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ACOUSTICAL TREATMENT FOR THE NACA 8- BY 6-FOOT SUPERSONIC PROPULSION WIND TUNNEL

By Leo L. Beranek, Samuel Labate, and Uno Ingard

Bolt Beranek and Newman, Inc.

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SUMMARY

This report summarizes the results of a project at the Lewis Flight Propulsion Laboratory to silence the 8- by 6-foot supersonic wind tunnel. Sound measurements in the neighborhood surrounding the tunnel were conducted to evaluate the noise-attenuation requirements. A muffler-development program was continued until these attenuations were achieved. The final design for the acoustic treatment is described and experimental performance curves are compared with anticipated theoretical results.

INTRODUCTION

This report presents results of a research and engineering program performed during the first half of 1950 that resulted in an acoustical treatment for the 8- by 6-foot supersonic wind tunnel at the Lewis Flight Propulsion Laboratory. This tunnel has a conical diffuser about 200 feet long which exhausts through acoustic filters to the atmosphere. The exit diameter of the diffuser is about 26 feet.

Prior to 1949, during the period when the tunnel was under design, a partial evaluation of the expected noise problem was performed and certain limited recommendations for acoustical treatment were made. An accurate estimate of the probable noise from a wind tunnel of this sort was not possible at that time because of the lack of concrete information on the acoustic power level and spectrum of the noise generated by a large ram jet burning in a supersonic air stream. Because of this uncertainty, it was decided by the National Advisory Committee for Aeronautics to progress with the acoustical treatment in a stepwise manner. Certain acoustical quieting measures were adopted in the initial construction. Nearly all of these measures were found to be necessary in the final acoustical design.

The initial acoustical treatment consisted of a concrete enclosure around the conical diffuser having a side wall thickness of 8 inches and a roof thickness of 6 inches. In addition, a large plenum chamber was constructed at the end of the tunnel which included a thick acoustical treatment placed directly in line with the air stream and openings through which the air stream could escape on either side of the plenum chamber at right angles to the flow of air. These openings were partially filled with parallel acoustic baffles.

The tunnel was first used in the late spring of 1949. No jet was in the test section. When the tunnel was operated at supersonic speeds, the noise proved to be objectionable after midnight to the neighbors. For low air velocities (Mach numbers of 1.2 and 1.6), the noise was barely objectionable, but it became more objectionable as the test-section speeds approached a Mach number of 2.0.

Measurements were conducted at the Lewis Flight Propulsion Laboratory in the summer of 1949 by the staff of Bolt Beranek and Newman, Inc., and by NACA personnel to determine the noise levels as a function of Mach number in the test section and as a function of distance from the tunnel. This study resulted in a series of recommendations for reducing the noise levels emanating from the tunnel.

In January 1950, prior to any acoustical revisions, burning by a 16-inch-diameter ram jet was initiated in the tunnel. Operation after midnight was highly objectionable to people living within a radius of 5 miles from the tunnel. The tunnel was immediately shut down and was not operated any further under those conditions of burning, except for a series of necessary acoustic tests which were used as a basis for the subsequent noise analysis, until a satisfactory acoustic design was completed in August 1950.

One of the special acoustic tests was made to obtain detailed data on the noise produced by the tunnel at two Mach numbers with the jet burning. It was soon revealed that high noise levels were produced at frequencies as low as 5 cps and as high as 10,000 cps. The very low frequencies were responsible for rattling of windows and for producing sounds similar to a series of explosions. It was necessary, therefore, to provide an acoustical treatment in the tunnel that would be effective over the frequency range from approximately 4 cps to very high frequencies.

In order to quiet a tunnel of this size with absolute certainty of success, it was necessary to enter into a concentrated research program involving scale models of the wind tunnel. These studies resulted in a treatment (see figs. 1 and 2) that comprised (1) a series of five resonators effective between 5 and 11 cps located in the space between the conical diffuser and the concrete outer housing, (2) a series of five resonators effective in the frequency range between 12 and 20 cps in an added-muffler section, (3) a special absorptive tuned-duct arrangement that produced high attenuation in the frequency range between 20 and

800 cps, (4) a series of parallel baffles at the exhaust end of the added muffler that removed those components of noise in the frequency range between 800 and 5,000 cps, and (5) two lined bends in the structure, one of which existed at the outlet end of the original construction and the other of which was added at the outlet end of the new construction.

The attenuation achieved in the final design was more than adequate to provide the required noise reduction to allow research investigation of supersonic jet engines in the tunnel. The treatment should be adequate for the testing of jet engines with fuel consumptions several times those used at the time the acoustical treatment was installed.

The experience gained on this large quieting job has revealed methods for the acoustical treatment of noise accompanied by steady air flow and has shown means for achieving high acoustic attenuations in structures with large open areas.

This work was conducted for the NACA in close cooperation with members of the NACA Lewis Laboratory staff who made substantial contributions to the research evaluations and engineering designs of the acoustic treatment. The present report is being published because of its general interest.

CHARACTERISTICS OF NOISE SOURCE

In order to design the acoustical treatment, it was necessary to determine (a) the noise characteristics in the vicinity of the wind tunnel and (b) the noise levels that were found to be annoying the neighbors. Data were taken on several occasions under various conditions of tunnel operation.

The first acoustical field survey was carried out during 1949. The tunnel was operated with test-section Mach numbers between 1.5 and 2.0, and data were taken at 20 stations about the tunnel and at a distance of approximately 2,000 feet. At the time of this survey no model was present in the test section.

Sound pressure levels taken at a position 3 feet in front of the outside face of one of the two sets of baffles at the outlet end are shown in figure 3. The four curves are for Mach numbers between 1.5 and 2.0. In figure 4 the noise levels measured at approximately 2,000 feet are shown for a test-section Mach number of 2.0. The curves near the tunnel show an orderly increase in level with increasing Mach number, while the levels farther away were not very far above the normal daytime background level.

The second set of data was also taken in the summer of 1949 and consisted of four groups of measurements as follows:

(1) Close-up measurements obtained around the outside of the concrete housing surrounding the tunnel along its entire length. Station numbers 1 to 8, indicated in figure 5, represent the measuring positions. For these measurements the microphone was mounted on a 20-foot pole and placed at a distance of approximately 2 feet from the radiating surface.

(2) Measurements obtained within the immediate area of the tunnel. Stations were marked on a 180° arc from the center of one of the original baffle sections at distances of 100 feet and 200 feet as indicated by stations 100 to 106 and 200 to 206 in figure 5.

(3) Measurements obtained within the concrete housing surrounding the tunnel. For these measurements the microphone was placed at a distance of approximately 1 foot from the steel shell of the tunnel. Stations 9 and 10 represent these measuring positions.

(4) Measurements obtained at various distances from the tunnel, extending as far as certain residences at distances as far as 2,000 feet.

Some of the data from those studies are shown in figures 6 and 7. The stations shown in figure 6 correspond to the positions indicated in figure 5.

It was quite apparent from those data that the noise was emanating primarily from the openings (stations 1 and 3 of fig. 5) at the end of the tunnel. The data at these two stations were approximately 17 to 30 decibels higher than those measured at the other stations. It seemed clear from observations that the noise was generated in the test section itself. At stations 100 and 101 (see fig. 5) increased levels were obtained because of noise coming from the exhauster building which was situated near station 7. Low-frequency bands of noise possess no noticeable directional properties.

As is often found to be the case, the sound levels decreased approximately at the rate of 6 decibels per doubling of distance up to a distance of about 3,200 feet (see fig. 8). Analysis also showed that there was no substantial attenuation gained from the propagation of the sound over the terrain, even in the 600- to 1,200-cps frequency band.

Operation of the tunnel to obtain the third group of measurements was restricted to two air flow velocities corresponding to Mach numbers of 1.45 and 2.0 under conditions of ram-jet operation of rough burning, smooth burning, and with the ram jet cold. Because of a restriction on the length of time the tunnel was allowed to operate for this particular test, a minimum number of five measuring stations were selected for each condition of operation. Four stations were located at distances of 3, 21, 300, and 2,000 feet from the south exit baffles of the tunnel. The fifth position was located within the concrete housing of the tunnel shell at a distance of 1 foot from the surface of the tunnel.

Figures 9 and 10 show, respectively, the noise spectra measured at a position 3 feet from the baffles and at a distance of approximately 2,000 feet from the tunnel. The data show that, for some reason, the noise levels with the model in the test section were lower by a small but significant amount than the levels obtained for the case without the model in the test section. The measurements further revealed that under constant burning conditions the sound spectra at a given position are independent of Mach number.

In figure 10 the quietest background spectrum measured is also shown. It is seen that this background level is considerably lower than that reported in figure 4. The measurements in connection with figure 4 were taken during daylight hours while those of figure 10 were taken at night.

In addition to the data shown in these figures, data were also taken by NACA personnel using Statham pressure gages placed within the operating ram jet itself. The data from these gages indicated that two low-frequency sound pressure levels were being generated in the engine or within the test section itself - one located approximately at 50 cps and the other located between 5 and 8.5 cps. From the Statham gage recordings approximate values of the alternating pressure amplitude of each of the two low-frequency components were obtained and converted to sound pressure levels. The sound pressure levels estimated from these measurements were 172 decibels at 8.5 cps and 170 decibels at 50 cps.

The low-frequency data were supplemented by further pressure and sound-level records obtained by NACA personnel. Analysis of typical records obtained from the measurements showed that during rough burning the predominant noise component lay between the limits of 5 cps and 10 cps. The sound pressure level in this range of frequencies at a distance of 25 feet from the south exit of the original wind tunnel lay between 118 and 125 decibels. The acoustic measurements also showed that during smooth burning major frequency components of the noise lay between 20 cps and 70 cps.

All measurements reported indicated that there was a considerable amount of sound energy below 80 cps with the principal frequency components lying in the ranges from 5 to 10 cps and 40 to 50 cps. The measured and calculated sound pressure levels and the predominant frequencies in this range as determined from the various methods of measurement were in general agreement with each other.

CRITERION FOR ACCEPTABLE BACKGROUND LEVELS

The discomfort and annoyance during jet-engine operation in the 8- by 6-foot tunnel were attributed by many observers as being largely due to the high levels of the low-frequency noise (below 300 cps). In addition to these reactions, the very low frequency noise also caused window rattling and body vibration.

It is a difficult matter to attempt to evaluate the discomfort to people produced by any type of noise. As a result, a design criterion was established by combining (a) the background levels measured at 2,000-foot distance and (b) the 20-decibel equal-loudness-level contour as shown in figure 11. The loudness-level contour has been adjusted in level to correspond to the case of octave bands containing random noise (see ref. 1). This criterion curve later was designated as the BBN nighttime criterion. In recent years, this particular criterion has been somewhat modified as a result of field experience based on accumulated statistical data. The present best estimate for this criterion is also shown in figure 11.

Many objections from neighboring residents were obtained when the tunnel was operated with steady burning at Mach 2.0 (see fig. 10). Some objections were also obtained to the noise produced when there was no burning and no model in the test section. This condition is shown by the second curve from the top in figure 10. Obviously, no objections could be registered against the tunnel when it was not operating. This condition is shown by the bottom curve in figure 10, which was used to determine a portion of the criterion curve for the 8- by 6-foot wind tunnel.

Based upon these studies, a design specification shown in figure 12 was obtained by subtracting the criterion curve in figure 11 (heavy line) from the top curve in figure 10. The air- and terrain-loss data shown in figure 12 were taken from the files of Bolt Beranek and Newman, Inc. These losses vary greatly with wind conditions.

DESIGN AND PREDICTED PERFORMANCE OF ACOUSTICAL TREATMENTS

Low-Frequency Resonators, 5 to 11 Cps

On the basis of the noise measurements mentioned in the section entitled "Characteristics of Noise Source" the conclusion was reached that in the frequency region between 5 and 40 cps the noise levels should be attenuated by 30 decibels if possible. A study of the tunnel construction revealed that it would be possible to place a series of resonators covering the frequency range between 5 and 11 cps in the space between the original concrete housing and the steel conical diffusing section of the tunnel. Resonators to control the frequencies in the range between 12 and 20 cps would have to be incorporated in sections forming an extension to the existing tunnel.

The acoustical resonators were designed according to formulas (1) to (7) given in the appendix, and these resonators were incorporated in the existing structure as shown in figures 1, 2, and 13. The openings of each of the five lowest frequency resonators consisted of four rectangular slots cut through the steel diffuser side walls of the tunnel.

In order to test the performance of the resonators, a scale model of the 8- by 6-foot wind tunnel was constructed with the scale 1 inch equal to 1 foot which resulted in a geometric scale factor of 1 to 12. However, since the scale study was made at room temperature and since the tunnel was to operate at higher temperatures, the effective acoustic scale factor was approximately 1 to 10. This scale model is discussed more fully in a subsequent section devoted to scale-model tests. The final design of the resonators is shown in table I. It is to be noted that the dimensions of the rectangular slots in the scale model forming the openings of the cavity resonators were different from those finally selected. This difference was based upon structural features and upon information derived from the measurements made on the scale model. The estimated noise-reduction characteristics of the full-scale resonators, based on the model tests described in a subsequent section, were as follows: (a) No attenuation below 3.5 cps, (b) rising attenuation between 3.5 and 4.5 cps, (c) 20 decibels of attenuation between 4.5 and 10.5 cps, and (d) no attenuation above 12 cps.

Low-Frequency Resonators, 12 to 20 Cps

For the frequency range between 12 and 20 cps an additional series of resonators was designed with the general appearance shown in figure 14. The cross section through this section of resonators comprises six ducts, each with an open cross-sectional area of 100 square feet. This configuration was chosen to match the design necessary for the glass-fiber tuned ducts which operate in the frequency range between 20 cps and 800 cps. The design data for these resonators are given in table II. The estimated noise-reduction characteristics of the full-scale resonators in this frequency range, based on model tests described previously, were as follows: (a) No attenuation below 8 cps, (b) rising attenuation between 8 and 11 cps, (c) 20 decibels of attenuation between 12 and 20 cps, and (d) no attenuation above 22 cps.

Tuned Duct, 20 to 800 Cps[1]

In order to control the noise in the frequency region between 20 and at least out to 400 cps, it was decided to use a special tuned-duct structure designed according to the theory given in the appendix. According to the theory, a tuned duct has the property of providing a maximum in the curve of attenuation versus frequency at a particular resonance frequency with appreciable attenuation at frequencies on either side of resonance. In this design it was decided to place that resonance frequency at or slightly below 100 cps in order that the range between 20 and 400 cps would be covered.

The theoretical performance of the tuned duct for a 10-foot-square open area is shown in figure 15. This chart was calculated under the assumption that the specific acoustic impedance measured at the surface of the material would be independent of the direction of the acoustic particle velocity. Actually, this assumption is probably not true as comparison of measured and calculated data shows. The effect of different air spaces behind the Fiberglas treatment and the effect of changing the Fiberglas thickness, calculated for a frequency of 40 cps, are shown for information purposes in figures 16 and 17. From these data it was decided that for a 10- by 10-foot-size duct the air-space depth behind the treatment should be 2 feet and that the acoustic blanket should have a density of 3 pounds per cubic foot and a thickness of 6 inches.

In order to prevent the sound waves that penetrate the acoustical material from traveling behind the material along the length of the lined duct and then reappearing at the far end substantially unattenuated, it was necessary to provide for partitions along the length of the tuned-duct structure. As a practical matter these partitions should be as close together as is possible. As a result of a cost analysis, it was decided that the partitions should be spaced sequentially at separations of 4.5, 6.25, and 7.5 feet. These spacings were chosen so that the standing waves in each of the compartments would be slightly different. Staggering the spacings of the partitions leads to beneficial results as is shown in a subsequent section covering the model tests.

Parallel Baffles, 800 to 6,000 Cps

In order to control the noise in the frequency range between 800 and 6,000 cps, it was recommended that a series of parallel baffles having a thickness of $3\frac{5}{8}$ inches spaced 16 inches on centers should be

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[1]It originally was believed this duct would perform only out to 400 cps.

used. The performance of these baffles is discussed in the appendix and is shown in figure 18.

Lined Bends

One lined bend already existed in the structure at the end of the diffuser at the time the special acoustical design was planned. This lined bend was expected to give the results shown by the curve labeled D = 25 feet in figure 19.

Inspection of the expected attenuations from the parallel baffles revealed that the attenuation of the higher frequencies would still be inadequate unless some further treatment were provided. It was decided that a second lined bend should be installed at the exit end of the Fiberglas tuned-duct section. On the wall opposite the outlet of the Fiberglas duct, it was recommended that 6 inches of acoustical material should be placed flat against the wall. The attenuation provided by this treatment, above about 200 cps, was expected to be up to 18 decibels.

Integrated Design

In a previous section the acoustic design requirements were derived and they are shown in figure 12. It was necessary to combine the resonators, the proper length of tuned duct, and the proper length and spacing of parallel baffles to achieve the required attenuation. Three schemes for achieving the noise-reduction requirements were considered. The first of these schemes (designated scheme A, fig. 20) was believed to provide adequate treatment for all future types of jets or Mach number conditions that could be anticipated at the present time. The second and less extensive scheme (scheme B, fig. 21) was designed on the basis that it was satisfactory for present types of ram jets and Mach number conditions. A third scheme (scheme C, fig. 21) was included as a possible future extension to scheme B.

The expected added attenuations from the three proposed schemes are shown in figure 22. These curves were obtained by adding together. the acoustical behavior of each of the component sections of the proposed acoustical treatments, and, where applicable, by subtracting the effect of removing the original baffles from the south exit of the original plenum. The curves for schemes A, B, and C, shown in figure 22, represent the estimated over-all behavior of the total acoustical treatment based on the data available at the time of the analysis. If these curves were recalculated based on the more recent data shown in figures 18 and 19 some minor changes would be noted, but the general appearance and orders of magnitude of attenuation would be the same.

Scheme A shown in figure 20 was adopted. It is seen that an adequate factor of safety was provided by this scheme.

MODEL TESTS

All of the component acoustical treatments used in the supersonic tunnel were studied in model form, ranging in scale from 2.5 to 1 to 10 to 1. The results of the model tests were interesting, both because they were successful in predicting the attenuation provided by the final structure and because they revealed some important information on scaling.

Scale Tests on 5- to 11-Cps and 12- to 65-Cps Resonators

Quiet-air tests.- In order to test the effectiveness of the proposed 5- to 11-cps resonators, which used the space between the steel diffuser and the outer concrete structure, a 12-to-1 scale model of the tunnel was constructed. Although the dimensional scaling was 12 to 1, the effective acoustical scaling factor was 10 to 1 because the model tests were made at 70° F while the tunnel was designed to operate at about 250° F.

Measurements were made on the model in the frequency range between 40 and 160 cps. The concrete housing around the full-scale tunnel was simulated by 1 inch of Masonite on the model. The steel shell of the diffuser was scaled in thickness so that its weight in pounds per square foot was, in the model, about one-tenth that of the actual tunnel.

The model tunnel was terminated with Fiberglas wedges to reduce spurious effects that might be introduced by the acoustics of the room in which the tests were made and to reduce the general noise level inside the model. The air volume between the Masonite housing and the tunnel diffuser was divided into five separate enclosures by vertical partitions. For the initial test horizontal partitions were also placed below the tunnel shell in order to form symmetrical volumes about the tunnel in each section.

The volumes of the air spaces between the partitions were about 0.0008 times those given for the full-scale tunnel in table I. In the middle of each partitioned section, four or eight slots were cut into the steel shell of the diffuser.

A loudspeaker sound source was introduced at the 8- by 6-inch throat of the model and a microphone was rigged on a wire so that it could be moved along the axis of the tunnel. Sound pressure levels were recorded at intervals of 1 foot along the entire length of the tunnel. Measurements were made both with the resonators opening into the tunnel and with the resonators blocked off by sheet metal. The differences between these two sets of readings yield the attenuation of sound, in decibels, which is attributable to the resonators alone.

The initial measured attenuations are shown in figure 23. It is seen that, in the frequency range from 50 to 95 cps, the attenuation is above 25 decibels, reaching peaks of more than 50 decibels at intermediate frequencies. The peak attenuation at 85 cps was not measurable because the levels inside the tunnel were too close to the ambient noise level in the room. Based on these tests, it was possible to readjust the resonance frequencies by proper choice of the slot sizes and the air volumes. This readjustment was made, and the dimensions of the slots used in the second series of tests are those given in table I for a full-scale tunnel.

Moving-air tests.- In the second set of tests, a number of changes were made for structural reasons. The most important objection to the initial design was that the slots of the first two resonators were too close to the test section. Pressure measurements in the full-scale tunnel showed that, because of the high speed of the air, the difference in pressure at the diffuser wall and outdoors at the proposed slot positions was too high to allow the introduction of openings in the tunnel shell, without major structural changes to prevent structural failures.

In order to alleviate this difficulty, the horizontal partitions located under the diffuser in the model were eliminated. This step made it possible to use the air volume below the partitions and thus to locate all five resonators farther downstream.

In the ensuing tests, a group of 14 resonators, tuned between 12 and 65 cps, were also added for evaluation at the end of the diffuser section, as shown in figure 24.

At this stage the method of testing was reassessed. A measurement of the true effectiveness of an acoustical resonator of the type described here presents a very difficult problem. Ideally, the performance of such an "acoustic filter" is determined by measuring its insertion loss in the transmission line of which it forms a part. This can be done by making measurements before the filters are installed in the tunnel and after they are installed. For this test, the acoustic impedance looking back toward the test section must be the same for the model tunnel as for the full-scale one. Also, the impedance at the open end must be the same for the model as for the actual tunnel. In the initial tests it was not feasible to simulate the impedance of the 8- by 6-foot test section, nor did it seem necessary to provide air flow until the resonator design was more fully developed. The initial tests, it was felt, would yield a valid indication of the relative performance of the resonators even though such measurements were made with reference only to a loudspeaker as a source of sound.

For the final set of tests, a steady flow of air was introduced into the tunnel to simulate actual conditions of operation. It was felt important to determine whether the efficiency of the resonators was reduced in the presence of the air stream. A 12-inch-diameter pipe approximately 30 feet in length was connected between an available source of air and the 8- by 6-inch section of the scale model. The speed of the air through the scale model was comparable in magnitude to that produced in the full-scale tunnel. Several different test setups were tried for each of two velocities of air flow, corresponding to Mach numbers of 0.052 and 0.066, as measured at the 25.8-inch-diameter section (large end) of the tunnel diffuser.

A plenum chamber containing a loudspeaker was located in turn at each of two positions along the 12-inch section of pipe. These two locations, designated as Ⓐ and Ⓑ, are shown in figure 24. With the chamber located at Ⓐ, the lower Mach number of air velocity was obtained (0.052). In this case, the loudspeaker was placed in a baffle that divided the chamber in halves. The baffle contained several holes to insure an equalization of pressure on either side of the speaker. This chamber was inserted between the 12-inch pipe section and the 8- by 6-inch section of the tunnel so as to form an integral part of the path through which the air flowed. The presence of such a large chamber in the path of the air stream created a highly turbulent condition in the immediate neighborhood of the chamber. Furthermore, this turbulent air, to a considerable extent, was carried downstream along part of the tunnel.

The chamber located at position Ⓑ was connected to the 12-inch pipe only through a small pipe of approximately 3-inch diameter. Also, the speaker was moved up to one corner of the chamber to feed the lead-in pipe directly. This setup resulted in a higher air speed (0.066 Mach number at the 25.8-inch end of the tunnel) and also produced a relatively smooth flow of air through the tunnel.

It was felt that these test setups simulated two conditions of air flow, turbulent and smooth, which would be encountered in actual operation. Also, the acoustic source impedance was more like that of the large tunnel, although its actual value was indeterminate. In this series of experiments the microphone was placed at the termination of the resonator section, flush with the upper inner wall of the resonator (position Ⓒ, fig. 24). The microphone was shielded from the wind by four layers of cheese cloth.

The following test procedure was adopted in carrying out this phase of the resonator studies. Measurements of sound levels were made at position Ⓒ. A General Radio Co. Rochelle salt crystal microphone was connected directly to a General Radio type 759-B sound-level meter, which, in turn, fed into a type 1550-A octave-band analyzer; this was then fed into a General Radio type 760-A narrow-band analyzer. With the chamber placed at each of the positions Ⓐ and Ⓑ, the following series of measurements was made:

(1) octave-band analyses of the wind noise alone over the entire frequency range (20 to 10,000 cps) with all the resonators blocked

(2) narrow-band analyses at discrete frequencies in the range from 30 to 700 cps of the wind noise alone with all the resonators (5 to 65 cps) blocked

(3) octave-band analyses of the wind noise alone with first the 5- to 11-cps resonator group open, then the 5- to 16-cps resonator group, and, finally, all the resonators (5 to 65 cps) open

(4) narrow-band analyses of the wind noise alone at discrete frequencies with first the 5- to 11-cps resonator group open, then the 5- to 16-cps group, and, finally, the 5- to 65-cps group open

(5) narrow-band analyses with pure tones introduced into the loudspeaker in the presence of wind noise, first with all the resonators blocked and then, in turn, with the 5- to 11-cps group, the 5- to 16-cps group, and all the resonators (5 to 65 cps) open.

(6) narrow-band analyses with pure tones introduced into the loudspeaker with no air flow through the tunnel, first with all the resonators blocked and then, in turn, with the 5- to 11-cps group, the 5- to 16-cps group, and all the resonators (5 to 65 cps) open.

In each case the attenuation in decibels attributable to the resonators was taken to be the difference in sound pressure levels at the microphone (position Ⓒ) as measured when all the resonators were blocked and when all the resonators were open. When pure tones were introduced into the speaker, they were set at constant voltage to enable direct comparison between the levels in each test. Care was taken throughout this series of tests to set the pure-tone levels as high as possible without overloading the electrical system.

Discussion of results.- Figure 25 shows the relative levels of the wind noise over the frequency range from 3 to 15 cps for the condition where the plenum chamber was located at position Ⓑ, as shown in figure 24. This setup represents the condition of smooth air flow through the tunnel, resulting in a Mach number of 0.066 at the 25.8-inch circular section of the tunnel. The wind-noise levels were taken for three conditions: (a) With all the resonators blocked (5 to 65 cps),

(b) with the 5- to 11-cps group open, and (c) with all the resonators (5 to 65-cps) open. It is important to note that the various levels represented by the three conditions of testing are of the same order of magnitude throughout the measured frequency range. This fact showed that in this case the presence of the resonator slots in the tunnel produced little change in the wind noise through the tunnel.

Figure 26 shows the relative levels of wind noise in the tunnel for the case where the plenum chamber was located at position Ⓐ for the conditions: (a) with all the resonators (5 to 65 cps) blocked, (b) with the 5- to 11-cps group open, and (c) with the 5- to 16-cps group open. This series of tests represents the condition of air turbulence as compared with the condition of relatively smooth flow obtained in the previous series. It is interesting to note that in these tests the turbulent air flow resulted in considerably higher levels of wind noise for the case where the resonators were all blocked. On comparing these levels with the levels obtained during smooth air flow, it is found that in the turbulent case the levels are from 5 to 20 decibels higher. These noise levels were reduced by the resonators in the same manner as were the test tones. It is important to observe that noise associated with turbulence or shock waves prior to the installation of resonators in the full-scale tunnel will be correspondingly reduced.

In figure 27 is plotted the attenuation in decibels of pure-tone levels in the presence of turbulent air. In this test the plenum chamber holding the loudspeaker was located at position Ⓐ and the values of attenuation plotted in figure 27 represent the difference in pure-tone levels between those measured when all the resonators were blocked and those measured when the 5- to 16-cps resonator group was open (with the 18- to 65-cps group blocked). The measurements as taken with the narrow-band analyzer represent the sum of the pure-tone levels and the wind-noise levels at the frequencies measured. From these values the absolute levels of the pure tone alone were calculated. These were the values used in establishing the curve in figure 27. The solid-step curve shown in this figure represents an average of the measured curve. It is seen from this curve that from 5.5 to 7.5 cps the average attenuation which can be attributed to the resonators is 14 decibels. In the frequency range from 8 to 20 cps approximately 19 decibels of attenuation is obtained.

These values of attenuation of pure tones as determined from the narrow-band measurements are verified by the measurements of the attenuation of wind noise alone taken by the octave bands. The results of the octave-band analyses are represented in figure 27 by the dashed lines and are seen to be in good agreement with the reductions obtained in the pure tones.

Figure 28 shows the attenuation of pure tones in the presence of smooth air flow as obtained with the plenum chamber at position Ⓑ for the case where the 5- to 11-cps resonators alone were open. In this case considerably more attenuation is achieved in the frequency range from 4 to 8 cps with an average attenuation of 20 decibels in the range of 5.5 to 12 cps. Measurements were not carried out to higher frequencies because the loudspeaker output was insufficiently high at position Ⓑ.

The attenuation in decibels as obtained for the case where pure tones were introduced into the tunnel with no air flow present is shown in figure 29. These measurements were taken with the loudspeaker located in the chamber in position Ⓐ. In this experiment all the resonators (5 to 65 cps) were open. The solid-step curve represents an average of the actual measured curve. As may be seen, in the frequency range from 5.5 to 12 cps an average attenuation of 20 decibels is obtained. Above 13 cps the reduction is approximately 25 decibels.

The results of the tests on the relative effectiveness of the 5- to 11-cps resonators under various conditions are summarized in figure 30. This figure represents the attenuation of pure tones as obtained from the following measurements: (A) With no air stream through the tunnel, (B) in the presence of turbulent air flow, and (C) in the presence of smooth air flow.

From this summary it is concluded that, in general, the behavior of the resonators is not appreciably affected by the presence of air flow as long as the air flow is relatively smooth in character. The presence of highly turbulent air in the vicinity of the resonator openings, however, reduces the efficiency of those resonators involved. It is further concluded that use of the 5- to 11-cps resonators results in an overall reduction of about 20 decibels.

The initial design of the model for the 12- to 65-cps resonators, for which data were just presented, was incorporated in a single square duct with the interior sides equal to 24.5 inches. This corresponded to 24.5 feet in the full-scale model since the scale factor was 12 to 1.

From an aerodynamic standpoint, it is desirable to conduct the air coming out of the diffuser through as smooth a path as possible. This requires the elimination of sudden changes in cross-sectional area in any extension to the tunnel. Since treatment for the control of frequencies above 20 cps was to be in the form of six lined ducts, each having an inside cross-sectional open area of 10 by 10 feet, it was considered desirable to maintain this configuration for whatever resonators were required above 10 cps. Figure 14 shows a sketch of the proposed scheme for a 12- to 65-cps resonator group. A model of one of these six ducts containing this resonator group was constructed at a scale of 6 to 1 and a series of tests was carried out to determine their acoustical performance. Exactly the same test procedure was followed as that used in tests for the 5- to 11-cps resonator.

The results of this series of tests are shown in figure 31. In the frequency range from 11 to 20 cps the resonators produce from 15 to 25 decibels of attenuation. Above this frequency range the attenuation averages about 30 decibels. The low attenuation below 15 cps is attributed to the proximity of the first two resonators to the sound source. In this case the loudspeaker was attached to the model duct at a distance of only about 2 feet from the first resonator (12 cps). When the resonators are at a reasonable distance from the sound source, the normal efficiency of the resonators is realized. There is no other apparent reason why the 12-cps and 14-cps resonators should not be as efficient as the remaining resonators of this group.

