No. 145

THE INSTITUTION OF
POST OFFICE ELECTRICAL ENGINEERS

# Room Noise & Reverberation as Problems in Telephony

BY

W. WEST, B.A., A.M.I.E.E.

**A PAPER**

*Read before the London Centre of the Institution on the 8th November, 1932, and at other Centres during the Session.*

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## INTRODUCTION.

About seven years ago a serious attack was launched by the Post Office on the general problem of the measurement of sound, the chief objective being the precise determination of the performance of acoustical apparatus (such as telephone transmitters and receivers) and the solution of allied problems. It was found necessary to construct special acoustical cabinets, whose interior surfaces should be capable of absorbing, without reflection, practically all the energy of sound waves reaching them. Methods were devised for measuring the sound-absorbing properties of materials; apparatus was constructed; and tests were made. It was realised that the possible number of different materials, and of different methods of assembly of the materials, is very great, and the investigations aimed primarily at a study of the processes of absorption sound by solids.

The apparatus was also employed for measuring the absorbing properties of a number of samples of proprietary and other materials, which have been suggested for the treatment of acoustical difficulties encountered in certain of the Department's offices, mostly switchrooms. During the course of these tests the author came into touch with a variety of cases of trouble attributed to faulty room acoustics, to the great advantage (to him) of widening the whole outlook on acoustical problems and phenomena generally.

The interest which has been displayed in this branch of acoustics has encouraged the writing of the present paper, which is intended to survey the subject of the acoustics of rooms and buildings—as seen from the standpoint of the telephone engineer. Attention will, for the most part, be confined to conditions usual in telephony, namely, when the speaker is close to the microphone and the listener hears from a telephone receiver, held to the ear. When the microphone is distant, even a foot or so, and a loud speaker is used for reception, the influence of room acoustics naturally becomes much more important, and the rooms themselves constitute definite links in the transmission chain.

In order to be reasonably self-contained, the paper includes some well worn extracts from acoustical publications, with which, however, it is not to be expected that telephone engineers are generally very familiar. It is divided into three parts, dealing respectively with :—

I. Definitions and Methods of Measurement.
II. Effects of Room Acoustics on Telephone Transmission, and
III. Methods for the Reduction of Room Noise and Reverberation.

## PART I.

## DEFINITIONS AND METHODS OF MEASUREMENT OF ROOM NOISE AND REVERBERATION.

2. The most important acoustical influences of a room, on sounds heard therein, are due to noise and transient distortions of the sound. The transient distortion is due to reflections of sound from the walls and other surfaces in the room. In most circumstances the most pronounced effect of these reflections is reverberation, and it is usual to measure the transient distortion in terms of the reverberation of the room, as will be defined later (Section 7).

### NOISE.

3. The most convenient definition of noise is, simply, all unwanted sound. The physical properties of noise are therefore restricted only to what is audible.

Methods of measuring noise may be divided into two classes, namely, objective measurements, for which instruments and apparatus do all the work except, perhaps, the recording of the test results, and subjective measurements, for which use is made of the hearing faculties of an observer.

4. *Objective Measurements of Noise.* It would appear that the minimum of apparatus required should include a high quality microphone (say, a condenser transmitter), a high quality amplifier with adjustable gain and a device for indicating or recording the electrical output from the amplifier. This device is usually in two parts, one for rectifying and the other a d.c. meter. Battery supplies and means

for routine calibration are obviously necessary, but inconvenient adjuncts.

The provision of this equipment, requiring a certain degree of technical skill for its proper maintenance and use, constitutes an awkward feature of objective measurements of noise in the present state of the art. There are, however, other difficulties yet to be finally overcome, by a proper standardisation of technique, as will now be indicated.

For exact measurement purposes a high quality microphone and amplifier are required, in order that there should be no considerable distortion. But if there is no frequency distortion the apparatus will not differentiate between sounds to which the ear is sensitive and insensitive, it can merely indicate the sum total of air-borne vibrational energy arriving at the microphone. For example, it might record the same reading for an audible tone as for an inaudible tone of different frequency, at which the ear is less sensitive. For this reason, in some practice, a distorting network is inserted in the amplifier, in order that the overall sensitivity to pure tones imitates that of normal hearing, as found by subjective tests on a number of observers (see Fig. 2).

The wave-forms of the sounds which may constitute noise can, of course, have any shape. Hence the method of rectification requires specification. For measuring the energy content, square-law rectification is indicated for obtaining r.m.s. values, but it does not follow that this is best for obtaining readings comparable with aural response.

In order to record a " noise level," either the noise must be level, or else it is necessary to take an average. Although many noise conditions appear to the ear to maintain a fairly uniform level of magnitude, there are as a rule rapid variations through extremely wide ranges. It is desirable in objective measurement that the averaging should be accomplished by the apparatus. This can be done by either or both of the rectifier and the indicating meter to any desired extent. The difficulty, however, lies in specifying a generally suitable method of averaging, and in unifying practice to the specification. Something has been done in this direction by the *Comite Consultatif International des Communications Telephoniques,** but the recommendations are restricted to measurements of speech, and different specifications are per-

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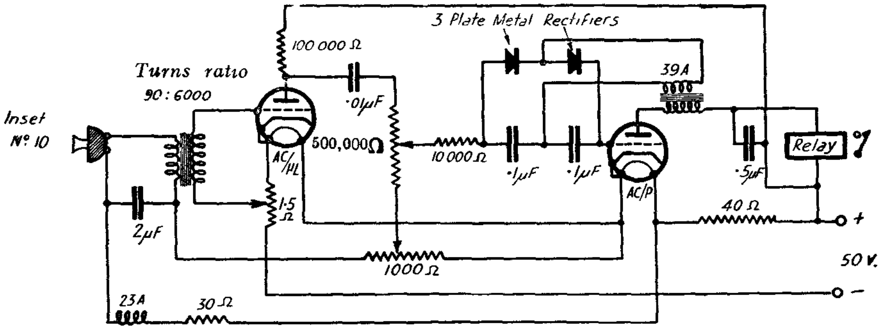
* Proc. of the Plenary Session of the C.C.I., September, 1931, 4th Commission Report.

mitted. This problem of averaging exists for measurements of speech volume and line noise, as well as for room noise, but there is little prospect at present of reaching any uniformity of procedure.

The difficulties just mentioned apply to the general question of measurement of noise. If it is desired merely to indicate relative magnitudes of noises of similar type, considerations of frequency-characteristic, methods of rectification and averaging are not so important, but the readings obtained will be particular to the instrument used, and observations on dissimilar noises will not necessarily be comparable.

A simple instrument of this kind—which may conveniently be termed a " Noise Indicator "—has been designed at the Research Station. The circuit—developed from a suggestion by the Telephone Section—for a model to work off 50 volts is shown in Fig. 1. Sound is picked up by a carbon microphone, followed by one stage of amplification and a rectifier (or A.C. Relay) incorporating the rectified reaction arrangement invented by Mr. L. H. Harris. When sound exceeds a certain magnitude for a sufficient length of time the relay operates, and the contacts can be used to light a lamp, or give any desired signal. The noise level required to operate the relay is controlled by the attenuator, which can be varied to measure this level if the instrument has been calibrated against noises of a similar nature and known magnitudes. In a later modification the carbon microphone



NOISE INDICATOR.

FIG. 1.

is replaced by a moving-coil microphone, with an additional stage of amplification, in order to overcome possible variations due to packing of the carbon granules.

5. *Subjective Measurements of Noise.* By making use of the ear, a considerable reduction can be effected in the amount of apparatus used. Some apparatus, however, is still required because memory of aural sensation is not to be trusted and a portable standard of comparison is therefore necessary. This standard may take different forms and can be used in different ways. Quite usually it is supplied as a tone from a telephone receiver, variable in magnitude by means of an attenuator. The observer then adjusts the standard tone until he judges it to be as loud as the noise to be measured. If an off-set ear-cap is used, so that both the standard tone and the noise can be heard simultaneously by the same ear, an alternative method is available by adjusting the magnitude of the standard tone until it is just inaudible—masked by the noise. These two methods may be termed " Balancing " and " Masking " measurements, respectively.

