SECTION 3

SPECIALIZED BROADCAST RADIO ENGINEERING

TECHNICAL ASSIGNMENT

STUDIO AND AUDITORIUM ACOUSTICS

306D

- TABLE OF CONTENTS -

STUDIO AND AUDITORIUM ACOUSTICS

	Page
THEORY OF REVERBERATION	1
REVERBERATION	1
Multiple Reflections	1
Effect of Multiple Reflections	2
EFFECT OF REVERBERATION	2
Reduction of Articulation	3
Effect on Music	4
REVERBERATION TIME	4
Sabine's Formula	5
Illustrative Example, The Sabine	5
Eyring's Formula	7
REVERBERATION TIME VS. FREQUENCY	8
Optimum Reverberation Time-Frequency Curve	9
Illustrative Example	9
Discussion of Example	9
High-Frequency Absorption	10
General Design Considerations	11
DIFFUSION OF SOUND	12
IRREGULARITIES IN REVERBERATION CURVE	12
Coupled Rooms	12
Effect of Balconies, etc.	13
ECHOES AND WALL FLUTTER	14
Focusing Effects	14
Parallel Wall Reflection	15
METHODS OF DIFFUSING SOUND	15
Use of Vee Serrations	16
Use of Circular Arcs	17
MEASUREMENT OF REVERBERATION TIME	21
SOUND-ABSORPTIVE MATERIALS	23
GENERAL PROPERTIES	23
Representative Materials	23
Practical Considerations	25

Page

SPECIAL SOUND-ABSORPTIVE MATERIALS 26

Minimizing Change in Reverberation 26

Practical Behavior of Sound Absorptive Materials . . 27

METHOD OF MEASUREMENT 28

TABLE OF SOUND ABSORPTIVE MATERIALS 28

SOUND INSULATION 29

GENERAL CONDITIONS 29

Permissable Noise Levels 29

Factors Pertaining to Sound Insulation 30

ISOLATION OF VIBRATION 31

Machine Vibration 31

Building Vibration 33

WINDOWS, DOORS, ETC 34

Use of Multiple Windows 35

Construction of Doors and Vestibules 36

Ventilating Systems 36

STUDIO DESIGN 37

SPECIAL CONSIDERATIONS 37

Studio Location and Layout 37

Studio Dimensions 39

Reverberation Time--Studios 40

EXAMPLE OF STUDIO DESIGN 41

NBC Studios 6A and 6B 41

WOR Studios 44

SAMPLE DESIGN 46

Determination of Dimensions and Reverberation Time . 46

Design of Diffusing Surfaces 47

Determination of Areas 49

CEILING 49

FRONT WALL 49

REAR WALL 50

SIDE WALLS 50

FLOOR 50

Calculations at 1,000 Cycles 50

Calculations at Other Frequencies 52

CONCLUSION 53

STUDIO AND AUDITORIUM ACOUSTICS

THEORY OF REVERBERATION

As important as any other factor in the successful pickup of a broadcast program are the acoustical properties of the studio in which the program originates. While certain types of microphone directional characteristics and a judicious choice of amplifier response characteristics can compensate to some extent for a poor auditorium, nevertheless for best results the latter should be designed according to principles to be discussed in this technical assignment.

REVERBERATION.--Sound energy is transmitted through air at the rate of 1,122 feet per second at 20° C. Upon reaching a boundary wall, the sound wave encounters a medium in which the mass and stiffness have an entirely different ratio from that of air. As a result three things can occur:

1). A portion of the wave is reflected because of the impedance mismatch between the air and the boundary wall.

2). The rest proceeds to pass through the wall. Of this, a portion is transmitted through the wall to the external space.

3). The rest is absorbed in the wall and is transformed into heat energy. If the wall is sufficiently thick then only a negligible amount of wave energy passes through it to the outside because most of the energy is absorbed in traversing this thickness of wall.

In the design of a studio both the reflection and transmission of the sound waves are of importance, as well as the absorption. The reflection is important because it determines the interfering effect of the reflection of a previous sound with the sound being produced at the moment. The transmission is important because it determines the interfering effect of noise and other sounds originating outside the studio with the sound being produced in the studio.

Multiple Reflections.--Consider a source of sound placed in a room as shown in Fig. 1.

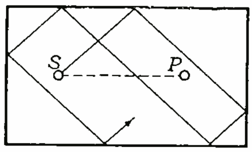


Fig. 1.--Multiple reflections of sound waves.

The source in general radiates acoustic energy over an angular spread that may vary from a few degrees (highly directional radiator) to a full 360° (non-directional radiator). Regardless of this, consider one ray of sound as shown. It will be reflected at discrete intervals from the walls of the enclosure and will pursue a zig-zag path as shown.

If the source radiates over an angular spread, then more rays will be involved and the total sound pattern will be more complicated. In general, any point such as P in the room will receive sound directly from S (along the dotted line) as well as a whole series of reflected waves. For some positions in the room no direct sound may reach such a point from S if the latter is directional in its acoustic radiation, but it will be clear from Fig. 2 that ordinarily it will be impossible to prevent reflected waves from reaching such a point, since the reflections are in general so random and so repeated that such energy is bound to reach every part of the room.

Effect of Multiple Reflections.--If the walls reflect all the energy impinging upon them, then the acoustic energy content of the room will constantly increase. On the other hand, if the walls absorb a certain fraction of the incident energy, then an equilibrium condition will ultimately be reached in which the energy emitted by the source is absorbed by a suitable number of contacts with the walls as fast as it is produced. Since no wall has perfect reflectivity, the latter condition obtains in practice, and hence the energy in the room builds up to a final value that theoretically, is reached an infinite time later.

This is illustrated in Fig. 2 by branch OA. Now suppose the source of the sound is cut off. The energy stored in the enclosure now starts to decrease owing to the absorption of the walls. The stored sound begins to "bounce" around on these and at every contact a certain fraction of the incident energy is

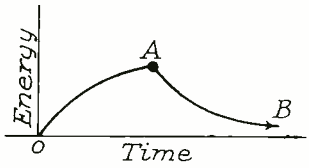


Fig. 2.--Growth and decay of sound energy in an enclosure.

extracted. The result is a decay curve illustrated by branch AB in Fig. 2.

Whenever a quantity increases or decreases by a fixed percentage *in discrete steps*, a geometric series is obtained. If the increase takes place *continuously* instead of in discrete steps, an exponential function is involved. Although absorption at the walls takes place in discrete steps, these follow one another in such rapid succession owing to the velocity of sound that the absorption can be regarded as taking place continuously. This is further justified by the fact that some portions of the total path length for any one ray are very short, and such short lengths are on the average staggered between various rays so that somewhere in the room a reflection is taking place almost instantly after another reflection somewhere else in the room has occurred.

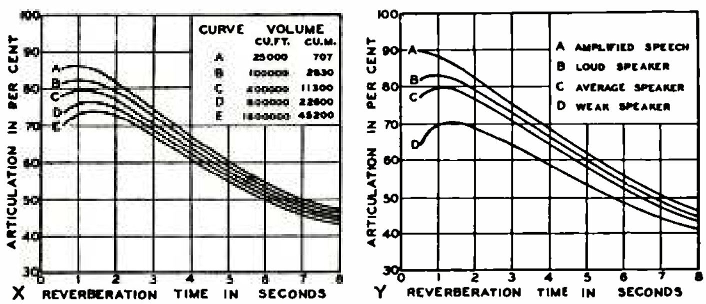
EFFECT OF REVERBERATION.--As a result the curves of Fig. 2 can be regarded as fairly smooth although actually, particularly in some auditoriums, a step here and there in the curve, or a succession of steps, may be noted. If the reflections follow one another in rapid succession, any sound produced is accompanied by a prolonged continuation of this sound that gradually dies out.

Reduction of Articulation. Unlike an echo that is a distinct repetition of the original sound occurring an appreciable time later, the above effect is an indistinct roar or confused continuation, and is known as a *reverberation*. If two sounds, such as two syllables of a word, are uttered in rapid succession, the reverberation of the first syllable tends to overlap and mask the second syllable, and the result is a blurring of the speech, i.e., the articulation is reduced.

This is an undesirable effect of reverberation. It is the reason why speech in a large auditorium having hard, highly reflecting walls, is so difficult to understand. The effect is particularly bad if the speech is rapid, as the reverberation from one sound is still fairly strong by the time the second sound is uttered.

A certain amount of reverberation, however, is useful. That part of the reflected energy that occurs immediately after the direct energy passes the pickup point may be regarded as occurring simultaneously with the direct energy--as far as the ear is concerned--and results in a reinforcement of the sound, i.e., an increase in the loudness of the sound. For weak sounds, such as from a speaker who does not have a loud voice, this reinforcement may be useful.

On the other hand, the effect of reverberation is in general to blur the speech and reduce the articulation. Hence reverberation produces two opposing effects that result in an optimum value which depends upon the loudness of the sound and the size of the auditorium. This is illustrated in Fig. 3. The left-hand diagram indicates how the per cent articulation (number of random syllables uttered that are correctly heard)



(Olson, courtesy of Elements of Acoustical Eng.)

Fig. 3.--X, the articulation of a speaker in various auditoriums. Y, the articulation in an auditorium of 400,000 cu. ft.

varies with the reverberation time (explained in the next section), for auditoriums of different volumes.

For example, if 75 per cent articulation is considered satisfactory, then an auditorium having a volume of 100,000 cu. ft. can have an amount of reverberation corresponding to about 2.7 seconds reverberation time, although 1 second is the optimum value. Further, an auditorium having a volume of 1,000,000 cu. ft. or greater cannot possibly be satisfactory because even for the optimum time of about 1.3 seconds, the articulation is below 75%. The reason is that the volume of sound from an average speaker is not sufficient to fill an auditorium of this size or greater, and if reverberation is employed to increase the sound intensity, the blurring effect becomes too great before sufficient reinforcement is obtained.

The remedy is to use a sound-reinforcing system. The relative effect is shown in the right-hand diagram of Fig. 3. The curves are for an auditorium of 400,000 cu. ft. It will be observed that when a sound-reinforcing system is employed, optimum results are obtained when the reverberation time is zero. This is to be expected, the sound system replaces the reverberation of the auditorium in increasing the loudness of the spoken sound. Fortunately, as long as the reverberation time is less than 1 second, the results obtained are nearly as good as for zero time. This means that practical amounts of acoustic treatment will furnish results very close to the optimum, which would require a prohibitive amount of material.

Effect On Music.--The effect of reverberation on music is less harmful. Music is generally a succession of periodic waves. Each note lasts for sufficient time (except in the most rapid passages) for its pitch to be established in spite of the interfering reverberation of the preceding note. As a matter of fact, reverberation tends to enhance the musical note and make it richer and more sonorous.

In addition, the artist unconsciously judges the pitch of the following note by the reverberation of the preceding note, particularly in the case of instruments that do not have fixed pitch, such as a violin or a trombone, and especially the human voice. In a very dead (absorptive) room the artist has difficulty holding to pitch, and the effect of the room on him is rather depressing owing to the lack of reverberation.

On the other hand, excessive reverberation will blur the more rapid staccato passages, and is consequently objectionable. It is therefore necessary to define a measure of the reverberation and to set suitable limits for this characteristic in order to obtain optimum results both for music and speech in the auditorium.

REVERBERATION TIME.--While reverberation is really too complex a phenomenon to be defined and measured by a single number, nevertheless it has been found useful to measure it in terms of reverberation time. This is defined as the time it takes a sound to die down to one-millionth of its initial intensity in the room. Expressed in db, this is a decrease in level of 60 db from the initial value.

The pioneer investigator in acoustics was Wallace C. Sabine.

His method of measuring the reverberation time was to blow into a 512-cycle organ pipe with a certain amount of force so as to establish an initial sound of a given intensity. Then, at the instant he stopped blowing, he would start a stopwatch, and measure the time until the sound decreased to the threshhold of hearing. This was roughly 60 db below the initial sound intensity, and thus the elapsed time was the reverberation time for the auditorium.

Sabine's Formula.--Sabine evolved a very simple formula for the reverberation time. This is

$$T = \frac{.05\ V}{\bar{\alpha}\ S} \qquad (1)$$

where T is the reverberation time in seconds,
V is the volume in cubic feet,
S is the surface of the enclosure in square feet, and
$\bar{\alpha}$ is the average coefficient of absorption.

The quantity $\bar{\alpha}$ is a fraction: it represents--on the average--the fraction of the incident sound that is absorbed by the surface and converted into heat energy. As an example, the coefficient of absorption for hair felt 1 inch thick is 0.51 at 512 c.p.s., i.e., 51% of the incident sound energy is absorbed and 49% is reflected.

Examination of Eq. (1) shows that the reverberation time is directly proportional to the volume, and inversely proportional to the surface and the average absorption coefficient. This is reasonable: the greater the volume, the greater is the path length, on the average, between reflections, and the longer does it take for energy to die down to one-millionth of its initial value, while the greater the surface area and the coefficient of absorption, the greater is the amount of absorption, and the faster does the sound die out.

Another point brought out by Sabine's formula is that if the linear dimensions of a room are doubled, the surface is increased four-fold, but the volume is increased eight-fold, so that the ratio of V/S is doubled. This in turn means that the reverberation time is doubled. Hence, in general, large rooms have longer reverberation times than small rooms and it is customary to permit longer reverberation times for large auditoriums, as will be discussed later.

Illustrative Examble, The Sabine.--As an example of the use of Sabine's formula, consider a studio auditorium in the form of a rectangular prism 20 feet in height, 30 feet wide and 50 feet long. The floor is covered with carpet on 1/8-inch felt, and the ceiling with rock wool, packed between firring strips, and used in conjunction with a diaphragm of proper weight and density. This is then covered with perforated sheetrock spaced about 1/4" from the acoustic material. The walls are of lime plaster 3/4-inch thick on wood lath on wood studs, smooth finish. Panels of acoustic material similar to that on the ceiling are provided on the walls. On the rear wall the panel is 20 x 20 feet, on the front wall two panels each 15 x 10 feet are provided, and on each side wall three panels each 20 x 10 feet are placed.

The arrangement is shown in Fig. 4, where the walls and ceiling are opened up to exhibit the dimensions and panel arrangements. The arrangement is not necessarily a desirable one for a studio, and the construction is nowadays modi-

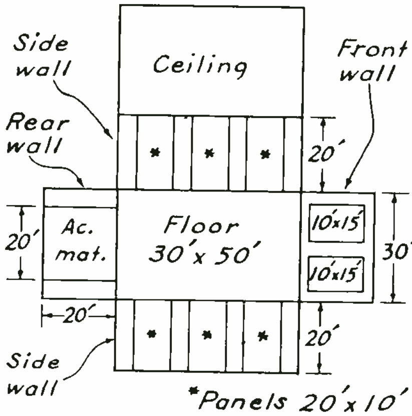


Fig. 4.--Arrangement of acoustic treatment in a studio.

fied by breaking up the wall surfaces to obtain a more uniform dispersion of the sound. However, the values given will serve as an illustration of the calculation of the reverberation time, and particularly of the average absorption coefficient, or rather, of the total absorption of the studio.

The coefficients of absorption of the various surfaces are found from a table of such values, and are as follows (for 512 c.p.s.):

Carpet on 1/8-inch Felt--0.37
Rock Wool,* as described--0.50
Plaster, as described----0.030

Instead of attempting to calculate directly an average coefficient of absorption, it is preferable to calculate the absorption of each type of material by taking into account

*(Table IV,-Low-frequency element)

its coefficient of absorption and its area. Thus, the floor (reference Fig. 4) has an area of 50 × 30 = 1,500 sq. ft. and on absorption coefficient of 0.37. A unit of absorption has been defined as 1 *sabine* if it has 100% absorption and an area of 1 sq. ft.* Therefore the floor has an absorption of 1,500 × .37 = 555 sabines. Similarly the ceiling has an absorption of 1,500 × 0.50 = 750 sabines.

The rear wall is composite in structure. The panel has an area of 20 × 20 = 400 sq. ft. and therefore an absorption of 400 × .50 = 200 sabines. The plaster portion is 30 × 20 - 400 = 200 sq. ft. times .03 = 6 sabines. The total is 200 + 6 = 206 sabines.

The front wall has an absorption of 2(10 × 15) (.50) = 150 sabines for the two panels. The plaster has an area of 30 × 20 - 2(10 × 15) = 300 sq. ft., and therefore the absorption is 300 × .03 = 9 sabines. The total is 150 + 9 = 159 sabines.

Each side wall has an absorption of 3(20 × 10) (.50) = 300 sabines for the three panels. The plaster portion has an area of 20 × 50 - 3(20 × 10) = 400 sq. ft. and hence an absorption of 400 × .03 = 12 sabines. The total per wall is 300 + 12 = 312 sabines, and hence 2 × 312 = 624 sabines for the two side walls.

The total absorption is 555 + 750 + 206 + 159 + 624 = 2,294 sabines. This is the quantity corresponding to $\bar{\alpha}S$ in Eq. (1).

*An absorption of 100 per cent can be obtained by an open window, as all the sound incident on it is lost to the outdoors. Thus an open window 1 ft. x 1 ft. has an absorption of 1 sabine.

From this, if it is desired, the *average* coefficient of absorption may be calculated. Thus the total surface is

$$S = 2(30 \times 50) + 2(20 \times 50) + 2(30 \times 20) = 6{,}200 \text{ sq. ft.}$$

Then

$$\bar{\alpha} = 2{,}294 \div 6{,}200 = 0.370$$

However, as is clear from the previous calculations, the quantity $\bar{\alpha}S$ = 2,294 sabines has been calculated without the need for knowing $\bar{\alpha}$ itself.

The reverberation time is now given by Eq. (1) as

$$T = \frac{.05(20 \times 30 \times 50)}{2{,}294} = 0.653 \text{ sec.}$$

This is less than the optimum value for a studio of this volume, as given in Fig. 31, to be discussed farther on. It will be interesting to note the reverberation time if the entire room had a coefficient of absorption of 0.03, i.e., that of the plaster walls. In this case

$$T = \frac{.05(20 \times 30 \times 50)}{.03 \times 6{,}200} = 8.07 \text{ sec.}$$

which is far too great. It is therefore evident that the use of acoustic material is necessary in order to make this studio usable.

*Eyring's Formula**.--For a room as "dead" as the one in the above example, for which the reverberation time is less than one-half second, the formula given by Sabine Eq. (1), results in a value of T that is too large. That Eq. (1) is in error can be seen very simply from the following: Suppose the coefficient of absorption were unity (100%). In this case all sound impinging on the walls would be completely absorbed, and there would be no reverberation, i.e., T would equal zero. On the other hand, substitution of $\bar{\alpha}$ = 1 in Eq. (1) results in T = .05V/S which is some number greater than zero and therefore clearly wrong.

A more accurate formula that recognizes the discontinuous nature of the decay of the sound has been developed by Eyring, and is as follows

$$T = \frac{.05V}{-S \log_e (1 - \bar{\alpha})} \qquad (2)$$

Here V, S, and $\bar{\alpha}$ have the same significance as in Eq. (1), but now *it is necessary to calculate the average coefficient of absorption* $\bar{\alpha}$, since it is not simply multiplied by S as in Eq. (1). For long reverberation times (greater than 1 second) Sabine's formula is fairly satisfactory, but for small values of T, as are encountered in broadcast studios, etc., it is necessary to employ Eyring's formula in spite of its greater complexity. In this formula, if $\bar{\alpha}$ = 1, $(1 - \bar{\alpha}) = 0$, $\log_e(1 - \bar{\alpha}) = -\infty$, so that the fraction equals zero since the denominator is

*Eyring, Carl F.: "Reverberation Time in Dead Rooms," *Jl. Acoust. Soc. of America*, I, (Jan. 1930), No. 2, p. 217.

infinite. Thus T = 0 if 100 per cent absorption is present.

