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ARCHITECTURAL ACOUSTICS

By Paul R. Heyl and V. L. Chrisler

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PREFACE

This Circular is a revised and enlarged edition of Circular C396 on Architectural Acoustics. It represents another step forward in the Bureau's efforts to provide the necessary basic information to architects, engineers, and others interested in the effective use of acoustic materials in auditoriums. It gives also a discussion as to how noise can be reduced in offices, cafes, public buildings, and other occupancies.

One of the interests of the National Bureau of Standards is the reduction of noise and the development of satisfactory ways of measuring noises occurring in buildings. Auditoriums which are acoustically defective may generally be corrected by the proper application of acoustic materials. Rooms in which the noise level is unduly high may be treated so as to greatly reduce the noise level.

The objective of this new edition has been to include recent significant advances in architectural acoustics and thus bring the presentation of the subject up to its present state of development.

Lyman J. Briggs, *Director*.

November 18, 1937.

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ABSTRACT

The fundamental principles governing the construction of an acoustically successful auditorium are no longer new, but are frequently ignored. The usual defects of auditoriums are discussed and some suggestions are made as to how these defects can be corrected. The principles of planning an auditorium are discussed, and an example is worked out showing their practical application to the planning of a new auditorium or to the curative treatment of one that has proved unsatisfactory.

The problem of noise quieting is discussed, and a method of computing the noise reduction due to an acoustic treatment is given.

CONTENTS

I. HISTORICAL ORIGIN

The scientific study of architectural acoustics has been undertaken only in recent years. In 1895, Harvard University had just completed the Fogg Art Museum, containing an auditorium which proved almost unusuable. The corporation of the university appealed to the scientific staff of the faculty for advice and assistance in the matter, and Prof. Wallace Clement Sabine undertook the study of the case. Two years were spent in the investigation of the questions involved, in the course of which experiments were made in a number of existing and satisfactory auditoriums. As a result, certain fundamental but previously unrecognized principles became clear, which later enabled Prof. Sabine to predetermine the acoustic design of the new Boston Symphony Hall [1].[1]

Prof. Sabine conducted some of the earliest investigations in this field. So completely and carefully were they carried out that subsequent workers, until very recently have for the most part merely enlarged our knowledge of the acoustic properties of the various materials commonly used in building construction. In fact, the follow-

[1] Numbers in brackets throughout the text indicate literature references given at the end of this paper.

ing statement of Sabine is a good summary of the requirements which one would set up today as the prerequisites for a good auditorium: "In order that hearing may be good in any auditorium, it is necessary that the sound should be sufficiently loud, that the simultaneous components of a complex sound should maintain their proper relative intensities, and that the successive sounds in rapidly moving articulation, either of speech or music, should be clear and distinct, free from each other and extraneous noise."

II. USUAL DEFECTS OF AUDITORIUMS

The usual defects of auditoriums are two—echo and reverberation. In the usual sense of the term, echo means a definite or articulate repetition of a sound after an interval at least equal to the total duration of the sound that is being repeated, whereas reverberation means a confused or inarticulate prolongation of the sound. Echo is always a bad feature in a hall; reverberation, on the other hand, is desirable up to a certain point; only in excess is it an evil. Of the two, echo is the more difficult to remove; prevention by foresight in construction, aided by expert advice, if necessary, is the best plan.

1. ECHO

Echo arises by regular reflection of sound from smooth walls, ceilings, or proscenium arches just as a mirror may reflect a beam of light. The lapse of time before an echo is heard is due to the fact that the reflected sound has traveled a longer path than the sound which comes directly from the source. If this amounts to 50 feet or more, the reflected sound of a spoken syllable or note of music may arrive at the ear at the same moment as a later syllable or note which has traveled by the direct path, and so cause confusion.

Generally speaking, auditoriums are less likely to exhibit troublesome echo when their outlines are rectangular. An instructive example of the trouble that may be caused by curved walls is cited by Watson [4] in the case of the auditorium at the University of Illinois, with an approximately circular floor plan and a hemispherical dome. The best that could be done in the way of after correction of the acoustics of the room was only partly satisfactory. Watson regards the complete cure of such a room as hopeless without "surgical treatment"; that is, straightening the walls.