A measurement of this kind is fairly simple when the two sounds to be compared are similar in type; such a condition is, however, seldom obtained. As with most subjective tests, reliance should not be placed on a single observer, unless it has been found that his readings agree with the mean obtained from several observers.

The tuning-fork method, devised by Dr. A. H. Davis,* deserves special mention on account of the extreme simplicity of the apparatus required. The fork, used as the standard tone, is struck and held to the ear in a standard manner, and the time interval is measured by stop watch from the striking of the fork until the sound has reached either the balancing or the masking level.

Apparatus for measuring deafness can also be used for measuring noise, in fact the masking test gives a measure of the temporary deafness caused by the noise. A very useful instrument constructed for this purpose is termed an " Audiometer." It comprises an oscillator, capable of generating a pure wave at certain frequencies distributed in the audible spectrum, an attenuator, variable in 5 d.b. steps, and a receiver. The zero reading of the attenuator is set to give a tone in the receiver equal in magnitude to the normal

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* " Nature," Vol. 125, p. 48, 1930.

threshold of hearing at the frequency in use. The deafness of a patient is thus indicated by the attenuator reading at the adjustment to his own threshold when listening to the tone in a quiet room. For measuring noise the adjustable tone is used as the standard of comparison.

The disadvantages of subjective methods of measurement of noise are fairly obvious; either a considerable number of observers should be employed, or individual observers should have frequent practice in the measurement of sounds of known loudness. The advantages are fundamental, since the measurement is directly related to the function of hearing. The usefulness of objective methods is more apparent when analysis of the noise as well as measurement of its loudness is desired.

6. *Loudness Units.* Whatever method of measurement is used it is desirable to quote the results in terms of a common standard. The most generally accepted practice defines the *loudness* of a noise as the *sensation level** of a pure tone of 1000 p.p.s. which is judged by average hearing to be equally loud. Thus, if the subjective balancing method of measurement is used, the standard being a pure 1000 p.p.s. tone, then direct readings of loudness, in this system of units will be obtained if the attenuator is set to the threshold of normal hearing—as is the case with an audiometer of the type just described. The frequency of the pure tone is not very critical, since the loudness and sensation levels of any pure tones near 1000 p.p.s. are the same.

Fig. 2, the data for which come from Fletcher's book, "Speech and Hearing," illustrates some typical frequency-characteristics of normal hearing. The ordinates are pressures on the ear in dynes per sq. cm., r.m.s., to a logarithmic scale. For convenience a decibel scale is also shown, with 1 dyne per square cm. as the zero of reference. The abscissæ are frequencies in periods per sec., also to a logarithmic scale. The upper and lower curves are the well known thresholds of feeling and hearing, respectively, and the space between is known as the Auditory Sensation Area. The two full line curves in the area are loudness contours at 40 db. and 80 db.; that is to say that any point on one of these curves represents a pure tone whose loudness is, in the

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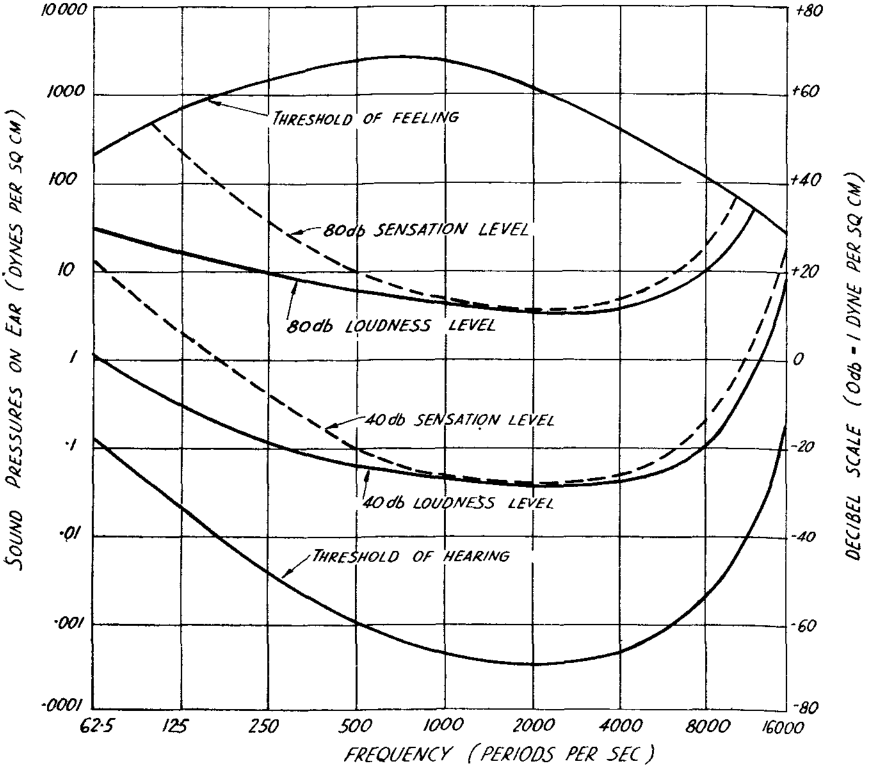
* The sensation level of a pure tone is the difference, in db., from the threshold of normal hearing; *i.e.*, the attenuation that would be required to reduce the tone just to inaudibility when no other sounds are present.



SOME FREQUENCY CHARACTERISTICS OF NORMAL HEARING

FIG. 2.

opinion of average hearing, equal to that at the point on the same curve at 1000 p.p.s. The broken lines are curves of sensation levels of 40 db. and 80 db.; these are based on the threshold curve, being respectively 40 and 80 db. above threshold of hearing at all frequencies.

It is clearly desirable that the loudness unit should be related to a magnitude capable of physical measurement, *i.e.*, that the pressure on the ear at the threshold level of the 1000 p.p.s. tone should be known. Measurements appear to vary between about 0.0003 and 0.001 dynes per sq. cm. It is believed that the question is receiving the serious attention of the Standardisation Committee of the Acoustical Society of America. In Germany a report on acoustical units has also recommended the use of the 1000 p.p.s. tone as a standard for gauging loudness values; but the standard itself is measured in terms, not of sound pressure on the ear, but of that of a free sound wave when heard in one ear only of an observer, facing the direction from which the sound arrives. By adopting the value 0.000316 dynes per sq. cm. to represent the threshold of the standard tone, loudness units are referred to a basis of physical measurement. With this system of units a sound wave whose pressure is 1 dyne per sq. cm. at 1000 p.p.s. has a sensation level of 70 db. Incidentally, the Germans have given the name " Phon " to the unit of loudness, the " Phon," as now defined, being numerically equivalent to the decibel.

## REVERBERATION.

7. The sound which is heard in an enclosed space, such as a room, is made up not only by that which is directly radiated from the source but also by that which is reflected from the walls and other solid surfaces. Naturally the reflections tend to augment the volume of sound in the room, they have, however, other effects. One of these is due to the fact that the velocity of propagation of a sound wave is only about 1,100 ft. per sec.; consequently it is possible for a perceptible time interval to elapse after a source of sound is started, or stopped, or changed in any way, before the readjustment of the sound heard in the room is completed. This phenomenon is termed reverberation.

8. *Interference Patterns.* Reverberation is, of course, not the only acoustical effect produced by reflections within a room. Not only the velocity of propagation, but also the wave-lengths of sound have finite magnitude—as judged by our ordinary perceptions; consequently the phase relationships between the initial and the reflected sound waves result in a complicated distribution of sound pressures within the room. That is to say, although sound energy may be practically uniformly distributed in the room, the kinetic and potential components, which are equal in a single progressive wave, are distributed in varying proportions in different parts of the room.