It will be of interest to compute the value of T for the previous example by means of Eyring's formula. The average value of $\bar{\alpha}$ was found to be 0.370. Substitution in Eq. (2) yields

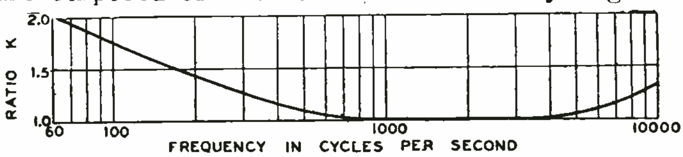
$$T = \frac{(.05)(30{,}000)}{-6200 \log_e (1 - .370)} = \frac{1{,}500}{-6200 \log_e .630} = \frac{1{,}500}{(-6200)(2.3)\log_{10} .630}$$

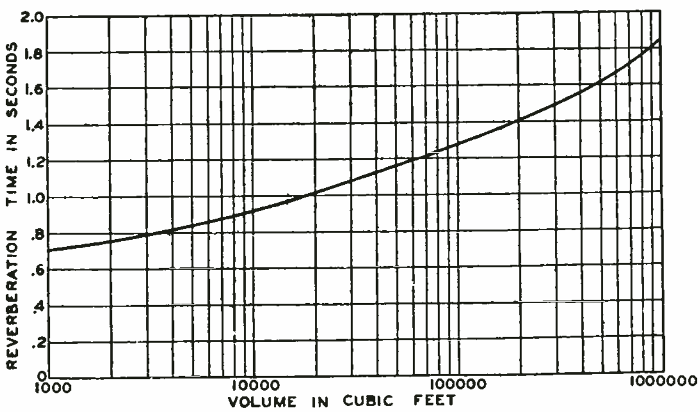
$$\doteq \frac{1{,}500}{-14{,}260\ (.7993 - 1)} = \frac{1{,}500}{(-14{,}260)(-.2007)} = 0.523 \text{ sec.}$$

which is 80.5% of the previous value of 0.653 second.

REVERBERATION TIME VS. FREQUENCY.--The calculations for T were made on the basis of 512 c.p.s. However, since speech and music are composed of a band of frequencies from about 30 to 15,000 c.p.s., it is clear that calculations at one frequency may be insufficient to determine the suitability of a studio or auditorium for speech or music. If the absorption of the walls varies with frequency, then T will become a function of frequency, and it may be necessary to adjust this functional relationship to obtain optimum results.

It has been mentioned in a previous technical assignment that the ear varies in sensitivity over the audio range, and exhibits maximum response at about 3,500 c.p.s. At very low and very high frequencies the sensitivity of the ear is much less. (The variation depends upon the intensity of the sound, and is a maximum for the thresh-





(Olson, courtesy of Elements of Acoustical Eng.)

Fig. 5.—Graphs showing relation between reverberation time and frequency and theatre volume at 1,000 c.p.s.

hold value.) The significance of this is that very low and very high frequencies will decay sooner from a given level to their higher threshhold values than the middle frequencies, so that their apparent reverberation time will be less. To offset this and make the reverberation time appear the same for all frequency components, it is desirable to increase the actual reverberation time for the very low and very high frequencies relative to the middle frequencies.

Optimum Reverberation Time-Frequency Curve.—A curve giving the relationship between reverberation time and frequency has been suggested by McNair. This is shown in Fig. 5 (upper curve). The lower curve shows the relationship between optimum reverberation time at 1,000 c.p.s. and the volume of the auditorium. It will be observed that the greater the volume, the higher is the reverberation time. This is because the ear has been so conditioned as to expect a greater reverberation time for a larger auditorium; the size of a room is in part judged by this factor.

The upper diagram gives the factor by which the reverberation time at any frequency *other than 1,000 c.p.s.* must be multiplied in order to give the optimum reverberation time at that frequency. The curves refer to a theatre auditorium. For a broadcast studio the optimum time will be lower, and the proper curves will be given farther on in this technical assignment.

Illustrative Example.—As an example of its use, suppose one has an auditorium 30 feet high by 50 feet wide by 100 feet long. It is desired to find the optimum reverberation time at 130, 250, 500, 1,000, 2,000, 4,000, and 10,000 c.p.s.

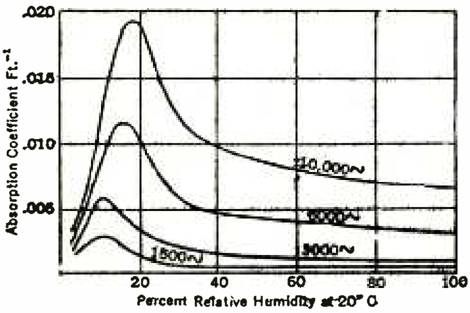
The volume of the auditorium is 30 × 50 × 100 = 150,000 cu. ft. The lower curve of Fig. 5 shows that the optimum time (at 1,000 c.p.s.) is about 1.35 second.

The factors for the other frequencies can be picked off from the top curve and are tabulated below. It will be observed that the maximum time is at 130 c.p.s., although there is also an appreciable rise at 10,000 c.p.s.

FREQ.	FACTOR	T
1,000	1	1.35
2,000	1	1.35
4,000	1	1.35
10,000	1.3	1.75
130	1.6	2.15
250	1.3	1.75
500	1.1	1.49

Discussion of Example.—The rise in reverberation time at the low-frequency end of the spectrum may be desirable for music, but may be undesirable for speech. This particularly is the case in broadcast studios and will be discussed farther on.

The rise in reverberation time at the high-frequency end of the spectrum is in general desirable for two reasons: the resultant increase in sound intensity at these frequencies tends to improve the articulation, since the intelligibility of speech depends in large measure upon its high-frequency components; and second, the air itself in the auditorium tends to be very effective in absorbing the high-frequency components, so that no assistance is required from the walls in this respect. This



(Pender and McIlwain, Courtesy Elec. Eng. Handbook)

Fig. 6.—Coefficients of absorption of sound in air containing different amounts of water vapor, for various frequencies.

absorption is a function of the humidity, and is illustrated in Fig. 6.

High-Frequency Absorption.—In order to take this effect into account at the higher frequencies, it is necessary to modify Eyring's formula as follows:

$$T = \frac{0.05\ V}{4mV - S\ \log_e(1 - \bar{\alpha})} \qquad (3)$$

where m is taken from Fig. 6 corresponding to the proper value of humidity and the frequency, and all other quantities have the same significance as in Eq. (2). In particular, $\bar{\alpha}$ refers to the average coefficient of absorption *of the boundary walls,* whereas m refers to the absorption coefficient of the atmosphere.

As an example, suppose one takes the case of the auditorium discussed previously, of dimensions 20 × 30 × 50 feet, and of volume = 30,000 cu. ft. Suppose the relative humidity is 60 per cent, and that the frequency under consideration is 10,000 c.p.s. The average coefficient of absorption for the walls, ceiling, and floor was calculated to be 0.370 at 512 c.p.s. Assume this coefficient is reduced to about 0.256 at 10,000 c.p.s. (the exact value of $\bar{\alpha}$ at 10,000 c.p.s. is unimportant).

The area was found to be 6,200 sq. ft. From Fig. 6, for 60 per cent humidity and f = 10,000 c.p.s., m has the value of about .008. Then

$$T = \frac{.05 \times 30{,}000}{4 \times .008 \times 30{,}000 - 6{,}200 \log_e(1 - .256)}$$

$$= \frac{1{,}500}{960 + (6{,}200)(2.3)(.1284)} = \frac{1{,}500}{960 + 1{,}831}$$

$$= .538 \text{ second}$$

Note that the air contributes more than half as many absorption units as the surface of the room, namely, 960 as compared to 1,831 sabines. Suppose the room surface was perfectly reflecting so that $\bar{\alpha} = 0$. Then $(1 - \bar{\alpha}) = 1$, $\log_e 1 = 0$, so that

$$T = \frac{1{,}500}{960 + 0} = 1.563 \text{ seconds}$$

While this is a fairly high reverberation time, it does represent appreciable damping in the room. Compare this with the previous example where with plaster instead of acoustic treatment on the room surfaces, the reverberation time went up from 0.523 second to 8.07 seconds (using Sabine's Formula).

If the volume is very large, then 4mV may be so much greater than $-S \log_e (1 - \bar{\alpha})$ that Eq. (3) will reduce approximately to

$$T = \frac{.05V}{4mV + 0} = \frac{.05}{4m} = \frac{.0125}{m}$$

In this case, for m = .008, T will be at least 1.563 seconds, i.e., a reverberation time no greater than 1.563 seconds can be obtained under any condition. Stated very broadly, at the higher audio frequencies the damping of the air itself holds the reverberation time down to a value on the order of one second in large auditoriums, even though the optimum time desired may be much greater than this. However, normally the damping of the air *predominates* only at supersonic frequencies, and at frequencies say below 1,000 c.p.s., this effect can be ignored in comparison with the damping of the room surfaces, and Eq. (2) used directly.

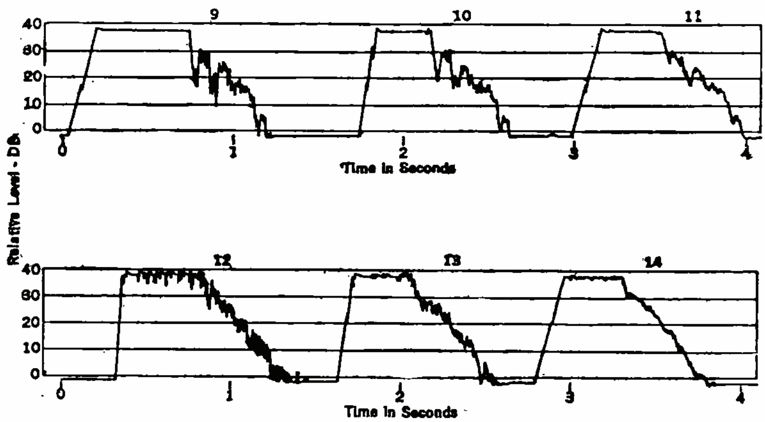
General Design Considerations.— In attempting to design a studio or auditorium that has the optimum reverberation time over the frequency range, one may find difficulty in obtaining an average coefficient of absorption that varies with frequency in the required manner. Acoustic treatment consists in replacing, in part, the hard, highly reflecting walls of the enclosure with absorbent acoustic material. As was illustrated in the previous problem, panels of acoustic material are used to cover at least part of the wall and ceiling area to an extent sufficient to obtain the desired reverberation time, say at 512 c.p.s. Whether or not the composite surfaces will then furnish the proper average absorption to give the correct reverberation time at other frequencies depends upon the variation in the coefficients of absorption of the various materials with frequency.

If this variation is not found to be that desired, other more suitable materials will be required in place of those chosen. A different amount of wall area may have to be covered, and the problem is essentially one of cut-and-try and hence rather tedious. There are available materials that have selective absorption over the frequency range. For example, one material may have a high value of absorption at low frequencies and a low value at high frequencies; another may have maximum absorption in the middle range, and a third material may absorb energy most readily at the high frequencies. In such a case, by the proper choice of area for each of these materials, an *average* coefficient of absorption may be obtained which varies with frequency in the desired manner. Again it is to be noted that the choice of area for each is found by a cut-and-try process, guided by intelligent guessing and previous experience.

Fortunately, most acoustic materials have a coefficient of absorption that varies with frequency in the right direction, i.e., the coefficient is a maximum in the middle range of frequencies. As a result, if the proper amount is chosen for optimum reverberation time at 512 c.p.s., similar calculations made at other frequencies will usually result in reverberation times that are not very different from the optimum values required at those frequencies. If such is the case the acoustic treatment may be regarded as satisfactory; if not, a redesign may be necessary in which selectively absorbing material is substituted in part for the original material in order to adjust the reverberation time in the requisite part of the audio spectrum.

DIFFUSION OF SOUND

IRREGULARITIES IN REVERBERATION CURVE.—The preceding theory and equations have all assumed that the sound was reflected from the walls in a completely random manner and that the reflections followed one another so rapidly that the build-up or decay in acoustic energy at any point in the enclosure followed a smooth curve, such as that portrayed in Fig. 2.



(*Pender and McIlwain, Courtesy of Elec. Eng. Handbook*)

Fig. 7.— Decay curves obtained with Bell Laboratories High-speed Level Recorder.

Actually the curves are in general very irregular, and have a shape illustrated in Fig. 7. These were taken by a High-speed Level Recorder made by the Bell Telephone Laboratories. In some cases one or more very pronounced humps may occur in the curve at certain discrete moments. Such a curve produces displeasing acoustical effects on the listener, and is therefore to be avoided. The cause of such an irregularity in the curve may be due to the following reasons.

Coupled Rooms.--Suppose the auditorium communicates through a door with another room that is fairly reverberant. It will take a certain amount of time for the sound from the second room to "drain" into the auditorium to which it is coupled, and in addition, before appreciable absorption begins most of the sound in the auditorium itself will have been absorbed. The result will be a decay curve such as that shown in Fig. 8. Portion AB represents the exponential decay of the sound intensity in the auditorium proper during the time t_0 to t_1. At t_1 sound from the adjacent room reaches the auditorium at a rate in excess of that capable of being absorbed by the latter so that the intensity rises from B to C. It then decays exponentially along the new curve CD.

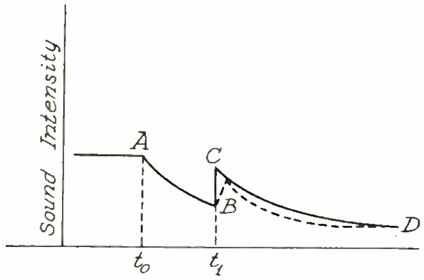


Fig. 8.--**Discontinuous decay obtained for two coupled enclosures.**

Actually sound from the adjacent room reaches the auditorium over an interval of time, so that the rise BC is more gradual. In addition, the sound is also decreasing in the adjacent room, so that the overall result may be a decay curve suggested by the dotted lines. Thus the actual decay curve may exhibit a peak at C instead of merely the beginning of a new exponential curve.

Another way of explaining the above phenomenon is to regard the two rooms as exchanging acoustic energy with one another. When the build-up of the sound during its establishment has reached an equilibrium or steady-state condition, as much energy flows from the auditorium to the other room as flows from the latter to the auditorium.

Upon the cessation of the actuating sound, the acoustic energy stored in the auditorium decays at a faster rate than that stored in the other room so that a time is reached when the flow of energy from the room into the auditorium exceeds that in the opposite direction. There consequently occurs a rise in the sound intensity in the auditorium, as shown in Fig. 8, with a new decay curve. From this latter viewpoint it is clear that such a discontinuity in the decay curve can be avoided if either the reverberation time in both rooms can be made the same, so that energy dies down at the same rate in both rooms, or else by some means the energy is interchanged so rapidly between the two enclosures that a thorough mixing occurs at all times. Since the configuration assumed--that of a connecting door--is not conducive to such thorough mixing, equal reverberation times would appear to be the only practical solution.

Effect of Balconies, etc.--In Fig. 9 is shown a theatre auditorium containing a balcony. If absorbing material is placed in the main portion of the enclo-

Fig. 9.--**Typical theatre having a balcony.**

sure, such as on the ceiling, then the space under the balcony will be relatively reverberent and will produce an effect similar to that described above. It is therefore advisable to make the region under the balcony as absorbent or more so than the auditorium proper, in order to have a smooth reverberation decay curve.

At one time studios were designed on the "live-end dead-end" basis. The portion of the room where the performers were located, such as the stage, was surfaced with relatively hard materials so that considerable reflection and reverberation occurred. This made the room appear "live" to the performers and made it easier for them to perform. The rear portion of the room was treated with more highly absorbing acoustic material so as to make this part of the studio more "dead". In this part of the room was placed the microphone, so that pickup here was more on the basis of direct sound from the live end of the studio rather than reflected sound from the walls close to the microphone.

Such a room tends to have an irregular reverberation decay characteristic, and may therefore not be satisfactory. It now appears more desirable to distribute the reflecting and absorbing surfaces more uniformly throughout the enclosure, and thereby avoid the above effect. This will be discussed shortly.

ECHOES AND WALL FLUTTER.--Another undesirable effect is that of echoes. An echo is a reflection that is delayed by an appreciable interval of time—about 1/16 second or more—after the direct sound has occurred. This corresponds to a difference in path length between the direct and reflected sound of about 65 feet, although a blurring of the sound has occurred even for a 50-foot difference in path length.

Focusing Effects.--In Fig. 10 is shown a possible construction

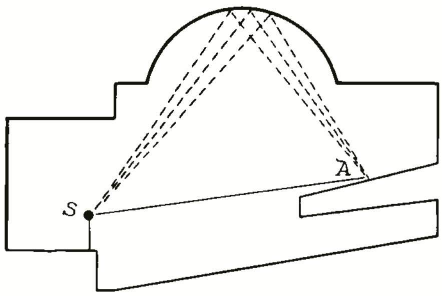


Fig. 10.--Focusing effect of a dome in an auditorium.

that will produce an echo effect. The dome in the ceiling has a focusing effect upon the incident sound and causes the sound to be concentrated at some point in the balcony denoted by A in Fig. 10. The dotted lines show the path for such reflected waves.

In addition there is the direct ray SA. If the difference between SA and the reflected rays is 65 feet or more, a distinct echo will be heard at A, and this produces a very distracting effect upon the listener. Another point is that if sound energy is concentrated by the dome at point A in the balcony, there will be less sound energy available in other parts of the auditorium. Furthermore, sometimes the direct ray is so spread out and therefore attenuated by the time it reaches the listener as to be very faint. On the other hand, the echo produced by a focusing effect, such as a dome, represents a concentration or convergence of sound energy. In such a case the echo may be louder than the direct sound, so that the listener hears the echo rather than the direct sound, especially for faint tones.

As a general rule, focusing effects are undesirable and should be avoided. This can be achieved by treating the dome-shaped portion heavily with acoustic material. Where the surface is a small portion of the total, such treatment is satisfactory, but where the surface area is a large fraction of the total, the damping introduced may be excessive with regard to reverberation time. Fortunately, dome-shaped ceilings are encountered mainly in large auditoriums and sound motion picture theatres, where a low reverberation time is in general desirable anyway. For example, in a large auditorium, Fig. 3 shows that when a sound reinforcing system is employed, maximum articulation is obtained when the reverberation time is zero.

Parallel Wall Reflection.-- Ordinarily rooms are built of rectangular shape, so that opposite walls, and the ceiling and floor, are planes parallel to one another. If the walls, for example, are 32.5 feet apart or more, (some claim even as near as 25 feet) multiple reflections in the form of flutter echoes will occur that are very annoying to the listener.

A general effect of an echo is to produce a rise or peak in the reverberation decay curve similar to that of two rooms coupled together. Wall flutter or multiple echoes produce a series of such peaks, i.e., standing waves are set up that modify the shape of the decay curve. The curves of Fig. 7 really illustrate such effects, but on a relatively small scale that is not too annoying.

Another effect is to prolong the reverberation time. If, for example, damping is present on the ceiling and floor, but not on two opposite walls, considerable sound energy can pass back and forth between the two walls without being appreciably absorbed by the ceiling and floor. Indeed, even if the opposite walls are treated with acoustic material, in the form of panels, but the latter are so arranged that hard surfaces on the opposite walls face each other, wall flutter may occur in the space between these hard surfaces, so that a microphone placed in this region will provide an unsatisfactory sound pickup.

METHODS OF DIFFUSING SOUND.-- The above all points to the need for diffusing the sound more thoroughly throughout the room. In laboratory measurements of acoustic material, rotating paddle wheels or vanes are often employed for this purpose, and in addition, the test sound is made to vary in frequency over a range of at least 100 cycles and at a rate of 4 to 5 per second in order to prevent standing waves that might occur if the pitch were held constant.

In an actual auditorium such means cannot be employed. Instead, diffusion must be obtained by making the reflections from the walls be entirely random in nature. This in turn is accomplished by breaking up the wall surfaces into irregular shapes, such as Vees or portions of a circle.

Use of Vee Serrations.-- The breaking up of the walls and ceiling into a series of vee serrations is illustrated in Fig. 11,

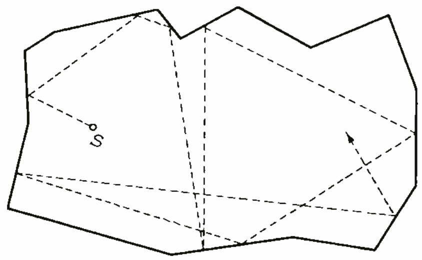


Fig. 11.-- Use of vee serrations in the walls of an auditorium to diffuse sound.

where a possible arrangement is indicated. Although such a variety of angles and lengths of flat surfaces are not ordinarily employed because of the peculiar effect that it will have on the appearance of the room, it is clear from the figure that any one ray of sound from a source S will have a very random path around the room. The totality of all rays will result in a very complete diffusion of the sound throughout the room, and the elimination of wall flutter.

One qualifying remark is necessary. Unless the vee serrations are of a size comparable to the wavelength of the sound, they will not tend to scatter the sound. For example, at low audio frequencies, such as 100 c.p.s., where a wavelength is $1{,}125 \div 100 = 11.25$ feet, the walls should jut out into the room a distance probably at least equal to $11.25 \div 4 = 2.8$ feet approximately. Vees of lesser depth will begin to act more nearly as flat surfaces, and specular (mirror-like), rather than diffuse, reflections will be obtained.