Smooth, hard-finished walls, such as the usual plastered type, are excellent reflectors of sound and are consequently likely to produce echo. In some cases it is possible to break up such surfaces so as to produce irregular distribution of the reflected sound. In the past this has frequently been done by coffering in the case of ceilings. Examples of this may be seen in many theaters. The ceiling, and in some cases, the proscenium arch, are broken up into depressions about 4 feet square containing a succession of steps totaling a depth of perhaps 8 or 10 inches. An irregular surface of this character breaks up the reflected sound and distributes it in such a way as to minimize echo. The dimensions which should be assigned to such coffering are not a matter of taste or accident. If the wave length of the incident sound is very large compared to the size of the irregularities it encounters there will be little dispersive effect produced; and, if very small, the smooth spaces inside the coffering may act as regular reflectors.

In many rooms reflections may occur from more than one surface. If these reflections reach the ear of the observer at different times so that they are heard as distinct repetitions of the original sound, then the effect is called a multiple echo. One of the most common examples is the multiple reflections from parallel walls and has often been termed a "flutter." Such "flutter" effects always occur where there are parallel surfaces, but generally are not noticed unless acoustic treatment is placed on some of the other surfaces.

2. REVERBERATION

A sound produced in a room is reflected back and forth from walls, floor, and ceiling, a portion being absorbed at each reflection until its intensity is so reduced that it becomes inaudible. This persistence of sound, due to repeated reflections, is called reverberation. The time required for a sound to decrease, after the source is stopped, to one millionth of its initial value, or 60 decibels, is called the reverberation time of the room. Owing to the high speed of sound there may be many reflections in the course of a single second in a room of ordinary size, and the greater the dimensions of the hall the more prolonged will be the reverberation time.

When the walls and ceiling of a room are covered with some highly sound-absorbent material, a few reflections may suffice to destroy the sound. If too much sound absorbent material is added, such a room may be acoustically "dead" and undesirable. A little reverberation is necessary to satisfy our established tastes and auditory habit. The proper amount of reverberation in a room is dependent upon a number of considerations, such as volume of room, the usual audience, and whether the room is intended for speech or music, or both, with or without a public address system, sound motion pictures, etc.

Excessive reverberation is an evil because it prolongs unduly each syllable or note of music, causing it to interfere with the next. The ideal conditions for intelligibility of speech are two—each syllable should die away before the next arrives, which in ordinary speech may be, perhaps, one-tenth of a second; and the sound must always be loud enough to be heard.

The first of these conditions can always be secured by providing enough sound-absorbing material in the room. For a small auditorium which can easily be filled by the speaker's voice, this is the most important consideration. For a very large room it may be that the amount of absorption dictated by the first condition is so great that the speaker cannot be heard in some portions of the room. Since the intensity of the human voice cannot be much increased it is necessary to compromise between these two conditions and to permit longer reverberation in larger rooms.

In the case of theaters used for sound motion pictures, or auditoriums which have public address systems, this compromise is not necessary, as the acoustic output of the loudspeaker is by no means as limited as that of the voice. For such auditoriums there may be employed to advantage a somewhat shorter reverberation time than is desirable for rooms of the same size used for speaking or musical performances.

Broadcasting studios are sometimes equipped so that the absorption can be varied to suit different types of programs.

Experience with a number of existing auditoriums of acceptable acoustic quality makes possible the formulation of a table or a diagram in which the acceptable limits of the standard reverberation time are expressed for rooms of different volume, used for speaking or musical performances. Such a diagram giving the optional reverberation time reproduced from an article by Knudsen [2], is given in figure 1.

