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Building Research Note

ACOUSTICAL INVESTIGATION OF CEILING PERFORMANCE IN AN OPEN OFFICE

by

A.C.C. Warnock

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DIVISION OF BUILDING RESEARCH · NATIONAL RESEARCH COUNCIL · OTTAWA · CANADA

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ACOUSTICAL INVESTIGATION OF CEILING PERFORMANCE IN AN OPEN OFFICE

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ABSTRACT

This Note describes an acoustical investigation of flat ceiling properties in an open office. The experiments were concerned particularly with the effects of different ceiling materials, baffle configurations and screen arrangements. The results obtained are analyzed in terms of articulation index giving a single figure rating that facilitates comparisons. A short theoretical outline of screen-ceiling interaction emphasizes the important ceiling and screen parameters and refers to areas where new test procedures are needed.

* * * * * * * * *

INTRODUCTION

The acoustical privacy of an open office is extremely dependent on the reflection of sound from the ceiling assembly. The experiments described in this Note were designed to compare the performance of three types of ceiling materials used with and without ceiling baffles. To determine the influence of screen height on the acoustical privacy behind a screen, two screen heights were used, 4 ft 8 in. and 6 ft. The experiments were designed and carried out by the Building Physics Section of the Division of Building Research, N.R.C., in a sixth floor office of the Kenson Building, Metcalfe Street, Ottawa.

I EXPERIMENTAL TECHNIQUE

The privacy conditions in an open office are closely related to sound propagation in the office space, and can be examined by making the appropriate acoustic measurements. In the open air, in the absence of obstruction and atmospheric disturbances, the sound pressure level from a continuous source will decrease by 6 dB each time the distance from the source is doubled. This condition can be approximated in a very absorbent room such as an anechoic chamber. At the other extreme, in a reverberant space bounded by highly reflective surfaces, one quickly enters the reverberant field where the sound pressure level does not decrease appreciably with distance from the source.

The objective of an open office is to approach, as closely as is practicable, an open air case, hence the specification of absorbent surfaces and furnishings. The propagation experiments described here were intended to measure the effects of ceiling materials, ceiling baffles and screen configurations on the propagation of sound in an office.

The office used for these studies was fairly narrow and, in an attempt to reduce possible reflections from a nearby wall, the wall was covered with about 2 in. of glass fibre. The ceiling boards in the office measured 4 ft by 2 ft and were supported on T-bars. Details of the three types of ceiling boards used are given in Appendix A. The baffles were simply constructed from pieces of 1/4-in. plywood measuring 4 ft by 1 ft and covered on one face with 5/8-in. glass fibre which had a perforated vinyl facing. When used these baffles were suspended on hooks from the T-bars with the glass fibre side facing the sound source.

The screens used were commercially manufactured and measured 4 ft 4 in. high, 5 ft wide and 3 in. thick. The bottom edges of the screens were 4 in. from the floor raising the tops to a height of 4 ft 8 in. One of the screens was modified by clamping to it a piece of 1/8-in. hardboard which was covered on both sides with 1 1/2 in. of glass fibre thereby increasing the over-all height to 6 ft.

Figure 1 outlines the experimental procedure used in making the continuous sound propagation measurements. The long axis of the column loudspeaker was placed horizontally in a further attempt to reduce the effects of the walls and windows. The recordings were analyzed in the laboratory on a real time analyzer and the third-octave band levels obtained were then reduced to octave band readings. The results are presented and discussed in the next section.

It is generally true that there are several acoustical paths between two points in an office. Continuous measurements do not separate these paths and give only the total effect produced by all of them. In an effort to sort out these paths, measurements were made using pulses of sound. It was found that if the duration of the pulse were short enough it was then possible, under appropriate conditions, to identify and separate the different components.

The apparatus used to carry out the pulsed study is shown in Figure 2. The three major paths of interest are shown in this figure.

Other horizontal reflecting paths could be present but it was hoped that they would not be a problem in this case as precautions were taken. The acoustic pulses were picked up by microphones and the electrical signals were displayed on an oscilloscope screen which was photographed. The interpretation of the results is discussed in the next section.

II RESULTS

(i) Continuous sound source:

(a) dB(A) analysis

Table 1 lists the A-weighted sound pressure levels measured as a function of distance under the different ceilings. Data from this table are plotted in Figures 3 to 5 to demonstrate the effects of the ceiling baffles. For material A, the baffles have an easily observable effect in that they generally reduce the received signal. To obtain a significant reduction however, the baffles should be used on 2-ft centres. The performance of the combination is then about the same as material C without baffles. This was perhaps a predictable result since the total absorption of ceiling A plus baffles is about the same as that provided by ceiling C. By contrast it was observed that the addition of baffles to ceiling C made a negligible improvement.

Figure 6 facilitates the comparison of ceiling materials, A and C. It can be seen that the use of the more absorbent material results in a lower signal at a given distance behind the screen. The difference is generally about 3 dB(A).

(b) Octave band analysis

Tables 2 to 8 show the octave band analysis of the signals and are included for completeness. The octave band analysis of the propagation measurements leads to essentially the same conclusions as the dB(A) results. Figure 7 is included to illustrate what is obtained for materials A and C. In the next section it is shown that an analysis of these octave band results, in terms of the articulation index, leads to a single figure rating for a given screen-ceiling combination.

Articulation Index

In the open-plan office the acoustician is generally concerned with those factors which have an effect on speech privacy. It is convenient, therefore, to express the results in terms of a quantity that measures the intelligibility of speech. The most common unit is the articulation index (AI). The articulation index is calculated by estimating speech signal-to-noise ratios in those frequency bands which are important in speech, multiplying the ratios by weighting factors and summing the products (1). The number resulting from this is the AI and lies between 0 and 1. The dependence of sentence intelligibility on AI is shown in Figure 8 where it is clear that intelligibility increases rapidly as AI increases from zero to 0.40. For acceptable privacy, free from distraction, the AI in an open office should be less than 0.15. For AI<0.3 a decrease in AI of 0.05 is very important and produces a decrease in sentence intelligibility of about 15%.

The data tabulated in Tables 2 to 8 can be used to calculate the changes in AI which occur as a result of changes in the ceiling or screen configuration. These calculations were made for three distances of interest, viz. 9, 12 and 15 ft, and the results are given in Tables 9-12. The results are expressed as the improvement over a reference condition consisting of material A with no intervening screen or baffles.

Considering the effects of ceiling baffles on the performance of material A, it can be seen that on 4-ft centres the baffles produce an insignificant decrease in AI. When the baffles are 2 ft apart the decrease in AI is quite marked, consistently about 0.1. As has already been pointed out, such changes are very important.

The use of baffles with material C also decreases the AI in a given situation. In this case the decrease is smaller and the differences between the 4-ft o.c. and the 2-ft o.c. case are even less and are somewhat random in nature. The fact that material C is almost acoustically transparent could account for the inconsistency of its behaviour; also, plenum reflections could introduce complications.

The effects of screen size and position can be found by reading vertically down a column in Tables 9-12. One finds, predictably, that a 6-ft screen provides more isolation than a 4-ft 8-in. screen and that moving the screen closer to the source is also an improvement.

The relative efficacy of the three ceiling materials can be determined by concentrating on the results obtained without ceiling baffles. With one exception, material C performs best. The exception is again a possible manifestation of the acoustical transparency of material C. Ceiling materials with Noise Reduction Coefficients (NRC) approaching 1.0 are now readily available and should be an improvement over the best system dealt with here. It was not possible to test such a material during the time available for this study.

The information found in the tables can be summarized as follows: the larger the screen, the larger the insertion loss; the more absorbent the ceiling, the better a given screen will perform. The limit is reached when there are no flanking reflections. In practice, one should use a highly absorbent material with an NRC as high as possible. Ceiling baffles can be used to improve a reflective ceiling but, when used, they need be spaced so closely that they become economically unfeasable. They can also slightly improve a more absorbent ceiling; again, however, benefits cannot be justified economically since highly absorbing materials are easily available and are probably more effective.

(ii) Pulse Measurements

Figure 9 illustrates the electrical signals produced by the receiving microphone shown in Figure 2. The figure caption identifies the experimental conditions. It is clear that there are several sources of reflection which complicate the trace.

From a knowledge of the path lengths in Figure 2 the time delay between two corresponding points on the diffracted pulse and the pulse reflected from the ceiling can be evaluated. Given the value of the time delay, it is then possible to delineate the expected ceiling pulse. In a few cases the similarity between the pulse shapes was close enough to allow identification of the ceiling pulse by direct observation. This permitted the verification of the calculated time delays. With this knowledge in mind, it becomes, in theory, a straightforward task to measure the amplitude of the diffracted signal and the ceiling reflection signal. Unfortunately, in many cases, the ceiling reflection signal was extremely distorted as a result of interference effects. This resulted in a large spread of values obtained for the ceiling reflection measurements. The values obtained for the direct and diffracted pulses behaved in a more predictable fashion and the results obtained for these pulses are displayed in Figure 10. These results are the average of the values obtained under all ceiling conditions. As expected, the direct pulse decreased 6 dB for each doubling of distance from the source. The small screen has an insertion loss about 10 dB less than that of the large screen. Theory, discussed later, predicts a larger value but this discrepancy is probably due to the relatively large size of the source.

The results for the reflected ceiling pulses are shown in Figure 11. The scatter in these measurements was very large and is not shown here. Upon examination some inconsistencies were very quickly discovered. Figure 11(a) seems to show, in contradiction to Figures 11b-d, that baffles on 4-ft centres are about as effective as those on 2-ft centres. Comparison of the levels of the pulse diffracted around the small screen with the levels of the ceiling bounces leads to the conclusion that the ceiling material and baffle configuration are not important. This is contrary to the continuous sound results and to theoretical considerations. Because of these and other discrepancies it must be concluded that the reflected ceiling pulses though qualitatively interesting, are not reliable for quantitative information.

III THEORETICAL CONSIDERATIONS

Sound, at the important speech frequencies, reaches the other side of a screen in various ways:

i) by direct transmission through the screen,
ii) by diffraction around the screen,
iii) by reflection from the ceiling,
iv) by reflection from vertical flanking surfaces.

Considering first the direct transmission, it is shown in standard texts (2) that the transmission loss for sound waves normally incident on a solid wall is

$$TL\,(dB) = -28.6 + 20 \log Mf$$

where M = mass/unit area in lb/ft^2
f = frequency in Hz.

The reduction of a signal caused by diffraction around a semi-infinite screen is given by (3)(4).

$$DL\,(dB) = 20 \log_{10} \left(\frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} \right) + 5 \qquad N \geq -.02$$

where $N = 2(A+B-d)/\lambda = 2\delta/\lambda$

The distances A, B, and d are shown in Figure 2. The distance δ is the difference between the path taken by the diffracted wave and that taken by the direct wave.

In Figure 12 the insertion loss due to diffraction for two semi-infinite screens is compared with the attenuation of signals propagating through the screen. It is quite clear from this figure that the loss due to transmission through the screen is easily made negligible for typical screen heights by using an acoustically opaque material with a surface density of $1/4\ lb/ft^2$ or greater as a membrane to separate the layers of absorbing material.