The large vees required for low-frequency diffusion are rather impractical from the viewpoint of appearance of the room (if it is small) and the waste space engendered, but probably the following practical consideration enters, and that is that low-frequency sound sources are much less directional than high frequency sources and hence inherently and initially spread the acoustic energy more uniformly through the room.

The reason for this is that musical instruments, for example, are more or less scaled to fit the human performer, and so a bass violin and a piccolo are not as widely different in size as are their frequency ranges. Thus a bass violin is not sufficiently large to act as a large source relative to the wavelength it radiates, and hence approaches a point source in furnishing nearly 360° radiation, while a piccolo is more nearly a large source relative to the wavelength it radiates and hence acts as a directional source of sound.

In actual studios the walls may be uniformly veed so as to present a more pleasing appearance. In some cases one wall will be veed and the other will be flat. Sometimes pilasters and other obstructions are employed to help break up and diffuse the sound. Usually, however, a non-uniform break-up is employed as far as possible.

The ceiling can be broken up quite readily by employing this as a means of concealing the lighting fixtures. This is illustrated in Fig. 12. In this way the ceiling acts as a foil for the floor, which must be flat, and thereby prevents flutter echoes between these two surfaces, as well as promotes diffusion.

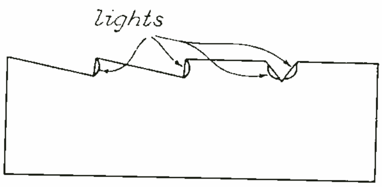
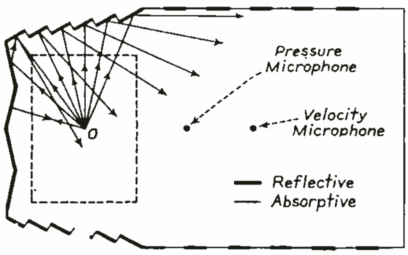


Fig. 12.--Break-up of ceiling to diffuse sound.

The absorbing material may be placed on all surfaces more or less uniformly, or it may be placed in panels on the vees so as to be opposite to a hard surface. This is illustrated by Fig. 13, which



(Michael Rettinger, Courtesy Comm. and Broad. Eng.)

Fig. 13.--Placement of absorption material in a studio so as to eliminate wall flutter.

shows a large radio studio. It will be observed that in the case of the flat portions of the side walls, absorptive material on one wall faces reflective material on the other.

Use of Circular Arcs.—Another method of diffusing the sound that has come into prominence is to make the walls in the form of a series of circular arcs. This is shown in Fig. 14. The arcs run vertically, like a series of columns intersecting one another. As a

Fig. 14.--Top view of a studio showing use of cylindrical arcs for walls.

variation, the arcs may be run in a horizontal direction, or even in an oblique direction, in order to obtain variety from one room to another. Very often the arcs are full semi-circles of a radius of 11 to 12 inches. Possibly the best arrangement for complete diffusion is to use polycylinders, as these are often called, in a vertical direction on one pair of opposite walls, in a horizontal direction on another pair of opposite walls, and in a direction perpendicular to the two above-mentioned sets on the ceiling, so as to have three mutually perpendicular sets of cylinders. These cylinders, furthermore, are often of various radii, and their cross sections may be various arcs of a circle.

There are several interesting features associated with this type of construction. The materials used may be plaster or plywood. In the latter case particularly, the wood acts like a diaphragm and absorbs sound energy impinging upon it and then re-radiates it. It therefore acts like a receiving antenna or array that intercepts electromagnetic energy, absorbing and re-radiating it. It will be recalled that the antenna responds best to a wave to which it is tuned, so that maximum current can flow in it.

In the same way the panel responds most strongly to a frequency to which it is resonant as a diaphragm. At this frequency it *absorbs* much more energy than at other frequencies, in spite of the fact that it might at first be thought that it would immediately re-radiate this energy as readily as it absorbed it. The reason for such good absorption will be evident from Fig. 15. Here an electrical

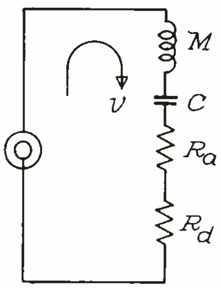


Fig. 15.—Electrical circuit equivalent to resonant wall.

circuit somewhat analogous to the mechanical characteristics of such a panel is shown. The inductance M represents the mass of the panel; the capacitance C represents the compliance of the panel; and R_a represents its acoustic radiation resistance, that is, the loading of the air surrounding it. Probably the surrounding air affects the inertia effect or mass M and the compliance C, but no special account need be taken of these additional and small effects. Finally R_d represents the internal frictional damping in the wood. This is not very great compared to the reactions of M and C although it probably exceeds R_a in magnitude.

When such a circuit is energized at its resonant frequency f_r, $j2\pi f_r M$ balances $1/j2\pi f_r C$, and a large mechanical current v (velocity) flows. This produces large power absorption effects in R_a and R_d, namely $v^2 R_a$ and $v^2 R_d$. The power $v^2 R_a$ represents energy initially absorbed that is re-radiated, i.e. reflected. But $v^2 R_d$ represents energy converted into heat energy, i.e. absorbed. It is clear from Fig. 15 that maximum absorption will occur at the resonant frequency.

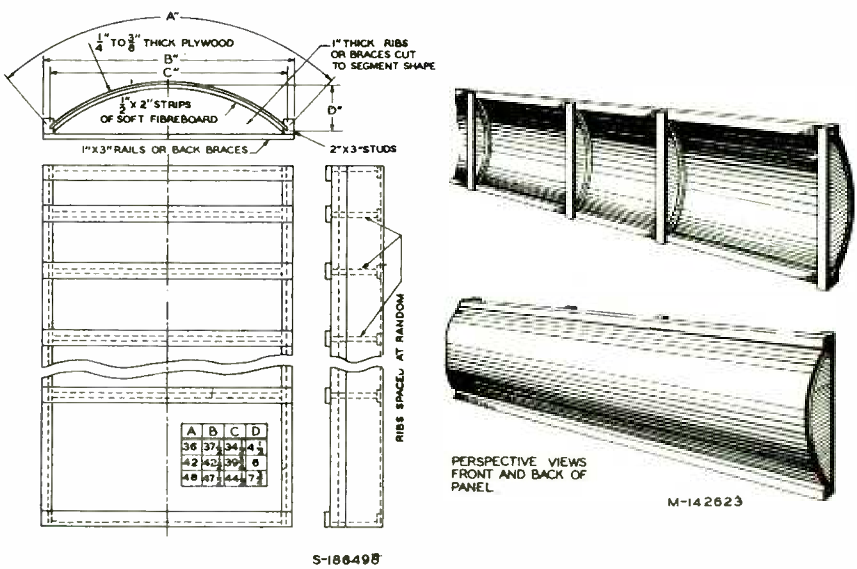
It would also seem that maximum reflection should occur at this frequency. This is not so because even at frequencies where the panel does not resonate, reflection of the sound wave can occur merely as a surface effect: the air particles bounce off the walls. Hence actually less *total* reflection occurs at the resonant frequency, and more absorption. This effect is utilized in many ways in acoustic problems and will be discussed farther on with regard to low-frequency absorption. Another effect considered important by many acoustic engineers is the re-radiation of the sound from the panels *after the incident sound has ceased.* This produces an effect similar to reverberation, but usually of short duration, and at the same time the re-radiated sound is widely dispersed. The reverberation effect is not considered as particularly harmful, and the dispersal of the sound, on the other hand, is considered beneficial, so that the re-radiation from such panels is deemed a desirable feature by many acoustical engineers.

The use of polycylinders

produces a decay of sound that is more nearly uniform, i.e., has less peaks and valleys. The reason is that the reflected sound is so spread out or diffused as to be unable to produce more than partial destructive interference with the incident sound at any point in the room, i.e., there are no marked standing waves produced in the room and hence no marked nodes and antinodes. This is an important point with regard to microphone placement in the room, as it permits the microphone to have more uniform pickup at all frequencies at all points in the room. In the case of a theatre auditorium, it makes all seats more satisfactory.

A further point to note is that sound is re-radiated from both the front and back of each cylindrical surface. That re-radiated into the hollow space within is often absorbed by placing rock wool inside the cylinder. Care should be taken not to have the rock wool touch the cylindrical surface itself, as it will tend to damp its vibration and prevent the diffusing effect mentioned previously.

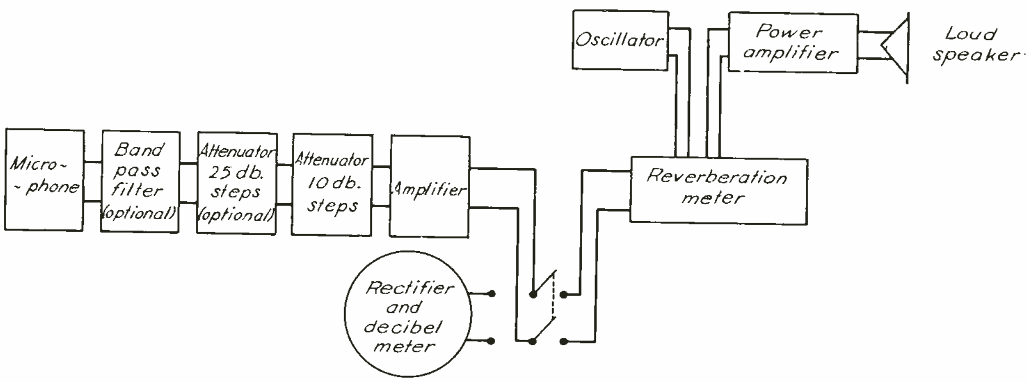
At this point, however, it will be shown how this property of absorption is utilized. The cir-



(Courtesy of RCA Review)

Fig. 16.—Constructional details of a polycylindrical wall.

cular panels are fastened on a series of frameworks as illustrated in Fig. 16. Here is shown a 4' x 8' plywood panel formed over curved segment braces and fitted at the edges with 2" x 3" strips which have been routed and held together with 1" x 3" back braces. The segment braces which must be spaced at random have strips of 1/2" Celotex or other soft fibreboard placed between them and the paneling to prevent rattles. These stiffening members cause the plywood areas between them to vibrate as individual diaphragms, and the irregular spacing causes these areas to have different resonant frequencies.



(Hale J. Sabine, Courtesy, Electronics.)

Fig. 17.—Equipment for measuring reverberation time.

Adjacent frameworks will have the stiffening members staggered with respect to the one shown. As a result of such a construction, panel areas are obtained that are resonant to a wide range of audio frequencies, particularly since each area in itself is resonant to a series of frequencies (multiple resonant effect of a diaphragm).

This type of surface therefore achieves two effects:

1). The convex curvature produces a dispersion of the reflected sound and hence fairly uniform diffusion throughout the enclosure. In connection with this it is to be noted that whereas a *concave* surface tends to produce focusing, a *convex* surface tends to produce the opposite effect, namely, dispersion, similar to the action of a convex mirror. Also the dispersion is not only of aerial sounds impinging upon the diaphragm, but also sound transmitted through the solid structural members of the room to the panel in question.

2). The multiple resonances of the entire surfaces produces a coefficient of absorption as high as 20 per cent from about 100 to 5,000 c.p.s. in the case of plywood panels. (Above 5,000 c.p.s. the air itself may be regarded as one of the major factors in producing absorption.) If the curved surface is made of plaster about 1 inch thick, then a rough figure is 20 per cent at the lower frequencies, tapering off to 10 per cent above about 200 c.p.s.

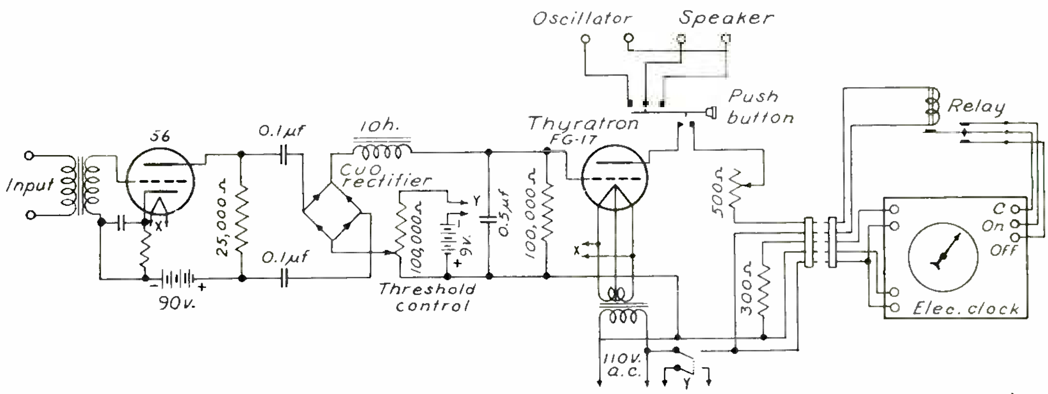
The exact values have to be determined by actual trial, and hence are a matter of experience. Indeed, it is to be stressed that acoustics is not an exact science, and that the design of a studio must be based to a large extent upon the previous experience of the designer. Nevertheless, the principles laid down here will furnish a valuable guide to such design, and a studio built according to these principles will be in general satisfactory.

MEASUREMENT OF REVERBERATION TIME.—There are several methods for measuring reverberation time. The following apparatus* is representative of one class of instruments. A block diagram is shown in Fig. 17. Essentially an oscillator, power amplifier, and loudspeaker act as a source of sound. This is turned on and after a few seconds, when the intensity of the sound has built up to its final, steady-state value, the arrangement is turned off. Automatically the reverberation meter is rendered operative, so that it can begin to record the sound decaying in the room.

*"Portable Reverberation Meter", H. J. Sabine, *Electronics*, March, 1937.

The diminishing sound is picked up by a microphone, extraneous noises (frequencies) filtered by means of the band-pass filter, if desired, and then the audio voltage attenuated to a desired degree and then amplified in the noise meter and fed to the reverberation meter. The noise meter is essentially a microphone, calibrated attenuator, amplifier, and output decibel meter. In Fig. 17 additional attenuation in 2.5 db steps is shown as well as the attenuator of 10 db steps that is part of the noise meter. The d.p.d.t. switch in the meter enables the external reverberation meter to be connected in place of the internal output meter.

The reverberation meter is shown schematically in Fig. 18. An amplifier stage is fed by the audio signal from the noise meter, and the output rectified and converted into a d.c. voltage. This acts in a positive direction to counteract the negative bias on a thyratron tube whose plate is fed with 60 cycles a.c. If the net negative bias on the thyratron is sufficiently low, the thyratron fires every positive half-cycle, current flows



(Hale J. Sabine, Courtesy, Electronics.)

Fig. 18.--Schematic diagram of a reverberation meter.

through a relay, which keeps the clock going.

When the sound decays to a certain threshhold value, the positive bias is unable sufficiently to counteract the thyratron negative bias, the tube ceases firing, and the relay shuts off the clock. The thyratron does not start firing until the loudspeaker source is shut off, owing to the action of the push button, so that the thyratron, relay, and clock are operative only during the period from the time the loudspeaker is shut off and the sound starts dying out, until it has died down to the predetermined threshhold value.

An initial adjustment of the negative thyratron bias, called "Threshhold Control," permits adjustment so that the ordinary noise in the room will not actuate the thyratron. To operate, the attenuators in the microphone circuits are set to a minimum so that this channel is in its most sensitive condition, and the Threshhold Control adjusted so that the thyratron just fails to fire.

The sound source is then actuated for a few seconds by means of the push button, and then the clock runs until the sound has decayed to a sufficiently low value so that the positive voltage output of the copper-oxide rectifier is unable further to keep the thyratron and clock operating. The elapsed time on the clock is noted.

Next the attenuator is set 10 db higher and the run repeated. In this case, when the sound has decayed to a value 10 db higher than in the previous case, the output of the noise meter and hence the d.c. voltage output of the copper-oxide meter will be of the same value as previously, because of the additional 10 db attenuation between the microphone and the noise meter. This means that the clock will now run for a shorter interval of time. If the sound fluctuates in intensity, the clock will operate each time the sound rises above the threshhold value, i.e., the elapsed time averages out the fluctuations.

Runs are made at increasing attenuation settings, and the latter are plotted against the corresponding elapsed times. The result is a curve such as that shown in Fig. 19. The attenuator

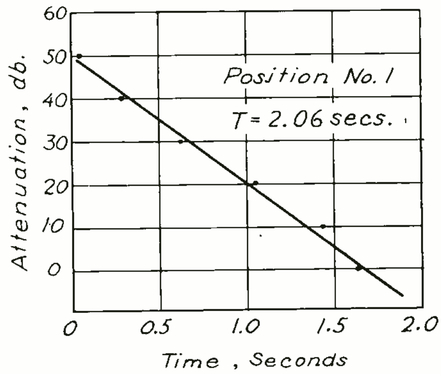


Fig. 19.—Relation between attenuation of a sound from a maximum level to some lower level, and corresponding elasped time.

db settings are the ordinates, and the clock readings are the abscissa. Each point on the curve represents the time it takes for the sound to die down from its initial value to a value so many db less. For example, the sound at the start (t = 0) is found to be 50 db (above some reference level not necessary to know). For the sound to drop down to 10 db, a decrease of 50 - 10 = 40 db, the decay time is approximately 1.4 seconds. The reverberation time, corresponding to a 60 db decay, or down to -10 db, is extrapolated to be about 2.1 seconds. Thus essentially only the slope of the line is required to give the reverberation time.

Readings are taken at various points of the room, since lack of complete sound diffusion may give different reverberation times at different points. Usually an average value is taken for the room. As stated previously, other forms of this apparatus are employed. For example, in one arrangement when the sound intensity has dropped to a certain value a neon tube just fails to flash. A clock closes a contact to the neon tube after a predetermined time. If the tube just fails to flash, the sound has decayed to just the threshhold value.

SOUND-ABSORPTIVE MATERIALS

GENERAL PROPERTIES.—A material that is sound-absorptive is one that converts the vibrational acoustic energy into heat energy. This material in general is required to absorb energy *from an incident air wave,* in contradistinction to the requirement of a phonograph pickup, for example, *where the vibratory energy of a solid material,* such as an armature, has to be absorbed by a material.

In the latter case a pad of rubber, or of a material known as viscoloid, is employed, and pressed against the vibrating member to absorb its energy. In the case of an air wave, the sound-absorptive material must extract the energy from the air in which it is immersed. Practically all such materials depend upon a cellular structure in which air is imprisoned so that it is not free to flow very readily.

Thus the sound energy from the outside air is transmitted to the enclosed air in the material partly through narrow passages or slits and partly through the solid material itself. In the previous technical assignment on microphones it was mentioned that in a narrow slit the air has relatively high viscosity and cannot be made to flow back and forth in such a slit without considerable friction. As a result the acoustic energy is converted into heat energy: the sound is absorbed.

Representative Materials.—A typical material used to a great extent for sound absorption is rock wool. This is a familiar material used in home insulation, and is made from rock that is melted and blown by steam into a floss or wool-like mass. There are millions of air cells enclosed in its fibres, and it is very effective in absorbing sound as well as acting as a heat insulator.

Another material that has found wide favor is Celotex. This is made from bagasse--the stalks and fibres remaining from sugar cane when it is processed into sugar. The bagasse is processed and pressed into sheets to form a wall board material. An important modification to the surface results in its becoming a very effective absorptive material: Circular holes are punched into its surface or clear through it of a size and spacing depending upon the particular characteristic desired with frequency.

This is illustrated in Fig. 20.

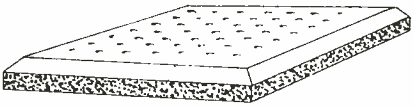


Fig. 20.--Celotex perforated acoustic tile.

Here a tile 12" x 12" is shown, into whose surface are punched as many as 441 small holes (21 per each direction). The holes may be 1/4 inch in diameter. The presence of these holes increases the absorption of the material. This is illustrated in Fig. 21,

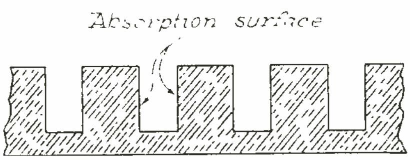


Fig. 21.--Showing how hole increase sound-absorbing surface.

which shows a cross-sectional view of the tile. The sound energy entering these holes is absorbed by their surface, and penetrates more deeply and effectively into the material than if no holes were present, and it impinged only on the surface of the material. This material, and others like it go under the trade name of Acousti-celotex.

A similar construction has been employed with rock wool. A tile made of metal whose surface is perforated is shown in Fig. 22 (A).