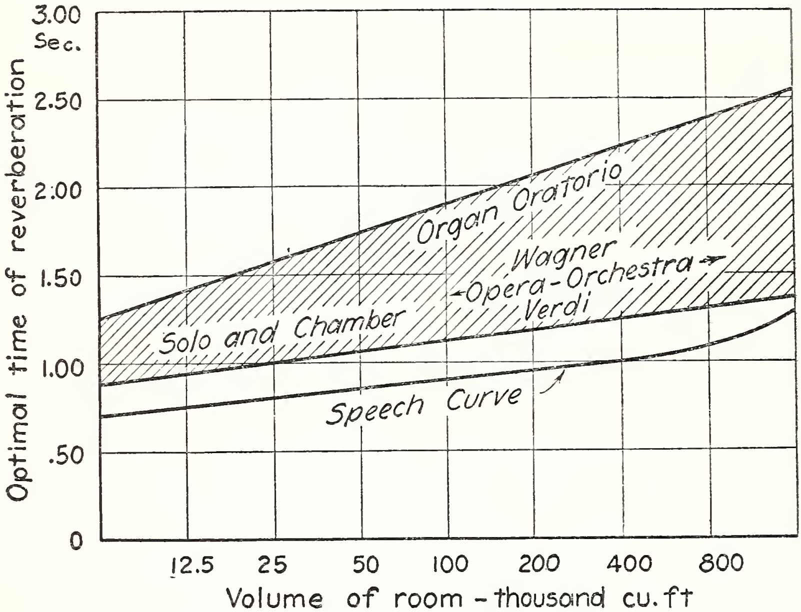

FIGURE 1.—*Acceptable limits of standard reverberation time.*

The limits given in this figure are not to be regarded as rigid. Auditoriums are known which exceed these limits in either direction by several tenths of a second and yet are acoustically satisfactory. And, as mentioned above, large auditoriums used for sound pictures may advantageously be designed for a figure somewhat less than the minimum here suggested

III. CALCULATION OF REVERBERATION TIME

As a result of the investigations of Professor Sabine and later workers [3] the reverberation time of a room may be expressed by a formula.

t=reverberation time in seconds.
V=volume of room in cubic feet.
s=total area of absorbing surfaces in square feet.
a=average coefficient of absorption of these surfaces.
$A=as$=total absorption of room.

Then, according to Eyring [3], the following relation holds:

$$t=\frac{0.05V}{-s\log_e(1-a)} \tag{1}$$

Sabine's formula is simpler, but less accurate. It is:

$$t=\frac{0.05V}{A} \tag{2}$$

Sabine's formula is sufficiently accurate for most rooms; in fact, practically all of the data which we have on the acceptable reverberation time for auditoriums are based on the use of this formula. Under special conditions where the absorption is excessive and the reverberation time very short Eyring's formula should be used.

The sound absorption coefficients at 512 cycles for several materials [Watson, 4] are as follows:

Concrete	0. 015
Glass, single thickness	. 03
Marble	. 01
Open window	1. 00
Plaster	. 03
Stage opening (depending on furnishing)	0. 25– . 40
Ventilators (50 percent of open space)	. 50
Wood, varnished	. 03

Absorption coefficients for a variety of materials have been measured at the National Bureau of Standards, and the results, at frequencies ranging from 128 to 4,096 cycles per second, are available on request.[2]

Below are given values of the total absorption of individual objects at a frequency of 512 cycles per second. These figures are numerically equal to the number of square feet of a material having an absorption coefficient of 1.00, which would absorb the same amount of sound energy.

Audience	per person	4. 0
Church pews	per seat	. 4
Seats, upholstered, depending on material and lining	per seat	1. 0–4. 5
Wood seats, for auditoriums		. 25

As an example of the use of these coefficients, let us take an auditorium of 100,000-cubic-feet capacity, including the stage. There is a wooden floor of 4,550 square feet, a plastered ceiling with the same area, 5,320 square feet of plastered walls, a stage opening of 600 square feet, and 400 plain wooden seats. The coefficients for plaster, wood, and glass being the same to the accuracy requisite for this calculation, no special allowance is necessary for closed doors and windows.

The calculation of the total absorption of the empty room is made as follows, the computations being carried to the nearest integer:

Wood floor	4, 550×0. 03=137
Plaster ceiling	4, 550× . 03=137
Plaster walls	5, 320× . 03=160
Stage opening (no furniture, bare walls)	600× . 25=150
Wooden seats	400× . 25=100
Total absorption of empty room	684

For the absorption of a full audience we must add 400×4=1,600 and subtract the absorption of 400 seats at 0.25, giving a net addition of 1,500 absorption units, and bringing the total absorption of the

[2] The following Federal specifications cover most of the acoustic materials: Plaster: Acoustic, SS-P-391; Tile: Acoustic, SS-T-302; and Products: Acoustic cast, SS-P-686. These may be obtained from the Government Printing Office, Washington, D. C., for 5 cents each.

room with full audience up to 2,184. The reverberation time, by Sabine's formula, is then:

$$\frac{0.05\times 100{,}000}{2{,}184}=2.3 \text{ seconds,}$$

which will be seen from figure 1 to lie above the upper limit for organ and oratorio music, and to be much too great for a few instruments or a speaker. As the absorption of an auditorium is usually not adjustable to the type of performance to be given, a compromise is necessary, and in this case the mean of the upper and lower curves, about 1.3 seconds, will be a suitable value. This would require a total absorption of

$$A=\frac{0.05V}{t}=\frac{5{,}000}{1.3}=3{,}846 \text{ absorption units.}$$

Since the untreated room with full audience has 2,184 absorption units, there must be added by acoustic treatment 1,662 units.