This series of tests also proved that, with the configuration used in the model experiments, it was possible to extend resonators of this design to at least as far as 65 cps. However, since the construction of special resonators of this type is a costly matter, it was felt that the minimum number of resonators necessary to provide adequate protection should be adopted in the final design. This minimum number was determined by the lower frequency limit of effectiveness of the tuned duct. In the final design, resonators up to only as far as 20 cps were utilized according to the construction shown in figure 14.

Scale Tests on Tuned Duct

A lined acoustical duct tuned for optimum performance at 100 cps was used for the attenuation of noise between 20 and 400 cps. In order to check the calculations discussed in the appendix a model of this duct was constructed at a scale of 2.5 to 1.

The model installation consisted of a 24-foot-long lined duct preceded by a section including the sound source. Spaced $9\frac{5}{8}$ inches from the interior of the outside wall was $2\frac{3}{8}$ inches of Fiberglas PF board having a density of 5.5 pounds per cubic foot and a flow resistance of approximately 11.5 rayls per centimeter. The inside walls were 4 by 4 feet. The outside walls of the duct consisted of two layers of $\frac{3}{4}$-inch plywood separated by about 12 inches of sand. The open end of the duct terminated in free space. Eight 16-inch loudspeakers were installed in a housing at the other end of the duct for a sound source.

This test installation provided a high degree of insulation against undesired sound leakage. Also, the loudspeaker array and geometry were such that the generated sound waves were nearly plane over the entire frequency range of interest in these tests.

In the initial test of this series the air space behind the acoustical lining was separated by partitions that were spaced regularly at intervals of 2.5 feet. Measurements of the attenuation through the duct were made in the frequency range from 30 to 1,000 cps which corresponded to full-scale frequencies of 12 to 400 cps. These data were obtained by moving a microphone through the duct and recording the sound pressure level at intervals of 1 foot or less. The slope of each curve yields the attenuation in decibels per foot for each frequency. Figure 32 shows typical examples of some of the measured basic data. In all cases the slopes were well defined. The results of the measurements are summarized in figure 33.

The general trend of these results is in reasonably good agreement with the theoretically calculated curve also shown in figure 33. At low frequencies the curve of measured attenuation is slightly higher than the calculated curve. The discrepancies that appear in the middle frequency range (50 to 150 cps) are the result of the wide and regular spacings of the partitions separating the air space behind the acoustical lining. The theoretical curve is based on the assumption that the spaces behind the acoustical lining are filled with a soft material such as kapok or that the partitions are spaced at intervals which are not greater than about one-eighth of the wave length of the highest frequency for which the duct is designed. In this case this assumption would demand that the partitions be spaced at approximately 6-inch intervals. Such close spacing, of course, is not practical and is certainly not required in the solution of the present problem. The greatest interest in this case is in the behavior of the duct at low frequencies (below 50 cps) because it is this range that determines the overall length of the duct.

Nevertheless, in order to eliminate the pronounced variations in attenuation in the 50- to 150-cps range, another series of tests was carried out in which the partitions behind the air space were irregularly spaced at intervals of 1.8, 2.5, and 3 feet. The results of this test are also shown in figure 33. The fluctuations in attenuation in the middle-frequency range were reduced and the attenuation in the low- and high-frequency limits was unchanged. The measured attenuation of 0.5 to 0.7 decibel per foot thus realized in the 50- to 150-cps range is more than sufficient to satisfy the requirements.

ACOUSTICAL PERFORMANCE OF COMPLETED STRUCTURE

Upon completion of the acoustical structure, measurements of the acoustical performance of the treatment in the frequency range between 5 and 1,800 cps were made. These measurements were made with the use of loudspeakers mounted in the test section of the tunnel. Data were taken at a number of locations along the length of the diffuser and along the length of one of the six passages in the acoustical extension. All measured data are presented in tables IV to VII.

A special loudspeaker was constructed to carry out the measurements covering the very low frequencies. This speaker consisted of a large conically shaped diaphragm driven by a variable-speed motor. This diaphragm was approximately 3 feet in diameter and the frequency of its vibration could be controlled to cover the range from 5 to 22.8 cps. With it, sound levels of the order of 80 to 100 decibels were produced at the beginning of the diffuser section.

At frequencies between 22.8 and 1,800 cps, two 15-inch loudspeakers mounted in box baffles were located at the beginning of the diffuser and data were taken at a number of measuring stations. Sound levels between 85 and 105 decibels were produced in the main diffuser section. Background noise levels were sufficiently low at all times during the tests to cause no interference with the measurements on the acoustical performance of the resonators and the plenum at the end of the diffuser. In the evaluation of the lined-duct section, however, insufficient sound level was produced in this section by the loudspeakers located at the beginning of the diffuser.

In order to achieve higher sound levels, subsequent tests were performed with the two 15-inch loudspeakers placed at the entrance of the bottom left-hand duct facing toward the Fiberglas section. Data were taken at the start of the Fiberglas section and at every partition downstream therefrom.

In the low-frequency region (between 5 and 18 cps), data were taken at various positions along the diffuser section with the aid of a special low-frequency microphone and amplifier, and a Brush high-speed graphic level recorder. These data showed the detailed wave form at each position where the measurement was made. From these data it was possible to determine the approximate harmonic content of the wave and to deduce the effect of the resonators on the fundamental frequency.

Acoustic Performance of Tunnel Resonators (5 to 11 cps)

Measurements were taken along the length of the diffuser at most of the 14 stations shown in figure 13. The number beside each of the resonator openings is the design resonant frequency. The measured sound pressure levels in decibels at each of the stations relative to an arbitrary zero reference level are shown in figures 34 and 35.

The attenuation of the sound wave traveling down the diffuser begins before the resonator is reached and continues after the resonator is passed. If the driving frequency is located part way between the resonance frequencies of two resonators, the curve of attenuation versus distance moves to part way between the two resonators just as though a resonator for that frequency were located there. In this report the "position of resonance" means the position of a hypothetical resonator that would have a frequency part way between the two adjacent resonator frequencies. At no one of the six frequencies indicated in figures 34 and 35 was the total amount of attenuation provided by the resonators measurable. The difficulty was that the low-frequency loudspeaker generated harmonic components which could not be filtered out of the receiving system. As a result, after passing from the upstream side to the downstream side of the resonator, the remaining sound wave consisted primarily of harmonic components. That made it impossible to determine accurately the magnitude of the fundamental component on the downstream side.

In order to estimate the total amount of attenuation provided by the resonator, it was decided to observe the result of assuming that the maximum possible attenuation would be double that preceding the resonator. For example, let us refer to the 6.5-cps curve of figure 34. The resonance position for this frequency is seen from figure 13 to be located about half way between stations 6 and 7. The difference between the sound level at this point and that at station 14 is 24 decibels. However, 5 decibels of this 24 decibels would have occurred without the resonator because of area change (see right-hand column of numbers in fig. 13). Accordingly, the net amount of attenuation provided by the resonator up to this point is 19 decibels. This amount is then doubled in order to estimate the maximum likely attenuation provided by the resonator. This quantity, 38 decibels, is plotted at 6.5 cps on the upper curve in figure 36. A similar procedure was followed for the other frequencies and the combined results are shown by the upper curve of figure 36.

It is difficult to believe that the attenuation provided by the resonators should rise as high as 40 decibels at any frequency. Hence, as a lower limit, the total measured attenuation (even though limited by distortion at the lower frequencies) has been plotted as the bottom (broken) curve in figure 36. The real answer is somewhere between those two curves. The attenuation has been estimated and is shown by curve B.

Acoustic Performance of First Plenum

In addition to the data taken along the length of the diffuser, data were also taken at numerous other stations. From these data it is possible to deduce the amount of attenuation occurring in the plenum in the frequency region between 10 and 1,800 cps. The results are shown in figure 37. Because of standing waves there is considerable scatter of the points around the average curve shown. It is fairly clear, however, that the attenuation increases from a few decibels at 13 cps to about 20 decibels at the higher frequencies. These data are to be compared with more general data shown in figure 19.

Acoustic Performance of Resonators in Acoustical Extension (12 to 20 cps)

An estimate of the performance of the resonators in the six-cell muffler was again difficult to make because of the presence of harmonics. The procedure used in this evaluation was as follows: The sound pressure levels measured along the acoustical extension were plotted as a function of distance. The sound levels were measured at stations 0 to 4 in the diffuser (see fig. 13). In the frequency region between 12 and 20 cps, the sound levels at stations 0 to 4 were reasonably constant. The average level for these four stations with the resonators open was used as a reference line. The level at the beginning of the Fiberglas section following the resonators was then observed from the plot.

The difference between the level at the beginning of the Fiberglas section and the average level at stations 0 to 4 gives the total attenuation of the sound due to the combined effects of (a) the first plenum, (b) the resonators, and (c) the acoustical discontinuity between the resonator section and the Fiberglas section. The discontinuity loss, which is described in detail in a following section, was estimated to be zero below 13 cps and gradually increased to 3 decibels at 20 cps. The attenuation provided by the plenum is shown in figure 37.

As an example, at 15.75 cps the total loss as determined from the plots with resonators open was 31 decibels. Of this, 4 decibels were attributable to losses in the first plenum and 2 decibels to the discontinuity between the plenum and the Fiberglas section, leaving a net loss in the resonators of 25 decibels. Computations of this type were made at 12, 14, 15.75, 18, and 22 cps. The results are shown in figure 38 along with the data from figure 36 for the lower frequency resonators.

Effect of Temperature on Resonator Performance

The performance of the resonators in the region between 5 and 22 cps at 75° F is shown by the solid curve in figure 38. The design for the resonators was based upon a temperature of 250° F. If the assumption is made that the resonance frequencies of the resonators shift upward in proportion to the square root of the absolute temperature, the result is shown by the dashed line of figure 38. The resonators are expected, therefore, to provide an attenuation in excess of 20 decibels over the frequency range between 5 and 20 cps. This was the performance estimated in advance of construction.

Loss at Junction Between Resonator and Fiberglas Sections

In the frequency region above 20 cps, the data indicate that a loss in sound level occurred at the junction between the Fiberglas section and the resonator section in the acoustical extension. This loss is established by determining the average sound level in the resonator section of the acoustical extension. Then a straight sloping line is drawn through the levels measured as a function of distance in the Fiberglas section. The difference between the average level in the resonator section and the level at the point where this straight sloping line passes through the point representing the entrance to the lined-duct section is a measure of the loss at the junction. The results of this analysis are shown in figure 39. It is seen that the junction loss is zero below 14 cps and increases to about 4 decibels at 25 cps and remains between 4 and 5 decibels at all higher frequencies.

Acoustic Performance of Fiberglas Tuned-Duct Section

The acoustic performance of the Fiberglas tuned-duct section was determined from the set of data obtained by placing two 15-inch loudspeakers at the entrance of the bottom duct on the left-hand side when facing downstream. Sound-pressure levels were measured from the start of the Fiberglas section and at every partition downstream. From the plots of the data giving sound levels as a function of distance the average slopes in decibels per foot were determined. The results of this determination are shown in figure 40. It is seen that the average attenuation was approximately 0.5 decibel per foot over the entire frequency range from 20 to 700 cps. In other words, the 90-foot Fiberglas section of the acoustical extension provided an attenuation of about 45 decibels over a range of more than five octaves.

In the original tests on the model, a higher attenuation per foot over a narrower band of frequencies was predicted. Part of the reason for the lower attenuation per foot in the completed acoustical extension arises from the fact that twelve 10-inch-thick spacers are used along the duct. This results in an effective reduction of the over-all length by 10 feet, that is, from 90 feet to 80 feet. Hence, the attenuation per actual foot of Fiberglas treatment is 1.125 times that shown in figure 40. This number falls short of our predictions by approximately 0.05 decibel per foot but the attenuation extends over a wider frequency band than had been estimated on the basis of the model measurements.

The reasons for the frequency band being wider than predicted are not clearly understood at this time. It is noticed, however, that the Fiberglas PF board occupied a smaller percentage of the total treatment thickness (Fiberglas plus backing air space) in the acoustical extension than it did in the model. It may be presumed, therefore, that the performance of a muffler of this type is determined not only by the flow resistance of the lining, but also by the ratio of the thickness of the lining to the total depth of the acoustical treatment.

Overall Performance of Acoustic Treatment in 8- by 6-Foot Wind Tunnel

A summary of the overall performance of the acoustical treatment in the tunnel is given in table III. In column ① the sound levels measured in the test section as produced by a 16-inch-diameter ram jet operating with a 3,000-pound-per-hour fuel consumption in a Mach number 2.0 airstream are given. These numbers are the average of three determinations made at the Lewis Flight Propulsion Laboratory. In column ② the loss due to wave expansion in the diffuser is shown; in column ③, the loss in the first plenum and bend; in column ④, the junction loss; in column ⑤, the loss in the Fiberglas section; in column ⑥, the loss in the second plenum; and in column ⑦, the loss in the parallel baffles. (The losses in columns ⑥ and ⑦ are estimated from more complete data taken at other installations.)

The losses given in columns ② to ⑦ are totaled in column ⑧. The difference between that column and the measured levels in the test section (column ①) yields the resultant noise at the exit of the baffles as shown in column ⑨.

There was actually more noise arriving outside the tunnel than that shown by column ⑨ of table III because of leaks at the expansion joints in the original construction. If those leaks were sealed, the low noise levels indicated in table III could be achieved.

It is interesting to compare the resultant expected noise at the exit of the baffles with the criterion used for the design. In figure 10 the nighttime background noise level in summer was given (bottom curve). This level was measured at a distance of 2,000 feet from the wind tunnel. In order that the noise from the wind tunnel lie below the background noise at a distance of 2,000 feet, it is necessary that the level at the exit of the wind tunnel lie below the upper curve A shown in figure 41. This curve is established by taking the background noise spectrum given in figure 10 and applying the losses estimated by inverse-square diminution; this gives the maximum allowable levels at the exit of the baffles. A plot of the resultant estimated noise levels at the exit of the baffles as given in table III (see column ⑨) is shown as curve B in figure 41.

It is seen that in the lower frequency bands the resultant noise level lies more than 15 decibels below the maximum allowable levels as determined from the lowest measured background levels. In the higher frequency bands, the noise will be somewhat lower than is shown by curve B because of the directivity of the radiating end of the acoustical extension which was not taken into account. In obtaining curve B, it was assumed that the sound would radiate uniformly in all directions. It is to be expected, however, that, since the tunnel is located near an airport, the sound will be radiated at the higher frequencies to a much greater extent in the direction of the airport than in the opposite direction where the background measurements were taken.

It is also interesting to plot the background noise measured at the end of the acoustical extension when no jet was burning in the tunnel but when the air was moving through the test section at Mach 1.9. These data are shown as curve C of figure 41. In all frequency bands, except the lowest, the noise measured at the outer end of the outlet baffles came from external sources and not from inside the tunnel. It should be noted that, when a 16-inch ram jet is in operation, the sound levels at low frequencies will hardly increase a noticeable amount. An increase of the noise in the higher frequency bands is to be expected, however, at the exit of the baffles.

Bolt Beranek and Newman, Inc.,
Cambridge, Mass., April 23, 1953.

APPENDIX

BASIC INFORMATION ON TREATMENTS USED IN ACOUSTICAL DESIGN

Parallel Baffles

Prior to 1950, the most commonly used type of acoustical treatment for the reduction of noise in moving airstreams comprised a series of parallel baffles, usually $3\frac{5}{8}$ inches thick and spaced 8, 12, or 16 inches on centers. At the time of the design of the treatment for the Lewis 8- by 6-foot wind tunnel very little information on the attenuation provided by parallel baffles was available in the literature. What information was available was contradictory (see refs. 2 and 3).

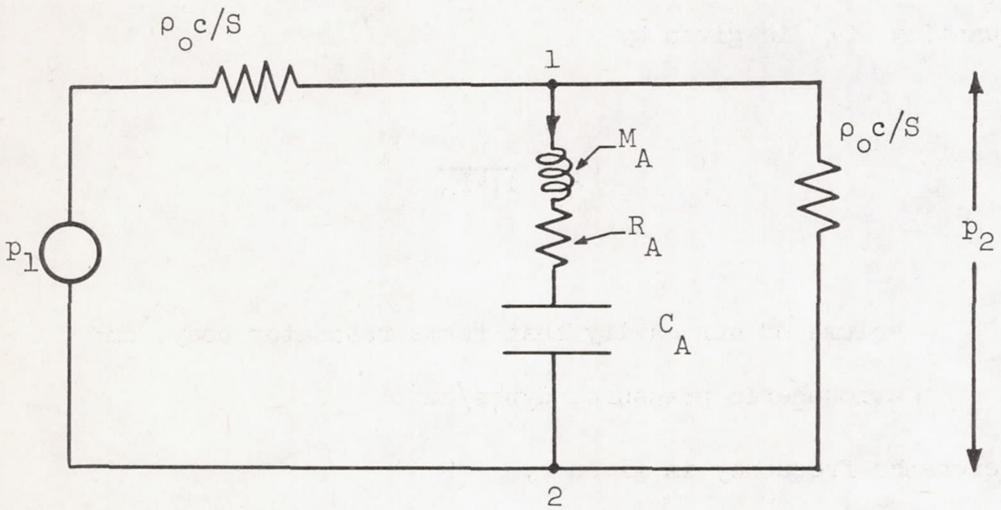
Accordingly, pure-tone tests were performed to determine the noise reduction provided by parallel baffles mounted 8 inches on centers inasmuch as this configuration had been successfully used in The Johns Hopkins University burner laboratory at Forest Grove, Maryland. These data revealed that the attenuations at some frequencies were much less than those shown in reference 3 and were in substantial agreement with those shown in reference 2.

Extensive data on the attenuation of sound in parallel baffles have been accumulated by Bolt Beranek and Newman, Inc., and by the Lewis Flight Propulsion Laboratory during the past three years. These data have also been confirmed by unpublished tests performed by the National Physical Laboratory in England.

Figure 18 shows the average of measured data in octave bands on parallel baffles whose thickness is approximately $3\frac{5}{8}$ inches for on-center spacings of 8, 16, $17\frac{1}{2}$, 24, and 32 inches. The data are given in decibels per foot of running length of baffle. It is assumed that the baffles are filled with 4-pound-per-cubic-foot glass fibers or 6-pound-per-cubic-foot mineral wool and that there is no other material, such as metal shavings or impervious coverings, in the baffles. It has also been assumed that the noise at the entrance end of the baffles is a continuous spectrum, shaped like that of a jet engine, and that the noise is measured with an octave-band analyzer. Slightly different results would be obtained with narrower band analyzers and with other noise sources.

Resonators

The absorption of frequencies below 20 cps cannot easily be accomplished in a structure of the size of the 8- by 6-foot wind tunnel using parallel baffles or other absorbing materials placed in the tunnel. It was necessary, therefore, to consider the possibility of incorporating resonators (see ref. 4) into the existing structure. It was expected that these resonators would act as acoustic filters in preventing sound produced in the test section from arriving at the exit opening of the tunnel. Study revealed that sufficient volume was available between the conical diffuser and the concrete housing around it to permit the installation of five resonators in the frequency range between 4.5 and 10 cps. The acoustical conditions at any point along the conical diffuser may be simply represented by the analogous circuit as shown by the following sketch.



The resonator is located at a point along the conical diffuser shown as terminals 1 and 2 in the sketch. The noise source and that portion of the diffuser upstream from the resonator may be represented by a lumped circuit, called Thevenin's generator, with an open-circuit pressure p_1 and an internal acoustic impedance $\rho_o c/S$. The downstream end of the conical diffuser may also be represented by the impedance $\rho_o c/S$ and the downstream sound pressure is represented by p_2. The quantity $\rho_o c$ is the characteristic impedance of air in rayls and the quantity S is the cross-sectional area of the tunnel in square centimeters at the position of the resonator.

The series elements M_A, C_A, and R_A are the constants of the resonator. The quantity M_A is given as follows:

$$M_A = \frac{(t + 0.96A)\rho_o}{A} \tag{1}$$

where

t thickness of metal side wall of diffuser, cm

ρ_o density of air, g/cm^3

A area of hole cut in metal side wall of diffuser to form resonator opening, cm^2

The quantity C_A is given by

$$C_A = \frac{V}{1.4P_o} \tag{2}$$

where

V volume of air cavity that forms resonator body, cm^3

P_o atmospheric pressure, $dynes/cm^2$

The resonance frequency is given by

$$f = \frac{1}{2\pi\sqrt{M_A C_A}} \tag{3}$$

The acoustic resistance R_A for resonator openings is given by

$$R_A = \frac{1}{A} 2\rho_o\sqrt{\pi\mu f}\left(t\sqrt{\frac{\pi}{A}} + 2\right) \tag{4}$$

where

μ kinematic coefficient of viscosity, cm^2/sec (for air at 20° C and 760 millimeters of mercury, $\mu = 0.156\ cm^2/sec$; this quantity varies about as $T^{1.7}/P_o$)

t thickness of metal side wall, cm

ρ_o density of air at 20° C, 0.00118 g/cm^3

A area of resonator opening, cm^2

P_o barometric pressure, $dynes/cm^2$ $\left(\text{under normal conditions, } P_o = 10^6\ dynes/cm^2\right)$

t temperature, $^\circ K$

Let

$$Z_A = R_A + j\left(\omega M_A - \frac{1}{\omega C_A}\right) \tag{5}$$

Solution of the equivalent circuit given in equation (5) reveals that, with the resonator present, the sound pressure downstream from the resonator p_2 divided by the sound pressure when there is no resonator present $p_1/2$ is given by

$$\frac{p_2}{p_1/2} = \frac{2}{2 + \dfrac{\rho_o c}{SZ_A}} \tag{6}$$

Also, let

$$\begin{aligned} Q_A &= \sqrt{\frac{\omega}{2\mu}}\,\frac{t + 0.96\sqrt{A}}{t\sqrt{\frac{\pi}{A}} + 2} \\ &\doteq 0.5\sqrt{\frac{A}{2\mu}} \end{aligned} \tag{7}$$

In the design of the resonator the Q_A of the circuit, the frequency ω, and the amount of attenuation desired at the resonance peak are available for specification. For this design, laboratory data taken in Cambridge showed that the area A should be at least 10 percent of the cross-sectional area S of the tube. With this cross-sectional area, it is possible to realize attenuations of the order of 20 decibels at the resonance peaks. In general, the value of Q_A should be as high as possible. With the area A of the resonator opening chosen, the volume V of the air space behind the resonator opening may be determined from equations (2) and (3).

Lined Bends

An important method for attenuating sound in a moving airstream is to place a bend in the duct carrying the air and to line with acoustical material the side of this bend against which the moving airstream is directed. At the time the 8- by 6-foot supersonic wind tunnel was being designed, no pertinent data were available on the attenuation provided by such a lined bend. Since that time it has been experimentally determined that the sound is attenuated by a lined bend according to the curves shown in figure 19 which were obtained from unpublished data from the research department of Bolt Beranek and Newman, Inc. If the wave length of the sound is greater than the width of the duct, the attenuation provided by a lined bend is very small.

The curves of figure 19 are based on the assumption that the lining for the bend has an absorption coefficient that is greater than 0.8 for wave lengths that are approximately twice the width of the duct. Two lined bends exist in the final design of the 8- by 6-foot supersonic wind tunnel, with the one nearest the diffuser having absorption coefficients in excess of 0.8 above 20 cps. The one at the exit of the muffler has absorption coefficients in excess of 0.8 above 200 cps.

Tuned Ducts

In 1942 it was shown by Beranek (ref. 5) that ducts can be built which provide high attenuations in a restricted frequency range and that these attenuations can be approximately predicted from a theory published by Morse (ref. 6). Prior to 1951, application of this observed phenomenon had not been made to large-scale sound-control problems. It was decided during the course of this problem to experiment with ducts for attenuating sound in restricted frequency ranges using the theory of Morse and subsequent papers by Beranek (refs. 7 and 8) as a guide to the design.

Determination of acoustic impedance.- The first step in determining the performance of a tuned duct is to ascertain the specific acoustic impedance of the lining. The specific acoustic impedance is defined as the ratio of the pressure to the particle velocity at the surface of the material. This impedance may be measured in an acoustic-impedance tube or it may be calculated if sufficient information about the acoustical material is available. The necessary quantities which must be known are as follows:

R_1 specific flow resistance, rayls/cm

ρ_o density of air, g/cm^3

Y porosity of acoustical material defined as volume of voids in a material to its total volume

k structure factor (structure factor is determined by configuration of fiber or pores in acoustical material)

K volume coefficient of elasticity of air in interstices, dynes/cm^2 (at very low frequencies $K = 1.4\ P_o$; at high frequencies, $K = P_o$)

P_o atmospheric pressure, dynes/cm^2

In order to determine the acoustic impedance, it is necessary to obtain the propagation constant for the material. The propagation constant b per centimeter is composed of a real and an imaginary part. The real part is the attenuation constant in nepers per centimeter and the imaginary part is the phase constant in radians per centimeter. In order to determine the propagation constant, figures 42 and 43 are used. The abscissa of figure 42 is obtained by dividing the flow resistance per centimeter of the material by the product of the angular frequency, the density of air, and the structure factor.

The flow resistances per inch of two commonly used acoustical materials, TWF Fiberglas and Fiberglas PF board, are shown in figure 44.

The parameter in figure 42 is found by multiplying the density of the air by the product of the structure factor and the porosity and dividing by K. Data on structure factors are not readily available in the literature. For Fiberglas materials of the types named in figure 44, the structure factor may be assumed to be 3.0. The porosity Y is approximately equal to 0.95 for Fiberglas materials.

Having determined the abscissa and the parameter, the ordinate is found from figure 42. The magnitude of the propagation constant b is determined by multiplying the ordinate by ω. The phase angle of b is found from figure 43. The abscissa and the parameter are the same quantities for this figure as for figure 42. Once the phase angle and the magnitude of b are known, the real and imaginary parts are determined in the usual manner. The quantity b is then substituted in equation (8) to obtain the impedance Z as follows:

$$Z = \gamma e^{j\phi} = -\frac{jK}{\omega Y} b \coth bd \tag{8}$$

where

coth hyperbolic cotangent

d depth of acoustical material

γ magnitude of specific acoustic impedance

ϕ phase angle of specific acoustic impedance

The hyperbolic cotangent of the complex quantity $bd = \left(\psi_1 + j\psi_2\right)$ may be found with the aid of a Smith chart (ref. 9). In order to use the chart, the hyperbolic cotangent of ψ_1 must be found. This quantity is equal to the quantity shown on the calculator as (Max/Min). In addition, the quantity on the edge of the chart called "wave lengths toward the load" must be determined. This quantity is equal to $0.25 = \psi_2/2\pi$. In case a Smith chart is not available, the real and imaginary parts of the hyperbolic cotangent of bd may be found from equations (9) and (10) as follows:

Real part,

$$\coth bd = \frac{\tanh \psi_1\left(1 + \tan^2\psi_2\right)}{\tanh^2\psi_1 + \tan^2\psi_2} \tag{9}$$

Imaginary part,

$$\coth bd = \frac{\tan \psi_2\left(1 - \tanh^2\psi_1\right)}{\tanh^2\psi_1 + \tan^2\psi_2} \tag{10}$$

It may be economical to replace part of the acoustical material by an air space. This is permissible, if the air space is located next to the back surface and if the flow resistance of the remaining material is increased. Also, if an air space is opened up behind the material, it must be subdivided by impervious partitions to reduce transmission along the length of the duct behind the lining.

Determination of attenuation of duct.- The attenuation of the duct in decibels per foot is determined from Morse's paper (ref. 6). For those who have not followed the mathematics in Morse's paper, it will be of help to outline simply the various steps necessary to calculate the attenuation of sound in a long square duct with all walls similarly treated as follows:

(1) Assume a duct of given transverse dimensions uniformly lined with a material whose specific normal impedance is known

(2) Calculate, from these facts, at each frequency two parameters μ and K which in turn are related by a formula to an attenuation constant σ.

(3) Multiply σ by $54.6f/c$ to obtain the attenuation in decibels per foot (or centimeter), where f is the driving frequency and c is the velocity of sound in feet (or centimeters) per second. For convenience in calculation, Morse has plotted two charts, one showing the transformation from the impedance, frequency, and dimensions of the duct to the parameters μ and K, and the other, the transformation from μ and K to the constant σ. These charts are presented as figures 45 and 46, respectively.

The procedure in obtaining the attenuation of sound in decibels per foot (or centimeters) in a square duct of cross section l^2 having all walls similarly covered with a material whose specific normal impedance is given by

$$\frac{Z}{\rho c} = \sqrt{\left(\frac{R}{\rho c}\right)^2 + \left(\frac{X}{\rho c}\right)^2}\, e^{j \tan^{-1}(X/R)} = \frac{|Z|}{\rho c} e^{j\phi} = \gamma e^{j\phi} \tag{11}$$

is as follows:

(1) Divide ϕ (in degrees) by 13.2

(2) Multiply γ by 2 and divide by η, where $\eta = 2f\frac{l}{c}$, f is the frequency, and c is the velocity of sound in feet per second (or centimeter per second)

(3) Use $\phi/13.2$ and $2\gamma/\eta$ as abscissa and ordinate, respectively, in figure 45 and obtain μ and K

(4) Multiply μ by 2.38 and divide by η and similarly for K

(5) Replace μ/η and K/η by μ'/η and K'/η in figure 46 and read σ from the ordinate

(6) Finally, determine the attenuation in decibels per foot (or centimeter) as $54.6\left(\sigma\frac{f}{c}\right)$

The multiplication of γ by 2 and of K/η and μ/η by 2.83 to replace γ, K/η, and μ/η is necessary because the charts presented by Morse are drawn for the case of a single absorbing wall, while here four-wall coverage is considered.

Frequently, it will be found for cases of small attenuation ($\sigma < 0.1$) that figure 46 is not usable and that one must use approximate formulas to determine σ; these formulas are given as follows:

$$\sigma \doteq (\mu'/\eta)\,\frac{(K'/\eta)}{\tau} \tag{12}$$

$$\tau \doteq \left[1 + (K'/\eta)^2 - (\mu'/\eta)^2\right]^{1/2} \tag{13}$$

Also it is often found that $\tau \doteq 1$, so that

$$\sigma \doteq (\mu'/\eta)(K'/\eta) \tag{14}$$

Reference to figure 45 shows that there is a region on the chart in the vicinity of $\frac{\phi}{13.2} = -3$ and $\frac{\gamma}{\eta} = 1.0$ where the attenuation will be very large. It is this region of the chart that holds the most interest and is the point at which the center frequency is chosen.

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TABLE I

DESIGN OF RESONATORS FOR 5- TO 11-CPS FREQUENCY RANGE

Resonator number	Number of slots	Scale-model slot dimensions, in.	Full-scale slot dimensions, ft (a)	Full-scale volume of air behind slot, cu ft	Full-scale distance between partitions, ft	Expected full-scale resonance frequency, cps
1	4	1.8 × 0.853	1.25 × 4	28,100	57.0	4.85
2	4	1.5 × 0.82	1.5 × 4.46	20,000	36.2	6.2
3	4	6.55 × 1.9	1.75 × 5.33	15,300	23.45	7.7
4	4	6.55 × 2.95	2 × 5.74	12,400	20.0	9.0
5	4	[b]6.55 × 2.5	2 × 6.53	9,730	17.4	10.5

[a]Dimensions are adjusted to account for experimental observation that measured resonance frequencies were approximately 10 percent higher than those calculated.