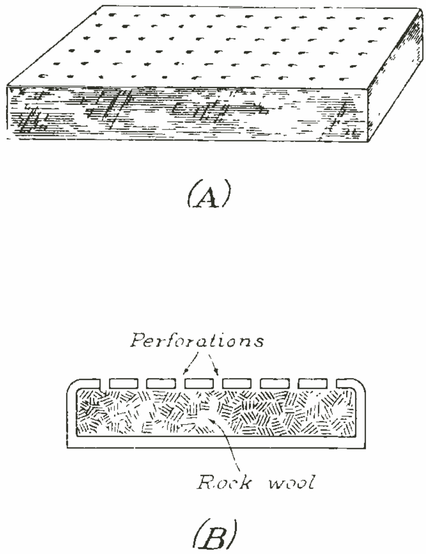


Fig. 22.--Acoustic tile composed of perforated metallic casing filled with rock wool.

The action is much the same, and in spite of the fact that a large part of the surface is of highly reflecting metal, the absorption is as good as for the rock wool by itself with its entire surface exposed to the wave.

The reason appears to be that directly over the holes the acoustic energy is absorbed and the sound intensity lowered. As a result, energy flows in from the regions directly above the metallic surfaces where the intensity is higher to the regions over the holes, i.e., the holes "suck in" energy from neighboring regions and therefore account for an amount of energy absorbed in excess of that directly in front of them.

Numerous other materials, such as cork, felt, balsam wool, asbestos fibre, and acoustic plasters, are available. Acoustic plasters are of special types that are very porous after setting, and thus absorb the acoustic energy in the form of viscous friction in these pores. The absorption characteristic of such plaster depends upon the composition, manner of applying, and drying. For example, if too much binder is employed, the plaster is not sufficiently porous; whereas if insufficient binder is used, the plaster does not set hard. The condition of the undercoating of plaster--whether it is too wet or too dry—also determines the action of the top coat of acoustic plaster. All this indicates that it must be applied by competent workmen.

In another type of construction, rock wool or its equivalent is applied to the surface to be treated, such as a ceiling area, in very loose form, so that it hangs at first somewhat like large cobwebs. It is then pressed up against the surface and forms a very porous, absorbent coating.

Similar to the acoustic tile previously mentioned is rock wool held in place by being laced or wired in, and then covered by a perforated sheet known as Transite. The latter is a composition of asbestos and portland cement. As in the case of the tile, the rock wool is the sound-absorbent, and the Transite, which can be painted, affords the sound wave access to the rock wool through its holes.

Practical Considerations.-- The choice of acoustic materials is governed as much by practical considerations of appearance, economy, etc. as it is by their sound-absorptive characteristics. Fortunately a fairly wide selection of materials is available that will meet the required specifications and still provide a pleasing variety in the treatment of the room.

Besides the sound-absorptive characteristics is the fire-proof qualities of the material. In this respect rock wool and similar substances are unexcelled, particularly when held in place by Transite sheets. Where the rock wool is held in place by cloth, the latter can be fire-proofed to a certain extent. In theatres velour curtains and drapes are often used both for their acoustic and decorative effect, and are fire-proofed as far as possible. Usually this means that they will burn in a flame, but go out when the flame is removed:

Another important characteristic is the adaptability of the material to cleaning and painting or other decorative possibilities. In this respect materials having holes in the surface, such as Acousti-celotex and acoustic tiles, are readily adapted to cleaning and painting. The painting covers the smooth surfaces, but ordinarily lacks the surface tension to bridge the holes. Since sound absorption takes place mainly through the holes, the covering of the smooth surfaces with paint, which forms a reflecting skin, does not impair the action of the material.

In the case of acoustic plasters, ordinary oil paints should be avoided since they tend to close up the pores through which absorption takes place. For such materials, and fibre boards, thin aniline dyes, gasoline or kerosene stains, thin lacquer sprays, and dry paint dusted on with a pounce bag are better suited as decorative mediums.

Other considerations are the vermin-proof qualities of the material, the amount of water it absorbs, its cost and ease of application, its durability and ease of application to the surface to be treated. In general, these factors about balance for most available materials, since the market is competitive, and any of the standard brands will be acceptable depending upon the requirements of the particular installation.

SPECIAL SOUND-ABSORPTIVE MATERIALS.--Many objects present in a room are of irregular surface, and appear in separate indivisible units. Reference is here made to persons and seats. Such objects have sound-absorptive properties, but are far too complicated in shape and surface to be calculated on the basis of a coefficient of absorption times the surface they present to the wave. Instead, they are regarded as presenting so many units or sabines of absorption.

For example, an audience, mixed, seated in theatre chairs having single padding on the back, have an absorption of 4.1 sabines per person at 512 c.p.s., and a chair having a plywood seat and back with the seat up, has an absorption of .24 sabine at 512 c.p.s. These units are added to those calculated for the walls--as shown previously in the examples given--to give the total number of units of absorption.

Minimizing Change in Reverberation Time.--The above brings out an important point in the design of studios, and particularly in the design of theatres and other auditoriums. The number of performers in a studio will have an effect upon the reverberation time, and hence must be taken into account. Fortunately, variation in the number of performers will not have a very large effect upon the reverberation time because a studio is generally well damped anyway in order to obtain the necessarily low reverberation time required, and the number of sabines contributed by the performers is not so very great compared to that furnished by the walls and ceilings, etc.

In the case of a theatre, however, the audience normally furnishes an appreciable part of the absorption. (The same can be true for a studio in which an audience is admitted, or for a studio that is used in an emergency for a larger number of performers than it ordinarily handles.) The difference in reverberation time for an empty and for a full house may be quite marked, and the sound quality may be quite different for the two cases.

Fortunately it is possible to use well-upholstered chairs that when empty have almost as high an absorption as that of persons sitting in them. For example, a chair with seat and back completely covered with thick mohair, has 3.5 sabines absorption at 512 c.p.s., and compares with the value of 4.1 sabines given above. As a result, a theatre so equipped has practically the same reverberation time regardless of the size of the audience, and hence has as good acoustic properties when empty as when full.

Another possibility is to construct the walls of the studio in such manner that hard-surface reflecting panels may be slid out from underneath absorbing panels to cover adjacent absorbing panels. Alternatively, panels may be arranged to be hard surfaced on one side and sound-absorptive on the other and suspended on hinges like a door. When opened up, they present a large reflecting surface; when folded under, they represent an absorptive surface. By this means the reverberation time of the studio can be altered to suit the number of performers or the character of the program or to meet any other requirement.

Practical Behavior of Sound-Absorptive Materials.—In the next section will be given a table of of sound-absorptive materials for use in the design of studios and auditoriums. The method of measuring the coefficients of absorption will be discussed at that point. While the values given in the table are correct for the method of measurement, and form a correct idea as to the relative merits of the various materials listed, it will be found that when these materials are actually employed in practice, the effective or actual coefficients of absorption are somewhat different, usually higher.

The reason seems to be similar to that mentioned for the perforated acoustic materials, namely, that if a panel of the acoustic material is adjacent to a more highly reflecting material, then the greater sound intensity in front of the latter causes sound energy to flow to the region in front of the sound-absorptive material, where the sound intensity is lower, and thus enables the sound-absorptive material to absorb more energy than its surface indicated under test conditions.

Another factor that influences the absorption, particularly at the lower frequencies, is the thickness of the material and the nature of the wall upon which it is placed. The action may be compared to that of a section of a transmission line having high internal losses, such as that owing to the series resistance of the wires.

This is shown in Fig. 23.

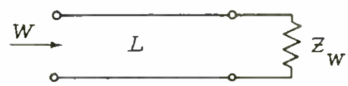


Fig. 23.—Equivalence of acoustic material mounted on a wall to a terminated transmission line.

Here L represents the section of high-loss line analogous to the sound-absorptive material, and Z_W represents the acoustic impedance of the wall. This may be complex, i.e., be comprised of mass, compliance, and damping. If the line is long when measured in wavelengths, which means, if the material is thick or the frequency is high, and the losses in L are high (material has high coefficient of absorption), then it is immaterial what the value of Z_W is, as even if Z_W is not equal to the characteristic impedance of the line (L mismatched), the high losses in L preclude any appreciable energy in the impinging wave W from arriving at Z_w (the wall) and being reflected therefrom, and of the small amount that is reflected at Z_w, only a negligible amount reaches the left-hand terminals to be reflected back into the room.

At low frequencies, however, the wavelength is long, and the amount of energy absorbed by L is small *because it is a small fraction of the wavelength.* In such a case the nature and magnitude of Z_w is important in determining the amount of reflection at the interface and hence eventually the reflection into the room. While an increase in the thickness of the sound-absorptive material will increase the amount of absorption in it (in L), nevertheless a prohibitive thickness of material may be found to be necessary at the lower frequencies--100 c.p.s. and below.

Instead, an expedient that has been found quite effective is to make the wall itself absorptive at this frequency by making it resonant in this range. Large wall surfaces will be inherently resonant at the lower frequencies. Their absorption can be increased by placing absorptive material behind them, such as rock wool. When this can be done, as in broadcast studios, it is found that the low-frequency absorption can actually be improved by making the sound-absorptive surface material thinner (L shorter). Thus this material functions effectively at the higher audio frequencies, while the wall itself serves to absorb the lower audio frequencies.

METHOD OF MEASUREMENT.—As in the case of reverberation time, there are various methods of measuring the coefficient of absorption of an acoustic material. A method that appears to approach the practical use of the material is to employ a highly reverberent room of say 10,000 cu. ft. or less. The walls are generally made of hard glazed white tile. The reverberation time of the room is first measured. Then an area of 72 sq. ft. or more is covered with the material to be tested, and the reverberation time again measured.

From these two readings the average absorption of the treated and untreated room can be calculated by substitution in Eyring's Formula, and then, from the known area of surface covered, the actual absorption coefficient of the material calculated. At frequencies above 2,000 c.p.s., however, the absorption of the air itself begins to mask the absorption effect of the material and makes the results less accurate. To improve the accuracy at *all* frequencies, a warble tone and rotating paddles are employed, as mentioned previously.

TABLE OF SOUND-ABSORPTIVE MATERIALS.—Table I, appearing at the end of this assignment, is a compilation of the absorptive and other pertinent characteristics of acoustic materials, and has been abridged in part from a booklet published by the Acoustical Materials Association, and in part from "Architectural Acoustics" by V. O. Knudson. The table is divided into subheadings such as Prefabricated Acoustical Units, Acoustical Plasters, Acoustical Felts, Wools, and Granulated Materials, etc. It can serve as the basis for estimating the properties of similar materials not listed, if these properties are not available from the manufacturer.

SOUND INSULATION

GENERAL CONSIDERATIONS.--Sound insulation is employed to keep sounds, considered generally as noise, out of an enclosure, such as an office, theatre, or studio. In the case of an office, where the windows must be kept open during the summer months, the outside noise cannot be prevented from entering. In such a case sound-absorptive materials in the office will help to absorb such outside noise, as well as noise generated within the office from typewriters, etc., and thus quiet the room. The decrease in noise effected by this means is quite marked, and the use of sound-absorbing materials in such places has been rather extensive. From this viewpoint any room treated acoustically to reduce its reverberation time will also experience a decrease in its noise level as well.

In the case of broadcast and sound-recording studios, it is necessary to isolate one studio from the other and from their respective control and client's booths. In this case there is more control over the noise transmission in that no windows are required in the studio (except for the control and client's booths), and air conditioning is employed instead. Hence noise may be more successfully prevented from entering the studio by transmission.

Permissible Noise Levels.--It is manifestly impossible to eliminate all noise from an enclosure, particularly from economic considerations, nor is it necessary to do so. The amount of residual noises that can be tolerated depends upon the function of the room, i.e.,--whether it is an office, or an apartment house, or studio, or reverberation room. As a unit of measure, 10^{-16} watt per sq. cm. has been agreed upon by the American Standards Association's Committee on Acoustical Measurements and Terminology as the reference level or 0 db. Noise is then measured as so many db

TABLE II

	DECIBELS	
	120	THRESHOLD OF FEELING
DEAFENING	110	THUNDER, ARTILLERY NEARBY RIVETER ELEVATED TRAIN BOILER FACTORY
	100	
VERY LOUD	90	LOUD STREET NOISE NOISY FACTORY TRUCK UNMUFFLED POLICE WHISTLE
	80	
LOUD	70	NOISY OFFICE AVERAGE STREET NOISE AVERAGE RADIO AVERAGE FACTORY
	60	
MODERATE	50	NOISY HOME AVERAGE OFFICE AVERAGE CONVERSATION QUIET RADIO
	40	
FAINT	30	QUIET HOME OR PRIVATE OFFICE AVERAGE AUDITORIUM QUIET CONVERSATION
	20	
VERY FAINT	10	RUSTLE OF LEAVES WHISPER SOUND PROOF ROOM THRESHOLD OF AUDITORIUM
	0	

above this level. Unfortunately most measurements that are available are based on the threshold of audibility, which corresponds to a sound intensity that varies with frequency and hence may be above or below the value given above, depending upon the frequency.

In Table II are given the intensity level of various sounds above the minimum audible intensity. Observe that the average auditorium is around 25 db above the threshold in level, whereas a sound proof room, such as may be used for reverberation or noise measurements, is less than 10 db in level above the threshold.

Factors Pertaining to Sound Insulation.--Sound insulation, like filtering in electrical circuits, can be applied to the source of the noise and to the space to be quieted with equal effectiveness. From a practical viewpoint it is often easier to insulate the room rather than the source of noise, although there are cases where an offending machine may be quieted with a minimum of effort and expense, such as by the use of spring mountings.

Sound is transmitted to a room in several ways. A very important form of transmission is through the air in holes and cracks in the walls and around doors. No matter how solid the wall may otherwise be, appreciable sound may come through such openings and ruin the sound-insulating qualities of the wall.

Sound may also be transmitted from the outside air to the wall and thence through it into the room. When a sound wave in air impinges on a solid wall, it experiences both reflection and refraction. The amount of reflection depends upon the difference between the acoustic impedance of the two media. The acoustic impedance of air is 42 dynes/cm./sec. for 1 sq. cm. or 42 mechanical ohms per sq. cm. The acoustic impedance of a brick wall may be thousands of times as great, and as a result the reflection will be very high owing to the impedance mismatch at the boundary surface. Normally the amount of energy that is refracted (transmitted) through such a wall from an air-borne sound is about one-millionth of the incident energy, and hence negligible.

For thinner partitions, such as glass windows, or for extremely loud sounds or extremely large attenuation, this effect may be of some consequence. A very effective means of increasing the attenuation effect is to provide several impedance mismatches in series. Thus the use of two thinner walls with an air space between them, or felt or rock wool in between, will generally give more attenuation than one thick wall. A preferred method for studios is to employ two 6-inch cinder block walls, with about 12" spacing between them. The latter space is not entirely wasted, as ducts can be run through it. The cinder block walls, owing to their porous nature, absorb very effectively the sound penetrating them, and this--in conjunction with the impedance mismatch effect--produces very effective sound insulation.

In special cases the surface may be resonant to frequencies in the audio band, and thus have an acoustic impedance at these frequencies more nearly equal to that of the air. In such an event much less of the sound energy will be reflected. Of the remaining large portion, a certain amount will be absorbed in the material, as has been discussed previously, but the rest will be transmitted into the enclosure. Such resonance effects are mainly noticeable at the lower frequencies, say below 100 c.p.s., and make the insulation of such components somewhat more difficult to accomplish.

Finally there is the generation of sound vibrations directly in the solid material, such as by the impact of a footstep upon a floor, and the transmission of such vibrations, with little attenuation, through the rest of the building. These vibrations may thereupon act upon a large surface, such as a floor, which will function as a fairly efficient diaphragm, and radiate appreciable sound into an enclosure. It will therefore be of interest to see more directly how sound insulation for the various types of transmission described above is accomplished in practice.

ISOLATION OF VIBRATION.--Some methods of sound insulation have been indicated above. It will be observed that a partition may insulate by reflecting or by absorbing the incident sound wave. Generally it is not feasible to try to absorb the vibration, at least completely, because a prohibitive thickness of material will be required. On the other hand, if a highly reflecting material is used, it is clear that this will reflect equally well from both sides, and while it will prevent appreciable sound from entering the enclosure, it will also increase the reverberation time therein to a prohibitive figure. Hence, in general, acoustic design requires an intelligent combination of the two methods of attack.

Machine Vibration.--As stated previously, where insulation can be employed at the source, it is very effective. This is particularly true of machine vibration. If this vibration is permitted to get into the building structure, it may enter the enclosure to be insulated, such as a studio, through such diverse channels as building members, water pipes, ventilators, etc. In such a case it is highly desirable to isolate the vibration at the source.

In Fig. 24 is shown a machine

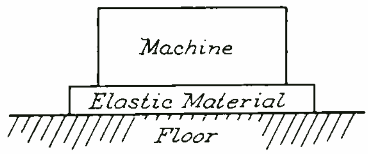


Fig. 24.--Use of elastic material to isolate machine vibration from floor.

that generates vibration when in operation, separated from the floor by means of an elastic material, such as cork, rubber, or felt. The action may be represented by an equivalent mechanical diagram and its electrical analogue, as shown in Fig. 25 (A) and (B). The machine may be regarded as a mass m that transmits its vibration to the floor of mass M through the compliance C and resistance r, (frictional effects) of the elastic material. The "give" C and friction r of the material prevent the vibration of m from being transmitted completely to M, so that M is shown as *shunting* C and r in Fig. 25 (B). The voltage e represents the mechanical forces in the machine that produce the vibration.

If e is of the frequency at which C and M resonate, the branch current (velocity) through M may exceed that in m, i.e., the

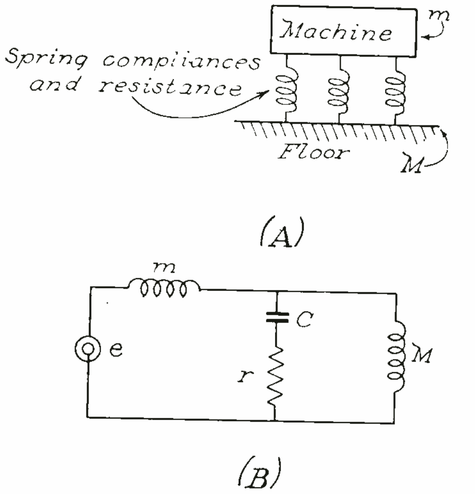


Fig. 25.--Electrical analogue of machine isolated from floor.

vibration in the floor is greater than if the machine were resting directly on it. However, if the isolating material is sufficiently elastic (compliance C is high), then e will be above the resonant frequency, and the amount of vibration transmitted into M will be very small. While simple formulas are available to calculate the the amount of attenuation, the difficulty in practice is in determining the actual effective mass M of the floor.

It is sufficient to note here that if the material is made compliant enough, very little vibration will be transmitted. The effectiveness of the material depends directly upon its thickness and inversely as its area. Twice the thickness provides twice the deflection for a given amount of force and hence twice the compliance. On the other hand, twice the area means half the *pressure* for a given amount of force, and hence half the deflection and consequently half the compliance. This means that high compliance is obtained *by using a small area of thick isolating material*, i.e., by loading it heavily.

Unfortunately, most materials available for the purpose cannot withstand more than a certain amount of pressure without ultimately breaking down. In Table III is given the safe loading for various materials. If the loading exceeds the above value, then continuous settling will occur over a period of time to an undesired extent, and the compliance of the material will decrease, thereby decreasing the sound insulating qualities. This will be discussed further with regard to the floating room construction employed for studios.

A further point to note regarding machine vibration is that certain forms of isolators are available in which the support is at certain fixed points. A typical form is shown in Fig. 26. A cir-

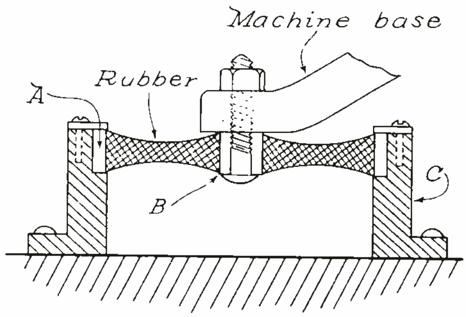


Fig. 26.--One form of vibration isolator.

cular rubber web is firmly vulcanized to an outer ring A and an inner ring B. The inner ring B is bolted to the machine base, and the other ring A rests in a holder C which is fastened to the floor.

cast and sound recording studios. The latter are built in the form of a shell that floats on the building proper on a series of springs,

TABLE III

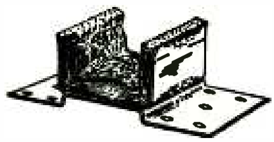
Material	Description of Material	Approx. Upper Safe Loading lbs./sq. in.
Corkboard	1.10 lb. per board ft	12
Corkboard	0.70 "	8
Flax-li-num	1.35 "	4 to 6
Celotex	Carpet lining	10
Celotex	Insulating board	12
Insulite	"	15
Masonite	"	15
Anti-vibro-block		5
Sponge Rubber	25 lb. per cu. ft.	1 to 3
Soft India Rubber	55 lb. per cu. ft.	3 to 6
Hair Felt	10 "	1 to 2
Punched Felt	10 "	35 to 40

The compliance involved is that of the rubber web acting in shear, and the viscosity of the rubber furnishes the resistance or frictional reaction. The electrical analogue in Fig. 25(B) applies equally well to this device, as well as the remarks above. The isolator comes in various sizes to carry various weights, and has the advantage over the flat slabs of material shown in Fig. 25(A) in that it more securely holds the machine in place under all conditions.