If a single note is sustained in a room for sufficient length of time for the attainment of steady-state conditions, regions of maximum and minimum sound pressure can be detected by ear, which responds to pressure variations. The distribution of regions of maximum and minimum pressure is often called an "Interference Pattern." While steady-state conditions last, the pattern is stationary, otherwise it is continually changing. Sounds usually heard in a room are not generally sustained and unchanged for sufficient time for the steady-state to be reached; for example, in speech a slight variation of pitch is usual, even during the enunciation of a single vowel sound.

9. *Echo.* The effect of reverberation is due to numerous reflected waves reaching the listener in rapid succession. If there is a time interval greater than about one tenth of a second between the initial and the reflected sound, the ear can appreciate the latter as a partially, or wholly separate sound, *i.e.*, as an echo. Naturally an echo is more usual in the open, but in large rooms, especially where there are concave surfaces, it is possible for reflected waves to arrive after sufficient time and with sufficient strength to give the impression of an echo superimposed on the reverberation.

10. *Reflection Images.* A useful indication of what happens to sound in a room is available by considering that the source of sound has reflection images in each of the boundary surfaces of the room. Each source, the real one or any of the images, will have an image in the plane of each surface. Hence the image sources extend outwards to infinity in all directions, becoming weaker as they proceed due to absorption and attenuation. Reverberation, thus interpreted, is due to the delay in the time of arrival from the distant image sources. When there is little to absorb the sound the combined effect of the image sources more than a mile away can be quite audible.

11. *Theory of Reverberation.* The simple theory, which is sufficiently accurate for our present purpose, may be stated in terms of the energy density E, assumed uniformly distributed throughout the room, at time $t$ after the sudden cessation of sound from a source which has previously been emitting sound energy at a steady rate W units per second. If the volume of the room is Q and the exposed surface area is S, the average coefficient of absorption* being

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* *i.e.*, the average ratio of absorbed to incident sound energy for a random direction of incidence.

$a$, then the energy density at time $t$ is

$$E = E_0 \epsilon^{-\frac{caS}{4Q}t} \qquad \text{.........................................(1)}$$

Where $c$ is the velocity of propagation (1,100 ft. per sec.)

$$\text{and} \quad E_0 = \frac{4W}{caS} \qquad \text{.........................................(2)}$$

is the energy density in the room during the steady-state, *i.e.*, before the source of sound was stopped.

Different absorption coefficients, $a_1$, $a_2$, etc., will be associated with different portions $S_1$, $S_2$, etc., of the surface area, so that the term $aS$ is made up by

$$aS = a_1S_1 + a_2S_2 + \text{.........................................(3)}$$

It is often convenient to designate the term " Absorption Units " to the product $aS$, which can be summed up by equation 3 for any room for which the appropriate data are known.

That the theory, outlined above, has its limitations is well known. It has, however, proved of great service for the treatment of reverberant rooms.

12. *Reverberation Time.* According to the theory the average sound energy in a room rises and falls according to an exponential law when a source is switched on and off—as does the electric charge on a condenser when current is switched on and off through a resistance. In the latter case it is usual to specify the exponential rate of growth or decay by a " time constant "—*i.e.*, the time required to change in the ratio $\epsilon : 1$. The same method could be used to specify reverberation, but an alternative, though essentially similar one is usual. Thus the reverberation time T of a room is the time taken for the average energy density to be reduced to one millionth after a source of sound is suddenly stopped.*

Quite recently it has become common practice to discard the reverberation time in favour of specifying the exponential rate in decibels per second—a method which has the advantage of applicability when variations from a truly exponential law are encountered. Since, however, such variations are not included in the subject matter of this paper, the generally

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* The ratio $1 : 10^6$ was used as a convenient representation of the relative magnitudes of just audible and normally loud sounds.

familiar reverberation time will be used. An energy ratio of one million is 60 db., hence a reverberation time T is equivalent to a rate of decay of $\frac{60}{T}$ db. per second. Also, from equation (1).

$$T = \frac{55.2Q}{caS} = \frac{.05Q}{aS} \text{ in ft, sec. units} \quad \text{(4)}$$

13. *Subjective Measurements of Reverberation.* The technique devised by W. C. Sabine is based on the measurement of the time taken, after a source of sound is suddenly stopped, for the energy density to fall from its initial, steady-state value $E_0$, to that value $E_z$ which corresponds with the threshold of hearing of the observer. If now the power W of the source is changed in a known ratio and the test is repeated, a different time will be measured, since $E_0$ has been changed in a known ratio, while $E_z$, for the same observer, remains unaltered. From these two observed times and a measurement of the volume Q of the room, the total absorption units $a$S in the room may be calculated by means of equation (1). The reverberation time T is thus found from equation (4).

Naturally it is desirable to make several observations, with different observers and levels of power, and to average to obtain a reliable result. It is, however, not necessary to assume that the threshold value $E_z$ is the same for different observers.

In order to carry out this test it is necessary that extraneous noise shall be practically absent from the room, and that the room shall be reverberant so that measurements are made of reasonably long time intervals. These requirements and the numerous observations necessary render the method, outlined above, not generally applicable to ordinary rooms. It is applied, therefore, chiefly in special reverberation laboratories, in which samples of interior wall surfaces, furniture, etc., can be introduced and their appropriate absorption coefficients measured. Thus a reasonably close estimate of the reverberation time of a room can be made by calculation, using equations (3) and (4). The difficulty, of course, lies in the collection of sufficient data, *i.e.*, in the measurement of absorption coefficients for all the interior surfaces of rooms.

An alternative method is available when the room to be measured is reasonably quiet and reverberant. A small organ pipe, blown by the mouth, may be used as a source of sound, and the time for the sound to die away to the threshold is measured in a calibrated reverberation laboratory. A similar measurement, by the same observer, made in the room under test provides sufficient data for calculating the reverberation time of the latter.

The reverberation time of a room is, of course, generally different at different frequencies, though the published frequency charts of reverberation of certain rooms show, on the whole, a fair degree of uniformity with frequency. It is usual for many purposes to take the reverberation time at 512 p.p.s. as average for the room.

14. *Objective Measurements of Reverberation.* If a high quality microphone and amplifier are used, the rate of decay of sound in a room can be measured by electrical apparatus. Since microphones generally respond to sound pressures, the electrical output includes irregularities due to the moving interference pattern during the decay. Hence an oscillographic record of the decay of a pure tone takes a form so uneven as to be difficult to reconcile with an exponential decay at all. The irregularities are considerably reduced by using a " warbling tone," *i.e.*, one of rhythmically varying frequency through a band of, say, $\frac{1}{4}$ octave or less, and this practice is therefore usual for objective measurement.

The oscillograph has frequently been used for such measurements; alternative methods include the measurement of time between pre-selected values of the electrical output from the amplifier (the process being made automatic by means of an electric relay operating a clock), and the measurement of the rate of decay by an electric bridge circuit.

## PART II.

## EFFECTS OF ROOM ACOUSTICS ON TELEPHONE TRANSMISSION.

15. *How the Contents of a Room affect Noise and Reverberation.* It will be necessary to distinguish between noise and reverberation, since the former can be shown to have measurable effects on the reception of telephone speech, while the latter, apart from augmenting the noise level, can create a sensation of discomfort, the effects of which can scarcely be interpreted in physical terms. First let us con-

trast the influence of the room itself on the noise and reverberation.

It can be seen from equation (2) that the average energy density of noise, due to a given source of power $W$ in a room, is independent of the volume $Q$ of the room. Since the total absorption units, $a$S, would be larger in a larger room—of similar construction and furnishing—the average noise due to a given source will be smaller in the larger room. The addition of furniture, by adding absorption units, also tends to lower the average noise.

It should, however, be remembered that it is not the average sound which is generally heard, because in any room sound due to a source is louder when heard near the source than at a greater distance. Thus, in an exchange manual switchroom, the internal noise is chiefly due to the voices of the operators. The loudest individual components of the noise, heard by any one operator, are the voices of the nearest operators, and the level at which she hears these would not depend so much on the acoustics of the room.

