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SOUND ABSORBING ACOUSTIC HORNS

BY RICHARD W. HARRISON (NSWC)
WALTER M. MADIGOSKY (NSWC)
BASIL VASSOS (UNIVERSITY OF PUERTO RICO)

RESEARCH AND TECHNOLOGY DEPARTMENT

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An exploratory study of acoustic horns as non-reflective liners for water-filled anechoic tanks was conducted. The goal was to determine if a suitably shaped horn could improve the reflection loss characteristics of acoustic materials. Horns were constructed and tested. In certain cases, the presence of a horn or an array of horns in an absorbing material clearly improved the process in which energy enters a material so that it may be absorbed.

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FOREWORD

This report describes an exploratory study of acoustic horns as non-reflective liners for water-filled anechoic tanks. The goal was to determine if a suitably shaped horn could improve the reflection loss characteristics of acoustic materials.

This work was the result of a 7-week effort by Professor Basil Vassos of the University of Puerto Rico and was sponsored by the ASEE Summer Faculty Research Program.

Approved by:

Carl E. Mueller

CARL E. MUELLER, Head
Materials Division

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CHAPTER 1

INTRODUCTION

The successful absorption of sound often depends on the availability of a material that has two characteristics: high internal sound absorption and low sound reflection.

This study investigates the possibility of decreasing the reflectivity of the walls of an anechoic tank by forming horns on the surface of an absorbing material, with the purpose of coupling the energy into the material, thereby providing diminished reflection.

There are several ways for implementing such a coupling:

1. The walls of the horn can be made reflecting and the throat absorbing with the sound entering the mouth of the horn. This is similar to the case of a loud speaker horn used backwards.

2. Both the horn walls and the throat are absorbing.

3. A number of small horns can be formed in the surface of an absorber.

4. A resistive-impedance horn can be designed to channel the wave into a sound trap.

These four approaches have been investigated and the results form the content of this report.

CHAPTER 2

THEORY

The first theoretical treatment of horns appears to be that of Bernoulli (1764) and Euler (1766). In more modern times, Rayleigh (1916) and Webster[1] (1919) deduced the basic differential equation governing sound propagation in a horn:

$$\frac{\partial}{\partial x}\left| E S \frac{\partial \xi}{\partial x} \right| = \rho s \frac{\partial \xi^2}{\partial_t 2} \qquad (2-1)$$

where E is Young's modulus, ρ the density of the medium, S the cross sectional area which is a function of the distance x (Figure 2-1). The symbol ξ denotes the displacement in the direction of x, and t is the time.

In organizing the information about horns, one must keep in mind that, in general, only three factors have to be considered:

1. General shape of the horn; i.e., the function S(x) in Figure 2-1.

2. The scale of the physical implementation. In other words we consider

$$S = S_0 \bullet F(x)$$

where S_0 is a scaling factor and F a function of x. The magnitude of S_0 relative to the wavelength λ, defines the response for a given general shape. This is a statement of the "principle of similarity."[2]

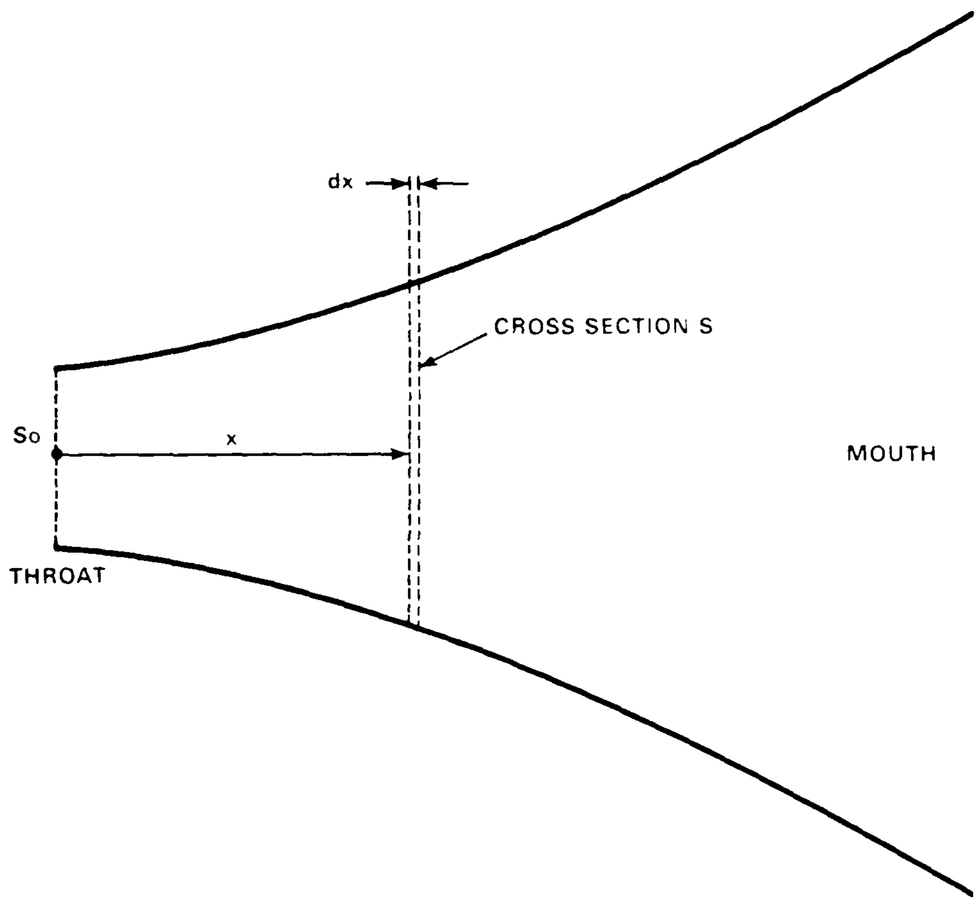
3. Energy dissipation in the walls.

Let us consider these three aspects in turn.

GENERAL SHAPE

The most commonly encountered horn shape or "flare" is the following exponential law:

$$S = S_0 e^{mx} \qquad (2-2)$$



NOTE: THE CROSS SECTIONAL AREA IS A FUNCTION OF THE DISTANCE FROM THE THROAT

FIGURE 2-1. AN ACOUSTIC HORN

where m is the flare constant. The units of m are cm^{-1}, and of S are cm^2. The flare constant is important in determining the frequency response since it can be shown that a horn cuts off at frequencies below

$$f_c = \frac{mc}{4\pi} \qquad (2-3)$$

where c is the speed of sound in the medium. The exponential horn has very advantageous resistive behavior above f_c (Figure 2-2) but a rather abrupt cutoff.

The horn cross-section can be either round or square with little acoustic difference. The theory of exponential horns has received considerable attention.[1, 3-8]

Other horn shapes have also been used such as conical, hyperbolic, or parabolic. Of them, the hyperbolic cosine type has often found application.[5] It obeys the formula

$$r = r_0 [\cosh(mx) + T \sinh(mx)] \qquad (2-4)$$

where the quantity r/r_0 is a dimensionless shape scaling term and m is the flare constant (cm^{-1}).

The parameter T describes a family of horns and can vary from zero to infinity. Very large values of T describe straight horns, while small values of T describe strongly flared horns. At unity, the shape is exponential. Note that for hyperbolic horns the radius and not the area is the variable (compare Equations (2-2) and (2-4)).

A special case[9] is the so called "catenoidal" horn. The name comes from the fact that a chain (from the latin "catena") takes this type of shape spontaneously. The catenoid shape corresponds to T = o in Equation (2-4) or

$$S = S_0 \cosh^2(mx) \qquad (2-5)$$

The great advantage of the catenoid horn is that its impedance at the mouth is more purely resistive than the exponential type if the horn is sufficiently long and the frequency sufficiently high (Figure 2-3).

Finally, mention should be made of the "tractrix" horn that follows the parametric equations

$$x = \mu - a \tanh(\mu/a) \qquad (2-6)$$

$$y = a \operatorname{sech}(\mu/a) \qquad (2-7)$$

where a is a parameter called the generating arm (the length of the tangent from any point on the curve, extending to the x axis), and μ is another parameter.

The tractrix horn[10] shows again a rather resistive behavior except close to cutoff. There are many peaks on the frequency response curve, shown in Figure 2-4. The equivalent to the flare constant in this case is the tractrix length a. When $a < c/w$ the horn cuts off, where w is the angular frequency and c is the speed of sound.