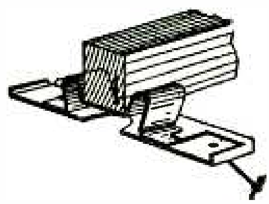
Building Vibration.--The arrangements shown in Figs. 25 and 26 for insulating the building from the vibrations of the machine can be used just as well in reverse fashion to isolate a room in a building, such as a studio, from the building vibrations. This method is in general used for broad-felt, or cork.

As an example of this, the floor is supported on the main concrete slabs on springs or felt cushions as shown in Fig. 27. In the case of the Johns-Manville floor chairs, the wooden sleepers, on which the flooring is nailed, rest in the felt pads of the chair. In the case of the United States Gypsum Company's method, the sleepers are supported on bent spring clips. The walls and ceiling are similarly supported. Often the intervening space is filled with some light sound-absorbing material such as mineral wool to prevent resonances in these spaces, particularly in the case of floors.

One precaution mentioned previously must be exercised, especially in the case of felt or cork supports: the loading must not exceed the safe working values, or else the compliance of the member and hence the attenuation will de-



Johns-Manville Floor Chair



U. S. Gypsum Company's Method
(Pender and McIlwain, courtesy Elements of Eng. Handbook)

Fig. 27.—Method of isolating floor of studio from building vibration.

crease with time. The construction illustrated above can be made to provide attenuations of 60 db to sounds as low as 64 c.p.s., and at higher frequencies the attenuation is much greater.

A practical note of caution is necessary here: the measure described above will be successful is decreasing the sound transmission in any building, but the amount of attenuation may be insufficient if the building is inherently noisy. For example, it is extremely unwise to locate a studio in a building in which there are printing presses or other heavy machinery operating. The vibration and rumble set up by such machines is well-nigh impossible to attenuate to a satisfactory degree; in short, the location must be in a building that is inherently quiet.

Similarly, the above measure may prove unsuccessful in some particular instance, such as noise transmitted through a water pipe. Stiffening the pipe by suitable braces may eliminate the noise at one point only to have it appear at some other point instead. Moreover, the water within the pipe itself can be a very good conductor of noise, and is hardly amenable to acoustic treatment.

Sometimes an undesirable noise appearing in one studio, that is generated in another studio, may be present, and when suitable means, such as above, are taken to eliminate it, undesirable noise may occur in another studio appreciably removed from the source, because of a change in the transmission through the building structure. Such troubles, when they arise, can be very baffling, and must be attacked individually. Nevertheless, the general method of building a studio as a box within a box is justified, in spite of the expense, in that it helps increase the sound insulation, even though at times it may not be the complete solution to a noise problem.

WINDOWS, DOORS, ETC.—Generally windows in a studio facing the outdoors can be eliminated and air conditioning employed instead. Nevertheless windows are required between the control and client's booths and the studio proper, and doors are required for entrance and exit to these rooms. Finally, the ventilating and heating system itself for the various studios and booths is fed from a central point, and sound originating in one studio may reach another via the circuitous path of the ventilating ducts. Adequate protection must be provided to prevent transmission of sound through the windows, doors, or ducts, as well as through the walls, themselves.

Use of Multiple Windows.--The method of impedance mismatch discussed previously is of value in decreasing the attenuation through a window. The latter is constructed of two or three panes of glass, of different thickness, and having air spaces between the panes. The panes themselves are suspended in felt or other absorbent material so that the where an earlier form of construction using three panes of glass was employed. More recent practice is to use two panes, one 5/8-inch and the other 3/8-inch thick. The different thicknesses insure the various panes of glass from being resonant at the same frequency. thus, sound striking the first pane is in part reflected and part transmitted as well as absorbed. (The absorption in a material like glass is normally small.)

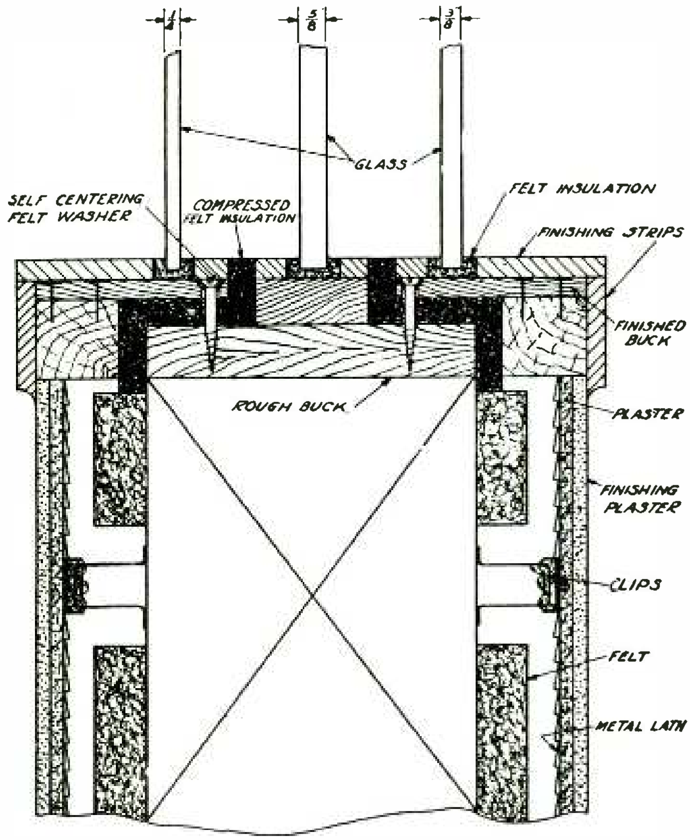


Fig. 10—Soundproof window construction.

(O. B. Hanson and R. M. Morris, Courtesy Proc. of IRE)

Fig. 28.--Use of multiple windows to prevent sound transmission between studio and control booth.

vibrations of one pane will not be transmitted to the next through solid contact with the surrounding frame. This is illustrated in Fig. 28, The amount transmitted will be greater at the resonant frequency of the pane, but now another reflection occurs at the inner surface between the pane and the enclosed air, so that some of the sound wave in the glass returns to the outer surface. Multiple reflections take place in the pane of glass at the outer and inner surfaces, but the amounts that leave the inner surface after the first reflection at that point are relatively small. Hence consider the fraction that gets through both surfaces of the first pane of glass.

This fraction of the original incident energy must now pass through the second pane. Similar reflections occur from both surfaces of this pane, and the amount that finally gets through two or more panes is very small, particularly since one or the other of the panes is not resonant at the frequency under consideration, and hence presents a high mechanical impedance to the wave trying to vibrate it.

As stated above, two panes are generally now deemed adequate. They are double glazed to prevent airbourne passage of sound through any cracks, and set in felt in the main frame. The latter is also lined with felt to decrease the sound transmission and to prevent any resonance of the confined air volume. The attenuation of such a construction is comparable to that of the walls themselves.

It has been found advisable to afford equalization of the barometric pressure between the windows, apparently to prevent clouding of the inner surfaces, which are normally inaccessible. Such equalization is furnished by a vent to the studio proper in the form of a pipe. The pipe is filled with acoustic material so as to attenuate any sound waves that try to get into the intervening region between the panes via the pipe. Such absorbing material, however, offers practically no opposition to the slow flow of air required for barometric equalization.

Construction of Doors and Vestibules.--It is in general cheaper to obtain the desired attenuation for doors by the use of two doors and an intervening vestibule than by the use of a single door alone. In addition the vestibule affords a kind of sound lock, so that even if a person enters the studio either from the outside or from the control booth, at no time is the studio completely connected to the other enclosure.

As an example, in the NBC studios to be discussed in more detail farther on, two doors are employed, each of solid wood 2-5/8 inches thick, and provided with sponge-rubber gaskets on head and sides to seal the edges and thus prevent sound leakage. They also have automatic door closers of sponge rubber to seal the gap at the sill. The intervening vestibule is acoustically treated to help absorb the sounds coming through either door. As a result, the attenuation through such doors and vestibules is even greater than that of the studio partitions themselves.

Ventilating Systems.--As mentioned previously, air conditioning is normally employed in the studios. The air conditioning equipment feeds the studios by means of ventilating ducts. These could be designed so that a main duct proceeds from the central plant to the nearest studio, from thence to the next, and so on. It is clear that this would require a minimum of duct, but also that the length of duct between any two adjacent studios would be so short as to permit entirely too much acoustic coupling between the two.

For this reason a more expensive arrangement is employed in that each studio is connected to the air conditioning through individual and independent ducts. For sound to flow from one studio to another it must pass through the two separate ducts in series; a much longer path.

In addition, sound-absorbing material is placed in each duct for part of its length to reduce the intensity of the transmitted sound to a satisfactorily low level. The material used is often a kind of grass (ell grass) known as Cabot's quilt. It is arranged in the form of a cellular construction, and is of a length of about 16 feet from the point where it enters the studio. In addition, where the duct pierces the studio partition, a double

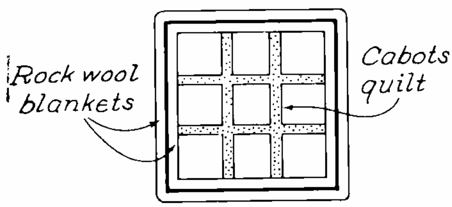


Fig. 29.--Arrangement of acoustic material in ventilating duct.

wrap of paper-covered rock-wool blanket is employed around it. The construction is illustrated in Fig. 29.

STUDIO DESIGN

SPECIAL CONSIDERATIONS.-- The previous discussion has covered the general considerations pertaining to acoustic design, together with such calculations and curves as apply more generally to auditoriums and sound motion picture theatres. Often these are existing structures whose acoustic properties have to be modified to render them satisfactory for sound production or reproduction. Such modification will of necessity consist mainly of the addition of acoustic treatment, rather than any important structural change to obtain better sound diffusion or insulation.

In the case of broadcast and sound recording studios more latitude in the design is in general possible since the design ordinarily precedes the actual construction. Moreover, the requirements are normally more stringent, and economic factors are generally not as important since the earning ability of a studio may be high compared to its first cost. As a result the construction can embody the features mentioned previously as regards shape of wall surface, floating room construction, and the like.

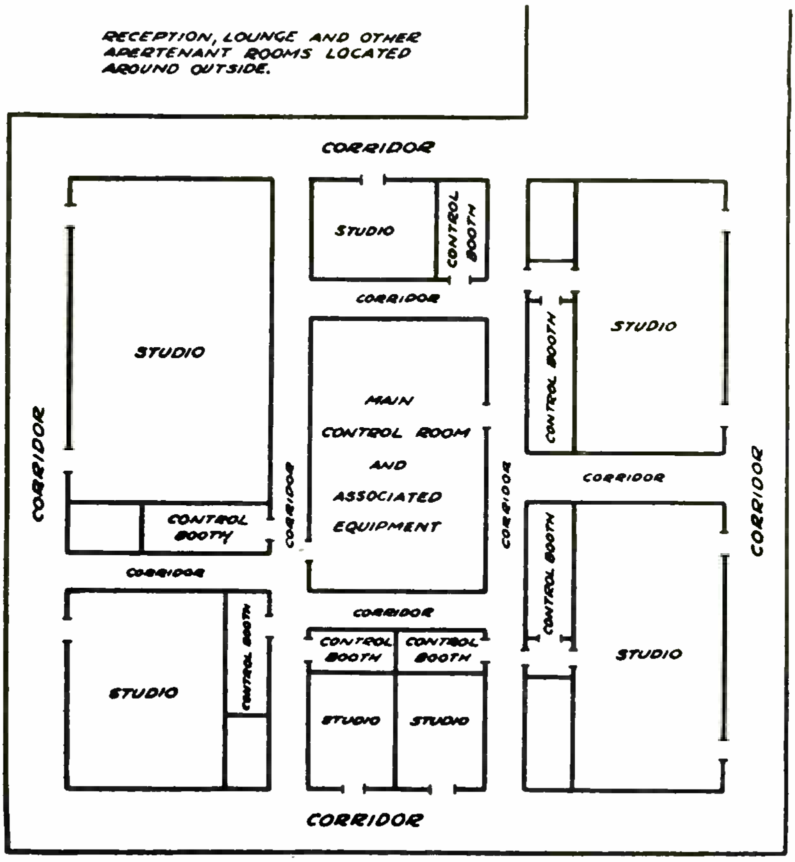
Studio Location and Layout.— The requirements for broadcast studios were discussed in a fundamental paper by O. B. Hanson and R. M. Morris* as long ago as 1931, and the statements made there are still applicable. In the first

*"The Design and Construction of Broadcast Studios," O. B. Hanson and R. M. Morris, *I. R. E. Proc.*, Jan. 1931.

place, it is desirable that the studio building be located in that part of the metropolitan area that is most accessable to artists, and on a street well known to the general public.

The building should have large clear areas unobstructed by columns if large studios are required. In a skyscraper this generally means the upper floors since the steel spans required for support of the upper stories would make a lower floor location too expensive. The upper floors of a loft building are usually satisfactory, but care must be exercised to see that no heavy manufacturing work is done in this building, as adequate sound insulation may be impossible to obtain.

There must be adequate power facilities for the required electrical load. Overhead lighting is most desirable, and about 20 foot candles is required to enable the musicians to read their music without requiring auxiliary lights entailing floor cords, etc. In a television studio the lighting load is particularly severe, and 60 kw per studio for this purpose is not unusual.



(O. B. Hanson and R. M. Morris, courtesy Proc. of I.R.E.)

Fig. 30.--Floor plan of a suggested studio layout.

The actual studio layout should be such that artists and members of the production staff can use separate corridors and exits, so as not to impede each other's progress. A suggested floor plan is shown in Fig. 30. The main control room is in the center. It is surrounded by studios and their associated control booths in such manner that the booths are accessible to the main control room and to the technical personnel.

Around the periphery of this floor plan are corridors and doors leading to the studios for the artists and performers. In this way interference between the two groups of personnel is reduced to a minimum.

It will be observed that each studio is surrounded by corridors and does not abut on another studio. Thus impedance discontinuities in the form of corridors are provided to increase the sound insulation between the various studios. More complicated layouts are illustrated in the above-mentioned article, but in any actual design special requirements are generally present, such as building shape, cost, etc., that serve to determine the actual layout, and the example shown in Fig. 30 will furnish a model for such work.

Studio Dimensions.—Experience indicates that from acoustic as well as esthetic or artistic considerations, the studio dimensions should have the ratios of 2-3-5 for the height, width, and length, respectively. For sound motion picture recording studios recent tests have indicated ratios of 2-3-4.8, which are practically in agreement with the values given above.

The size of the studio is closely dependent on the number of performers to be accommodated, as well as the size of the audience, (in the case of the audience type of studio). For the former type, the volume of the studio, rather than its surface, is determined by the number of performers, as follows:

$$V = KN \qquad (4)$$

where V is the volume in cubic feet,
K is a constant whose value is 750,
and N is the number of artists for normal capacity.

The minimum height h should not be less than 8 feet. In view of this and the relationship between the three dimensions, there is finally obtained

$$h = 5.87 \sqrt[3]{N + 2.5} \qquad (5)$$

As an example, suppose it is desired to design a studio for eight performers. Then, from Eq. (5)

$$h = 5.87 \sqrt[3]{8 + 2.5} = 5.87 \sqrt[3]{10.5}$$

log 10.5 = 1.0212; 1/3 log 10.5 = .3404; anlg(.3404) = 2.19 so that h = (5.87)(2.19) = 12.88 feet

The width will then be

$$w = (3/2)h = (3/2)(12.88) = 19.32 \text{ ft.}$$

and the length will be

$$l = (5/2)h = (5/2)(12.88) = 32.2 \text{ ft.}$$

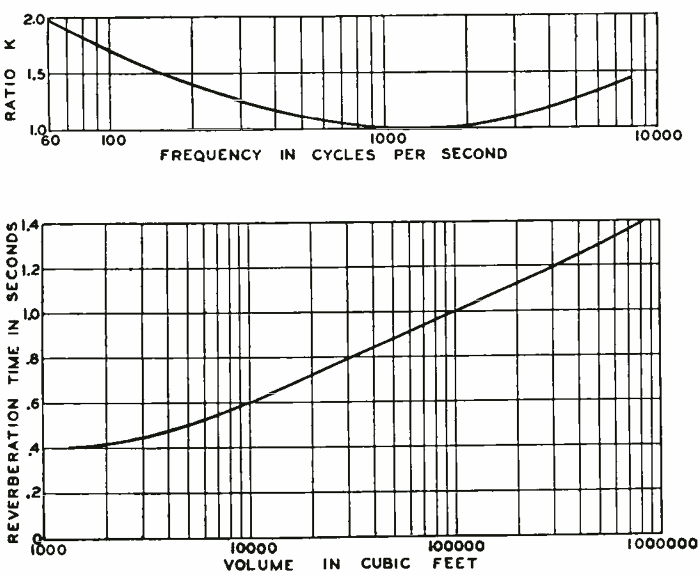
The volume will be

$$V = (12.88)(19.32)(32.2) = 8{,}000$$ cu. ft.

It is understood, of course, that the actual room dimensions will not have to be exactly those calculated by Eq. (5), but will be determined to a large extent by other considerations. Nevertheless, the proportions of a studio should not depart too greatly from those given above.

Reverberation Time—Studios.— The optimum reverberation time for for a broadcast studio is roughly about two-thirds that for an auditorium. This is because essentially two enclosures are involved: the studio and the room in which the receiver is placed, and in addition, the question of monaural pickup in the studio is involved. In Fig. 31 is given the optimum reverberation time vs. volume for broadcast studios, as well as the factor by which the 1,000-cycle reverberation time must be multiplied to get the optimum time at other frequencies. For example, in the case of the studio for eight performers just calculated, the optimum time is about 0.56 second for a volume of 8,000 cu. ft.

Broadcast studios are used mainly for speech purposes, even though musical selections comprise an appreciable portion of the program content. On the other hand, recording studios are mainly for musical recordings. As stated previously, the optimum reverberation time for music is in general greater than that for speech, hence for recording studios, the above values of the lower graph of Fig. 31 can be multiplied by a factor of 1.3.



(Olson, Courtesy El. of Ac. Eng.)

Fig. 31.--Relation between optimum reverberation time and volume of a broadcast studio.

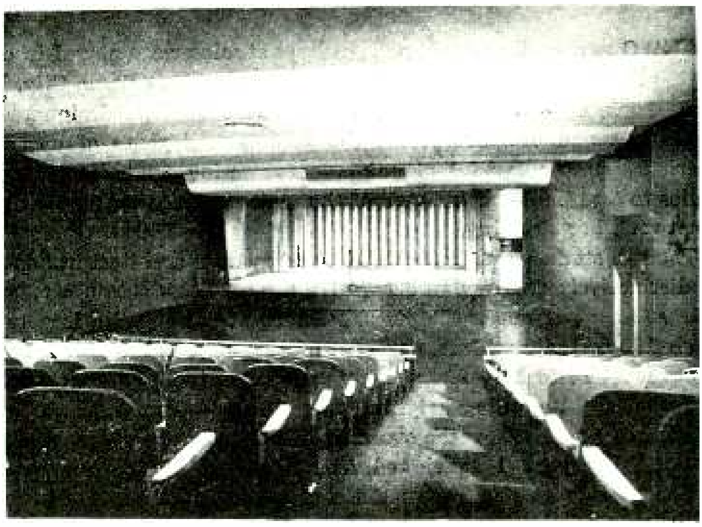
In the case of television studios, a value of 0.5 second is in general desirable. This is because the set itself may be "hard" and may therefore increase somewhat the reverberation in its enclosed volume. A similar value is indicated for sound motion picture studios, since the requirements are practically identical.