Because the diffraction loss is greater for higher screens that are occasionally used, the mass per unit area of the separating membrane must be increased. If one adopts as a criterion the requirement that the transmission loss should be about 6 dB greater than the diffraction loss at 1000 Hz, then the surface density of the screen membrane should satisfy

$$M \geq \sqrt{\delta}/3$$

With this condition met the screen will perform close to the limit set by diffraction provided there are no flanking reflections.

A theoretical consideration of specular reflection from a flat, absorbing ceiling is straightforward. Referring again to Figure 2, the reflected signal arriving at the microphone is smaller because of absorption and because of the longer path length travelled; in fact, the attenuation relative to the direct signal is

$$20 \log 2C/d - 10 \log\rho$$

where ρ is the reflection coefficient of the ceiling at the particular frequency and angle of incidence considered.

In order to demonstrate the effects of ceiling absorption on screen performance, Figure 13 has been constructed. This figure shows the variation of articulation index as a function of ceiling reflectivity calculated at the listener's position when a screen is interposed halfway between listener and talker. For the purpose of this figure a background noise of 48 dB(A) has been assumed. Table 13 shows the voice levels, noise levels and diffraction losses used in the calculation of the articulation index. The talker-listener separation assumed was 12 ft and the ceiling height was taken as 9 ft. The absorption coefficient was assumed to be equal in all bands.

Specular reflection from vertical surfaces can also create problems. Vertical surfaces are usually treated with an absorbing layer. A short study of the effectiveness of different treatments is described in another Note (5).

IV CONCLUSIONS

The following conclusions can be drawn from this study:

1. Assuming a screen constructed in accordance with the recommendation made in the previous section, the larger a screen, the greater its insertion loss.

2. The ceiling system in an open office should have a reflection coefficient low enough to permit the screens to perform close to their maximum, diffraction-limited capabilities. The simplest way of achieving this condition for a flat ceiling is to use highly absorbent ceiling boards. Ceiling baffles are not recommended except possibly as a way of improving the performance of a poor ceiling.

V FUTURE WORK

The theoretical discussion of screen performance under an absorbent ceiling emphasizes the need for further work in the field. At this writing, flat and coffered ceiling systems are tested in reverberation chambers where the absorption coefficient averaged over-all angles is measured. It would be more appropriate to have a test procedure where the reflection coefficient is measured as a function of frequency and angle. If such a test were available it would also be possible to deal with those ceiling systems which are composed entirely of absorbent baffles suspended from exposed ductwork.

At present, screens are typically rated in terms of their surface absorption (averaged at the Noise Reduction Coefficient). It might also be relevant to introduce a simple test to measure the insertion loss of screens to ensure that as well as being absorbent they also have a high enough transmission loss.

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TABLE I

REDUCTION IN A-WEIGHTED SOUND PRESSURE LEVEL IN dB RELATIVE TO 3-FT LEVEL

			Distance from loudspeaker (ft)					
Material	Screen Condition	Baffle Condition	6	9	12	15	18	24
A	No screen	No baffles	5	7.5	10	10.5	11.5	12.5
A	4-ft 8-in. screen at 3 ft	"	10	11.5	13.5	13.5	15.5	18
A	6-ft screen at 6 ft	"	-	15.5	14	14.5	15.5	18
A	6-ft screen at 3 ft	"	14	15.5	18	18	19	19.5
A	No screen	Baffles on 4-ft centres	3.5	6	7.5	9.5	10	12.5
A	4-ft 8-in. screen at 3 ft	" "	8.5	11	12.5	13.5	15	17.5
A	6-ft screen at 6 ft	" "	-	14	13	14	17	18
A	6-ft screen at 3 ft	" "	13.5	15	16.5	18	19	21
A	No screen	Baffles on 2-ft centres	5	8.5	10	11.5	13	15
A	4-ft 8-in. screen at 3 ft	" "	11.5	14	14	16.5	17.5	21
A	6-ft screen at 6 ft	" "	-	16	14.5	16	19	19.5
A	6-ft screen at 3 ft	" "	15.5	17.5	18	19.5	20.5	23
B	No screen	No baffles	4.5	7.5	9.5	10.5	11.5	14
B	4-ft 8-in. screen at 3 ft	"	11	13	15	15.5	17	19.5

TABLE I (Cont'd.)

REDUCTION IN A-WEIGHTED SOUND PRESSURE LEVEL IN dB RELATIVE TO 3-FT LEVEL

Material	Screen Condition	Baffle Condition	Distance from loudspeaker (ft)					
			6	9	12	15	19	24
B	6-ft screen at 6 ft	No baffles	-	16	14.5	17	18.5	20
B	6-ft screen at 3 ft	"	16.5	19.5	20.5	21	21.5	23
C	No screen	No baffles	5	8.5	10.5	12	13	15.5
C	4-ft 8-in. screen at 3 ft	"	12	14.5	16	16	18	21
C	6-ft screen at 6 ft	"	-	18	17	17	19	21
C	6-ft screen at 3 ft	"	16	18	21	20	22	26
C	No screen	Baffles on 4-ft centres	5	7.5	10	11.5	13	15
C	4-ft 8-in. screen at 3 ft	" "	12	15	16	17	20	21
C	6-ft screen at 6 ft	" "	-	17.5	17.5	17.5	19.5	20.5
C	6-ft screen at 3 ft	" "	16.5	18	19	20.5	21	24.5
C	No screen	Baffles on 2-ft centres	5.5	8	10	12	13.5	15.5
C	4-ft 8-in. screen at 3 ft	" "	11.5	14.5	16	17	18.5	22
C	6-ft screen at 6 ft	" "	-	17.5	17	18	19.5	22
C	6-ft screen at 3 ft	" "	17	18.5	19.5	20	20.5	24

TABLE 2 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TC LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL A USED WITH NO CEILING BAFFLES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
NO INTERVENING SCREEN						
3	0.0	0.0	0.0	0.0	0.0	0.0
6	8.5	4.7	5.4	6.6	6.0	5.7
9	12.8	8.1	6.1	8.2	7.9	6.7
12	10.0	9.2	8.5	11.3	9.4	8.3
15	9.8	12.1	8.4	11.8	10.5	10.0
18	9.8	11.6	10.6	11.8	10.8	11.1
24	11.8	10.2	13.3	12.9	12.5	12.7
6-FT HIGH SCREEN AT 3-FT						
6	13.4	11.2	11.7	15.7	15.4	19.5
9	12.3	12.1	15.3	17.5	15.6	17.6
12	10.9	12.8	17.6	18.6	18.3	19.6
15	11.9	13.5	16.0	20.3	18.6	20.5
18	13.7	13.4	17.6	24.1	21.0	22.8
24	15.9	12.6	20.2	25.7	23.1	24.2
6-FT HIGH SCREEN AT 6-FT						
9	11.9	12.7	14.4	17.0	16.4	18.3
12	9.0	9.9	9.8	18.0	16.1	18.7
15	9.5	12.4	9.6	19.3	16.7	19.0
18	10.6	11.7	12.8	19.2	16.4	18.8
24	13.2	11.3	16.1	21.7	19.3	20.2
4-FT 8-IN HIGH SCREEN AT 3-FT						
6	10.1	5.2	7.4	12.2	14.5	19.5
9	12.0	8.6	9.4	13.5	13.6	17.7
12	10.9	10.4	11.2	14.5	14.5	18.2
15	11.1	12.8	8.3	15.9	15.1	17.7
18	11.8	12.7	10.7	18.5	14.9	16.8
24	15.1	12.1	16.9	20.2	18.3	20.8

TABLE 3 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TC LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL A USED WITH CEILING BAFFLES ON 4-FT CENTRES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	6.5	3.6	4.3	3.8	2.9	2.3
9	11.6	7.7	4.2	6.8	6.7	5.6
12	9.7	7.4	7.2	8.9	7.4	7.5
15	9.5	10.9	7.9	10.1	10.0	9.6
18	9.0	10.1	10.3	10.1	9.3	10.2
24	10.9	10.3	11.6	11.8	12.4	12.8
	6-FT HIGH SCREEN AT 3-FT					
6	12.7	11.3	11.4	15.6	14.0	18.4
9	12.2	9.1	14.7	15.9	17.5	20.8
12	10.0	10.6	16.8	18.7	19.1	23.2
15	11.4	12.5	16.9	21.5	23.8	24.8
18	12.6	13.0	16.1	24.5	22.5	25.7
24	14.3	14.8	16.3	25.5	27.8	28.1
	6-FT HIGH SCREEN AT 6-FT					
9	12.4	8.3	12.5	16.7	18.1	19.9
12	9.0	7.9	9.4	17.0	17.6	20.6
15	8.9	10.8	10.1	20.1	17.4	21.6
18	10.7	12.3	15.1	19.9	20.8	24.3
24	12.6	12.8	13.3	24.5	24.6	26.8
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	8.6	4.6	5.7	10.0	13.0	18.1
9	10.5	6.9	8.4	11.9	14.0	18.6
12	9.6	8.2	10.1	14.0	14.9	19.5
15	11.0	11.4	9.2	15.9	16.1	19.4
18	11.5	11.6	11.8	17.8	17.8	20.2
24	14.1	12.1	15.5	21.3	22.0	24.8

TABLE 4 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TO LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL A USED WITH CEILING BAFFLES ON 2FT CENTRES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	7.0	4.4	5.3	5.0	4.4	2.1
9	13.4	8.9	6.9	8.8	9.2	5.6
12	12.3	9.3	9.5	11.2	10.0	7.8
15	12.4	10.7	10.3	12.4	12.0	10.1
18	11.9	12.0	13.3	13.8	11.8	10.7
24	12.5	13.0	14.3	14.5	14.1	13.3
	6-FT HIGH SCREEN AT 3-FT					
6	15.1	13.1	12.5	18.4	18.9	21.8
9	14.4	11.6	16.7	19.8	22.2	22.9
12	12.5	10.8	17.6	21.2	24.3	24.8
15	13.1	13.0	18.5	22.8	26.8	26.1
18	14.5	14.0	18.1	27.5	27.4	26.9
24	17.0	17.6	18.9	28.7	31.6	31.3
	6-FT HIGH SCREEN AT 6-FT					
9	15.3	10.6	15.0	18.8	19.6	19.9
12	11.5	8.4	11.5	21.3	21.6	22.0
15	11.9	11.1	12.7	21.9	21.6	23.2
18	12.4	12.8	16.2	25.0	23.0	24.7
24	14.2	14.5	15.4	26.3	28.9	26.7
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	10.3	7.2	9.1	13.1	16.9	20.4
9	12.3	9.7	12.5	14.5	17.3	19.5
12	12.4	10.6	13.9	18.2	18.6	20.5
15	13.3	13.2	11.8	19.1	20.1	21.5
18	14.8	14.3	14.2	20.7	21.1	22.6
24	16.3	15.3	19.1	24.4	25.2	26.1