The choice of an absorbing material is a question of appearance, price and convenience, and sometimes of the space available for acoustic treatment. It should be noted that it is not necessarily the case that materials of the highest coefficient are the most advantageous. Where there is space enough to apply the requisite quantity, a material of low coefficient will give better results than one of higher absorption, because of the more uniform distribution of material.

Assuming plenty of space, our problem is to replace a certain area of ordinary plaster, having a coefficient of 0.03, by a sound absorbent material so as to add 1,662 units of absorption to the room. Let us assume that the ceiling is coffered so that an area only 2,500 square feet is available for acoustic treatment. If it is decided to place all of the treatment in the ceiling then the coefficient of the material must be

$$\frac{1{,}662}{2{,}500}-0.03=0.63.$$

According to the formula, the room would be satisfactory if treated in the above manner, but actually when all of the treatment is put on a ceiling that is relatively high, the treatment is generally not entirely satisfactory.

A better treatment can always be obtained under the above conditions if part of the treatment is placed on the rear and side walls. For instance, if the above-mentioned ceiling is treated with a material having a coefficient of sound absorption of 0.35 at 512 cycles per second, then the absorption added to the ceiling is

$$2{,}500\times(0.35-0.03)=800 \text{ units}$$
$$\text{and } 1{,}662-800=862 \text{ units,}$$

which can be added to the rear and side walls. It is generally desirable to add a considerable portion of this treatment to the rear wall. As a rule, this means that only a portion of the side walls is covered and the acoustic materials have to be worked in as a panel effect. Frequently draperies can be placed at windows to give the additional absorption which is desired on the side walls. It is not desirable to apply many of the acoustic materials on the lower portion of the walls, where they are likely to be damaged.

In making the above computations, only the coefficient at 512 cycles has been considered. The Federal specification for acoustic tile states that the coefficient of sound absorption at 128 cycles shall not be less than one-eighth that at 512 cycles, and at 2,048 cycles it shall not be less than three-fourths that at 512 cycles. For sound studios and applications of a similar nature, the requirements are more drastic [6].

In the above example it will be noticed that all of the added absorption was placed in the auditorium and none on the stage. Experiments conducted by Watson [5] indicate that both speakers and musicians prefer reflecting surfaces about them to intensify the sound, whereas the listeners prefer absorbent material in their neighborhood.

IV. PLANNING AN AUDITORIUM

In planning an auditorium three factors must be considered—shape, size, and interior finish.

1. SHAPE

As stated in the section discussing echo, curved surfaces should be avoided unless great care is taken to have the center of curvature at a considerable distance from the source of sound or from any point where one would be listening. Unless this precaution is taken, an attempt to introduce such features for their artistic effect is almost certain to be detrimental to the acoustic quality of the room. Avoidance of curved surfaces and the use of a rectangular shape does not necessarily mean that a room will be acoustically satisfactory. One often hears that "the best shape for an auditorium is rectangular with dimensions in harmonic proportions of 1:2:3." Under this rule, the width of an auditorium would be twice its height and the length three times its height. Many auditoriums have been built which do not conform to this rule, yet they are accoustically satisfactory if they have an appropriate acoustic treatment. If a room is excessively long compared to the width and height, it is difficult to obtain enough sound energy at the rear of the room to make hearing conditions satisfactory. Also, if a room is excessively wide, hearing conditions will always be poor at the front on either side. A fan-shaped plan, with the source of sound at the narrow end, is one of the best forms of design from the standpoint of good acoustics. A more complete discussion of this subject can be found in a number of books on architectural acoustics [7, 8, 9, 10].

2. SIZE

The question of room size must be determined principally by the purpose for which the room is to be used. Modern amplifying practice makes it possible to use a very large auditorium for speaking, but if it is to be used without amplification the size is limited. Generally speaking, a theater must be moderate in size, whereas an auditorium for musical numbers, such as orchestral or choral performances, may be much larger.