In passing, it is interesting to note that in many foreign countries, such as England, Belgium, Germany, etc., engineers prefer a reverberation time that is about 50 per cent higher than the values given in Fig. 31.

EXAMPLES OF STUDIO DESIGN.—It will be of interest at this point to examine some modern examples of studio design, so as to note the methods of sound isolation, sound dispersion, and sound absorption, as well as other factors involved.

NBC Studios 6A and 6B.*—The first example will be two auditorium-type broadcast studios, 6A and 6B, that were placed in operation in November, 1941 at Radio City, New York. These are similar in design but distinctively different in decorative treatment to obtain a pleasant contrast in appearance. The psychological effect of a studio is an important factor in influencing the performance of the artists, and must not be ignored.

The overall length of each is approximately 100 feet; the width averages 48 feet; and the ceiling height varies from 13 to 19-1/2 feet. The stage section is 37 feet deep and 45 feet wide, with a ceiling height varying from 13 to 16 feet.



(George Nixon, Courtesy RCA Review)

Fig. 32.--NBC Studio 6A as viewed from the rear.

A view from the rear of Studio 6A is shown in Fig. 32. Note particularly the manner in which the ceiling is broken up to provide for sound diffusion and to conceal the border lights and "spots" from the eyes of the audience. It will also

*See "NBC Studios 6A and 6B," G. M. Nixon, *RCA Review*, Jan. 1942.

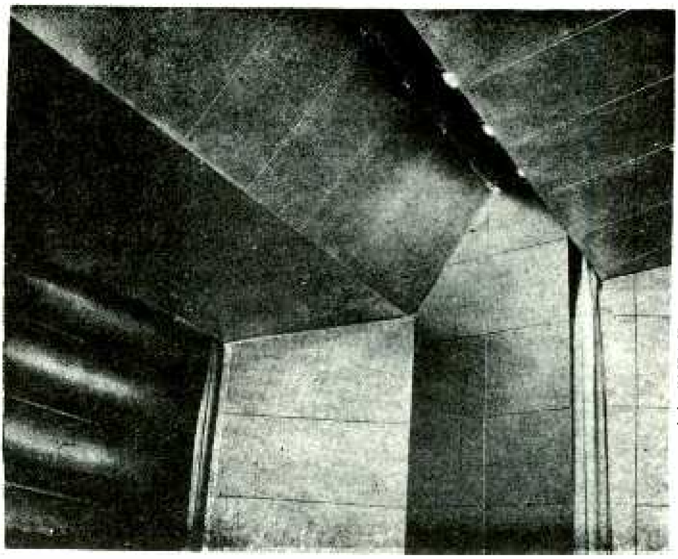
be observed that the rear (stage) wall is broken up into vertical semi-cylinders of plaster that act to absorb as well as to diffuse the sound.

An audience of about 450 can be seated in either studio, and the upholstered chairs provide about the same amount of damping as the audience, so that the reverberation time of the empty studio is about the same as that with a full audience. About 150 of the front seats are removable so that the stage may be enlarged or the space otherwise used for large performing groups.

Note also in Fig. 32 that one wall is flat, and the other is deeply "veed" in flat sections of wall, each 4 feet wide and 2 feet deep. Note also the control booth window to the right, and the window of the client's booth, also to the upper right.

Fig. 33 shows the detail of the stage and ceiling of Studio 6B. It will be observed that in contrast to Studio 6A, the rear wall here consists of horizontal plaster semi-cylinders, although the effect is the same as for the vertical semi-cylinders of Studio 6A. Note also the serrated ceiling construction, arranged so as to conceal the stage lighting from the audience, and the method of concealing the draperies in "curtain pockets." These draperies can be drawn across the stage as a stage curtain, thus heightening the effect of a theatre performance.

The color schemes of the two studios are of interest. Studio 6A has walls and stage ceiling of a rich warm copper color, while the chairs are of a dark-green upholstery, and the flooring has a carpet laid on a rubber covering. Studio 6B, on the other hand, has



(George Nixon, Courtesy RCA Review)

Fig. 33.—Detail of stage and ceiling of Studio 6B.

walls and stage ceiling of a bright cheerful silver color, and a red rubber flooring, with red carpeting, and blue upholstered chairs.

In the case of either studio, a drape can be drawn across the curved surfaces to alter the acoustical conditions in the studio, if desired, and another drape, about midway along the side walls of the stage can be drawn to reduce the apparent size when small performing groups use the studio.

A further contrast between the two studios is that in 6A one side wall and the rear wall of the auditorium are "veed" vertically, whereas in Studio 6B the side walls and rear wall of the auditorium are "splayed" horizontally, and in such manner that in the case of the side walls very few opposite parallel surfaces exist.

In neither case is any acoustical treatment given to the side walls or ceiling of the auditorium, so that these surfaces produce beneficial reflections which aid in the transmission of the sound from the stage to the listeners. On the other hand, the rear wall of the auditorium is treated with 2 inches of rock wool covered with asbestos board. This wall thus absorbs most of the energy impinging on it, and the small amount reflected is so well diffused that no annoying discrete, delayed reflections or echoes are sent back to the listeners in the front seats. Absorption is further aided by the upholstered seats and the broadloom carpeting lined with felt on the aisles.

The rear portions of the stage ceiling have 4-inch rock wool treatment, as compared to 2-inch rock wool for the other parts of the studio. Instead of perforated asbestos board, perforated metal is used to cover the rock wool on the stage ceiling to provide greater absorption at the higher audio frequencies. The side walls of the stage are treated with rock wool covered with perforated asbestos board, in 2-foot squares. The ceiling and side walls of the auditorium section are untreated except near the stage so as to permit the use of a microphone in this vicinity.

To isolate the studio from outside noise, double 6-inch solid-cinder block partitions are employed. Cinder composition has been found preferable to terracotta. The use of two walls with a break in between affords additional isolation owing to the impedance discontinuities encountered by the sound. In addition, to reduce "solid-borne" sounds transmitted through the building structure, the walls, floor, and ceiling of the stage section are supported on metallic springs damped with felt.

The control and client's booth windows are constructed of double panes, 5/8-inch and 3/8-inch thick, as described previously. Double doors and a vestibule, also described previously, are employed for entrance and egress from the studio. The air-conditioning ducts have the outer wrap and inner cellular Cabot's quilt construction discussed above.

With reference to the control room, the treatment is to make it relatively "dead", as no additional reverberation is desired here. The lighting is normally of low level here so that no eye strain is experienced and the better-lighted studio is more easily observed under such conditions. Individual components, such as the volume indicator and the mixer controls, are illuminated more strongly by means of concentrated "down" lights. Auxiliary lights furnish a higher level of illumination in the booth during rehearsals or maintenance of the equipment.

In a studio containing an audience, it is desirable to have the spectators hear the program more nearly as it goes out on the air. This is particularly true in the case of artists who perform close to the microphone. Hence a sound-reinforcing system is employed in in the studio and energized from the broadcasting program circuit.

WOR Studios.--Three studios have been built for WOR of volumes varying from 1,000 to 1,600 cu. ft. for use in speech pickup.* These small studios employ methods of sound diffusion similar to those described in the preceding section, and in addition have a curve of reverberation time versus frequency that is eminently well suited for speech pickup purposes.

Specifically, the calculated reverberation time varies from 0.4 to 0.5 second over the frequency range 128 to 2,048 c.p.s., and then rises to approximately 0.6 second at 4,096 c.p.s. The actual as well as calculated reverberation times are shown in Fig. 34 for Studio 8, of irregular shape, 14 x 15 x 8.5 feet in size, and of approximately 1,600 cu. ft. volume. It is interesting from a practical viewpoint, to note the discrepancies between the curves. In curve A1 the microphone was placed directly in front of the speaker source, face to face about 2 feet away from it, and both near the center of the room. In curve A2 the microphone and speaker were placed back to

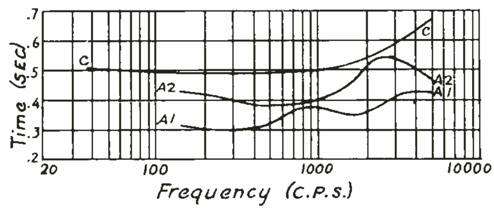


Fig. 34.--Actual and calculated reverberation time vs. frequency for WOR Studio 8.

back about 2 feet apart and facing opposing walls. The discrepancies between these two curves may in part be due to errors in measurement, but are probably mainly due to the variation in diffusion of the sound through the room and the directional effects of the speaker, which in curve A1 produced a large ratio of direct to reflected sound and so caused a quicker drop in decay of the sound when the speaker ceased.

Curve C-C is the calculated reverberation time, in which the absorption coefficients from test values were used. These coefficients are based on the use of a solid area of material rather than a number of small areas, as actually used in treating a room. As a result, the coefficients are too small, since--as mentioned previously--small areas tend to "suck in" sound energy from adjacent areas and hence make the actual coefficient larger. The effect can be seen from the curves of Fig. 34: the reverberation time

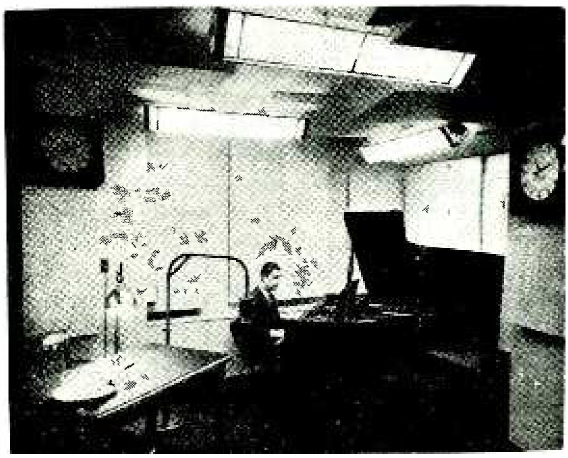
*See "Acoustical Design and Treatment for Speech Broadcast Studios", E. J. Content and L. Green, Jr., I.R.E. Proc., Feb. 1944.

as calculated is too high, particularly at the lower frequencies, where the longer wavelengths promote the diffraction effect that produces the "sucking in" of the sound.

The actual reduced reverberation time has been found to be of advantage in these speech studios, and is to be contrasted with the curve shown in Fig. 31 based on the researches of McNair. It is claimed that the reduced low-frequency reverberation time (below 500 c.p.s.) permits the speaker to be a few feet rather than 3 or 4 inches from the microphone, and yet produces that intimate effect in the room where the receiver is located, without excessive "boominess" on the one hand, or the breath and lip sounds on the other hand (for close talking).

Studio 8 is illustrated in Fig. 35, from which may be obtained some idea of the size and placement of the acoustic material, as well as the breakup of the walls and ceiling in the form of "Vees". The ceiling and walls are of plaster, on which special acoustic material is placed. This consists of three types of sound-absorptive material manufactured by Johns-Manville, known as High-frequency, Low-frequency, and Triple-tuned elements. They are all composed of rock wool of different densities and thicknesses, used in conjunction with diaphragms of various densities and weights, and all in turn covered with perforated Transite. The latter has the characteristic of producing more reflection above 2,000 c.p.s. and thus helps increase the high-frequency reverberation time somewhat.

The sound-absorbent properties of the three materials are given in Table IV. It will be observed that the high-frequency element has the maximum absorption at the high-frequency end, whereas the low-frequency element has maximum absorption at the low-frequency end. The triple-tuned element represents



(Content and Green, Courtesy Proc. of IRE)

Fig. 35.--View of WOR Studio 8.

commercially, an element that is substantially flat in its absorption characteristic.

to design a studio of moderate size for the reproduction of speech and music. In this case the curves

TABLE IV

	Frequency in cycles per second.					
	128	256	512	1024	2048	4096
	Percentage—Sound Absorption.					
High-frequency element	20	46	55	66	70	75
Low-frequency element	66	60	50	50	35	20
Triple-tuned element	66	61	80	74	79	75

It is interesting to observe the use of such diverse elements to obtain the curves shown in Fig. 34. By the judicious choice of areas for each of the three elements, any desired reverberation time vs. frequency curve, within reason, can be obtained.

In conclusion, it may be noted that sound diffusion is promoted by breaking up the acoustical treatment into small panels, distributing these panels in irregular arrangement on the walls and ceiling, and sloping the panels from 5 to 10 degrees in an irregular manner so that the slopes on opposing parallel surfaces are *in different planes*, thereby obtaining three-dimensional dispersion. In addition, the ceiling is broken up to conceal ventilating ducts, and the floor is of linoleum.

SAMPLE DESIGN.—With the foregoing in mind, it will be of value to design a studio of moderate size for the reproduction of speech and music. In this case the curves of Fig. 31 will be used, as a rising reverberation time at the lower frequencies is not too objectionable for speech, and is desirable for music. Suppose a studio for 6 performers (and no audience) is desired.

Determination of Dimensions and Reverberation Time.—From Eq. (5), the height is

$$h = 5.87\sqrt[8]{6 + 2.5} = 5.87 \times 2.04$$

$$= 11.97 \text{ ft. or } 12 \text{ ft.}$$

whereupon the width is (3/2) (12) = 18 feet, and the length is (5/2) (12) = 30 feet. The volume is

$$V = 12 \times 18 \times 30 = 6{,}480 \text{ cu. ft.}$$

From Fig. 31, the optimum reverberation time at 1,000 c.p.s. for 6,480 cu. ft. is .54 second. From the same figure, the multiplying factor for the reverberation time at other frequencies, and hence the reverberation times, can be found. These are:

Freq.	60	100	250	500	1,000	2,000	4,000	6,000
K	1.95	1.75	1.3	1.1	1	1.05	1.2	1.35
T	1.052	.945	.702	.594	.54	.567	.648	.729

Design of Diffusing Surfaces. Since the diffusing surfaces can also act as absorbing surfaces, and since they alter somewhat the surface area (as well as the volume), it is desirable to lay out the shape of the room with regard to this feature before determining where to add additional sound-absorptive material.

A suggested layout is shown in Fig. 36. The front wall has a row of nine semi-cylinders, each 1 foot in radius. (Actually the wall will be 19 feet wide to give the room an *average* width of 18 feet.) These semi-cylinders will be made of plywood 1/4" or 3/8" thick, and will be assumed to have the construction described previously, and hence a coefficient of absorption of 0.2. While it may be desirable to vary the size of these cylinders, all will be assumed to be of the same shape and size, as indicated above.

The rear wall will be flat, and of plaster applied to the inner cinder block wall. Since the absorption coefficient is quite small, no appreciable error will be obtained if the value for plaster on wood lath given in the table, is employed. This wall will then be covered, at least in part, by 4 inches of rock wool. The values for rock wool finished with perforated sheet rock and B-068 Kribble Kloth given in the table, will be employed.*

The side walls are "veed" vertically in two sets of vees. One set has a span of 6 feet per vee; the other 4 feet per vee, and all are 1 foot deep. The two kinds of vees are alternated, as shown, and the use of different spans or widths, yet equal depth for the two kinds, provides two different angles for reflecting the sound. Note also that a 4-foot vee on one wall is opposite a 6-foot vee on the other side wall, so that more complete diffusion will be obtained. These walls will be of plaster one inch thick. Below 200 c.p.s. the coefficient of absorption will be taken as 0.2: and above 200 c.p.s. as 0.1. Considerable variation from this value may be found in practice, but it will serve as an average value.

The ceiling will be broken up as indicated in the cross-sectional view of the ceiling in Fig. 36. The coves thus produced can be used to hold the lighting fixtures, similar to that employed by N.B.C. in Studios 6A and 6B described previously. The plaster will have to be quite solid to support its own weight, and hence a low coefficient

*Although Kribble Kloth has not been employed for many years, the values given in the table will be used for rock wool laced in place and covered with Transite.

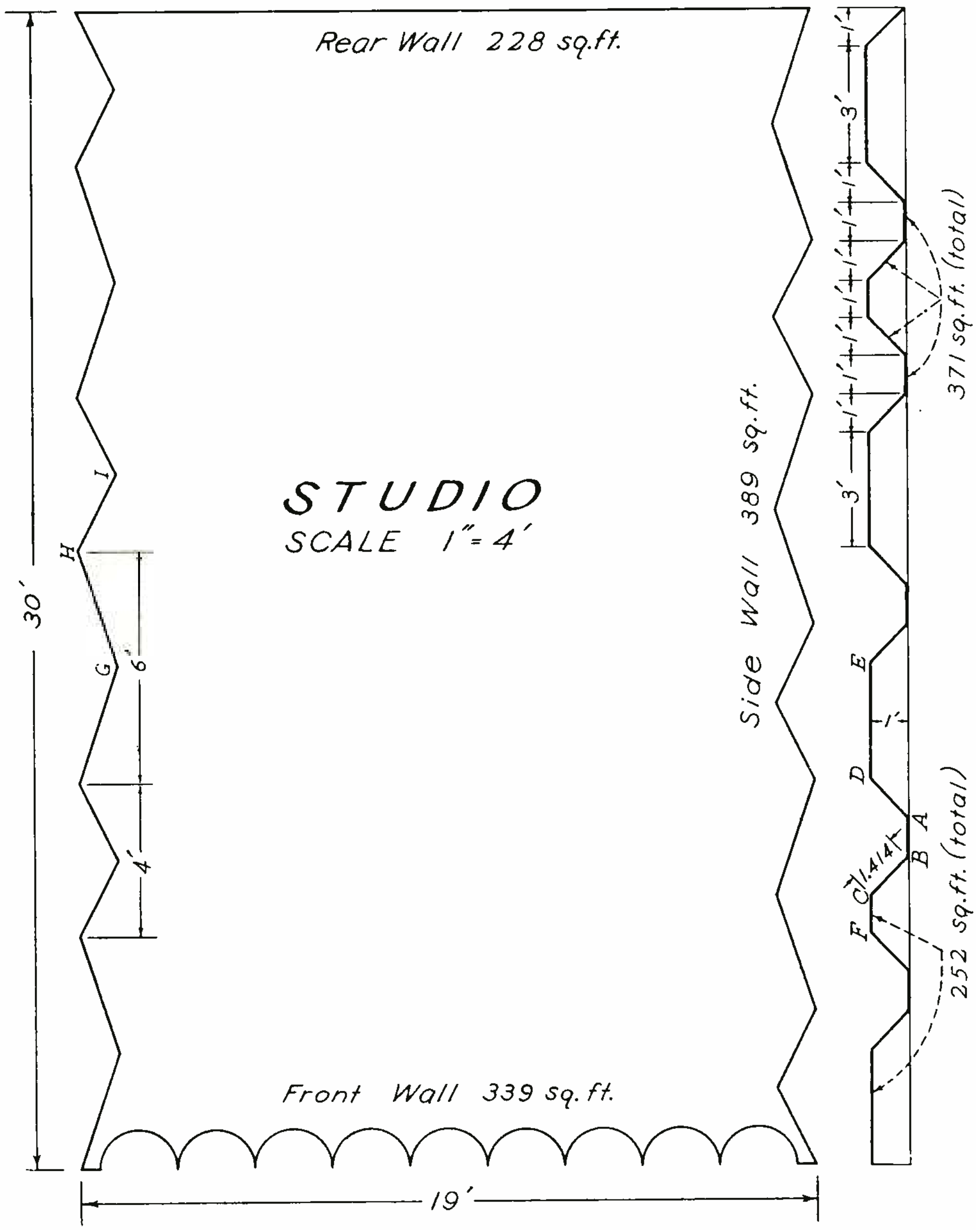


Fig. 36.—Plan view of proposed studio, and cross-sectional view of ceiling.

of absorption, equal to that used for the rear wall, will be employed here. The bottom ceiling surfaces of 3 feet and 1 foot in width, and averaging 18 feet in length, will be treated with 4 inches of rock wool similar to that used for the rear walls.

Area = 18 × 1.414 = 25.5 sq. ft.

AB = 1 ft. Area = 18 × 1 = 18 sq.ft.

There are 11 surfaces like BC, so that the total area is

11 × 25.5 = 280.5 sq. ft.