TABLE 5 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TO LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL B USED WITH NO CEILING BAFFLES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	8.4	4.3	6.4	4.6	4.2	3.7
9	13.7	9.1	9.7	8.4	7.0	6.0
12	11.5	11.1	11.2	10.2	8.3	7.3
15	11.2	15.0	10.6	11.3	9.3	8.5
18	11.6	14.1	11.8	12.4	11.5	9.1
24	13.3	12.7	17.3	15.7	13.3	10.8
	6-FT HIGH SCREEN AT 3-FT					
6	14.9	12.8	16.4	18.1	19.0	19.5
9	14.2	16.9	21.0	21.0	21.6	22.8
12	11.0	16.6	20.9	22.4	23.8	25.3
15	13.2	18.9	20.7	24.3	24.4	24.1
18	13.2	16.3	21.8	25.9	25.9	25.2
24	18.2	17.3	24.7	27.9	27.8	28.9
	6-FT HIGH SCREEN AT 6-FT					
9	15.5	12.5	16.0	18.8	17.9	17.9
12	10.9	11.0	13.9	19.7	18.0	17.8
15	11.1	16.5	14.7	20.4	16.9	18.7
18	12.7	15.4	18.3	23.3	20.0	19.9
24	15.8	15.1	20.6	25.6	21.8	23.1
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	10.8	7.9	10.9	12.1	14.0	17.1
9	11.6	10.1	14.0	13.0	15.3	17.5
12	11.0	12.4	15.0	16.5	14.9	17.9
15	12.0	16.0	14.0	18.4	16.2	17.9
18	13.1	15.6	15.5	20.2	17.0	19.0
24	17.5	15.9	19.9	22.6	20.5	21.6

TABLE 6 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TO LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL C USED WITH NO CEILING BAFFLES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	8.3	3.5	4.5	4.9	4.4	4.0
9	13.3	8.7	5.8	7.3	7.5	7.5
12	11.3	11.6	8.9	10.8	9.6	9.4
15	10.0	16.1	9.4	11.9	11.2	10.5
18	10.9	14.9	11.8	12.3	11.3	11.6
24	12.2	12.9	16.1	14.7	14.8	12.8
	6-FT HIGH SCREEN AT 3-FT					
6	13.6	12.9	11.7	18.0	18.9	23.7
9	13.7	12.7	15.7	18.7	20.6	22.0
12	11.4	15.2	18.8	20.3	22.8	22.3
15	12.4	15.5	15.6	21.7	24.1	25.0
18	14.8	16.6	16.7	26.6	25.2	21.8
24	17.2	18.1	21.8	28.0	28.5	29.6
	6-FT HIGH SCREEN AT 6-FT					
9	12.9	12.6	15.2	17.9	18.9	19.0
12	10.5	12.3	12.4	20.4	21.1	20.9
15	11.0	13.5	12.6	21.5	20.9	22.4
18	12.5	13.7	15.7	20.8	22.6	20.3
24	14.9	14.9	16.6	22.4	26.0	25.5
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	10.1	7.4	8.0	12.1	15.2	20.5
9	13.7	10.7	11.1	14.5	17.3	21.6
12	12.2	14.3	12.1	17.3	18.3	21.1
15	12.7	17.5	10.7	18.2	19.2	21.5

TABLE 7 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TO LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL C USED WITH CEILING BAFFLES ON 4-FT CENTRES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	8.6	5.2	6.3	5.6	5.2	4.5
9	13.4	10.2	6.9	7.4	8.2	6.8
12	12.9	12.5	10.1	11.0	9.7	8.7
15	12.2	16.1	11.8	12.5	12.0	11.5
18	12.1	15.7	14.8	13.0	11.6	11.8
24	13.8	14.6	17.8	13.9	14.9	14.5
	6-FT HIGH SCREEN AT 3-FT					
6	15.1	15.2	14.4	18.8	19.7	23.4
9	15.4	12.9	18.2	19.8	22.9	24.3
12	14.1	14.7	19.5	21.1	23.8	24.1
15	14.0	16.2	20.6	23.3	26.4	25.8
18	15.7	18.1	18.3	27.1	26.5	23.0
24	17.1	20.7	21.3	28.4	29.6	30.4
	SIX FT HIGH SCREEN AT SIX FT					
9	14.7	13.6	17.1	19.1	21.1	21.9
12	13.4	12.7	14.4	22.2	23.8	22.9
15	12.1	15.1	14.0	23.0	22.0	22.3
18	13.9	16.4	18.2	22.5	24.5	21.8
24	15.6	17.3	16.8	26.3	26.6	27.4
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	12.0	7.7	10.4	12.7	15.6	21.7
9	14.6	11.9	13.7	16.3	18.9	23.7
12	14.7	15.2	14.6	18.2	19.6	23.0
15	14.4	16.8	13.8	18.6	20.2	22.8
18	15.9	17.3	15.7	20.3	21.3	21.0
24	16.5	17.0	19.0	22.2	23.6	25.9

TABLE 8 : OCTAVE BAND SIGNAL ATTENUATION IN DB RELATIVE TO LEVEL 3-FT IN FRONT OF LOUDSPEAKER. CEILING MATERIAL C USED WITH CEILING BAFFLES ON 2FT CENTRES

	OCTAVE BAND CENTRE FREQUENCY (HZ)					
DISTANCE (FT)	125	250	500	1000	2000	4000
	NO INTERVENING SCREEN					
3	0.0	0.0	0.0	0.0	0.0	0.0
6	8.0	4.8	6.6	5.6	4.9	5.8
9	12.0	10.0	6.6	8.4	7.8	7.2
12	12.1	10.5	9.5	11.4	9.6	9.9
15	11.5	13.1	11.2	12.1	11.0	10.9
18	13.3	14.5	13.7	13.0	11.8	13.2
24	13.8	13.9	17.1	14.6	14.9	15.2
	6-FT HIGH SCREEN AT 3-FT					
6	14.4	14.0	14.8	18.7	21.0	25.8
9	14.4	11.5	17.7	20.5	23.1	26.6
12	13.2	12.5	18.9	22.6	24.6	25.1
15	14.3	15.8	19.5	23.2	25.5	25.5
18	16.4	16.3	17.8	27.0	26.5	23.4
24	16.8	18.3	20.9	28.4	27.6	27.2
	6-FT HIGH SCREEN AT 6-FT					
9	15.7	11.7	17.1	18.6	22.0	24.6
12	12.7	11.2	14.5	22.7	23.7	25.4
15	12.8	13.6	15.1	22.6	22.5	25.5
18	14.7	14.6	18.0	24.6	23.9	27.3
24	14.7	17.4	17.0	26.8	27.9	28.5
	4-FT 8-IN HIGH SCREEN AT 3-FT					
6	9.9	7.7	9.6	12.3	15.5	22.4
9	12.6	11.8	11.9	15.5	16.6	21.9
12	13.0	13.8	13.4	17.9	19.1	23.4
15	14.7	15.5	13.1	19.5	20.7	24.2
18	15.2	17.2	14.5	20.5	21.4	25.6
24	16.8	17.9	19.4	22.5	24.5	26.4

TABLE 9

CALCULATED RELATIVE DECREASE IN ARTICULATION INDEX (WITH RESPECT TO CONDITIONS UNDER MATERIAL A WITH NO INTERVENING SCREEN AND NO CEILING BAFFLES) FOR A DISTANCE OF 9 FT FROM THE LOUDSPEAKER

	Material A NRC = 0.55			Material B NRC = 0.65	Material C NRC = 0.85		
Baffle Conditions Screen Conditions	No Baffles	4' o. c	2' o. c.	No Baffles	No Baffles	4' o. c	2' o. c.
No Screen	Reference 0	- .04	.01	0.0	- .01	.01	.01
4-ft 8-in. Screen at 3 ft	.20	.19	.28	.24	.29	.36	.30
6-ft Screen at 6 ft	.30	.31	.36	.33	.34	.41	.43
6-ft Screen at 3 ft	.29	.32	.43	.46	.39	.46	.46

TABLE 10

CALCULATED RELATIVE DECREASE IN ARTICULATION INDEX (WITH RESPECT TO CONDITIONS UNDER MATERIAL A WITH NO INTERVENING SCREEN AND NO CEILING BAFFLES) FOR A DISTANCE OF 12 FT FROM THE LOUDSPEAKER

	Material A NRC = 0.55			Material B NRC = 0.65	Material C NRC = 0.85		
Baffle Conditions Screen Conditions	No Baffles	4'o.c.	2'o.c.	No Baffles	No Baffles	4'o.c.	2'o.c.
No Screen	Reference 0	-.06	.01	0.0	.02	.02	.02
4-ft 8-in. Screen at 3 ft	.16	.17	.28	.21	.25	.32	.29
6-ft Screen at 6 ft	.20	.23	.33	.26	.32	.39	.41
6-ft Screen at 3 ft	.28	.32	.41	.44	.38	.40	.47

TABLE 11

CALCULATED RELATIVE DECREASE IN ARTICULATION INDEX (WITH RESPECT TO CONDITIONS UNDER MATERIAL A WITH NO INTERVENING SCREEN AND NO CEILING BAFFLES) FOR A DISTANCE OF 15 FT FROM THE LOUDSPEAKER

	Material A NRC = 0.55			Material B NRC = 0.65	Material C NRC = 0.85		
Baffle Conditions / Screen Conditions	No Baffles	4'o.c.	2'o.c.	No Baffles	No Baffles	4'o.c.	2'o.c.
No Screen	Reference 0	-.03	.03	-.01	.02	.06	.03
4-ft 8-in. Screen at 3 ft	.14	.16	.26	.21	.25	.29	.31
6-ft Screen at 6 ft	.20	.23	.32	.24	.30	.34	.37
6-ft Screen at 3 ft	.27	.37	.43	.43	.38	.45	.43

TABLE 12

MEAN CALCULATED RELATIVE DECREASE IN ARTICULATION INDEX (WITH RESPECT TO CONDITIONS UNDER MATERIAL A WITH NO INTERVENING SCREEN AND NO CEILING BAFFLES) FOR A DISTANCE OF 9-15 FT FROM THE LOUDSPEAKER

	Material A NRC = 0.55			Material B NRC = 0.65	Material C NRC = 0.85		
Screen Conditions / Baffle Conditions	No Baffles	4'o. c.	2'o. c.	No Baffles	No Baffles	4'o. c.	2'o. c.
No Screen	Reference 0	-0.04	0.02	0	0.01	0.03	0.02
4-ft 8-in Screen at 3 ft	0.17	0.17	0.27	0.22	0.26	0.32	0.30
6-ft Screen at 6 ft	0.23	0.26	0.34	0.28	0.32	0.38	0.40
6-ft Screen at 3 ft	0.28	0.34	0.42	0.44	0.38	0.44	0.45