The average reverberation time (equation 4) is proportional to $\frac{Q}{.aS}$, hence for rooms of similar shape and construction, but different size, it is larger for the larger room in the ratio of the linear dimensions. The addition of furniture alters the room; it tends to reduce $Q$ (usually to a small extent only), and it adds absorption units to $a$S. The acoustical effect produced by adding furniture to a bare room is familiar; initially the absorption units at the wall surfaces are comparatively few, but the presence of carpet, curtains, upholstered furniture and the like, having a greater absorbing capacity, greatly reduces the reverberation.

16. *Effects of Room Noise on the Reception of Telephone Speech.* An investigation has recently been carried out to provide quantitative information concerning the effects of room noise on the intelligibility of telephone speech. Factors affecting the intelligibility of a telephone conversation may briefly be summarized as follows:—

(*a*) The volume and articulateness of speaking, and the speaking distance from the transmitter.

(*b*) The volume and articulation efficiencies of the circuit.

(*c*) The masking effect due to noise reaching the listening ear. This includes line noise and room noise at both terminations. The room noise at the speaking end is generally very small by comparison with the speech, when the transmitter is close to the mouth. At the listening end it can reach the ear by direct air-borne sound, by bone conduction, and indirectly by side-tone. The proportion of air-borne sound may depend critically on the fit of the receiver and its pressure on the ear.

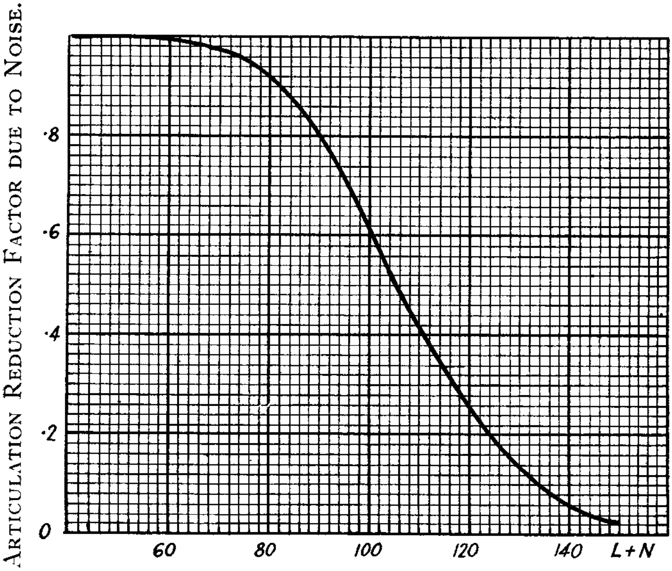
(*d*) The listener's acuteness of perception and the difficulty to him of the ideas transmitted. His concentration can be affected by fatigue or distracted by noise.

As a convenient measure of intelligibility, articulation tests are employed by telephone engineers; these aim to eliminate all factors except those attributable to the circuit under test, and are therefore usually carried out in silence.

In the series of tests investigating the effect of room noise, three controlled variables only were admitted, namely, the amount of room noise, the volume of received speech, and the side-tone at the receiving end. Elimination of other variables was aimed at by using the same, well-practised testing crew and the same telephone instruments for all the tests, the usual method of articulation testing being employed. Briefly stated, an articulation test is carried out by speaking a large number of meaningless syllables over the circuit under test, the listener being given time to write down the sounds he hears. The percentage of syllables correctly received is commonly known as the Articulation Efficiency of the circuit.

A few details concerning the tests may be of interest. The room at the listening end was a sound proofed testing cabinet, and the noise was produced by a loud-speaker supplied with the " warble-tone " current used for mechanical transmission testing. This tone is less variable than that from gramophone records of room noise, and consequently requires tests of shorter duration for obtaining average results. The current supply gave a steady reading on an A.C. milliammeter, which therefore was used for controlling the noise level. The noise level was measured, at different magnitudes, by balance against the 1000 p.p.s. tone of an audiometer, the readings giving therefore loudness units—as defined in Section 6. An average by 12 observers gave the noise level, which was thereafter maintained by means of the milliammeter.

A standard C.B. circuit was used with standard type transmitters and Bell receivers, a variable non-reactive junction line controlling the volume of the received speech. No control was imposed on the speaking volume of the testing crew, who were sufficiently practised to maintain reasonable uniformity. The volume of the received speech is therefore quoted in terms of decibels in the junction of a C.B. circuit, with instruments equal to the Department's standard, for a male voice speaking at normal loudness for telephone conversation. This system of units is probably the most convenient for general application of the test results; the speaking volume of the testing crew was measured for reference purposes, and variations of speaking volume would produce similar results to equal variations of circuit efficiency, *i.e.*, of attenuation in the junction.



L ( $> 15 < 50$ db.) = Volume efficiency of circuit in terms of attenuation in the junction of Std. C.B. Circuit with 300Ω local line.

N ( $> 40 < 80$ db.) = Room noise level in loudness units.

FIG. 3.

In the first instance let us take the case of no side-tone at the receiving end—a condition which is readily obtainable for test purposes either by replacing the exchange battery by a short circuit, or by shielding the transmitter from noise. It was found that the articulation efficiency of the circuit, in silence, was reduced by room noise at the receiving end by a factor which varies with the noise level and the volume efficiency of the circuit in the manner shown in Fig. 3.

The method of plotting the curve is based on considerations of the range of auditory sensation available between the wanted sound and the deafening level due to noise. The units employed for L and N have been described above, and the limits used in the tests are indicated in Fig. 3. These limits cover practical cases, but the curve may not apply if they are exceeded; for example, the articulation efficiency, in silence, is reduced if the volume efficiency is so great as to produce exceptionally loud sound in the ear.

The orders of magnitude of L which are commonly encountered are probably well known to telephone engineers; those of N may not be so familiar. It may therefore be mentioned that, loudness being relative, if we take as a standard an office containing a staff of several persons, a loudness of 50 units would be about average; 40 units would represent a quiet office and 60 units a rather noisy office. A condition of zero noise is, for most of us, an exceptional experience, and even 20 units would generally be classed as "practically silent." Fig. 4, which is reproduced from an article* by Dr. G. W. C. Kaye, serves well to illustrate loudness levels from noises of common occurrence.

As an example in applying the curve of Fig. 3, suppose that a circuit, whose articulation efficiency in silence is 70 per cent. is terminated in an office where the noise level is N = 50. Then if the volume efficiency is L = 30, side-tone being negligible, the actual articulation efficiency will be 70 × 0.93, *i.e.*, 65 per cent. If the volume efficiency is reduced to L = 40, due either to a change of circuit, or to the speaker lowering his voice or moving away from the transmitter, the articulation efficiency becomes 70 × 0.815, *i.e.*, 57 per cent.

17. *The additional effect of Side-tone.* The masking effect of room noise is increased by side-tone by an amount

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* "Nature," Vol. 128, p. 253, 1931.

