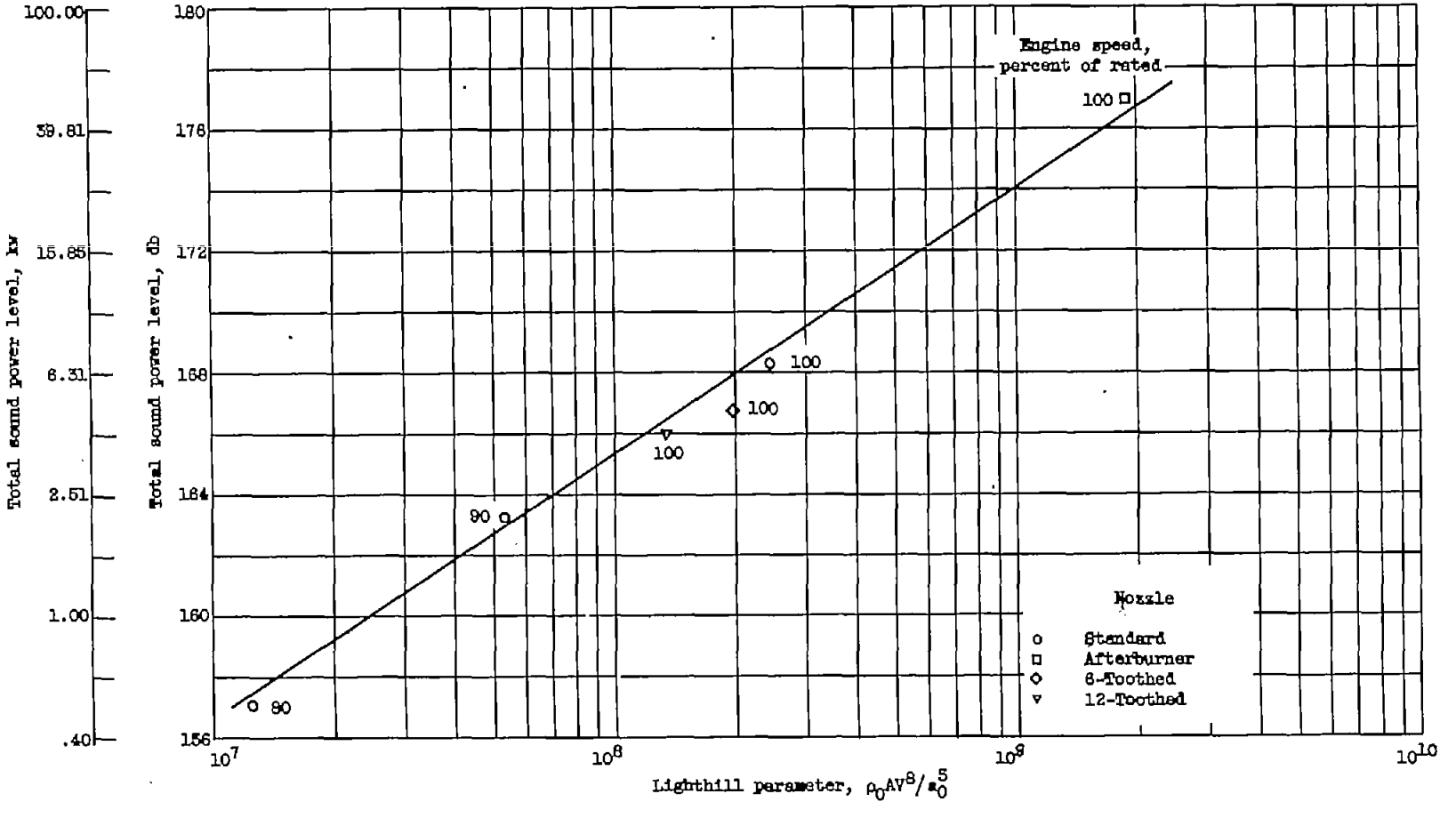



Figure 6. - Variation of total sound power with Lighthill parameter.