TABLE 13

SOUND LEVELS IN dB USED IN THE CALCULATION OF ARTICULATION INDEX BEHIND A SCREEN

	Octave Band Centre Frequency, Hz				
	250	500	1000	2000	4000
Peak ideal voice signal at 12 ft	60	61	56	50	46
Noise level [48dB(A)]	48	47	43	37	31
Diffraction loss for 5-ft high screen	7.5	8.5	10	11.5	13.5
Diffraction loss for 6-ft high screen	9.5	11.5	13	16.5	19.5

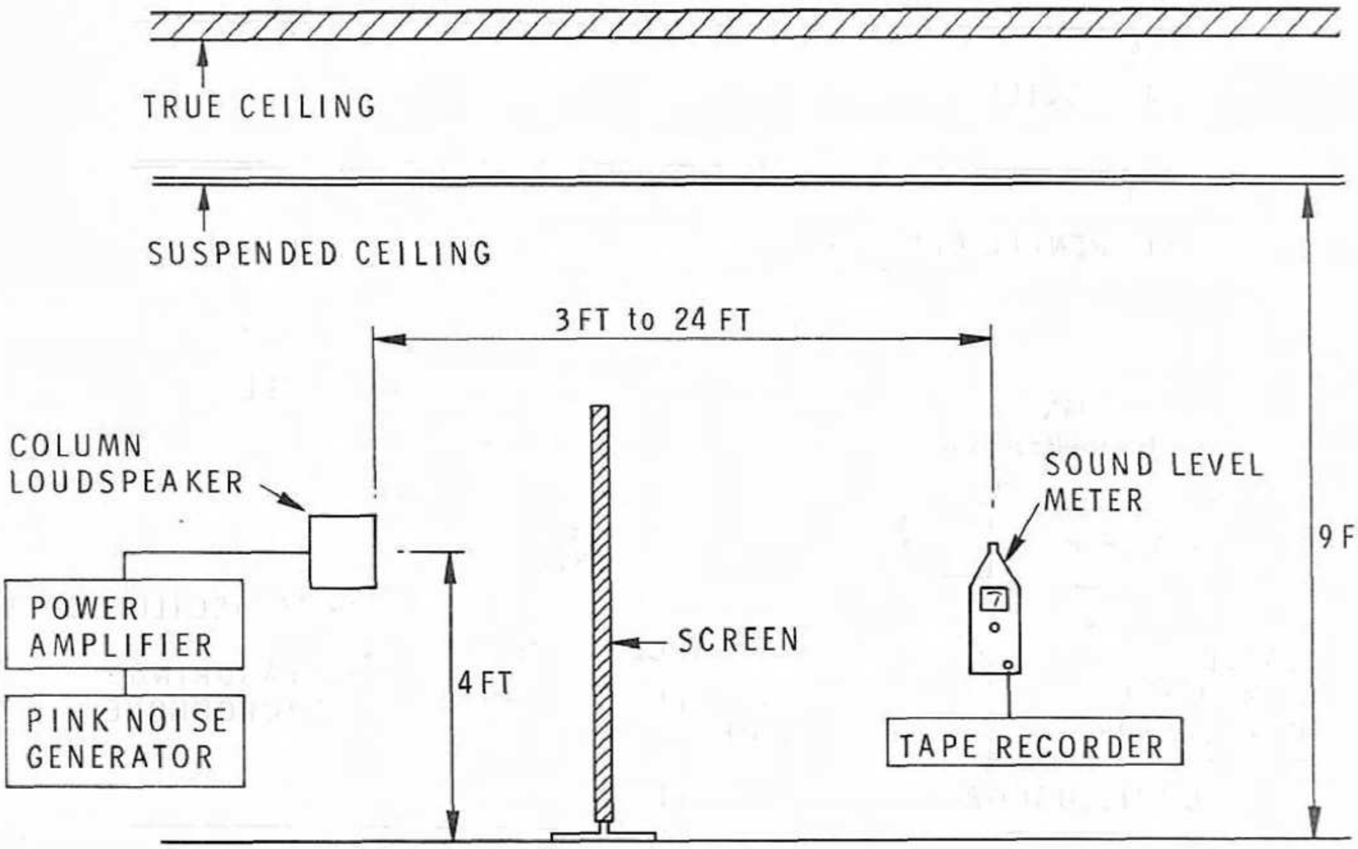


FIGURE 1

METHOD USED FOR CONTINUOUS PINK NOISE PROPAGATION MEASUREMENTS. SCREENS WERE INSERTED AT DISTANCES OF 3 FT OR 6 FT

BR 5058 – 1

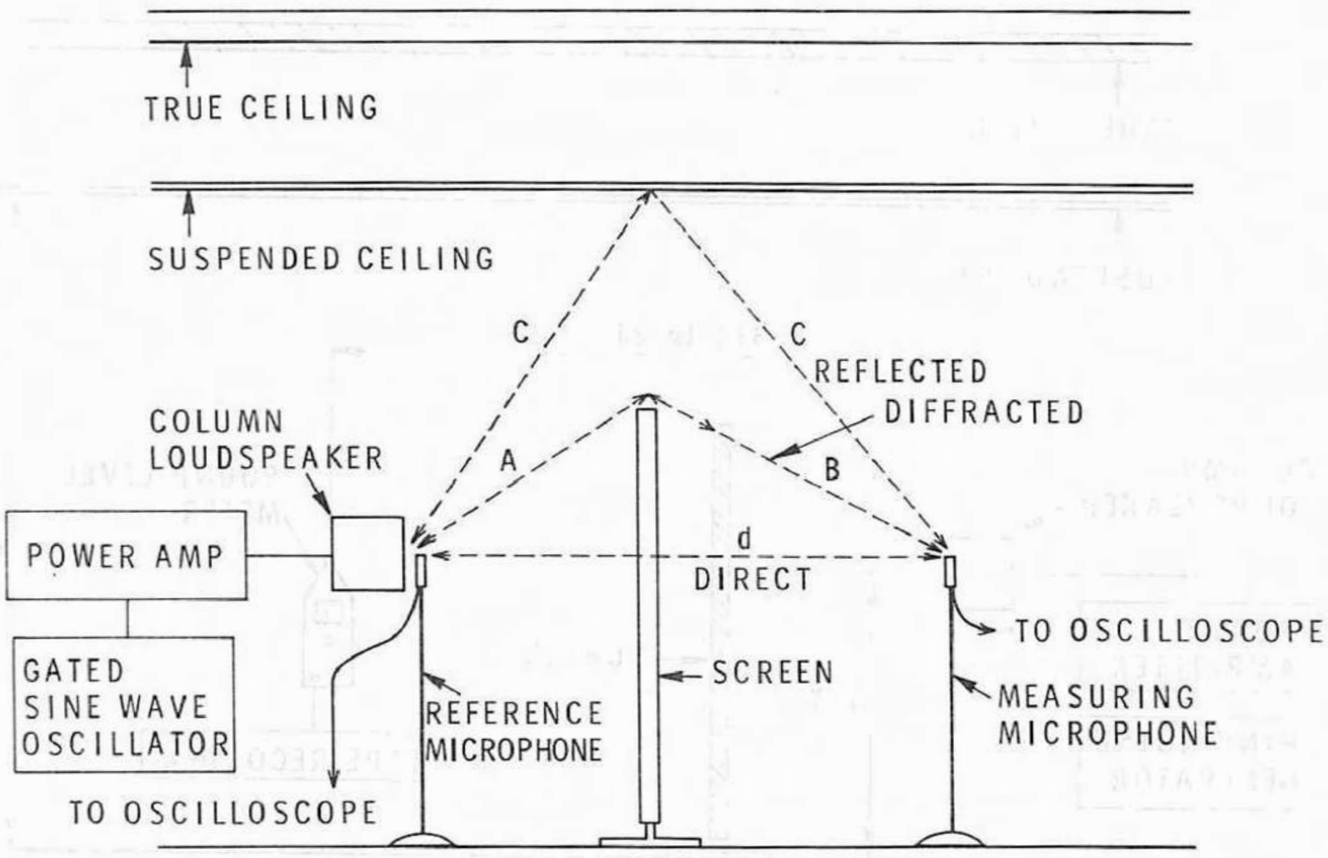
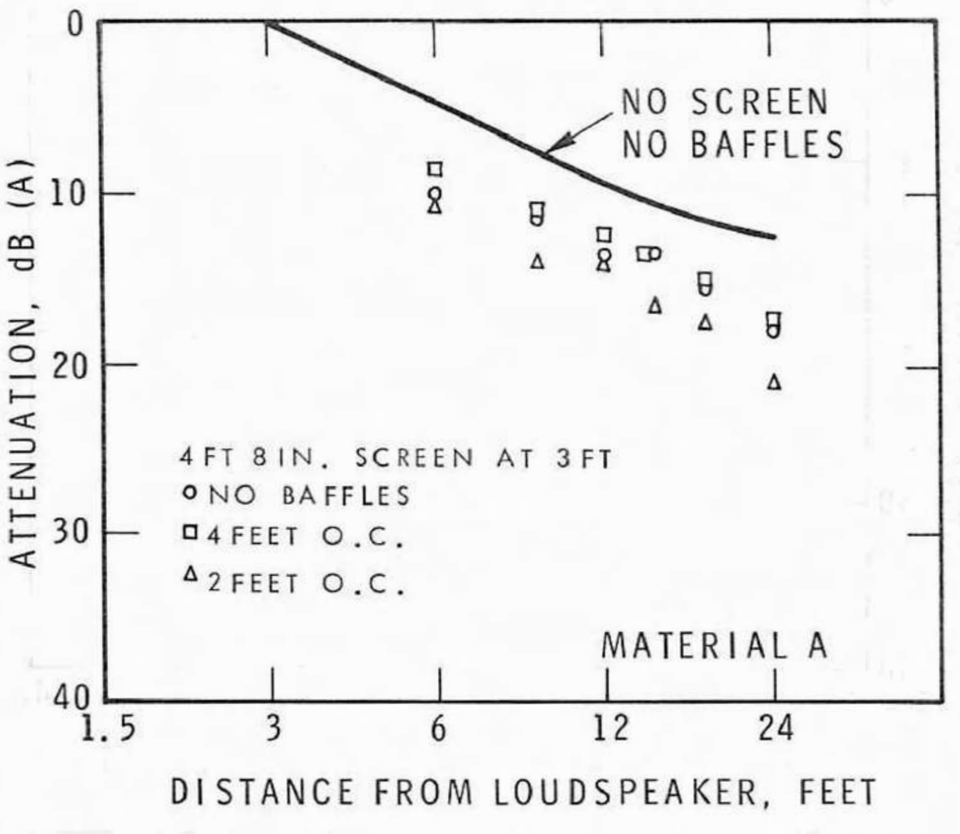