This question of size has been discussed by Knudsen [7] for rooms where different kinds of music are to be played. He has reached the following conclusions: ". . . it is apparent that there is considerable latitude in choosing the most favorable size of music rooms. Experience has shown that if a small studio has a volume of about 3,500 to 18,000 cubic feet, if a recital hall has a volume of 18,000 to 100,000 cubic feet, and if a concert hall has a volume of about 180,000 to 1,000,000 cubic feet, entirely acceptable conditions will prevail from the standpoint of volume or loudness of sound, provided, of course, that the reverberation has been properly adjusted. As would be expected, oratorio, with combined orchestra and organ, requires a very large room, probably of the order of 500,000 to 2,000,000 cubic feet. The most sublime effects of oratorio can be obtained in spacious rooms." This problem has also been discussed by Lifshitz [11] and Glover [9].

3. INTERIOR FINISH

Interior finish should be planned with both echo and reverberation in mind. An adequate space in the form of panels or other areas should be set aside in the original design for acoustic treatment. Care should also be taken to see that these areas are properly located so that the acoustic treatment will be effective. As there is quite a choice in acoustic materials, it should be possible to make the acoustic treatment harmonize with the rest of the interior finish. As may be seen from the example worked out in section III, the sound absorption of the audience is usually a large part of the total absorption of the room. Almost any room will have passable acoustic properties with a capacity audience, but with half the seats empty, conditions may be very unsatisfactory. By the use of upholstered seats the absorption of the room may be rendered more nearly independent of the audience, but as a rule it is still necessary to place sound-absorbent material on the surfaces of the room.

It is generally considered that the reverberation time is independent of the positions of the absorbing material and the source of sound. In many cases, this statement is true, but there are some important exceptions. For instance, if the absorbing material is placed back under a balcony or in some other place where the sound intensity is low, the absorbing material will not be as effective as if it were placed where the intensity is greater.

Also, in many cases, the proper distribution of the absorbent material is as important as placing a sufficient amount of acoustic material in the auditorium. For instance, if all of the acoustic treatment is placed on the ceiling of a small room it may not be more than 50 percent effective [12], if the effectiveness of absorbent material can be judged by measurement of reverberation time. The reason for this is quite apparent. With no absorbent material on the walls there is a "flutter" effect or something similar to it, with a resultant prolongation of the sound. This is particularly true in small rooms. Even in large rooms it is essential, when two surfaces are exactly parallel, that one of them should receive acoustic treatment, if one wishes to avoid multiple reflections.

Where a public address system or sound motion-picture equipment is used it is necessary to avoid any large reflecting surfaces on the rear wall. In fact, such surfaces often cause trouble, even when there is no sound reinforcement.

V. NOISE QUIETING

Previous sections of this paper have dealt with rooms in which one is primarily interested in obtaining good acoustical conditions for either speech or music. It is probable, however, that not more than 10 percent of all the acoustic material that is sold is used in such rooms. The other 90 percent is installed in rooms or corridors where the primary object is to reduce the noise level.

One of the reasons for installing acoustic treatment in such places is well expressed in an address by Harry Arthur Hoff, delivered before the Chicago Chapter of the American Institute of Architects, as follows:

> Finally, we have to consider briefly the subject of noise. Acoustical conditions are largely affected by three factors, namely, size, shape, and materials. It is the one defect worthy of note in connection with the planning of large open offices that operating conditions are not conducive to quiet. This is, of course, mainly due to the fact that so much office machinery is constantly in operation and that the noise incident thereto is disseminated to all parts of the open area.
>
> The statement is commonly made that individuals can adjust themselves to noisy conditions and that they do not mind them. In point of fact, they are obliged to use energy in combating such conditions and this energy is therefore lost as far as its effective use for working purposes is concerned. Although it is difficult to adduce scientific evidence in support of the detrimental effect of noise upon production, long experience and observation of scores of offices lead to the conclusion that the difference between noisy and reasonably quiet conditions may be expressed in terms of about ten percent of the total output. Even though this figure cannot be verified, it is substantial enough when translated into terms of clerical costs to more than support the investment required to correct noisy conditions by the installation of acoustical treatment.