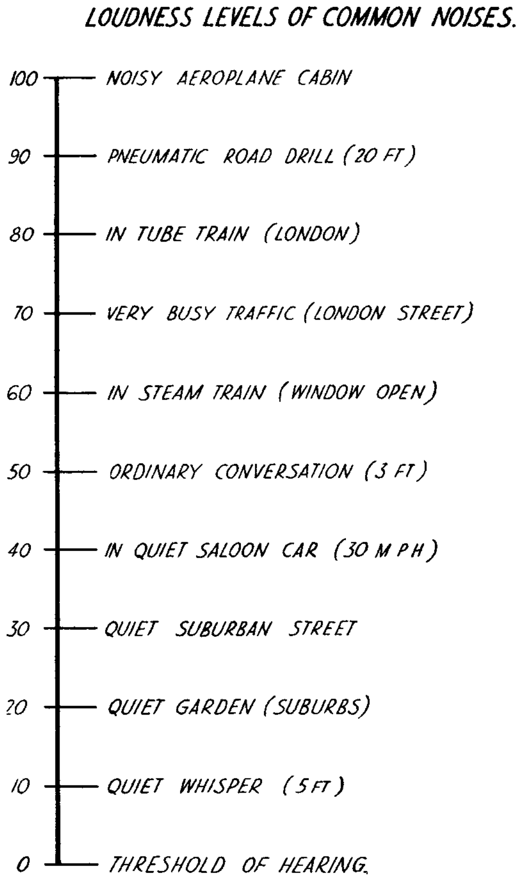
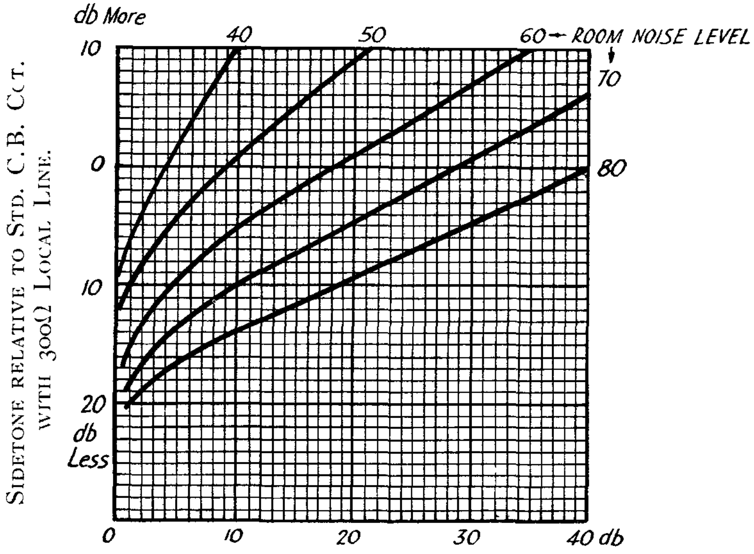


FIG. 4.

which depends on both the noise and the side-tone. As with volume efficiency, the standard used for quoting side-tone is the C.B. circuit with standard transmitter and Bell receiver and 300 ohms local line. The side-tone of a circuit is therefore stated as db. more or less than that of the standard circuit. Variations of side-tone were effected, without altering the receiving volume efficiency, by changes in the exchange battery voltage at the receiving end; and the side-tone was measured by as direct a method as could be devised for voice-ear comparison with the standard circuit.

Side-tone, as such, is a subject outside the scope of the present paper, but its influence on the effect of room noise at a subscriber's termination cannot be ignored. It was found that side-tone could be taken into account in the curve of Fig. 3 by an addition to N of the appropriate quantity as read from the group of curves in Fig. 5.



EFFECTIVE INCREASE IN NOISE DUE TO SIDETONE.

FIG. 5.

Take, for example, the case mentioned above of a circuit whose articulation efficiency in silence is 70 per cent., L = 30 and N = 50, and suppose that side-tone, instead of being zero, is equal to standard. The addition of 10 db., due to side-tone, makes the actual articulation efficiency 70 × 0.815, *i.e.*, 57%.

Or again, suppose that it is proposed to fit an anti-side-tone circuit, giving a side-tone reduction of 15 db., but involving a reception loss of 4 db., to an instrument whose side-tone is 5 db. greater than standard (*e.g.*, a C.B. termination with short local line). Since the difference between the curves of +5 db. and −10 db. side-tone represents an addition greater than 4 db. for all room noise greater than about 35 loudness units, it follows that the anti-side-tone circuit will give an overall improvement in reception in all except very quiet locations. If, however, the circuit had initially 5 db. less side-tone than standard, the anti-side-tone circuit will not improve reception unless the room noise appreciably exceeds 50 units.

These considerations apply, of course, only to receiving, not to sending conditions. When the microphone is close to a speaker's mouth, the speech sounds it receives are so much stronger than the reflected waves, or room noise, that the effect of room acoustics is practically negligible—apart from any psychological effect on the speaker. It is probable that a louder room noise causes a speaker to raise his voice, his sense of acoustic values being under the influence of his surroundings. This is a logical procedure for conversations in air; it is not necessary, though understandable, with telephone conversations. The speaker's reaction to room noise may, therefore, be interpreted as a tendency towards a gain in the sending volume efficiency.

18. *Application to Operators' Circuits.* The articulation measurements, described above, were carried out on a subscriber's circuit; the conditions of reception by an operator at the exchange differ in two important particulars. Heavy side-tone is more usual on the subscriber's instrument, in fact the side-tone effect on an operator's instrument is generally so small as to be negligible. On the other hand the operator's receiver is worn, not held by hand to the ear, consequently lighter pressures of fit to the ear are to be expected, involving greater penetration of noise, and weaker reception of the wanted sound.

The tests on the subscriber's circuit were made with the receiver held in the manner usual to difficult reception, *i.e.*, with firm hand pressure. Some other articulation tests have also been made in a phonogram room during busy times; the results indicate that an addition of 10 or 12 db. to the value of N is suitable, in applying the curve of Fig. 3, to allow for the looser fit of an operator's receiver. It is of course fairly common practice for an operator to press the receiver by hand when reception conditions are difficult.

19. *Effects of Reverberation.* Apart from the influence of reverberation—or rather of the causes of reverberation—on room noise, no very tangible adverse effect on a telephone

conversation can be reasoned—since neither the sent nor the received sounds are exposed to reverberation.

A measurement of reverberation time suffices for a calculation of the total number of absorption units in the room (equation 4), and the effect on room noise has been deduced, in Section 15, for a sound source of given power. When, however, the sound is due mainly to speech, the combined distortions of noise and reverberation cause individual speakers to raise their voices, thus increasing the noise heard by other speakers, and a sort of vicious circle is set up. This is a natural and common experience for air-borne sounds in rooms, wherein conversation is general; it probably applies also in manual switchrooms, although there is no necessity for raising the voice (on account of room distortions) for telephone speech. Although it is difficult to control one's voice to a level which is independent of the surroundings, the matter is worthy of attention in the training and supervision of operators, especially in cases where it is thought that the acoustics of the switchroom exert a bad influence on the service.

The complaints which have been received of faulty acoustics in switchrooms appear to be directed as much against reverberation as against noise; in fact many of these arise in newly occupied rooms which, to allow for development, are at present only staffed to a fraction of capacity. The noise level in such rooms is certainly lower than in many other rooms, with a larger staff, by whom no complaint is made; on the other hand the rooms are comparatively bare and empty and reverberation is very noticeable.

It is therefore difficult to account for the reasons of such complaints of reverberation affecting the service from the switchroom. It may be that the noise level, though comparatively low, is recognised to be larger than necessary, due to reflections of sound in the room; and it is well known that an unnecessary noise can be more annoying than one which is felt to be unavoidable.

There is, however, a wider aspect, in that excessive reverberation creates a sensation of discomfort, consequent on the distortion of sounds heard in the room. The fact that the telephone sounds are not subject to this distortion may not remove the sensation of discomfort. Similar discomfort is noticed in any room which is excessively reverberant, and it is an interesting commentary that complaints of acoustical defects in switchrooms have drawn attention to this acoustical discomfort, the consequences of which are often more severe in rooms used for other purposes.

20. *When is Reverberation Excessive?* The question whether the reverberation of a given room, used for a stated purpose, is excessive or not is one which can only be answered by experience—that is to say by the collective opinion of a number of persons accustomed to use rooms for a similar purpose. The information has been collected in a particular case, viz., the use of a room as an auditorium.

In this case too little reverberation is objectionable, as well as too much; in other words there is an optimum reverberation. The author is of opinion that a rough and ready rule, based on the recognised optimum reverberation time for an auditorium, would meet the majority of other usages of rooms, for which the acoustical conditions are not so important. Thus if T is the optimum reverberation time of a room of volume Q, when used as an auditorium, then for most other uses a reverberation time not greater than, say, 2T for the unfurnished room would not be considered excessive.