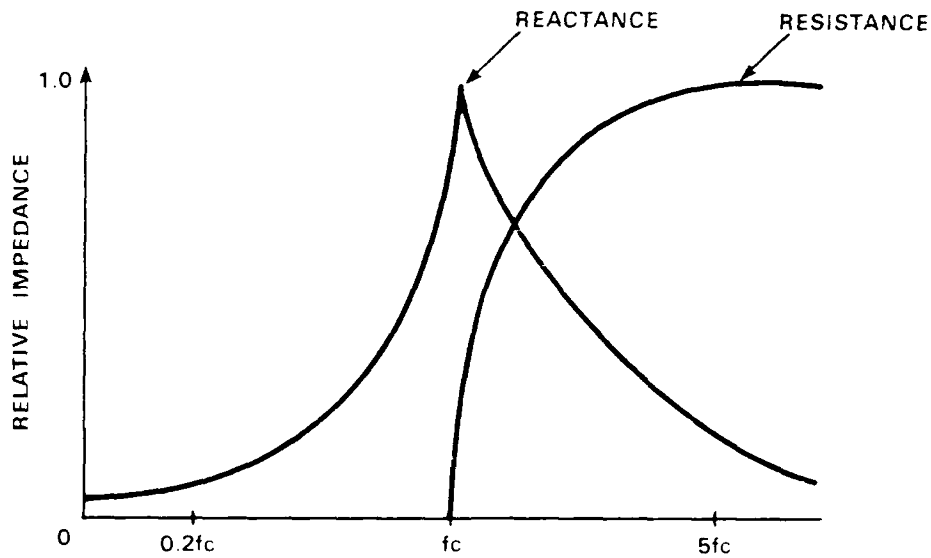


FIGURE 2-2. IMPEDANCE IN AN EXPONENTIAL HORN AT THE MOUTH OF THE HORN

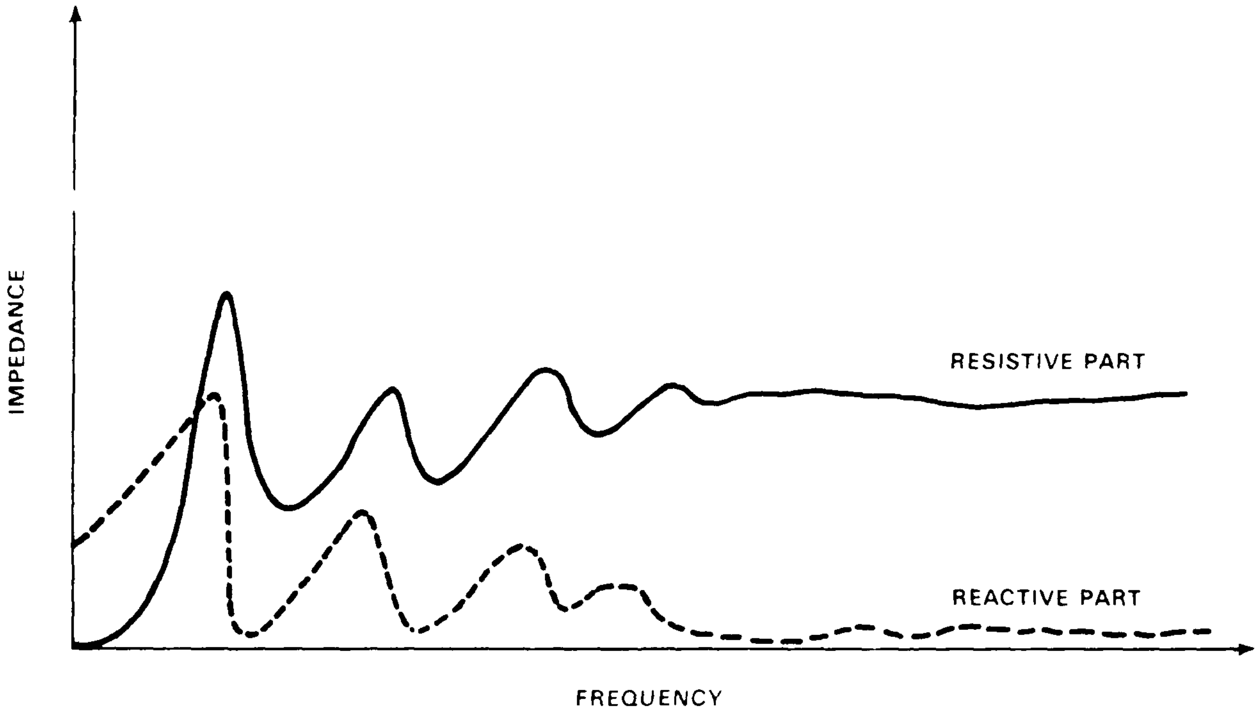


FIGURE 2-3. HORN IMPEDANCE AT THE MOUTH OF A CATENOIDAL HORN

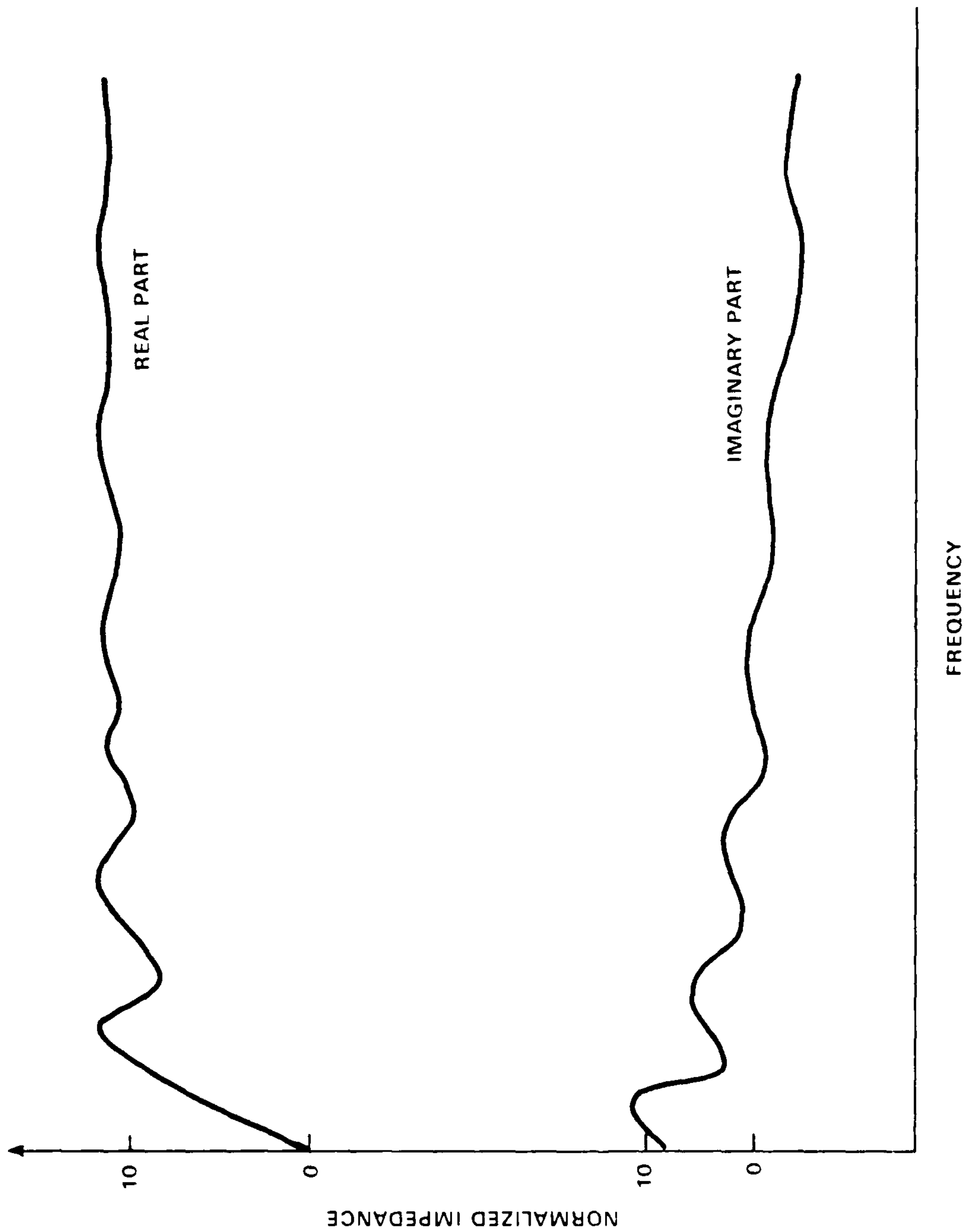


FIGURE 2-4. TYPICAL TRACTRIX IMPEDANCE

SCALE OF IMPLEMENTATION

An experimental proof of the principle of similarity as applied to horns is given by Goldman.[2] In general, the water-filled horn will have the frequencies scaled from the air horns by the ratio R of the two sound velocities

$$R = \frac{c_{WATER}}{c_{AIR}} = \frac{1500}{330} = 4.5 \qquad (2-8)$$

In practice for a given horn size, the cutoff and any other feature related to wavelength occur at higher frequencies.

WALL ABSORPTION

The case where there is dissipation within the horn has been discussed in 1940 by Phelps[11] and more recently by Kergomard[12] and Watkinson.[13] Sound absorption in ducts and bars received, of course, extensive attention, see for example Sivian,[14] Snowdon,[15] or Benson.[16]

In a horn in which the walls absorb energy[11] the sound transmission can be expressed in terms of a coefficient β':

$$\beta' = \rho_0 c \frac{1 + (1 - a)^{\frac{1}{2}}}{1 - (1 - a)^{\frac{1}{2}}} \qquad (2-9)$$

where a is the absorption coefficient of the wall.

This defines a coefficient a given by

$$a = \frac{2\rho c}{m\beta} \left(\frac{n}{50}\right)^{\frac{1}{2}} \left(1 - e^{\frac{-mx}{2}}\right) \qquad (2-10)$$

where m is the exponential flare constant, S_0 is the throat area, and x is the coordinate along the axis of the horn. The quantity within the parenthesis tends to unify if the horn is sufficiently long.

The coefficient a, in turn, enters in the power loss expression:

$$\text{Power} = P = \frac{SoA^2}{\rho c} e^{-2a} \qquad (2-11)$$

Consequently, large attenuations will be obtained if: m is small (slow taper), if S_0 is small (small horns), and if β is small (absorption coefficient is large).

We now consider the problem of impedance matching. The specific acoustic impedance is defined as:[5]

$$Z = \frac{\text{SOUND PRESSURE}}{\text{Particle Velocity}} \qquad (2-12)$$

If the medium has an impedance for longitudinal waves of ρc (density times speed of sound), then we can define the dimensionless impedance

$$\zeta = \frac{Z}{\rho c} \qquad (2-13)$$

Admittance is the reciprocal of impedance. At high enough frequencies ζ_{THROAT} becomes unity. The acoustic impedance for a duct is defined as the specific acoustic impedance divided by the cross-sectional area, Z/S.

In order to obtain an expression of the impedance let us consider the exponential horn equation[1, 4, 17] that can be written as:

$$\frac{\partial^2 \xi}{\partial t^2} = c^2 \left[\frac{\partial^2 \xi}{\partial x^2} + m \frac{\partial \xi}{\partial x} \right] \qquad (2-14)$$

where ξ = particle displacement along the x-axis, c = sound velocity in water, m = horn flare constant, and t = time. Upon solving the equation for ξ and obtaining the acoustic impedance, the following expression is obtained (for a long horn):

$$Z = \frac{\rho c}{S_0} \left[\sqrt{1 - \left(\frac{m}{2k}\right)^2} + j\frac{m}{2k} \right] \qquad (2-15)$$

where k = w/c,

A graph of the imaginary part of the impedance versus the real part of the impedance in units of $\rho c/S_0$ is given in Figure 2-5 and a set of values is given in Table 2-1. It is apparent that beyond about 20 kHz the horn should behave purely resistive. This horn was constructed and the results are reported in a later section.