[b]Eight slots were used in scale model for this resonator. In all other cases four slots were used.

TABLE II

DESIGN OF RESONATORS FOR 12- TO 20-CPS FREQUENCY RANGE

Resonator number	Number of slots	Full-scale slot dimensions, ft	Full-scale volume of air behind slot, cu ft	Full-scale distance between partitions, ft	Expected full-scale resonance frequency, cps
6	4	1 × 2.5	1,950	18.7	12
7	4	1 × 2.5	1,430	13.7	14
8	4	1 × 2.5	1,095	10.5	16
9	4	1 × 2.5	865	8.3	18
10	4	1 × 2.5	700	6.75	20

TABLE III

SUMMARY OF OVER-ALL PERFORMANCE OF ACOUSTICAL TREATMENT

Frequency band, cps	(1) Measured levels in test section 16-in. ram jet, db (a)	(2) Loss due to wave expansion in diffuser, db	(3) Loss in first plenum and bend, db	(4) Loss at junction between concrete and glass sections, db	(5) Loss in 90 ft of Fiberglas, db	(6) Loss in second plenum, db	(7) Loss in parallel baffles, db	(8) Total loss (exclusive of flanking noise leaks), db	(9) Resultant noise at exit of baffles (exclusive of flanking noise), db
20 to 75	146	10	13	5	50	[b]0	1	79	67
75 to 150	151	10	17	6	49	[b]0	4	86	65
150 to 300	153	10	15	6	44	[b]0	14	89	64
300 to 600	153	10	15	6	42	[b]3	26	102	51
600 to 1,200	151	10	16	6	2	11	30	75	76
1,200 to 2,400	148	10	18	6	0	16	21	71	77
2,400 to 4,800	143	10	19	6	0	17	14	66	77
4,800 to 9,600	138	10	20	6	0	18	10	64	74

[a]Mach number, 2.0; fuel consumption, 3,000 lb/hr.

[b]These levels are probably higher, although the limited available data do not so indicate.

TABLE IV

SOUND PRESSURE LEVELS ALONG DIFFUSER AND ACOUSTICAL EXTENSION (RESONATORS OPEN)

[Source, motor-driven cone; instrument, General Radio sound-level meter]

Tunnel station (see fig. 13)	Distance from station 6 along diffuser, ft	Distance along acoustical extension, ft	Sound pressure levels, db, for a frequency of -					
			12 cps	14 cps	15.75 cps	18 cps	20.5 cps	22.8 cps
6	0		104	106	108			
5	12		104	107	111	110	108	107
4	24		96	104	104	108	110	102
3	36		96	99	101	96	107	108
2	48		100	102	108	106	107	95
1	60		99	104	106	106	108	106
0	72		96	105	99	99	99	102
17	100		88	89	90	98	101	96
A		0	88	100.5	104	94	104	99
B		10	86	95	102	104	100	99
C		26	86	85	96	105	105	93
D		39.5	86	80	84	98	103	101
E		50	86	79	79	89	96	98
F		58	87	70	81	85	89	92
G		74	78	71	71	74	82	84
H		90	68	62	66	68	76	77
I		103.5	65	55	61	64	73	73
J		119.5	67	55	59	62	69	67
K		132.5	66	53	58	57	64	64
L		153.5	63	58	63	64	66	65
M		170.5	70	63	67	69	70	71

TABLE V

SOUND PRESSURE LEVELS ALONG DIFFUSER AND ACOUSTICAL EXTENSION (RESONATORS CLOSED)

[Source, motor-driven cone; instrument, General Radio sound-level meter]

Tunnel station	Distance from station 6 along diffuser, ft	Distance along acoustical extension, ft	Sound pressure levels, db, for a frequency of -											
			5 cps	6 cps	6.5 cps	8.2 cps	9.4 cps	12 cps	14 cps	15.75 cps	18 cps	20.5 cps	22 cps	22.8 cps
6	0		79.0	81.0	Speaker resonance	88.0	96	98.5	100.0	92.0	98.0	Speaker resonance	95.0	93.0
5	12		78.0	81.0		89.0	88	100.0	93.5	92.0	91.0		96.0	102.0
4	24		76.0	81.0		94.0	86	96.3	99.0	93.5	98.0		89.5	88.0
3	36		75.0	78.5		96.5	93	89.0	98.0	90.0	93.0		100.0	101.0
2	48		74.0	79.0		96.0	95	95.5	91.0	88.5	95.5		84.0	88.0
1	60		73.0	78.0		93.5	94	98.3	94.5	88.0	96.0		99.0	100.5
0	72		75.0	77.0		86.0	87	95.5	97.0	89.0	92.0		92.0	95.5
17	100		75.5	74.0		82.0	76	85.5	84.5	88.5	90.5		88.0	89.0
A		0	69.5	73.0		80.0	74	81.0	93.5	92.5	91.0		80.0	85.5
B		10	68.0	72.0		80.0	69	79.0	92.0	92.5	93.0		73.5	82.5
C		26	66.0	72.0		78.5	71	82.0	87.0	90.0	89.0		78.0	85.0
D		39.5	62.0	72.5		79.0	71	83.0	92.5	92.0	87.0		79.0	82.0
E		50	62.0	73.0		79.5	70	83.5	93.0	92.0	90.5		75.5	84.5
F		58	63.0	72.0		79.0	69	78.0	90.5	90.5	89.0		81.0	84.0
G		74	64.0	67.0		76.0	63	72.0	84.5	85.5	82.0		67.0	77.5
H		90	64.0	64.0		73.0	64	69.0	85.5	86.0	81.5		63.0	71.0
I		103.5	61.0	67.0		69.0	60	71.5	81.5	81.0	78.5		59.0	65.0
J		119.5	56.0	72.5		73.0	57	67.0	85.0	81.0	73.5		55.0	64.0
K		132.5	64.0	74.0		75.0	63	67.0	77.0	76.5	69.0		52.0	59.0
L		153.5	67.0	75.0		74.0	62	70.0	83.0	80.0	70.5		53.0	56.5
M		170.5	70.0	71.0		69.0	59	61.0	71.0	70.0	58.0		60.0	60.0

TABLE VI

SOUND PRESSURE LEVELS ALONG DIFFUSER AND ACOUSTICAL EXTENSION (RESONATORS CLOSED)

[Source, two 15-inch loudspeakers; instrument, General Radio sound-level meter]

Tunnel station	Distance from station 6 along diffuser, ft	Distance along acoustical extension, ft	Sound pressure levels, db, for a frequency of -								Daytime background noise level, cps
			22.8 cps	30 cps	50 cps	100 cps	225 cps	450 cps	750 cps	1,800 cps	
6	0		86.0	91.0	88.5	105.0	94.0	97.0	99.0	98.0	50
5	12		87.5	93.0	86.5	109.5	95.5	94.0	93.0	98.0	49
4	24		89.0	88.5	90.0	104.0	91.0	97.0	94.0	88.0	49
3	36		89.5	93.0	88.0	112.0	89.0	99.5	96.0	98.0	49
2	48		85.5	89.5	89.5	107.0	87.0	93.0	92.5	98.0	52
1	60		85.0	89.5	92.5	102.0	89.5	92.0	88.0	93.0	52
0	72		84.5	87.5	87.0	107.5	88.0	93.0	96.5	92.0	48
17	100		82.5	88.5	86.0	104.5	77.5	77.0	82.0	83.0	46.5
A		0	76.5	79.0	74.0	104.0	75.5	78.5	78.0	81.0	44
B		10	76.0	83.0	70.5	88.0	78.5	77.5	82.0	83.5	44
C		26	75.0	82.0	72.0	91.0	76.5	76.5	81.0	71.5	43
D		39.5	74.5	79.0	68.0	89.5	79.0	81.0	82.0	73.0	44
E		50	71.5	82.0	68.5	83.5	75.5	77.0	77.0	71.0	44
F		58	73.5	80.0	66.5	81.0	77.5	81.0	79.5	75.0	44
G		74	64.0	71.0	57.5	79.0	65.5	64.0	67.5	60.0	40
H		90	55.5	60.0	51.5	69.5	56.0	62.0	61.5	61.0	38
I		103.5	56.0	54.5	55.0	60.5	56.5	51.0	52.0	61.0	37
J		119.5	58.0	60.0	57.0	59.0	58.5	57.0	57.0	59.0	41
K		132.5	55.0	47.0	55.5	55.0	57.0	51.0	54.0	56.0	45
L		153.5	52.0	51.0	55.5	57.0	54.0	55.0	56.0	60.0	48
M		170.5	61.5	59.0	61.5	62.0	63.0	59.0	62.0	62.0	60
Out-Side							64.0				

TABLE VII

SOUND PRESSURE LEVELS ALONG FIBERGLAS SECTION OF ACOUSTICAL EXTENSION

[Source, two 15-inch loudspeakers; instrument, ERPI sound-level meter and octave-band analyzer]

Distance along section, ft	Sound pressure levels, db, for a frequency of -																
	20 cps	30 cps	40 cps	50 cps	60 cps	70 cps	80 cps	100 cps	125 cps	150 cps	175 cps	200 cps	400 cps	700 cps	1,000 cps	2,000 cps	3,000 cps
0	88	82	84	96	98	96	91	102	112	114	108	116		113	106	108	107
5	83	78	83	92	92	95	89	95	103	104	106	102	106	112	110	105	108
12	81	75	77	87	88	90	82	80	83	95	101	83	101	111	107	110	95
21	76	65	71	80	82	87	76	85	85	92	96	87	96	105	91	101	94
28	71	65	69	74	77	84	72	80	86	88	86	86	99	98	97	87	85
33	69	63	63	71	76	83	60	82	78	82	83	80	98	96	97	96	95
41.5	65	57	60	65	71	80	61	76	83	80	79	85	96	93	96	90	80
48	61	54	67	50	66	79	58	70	80	74	77	70	93	92	100	94	85
56.5	57	48	52	54	62	75	58	65	74	70	70	69	88	85	104	89	90
62	55	48	48	50	61	73	53	63	70	66	64	65	83	78	105	83	85
70	50		48		57	70	50	57	69	65	63	62	81	68	104	94	85
77	50				51	67	50	52	65	59	59	59	76	67	104	86	94
82	49				52	65	48	52	61	59	58	59	82	80	102	97	89
90.5	54				52	63	55	50	60	57	55	58	77	85	102	92	90

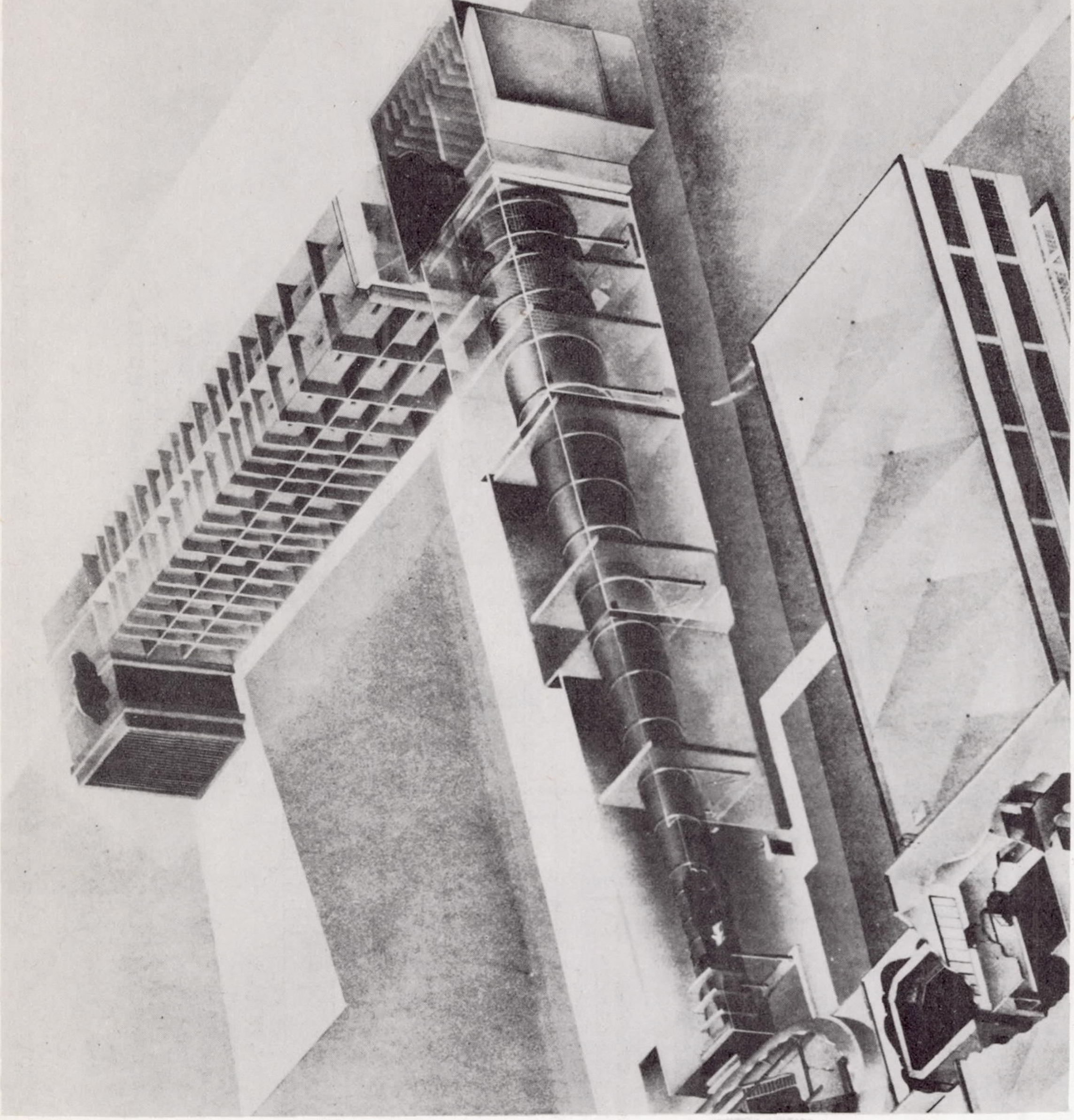


Figure 1.- Transparent view of completed 8- by 6-foot supersonic wind tunnel at Lewis Flight Propulsion Laboratory.

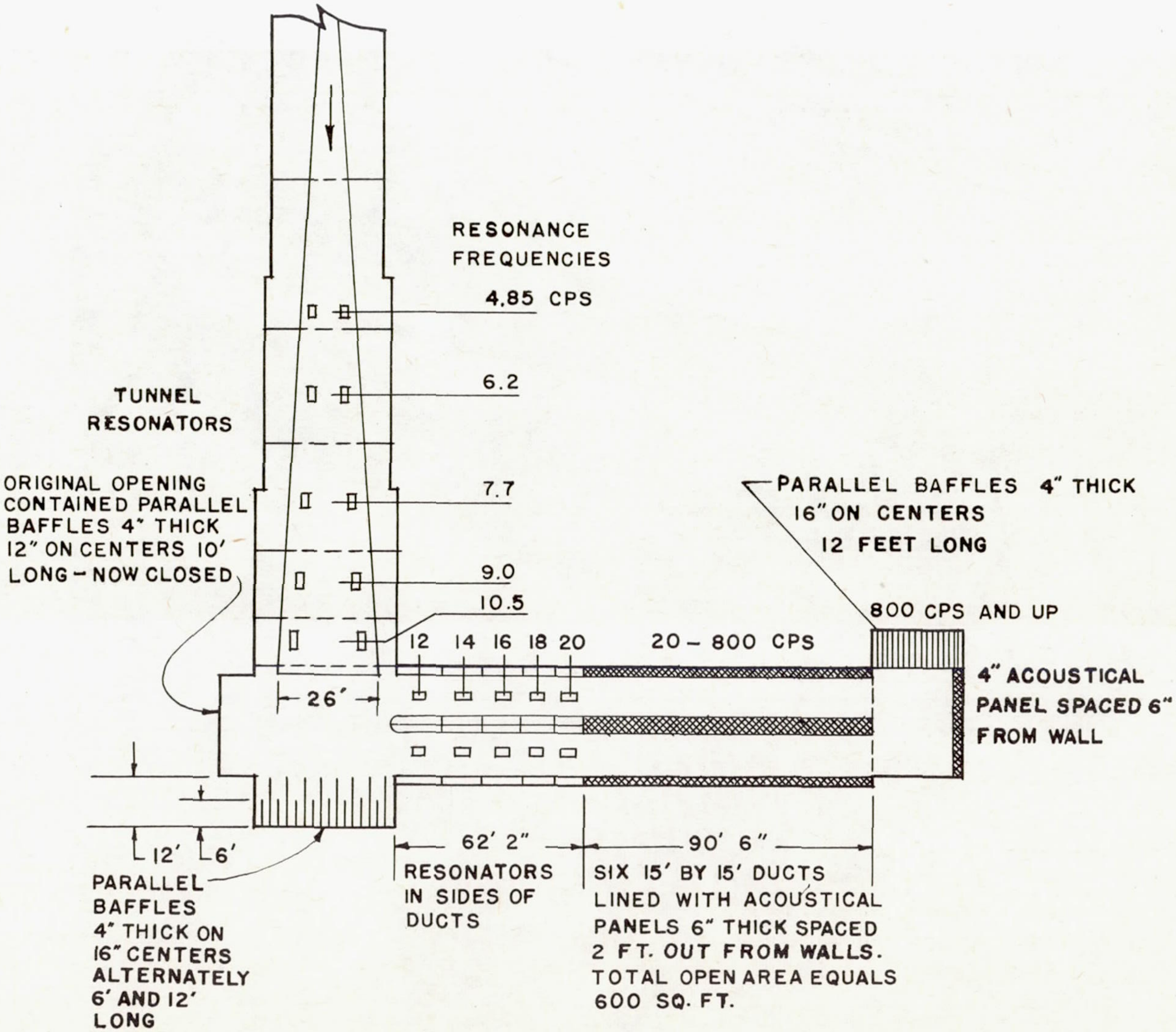


Figure 2.- Acoustical treatment for 8- by 6-foot supersonic tunnel.

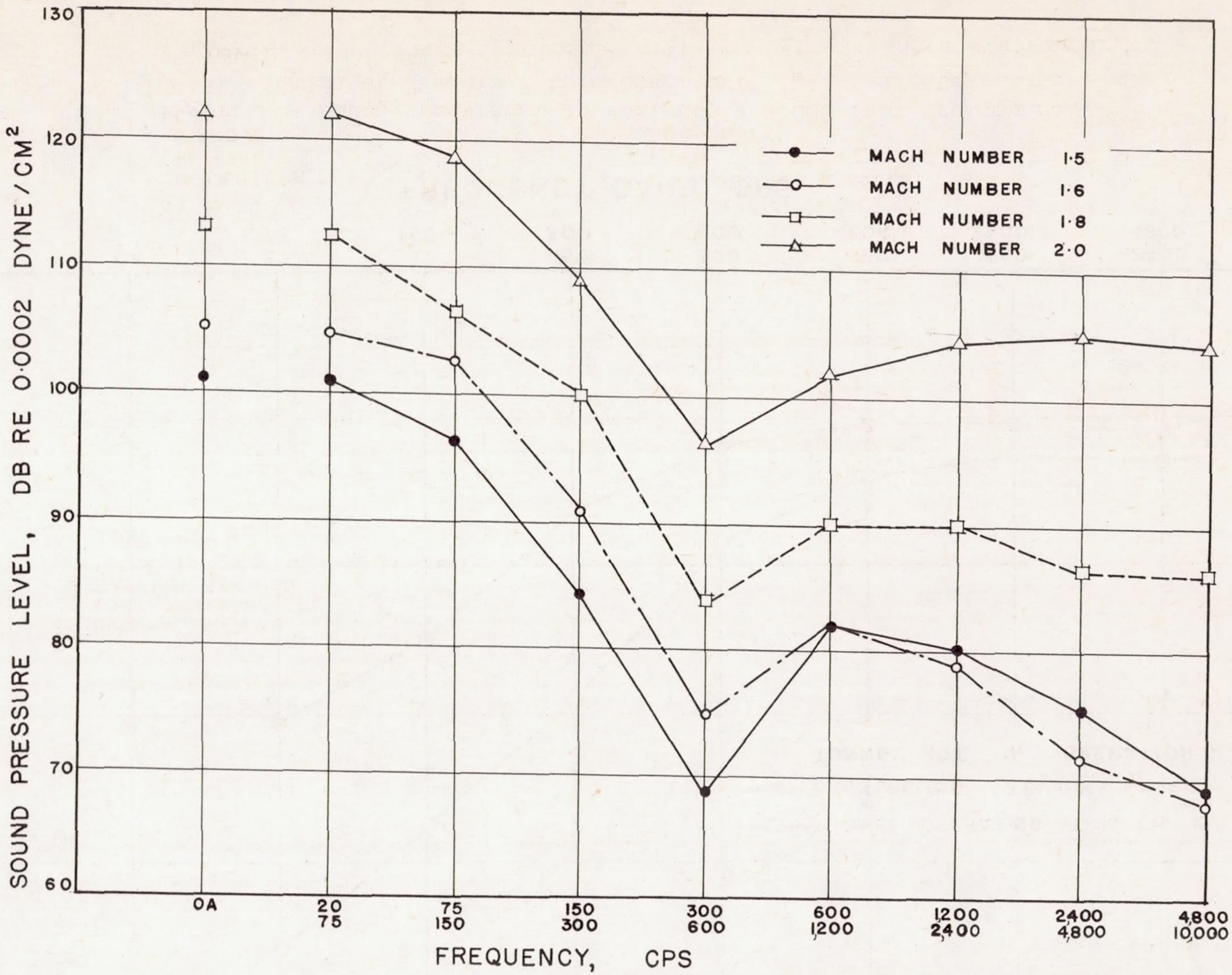


Figure 3.- Sound pressure level at a station 3 feet in front of baffles. RE indicates "referred to a level of." OA indicates overall level.

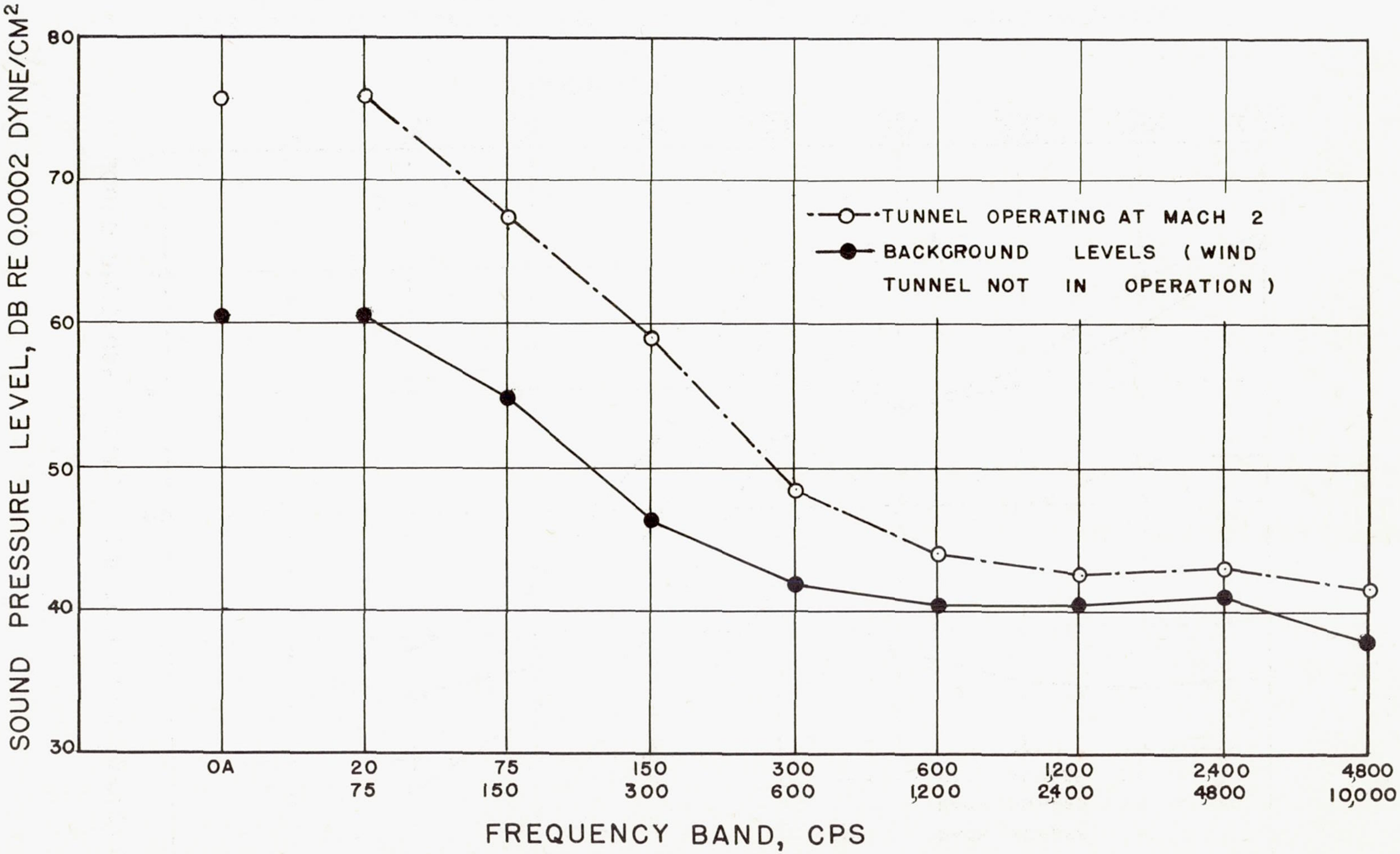


Figure 4.- Sound spectra at approximately 2,000 feet from tunnel. RE indicates "referred to a level of." OA indicates overall level.

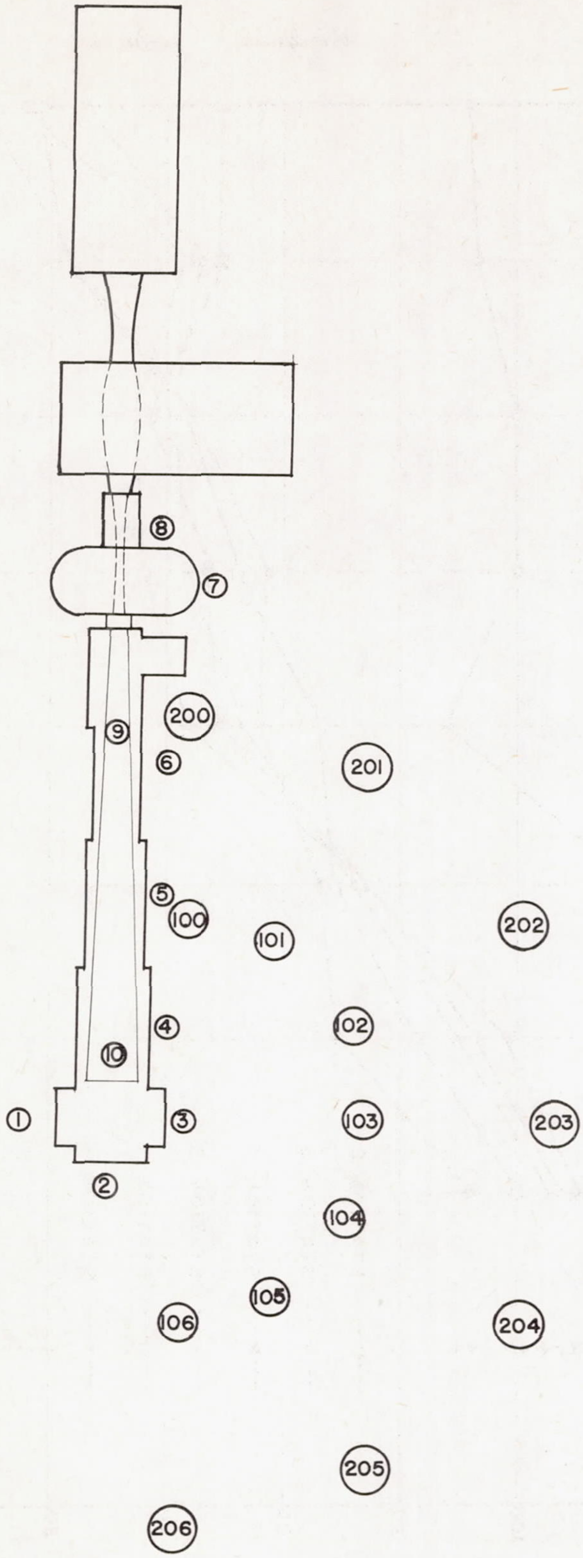


Figure 5.- Stations for noise measurements.

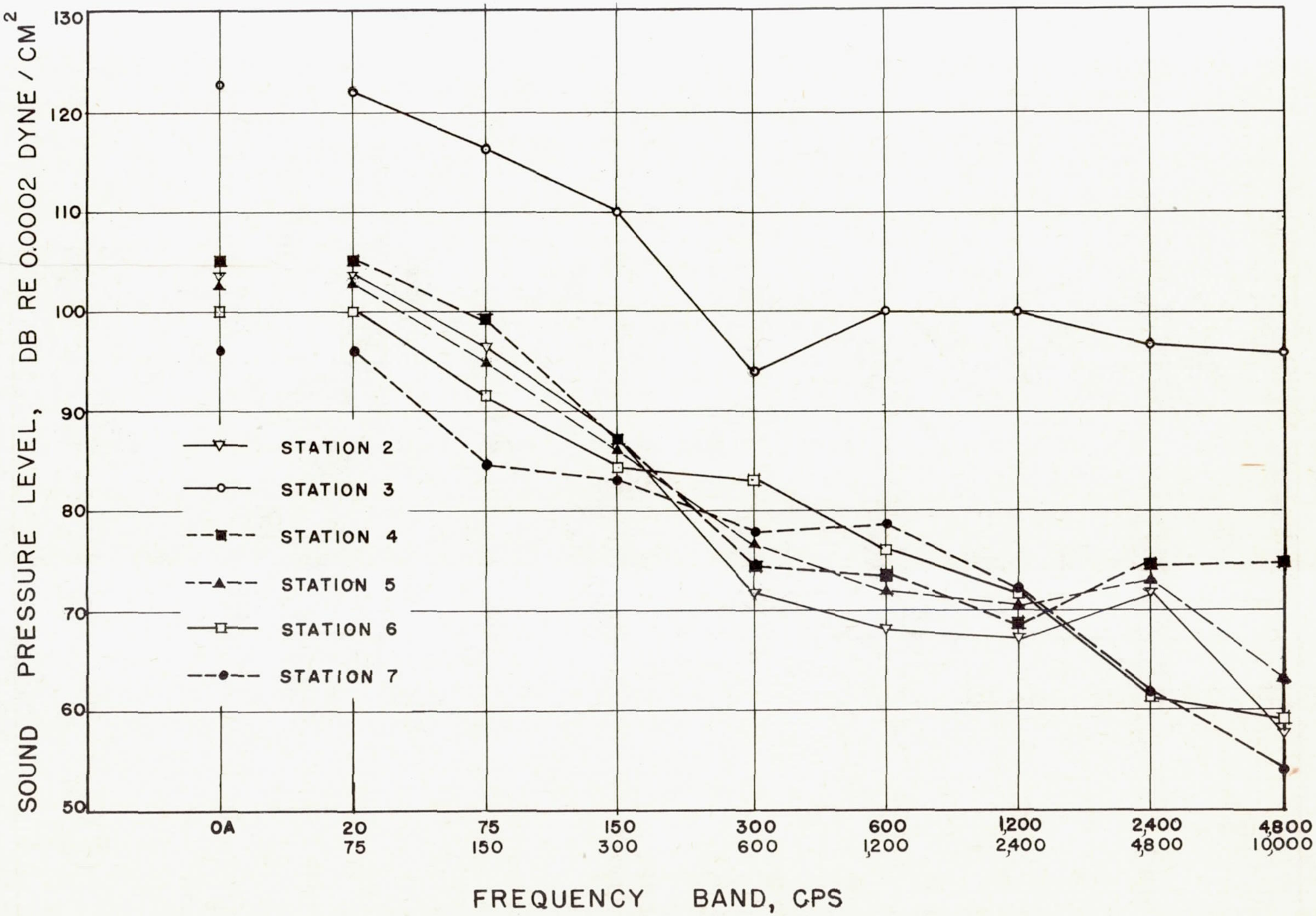


Figure 6.- Noise spectra at stations 2 to 7 with tunnel operating at Mach number 2.0. RE indicates "referred to a level of." OA indicates overall level.