A rule of this kind is intended merely as a guide; we are working, not to an optimum value, but to an upper limit of what is tolerable. The rule is intended for application in cases where the furniture itself has little absorbing capacity—as is frequently the case in the Department's rooms. In domestic living rooms the furniture is usually such as to provide sufficient absorption by itself, so that the question of treatment of the room does not arise.

The following table shows the optimum reverberation time T (at 512 p.p.s.) for rooms of volume Q—used as auditoriums—and also the number of absorption units (obtained from equation 4) required to limit reverberation to the value 2T:—

TABLE.

| Volume of Room, Q, Cu. ft. | Optimum Reverberation Time, T, secs. | Absorption Units for 2T secs. reverberation. |
|---|---|---|
| 5,000 | 1.0 | 125 |
| 10,000 | 1.1 | 228 |
| 20,000 | 1.25 | 400 |
| 40,000 | 1.35 | 740 |
| 80,000 | 1.5 | 1330 |

## PART III.

## METHODS FOR THE REDUCTION OF ROOM NOISE AND REVERBERATION.

21. The reduction of room noise and reverberation can be effected by the application of simple general rules on the lines stated in sections 27 and 28. Some knowledge is, however, required of the behaviour of different kinds of solid materials to vibrations at audible frequencies. Exact quantitative measurements are not always available; but they are frequently not essential, common experience being sufficient to show whether a material is likely to be suitable for an acoustical treatment. In any case the performance of a material can depend very largely on the manner of its fixing or assembly, and there may be wide variations between different samples.

An outline only of the behaviour of solids to vibrations can be attempted here. It will be convenient to refer separately to the insulation of sound vibrations, isolation of sound waves, and absorption of energy from sound waves.

22. *Materials for Insulating Sound Vibrations.* This feature of the performance of the material is not concerned with sound waves in air, but with the transference of vibrations through the solid by any means of wave propagation.

Many types of noise originate at the junction of air and solid (*e.g.*, sounds of footsteps, slamming of doors, etc.). Vibrations are transmitted into both media; those in the air are heard as sound, those entering the solid may travel some distance through the solid. The latter may not appear as sound to an appreciable extent, unless the solid connects with a structure which can act as a sounding board.

Examples of materials which are good insulators of vibrations are felt, soft rubber, cork and leather. Good conductors are concrete, most metals, wood, etc. Similar laws govern the combining of insulators or conductors as in electrical circuits, but what would correspond with the *specific resistance* of a material is not a fixed quantity for the material; it probably depends considerably on the state of compression.

23. *Materials for Isolating Sound Waves.* The prevention of the transmission of sound waves in air across a solid partition is not difficult, unless the partition is so thin

as to bend, like a membrane, under the sound pressures at its surface. The density of any solid is great by comparison with that of air, consequently most of the sound energy incident on the surface will be reflected back into the air; and the small residue entering the solid will encounter similar reflection before it can re-enter the air, as a sound wave, on the farther side. Naturally the partition should not be porous in a manner to allow complete air passages through from one side to the other.

For a number of building partition constructions, observations by different investigators indicate that the equation

$$X = 25 + 15 \log_{10} W \quad \dots\dots (5)$$

serves, to a reasonable approximation, to relate the transmission loss, X decibels, across the partition with the weight W in lbs. per sq. ft.

Composite structures made up of two or more partitions, nowhere in contact except through insulators, are generally more effective than would be the same amount of material used as a single partition.

24. *Materials for Absorbing Sound (Non-porous surfaces).* It follows from the remarks in the preceding section that the transfer of sound energy from air to a non-porous solid surface must be very small indeed if the surface is substantially rigid—i.e., unless the surface actually in contact with the air is sufficiently flexible to vibrate with amplitude comparable with that of the vibrations in the air. Even when such vibrations of the surface do occur, they radiate sound, but they can also absorb energy by virtue of the fact that work is expended in the material by the forces vibrating it.

As an example of this process of absorption some tests may be mentioned which showed that sheet paper can give quite large absorbing values. The actual absorption coefficients obtainable would depend on the manner in which the paper is mounted and the forces of sound applied.

Surfaces of paint or distemper deserve special mention on account of their general use in rooms. As usually applied they present non-porous surfaces of a kind unsuitable for absorption of sound. No matter what material is behind, if it is completely painted over there can be little absorption.

Absorption of sound therefore requires that the exposed surface shall be essentially non-rigid; with non-porous solids this is difficult to achieve, consequently sound absorbents generally provide access for sound to porous surfaces.

25. *Materials for Absorbing Sound* (*Porous Surfaces*). When a solid is porous—not with isolated bubbles of air, but with crevices which interconnect to form small air channels throughout the material—sound can pentrate into and even through the air passages, without involving a transference of vibrations from air to a solid medium; hence copious reflection can be avoided. Absorption of sound energy is effected in the narrow passages by viscosity and heat conduction.

The amount of absorption obtainable depends on the number, width and depth of the passages and on the frequency of the sound. The width of the passages should be quite a small fraction of a millimetre, unless the depth is great. Low frequencies penetrate further than high frequencies, which are more rapidly absorbed. Thus a sheet of hair felt, $\frac{1}{2}$ inch thick, is a very effective absorbent at frequencies above, say, 1000 p.p.s. but is only slightly absorbing at low frequencies.

Fabrics of cloth, carpets, upholstery, etc., are familiar examples of porous solids of the kind suitable for absorbing sound. Linings of cotton waste or cotton wool are used at the Post Office Research Station on the walls of acoustic testing cabinets wherein reflections of sound are to be avoided. The linings extend to a depth, in some cases, greater than 1 foot, in order to deal reasonably effectively with quite low frequencies. In fact the only limits to the absorbing capacity of porous materials of this kind are imposed by the amount of material and the space it may occupy.

26. *Some Materials used for Sound Absorbing Treatment.* Cloth and similar materials are not generally suitable for the acoustical treatment of offices on grounds of hygiene, fire risk, etc.; they are, in fact, rigorously excluded from exchange manual switchrooms, except in the form of clothing of the staff and covering of jumper wires. There are, however, a number of proprietary materials, especially devised for assembly as interior wall or ceiling surfaces, capable of absorbing sound.

Among such may be mentioned porous plasters and tiles. Building board, mounted on battens and unpainted, is superior to ordinary plaster, but the compressed faces are not generally very porous and further absorption may be obtained by numerous cuts in the board to expose a larger and more porous surface. In the "Acousti-Celotex" treatment, for example, the cuts take the form of numerous perforations, 400 per sq. ft., each 3/16 inch in diameter. Mineral wool can be obtained which does not burn or harbour vermin, but is unsuitable for exposure in the room; it may be applied behind a porous or perforated surface which permits sound readily to pass through. For example, it can be laid over a false ceiling, perforated with numerous small holes.

In this connection it is of interest to observe that the fraction of sound which can pass through a perforated sheet of solid is greater than the ratio of the perforated to the unperforated parts of the solid, so that the surface, though apparently almost solid, is in fact transparent to sound. Exact calculation is difficult; it has been made in a few simple cases; for example, the fraction of energy reflected from a thick, solid wall, perforated by narrow channels, is $\left[\frac{x}{2+x}\right]^2$ where $x$ is the ratio of unperforated to perforated parts of the wall, so that if only one third of the wall is cut away, 75 per cent of the sound enters the channels. Or again, a grating comprised by long slits, each 0.5 cm. wide, spaced 5 cm. apart in a thin solid screen, transmits nearly 99 per cent at 200 p.p.s., 80 per cent at 680 p.p.s., and 46 per cent at 2000 p.p.s.