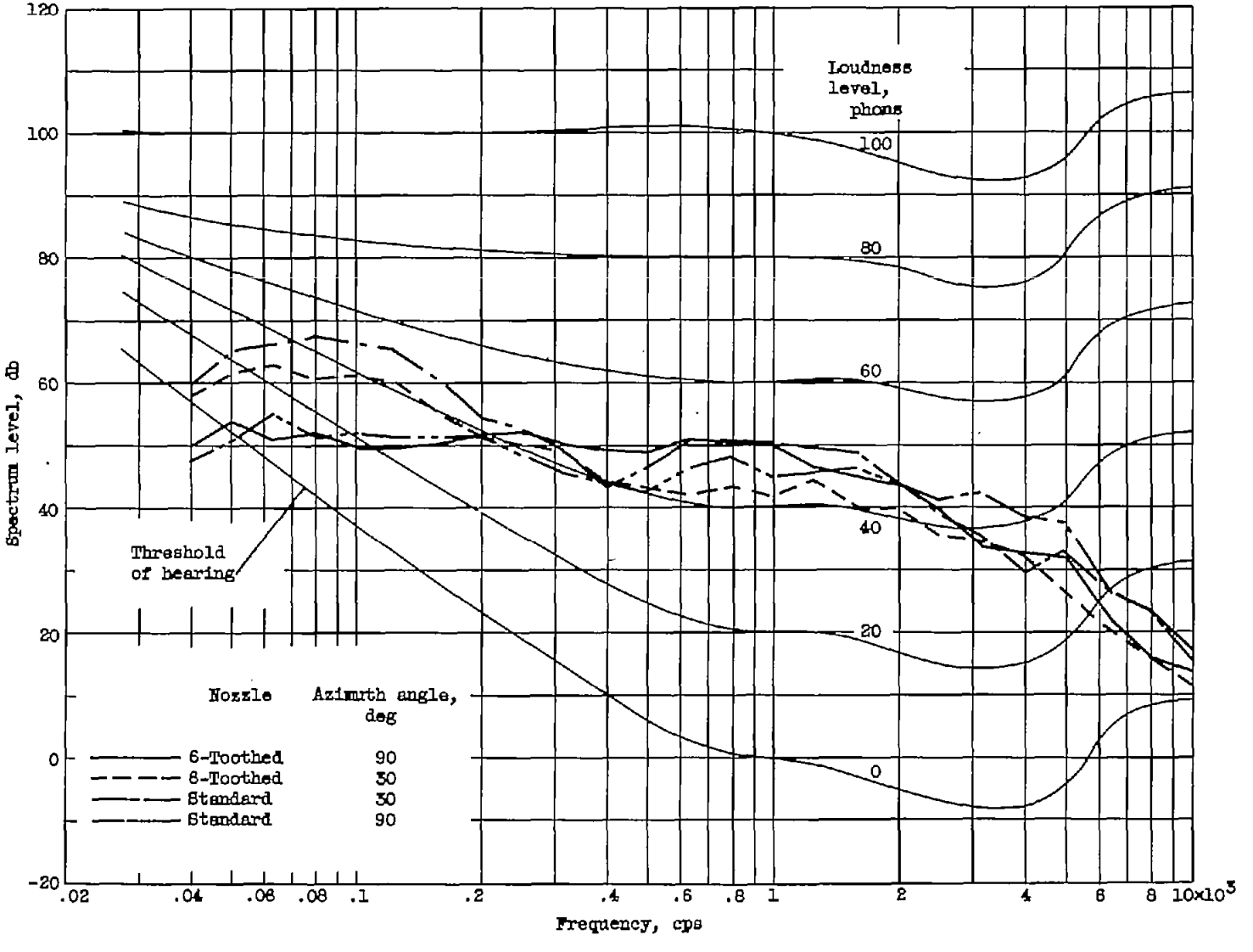



Figure 7. - Sound spectrum levels 3/4 mile from flight path.



NACA - Langley Field, Va.