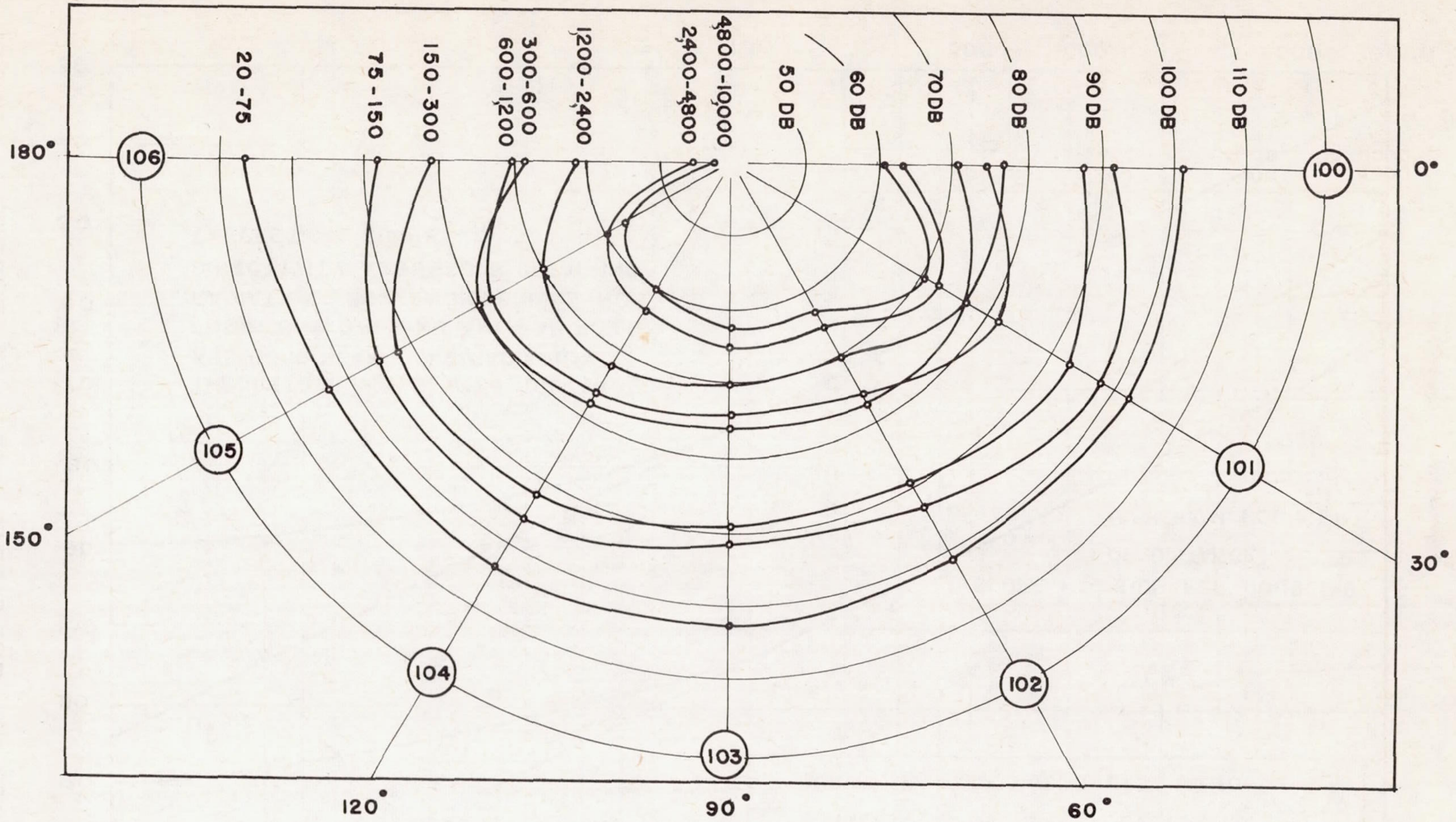


Figure 7.- Directivity pattern at 100-foot distance from baffles. Mach number 2.0; sound pressure level in band versus angles of measuring stations with frequency band as parameter.

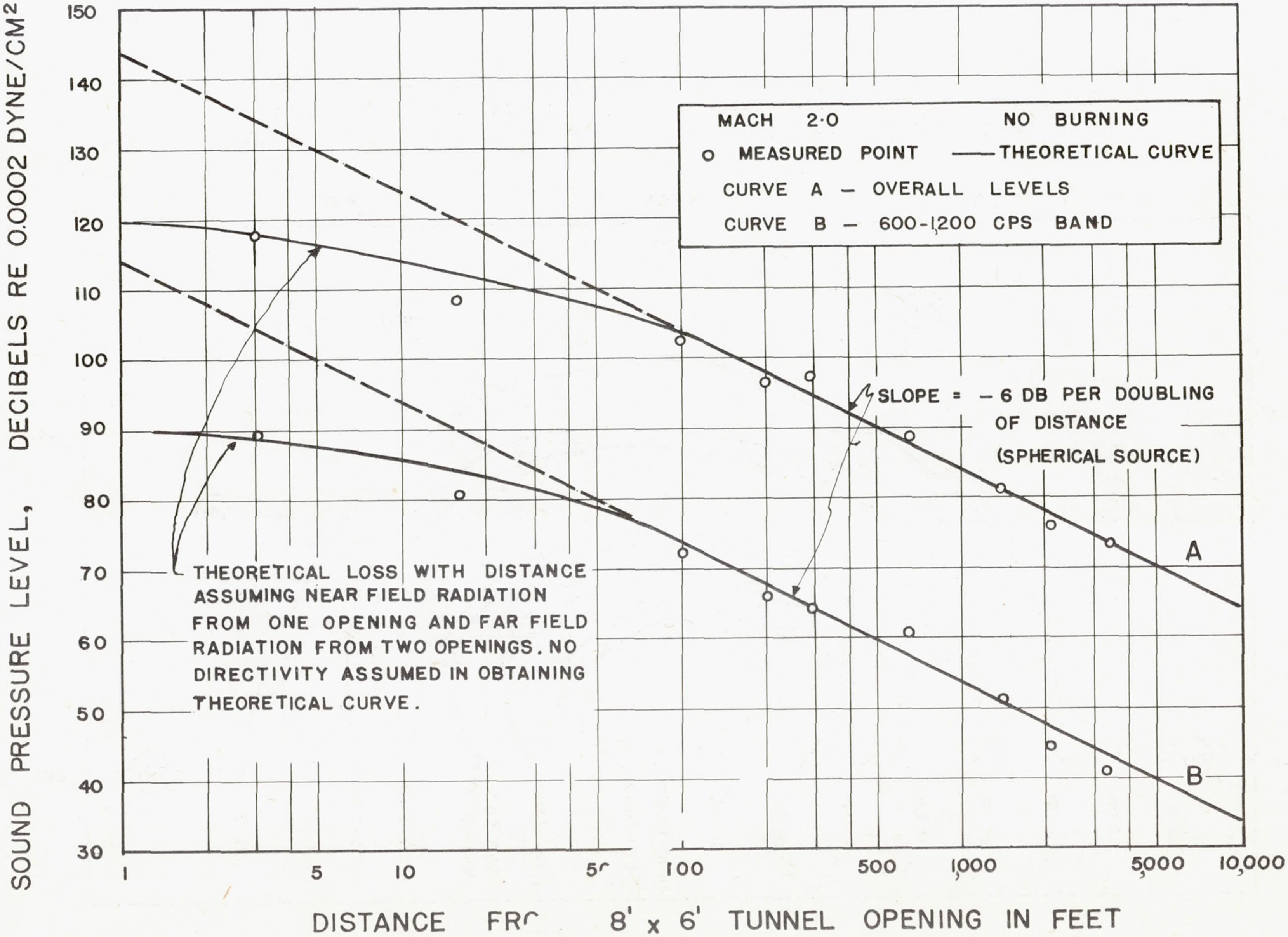


Figure 8.- Sound press level versus distance. RE indicates "referred to a level of."

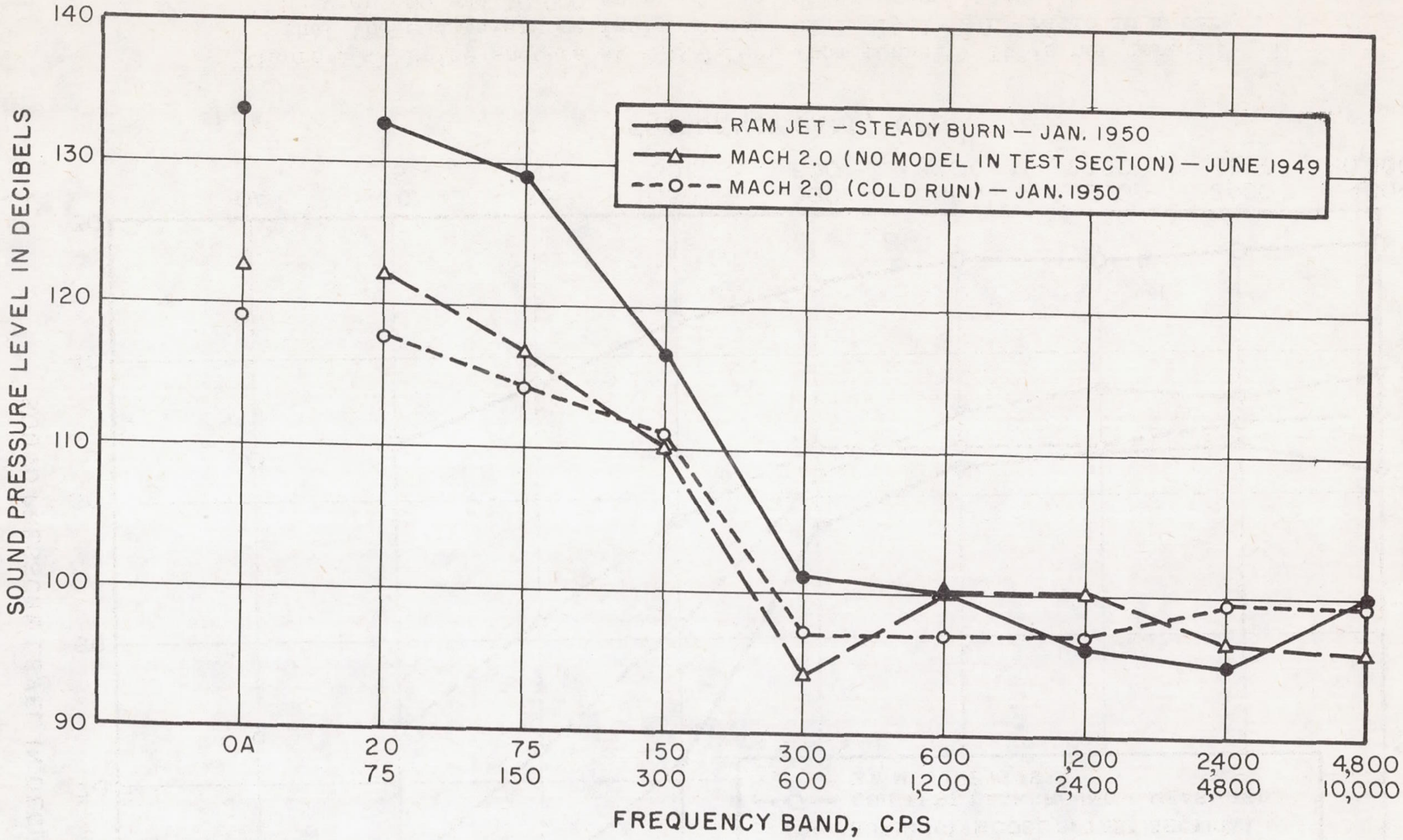


Figure 9.- Noise spectra 3 feet in front of original exit. It is not certain that these data are reliable because of limited s/n ratio in meter between 600 and 10,000 cps. OA indicates overall level.

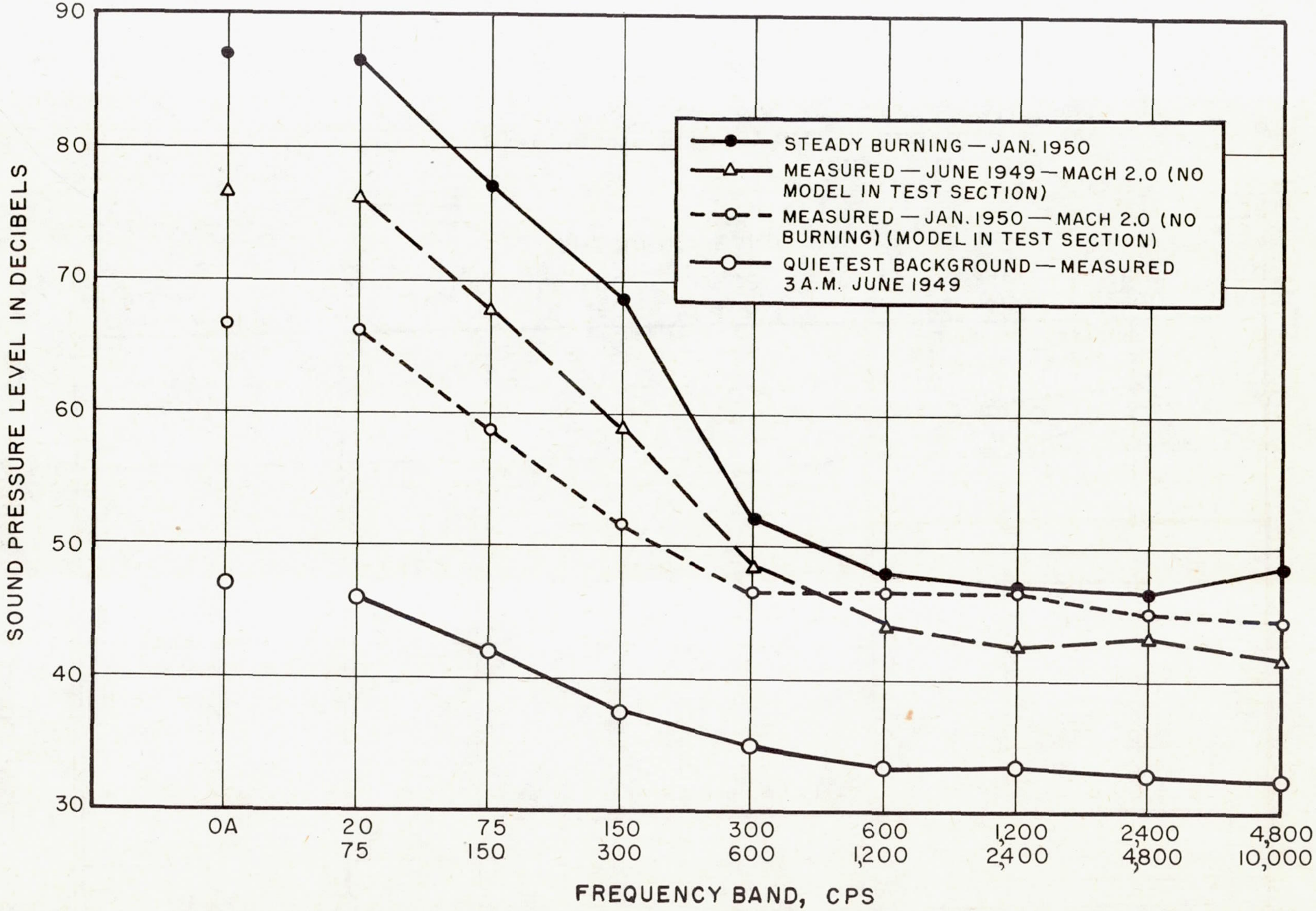


Figure 10.- Noise spectra at 2,000 feet from tunnel. It is not certain that these data are reliable because of limited s/n ratio in meter between 600 and 10,000 cps. OA indicates overall level.

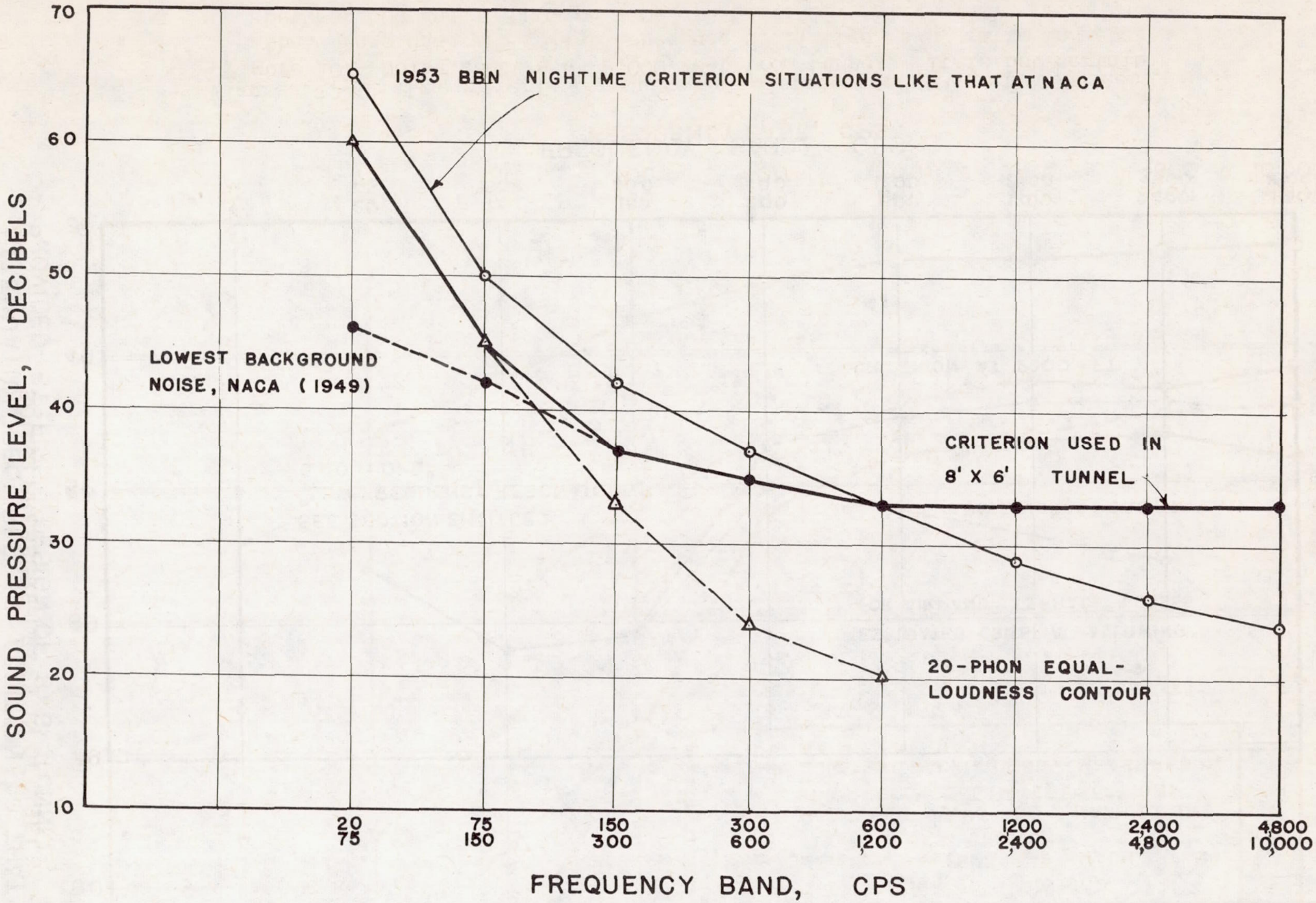


Figure 11.- Noise-level contours.

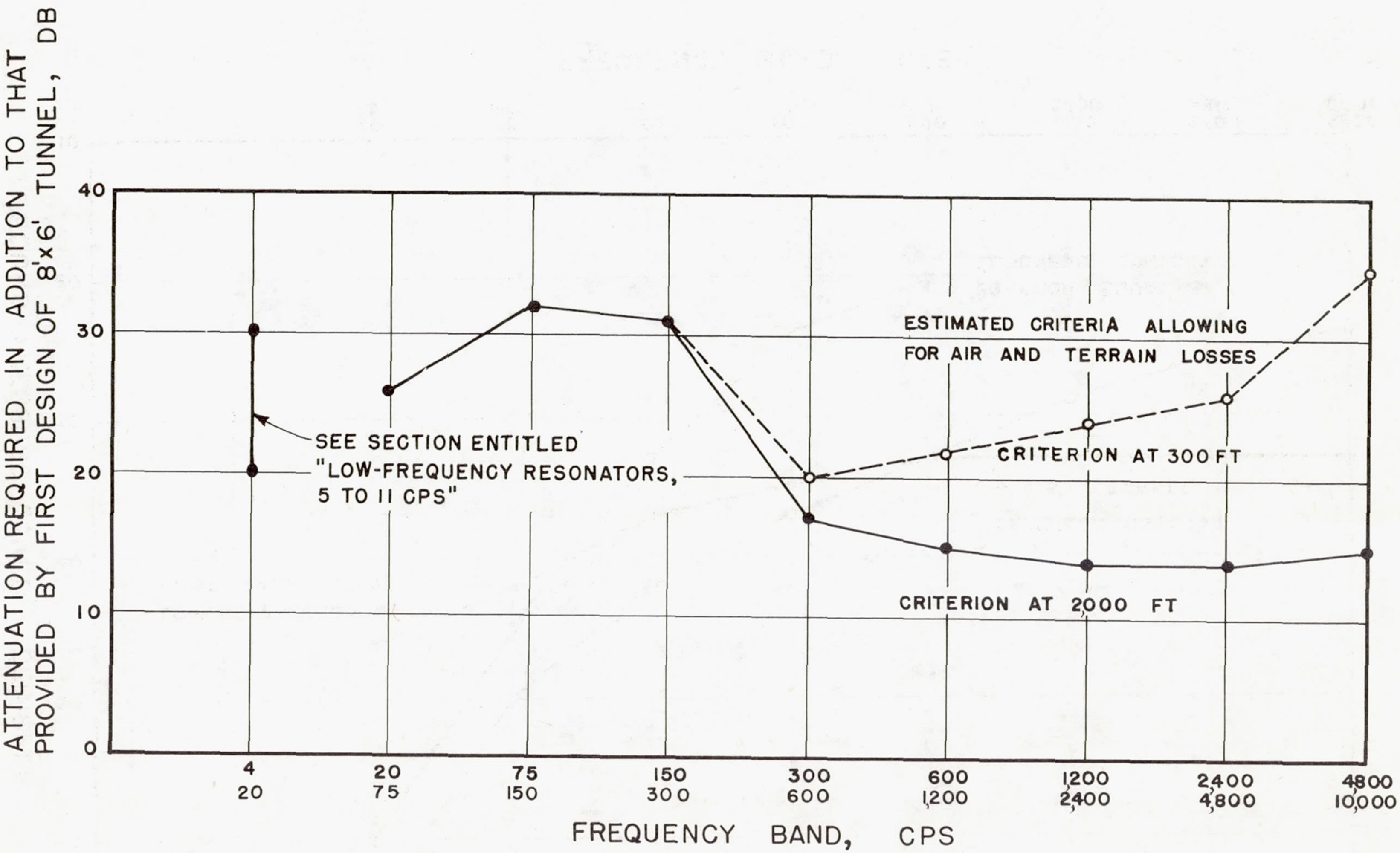


Figure 12.- Design criteria for tunnel at distances of 300 and 2000 feet.

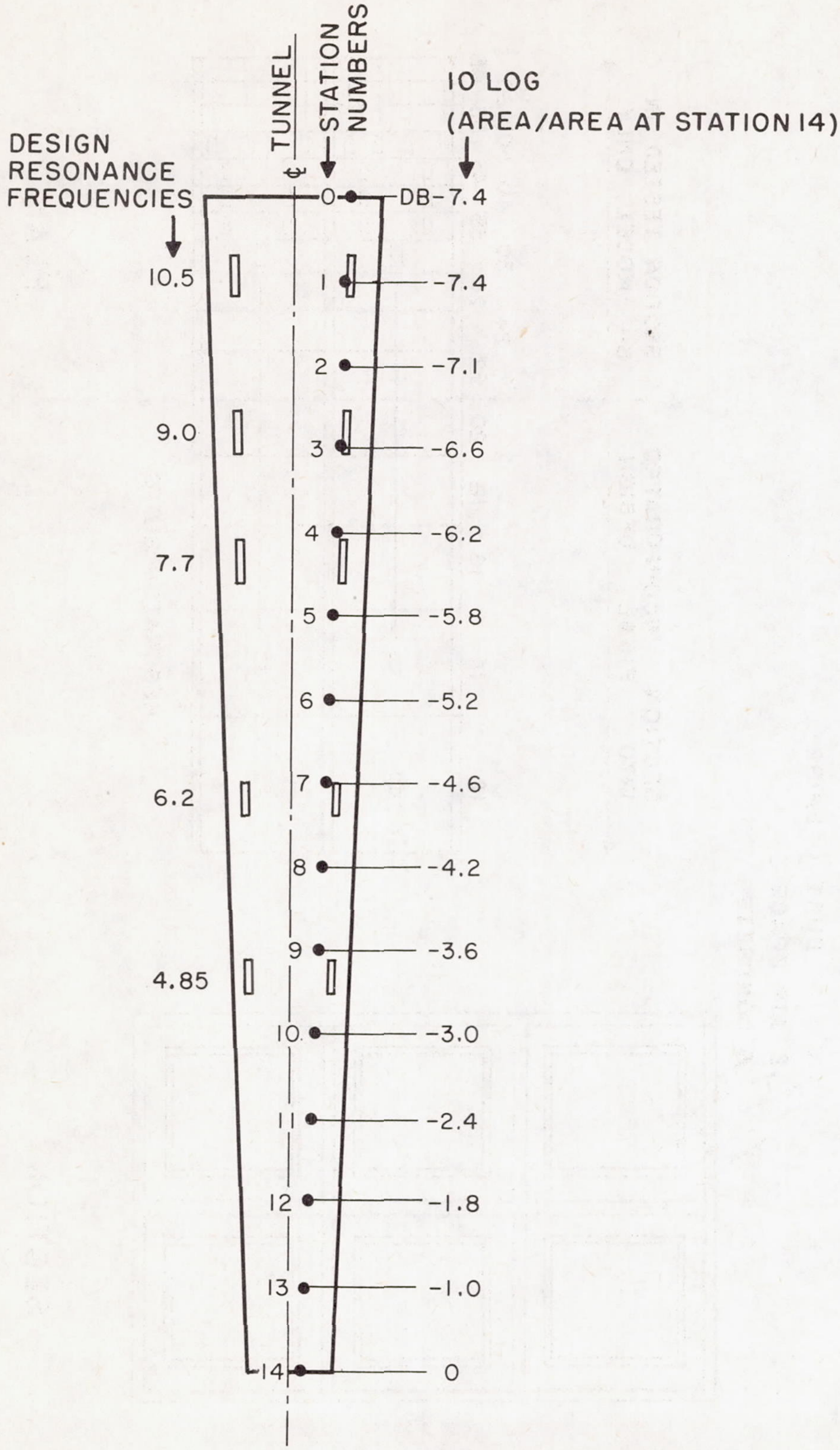


Figure 13.- Sketch showing design resonance frequencies.

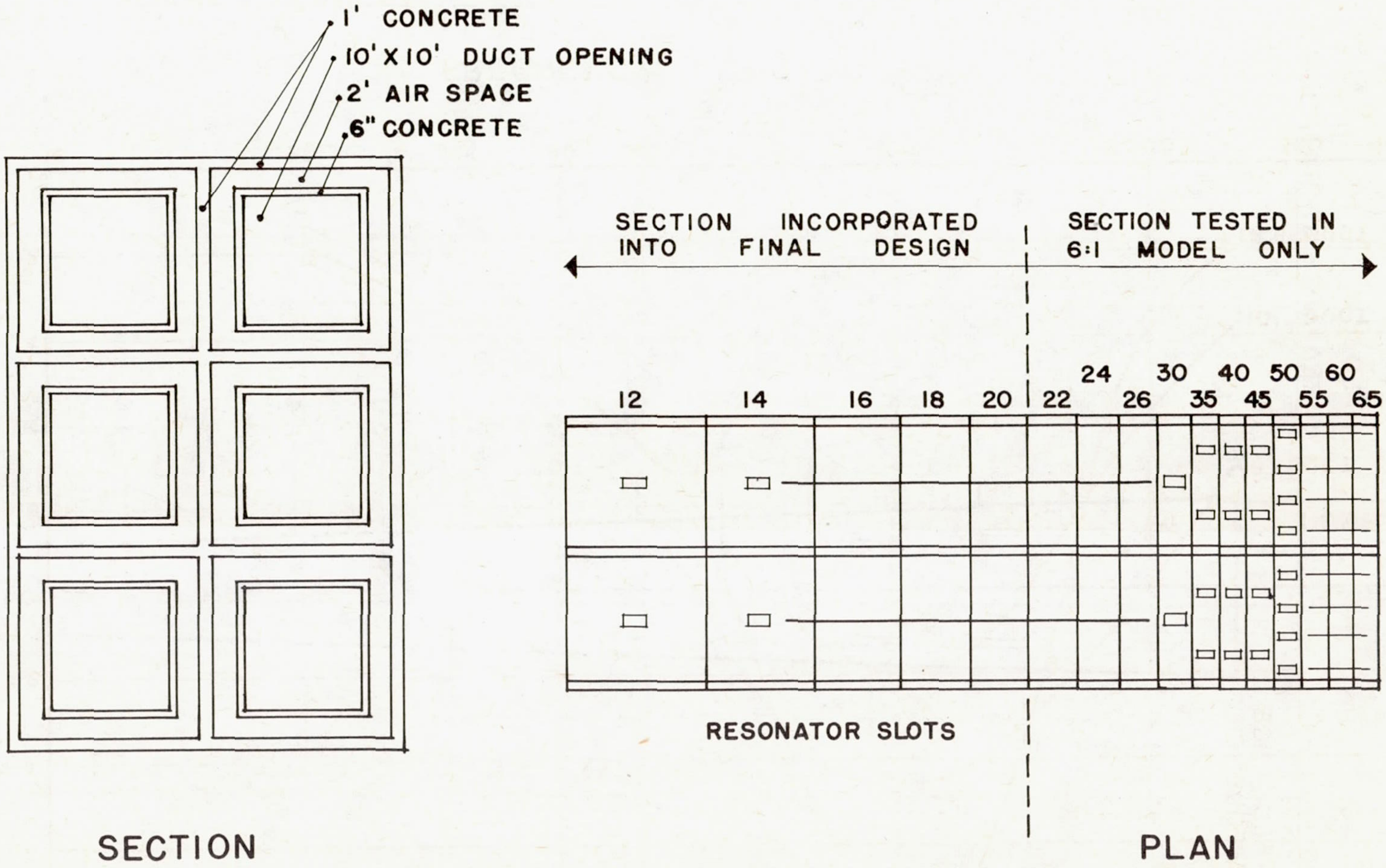


Figure 14.- Diagram showing 12- to 70-cps resonator group. In the final design only five resonators were employed (see table II).