FIGURE 2

APPARATUS USED TO MEASURE PROPAGATION OF SOUND PULSES AND THE PATHS IMPORTANT IN DETERMINING THE SCREEN PERFORMANCE

BR 5058 – 2



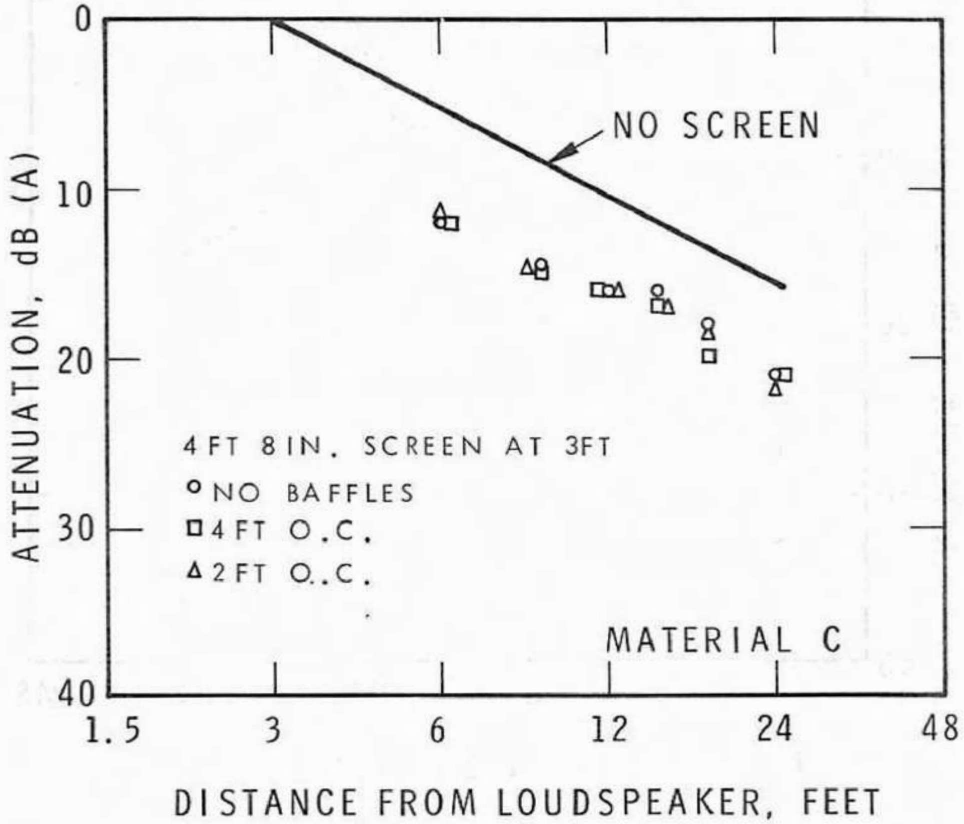


FIGURE 3

CONTINUOUS PINK NOISE PROPAGATION,
dB (A) ANALYSIS

BR 5058 — 3

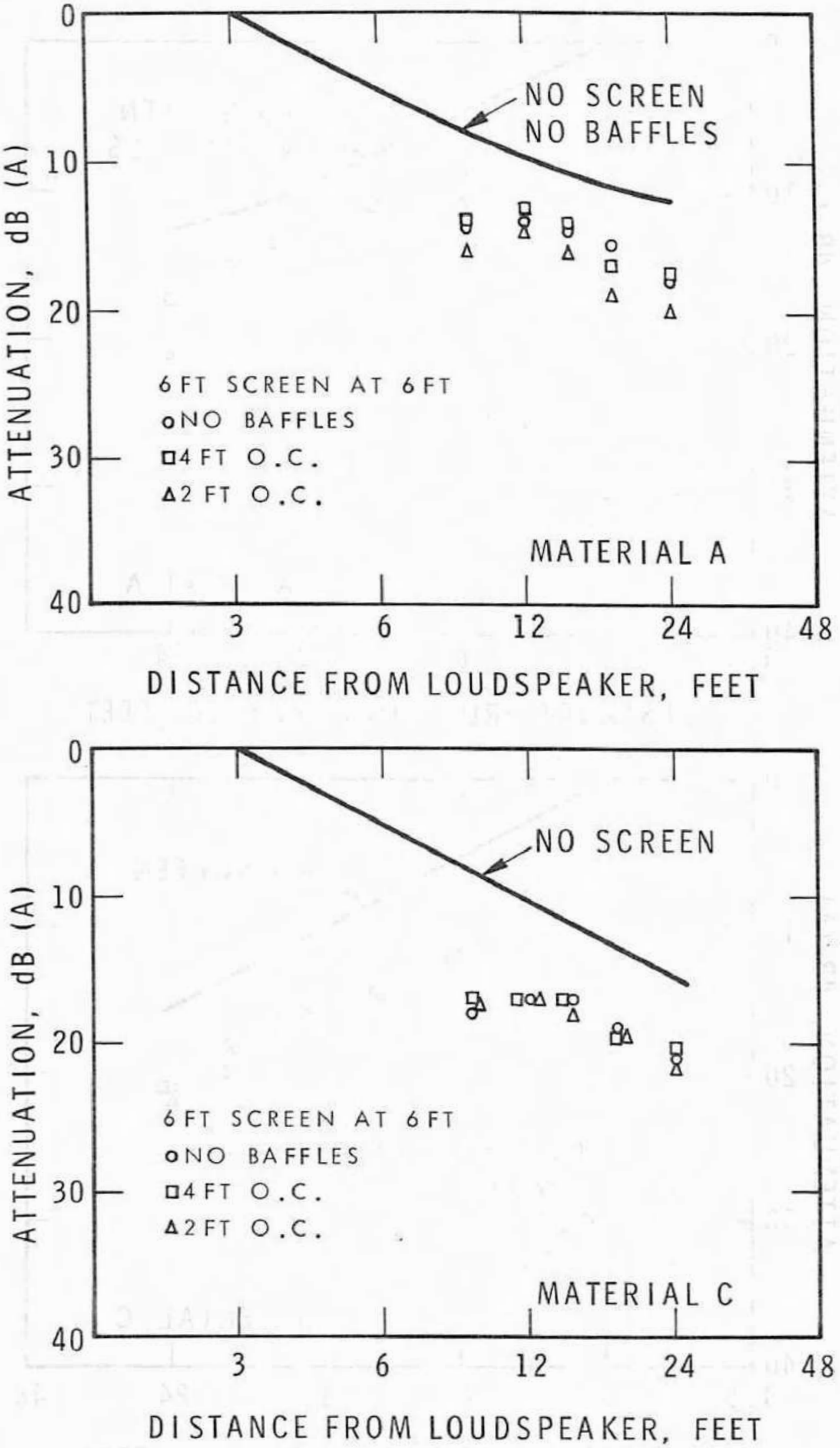


FIGURE 4

CONTINUOUS PINK NOISE PROPAGATION, dB (A) ANALYSIS

BR 5058 — 4

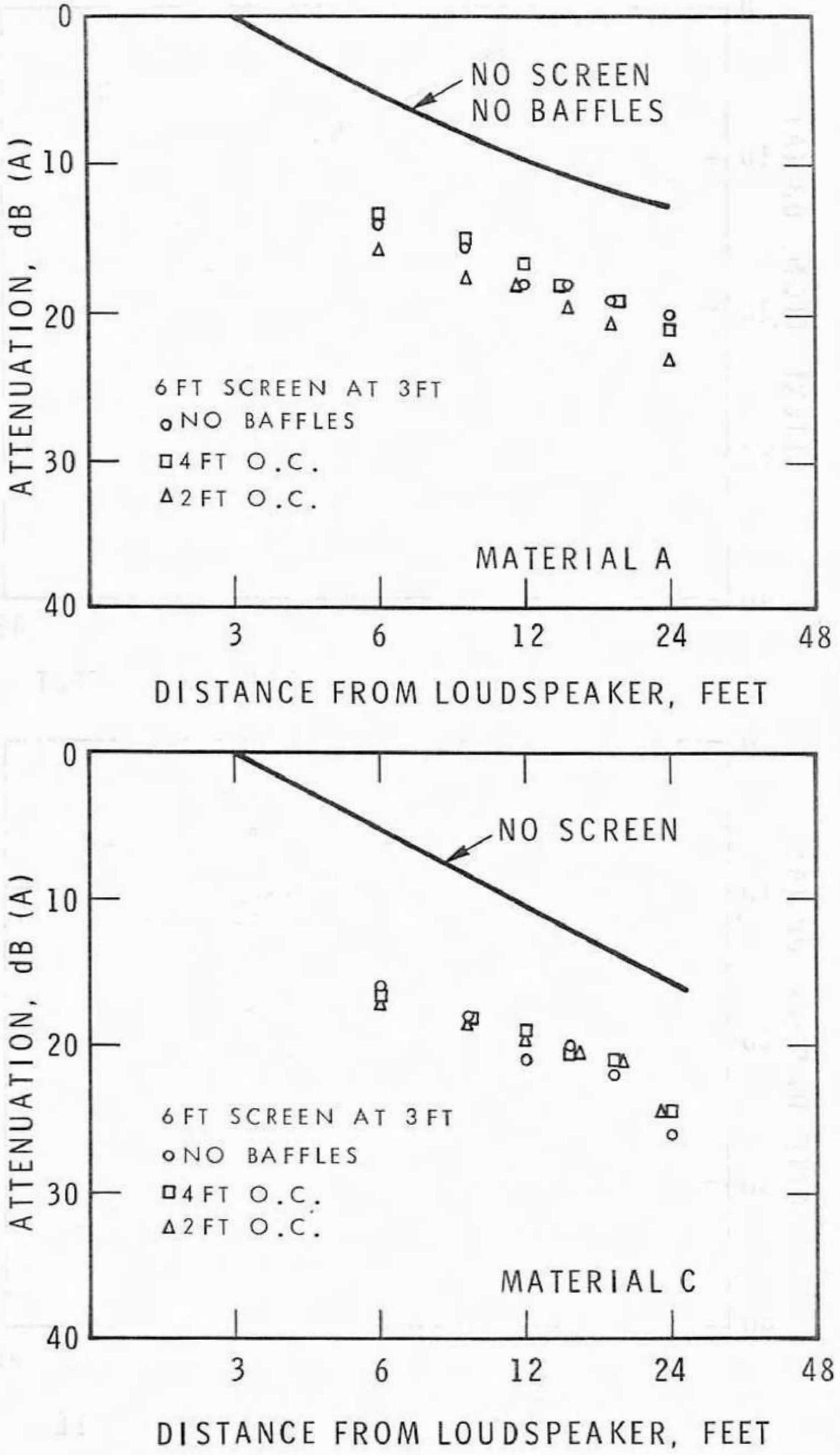


FIGURE 5

CONTINUOUS PINK NOISE PROPAGATION, dB (A) ANALYSIS