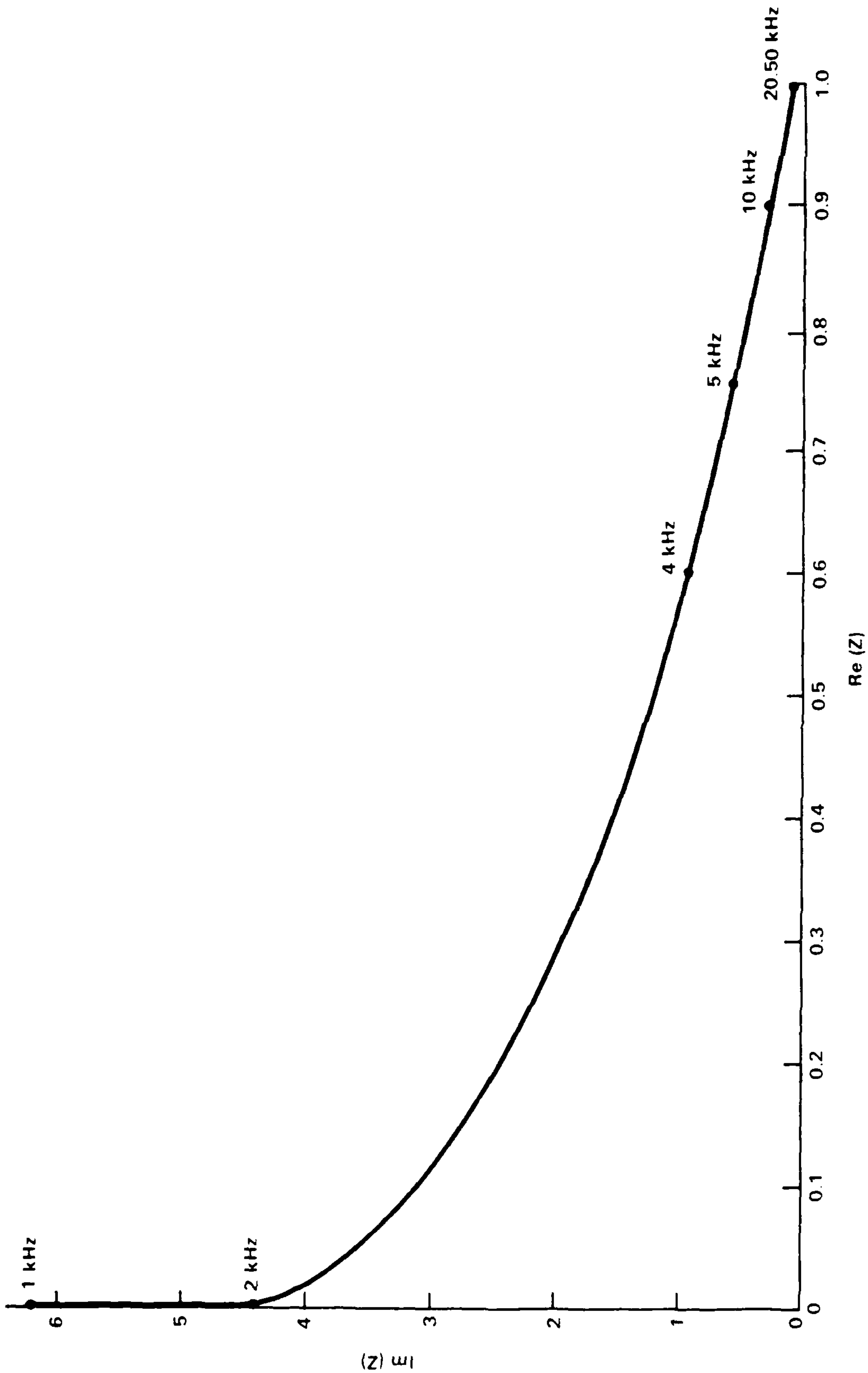


FIGURE 2-5. COMPLEX IMPEDANCE OF HORNS WITH THE FLAIR CONSTANT M=0.27

TABLE 2-1. IMPEDANCE VERSUS FREQUENCY FOR HORN WITH FLARE CONSTANT M = 0.27

f	m/2k	Z
1 kHz	3.2	0 + j 6.2 (double valued)
2 kHz	1.6	0 + j 4.4 (double valued)
5 kHz	0.64	0.76 + j 0.64
10 kHz	0.32	0.89 + j 0.32
20 kHz	0.16	0.97 + j 0.064
50 kHz	0.064	0.99 + j 0.032
100 kHz	0.032	0.999 + j 0.016

CHAPTER 3

REFLECTING WALL HORNS

As shown in Figure 2-5, the impedance of the horn becomes resistive at higher frequencies. It should therefore be possible to acoustically match water to steel using an appropriate ratio of mouth to throat areas.

A horn of sheet aluminum covered with closed pore air foam was constructed for this purpose, with sides shown in Figure 3-1. The ratio S_{MOUTH}/S_{THROAT} is 197/6.25 = 31.5 thus in water, at the throat, the impedance should be increased by a factor of 31 to match that of steel.

The factor of 31 was chosen so that

$$\frac{(\rho c)_{STEEL}}{(\rho c)_{WATER}} = \frac{7.9 \times 5940}{1 \times 1500} = \frac{S_{Mouth}}{S_{Throat}}$$

The flare rate of 0.27 is the same as the one used in obtaining the graph of Figure 2-5 which indicates no imaginary component over 50 kHz. A 1-foot steel rod was connected to the horn as shown in Figure 3-2. It was expected, that if the coupling was effective, and echo from the back surface of the steel rod would be obtained. It was found to our surprise that an echo was obtained within the horn, possibly at the throat or about 1-inch forward of the throat. These results have not been explained satisfactorily, but several additional experiments with the horn alone showed the same type of in-horn reflection. Therefore, a longer horn with the same curvature as the one shown in Figure 3-1 was constructed with a throat area of $2cm^2$.

The reflections obtained are shown in Figure 3-3 as a function of the angle through which the horn was rotated. The frequency of measurement was 200 kHz.

An overall attenuation of 4 dB on axis is present with practically no response off axis. The major reflections occur at 0.75 cm and 2.5 cm from the throat inside the horn. A weaker reflection was obtained at 5 cm from the throat. The phenomenon is not clear to us. Defects in the construction of the horns (that were hand-assembled and glued) might be responsible.

We now consider the case of reflecting horns with inserted absorbers. If a small piece of rubber is placed on axis (Figure 3-4 and 3-5), considerable reflection loss can be obtained. The nitrile rubber used was the Naval Surface Warfare Center (NSWC) formulation 299-42 and the sample #3400 contained 3 percent air. The polar graphs are shown in Figures 3-4 and 3-5.