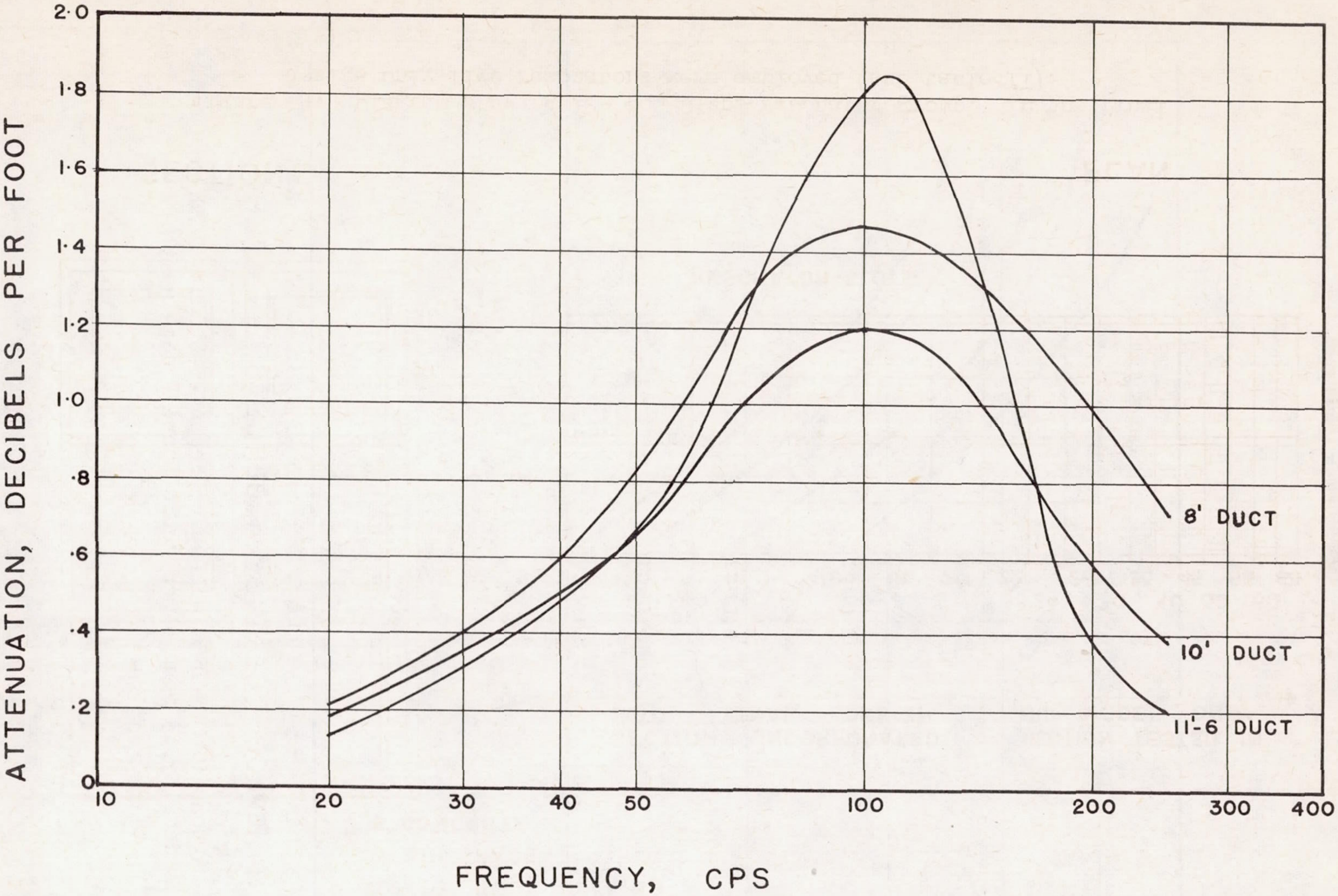


Figure 15.- Attenuation through a lined duct. Fiberglas density, 3 pounds per cubic foot; thickness, 6 inches; air space, 2.0 feet deep.

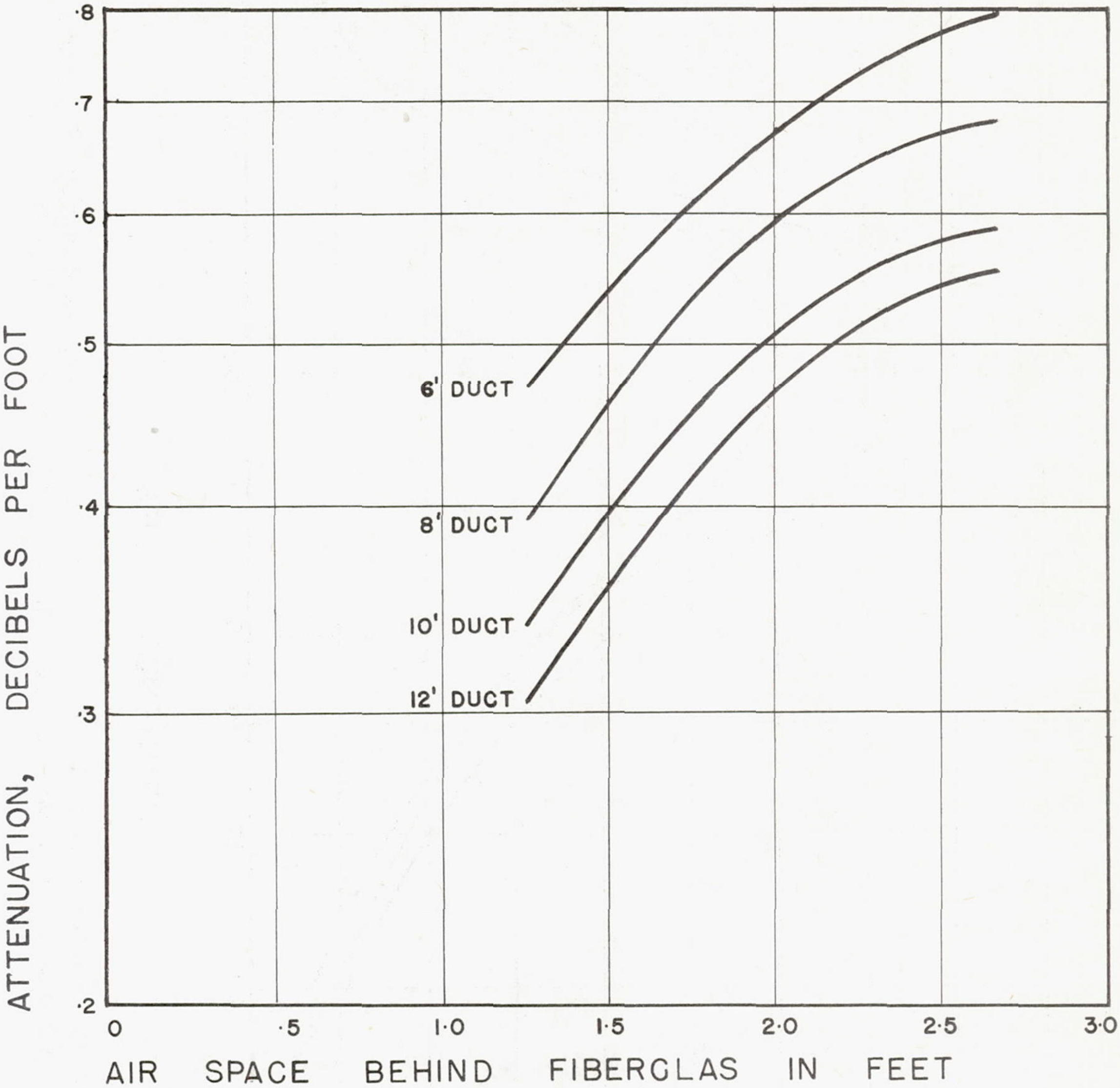


Figure 16.- Attenuation versus air-space depth with duct width as parameter. Fiberglas density, 3 pounds per cubic foot; Fiberglas thickness, 6 inches; frequency, 40 cps.

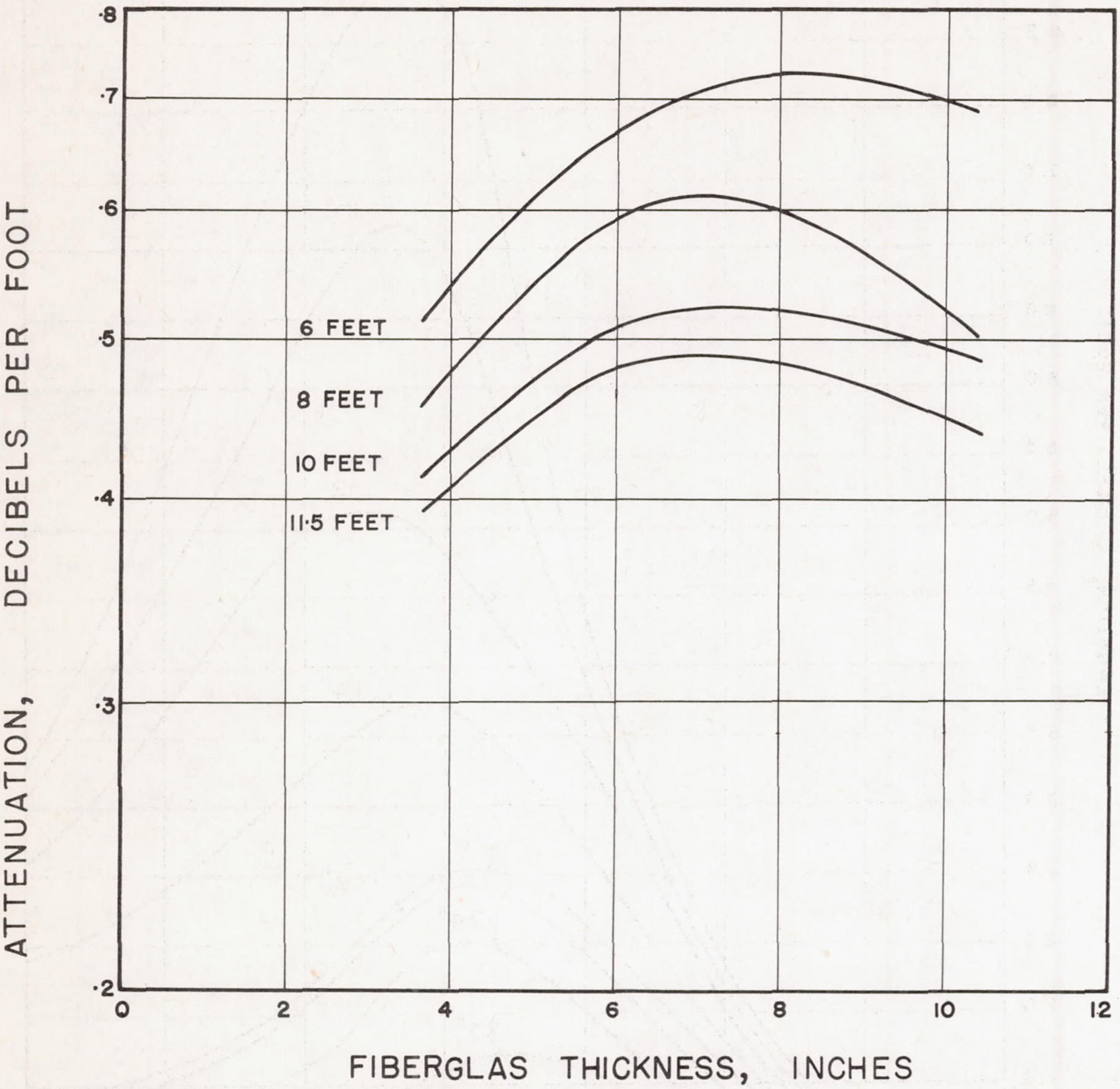


Figure 17.- Attenuation versus Fiberglas thickness with duct width as parameter. Fiberglas density, 3 pounds per cubic foot; air-space depth, 2 feet; frequency, 40 cps.

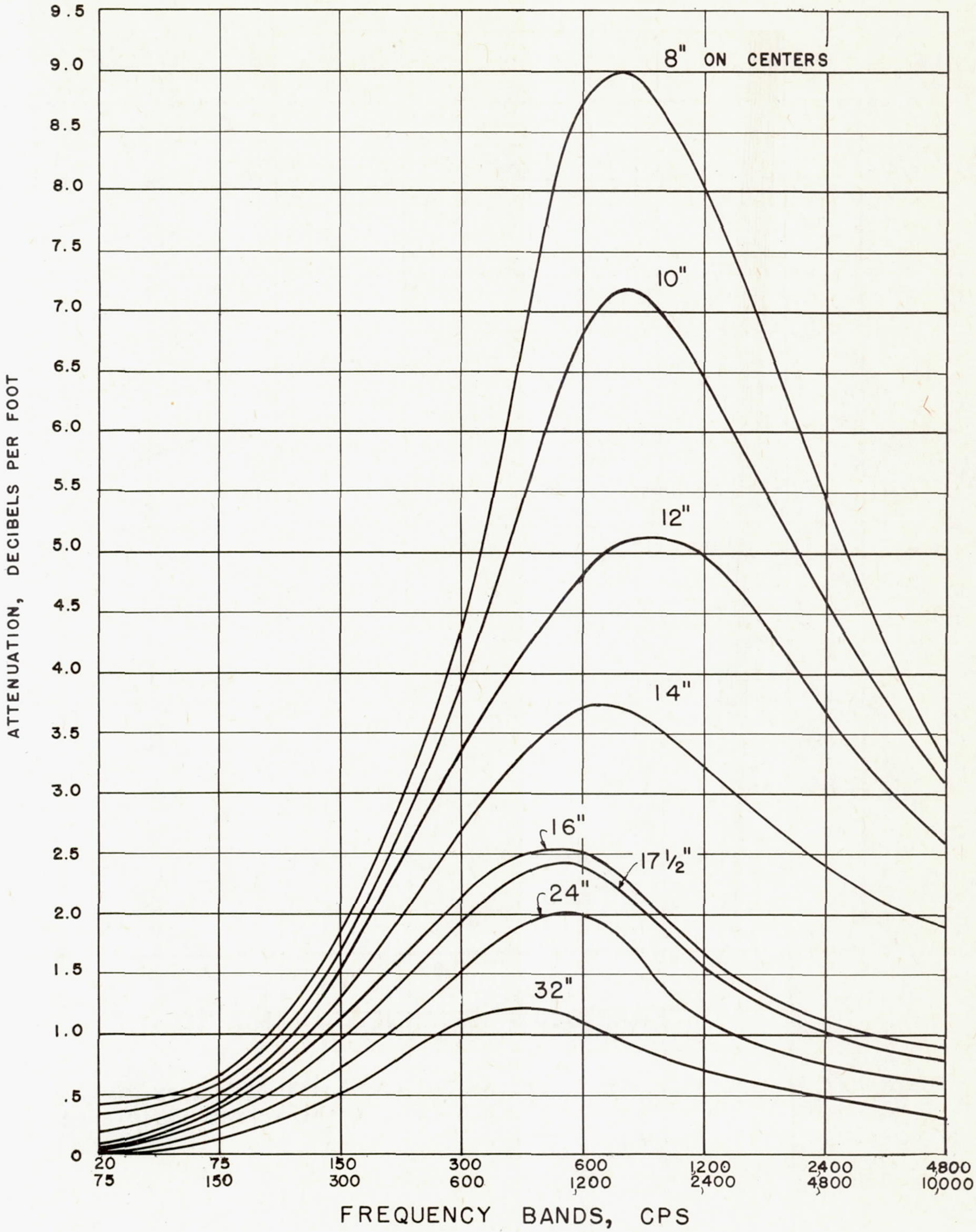


Figure 18.- Attenuation of parallel baffles nominally 4 inches thick filled with 4-pounds-per-cubic-foot P.F. Fiberglas or 6-pounds-per-cubic-foot rockwool. Continuous spectrum noise is assumed.

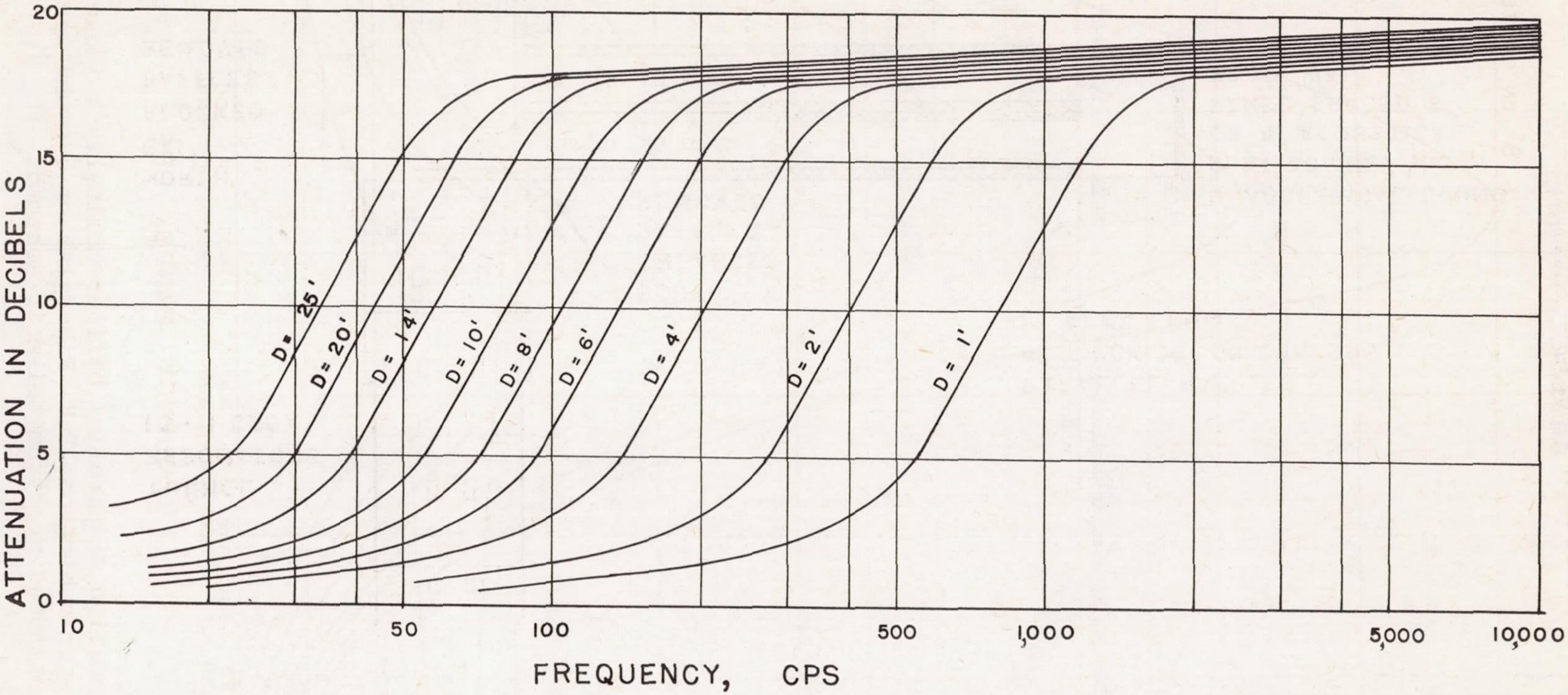


Figure 19.- Attenuation by one bend in a lined square duct. D = duct width; C = 1,120 feet per second.

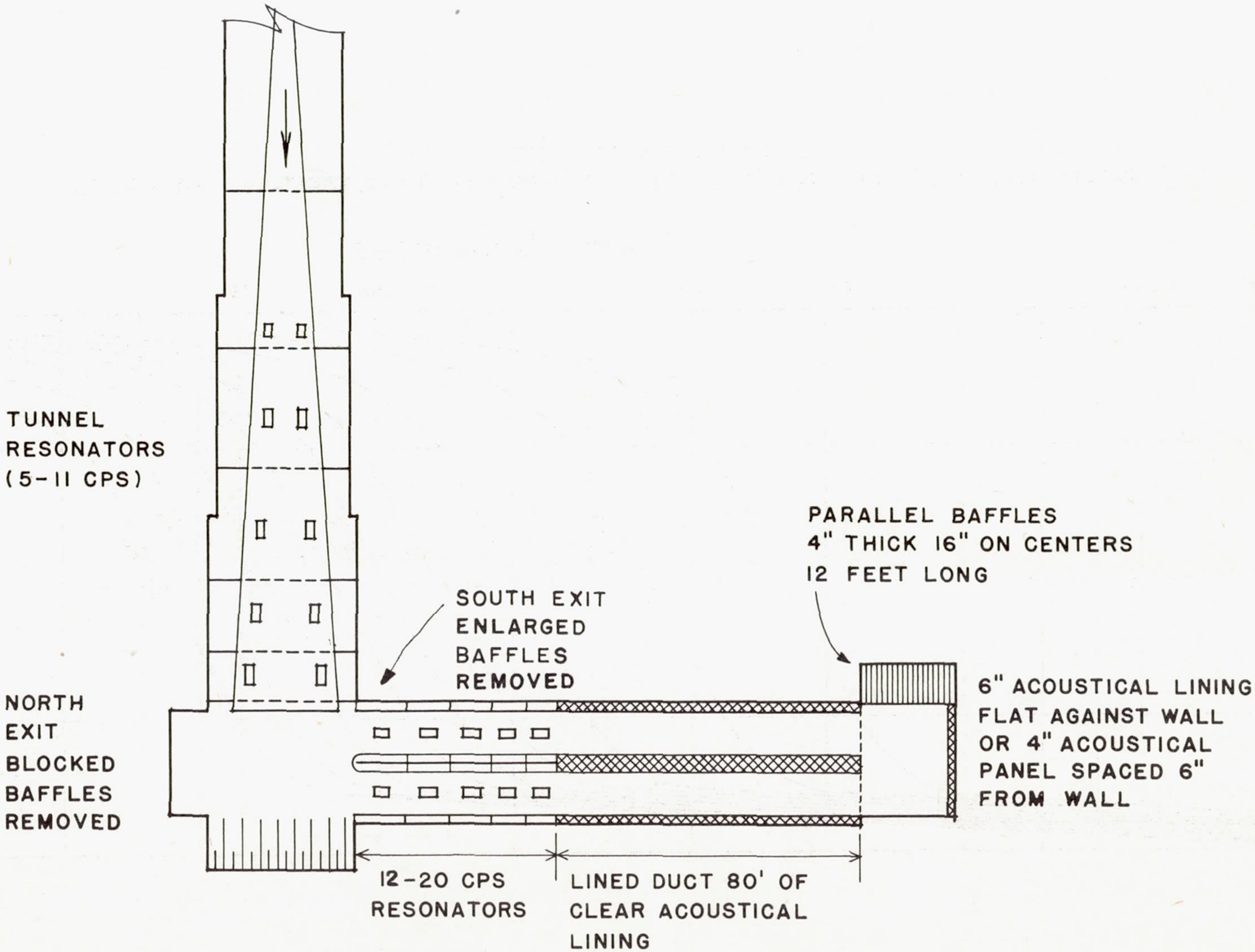


Figure 20.- Scheme A for achieving noise-reduction requirements.

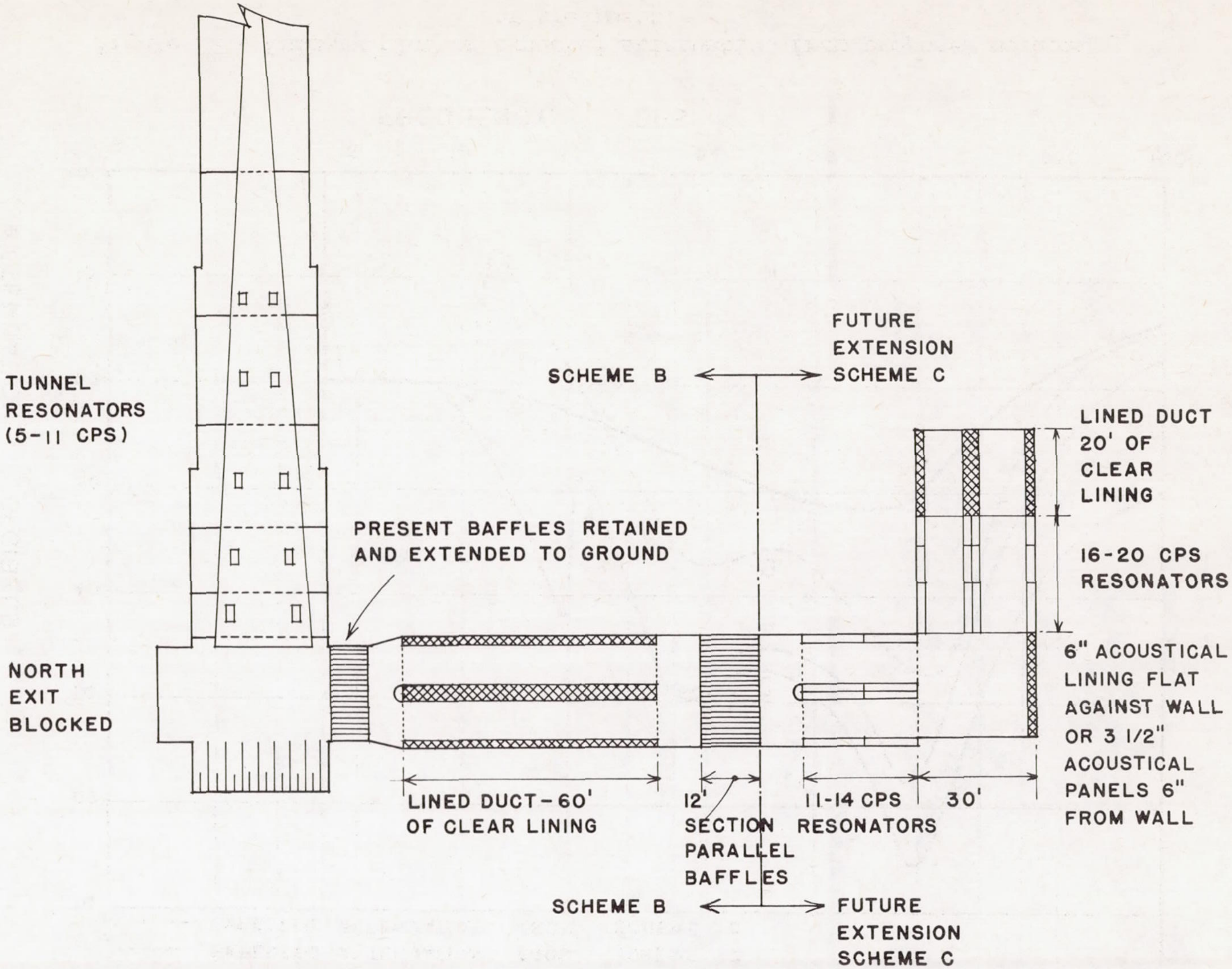


Figure 21.- Schemes B and C for achieving noise-reduction requirements.

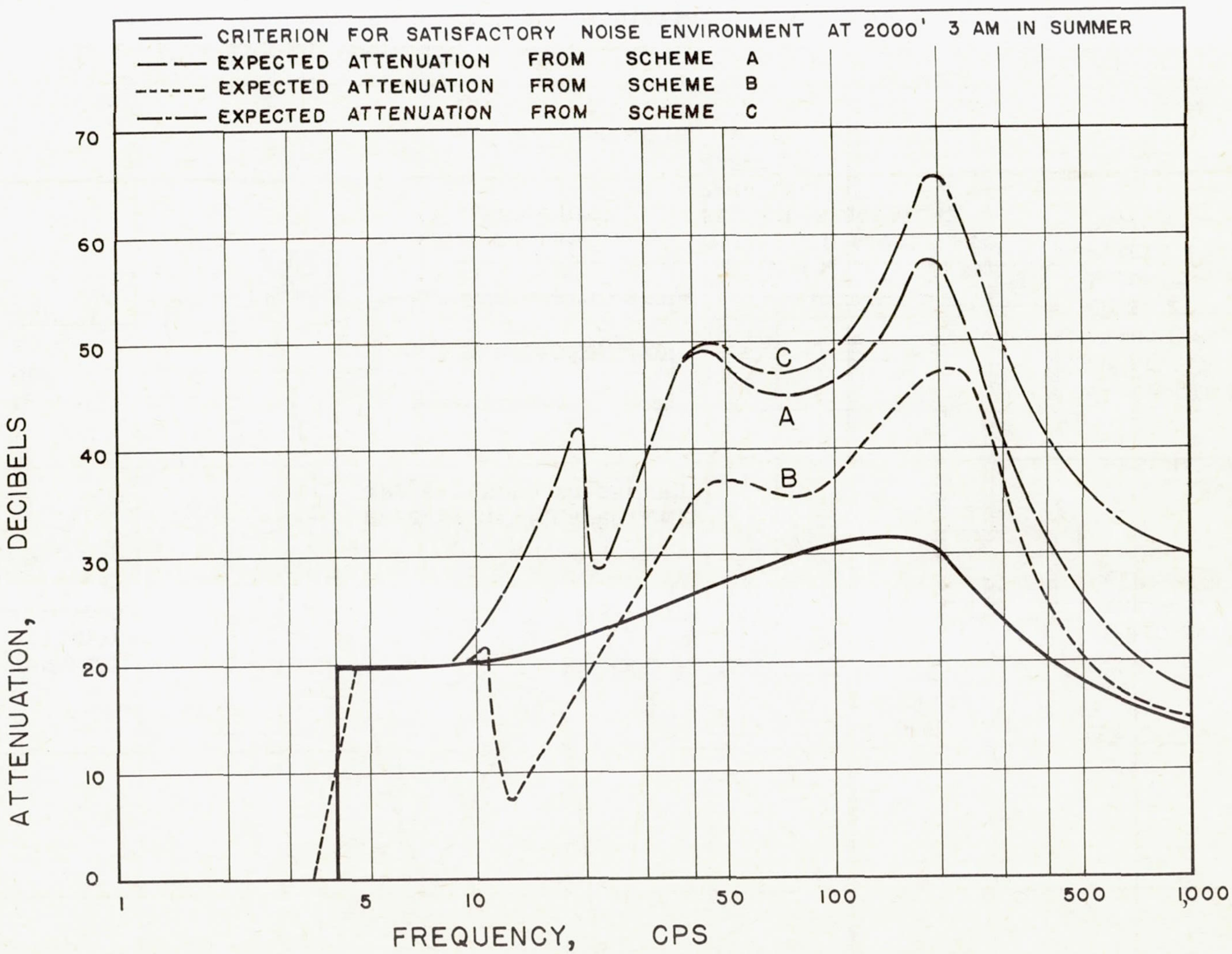


Figure 22.- Summary plot of expected attenuation from proposed methods of treatment.