BR 5058 – 5

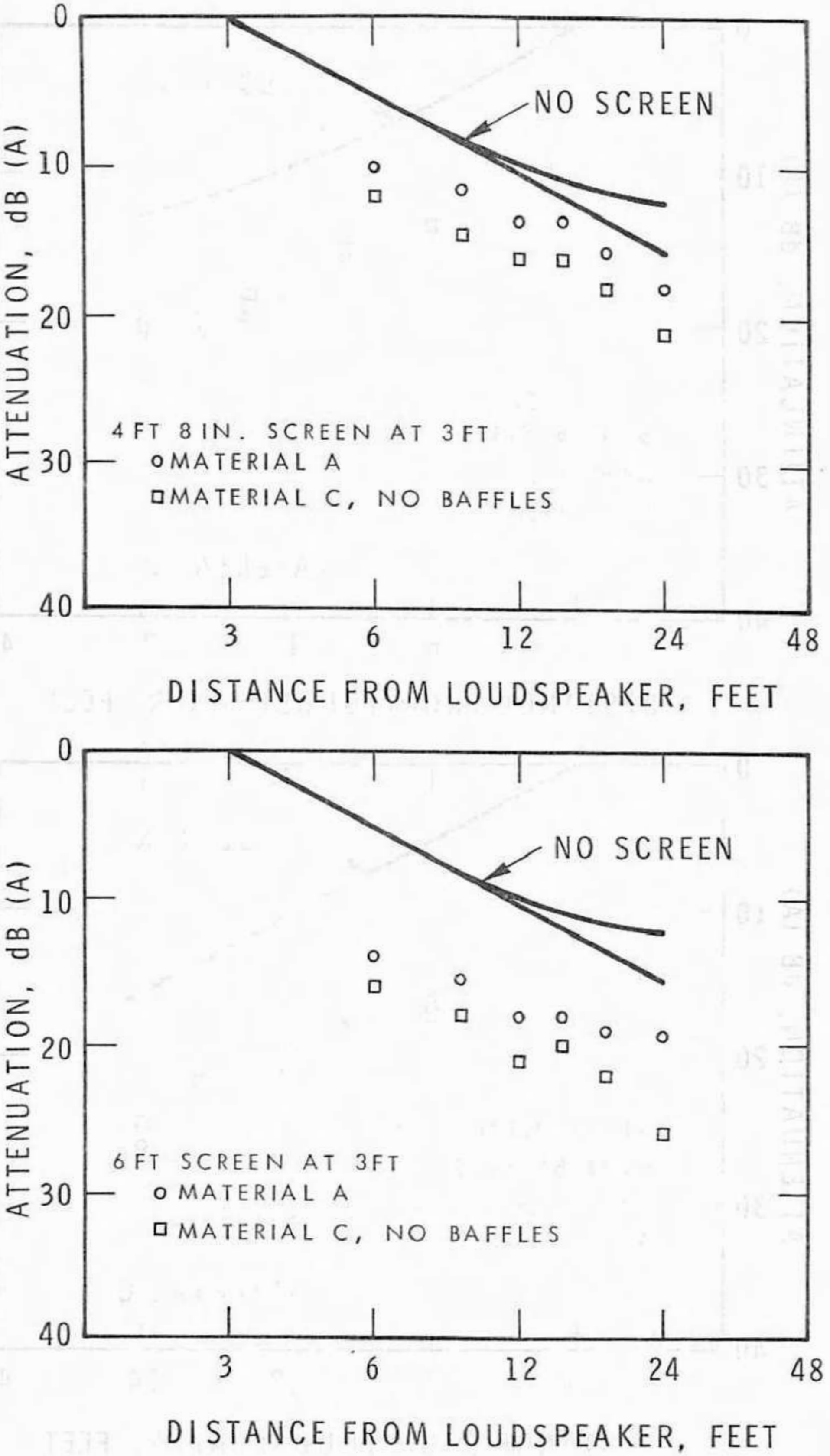


FIGURE 6

CONTINUOUS PINK NOISE PROPAGATION, dB (A) ANALYSIS

BR 5058 – 6

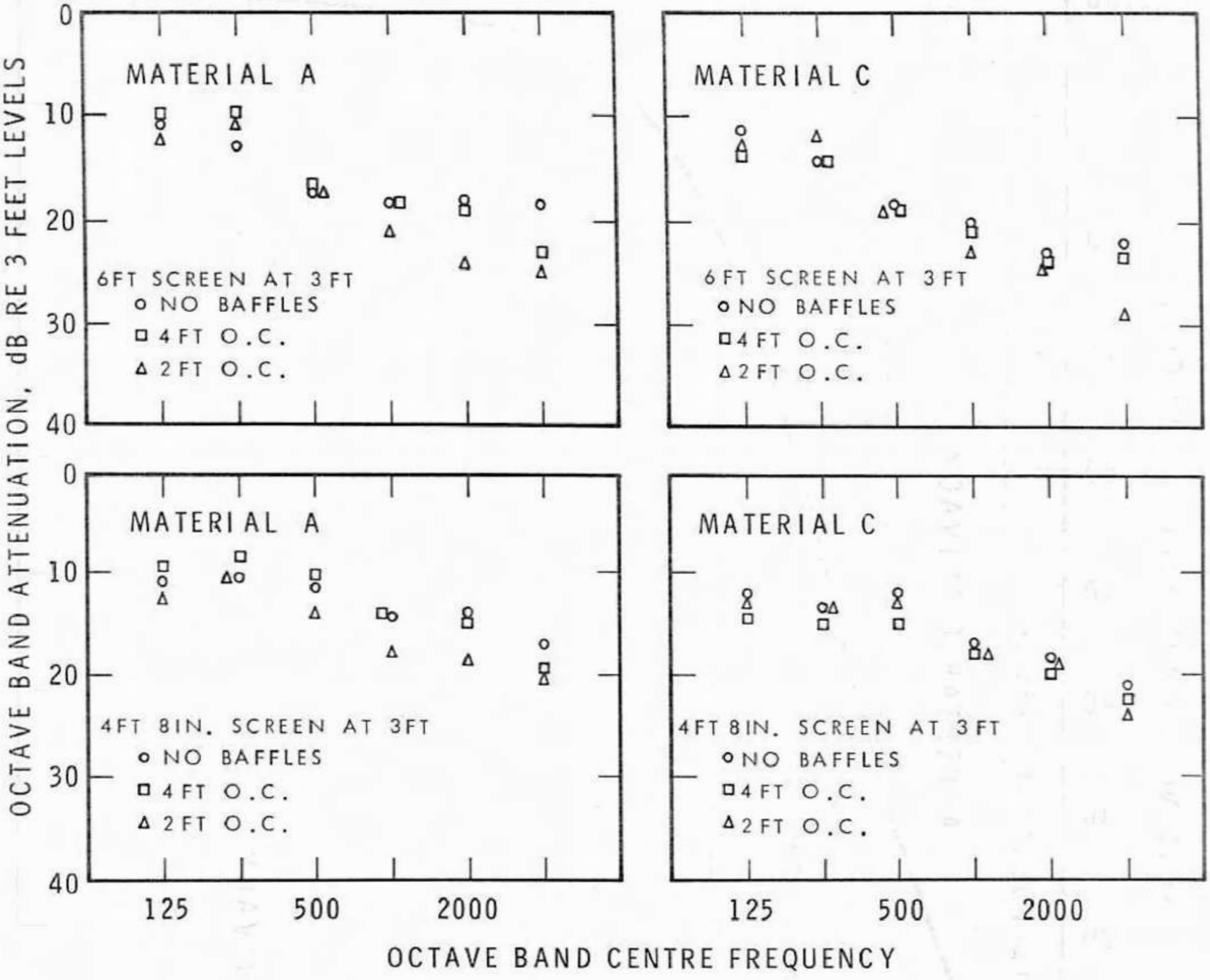


FIGURE 7

OCTAVE BAND ATTENUATION MEASURED AT 12 FEET FROM LOUDSPEAKER

BR 5058 - 7

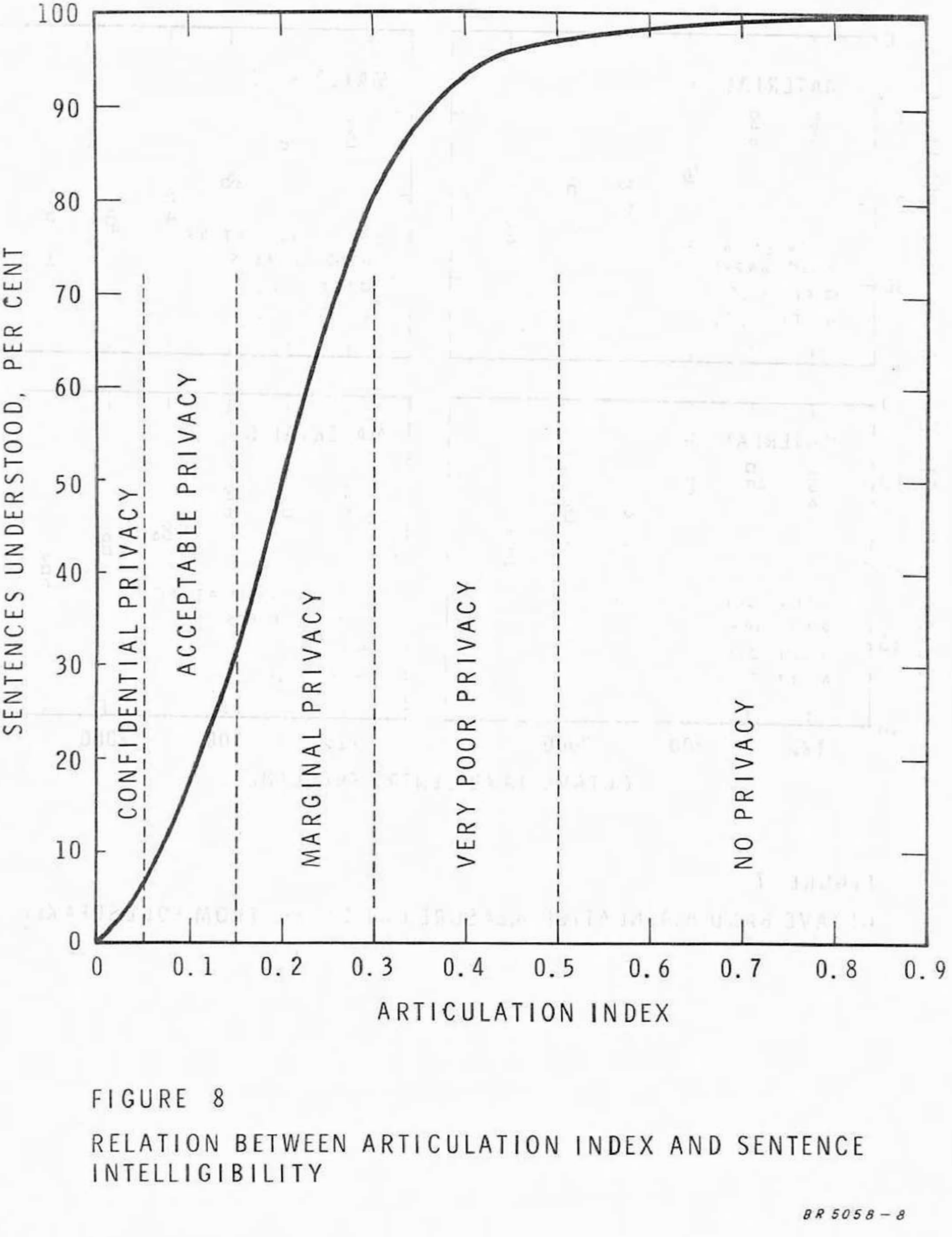
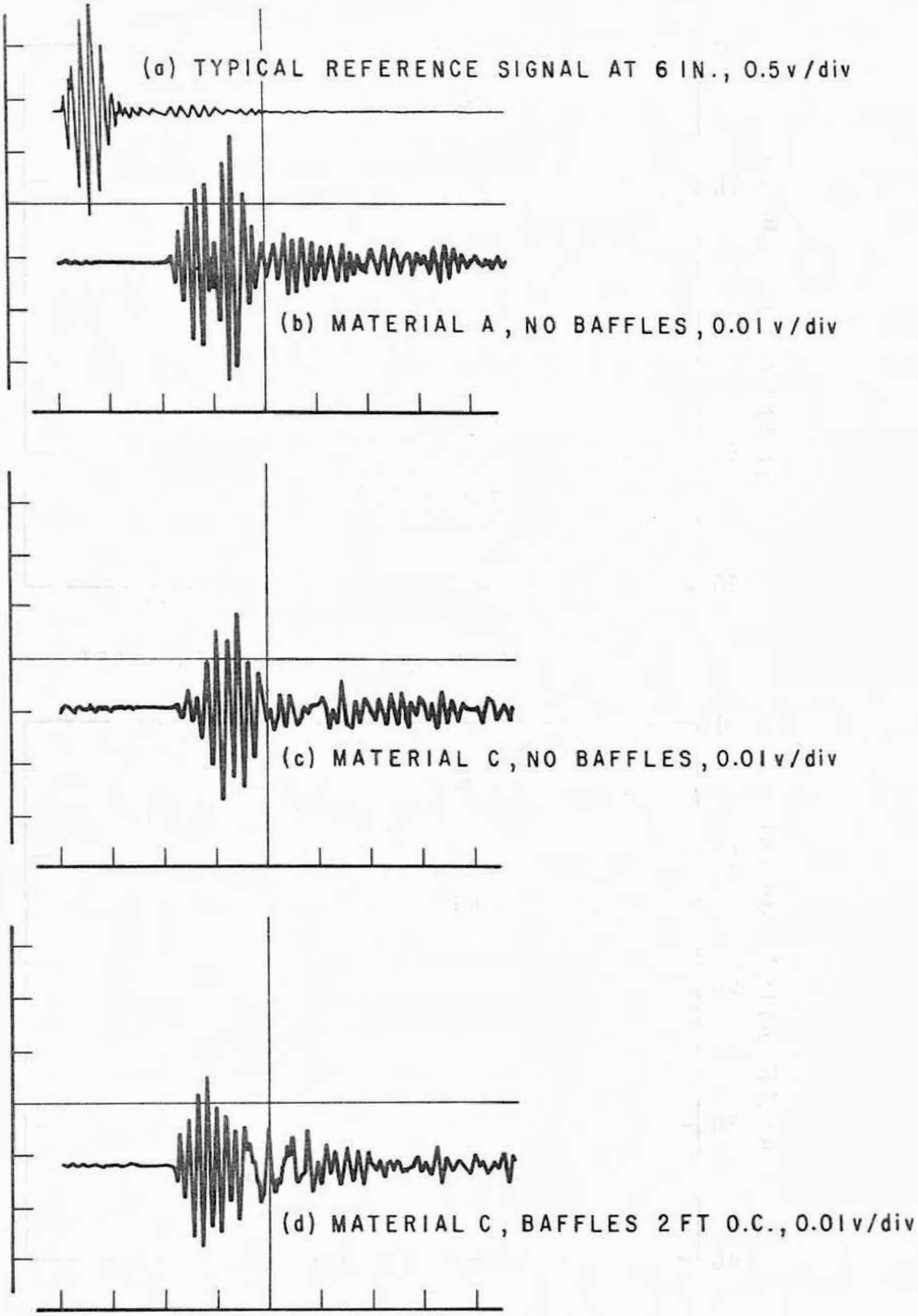


FIGURE 8

RELATION BETWEEN ARTICULATION INDEX AND SENTENCE INTELLIGIBILITY

BR 5058 – 8



SIGNALS RECEIVED AT 12 FT FOR (b), (c), (d)