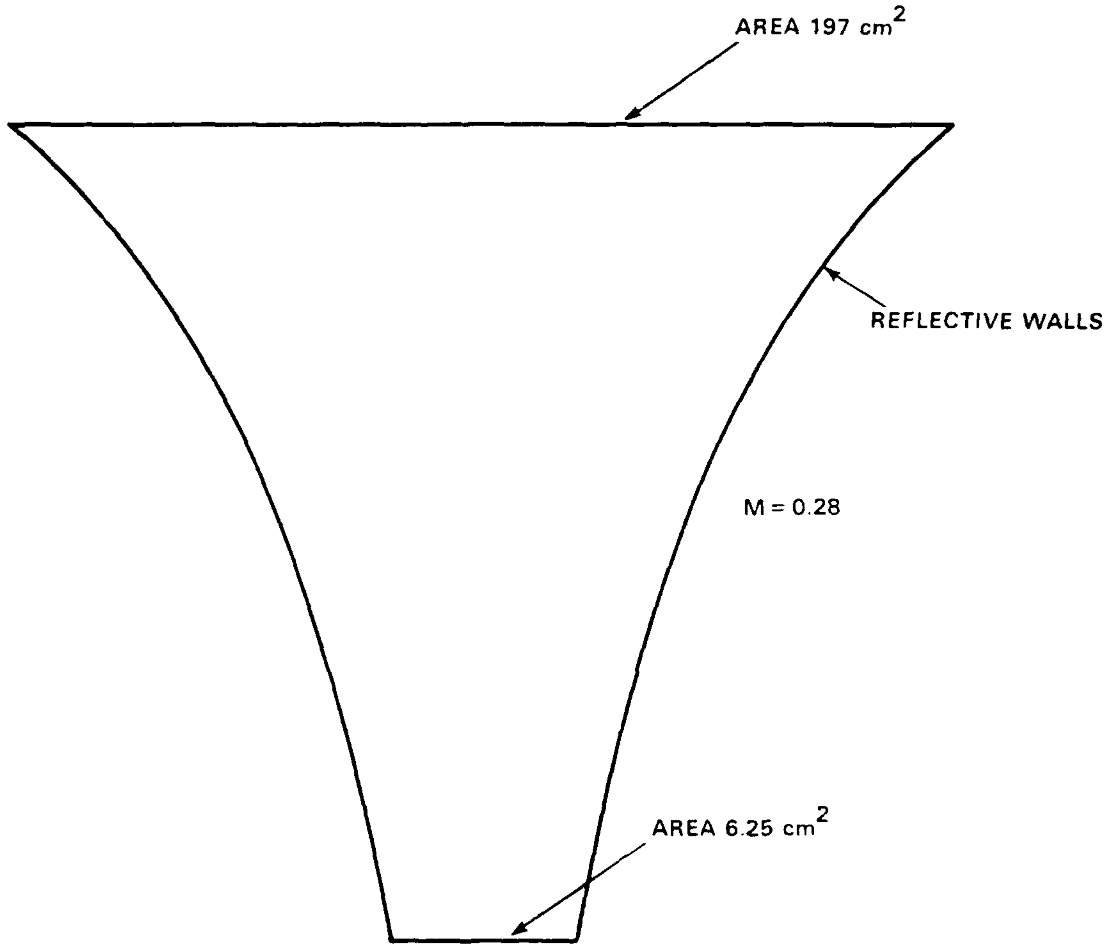


FIGURE 3-1. HORN INTENDED TO MATCH THE IMPEDANCE OF WATER TO THAT OF STEEL

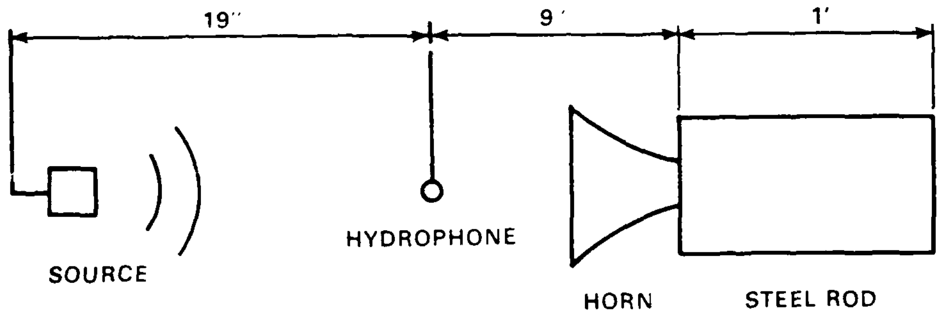


FIGURE 3-2. EXPERIMENTAL ARRANGEMENT FOR DETERMINING THE MATCHING OF THE IMPEDANCE OF WATER TO THAT OF STEEL

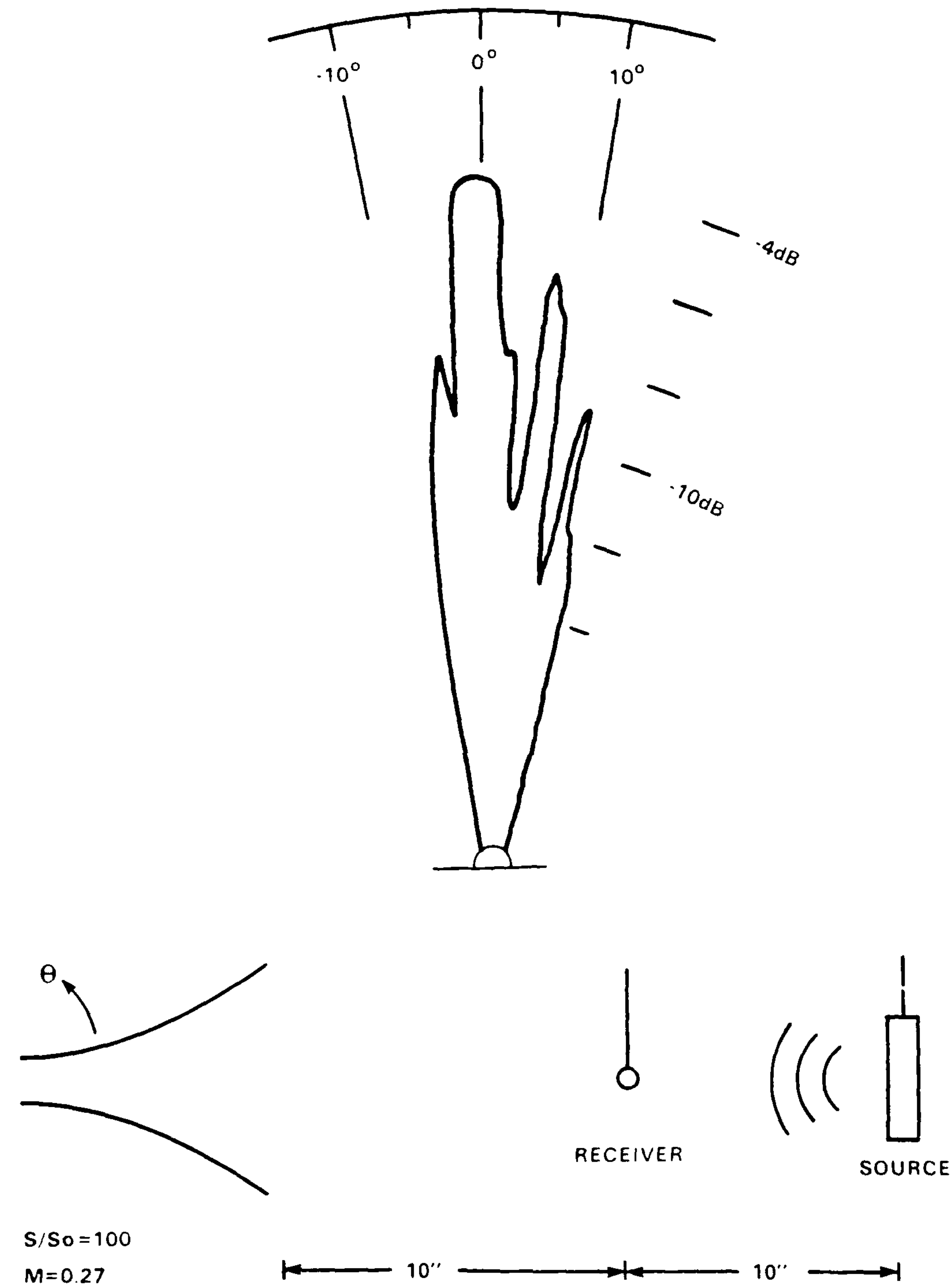


FIGURE 3-3. BEAM PATTERN OF A HORN WITH 2 cm^2 THROAT AT 200 kHz

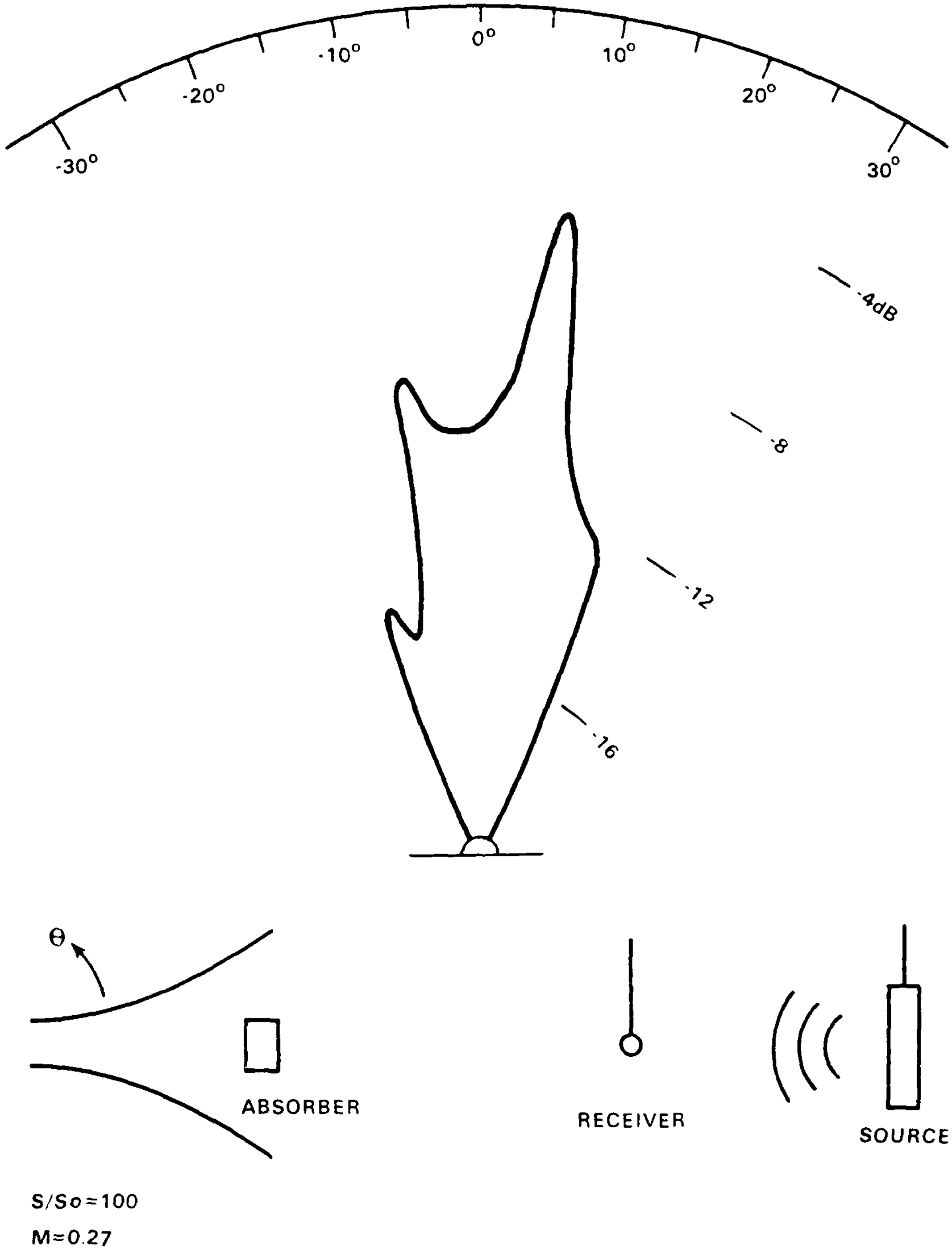


FIGURE 3-4. BEAM PATTERN MEASUREMEN AS IN FIGURE 3-3 WITH ¾ INCH RUBBER ABSORBER, SAMPLE 3400, IN FRONT OF HORN AT 200 kHz

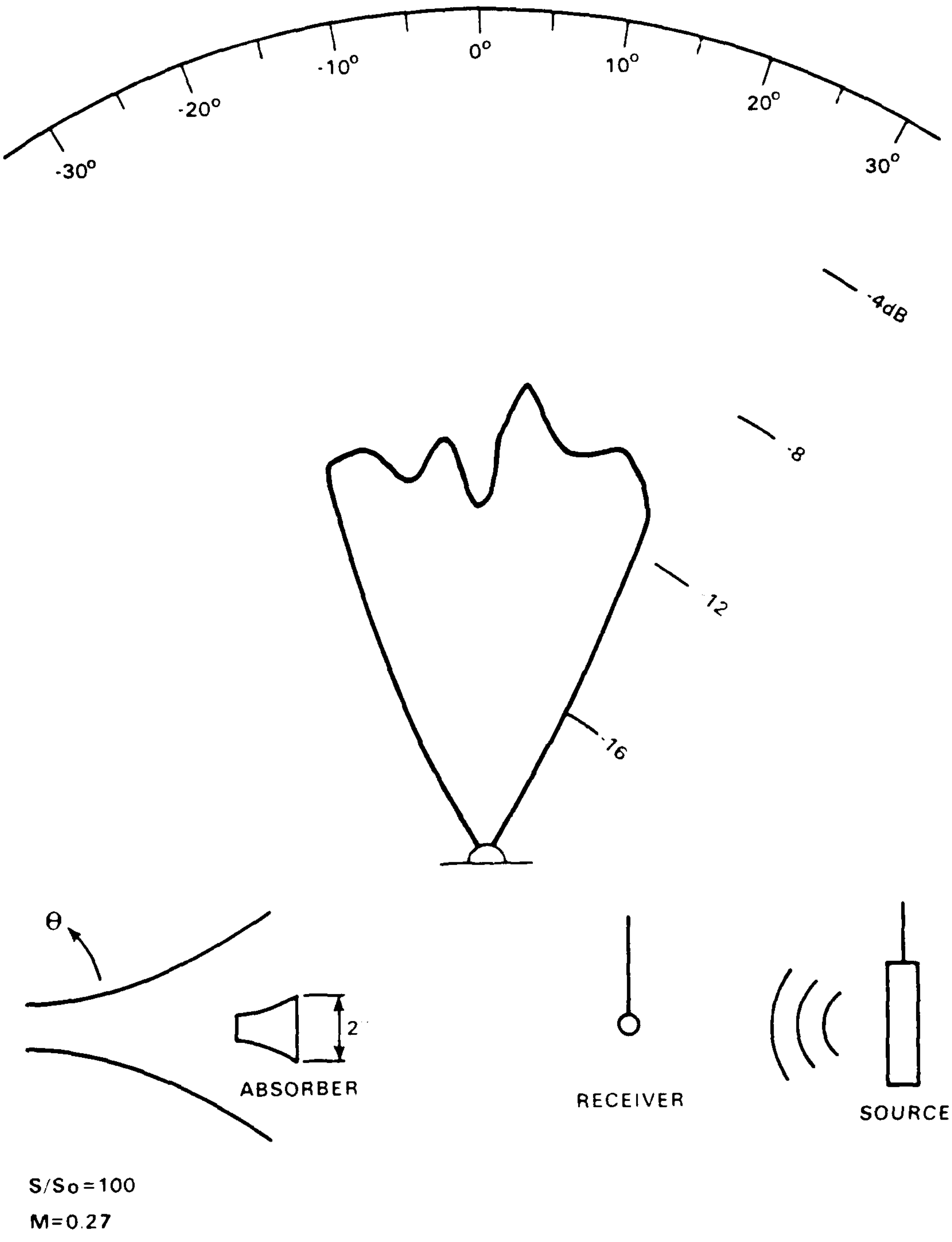


FIGURE 3-5. BEAM PATTERN OF HORN AS IN FIGURE 3-3 WITH EXPONENTIALLY SHAPED ABSORBER 1 INCH BY ¾ INCH BY 2 INCHES, SAMPLE 3400, IN FRONT OF HORN AT 200 kHz

In conclusion, owing to the limited success of the experiments, little was gained by using a horn as a reflection loss device. The 10 dB reduction shown in Figure 3-5 could probably be easily optimized to perhaps 15 to 20 dB by proper use of horn flare, horn shape, and rubber absorber. However, other simple absorption mechanisms could do as well or better at these frequencies. Lower frequency behavior using the same size horn is theoretically possible but was not investigated due to the limited time available.

An application that might make a superior sound absorber is shown in Figure 3-6. This arrangement would operate as a sound trap coupling the sound into an absorbing cavity.