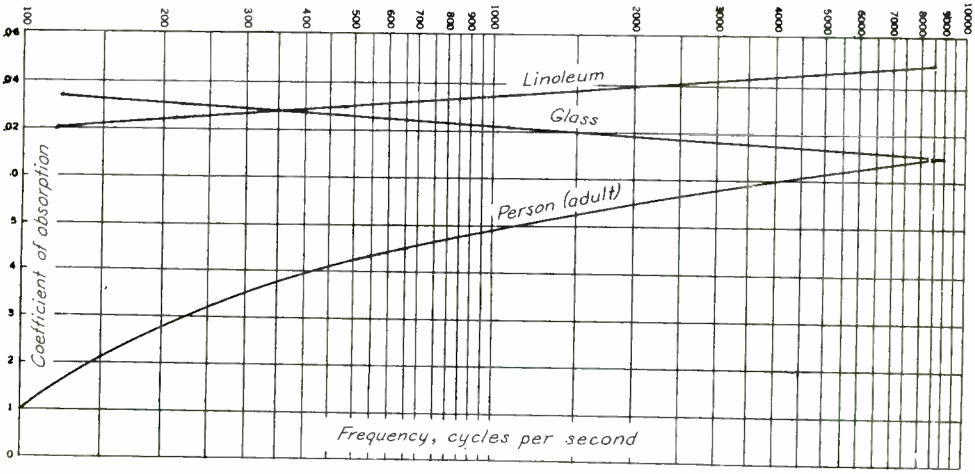


Fig. 37.--Absorption coefficients of various materials at different frequencies.

Determination of Areas.--The next step is to calculate the areas of the various surfaces involved, and then the total surface of the studio. Although the latter could be calculated approximately from the average dimensions of the room, the more accurate value taking into account the broken-up condition of the surfaces will be employed since the areas of these individual surfaces are required anyway in order to calculate the absorption.

CEILING.--Surfaces such as AB, BC, and AD are untreated, and of hard plaster; surfaces such as CF and ED are to be treated with 4 inches of rock wool. All are 18 feet in length.

$$BC = \sqrt{(1\text{ ft.})^2 + (1\text{ ft.})^2} = 1.414\text{ ft.}$$

There are 5 surfaces like AB, so that the total area is

5 × 18 = 90 sq. ft.

The overall total of untreated surface is then

280.5 + 90 = 371 sq. ft.

Surfaces such as FC and DE are treated with 4" of rock wool. These total

18[(4 × 3) + (2 × 1)] = 252 sq. ft.

FRONT WALL.--Each semi-cylinder has a radius of 1 ft., hence a semi-circumference of

π = 3.14 ft.

Since the height is 12 feet, and since there are nine semi-cylinders, the total area will be

$$12 \times 3.14 \times 9 = 339 \text{ sq. ft.}$$

The small flat surfaces at either end will be disregarded, since they are of plaster and have negligible absorption.

REAR WALL.--The area of this wall is

$$12 \times 19 = 228 \text{ sq. ft.}$$

It will be found necessary to treat this wall in part, i.e., part of the surface will be of 4-inch rock wool, and the rest will remain plaster.

SIDE WALLS.--Each side wall has surfaces of two different lengths and slopes:

$$GH = \sqrt{(6/2)^2 + (1)^2} = 3.16 \text{ ft.}$$

and

$$HI = \sqrt{(4/2)^2 + (1)^2} = 2.24 \text{ ft.}$$

There are six surfaces like GH, 12 feet high, and six like HI, so that the total area is

$$6 \times 3.16 \times 12 + 6 \times 2.24 \times 12$$
$$228 + 161 = 389 \text{ sq. ft.}$$

This area will be assumed to have a coefficient of absorption of .2 below 200 c.p.s., and of .1 above 200 c.p.s.

FLOOR.--The floor will be assumed covered with linoleum. Its area is

$$30 \times 18 = 540 \text{ sq. ft.}$$

The total surface is

$$252 + 371 + (389)(2) + 228 + 339 + 540 = 2{,}508 \text{ sq. ft.}$$

Calculations at 1,000 Cycles. From Table I the following values will be taken:

Material	Absorption Coefficient — Frequency 128	256	512	1024	2048	4096
Linoleum	.02	.025*	.03	.035	.04	.045
Person (adult)	1.8	3.23	4.2	4.9*	5.5	6.04*
Rock Wool**	.34	.56	.76	.80	.56	.43
Plaster, lime, etc.	.012	.013	.018	.045	.028	.055

*Values obtained by interpolation from Fig. 37.

**Packed between 2" x 4" studs, finished with sheetrock, etc.

The optimum reverberation time at 1,000 c.p.s. is 0.54 sec. The total surface is 2,508 sq. ft., and the volume is 6,480 cu. ft. From Eq. (2), the average absorption coefficient $\bar{\alpha}$ can be found. Thus

$$.54 = \frac{(.05)(6480)}{-2508 \log_e (1-\bar{\alpha})}$$

$$= \frac{324}{(-2508)(2.3)\log_{10}(1-\bar{\alpha})}$$

or

$$\log(1-\bar{\alpha}) = \frac{324}{(-2508)(2.3)(.54)}$$

$$= -.1042 = -1 + .8958$$

(The reason for subtracting -.1042 from -1 to obtain .8958 is that the latter value is to be found in the log table.)

$$1 - \bar{\alpha} = \text{anlg}(-1 + .8958) = .787$$
$$\bar{\alpha} = 1 - .787 = 0.213$$

The total number of absorption units will be

$$0.213 \times 2508 = 534 \text{ sabines}$$

The fact that the side walls and semi-cylinders have the maximum absorption of all untreated surfaces, namely 0.2, and that the average value $\bar{\alpha}$ is 0.213, indicates that some additional absorption will be required. First treat all the lower surfaces of the ceiling, such as CF and DE of Fig. 36 with 4 inches of rock wool. As will be shown directly, this will not provide the 534 sabines required, so that additional treatment will be required on the rear wall.

The calculations for the absorption units is as follows:

Ceiling, untreated surfaces:	(371) (.045)	=	16.7 sabines
Ceiling, surfaces treated with Rock Wool	(252) (.8)	=	201.6 sabines
Semi-Cylinders:	(339) (.2)	=	67.8 sabines
Side Walls:	(778) (.1)	=	77.8 sabines
Six Performers:	(6) (4.9)	=	29.4 sabines
Floor:	(540) (.035)	=	18.9 sabines
Total (excluding rear wall) =			412.2 sabines

The difference, or 534 - 412 = 122 sabines, must be provided by the treatment on the rear wall. Assume that the treatment is in the form of panels 12 feet high, and that the untreated parts of the wall provide negligible absorption in comparison. The panels will have to have an area of

$$122 \div .8 = 152.5 \text{ sq. ft.}$$

If the panels are 12 feet high, their overall width will be

$$152.5 \div 12 = 12.7 \text{ feet}$$

Since the overall width is 19 ft., the untreated portion of the wall will be

$$19 - 12.7 = 6.3 \text{ feet}$$

This, if in one piece, will provide more than ample width for a door. In fact, assume a door 3 feet wide, including the frame. This leaves 6.3 - 3 = 3.3 feet additional, which can be split in half to furnish two untreated strips 3.3 ÷ 2 = 1.65 ft. on each end of the wall. Thus the layout will be as in Fig. 38.

In the actual design, provisions will have to be made for a window and door between the studio and the control booth. Since glass and for that matter wood, do not have coefficients of absorption markedly different from that of plaster, and since plaster contributes very few sabines to the total for the studio, it is clear that the above design will not be altered appreciably by the substitution of the above window and door for

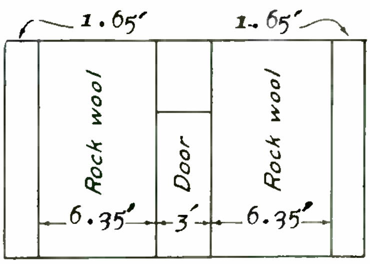


Fig. 38.--Rear wall of proposed studio, showing layout of acoustic material and door.

the plaster surfaces they replace unless these are along the side walls, for which $\alpha = 0.1$. In the latter event, suitable additional treatment, such as on the door itself, will compensate for the wall it replaces.

Calculations at Other Frequencies.--The reverberation time at other frequencies, such as at 128, 256, 512, 2,000, and 4,000 c.p.s. can now be calculated. Consider, for example, 128 c.p.s. First, the appropriate absorption coefficient for each material at 128 c.p.s. is chosen, and from the known area, the sabines absorption by that surface, can be calculated. The total for all surfaces is then divided by the total surface, to give the *average* absorption coefficient, $\bar{\alpha}$, and then Eyring's formula is employed to give the reverberation time.

Thus, at 128 c.p.s.,

In Fig. 39 there has been plotted the optimum curve as well as that calculated for this studio. From the optimum curve it will be observed that the optimum time is 0.87 sec. instead of 0.77 sec. as calculated. The difference, however, is possibly on the right side in view of the excellent results obtained in the WOR Studios described previously, in which there was no rise at all in the reverberation time at the lower frequencies.

Similar calculations are made at 256, 512, 2,000 (actually 2,048), and 4,000 (actually 4,096) c.p.s. These come out to be:

Freq. c.p.s.	Reverb. Time in seconds Calc.	Opt.
256	.723	.702
512	.572	.59
2,000	.673	.565
4,000	.733	.648

Ceiling, untreated:..................	(371) (.012)	=	4.5 sabines
Ceiling, treated......................	(252) (.34)	=	85.7 sabines
Semi-cylinders:......................	(339) (.2)	=	67.8 sabines
Side Walls:............................	(778) (.2)	=	155.6 sabines
Six Performers:......................	(6) (1.8)	=	10.8 sabines
Floor:..................................	(540) (.02)	=	10.8 sabines
Rear Wall, treated:.................	(152.5) (.34)	=	51.9 sabines
Rear Wall, untreated:.............	(6.1)-(12) (.012)	=	.91 sabines
Total:..................................			388.0 sabines

The average coefficient of absorption is 388.0 ÷ 2508 = 0.1545. From Eq. (2), the reverberation time is

$$T = \frac{(.05)\,(6480)}{(-2508)\,(2.3)\log_{10}(1 - .1545)}$$

$$= 0.772 \text{ second}$$

The calculated and optimum results have been plotted in Fig. 39 for comparison. The calculated curve does not have the optimum shape, but its departure from such a shape is possibly in the right direction, in that the low-frequency reverberation time is somewhat too short, and the high-frequency time is somewhat too long. Such a curve will probably be quite satisfactory within the limits of error inherent in acoustic design.

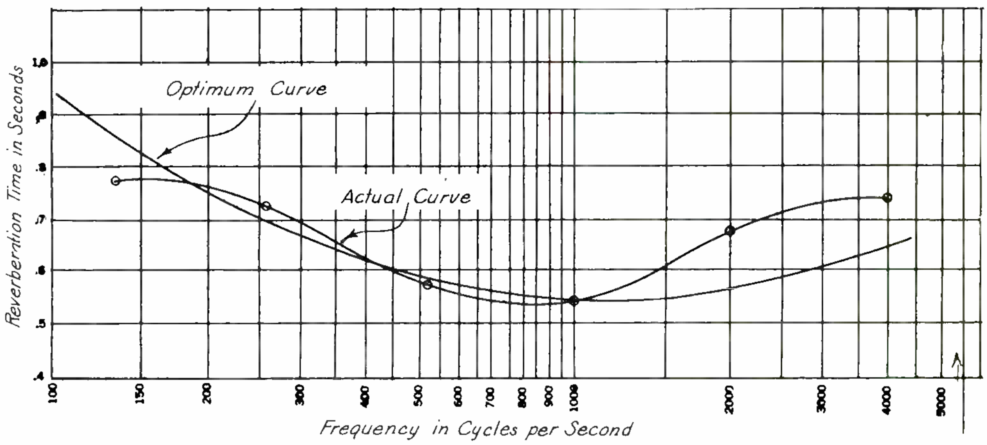


Fig. 39.--Calculated and optimum reverberation time for proposed studio.

satisfactory for speech: the short reverberation time at low frequencies will tend to obviate any "boominess", and the longer reverberation time at the higher frequencies should help accentuate the higher frequencies and thus increase the articulation.

If it is desired to reshape the curve to some extent, possibly the use of high-frequency material whose coefficients are given in Table IV, to replace some of the rock wool, may be of benefit. This material could replace the rock wool, in part, either on the rear wall or on the ceiling. Its effect would be to decrease the reverberation time at the high frequencies, and to increase it at low frequencies, and thus bring the calculated curve more nearly in line with the optimum one. However, as stated previously, the curve given in Fig. 39 is probably satisfactory within the limits of error inherent in acoustic design.

CONCLUSION.--This concludes the technical assignment on Studio and Auditorium Acoustics. The subjects covered have been reverberation and its effects upon speech and music; the calculation of reverberation time and its variation with frequency; methods of diffusing sound in an auditorium by break-up of the wall surfaces; the practical features and characteristics of sound-absorptive materials; the isolation of vibration from an enclosure; and finally a sample studio design. While experience is a most important factor, this lesson nevertheless will be a safe guide in proceeding with such a design and will also aid the engineer in gaining practical experience and at the same time enable him to avoid flagrant errors in such design.

TABLE I

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS OF TEST SAMPLES
PREFABRICATED ACOUSTICAL UNITS

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
		128	256	512	1024	2048	4096				
Corkoustic B4	1-1/4	.08	.13	.51	.75	.47	.46	Acoustical Materials Association	June 1941	1	Painted by mfgr.
Corkoustic B4	1-1/4	.11	.34	.67	.47	.57	.53	"	"	2	Same as above.
Corkoustic B5	1-1/2	.06	.16	.73	.69	.56	.69	"	"	1	Same as above.
Corkoustic B5	1-1/2	.18	.41	.70	.51	.58	.65	"	"	2	Same as above.
Corkoustic B6	1-3/4	.15	.28	.82	.60	.58	.38	"	"	1	Same as above.
Corkoustic B6	1-3/4	.22	.55	.61	.54	.51	.50	"	"	2	Same as above.
Cushiontone A1	1/2	.05	.18	.58	.72	.71	.71	"	"	1	Painted by mfgr. Perforated 484 holes per sq. ft., 3/16" diam., 3/8" deep.
Cushiontone A1	1/2	.10	.45	.56	.61	.73	.64	"	"	2	Same as above.
Cushiontone A2	5/8	.12	.35	.59	.70	.73	.74	"	"	1	Painted same as above. Perforated same as above, 1/2" deep.
Cushiontone A2	5/8	.11	.54	.53	.64	.70	.73	"	"	2	Same as above.
Cushiontone A3	7/8	.13	.39	.75	.94	.81	.70	"	"	1	Painted same as above. Perforated same as above, 3/4" deep.
Cushiontone A3	7/8	.17	.58	.70	.90	.76	.71	"	"	2	Same as above.

* Unless otherwise noted, the thickness given is the thickness of the sound-absorbing element forming the face of the construction. The thickness of other sound-absorbing elements in the construction, if used, is indicated by the type of mounting.

\+ Types of mounting
1. Cemented to plaster board. Considered equivalent to cementing to plaster or concrete ceiling.
2. Nailed to 1" x 2" wood furring 12" o.c. unless otherwise specified.
3. Attached to metal supports applied to 1" x 2" wood furring.
4. Laid directly on laboratory floor.
5. Laid on 24 ga. sheet iron, nailed to 1" x 2" wood furring 24" o.c.
6. Attached to special metal supports mounted on 2" x 2" wood furring.
7. Nailed to 2" x 2" wood furring 18" or 20" o.c. 2" mineral wool between furring.

TABLE I (Continued)

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
		128	256	512	1024	2048	4096				
Kencoustic	1-1/2	.05	.13	.61	.71	.56	.60	Acoustical Materials Association	June 1941	1	Painted by mfgr.
Koustex	1	.10	.24	.64	.92	.77	.75	"	"	1	Unpainted.
Koustex	1	.15	.27	.75	.99	.80	.87	"	"	2	Painted by mfgr.
Sanacoustic, pad plus metal facing and pad supports plus furring	1-1/8 1-9/16 2-1/2	.25	.56	.99	.99	.91	.82	"	"	3	Perforated enameled metal .068" diameter perforations, 4608 per sq. ft.
Sanacoustic, pad plus metal facing and pad supports plus furring	1-1/8 1-9/16 2-1/2	.22	.70	.63	.67	.52	.48	"	"	3	50/50 Pattern, one-half perforated enameled metal backed with pads, .068" diam., 4608 holes/sq. ft.; one-half enameled metal unperforated, unbacked.
Transite Acoustical Unit, pad plus Transite facing	1 1-1/8	.28	.55	.83	.91	.76	.67	"	"	2	Painted by mfgr. 576 holes per sq./ft-5/32" diameter.
Permacoustic	3/4	.19	.34	.74	.76	.75	.74	"	"	1	Unpainted.
Permacoustic	1	.23	.44	.71	.68	.70	.73	"	"	1	Painted by mfgr.
Fibracoustic	1	.17	.43	.79	.93	.79	.73	"	"	1	Painted by mfgr.
Fibracoustic	1	.18	.65	.82	.83	.85	.83	"	"	2	Same as above.
Sound Isolation Blanket MK	1/2	.05	.13	.48	.81	.86	.80	"	"	4	Muslin covered, unpainted.
Sound Isolation Blanket MK	1	.15	.37	.89	.98	.89	.86			4	Muslin covered, unpainted.
Sound Isolation Blanket MK	2	.43	.64	.97	.99	.87	.90	"	"	4	Muslin covered, unpainted.

TABLE I (Continued)

MATERIAL	THICK-NESS IN. *	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNT-ING OR APPLI-CATION†	REMARKS
		128	256	512	1024	2048	4096				
Fibretex	5/8	.09	.16	.45	.84	.77	.66	Acousti-cal Mate-rials As-sociation	June 1941	2	Painted by mfgr.
Fibretex	3/4	.09	.17	.59	.90	.75	.73	"	"	2	Same as above.
Fibretex	7/8	.09	.25	.67	.91	.78	.80	"	"	2	Same as above.
Fibretex	1	.14	.28	.81	.94	.83	.80	"	"	2	Same as above.
Airacoustic	1/2	.22	.31	.48	.73	.86	.76	"	"	5	Unpainted.
Airacoustic	1	.44	.44	.74	.80	.93	.74	"	"	5	Unpainted.
Airacoustic	1-1/2	.50	.44	.67	.78	.86	.87	"	"	5	Unpainted.
Absorbatone A	1	.15	.28	.82	.99	.87	.98	"	"	2 (24" o.c.)	Unpainted.
Absorbatone A	1	.11	.29	.80	.99	.80	.96	"	"	2 (24" o.c.)	Painted by mfgr.
Absorbatone A	1	.25	.55	.99	.99	.85	.96	"	"	5	Same as above.
Acoustex 30R	5/8	.09	.16	.45	.84	.77	.66	"	"	2	Painted by mfgr.
Acoustex 30R backed by 1" rock wool	5/8	.17	.38	.98	.96	.85	.75	"	"	2	Same as above.
Acoustex 40R	3/4	.09	.17	.59	.90	.75	.73	"	"	2	Same as above.
Acoustex 40R	3/4	.18	.35	.87	.89	.87	.65	"	"	6	Same as above.
Acoustex 50R	7/8	.09	.25	.67	.91	.78	.80	"	"	2	Same as above.
Acoustex 60R	1	.14	.28	.81	.94	.83	.80	"	"	2	Same as above.
Acoustimetal, Type P pad plus metal facing and pad supports plus furring	1-1/4 1-5/8 2-1/2	.23	.63	.99	.98	.78	.62	"	"	3	Perforated enameled metal .068" diameter perforations, 4608 per sq. ft.
Econacoustic	1/2	.05	.31	.54	.84	.76	.90	"	"	1	Painted by mfgr.
Econacoustic	1/2	.09	.39	.73	.71	.78	.82	"	"	2	Same as above.
Econacoustic	1	.25	.40	.78	.75	.79	.68	"	"	1	Same as above.
Travacoustic	1	.14	.29	.80	.98	.85	.74	"	"	1	Unpainted.