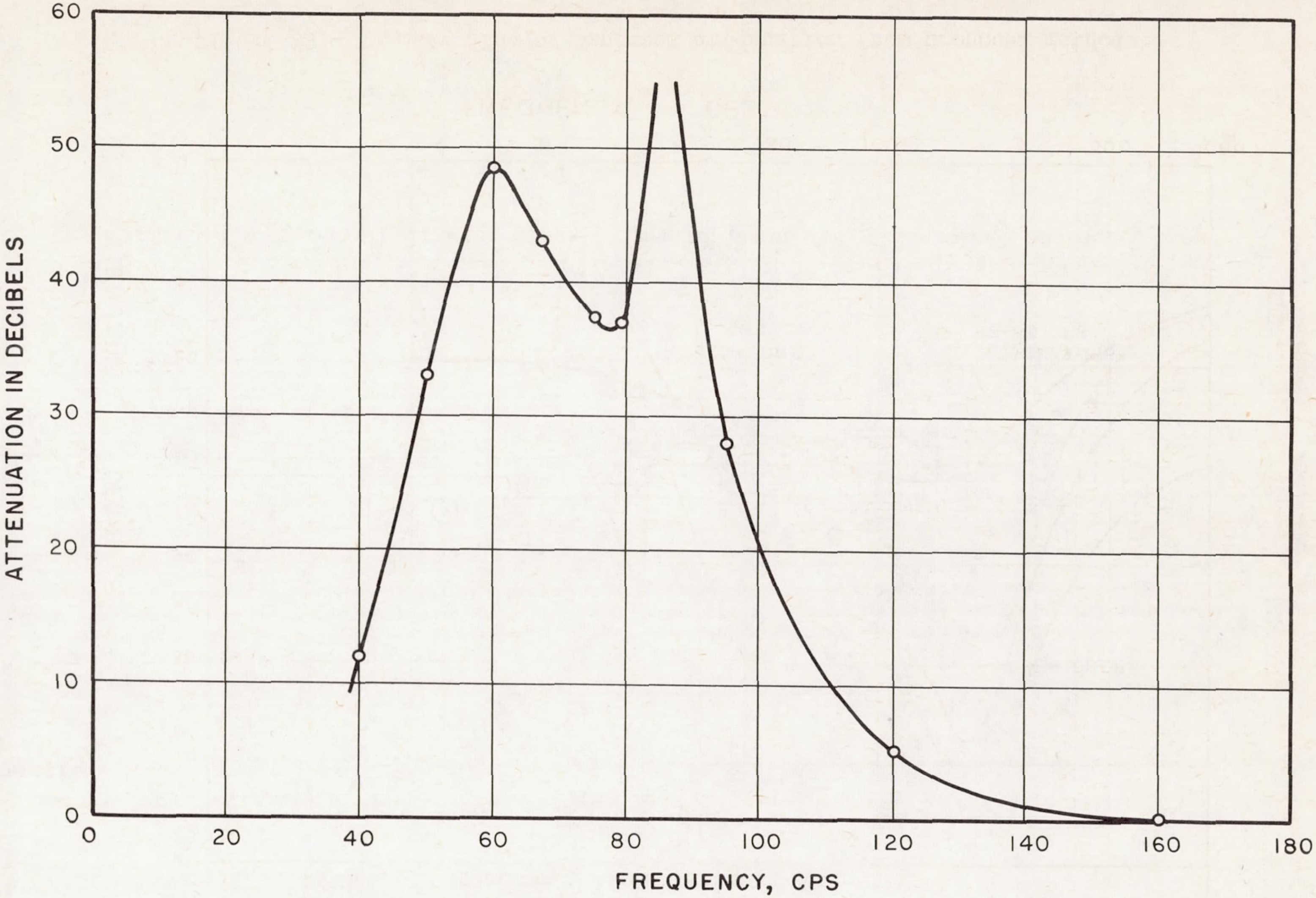


Figure 23.- Attenuation due to resonators in 10:1 scale model of 8- by 6-foot supersonic wind tunnel.

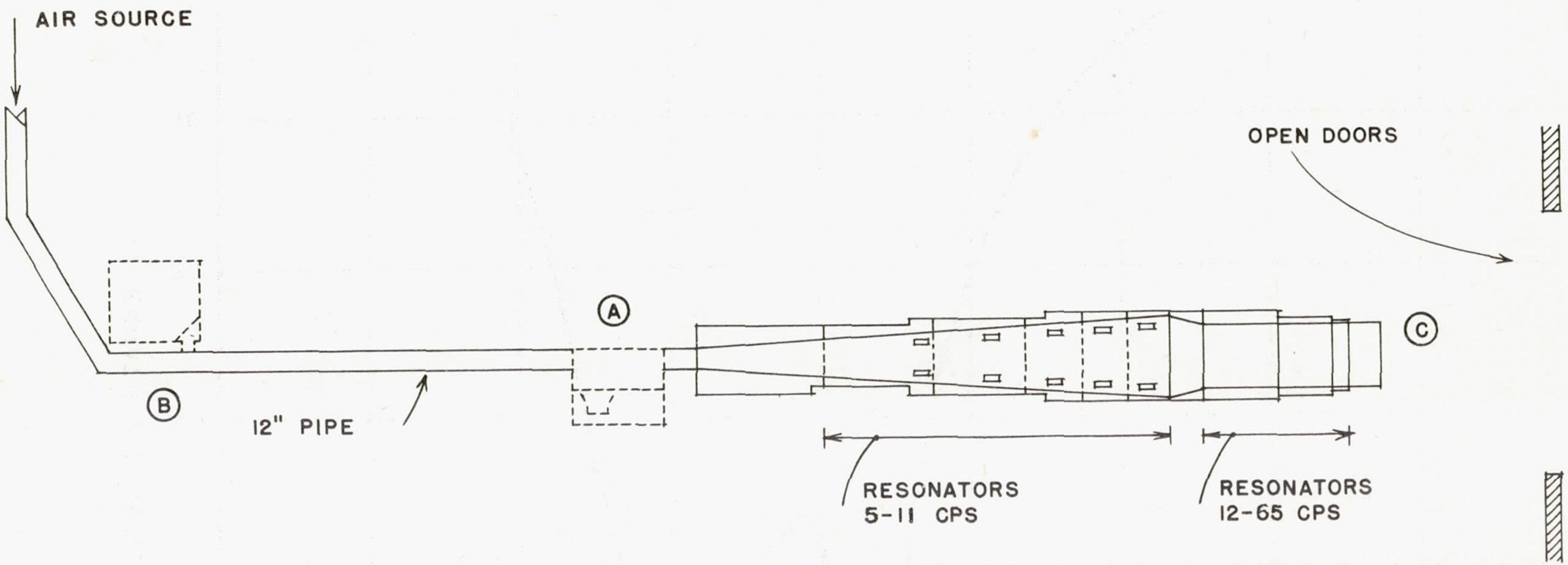


Figure 24.- Schematic drawing of experimental setup for wind-tunnel tests.

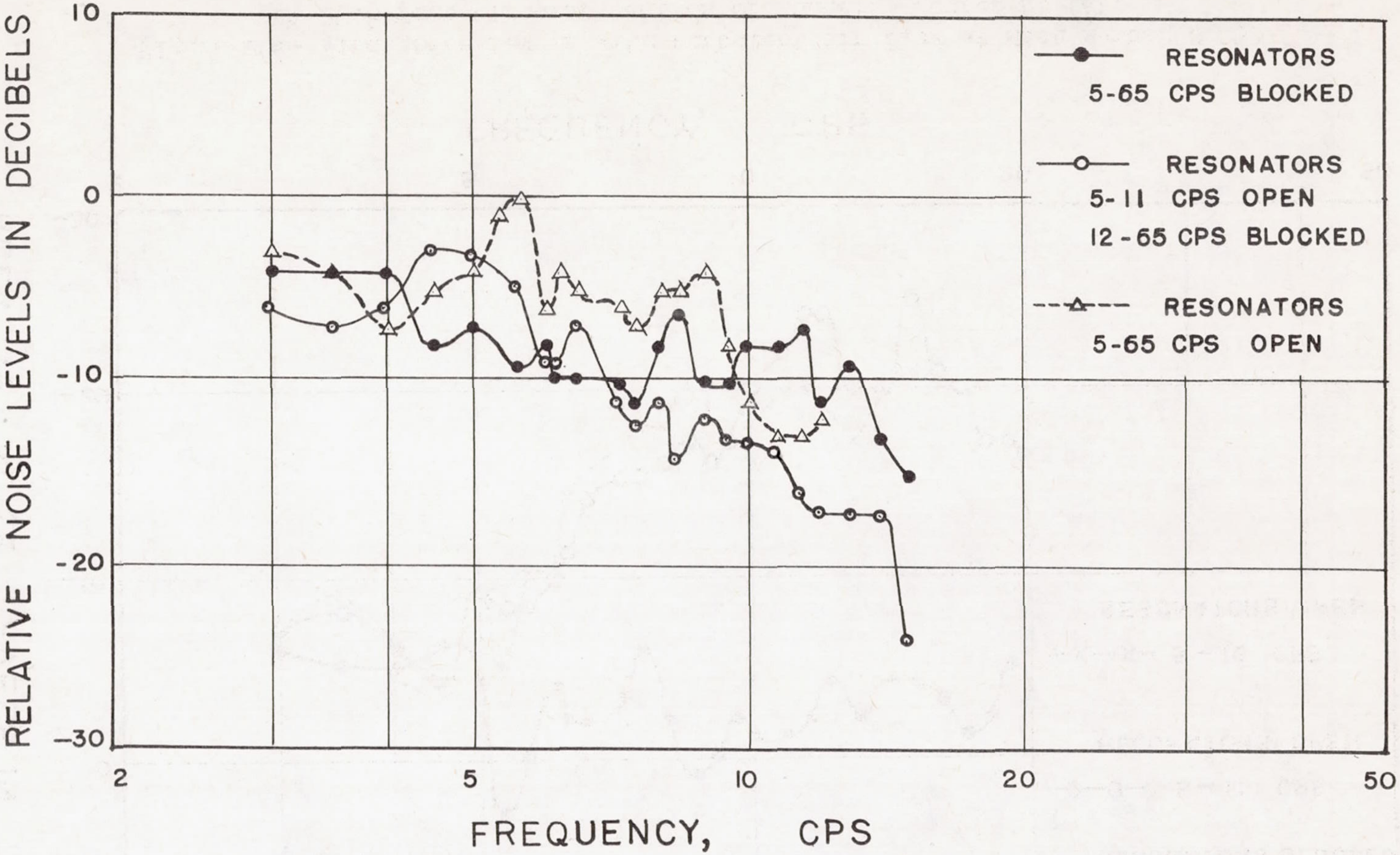


Figure 25.- Wind noise levels with smooth air flow at Mach number 0.066 at 25.8-foot circular section of tunnel. Source at Ⓑ.

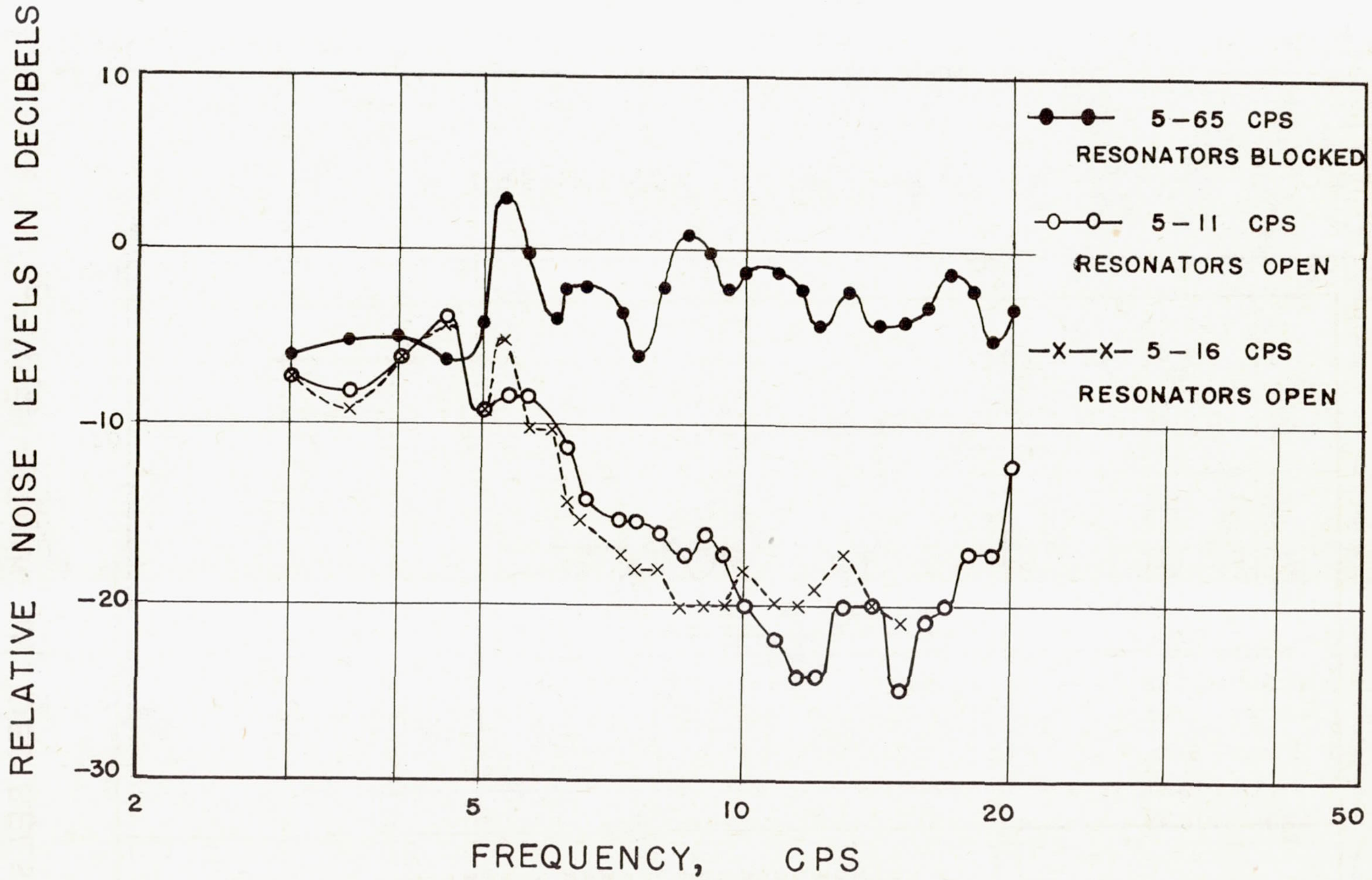


Figure 26.- Wind noise levels with turbulent air flow at Mach number 0.052 at 25.8-foot circular section of tunnel. Source at Ⓐ.

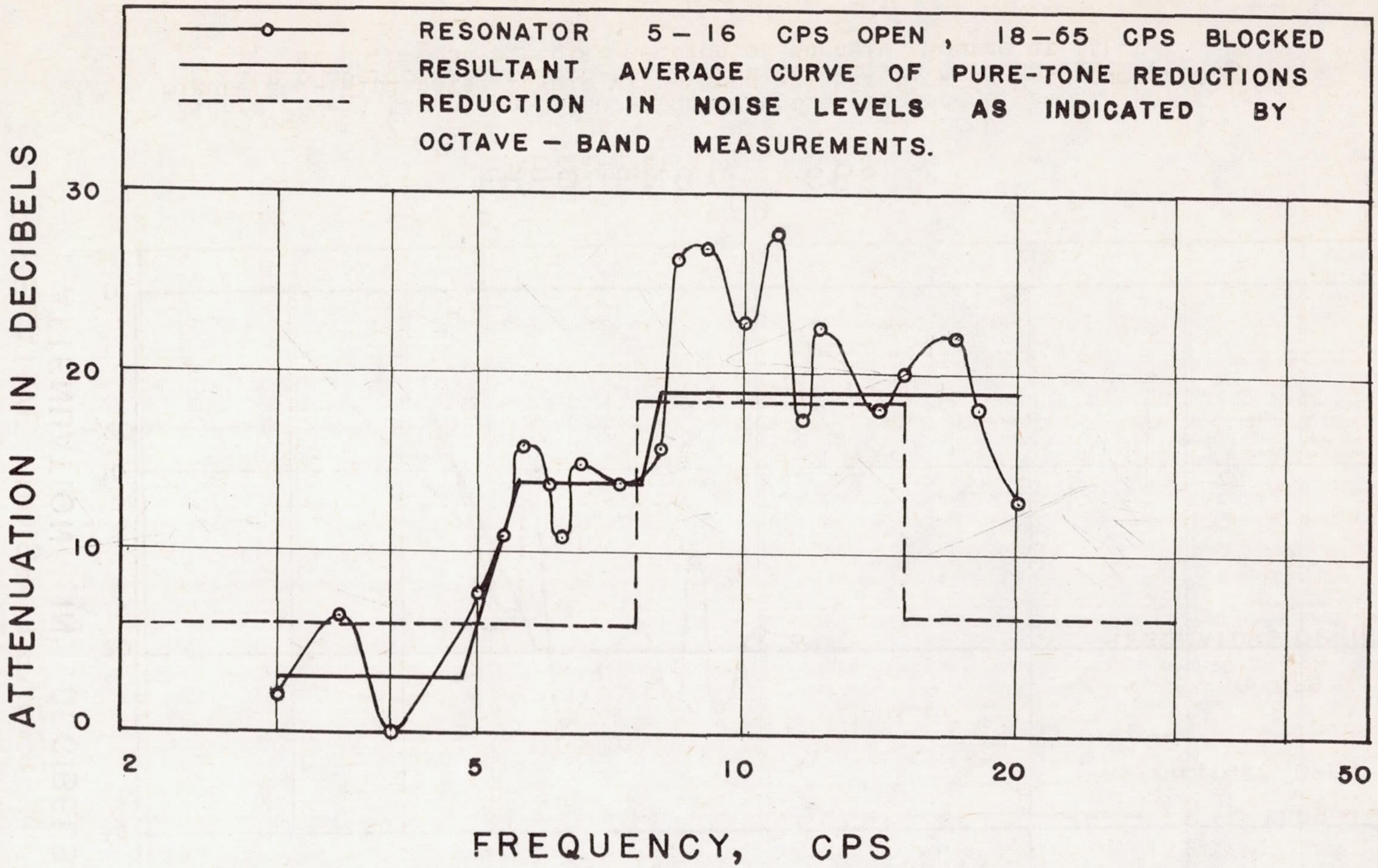


Figure 27.- Attenuation of pure tones in the presence of turbulent air. Mach number 0.052 at 25.8-foot circular section of tunnel; source at (A).

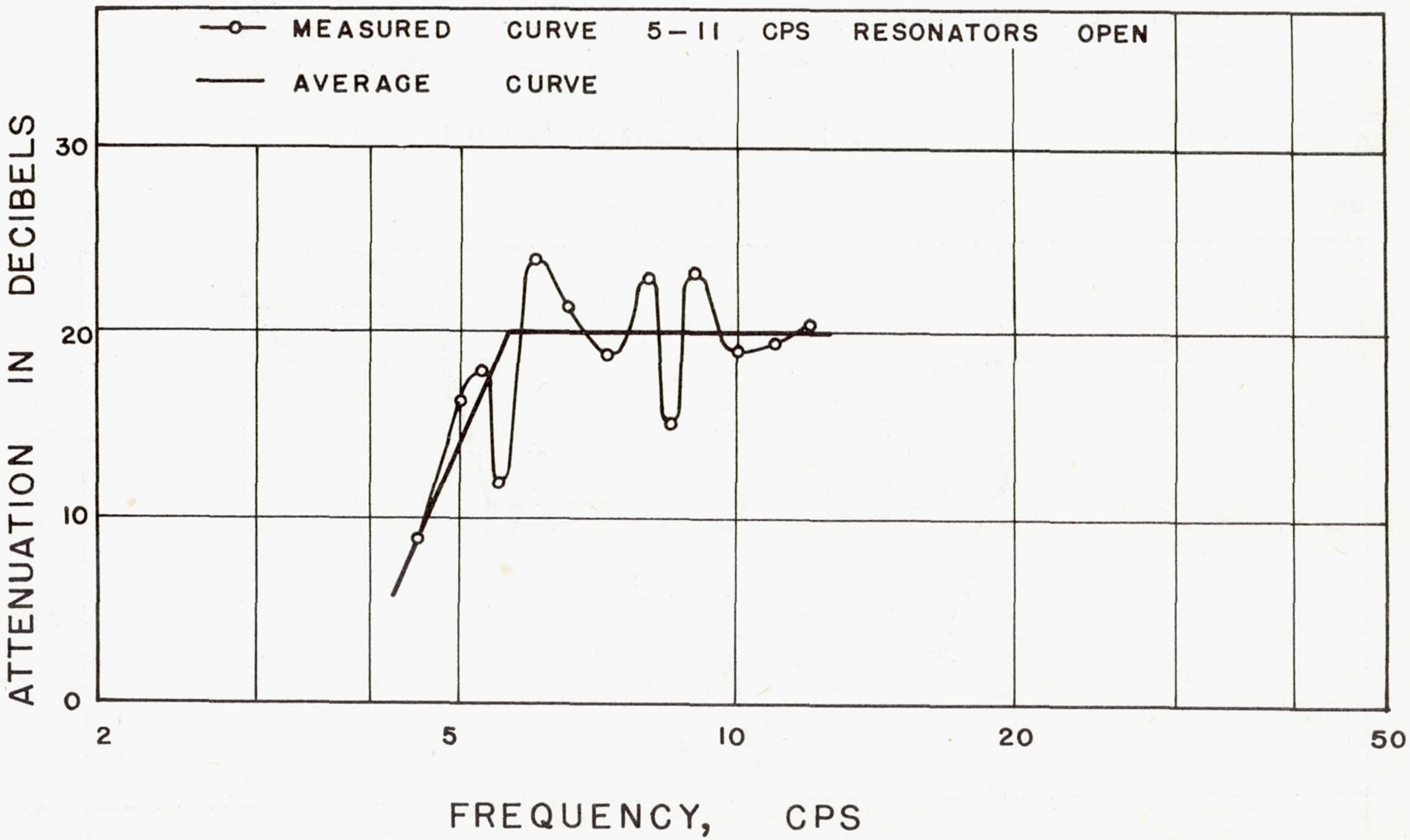


Figure 28.- Attenuation of pure tones in the presence of smooth air flow. Mach number 0.066 at 25.8-foot circular section of tunnel; source at (B).

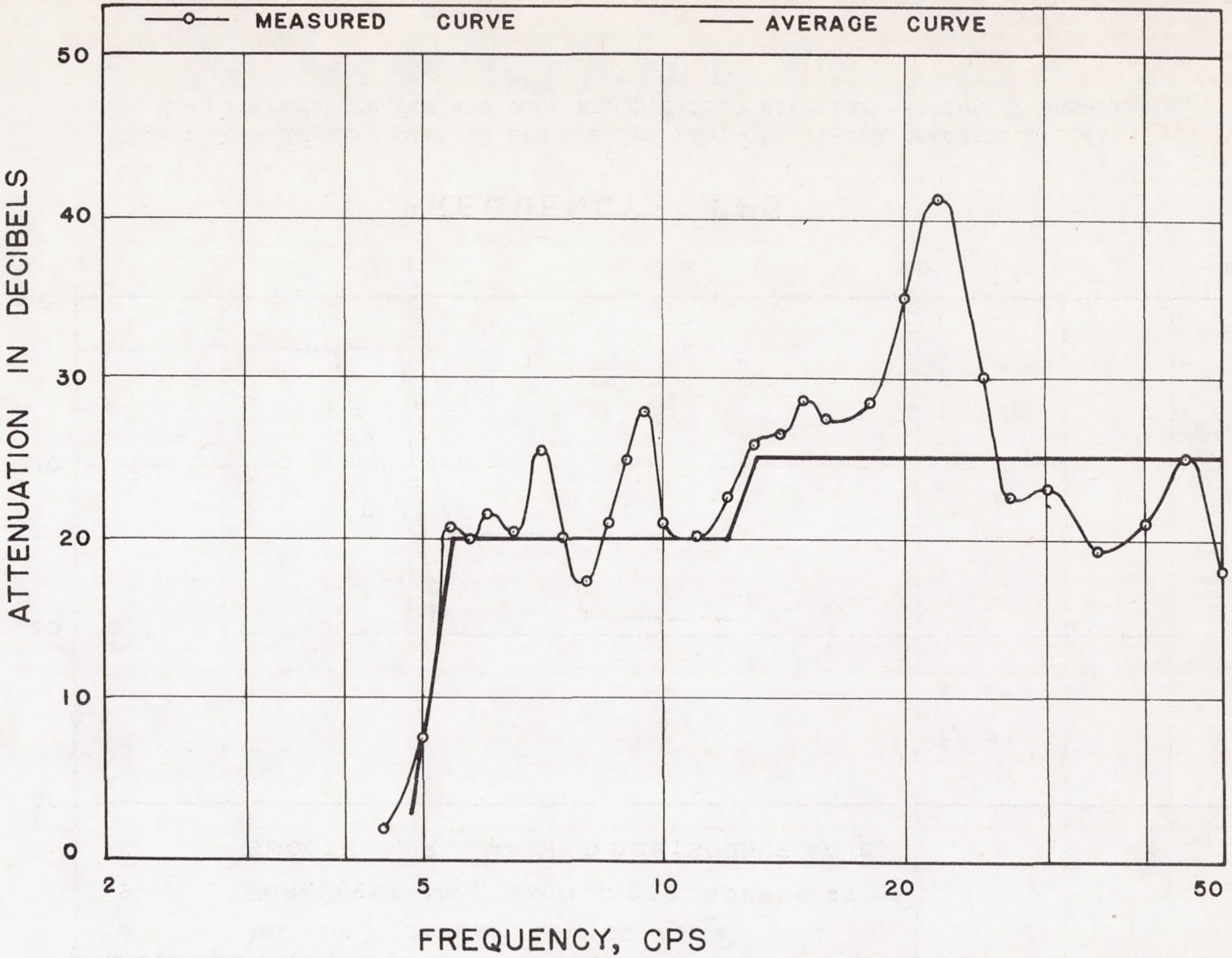


Figure 29.- Pure-tone-attenuation measurements. No wind; all resonators 5 to 65 cps open; source at (A).

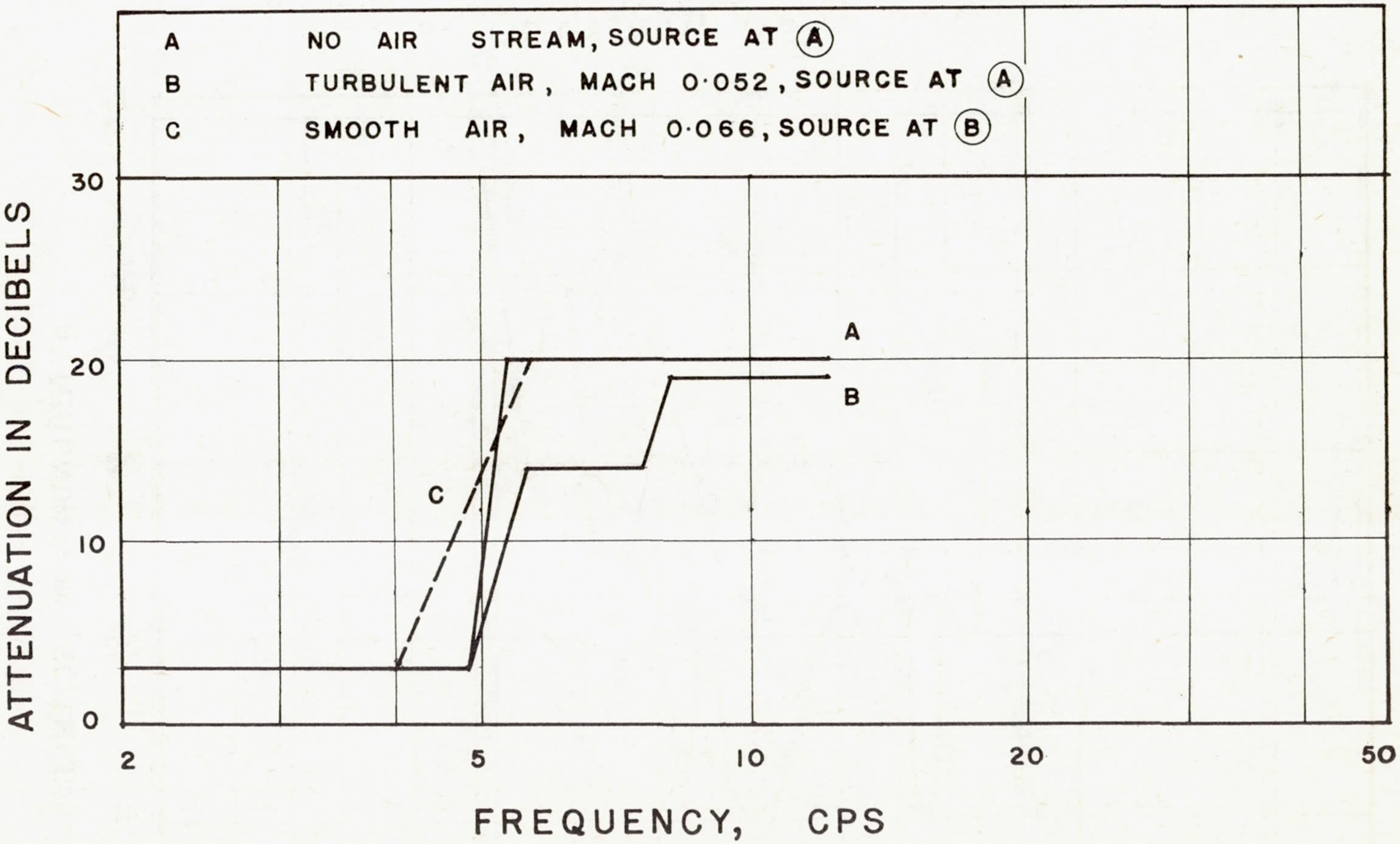


Figure 30.- Summary plot of attenuation of 5- to 11-cps resonators. All Mach numbers are for air flow at 25.8-foot circular section of tunnel.