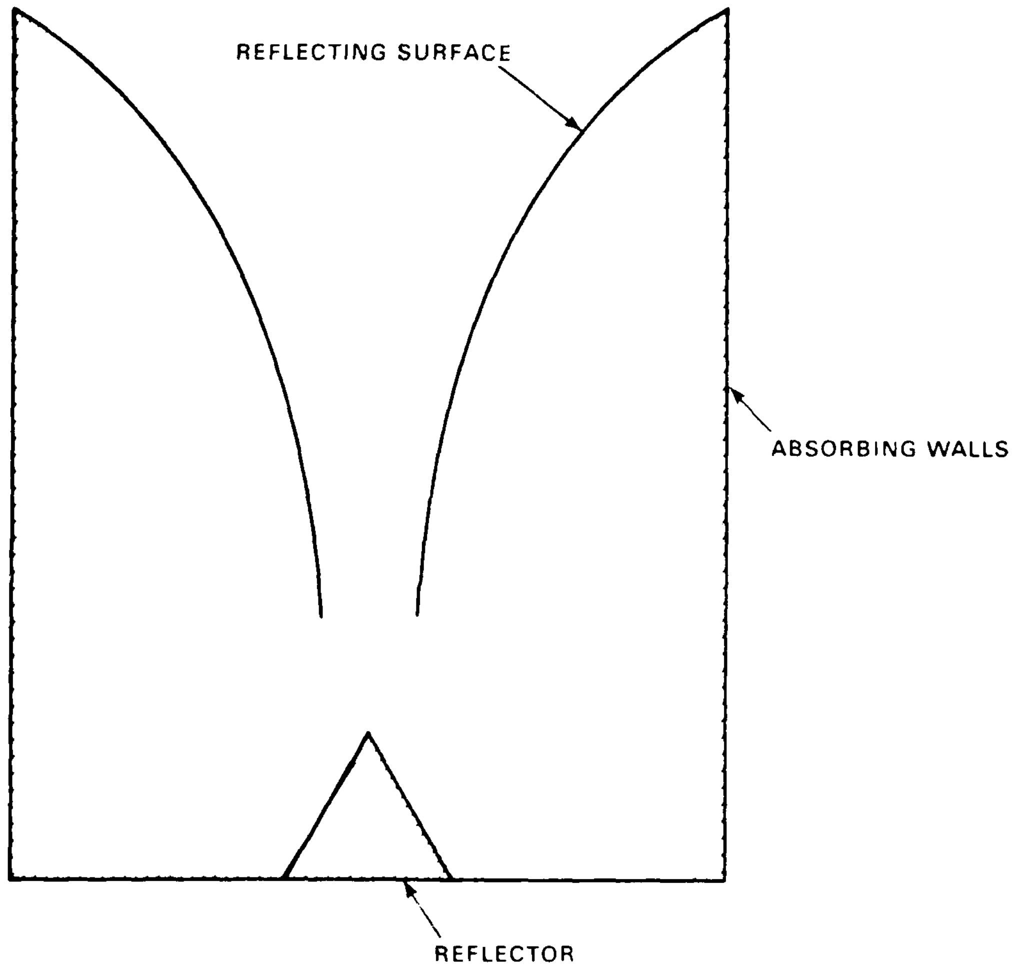


FIGURE 3-6. PROPOSED SOUND TRAP

CHAPTER 4

ABSORBING WALL HORNS

A study was made of an exponential horn of $m = 0.27\ cm^{-1}$ (same as in Chapter 3) with a mouth area of $200\ cm^2$ and a throat area of $2\ cm^2$.

The material used was NSWC formulation 299-42 type Nitrile rubber with no air inclusion and 1/4-inch thickness. The material has the following characteristics:

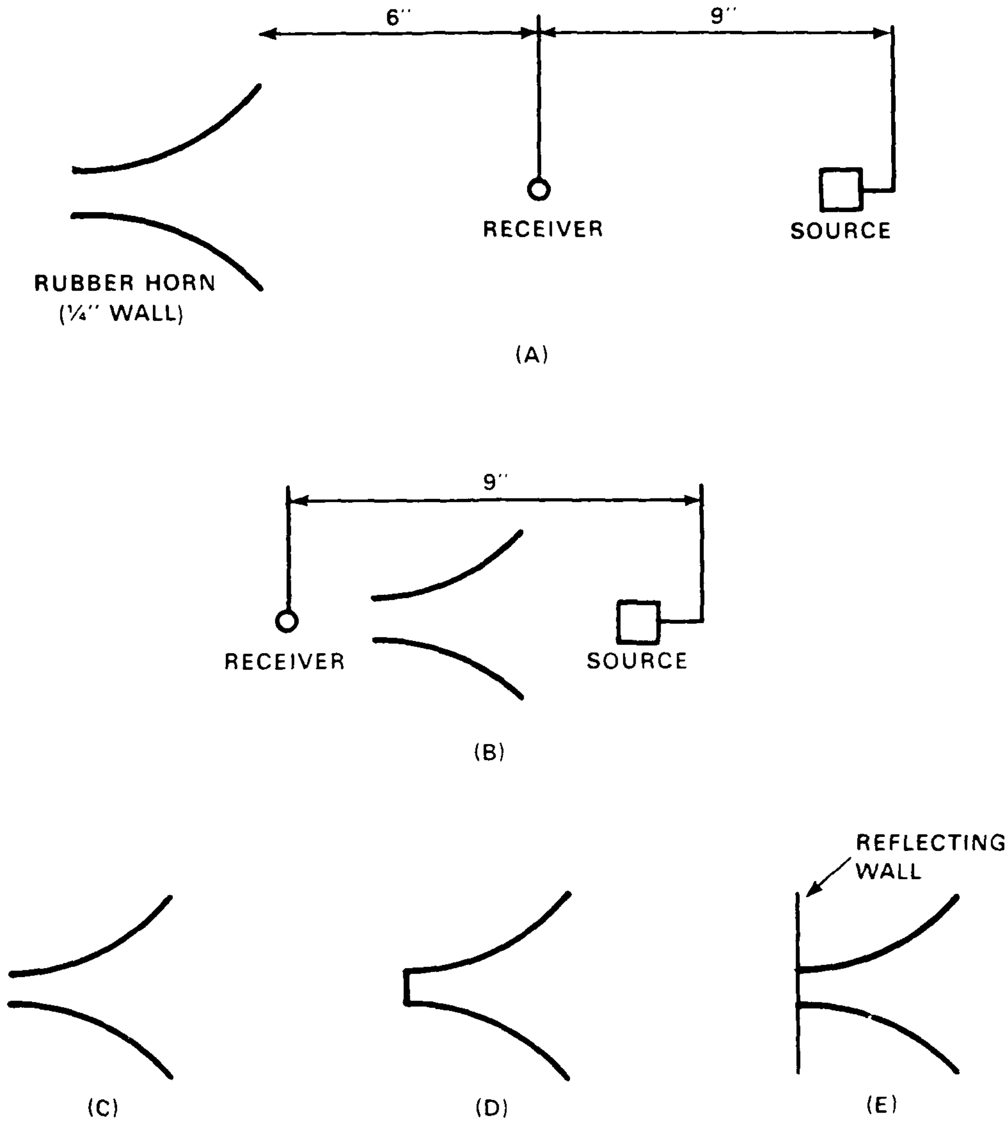
f	Insertion Loss (dB)	Reflection Loss (dB)
2 kHz	0	-4
5 kHz	0	-1
10 kHz	-1	-1
25 kHz	-1	-2
50 kHz	-1	0
100 kHz	-1	0
200 kHz	-4	-3

The reflection attenuation was measured with a good reflector backing. The reflector alone was taken as 0 dB. The measurements below 50 kHz are not very reliable owing to the large wavelength and small tank size. The horn was measured in three different arrangements as shown in Figure 4-1.

In configuration (D) the reflection data show very low values, in the 20 to 30 dB range at 200 kHz. At lower frequencies, the attenuation dropped to about 10 dB, but note that the material alone exhibits only 1 dB or less attenuation at those frequencies. The data are shown in Figures 4-2 and 4-3.

In configuration (C) the horn shows, at 200 kHz, an insertion loss of 20 dB and a reflection attenuation of 14 dB compared to a perfect reflector of the same size as the mouth. As expected, the lack of throat loading had a negative effect on the reflected sound.

The question remains, however, as to what shielding effect the horn has on a reflecting wall. For this, the experiment on Figure 4-1 (E) was implemented. The data are shown in Figure 4-4. The loss is a consistent 10 dB or more at high frequencies. The data at low frequencies (< 50 kHz) must be considered tentative due to the abundance of echoes in the response.



NOTE: (A) AND (B) SHOW THE EXPERIMENTAL ARRANGEMENT FOR REFLECTION AND INSERTION LOSS. (C), (D), AND (E) ILLUSTRATE VARIOUS TYPES OF HORN CONFIGURATIONS