VI. CALCULATION OF NOISE REDUCTION

It is common engineering practice to express the reduction of noise level in terms of decibels, where acoustic treatment has been applied.

Where a_1 is the total absorption before treatment and a_2 the total absorption after acoustic material has been applied, we have the following relation

$$\text{Reduction in decibels} = 10 \log_{10}\frac{a_2}{a_1}$$

Figure 2 gives this reduction in decibels for various absorption ratios. This curve shows that as a rule it is not practical to reduce the noise level more than 5 to 8 decibels, as a greater reduction requires an excessive amount of acoustic material.

If the original sound level were 80 decibels and it were possible to reduce this level only 5 decibels, such a reduction would appear to be negligible. Fortunately, the apparent reduction in loudness as judged by the ear is greater than this amount. A considerable amount of work [13, 14, 15] has been done by different investigators to determine the relation between loudness level reduction in phons [2] and the percentage of loudness reduction as judged by the ear. The work of Fletcher and Munson gives a relation between what has been termed "loudness" and loudness level in phons [16]. Figure 3 shows their results in a somewhat different form from that given in the original paper. Referring to this curve, we find that if sounds in a room have

[2] The phon has been internationally adopted as the name for the unit of loudness. Previously, loudness level as well as sound intensity level has been expressed in decibels. The term decibels has been retained for expressing intensity levels.

a loudness level of 75 phons, and by means of acoustic treatment we lower this level 7 phons, the "percent loudness reduction" will be 42.

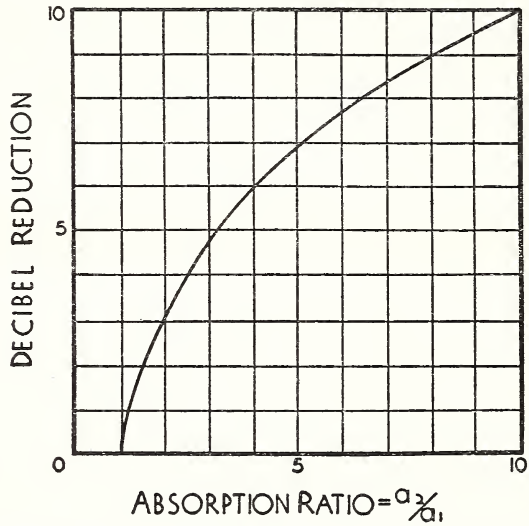

FIGURE 2.—*Relation between the decibel reduction and the ratio of the total absorption after and before treatment.*

In making such a computation we must remember that it is only an approximation as certain factors are variables. For instance, the absorption varies with the frequency. For this reason it has been

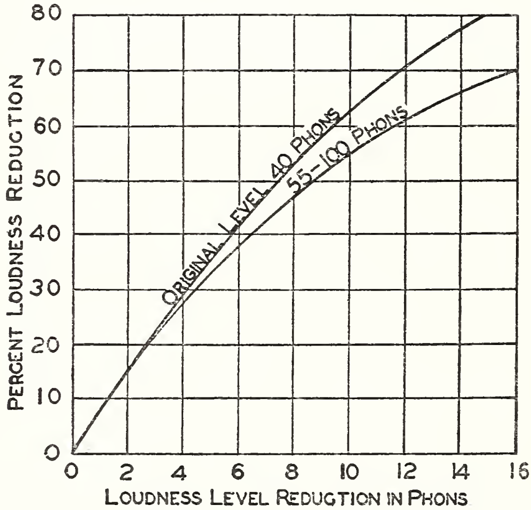

FIGURE 3.—*Relative loudness reduction as judged by the ear to loudness level reductions from various original levels.*

recommended by the manufacturers of acoustic material that a noise coefficient be used which is the average to the nearest 5 percent of the coefficients at 256, 512, 1,024, and 2,048 cycles per second. The composition of the noise also varies between different locations. The effect of a complex noise on the ear is not the same as that of a pure tone. These and other factors make the problem of computing the sound reduction a complicated one, but the method suggested above does give results which approximate what one hears, hence we are justified in using it until some better method can be found.

In fact, one is probably more interested in an annoyance factor than merely in the reduction of the loudness level. Everyone knows that some sounds are more irritating than others, but up to the present time no relation has been worked out between the character and loudness of a sound and the annoyance created by that sound. Until some satisfactory relation is worked out all the engineer can do is to reduce the loudness as much as possible.

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