TABLE I (Continued)

MATERIAL	THICK-NESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNT-ING OR APPLI-CATION+	REMARKS
		128	256	512	1024	2048	4096				
Fiberglas Acoustical Tile, Type TW-PF 9D	1/2	.08	.24	.67	.93	.71	.46	Acoustical Materials Association	June 1941	2	Painted by mfgr.
Fiberglas Acoustical Tile, Type TW-PF 9D	1	.22	.46	.97	.90	.68	.52	"	"	2	Same as above.
Fiberglas Decorative Acoustical Blanket	1	.26	.40	.70	.93	.88	.82	"	"	2	Fiberglas cloth.
Acoustone D	9/16	.06	.16	.61	.90	.82	.82	"	"	1	Unpainted.
Acoustone D	9/16	.08	.21	.70	.87	.71	.66	"	"	1	Painted by mfgr.
Acoustone D	11/16	.08	.22	.73	.91	.81	.85	"	"	1	Unpainted.
Acoustone D	11/16	.13	.26	.79	.88	.76	.74	"	"	1	Painted by mfgr.
Acoustone D	13/16	.15	.26	.79	.92	.85	.85	"	"	1	Unpainted.
Acoustone D	13/16	.11	.30	.81	.88	.77	.76	"	"	1	Painted by mfgr.
Acoustone D	15/16	.20	.40	.84	.88	.85	.88	"	"	1	Unpainted.
Acoustone D	15/16	.12	.37	.83	.88	.83	.80	"	"	1	Painted by mfgr.
Acoustone F	9/16	.11	.12	.44	.89	.90	.93	"	"	1	Unpainted.
Acoustone F	9/16	.04	.12	.53	.95	.85	.85	"	"	1	Painted by mfgr.
Acoustone F	11/16	.14	.17	.65	.93	.85	.89	"	"	1	Unpainted.
Acoustone F	11/16	.04	.18	.75	.96	.80	.80	"	"	1	Painted by mfgr.
Acoustone F	13/16	.14	.26	.81	.88	.85	.83	"	"	1	Unpainted.
Acoustone F	13/16	.16	.33	.85	.89	.80	.75	"	"	1	Painted by mfgr.
Acoustone F	15/16	.16	.31	.87	.92	.83	.87	"	"	1	Unpainted.
Acoustone F	15/16	.16	.33	.91	.87	.83	.88	"	"	1	Painted by mfgr.
Perfatone, Pad plus metal facing and pad supports plus furring	1-1/4 1-5/8 2-1/2	.23	.59	.98	.99	.87	.68	"	"	3	Perforated enameled metal, 4608 holes per sq. ft., .073" diameter.

TABLE I (Continued)

MATERIAL	THICK-NESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNT-ING OR APPLI-CATION†	REMARKS
		128	256	512	1024	2048	4096				
Acousti-Celotex, Type C-1	1/2	.07	.14	.57	.59	.64	.63	Acoustical Materials Association	June 1941	1	Painted by mfgr. Perforated 441 holes per sq. ft. 3/16" diameter, 3/8" deep.
Acousti-Celotex, Type C-1	1/2	.11	.54	.45	.53	.58	.64	"	"	2	Same as above.
Acousti-Celotex, Type C-2	5/8	.16	.20	.67	.78	.69	.59	"	"	1	Painted by mfgr. Perforated same as above, 1/2" deep.
Acousti-Celotex, Type C-2	5/8	.17	.55	.59	.67	.65	.58	"	"	2	Same as above.
Acousti-Celotex, Type C-3	13/16	.15	.27	.82	.94	.63	.52	"	"	1	Painted by mfgr. Perforated same as above, 11/16" deep.
Acousti-Celotex, Type C-3	13/16	.22	.50	.76	.84	.66	.40	"	"	2	Same as above.
Acousti-Celotex, Type C-3	13/16	.22	.56	.76	.87	.60	.25	"	"	6	Same as above.
Acousti-Celotex, Type C-4	1-1/4	.13	.35	.99	.81	.60	.50	"	"	1	Painted by mfgr. Perforated same as above, 1-1/8" deep.
Acousti-Celotex, Type C-4	1-1/4	.28	.56	.98	.78	.59	.49	"	"	2	Same as above.
Acousti-Celotex, Type C-5	13/16	.12	.20	.78	.94	.83	.62	"	"	1	Painted by mfgr. Perforated 441 holes per sq. ft. 1/4" diameter, 11/16" deep.
Acousti-Celotex, Type C-6	1-1/4	.30	.56	.94	.96	.69	.56	"	"	2	Painted by mfgr. Perforated same as above, 1-1/8" deep.

TABLE I (Continued)

MATERIAL	THICK-NESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNT-ING OR APPLI-CATION+	REMARKS
		128	256	512	1024	2048	4096				
Acousti-Celotex, Type C-8	1	.31	.47	.58	.73	.73	.60	Acoustical Materials Association	June 1941	2	Painted by mfgr. Perforated 441 holes per sq. ft. 3/16" diameter, 7/8" deep.
Acousti-Celotex, Type M-1	5/8	.10	.15	.55	.85	.89	.76	"	"	1	Painted by mfgr. Perforated 676 holes per sq. ft. 5/32" diameter, 1/2" deep.
Acousti-Celotex, Type M-1	5/8	.17	.43	.53	.79	.88	.66	"	"	2	Same as above.
Acousti-Celotex, Type M-2	1	.12	.26	.82	.99	.80	.67	"	"	1	Painted by mfgr. Perforated same as above, 7/8" deep.
Acousti- Celotex, Type M-2	1	.22	.53	.69	.99	.74	.63	"	"	6	Same as above.
Calicel, Standard	3/4	.12	.15	.47	.95	.78	.72	"	"	1	Painted by mfgr.
Calicel, Standard	1	.11	.17	.66	.95	.74	.75	"	"	1	Same as above.
Calistone, SW	1	.08	.14	.40	.76	.66	.60	"	"	4	Unpainted.
Absorbex, Type A	1	.13	.23	.70	.99	.79	.84	"	"	1	Painted by mfgr.
Absorbex, Type A	1	.17	.34	.85	.94	.84	.87	"	"	2 (18" o.c.)	Same as above.
Absorbex, Type A	1	.41	.71	.96	.88	.85	.96	"	"	7 (18" o.c.)	Same as above.
Absorbex, Type F	1	.15	.18	.59	.93	.61	.67	"	"	1	Same as above.
Absorbex, Type F	1	.11	.22	.73	.72	.77	.75	"	"	2	Same as above.
Absorbex, Type F	1	.37	.77	.91	.70	.73	.63	"	"	7 (20" o.c.)	Same as above.

TABLE I (Continued)

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES 128	256	512	1024	2048	4096	AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
Absorbex, Type F	2	.20	.43	.99	.67	.90	.71	Acoustical Materials Association	June 1941	1	Same as above.
Muffletone (Std.)	3/4	.17	.29	.63	.75	.74	.80	"	"	1	Unpainted.
Muffletone (Std.)	1	.18	.40	.72	.79	.79	.77	"	"	1	Painted by mfgr.
Acousteel-B, pad plus metal facing and supports	1-1/4	.29	.57	.98	.99	.85	.57	"	"	3	Perforated enameled metal .068" diameter perforations, 4608 per sq. ft.
	1-5/8										
plus furring	2-1/2										
Acousteel-B, pad plus metal facing and supports	1-1/4	.25	.66	.71	.71	.55	.49	"	"	3	50/50 Pattern, one-half perforated enameled metal, backed with pads, same as above; one-half enameled metal unperforated, without pads.
	1-5/8										
plus furring	2-1/2										
Q-T Ductliner	1/2	.14	.38	.43	.76	.75	.75	"	"	5	Unpainted.
Q-T Ductliner	1	.29	.41	.78	.89	.88	.78	"	"	5	Unpainted.

TABLE I (Continued)

ACOUSTICAL PLASTERS

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
		128	256	512	1024	2048	4096				
Macoustic Plaster, Type 55V, Trowel finish	1/2	.32	.24	.53	.81	.68	.67	Acoustical Materials Association	June 1941	1st coat applied to dry base. 2nd coat applied after 1 day interval.	Finished with steel trowel.
Reverbolite Acoustical Plaster	1/2	.29	.30	.40	.49	.54	.60	"	"	1st coat applied to dry base. 2nd coat applied same day.	Strippled with rice brush.
Reverbolite Acoustical Plaster	1/2	.26	.26	.47	.57	.65	.59	"	"	1st coat applied to dry base. 2nd coat applied same day.	Finished with steel trowel.
Sabinite Acoustical Plaster	1/2	.26	.16	.32	.70	.73	.72	"	"	2nd coat applied day after 1st coat.	Floated with cork float.

TABLE I (Continued)

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION†	REMARKS
		128	256	512	1024	2048	4096				
Veneered flats, papered with crepe paper	...	.116	.109	.062	.081	.091	.121	V.O. Knudsen	1930		
Masonite, papered with crepe paper.	7/16	.179	.174	.113	.099	.117	.115	V.O. Knudsen	1930		
Celotex, papered with crepe paper	7/16	.166	.143	.106	.111	.119	.109	V.O. Knudsen	1930		

HANGINGS, FLOOR COVERINGS, AND MISCELLANEOUS MATERIALS

MATERIAL	THICKNESS IN.*	128	256	512	1024	2048	4096	AUTHORITY	YEAR	MOUNTING OR APPLICATION†	REMARKS
Carpets, lined	...	.10*	...	.25	...	.40*	...	W.C. Sabine			
Carpets, unlined	...	.08*	...	.15	...	.25*	...	"			
Carpet, pile	3/8	.11	.14	.37	.43	.27	.25	Building Research Station		On 1/8" felt.	
Cork flooring	3/4	.04	.03	.05	.11	.07	.02	"		Glued down.	Slabs, waxed and polished.
Cotton fabric	...	.07	.31	.49	.81	.66	.54	P.E. Sabine		Draped to 3/4 its area.	14 oz. per sq. yd.
Draperies, velour	...	.05	.12	.35	.45	.38	.36	"		Hung straight, in contact with wall.	18 oz. per sq. yd.
Linoleum	...	.02*	...	.03	...	.04*	...	V.O. Knudsen			

*These coefficients are estimates made by the author.

TABLE I (Continued)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

MATERIAL	THICKNESS IN.*	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
		128	256	512	1024	2048	4096				
Auditec, de Luxe	3/4	.10	.23	.45	.72	.58	.50	P.E. Sabine	1931	On 1"x2" furring strips, 24" o.c.	
Balsam Wool	2	.23	.40	.58	.69	.70	.66	V.O. Knudsen	1928		0.52 lb. per sq. ft.
Felt, Asbestos-Akoustikos	3	.35	.57	.78	.84	.78	.67	Average			Hair and asbestos fibre.
Rock Wool	4	.34	.56	.76	.80	.56	.43	P.E. Sabine	1929	Packed between 2"x4" studs.	Finished with sheet rock, perforated with 1" holes 1-1/2" o.c., finished with B-068 Kribble Kloth.
Rock Wool+	4	.43	.53	.59	.69	.70	...	V.O. Knudsen	1928	Filled between 2" x 4" wood studs, 16" o.c.	Granulated, 12 lb. per cubic ft., covered with cheese cloth.
Nashkote AIS	1/2	.07	.19	.3	.4	.42	.33	Bu. Stds.	1929		

*Two 1/4" coats on gypsum plaster base.

+See also Table IV.

FIBRE AND WALL BOARDS, AND MATERIALS USED FOR SETS IN SOUND PICTURE STUDIOS

Flax-li-num	1/2	.12	.21	.33	.45	.46	.44	Average		Nailed on 2" x 4" wood studs, 16" o.c.	Flax fibre felted into semi-stiff board
Masonite	7/16	.18	.25	.32	.35	.33	.31	Average		On 2"x4" studs, 16" o.c.	

TABLE I (Continued)

MATERIAL	THICKNESS IN. *	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
		128	256	512	1024	2048	4096				
Oregon pine flooring	3/4	.09	...	.08	...	.10	...	V.O. Knudsen			
Rug, Axminister	...	.11	.14	.20	.33	.52	.82	Wente and Bedell	Before 1928		
Ventilators, 50 per cent open	...	.30*	...	.50	...	.50*	...	F.R. Watson			

HARD PLASTERS, MASONRY, WOOD, AND OTHER STANDARD BUILDING MATERIALS

MATERIAL	THICKNESS IN. *	128	256	512	1024	2048	4096	AUTHORITY	YEAR	MOUNTING OR APPLICATION+	REMARKS
Brick wall, unpainted	18	.024	.025	.031	.042	.049	.07	W.C. Sabine			
Brick wall, painted	18	.012	.013	.017	.02	.023	.025	"			
Glass	...	.035*	...	.027	...	.020*	...	"			
Plaster, lime with finishing coat	...	.012	.013	.018	.045	.028	.055	"		On wood lath.	
Poured concrete, unpainted	...	.010	.012	.016	.019	.023	.035	V.O. Knudsen			
Wood sheathing, pine	3/4	.098	.11	.10	.081	.082	.11	W.C. Sabine			

*These coefficients are estimates made by the author.

TABLE I (Continued)

AUDIENCE, INDIVIDUAL PERSONS, CHAIRS AND OTHER OBJECTS

MATERIAL	COEFFICIENTS AT VARIOUS FREQUENCIES						AUTHORITY	YEAR
	128	256	512	1024	2048	4096		
Audience, mixed, seated in theatre chairs, single padding on back..........................	...	8.5	4.1	4.9	4.2	...	Bureau of Standards	Before 1930
Audience, mixed, seated in church pews..........................	...	2.7	3.3	3.8	3.6	...	"	"
Chairs, American Loge, full upholstered in mohair...............	...	...	4.5	...	...	...	"	"
Chair, plywood seat, plywood back; seats up....................	...	.19	.24	.39	.38	...	F.R. Watson	"
Chair, spring edge mohair seat and back, plywood panel on rear; seat down........................	...	3.1	3.0	3.3	3.5	...	"	
Chair, like above, with thick completely covered seat and back; seat up........................	...	3.3	3.5	3.7	3.8	...	"	
Person, adult......................	1.8	...	4.2	...	5.5	...	V. O. Knudsen	1928
Person, man, without coat, seated in open-back cane chair..........	1.3	2.1	4.1	5.5	7.4	...	Bureau of Standards	Before 1930
Person, with coat, man, seated as above..........................	2.3	3.2	4.8	6.2	7.6	...	"	"
Person, woman, without coat, seated as above.......................	.7	1.3	2.3	3.6	4.6	...	"	"
Person, woman, with coat, seated as above.......................	1.3	2.4	4.0	5.8	6.7	...	"	"

STUDIO AND AUDITORIUM ACOUSTICS

EXAMINATION

1. (A) What is the difference between reverberation and an echo?

   (B) What effect has reverberation upon speech?

   (C) What effect has reverberation upon music?

2. (A) What is reverberation time, and how does it indicate the acoustic quality of a room?

   (B) How is it affected by the surface damping of the enclosure, and by the volume of the enclosure?

3. (A) Why does the reverberation time vary with frequency?

   (B) How can this variation with frequency be employed to give an optimum curve?

4. (A) Check the first illustrative example of an auditorium by means of Eyring's formula for the case *of no damping, using plaster walls only.*

   (B) Compare this with the value of 8.07 seconds obtained by Sabine's formula, and explain why the two results are in better agreement than for the case of damping in the auditorium.

5. In the illustrative example of the design of a broadcast studio, calculate and check the values for the reverberation time given in the text for 256, 512, 2,000, and 4,000 c.p.s.

The following five questions deal with the design of a broadcast studio. The design has been broken up into five questions of equal weight to facilitate the solution and marking of the questions.

6. Given a broadcast studio to accommodate 10 performers and no audience. Calculate the dimensions and volume required. Convert fractional parts of a foot to the nearest foot; example, 16.4 to 16 feet, and 20.6 to 21 feet.

7. For the above volume, find the optimum reverberation time at 100, 250, 500, 1,000, 2,000, and 4,000 c.p.s., and plot the time versus frequency on a sheet of 2-cycle semi-log graph paper.

8. Lay out the studio. In order to obtain some uniformity of results, it is suggested that a design very similar to that given in the text be employed. Since the appearance of the studio is often determined by the architect, the following specific instructions will therefore be given:

   (A) Use *horizontal* plywood semi-cylinders on the front wall each 1 foot in diameter. It will be found that the height of the studio accommodates an integral (whole) number of these cylinders.

   (B) Use eight 2-foot *vertical* plywood cylinders on each side wall from the back to a point approximately half-way down. Then employ plywood "vees" of two different sizes for the rest of each side wall. Choose vees alternatively six feet and three feet long, and one foot deep. If the dimensions of the room have been properly calculated, it will be found that an integral number of vees of the above two sizes, together with eight cylinders, can be fitted into each side wall. Assume a coefficient of absorption of .2 for the cylinders and for the vees over the frequency range.

   (C) The rear wall is to be flat, have a three foot door in it, and is to be adequately treated with rock wool, as determined by the 1,000-cycle reverberation time.

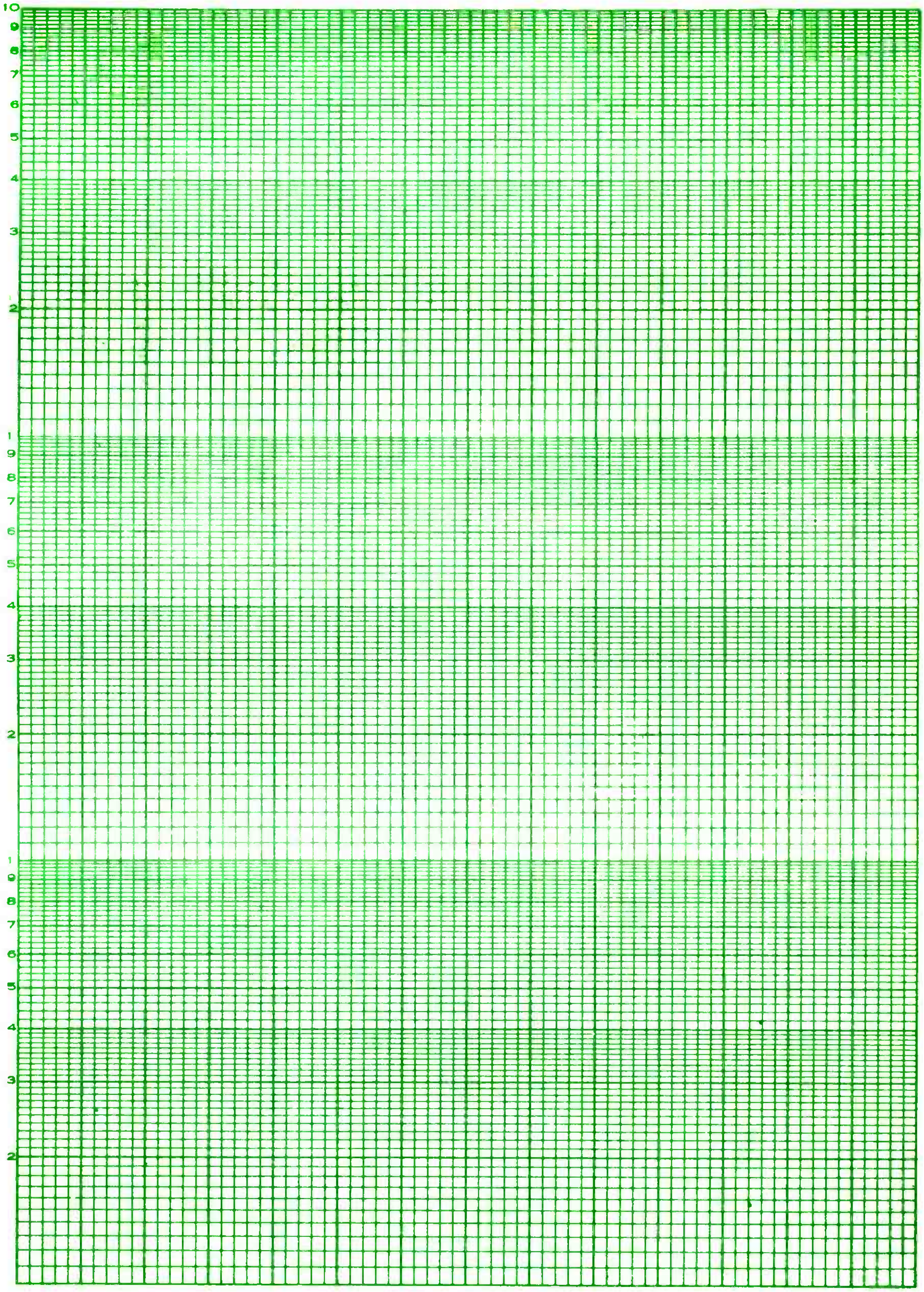
   (D) The ceiling is to have coves similar to those employed in the text example. These coves are to have alternatively three-foot and one-foot flats, which are to be treated. It will be found preferable to treat these portions with Nashkote AIS, 1/2-inch thickness rather than rock wool in the form used for the rear wall. The coefficient of sound absorption for Nashkote, as well as other materials, will be found in the text.

(E) To vary the problem somewhat, and to improve the reverberation time curve, use cork flooring slabs, waxed and polished.

9. Calculate the amount of rock wool treatment required on the rear wall to give the desired reverberation time for 1,000 c.p.s.

10. (A) Calculate the reverberation time at 128, 256, 512, 2,000, and 4,000 c.p.s.

(B) Plot the above values vs. frequency and compare with the optimum curve.



10
9
8
7
6
5
4
3
2
1
9
8
7
6
5
4
3
2
1
9
8
7
6
5
4
3
2