FIGURE 4-1. EXPERIMENTAL ARRANGEMENT FOR REFLECTION AND INSERTION LOSS AND VARIOUS TYPES OF HORN CONFIGURATIONS

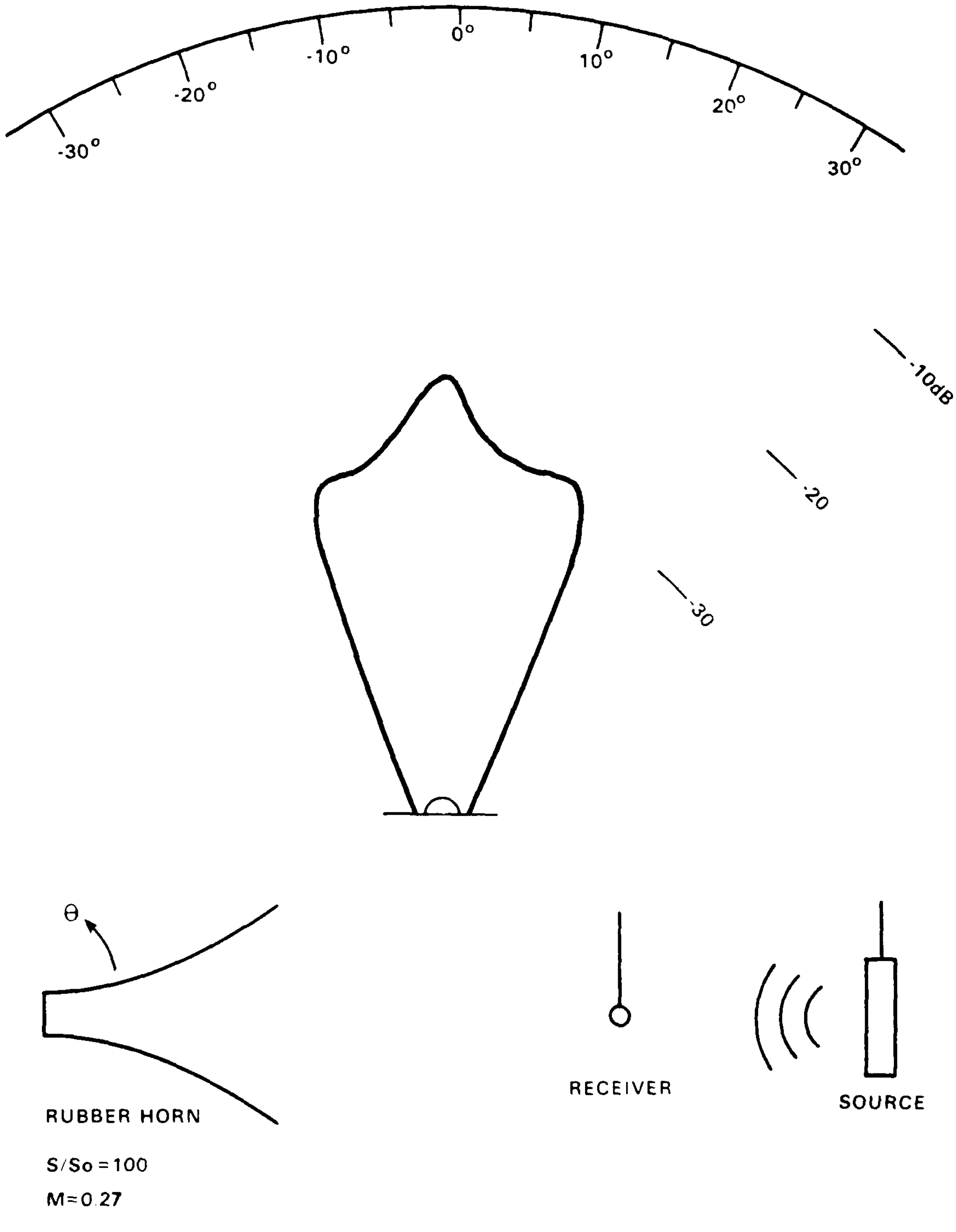


FIGURE 4-2. POLAR DIAGRAM OF REFLECTION FROM RUBBER HORN OF FIGURE 4-1 (D) AT 200 kHz

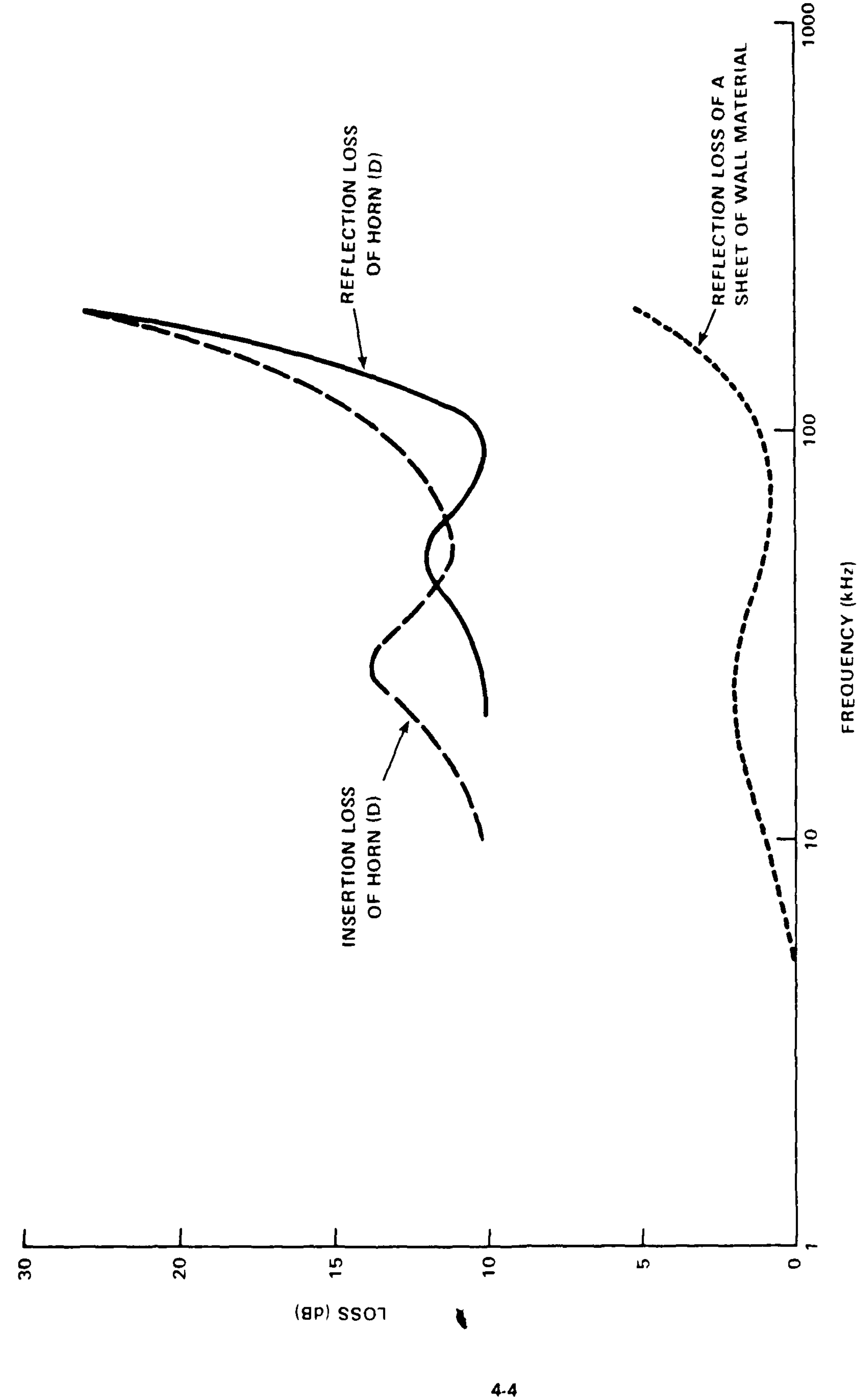


FIGURE 4-3. FREQUENCY RESPONSE OF HORN OF FIGURE 4 (D)

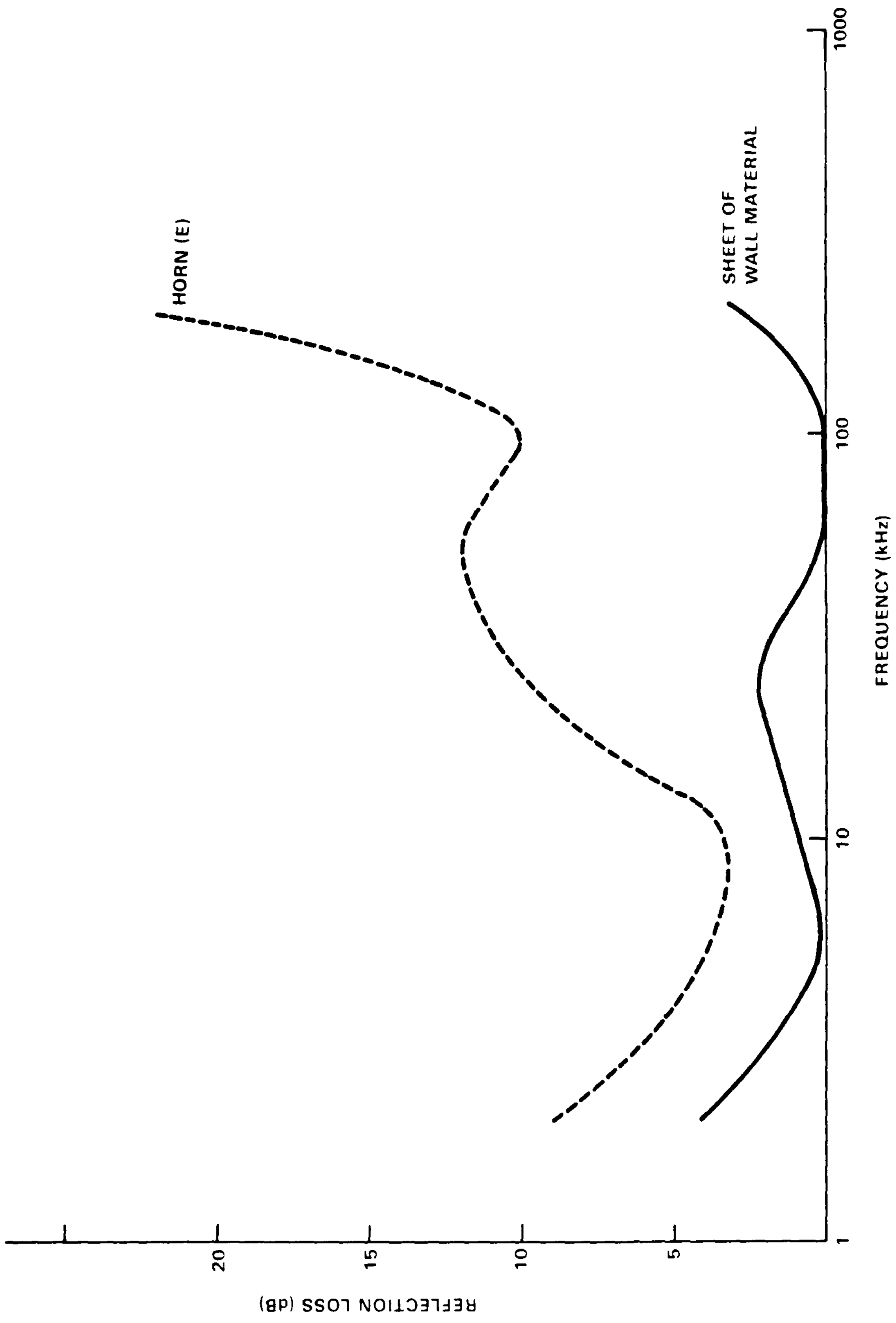


FIGURE 4-4. REFLECTION LOSS OF RUBBER HORN OF FIGURE 4-1 (E)

CHAPTER 5

SURFACE-MODIFIED MATERIALS

Given a sound absorbing material, a certain amount of acoustic energy is always reflected upon entering the material.

Since the reflection in a horn may be smaller than that of a flat piece of the same substance (see Chapter 4 for experimental data), it should be possible to reduce the sound reflection from any sound absorber by creating a number of exponential indentations in the surface as in Figure 5-1.

Since the only materials considered are those that have good sound absorption, the appropriate situation is that of a horn with wall loss. Phelps[11] shows in this case, that the attenuation is exponentially dependent on a factor which is dependent on various parameters as given in Equation (2-10).

EXPERIMENTAL DATA

The materials, whose surfaces were modified, were polyurethane foams obtained from the Witco Chemical Corp., New Castle, Delaware. They had the following characteristics:

Material Description	Density	Sound Velocity (M/S)
DRZ 22-95	0.89	801
DRZ 22-138	0.96	600

The material was machined into two forms: (1) a 2-inch thick disk of 2-inch diameter and (2) the same form but with a horn shaped cavity machined in it (see Figure 5-2). The curvature of (2) was approximately exponential with $m = 0.7$. A special tool was made for this purpose.

The samples were measured in a 2-inch diameter by 13-foot long impedance tube. The results are shown in Figure 5-3. An improvement in high frequency reflection loss of roughly 5 to 10 dB is obtained to the presence of the exponential shaped cavities.