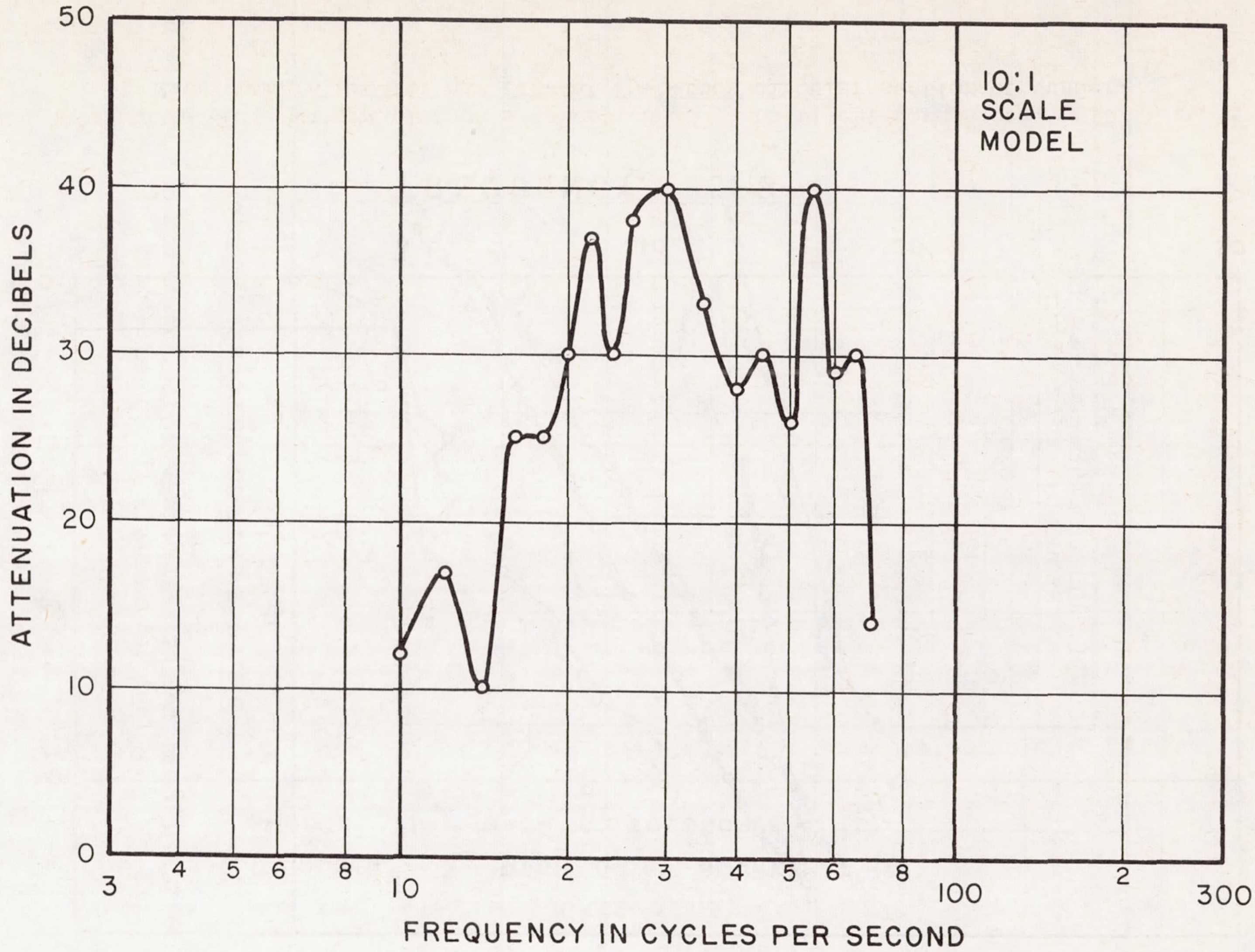
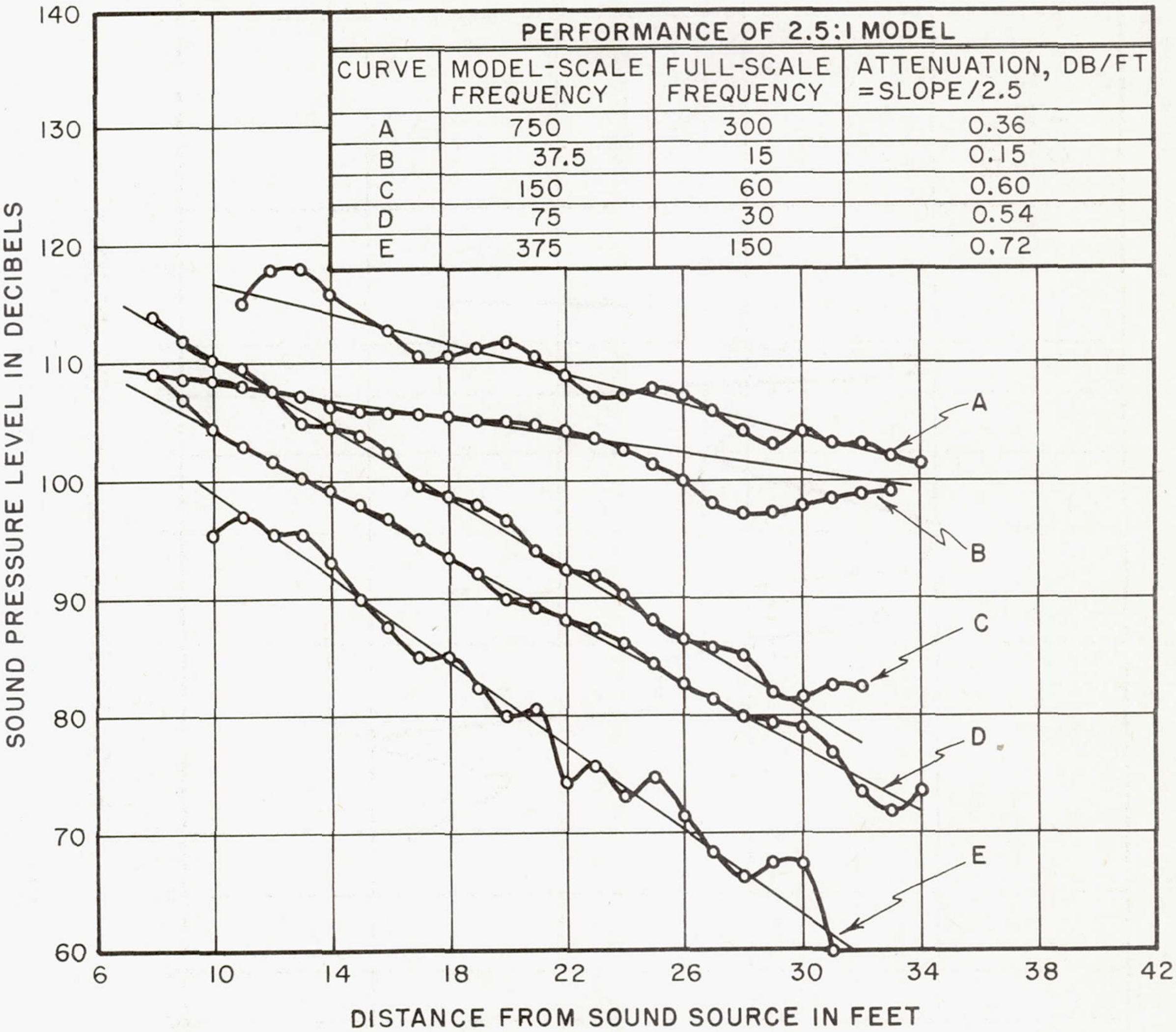


Figure 31.- Attenuation due to resonators 12 to 65 cps.



PERFORMANCE OF 2.5:1 MODEL			
CURVE	MODEL-SCALE FREQUENCY	FULL-SCALE FREQUENCY	ATTENUATION, DB/FT =SLOPE/2.5
A	750	300	0.36
B	37.5	15	0.15
C	150	60	0.60
D	75	30	0.54
E	375	150	0.72

Figure 32.- Performance of scale model having inside dimensions of 4 by 4 feet and randomly spaced partitions.

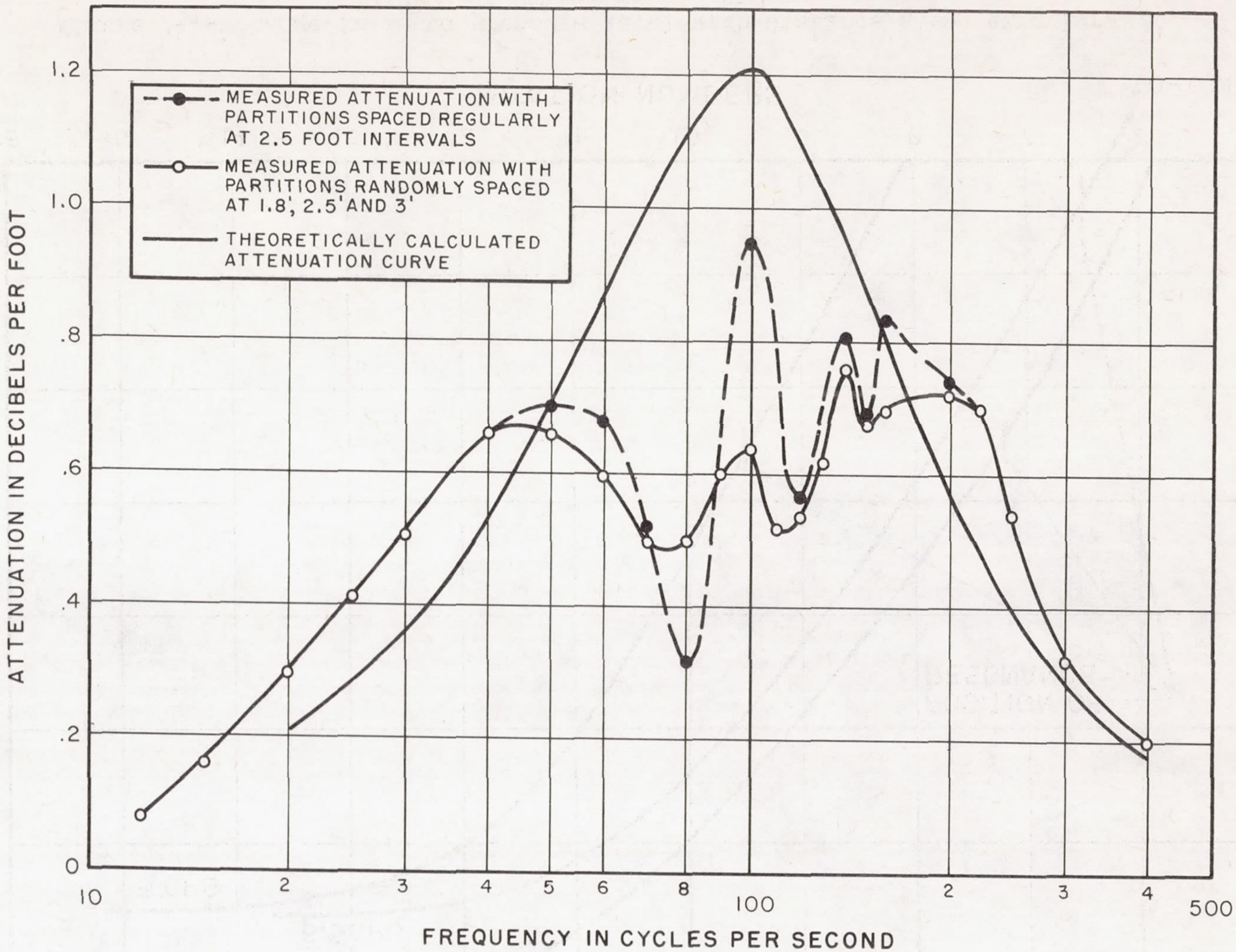


Figure 33.- Lined-duct tests on model having inside dimensions of 4 by 4 feet and a length of 24 feet. All values are converted to full scale.

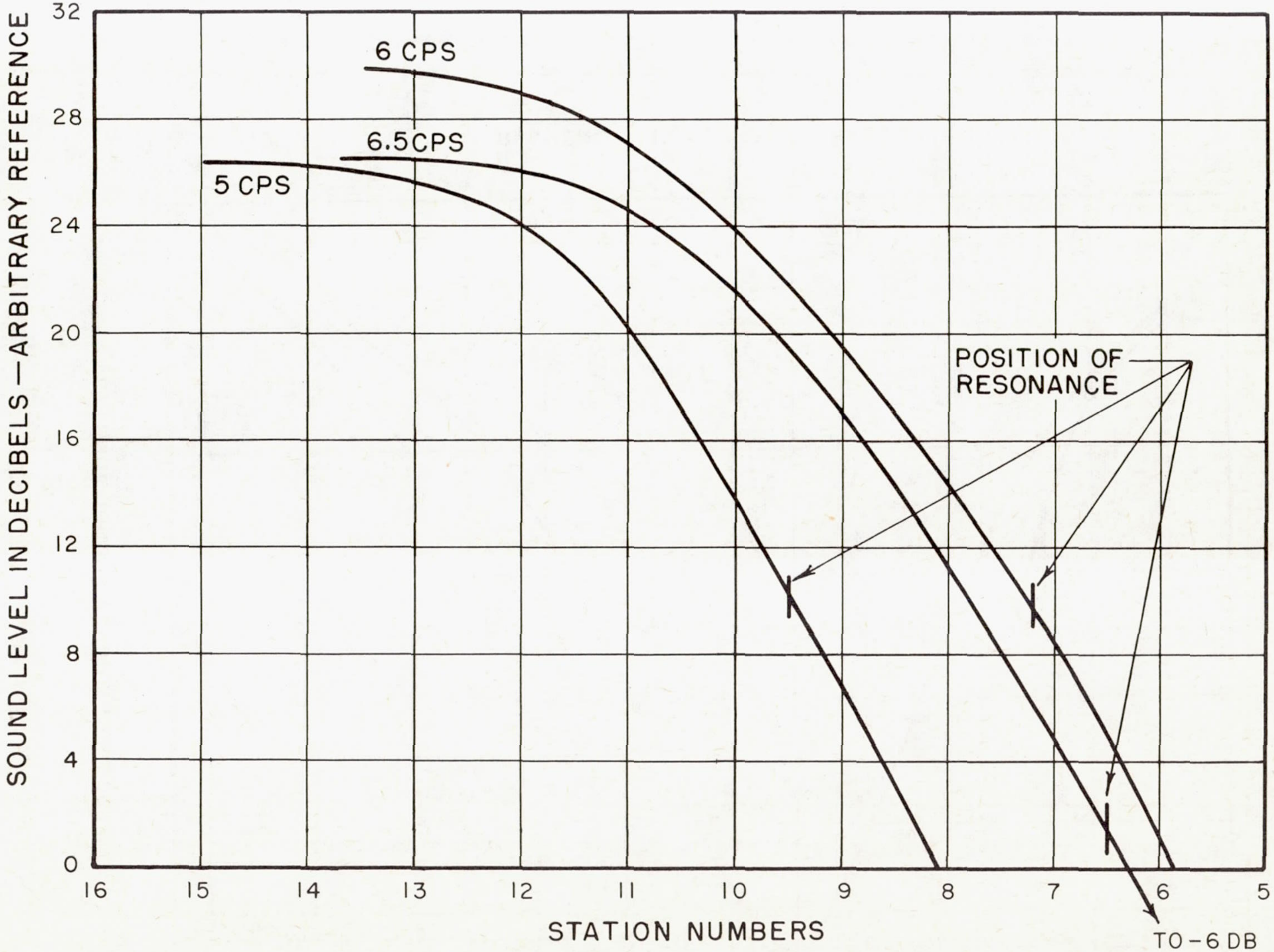


Figure 34.- Change in sound pressure level with distance along circular diffuser. Temperature, 75° F.

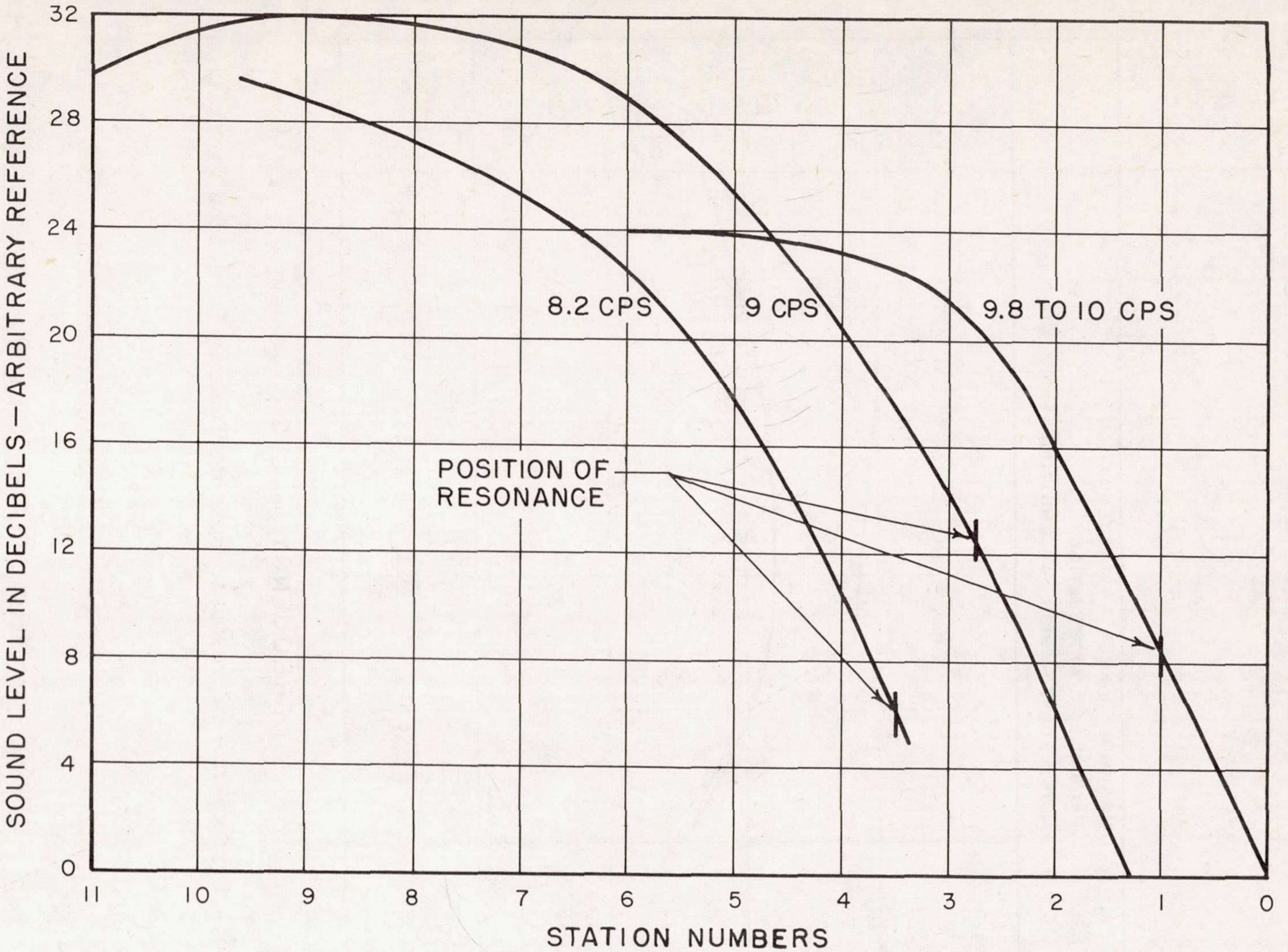


Figure 35.- Change in sound pressure level with distance along circular diffuser. Temperature, 75° F.

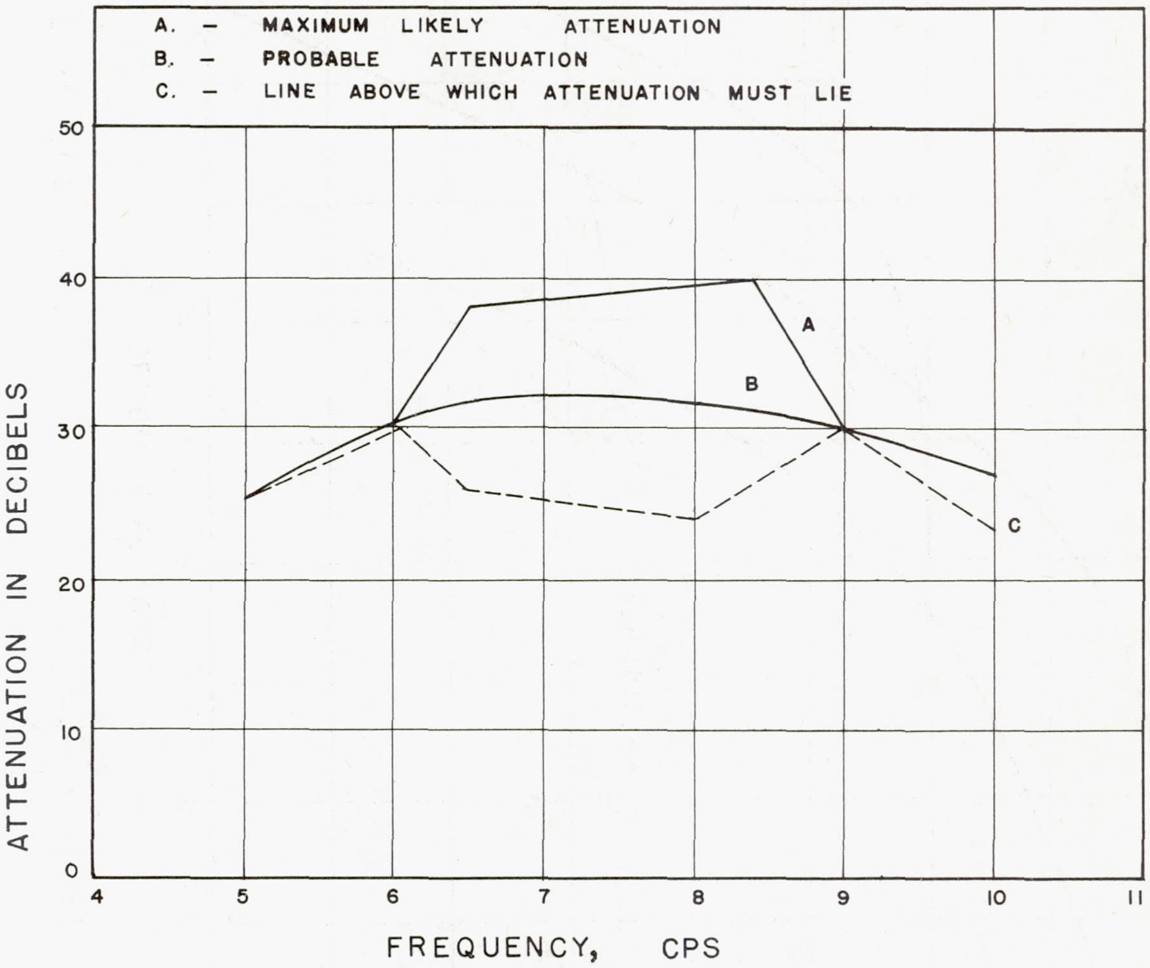


Figure 36.- Performance of resonators in diffuser. Pure-tone excitation.

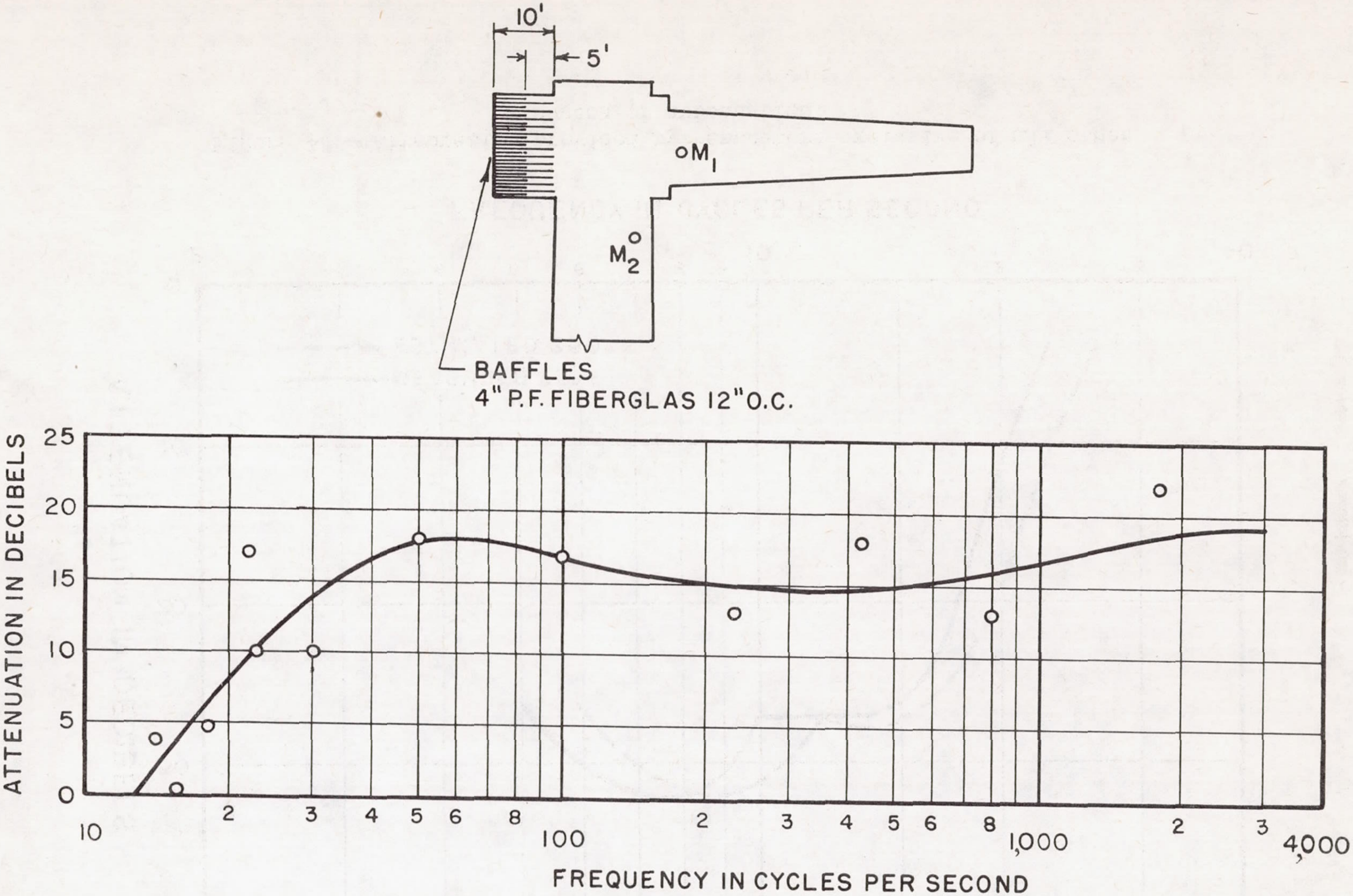


Figure 37.- Losses in first plenum measured with resonators open and with resonators closed. Temperature, 75° F.

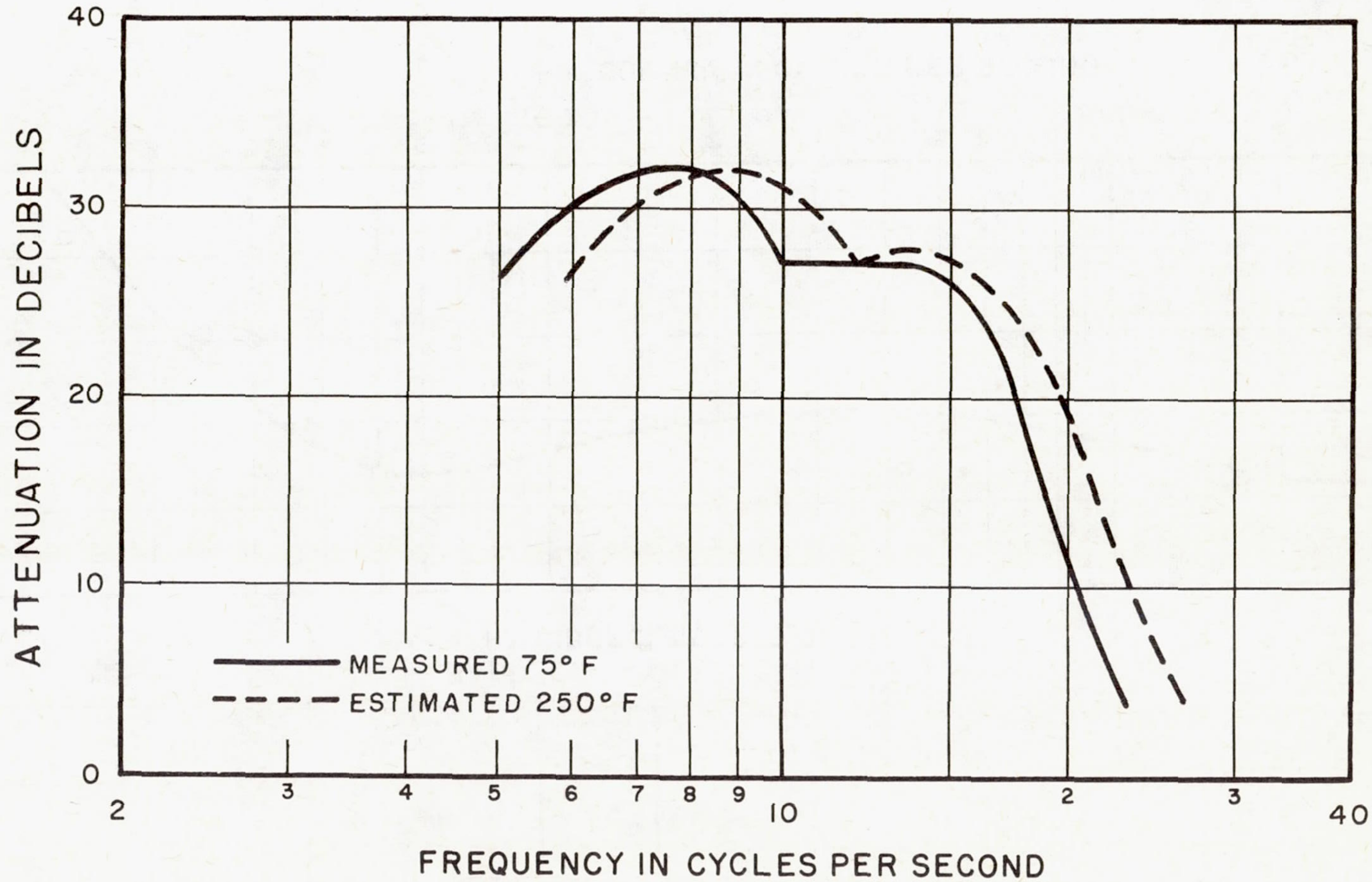


Figure 38.- Attenuation provided by resonators exclusive of all other sources of attenuation.