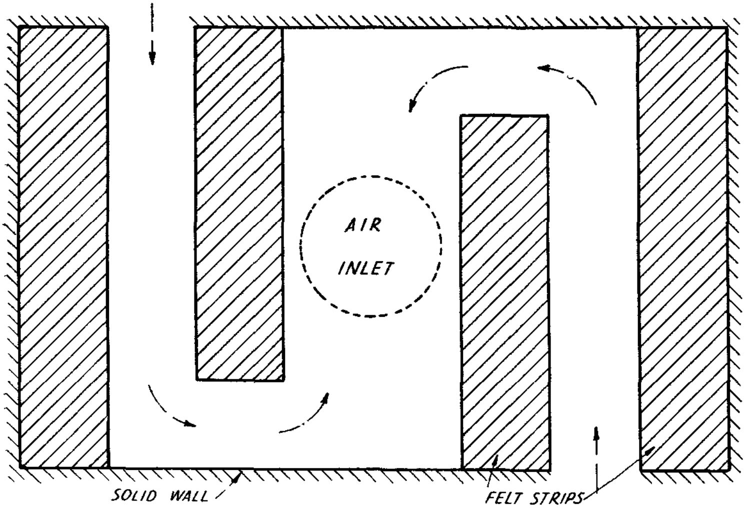
Proprietary methods of treatment applied to existing rooms are expensive, and an endeavour has been made to reduce the cost of treating switchrooms, where necessary, by devising a ceiling treatment combining the absorbing properties of cut building board and paper. The treatment can be made up in slabs, say 6 ft. by 4 ft., comprising a layer of paper, held in a frame of wood $\frac{3}{4}$ inch below the ceiling, and covered with strips of building board, 2 inches wide, spaced about 3/16 inch apart. Whatever method of treatment is used it should involve less expense if it is applied at the time of building than if it is added to the room afterwards.

27. *The Reduction of Noise in Rooms.* The general procedure to be recommended commences with a study of the sources of the loudest and most objectionable noises in the room with a view to their reduction at, or near the source, and if the noises are external, the prevention of their entry into the room. When it has been decided what steps can be taken in this direction, attention should be turned to the room

itself to determine the advisability of adding sufficient absorption units to make an appreciable reduction in the average noise level (see Section 15). In considering such a procedure it must, of course, be realized that there are always other and more important considerations to be taken into account, so that compromise is necessary. It is usual for acoustical considerations to receive insufficient attention during the design, construction and equipment of the room, with the result that when acoustical difficulties are encountered they are unnecessarily magnified.

If noise is due to machinery in a room, it may be possible to effect an appreciable reduction by a modification of the mechanism. When this is not feasible the machine can, perhaps, be partially or wholly isolated from the rest of the room by a suitable cover.

As an example of the application of acoustical principles, let us consider a design for the screening of a small, noisy machine which does not require frequent manipulation. First, suppose that a complete sheet-iron cover is made to fit over the whole machine; this cover will be reasonably effective for the isolation of air-borne sound, but it may not be satisfactory. In fact, it is possible that more sound may be radiated with the cover on than when it is off; the reason being that vibrations, transmited through solids, are radiated by the cover, which would act as an efficient sounding board, especially at the lower frequencies. It would therefore be desirable to stand the machine and cover on separate sound insulators (see Section 22). There is now no allowance for ventilation unless holes are cut in the cover; these, however, allow some air-borne sound to escape. The admission of air, without much sound, to or from an enclosure, can be effected by providing a fairly long ventilating duct, lined with absorbing material. In the case we are considering, instead of cutting holes in the cover, let the air inlet be through a hole in the base-board of the machine, and let this board rest on strips of felt, arranged as indicated in Fig. 6. Then sound leaving the hole will be attenuated in its passage past the felt. Still more attenuation is available by standing the whole on an under sheet of felt, and the felt serves the additional purpose of insulating the machine. An air outlet could similarly be arranged as a top to the cover. Finally, a lining of felt on the inside of the cover lowers the noise level inside the enclosure (and therefore the amount of sound which escapes) and tends to reduce any vibrations of the sides of the cover.



PLAN OF VENTILATING BASE FOR SMALL MACHINE.

FIG. 6.

When frequent manipulation of the machine is necessary a complete cover is inconvenient, but it may be possible to make use of a partial cover, leaving access to parts of the machine, as is done in the case of teleprinters. If a few small apertures only are exposed, low frequency sounds are radiated from these at low efficiency and high frequency components would mostly be subjected to several internal reflections before escaping. If, however, the machine is running with faulty adjustment, or if the cover is not effectively insulated, the noise is enhanced. With some designs of teleprinter cover so little clearance is allowed between the machine (and its base board) and the cover (and any connected metal parts) that faulty insulation is frequently to be expected, resulting in unnecessary radiation of sound by the cover.

Typewriters provide a very difficult problem in acoustical screening. Sound absorbing surfaces placed round and over the typewriter—in such manner as not to hinder manipulation —are effective to an extent determined chiefly by the solid angle which they subtend at the source of noise, and their capacity for absorbing sound. The noise contains chiefly high frequency components. This method of acoustical screening of typewriters has obvious disadvantages. The neatest method of reducing room noise due to typewriters is the reduction at source by the use of more silent machines.

When noise is mainly due to speech, reduction at the source is practicable only if the speakers can be persuaded to lower their voices, either by instruction or by a suitable change of their acoustical surroundings. The influence of reverberation has already been mentioned (Section 19); the size of the room may also have some bearing, and if a large room may conveniently be sub-divided by partitions, acoustical difficulties will be reduced—they are generally less troublesome in smaller rooms. It is also to be expected that, as far as room noise is concerned, local applications of sound absorbents near the speakers would be rather more effective than the application of the same absorbents at more remote positions.

Another consideration of particular interest in connection with operators' positions in switchrooms, etc., is this: if the positions are packed close together in one part of the room the noise is concentrated at this part of the room—where it is least desired—and the noise level here is greater than the average for the whole room. If, however, the positions are well distributed throughout the room, the noise level at any one position will be lower.

If the source of noise is external to the room, and not susceptible to direct acoustical treatment, the problem devolves into one of effectively sound-proofing the room. Adequate sound isolating materials (see Section 23) are required for the walls, floor and ceiling and, in addition and especially, the entry of air-borne sound should be restricted. This latter is often the more difficult part of the problem and it may involve a special ventilating scheme. Ventilation to restrict noise, requires either that the air shall be taken to and from a quiet locality and shielded from sound in its passage to the room, or else that the ducts conveying the air shall be lined, for a sufficient length, with some sound absorbing material.

Street traffic noise is a particular and important case in point. With the usual building constructions ventilation depends mainly on the windows, and if these are open it is very difficult to prevent the entry of noise. When, therefore, a building is to be erected adjacent to a noisy street, it is only reasonable to arrange, as far as possible, that rooms required for any purposes for which noise is an important consideration should not depend for ventilation only on windows overlooking this street. It is recognised, for example, that a quiet room is very desirable for operators receiving phonogram messages, hence acoustical considerations deserve attention in the selection of rooms to be used for this purpose.

When all practicable steps have been considered for reducing the noises created in or entering the room, attention may be given to the question of introducing absorption into the room. It has already been mentioned that, for a source of noise of constant power the average energy in the room is inversely proportional to the total number of absorption units; and also that, if the noise is chiefly due to speech, the addition of absorption may influence speakers to lower their voices.

28. *The Reduction of Reverberation.* The obvious procedure for reducing the reverberation of a room is the introduction of additional absorbing surfaces into the room. As a general rule the position of the absorbent is of minor importance in its effect on reverberation, a distributed arrangement has, however, sometimes been found to give greater absorption than a concentration of the same quantity at one position. An effect of this kind is shown up by absorption tests of samples with different methods of assembly; in any case it is important that a material introduced as an absorbent should be assembled in a similar manner to that used for the tests, in order to obtain the absorbing value attributed to the material. In particular, if any painting or other finishing process is to be applied, enquiry should be made as to the effect on the absorption coefficient.

For a permanent treatment the ceiling, or upper part of the wall, is generally the surface chosen for covering with sound absorbents. In effect, the treatment thus comprises a false ceiling under the hard surface, and its presence is unobtrusive. Where it is convenient to apply an absorbent as a partial or complete partition, additional reduction of reverberation results from the reduction in the volume of the room.