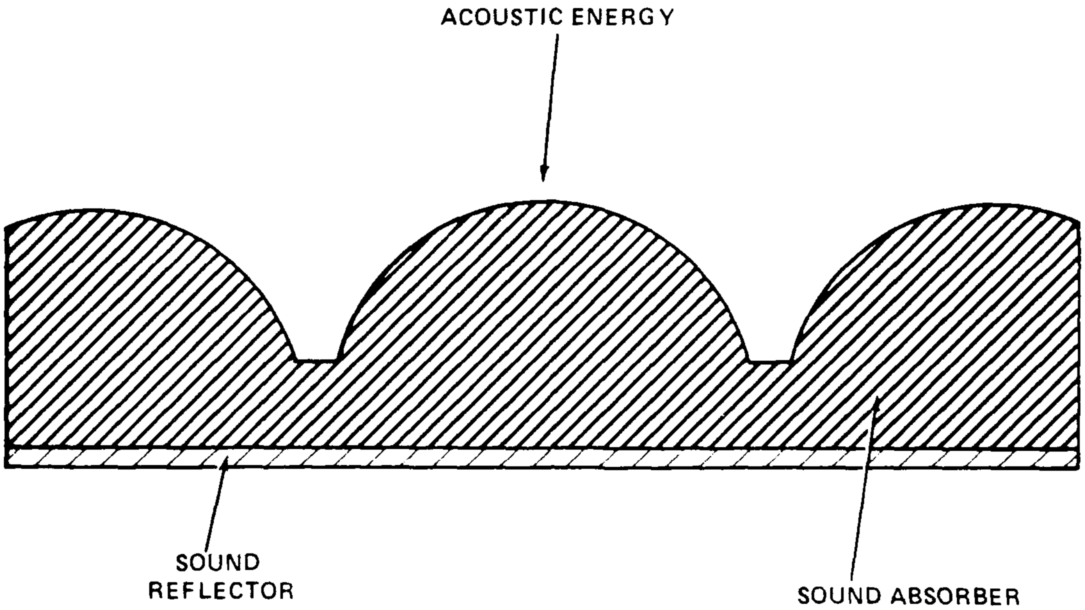


FIGURE 5-1. CROSS SECTION OF EXPONENTIAL INDENTATIONS IN THE SURFACE OF A SOUND ABSORBER

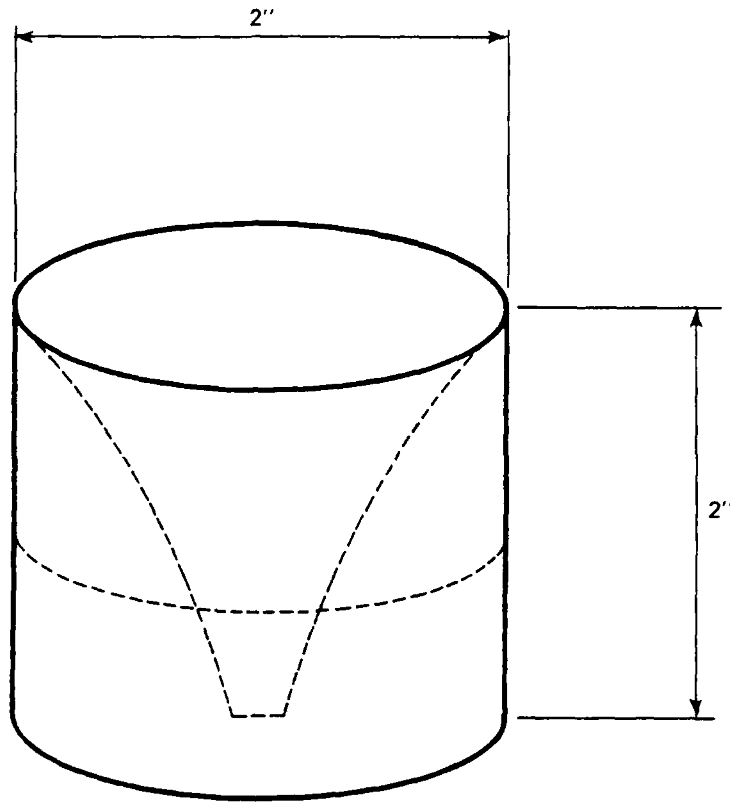
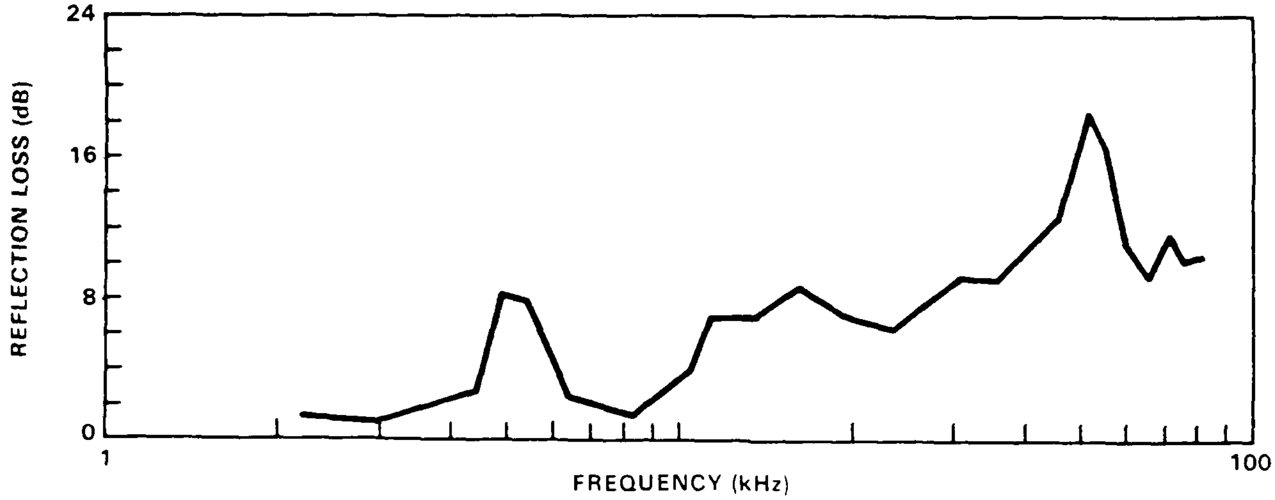
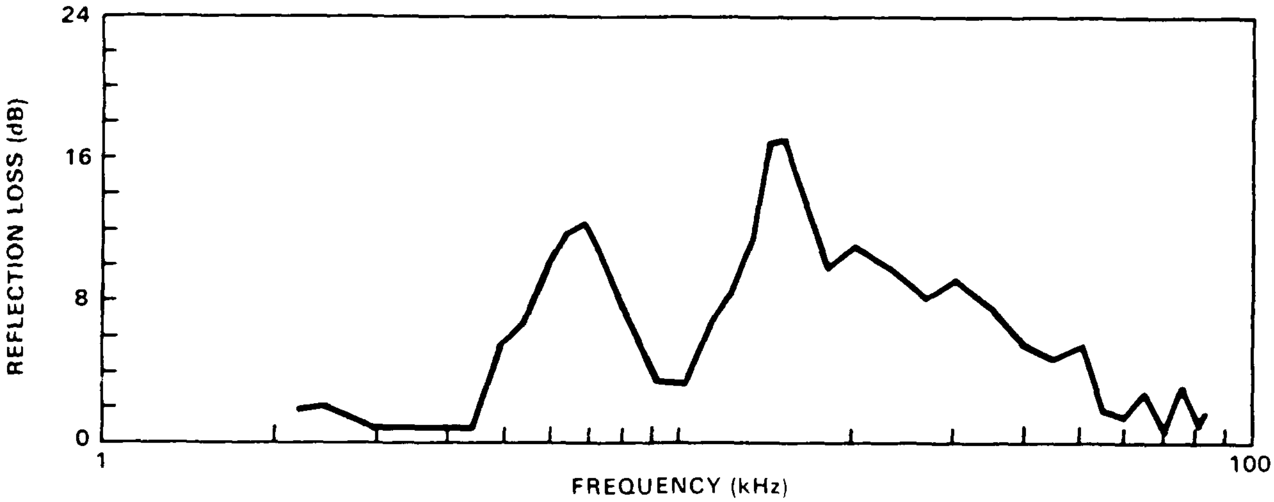


FIGURE 5-2. CYLINDRICAL URETHANE HORN





NOTE: UPPER FIGURE HORN SHAPE, LOWER FIGURE NO HORN

FIGURE 5-3. REFLECTION LOSS OF A 2-INCH SAMPLE OF DRZ-22-138

The effect for the horn used, which is of high "m," cuts off (Equation (2-3)) at about:

$$f_c = \frac{mc}{4\pi} = 8\ \text{kHz}$$

It is expected that perhaps the improvement can be extended down to about 5 kHz or even to 2 kHz by rearranging the horn shape.

Note that the quantity of material present in the horn is smaller than in the disk. Some of the peaks in the disk response are favorably due to half wave thickness resonances. In Figure 5-3 these resonances appear at 6.5 and 13 kHz which are harmonically related.

MULTIPLE HORNS ON POLYURETHANE

It is expected that, for a small flare m, the wavelength limitations of the horn mouth can be improved by forming a multitude of horns on a surface. Such a unit was constructed on a sheet of polyurethane DRZ-TOTO-138, 1-inch thick and 1-foot square. The polyurethane density was 64 lb/ft^3. The ensemble is shown in Figure 5-4.

The horns (holes) were 2 cm deep and approximately 3/4-inch apart. The exponential flare was 2.0 cm^{-1}.

The responsc was compared between direct and reversed position of the horns with respect to the sound beam. In this way the same amount of absorber is compared for two different cases. The results are shown in Figures 5-5 and 5-6 where both insertion and reflection loss (backed by a good reflector) were measured.

From Figure 5-5 it can be seen in both cases that the insertion loss is high indicating that little energy is being transmitted through the material. Thus, almost all of the incident beam is either absorbed or reflected. From Figure 5-6 it can be seen that when the horn surface is facing the incident wave, an additional 2 to 6 dB increase in reflection loss is obtained over the reverse case. Thus the presence of the horn array clearly improves the process in which energy enters the material so that it may be absorbed.