FIGURE 9
ELECTRICAL SIGNALS FROM MICROPHONES, 5ms/cm

BR 5058 - 9

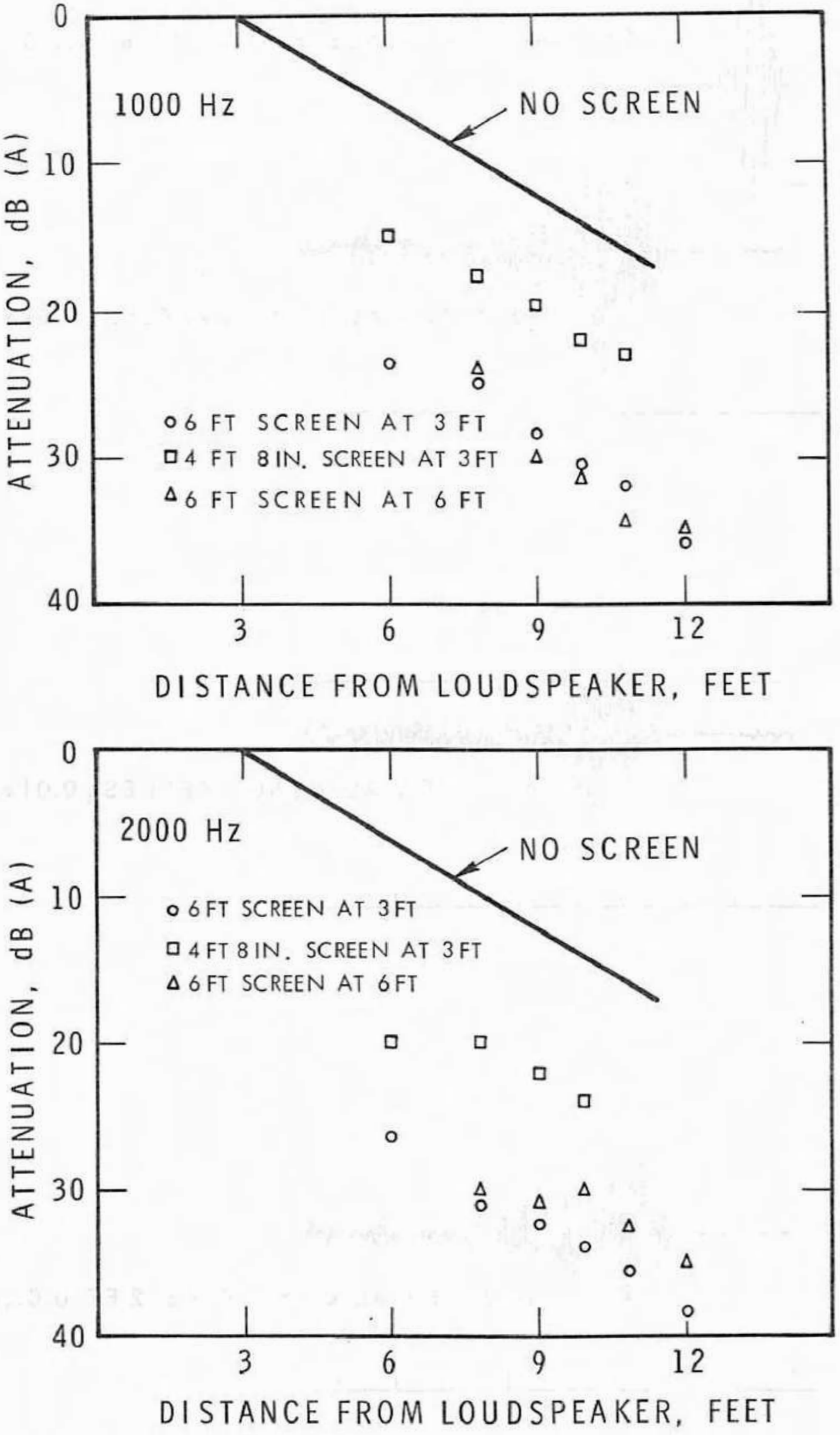


FIGURE 10

DIRECT PULSE MEASUREMENTS IN OFFICE

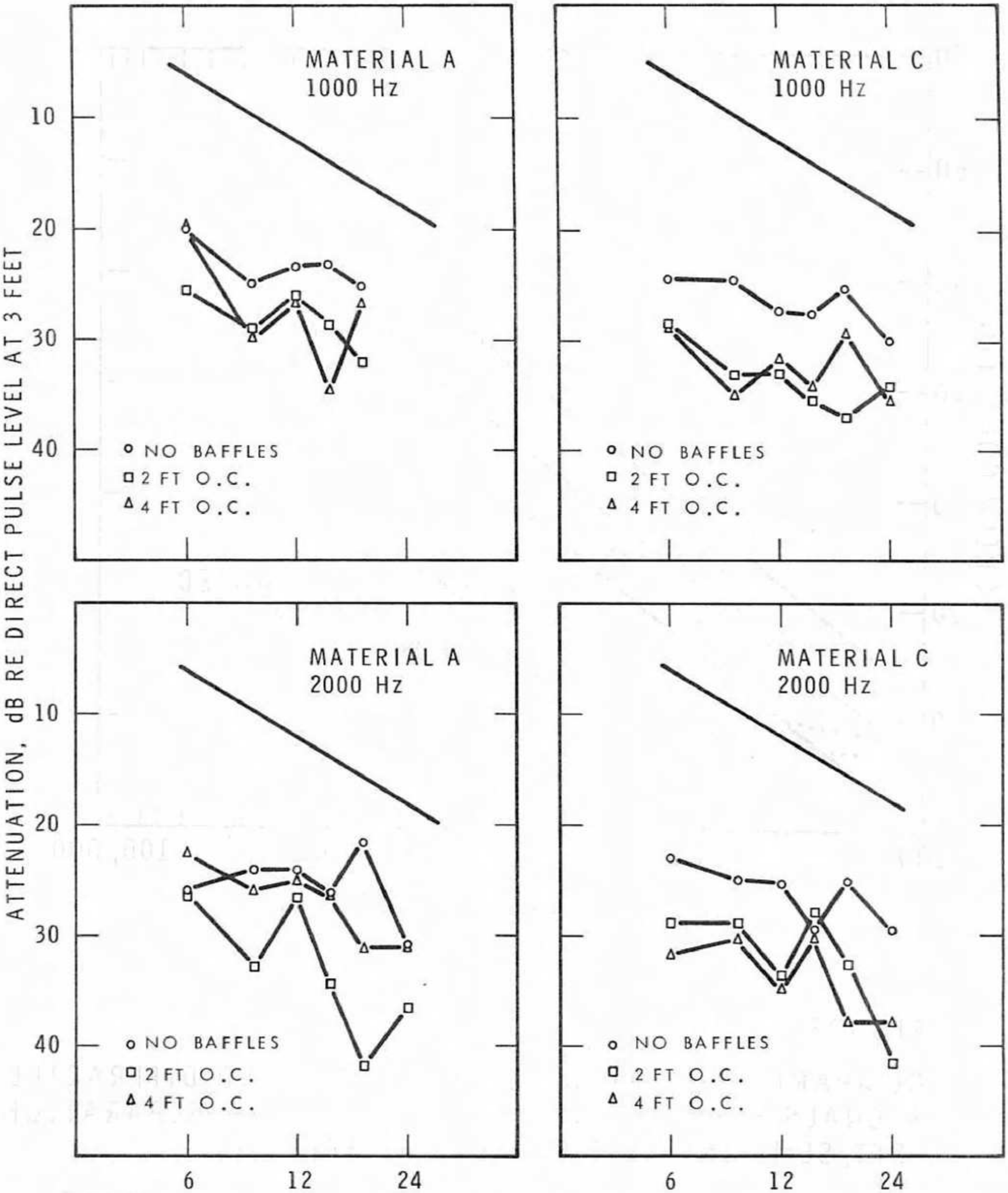


FIGURE 11

BOUNCE SIGNALS FROM CEILINGS WITH AND WITHOUT BAFFLES. THE CONTINUOUS LINE IS FREE-SPREADING LEVEL

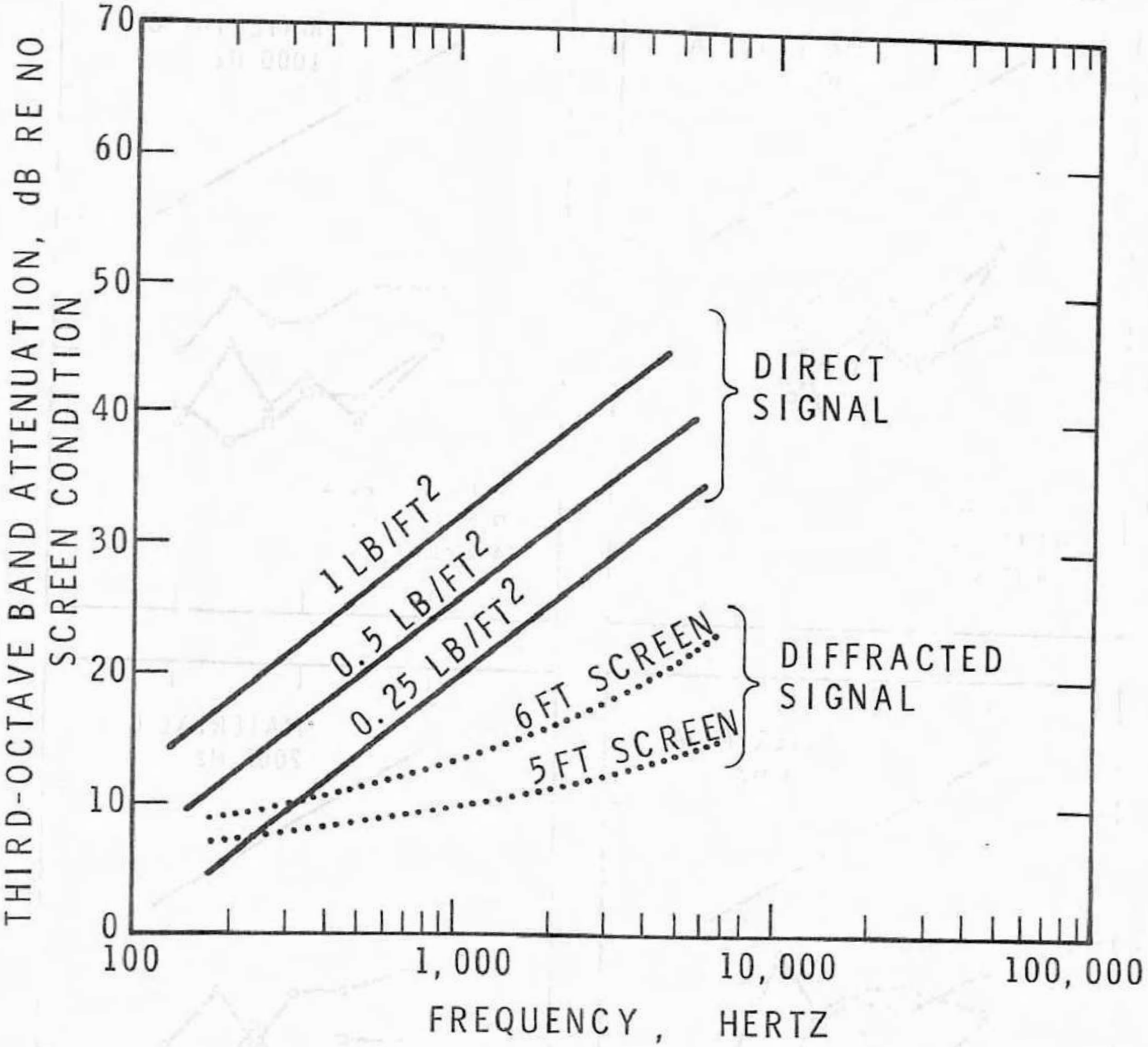


FIGURE 12

COMPARISON OF THEORETICAL DIRECT AND DIFFRACTED SIGNALS FOR SCREENS. SOURCE RECEIVER SEPARATION 12 FT, SEMI-INFINITE SCREENS AT 6 FT

BR 5058 – 12

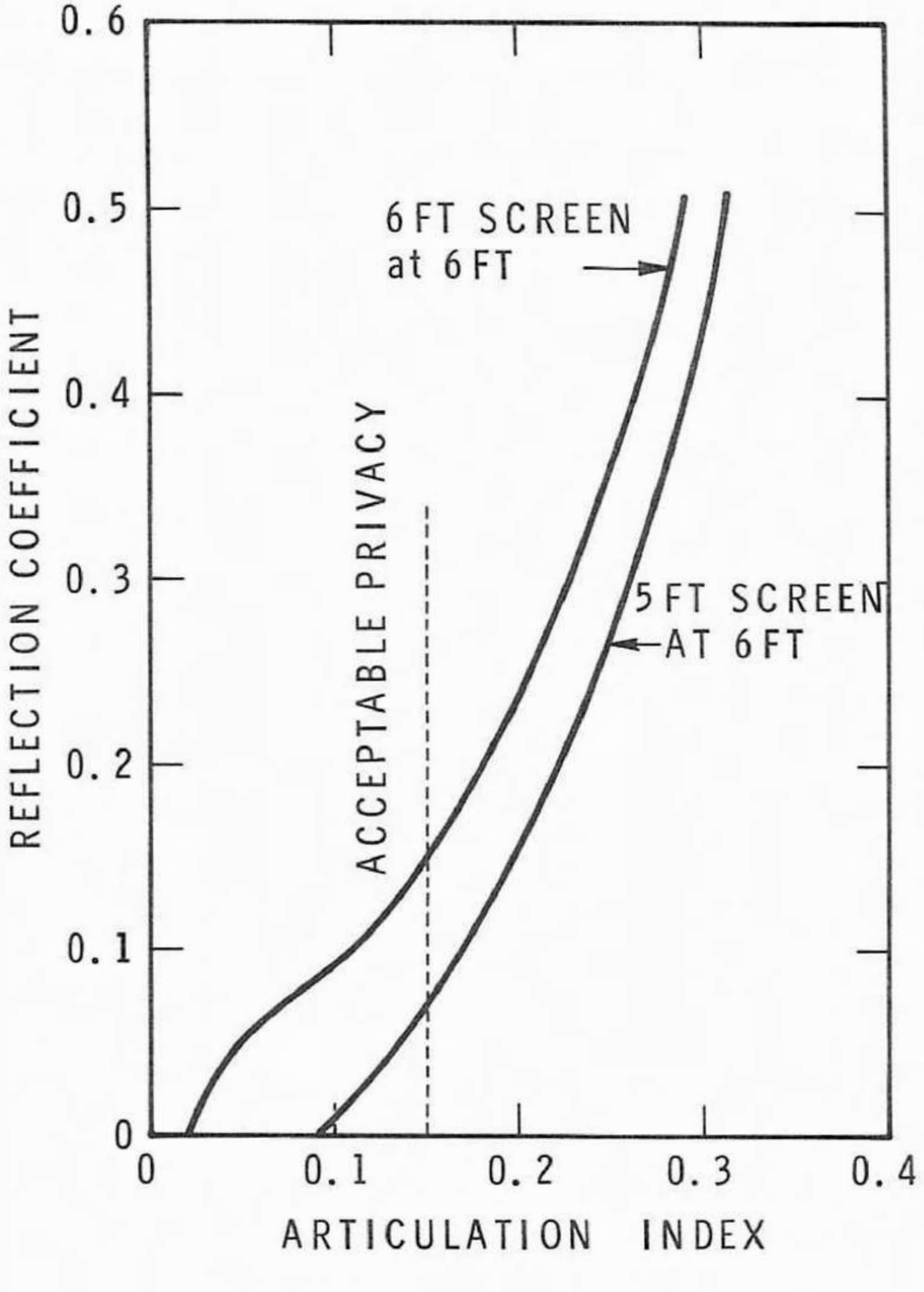


FIGURE 13

ARTICULATION INDEX BEHIND SCREENS AS FUNCTION OF CEILING REFLECTION COEFFICIENT

BR 5058 – 13

Appendix A

Sound absorption tests conducted on lay-in type ceiling panels from the Kenson Building Landscaped Office in Ottawa. Sample tested on Mounting Number 7.