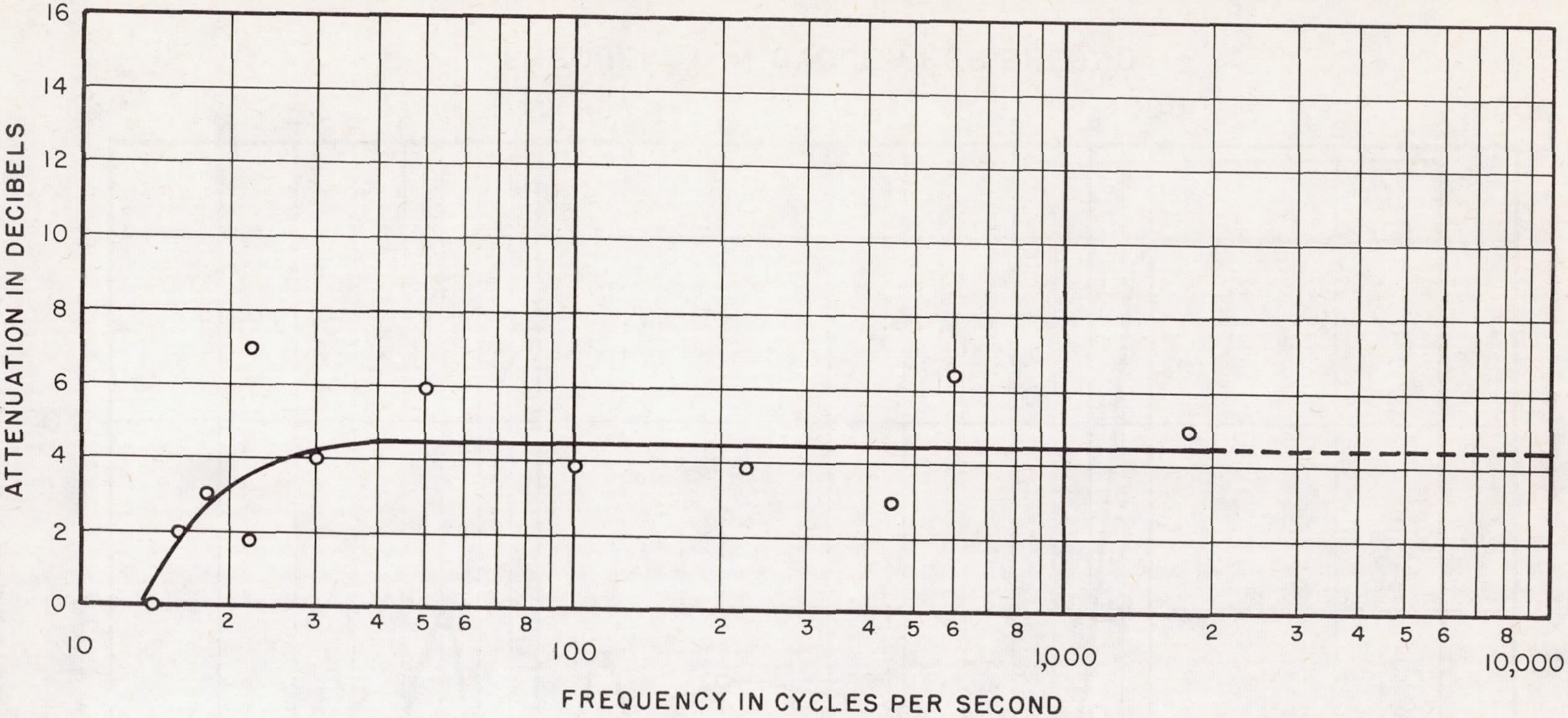


Figure 39.- Attenuation provided by the discontinuity at joint between concrete section and Fiberglas section at center of new construction. Temperature, 75° F.

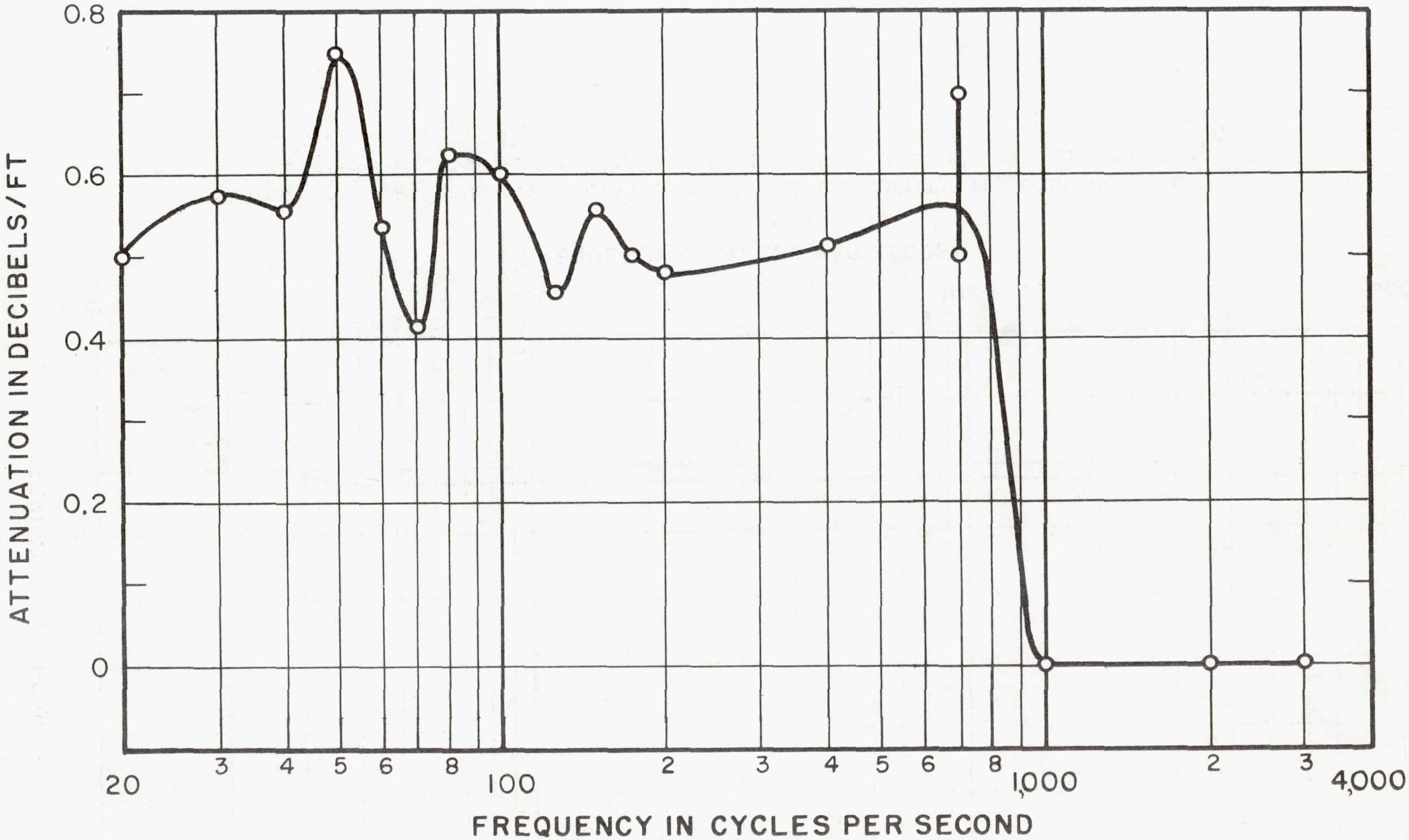


Figure 40.- Fiberglas section of new construction. Attenuation in decibels per foot of actual length; temperature, 75° F. Exclusive of flanking total attenuation may be determined by 90 feet.

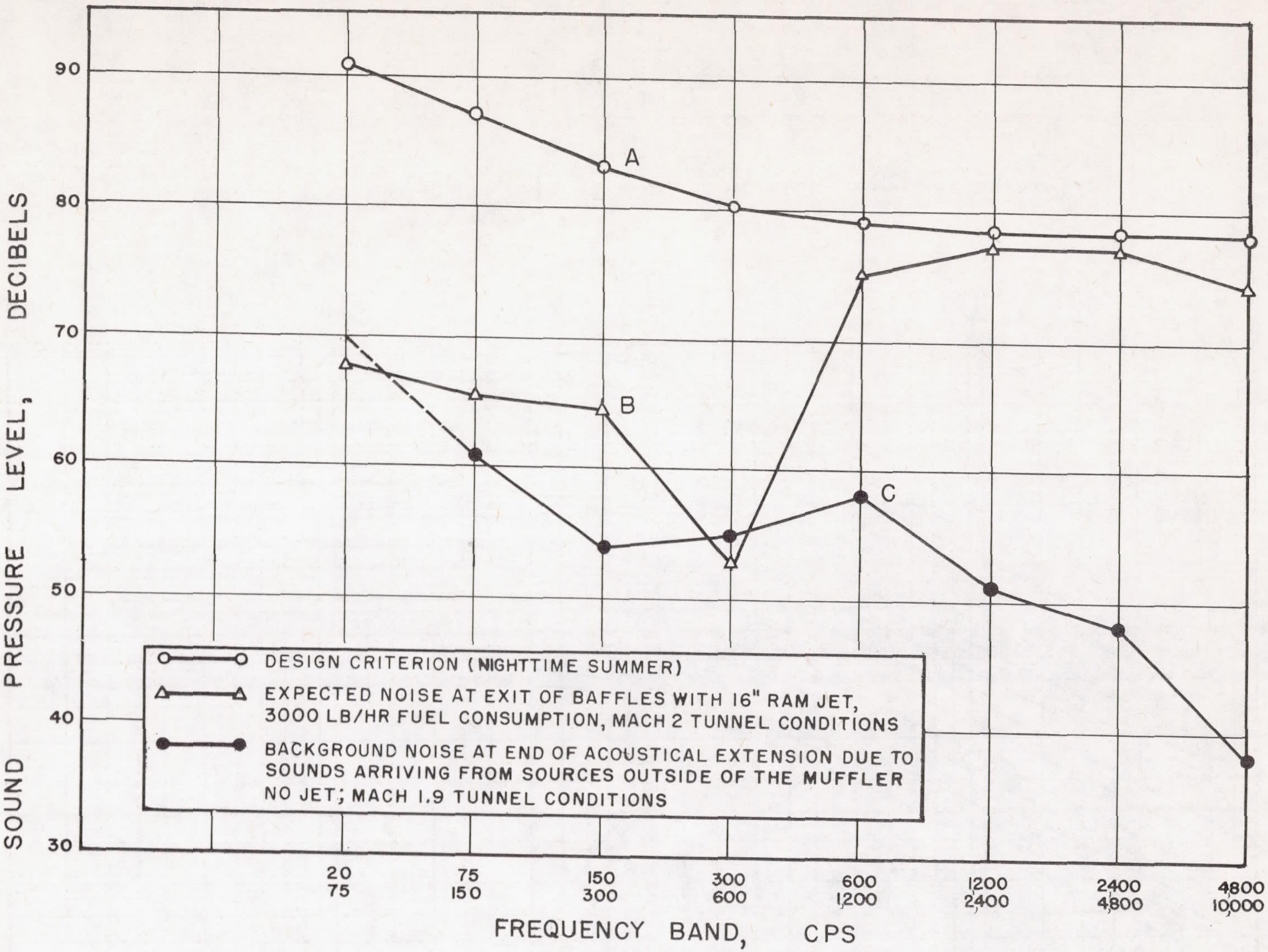


Figure 41.- Levels at exit of baffles.

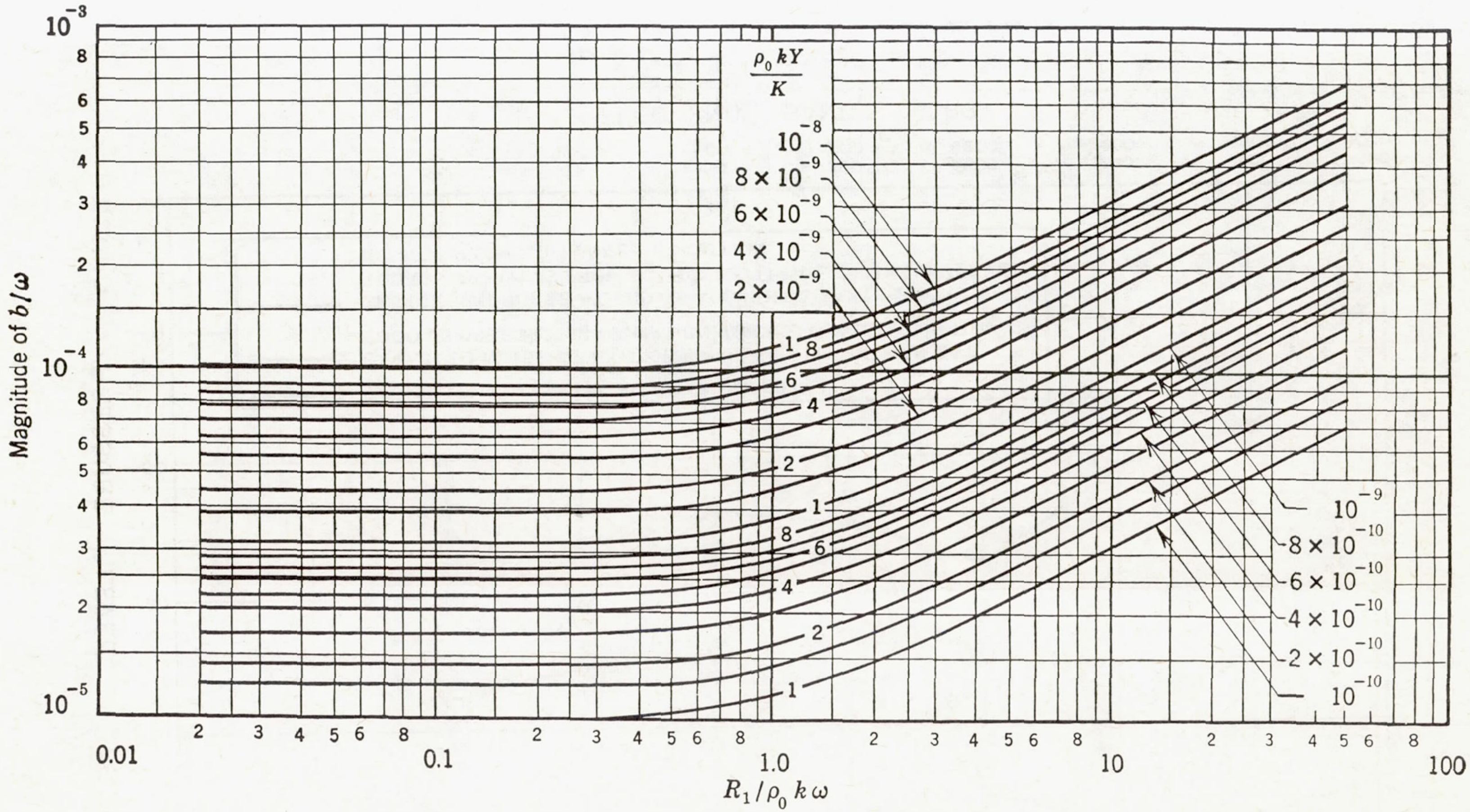


Figure 42.- Chart of $\left|\frac{b}{\omega}\right|$ versus $\frac{R_1}{\rho_o k\omega}$ with $\frac{\rho_o kY}{K}$ as parameter.

$$b = j\omega\sqrt{\frac{\rho_o kY}{K}}\sqrt{1 - j\frac{R_1}{\rho_o k\omega}}.$$

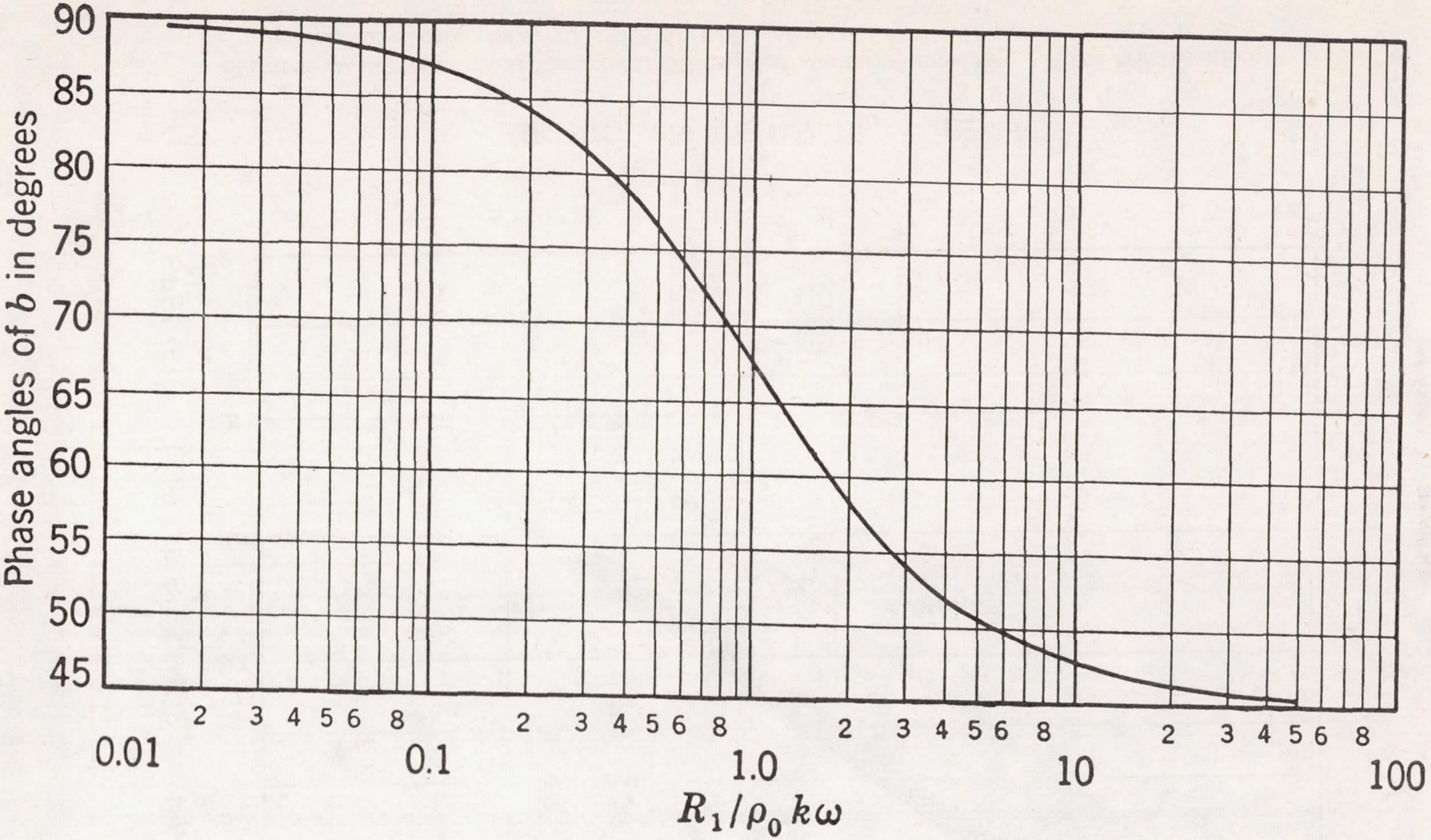


Figure 43.- Phase angle of b versus $R_1/\rho_o k\omega$. $b = \left(\pi - \tan^{-1} \frac{R_1}{\rho_o k\omega}\right) \times 28.7$.

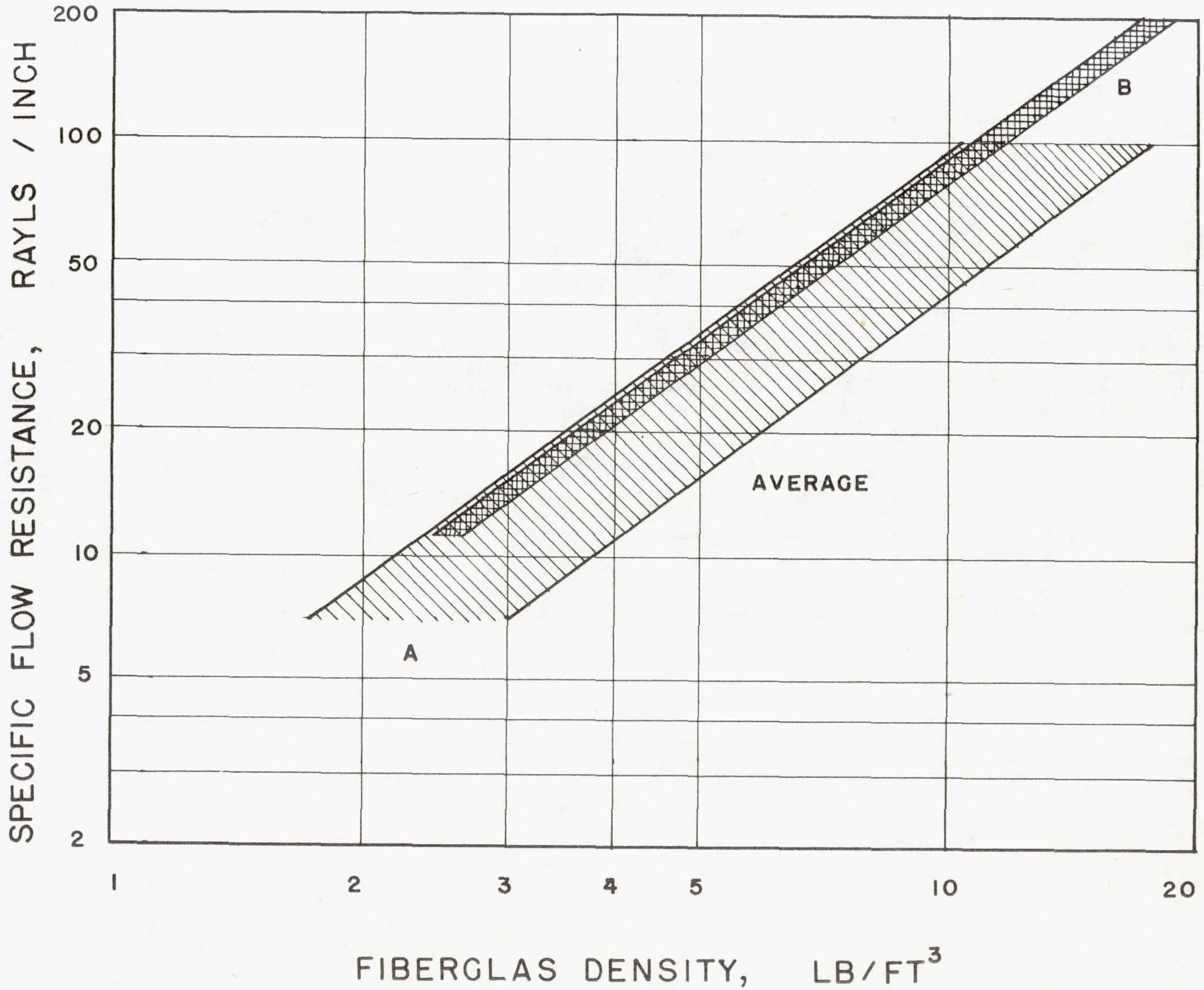


Figure 44.- Flow resistance of Fiberglas versus density. Flow resistance measured along axis of cylindrical sample. A indicates Fiberglas PF board (cylindrical sample); B indicates TWF Fiberglas.

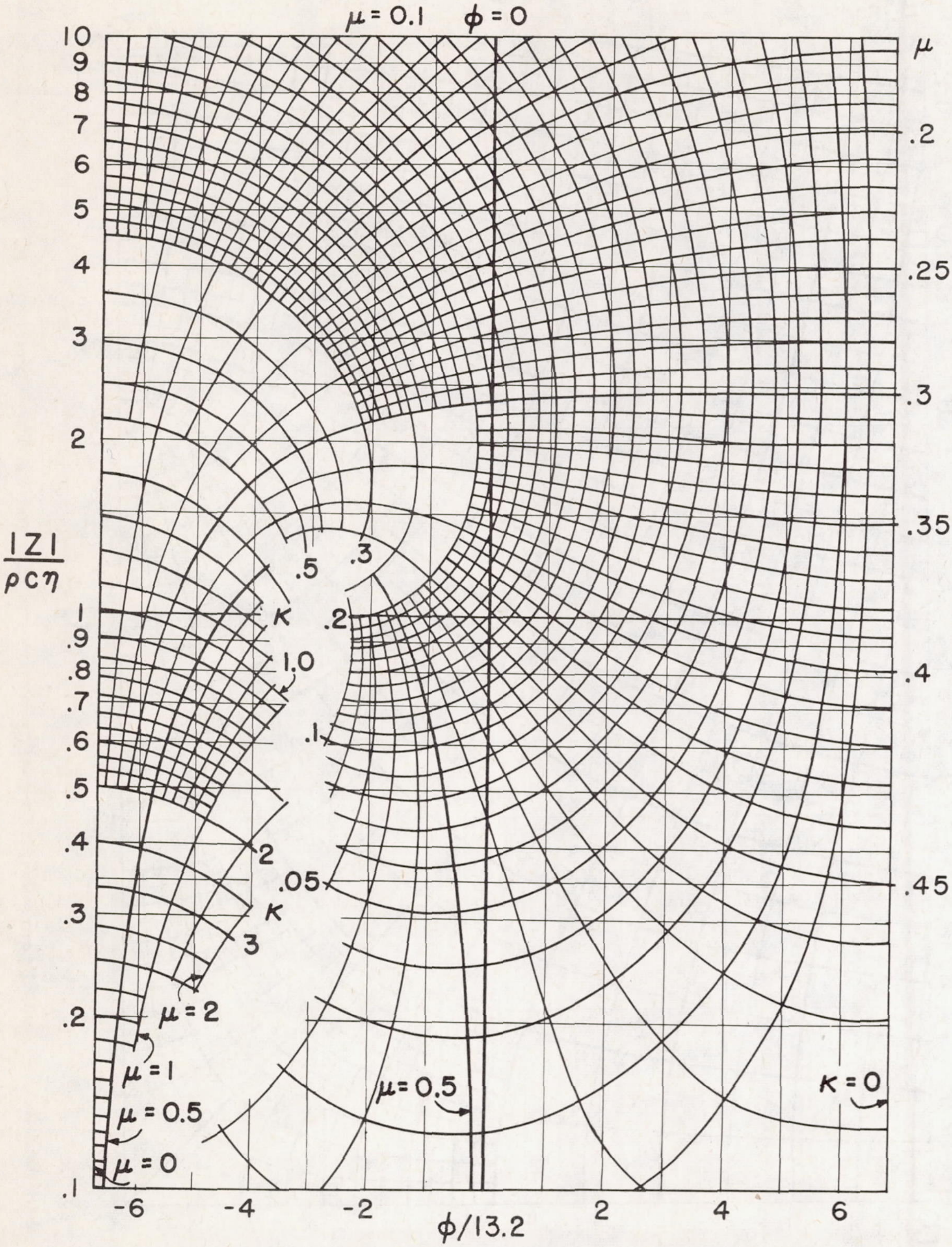


Figure 45.- Transformation from impedance, frequency, and dimensions of duct to parameters μ and K.

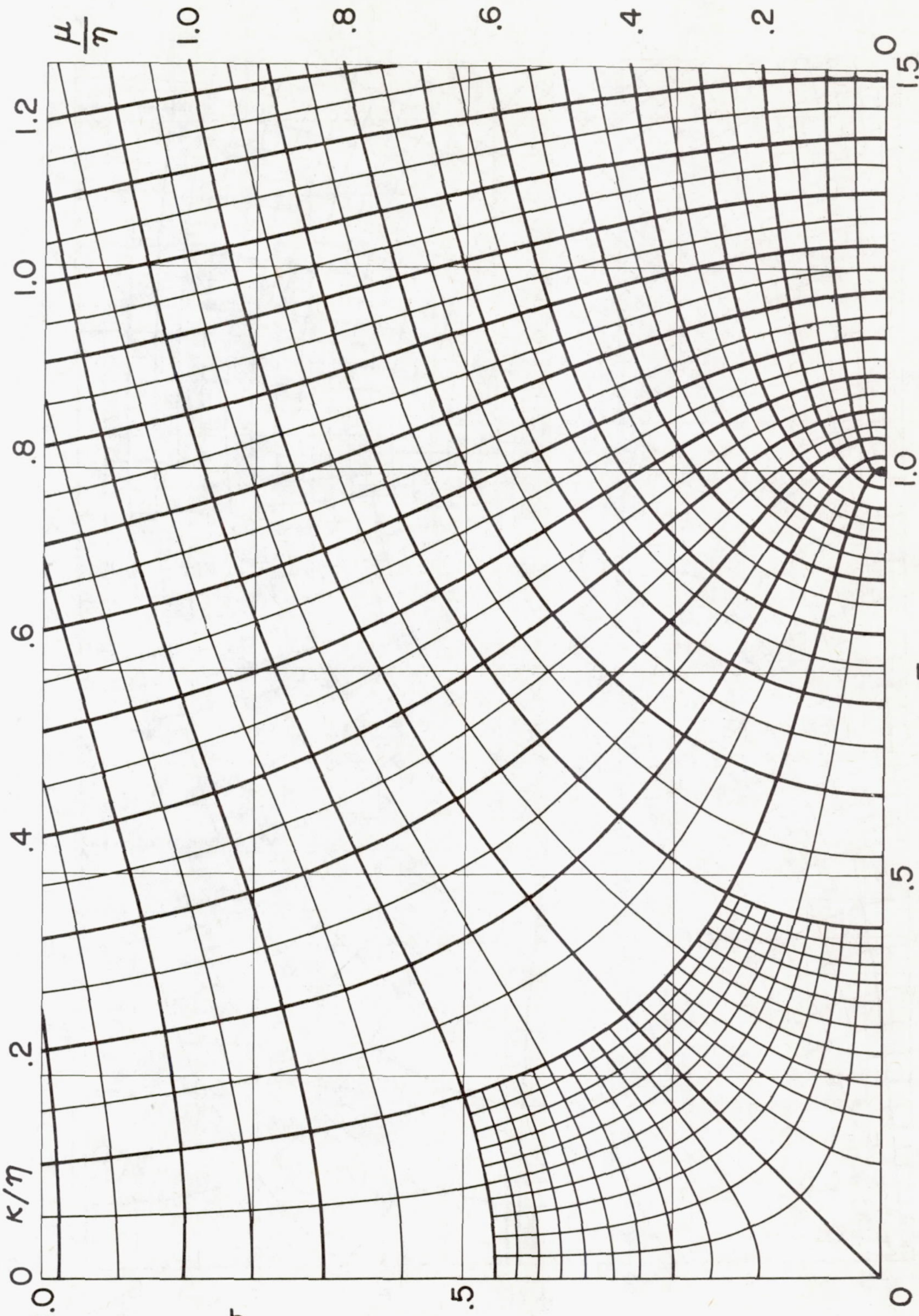


Figure 46.- Transformation of μ and K to constant σ.