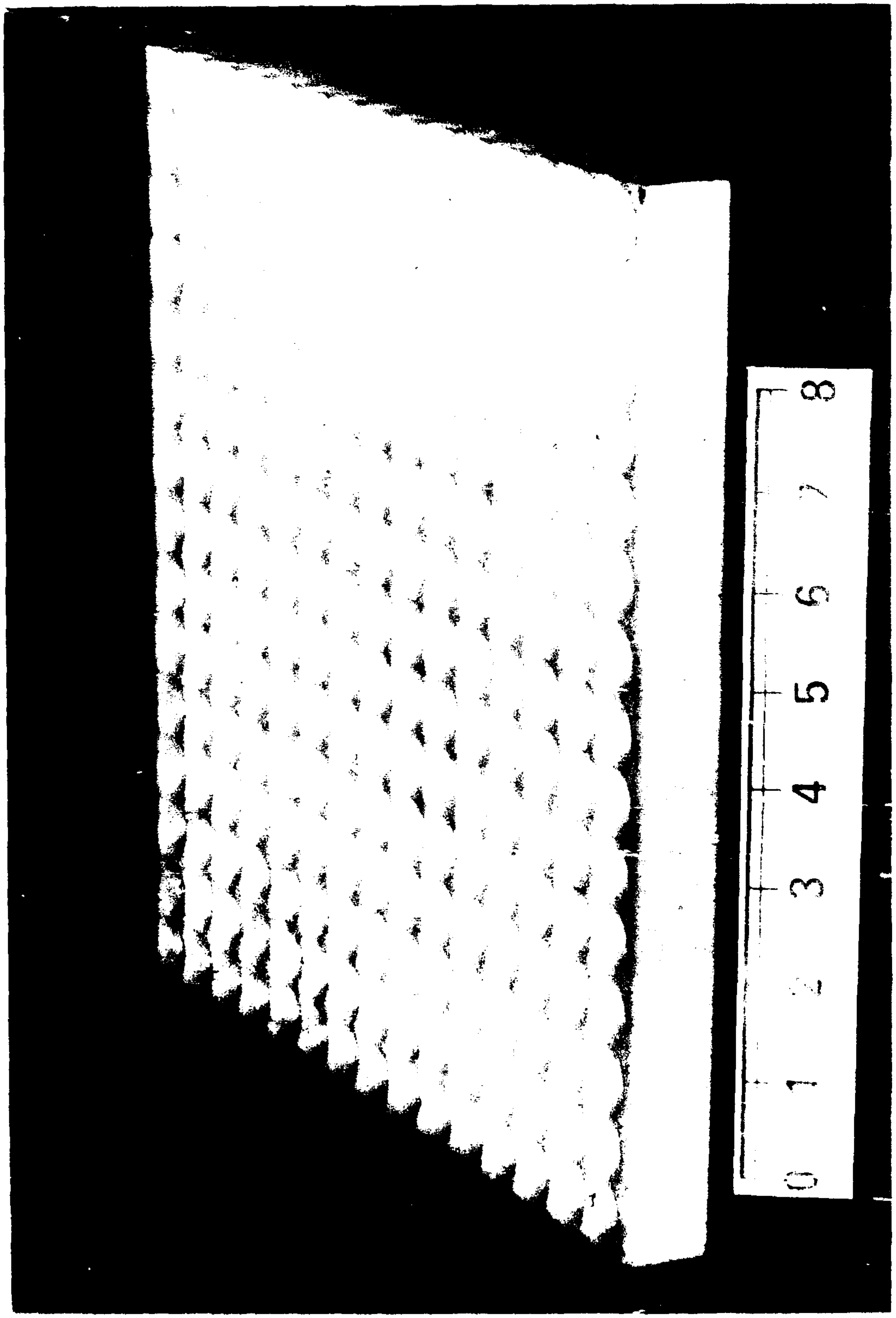


FIGURE 5-4. AN ARRAY OF HORNS IN AN ABSORBING MATERIAL

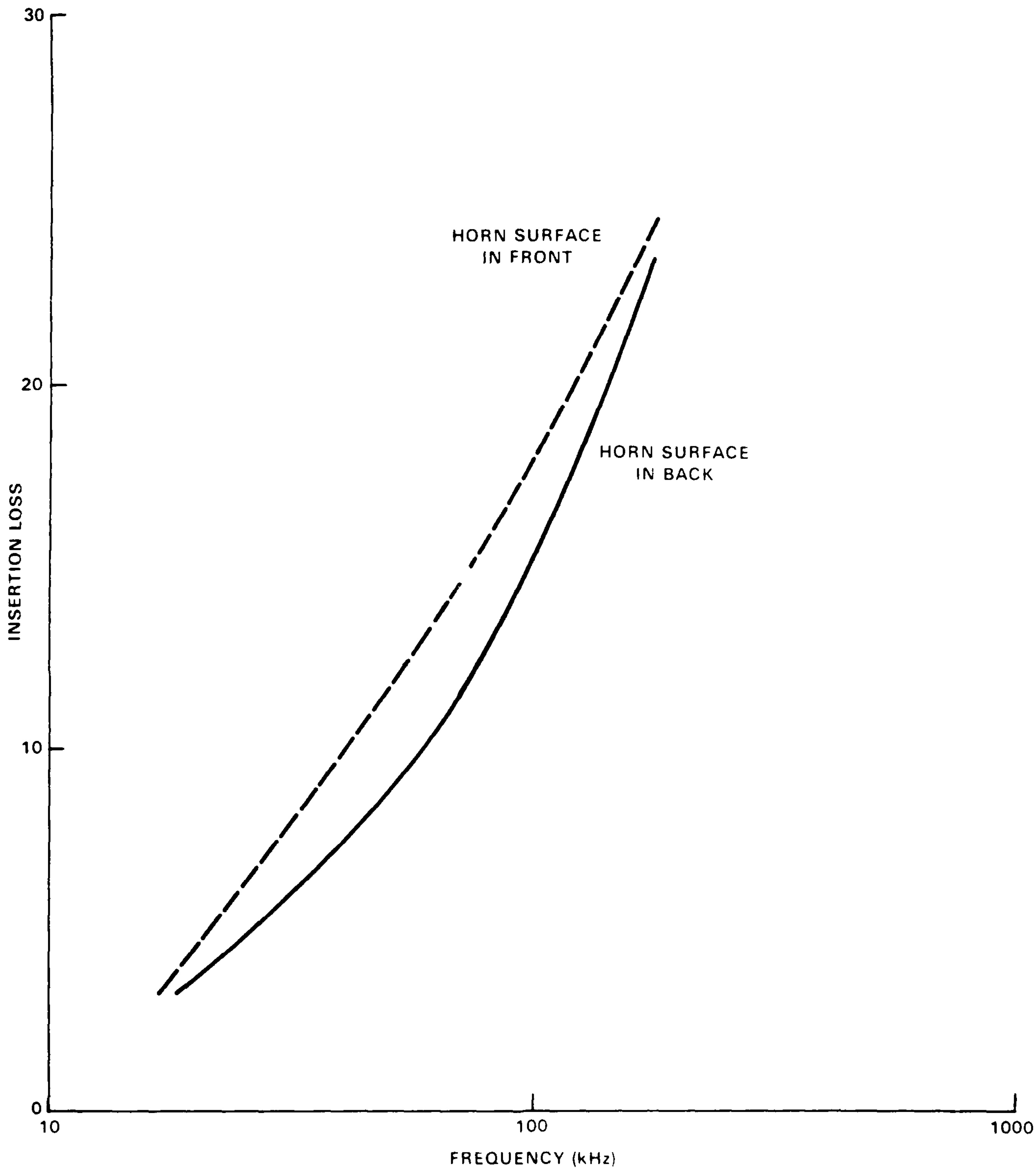


FIGURE 5-5 INSERTION LOSS FOR HORN ARRAY

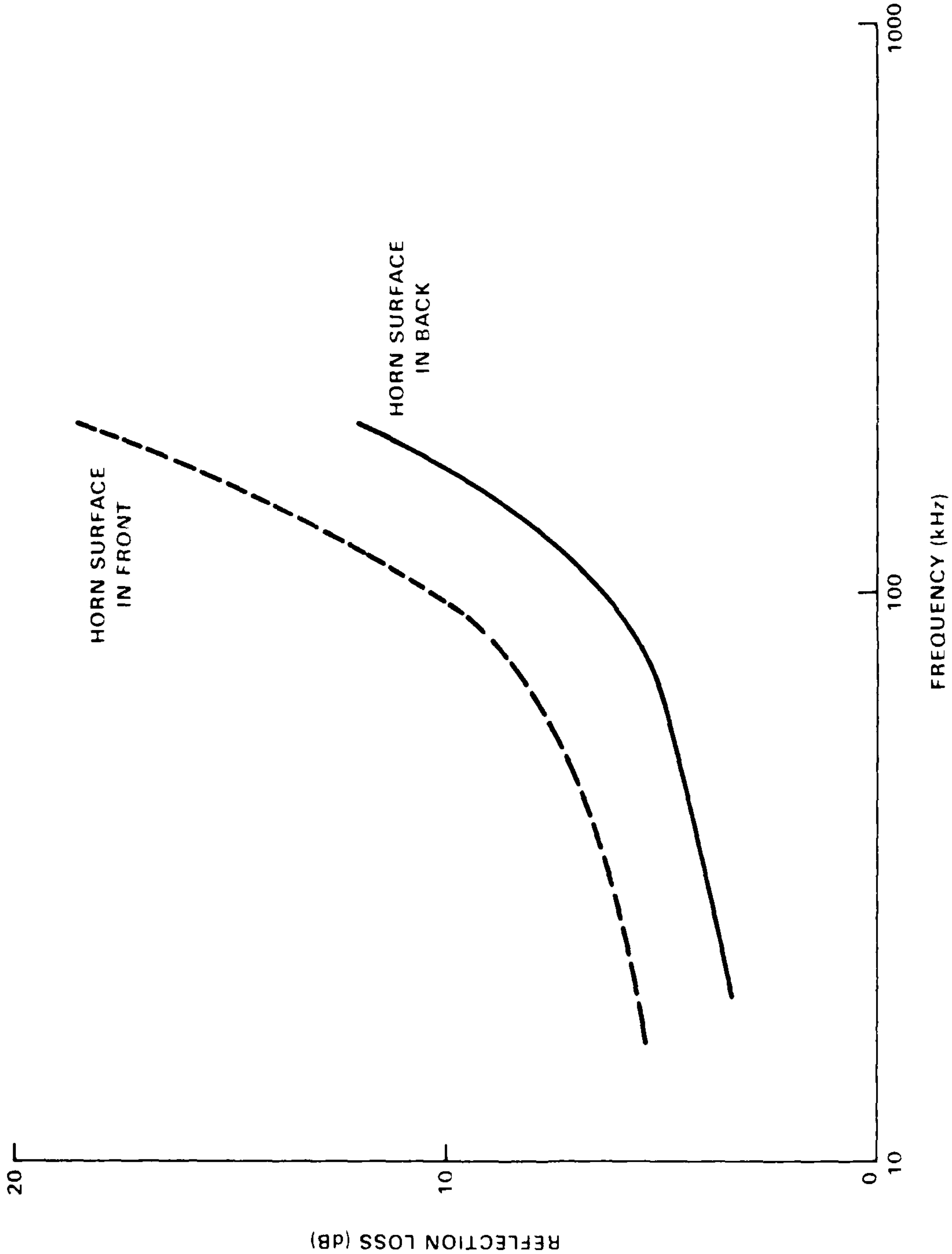


FIGURE 5-6. REFLECTION LOSS FOR HORN ARRAY AND FLAT SURFACE

CHAPTER 6

CONCLUSIONS

It has been shown that an exponentially shaped surface in a polyurethane foam can be used to absorb waterborne acoustic energy. Testing clearly demonstrated that a set of these cavities could be placed in the surface of a viscoelastic material to achieve acoustic energy absorption over a large area. There is the possibility, however, that this system could give rise to diffraction effects which could increase the reflected signal at certain spatial points. Due to time limitations, this area was not explored.

It is very possible that an efficient underwater measurements tank lining could be developed using the principle of an absorbing horn.

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