Sample A: Mineral fibre painted and perforated on one face (installed in ceiling). Panel size - 23 3/4 in. wide by 47 3/4 in. long by 9/16 in. thick. Panel Weight - 9.5 lb. Approximate number of perforations per sq ft - 1,400. Size and number of perforations -

600 - 1/16 in. diam. by 3/8 in. deep
800 - 1/32 in. diam. by 3/8 in. deep

Sample B: Mineral fibre panel painted and perforated on one face (new sample). Panel size - 23 3/4 in. wide by 47 3/4 in. long by 5/8 in. thick. Panel weight - 7.5 lb. Approximate number of perforations per sq ft - 1,400. Size and number of perforations -

600 - 1/16 in. diam. by 1/2 in. deep
800 - 1/32 in. diam. by 1/2 in. deep

Sample C: Glass fibre panel with 0.010 in. thick painted porous face. Panel Size - 23 3/4 in. wide by 47 3/4 in. long by 11/16 in. thick. Panel Weight - 5.2 lb.

Sound Absorption Coefficients

Sample	Frequency in Hz 125	250	500	1000	2000	4000	Noise Reduction Coefficient
A	0.29	.28	.52	.70	.67	.44	0.55
B	0.29	.38	.63	.79	.71	.46	0.65
C	0.45	.69	.75	.94	1.04	.99	0.85