## IN CONCLUSION.

It will be of interest just to glance at the wider problems involved in the field of loud-speaker reproduction—including sound films, gramophones and radio broadcast reception. In this connection may be mentioned a paper by Ashbridge entitled, "The Acoustical Problems of Broadcasting Studios" ("Engineering," pp. 505 and 537, October, 1931).

Consider first the auditorium with no electrical transmission, the audience hearing the sounds direct from the artists, as in theatres, concert and lecture halls. Noise is easier to deal with than in many of our own problems; there is little to cause internal noise—apart from the audience—and there is no point in reducing the penetration of external noise to a level much below that usually to be expected from the audience. Moreover, ventilation need not, as a rule, depend on windows overlooking a street.

Reverberation, however, is of great importance and it varies with the number in the audience. In order to give their best the artists require proper reverberation; also it is not sufficient only to consider average reverberation (as we have done). To ensure proper hearing in all parts of the room the paths of the direct and the more powerful reflected rays are studied. Reinforcement by reflections is desired by distant listeners, but it is also important that the time between the arrivals of the direct and reflected sounds should not be so great as to give an echo effect.

With loud-speaker reproduction the problem is at the same time simplified and complicated. Simplified because artists and audience are in separate rooms and the sometimes conflicting requirements of each are separated; complicated because two rooms are involved and the placing and directive properties of microphone and loud-speaker are additional factors to be considered. It would seem that the ideal to aim at is to make the room at the sending end suitable for the artists and to the programme, and that at the receiving end acoustically neutral. An electrical transmitting system is capable of great flexibility; for example, a highly directive microphone facing a speaker in a reverberant room will transmit his voice, eliminating much of the reverberation. If at the same time another microphone is used, not directed to wards the speaker, and the outputs combined, the reverberation effect can be brought into the transmited sound to an extent which can be varied by the proportions contributed by each microphone.

When a microphone and loud-speaker are used in one room, as a telephone circuit termination, the avoidance of oscillation due to acoustic coupling often presents a difficulty.

The problem is essentially one of side-tone reduction, but the acoustic coupling is increased by reflections of sound, so that an arrangement which is satisfactory in one room may oscillate in another if there is insufficient margin for the variation of acoustic coupling.

Finally, to revert to the subject of our own acoustic difficulties, the main object of this paper has been to state these difficulties, their causes and effects and the means at our disposal for minimising them. Apart from some technical jargon—inevitable in all arts and sciences—little technical knowledge is involved; in fact, it is feared that at times the obvious may have been unduly stressed. However, prevention is better, and cheaper, than cure, and it is typical of the general neglect of acoustical considerations that although, in Technical Instructions, details of interior decoration of switchrooms and the like are laid down, even to the colour of the paint to be used, the possibility of acoustical difficulties or discomfort is ignored. If the matter is regarded only from the point of view of physical comfort, it may surely be contended that excessive noise or reverberation can be as much an offence against the ordinary amenities of life as unsuitable illumination, inartistic decoration, or uncomfortable furniture.

# NOTES OF THE DISCUSSION

Captain B. S. **Cohen** :—

The subjects which Mr. West has treated in his paper are undoubtedly of very considerable importance, and I am fully in agreement with his conclusions and particularly with his last statement.

I firmly believe that money spent on acoustical treatment of offices, switchrooms, and similar places would bring in substantial returns, and there appears to be little doubt that architects will, in the future, have to consider the acoustics of all classes of rooms.

One telephone development of the future particularly emphasizes the importance of acoustical treatment of rooms: I refer to the possibility that telephone instruments will develop on such lines that the receivers will emit speech at conversational levels, and the transmitters will be capable of operating at considerable distances from the speaker's mouth—say, two to three feet. Instruments of this type have, in certain circumstances, considerable advantages from the point of view of convenience, but they are affected by room reverberation to an extent which is, I think, not completely explained.

As an example, a microphone placed at, say, 3 ft. from a speaker and connected to a receiver in another room is considerably more affected by reverberation than is the case when the microphone is replaced by a person at the same position in the room. The usual explanation—that the difference is due to monaural reception in one case and binaural in the other—is not borne out by trials with two microphones connected binaurally. Also a person with one ear closed does not experience this difficulty of reverberation to anything like the same extent, and I would ask Mr. West whether he considers that the effect might partly be due to the differences between the acoustic pressure sensitivity of the ear at varying distances and directions as compared with the sensitivity of the microphone.

A committee on Architectural Acoustics has recently been considering two interesting cases—the Assembly Hall of the League of Nations, and the Shakespeare Memorial Theatre at Stratford-on-Avon. It is of interest to note that, in their recommendations they stressed the importance of the use of carpets and the incorporation of sound absorbing materials in the seating accommodation.

As regards side-tone, this is an important factor in telephone efficiency, and one on which it is extremely difficult to get any quantitative data in the laboratory. The difficulties have led to a study of what is known as effective transmission by methods which are not directly applicable to laboratory measurements, and one of the methods which has been investigated in America is the repetition rate, *i.e.*, the measurement of effective transmission in terms of the number of repetitions due to unintelligibility in a certain length of telephone conversation. We are now carrying out measurements to find out the effects of side-tone and other characteristics by the repetition rate method at Denman Street, where an observation board has been installed for the purpose.

It is probable that the use of anti-side-tone devices has progressed further in America than here. We have, however, introduced anti-side-tone devices in our latest telephone, and there is no doubt that we shall never introduce a telephone in future with a circuit whose side-tone effects have not been carefully considered in relation to the over-all efficiency and the level of noise to be expected in typical telephone installations.

In American cities the conditions are undoubtedly very different from those in this country, and the general noise level is decidedly higher. The liability to side-tone is also greater because the local lines are short, due to the very great telephone density and to the fact that the telephone distribution there is generally in three dimensions instead of two. In New York, for example, there are some 200 large central offices, and in one case—West Street Office—there are six separate telephone exchanges with a total of about 120,000 lines. Furthermore, in the big skyscraper buildings there may be as many as 5,000 telephone subscribers in one building; in the new Empire State building 7,000 subscribers are anticipated. This means that the local lines are extremely short, the instruments receive the full exchange battery voltage and side-tone effects are much more important.

Mr. E. P. Fairbairn :—

I should like first of all to congratulate Mr. West both on his paper and on his choice of subject. Until recently acoustics have hardly been considered by the telephone engineer and little has been known about the subject.

In a telephone conversation, sound must be converted into electrical energy; two people must be connected together, and the energy must be transmitted between them. The connecting together of the two parties and the transmission of the energy have been largely investigated, but the conversion of sound into electrical energy has hardly been touched and it is only very recently that any attempts have been made to perform it efficiently.

There are three points which particularly interest me at the moment and on which I should like to ask questions.

In his paper Mr. West states that side-tone has not much effect at the transmitting end of the circuit, but there are two effects which I should like to know whether he has investigated. First, a speaker using a telephone in a noisy place has a tendency to raise his voice because of the noise, but the person at the other end does not notice the noise because the speaker's voice is greater than the noise. The speaker gets the side-tone in his own ear and so raises his voice which probably causes the speech at the other end to be too loud. The speaker at that end consequently drops his voice thereby further accentuating the difficulties of the first speaker so that he still further raises his voice and a vicious circle is set up. I wonder whether Mr. West could enlighten us on this matter.

Secondly, there is the influence of side-tone on the voice of the speaker. In comparing circuits with different amounts of side-tone two methods may be used, first the standard method in which the speaker does not hold the receiver to his ear and the second in which he does hold the receiver to his ear. The first method gives the true efficiency of the circuit and the second gives more nearly the conditions of actual use. In a particular test made recently comparing a standard circuit with one on which the side-tone was about 15 db. below the standard, the first method gave a transmission efficiency of about 4 db. worse and the second 2.5 db. worse. A purely electrical test on the same circuits showed that 4 db. worse was about the right value. It looks then as if a speaker expects to hear side-tone at a certain level and, if he does not, raises his voice until he does. The question is whether this effect has been noticed in his tests and whether in his opinion circuits with low side-tone, even at the cost of transmission loss, might not in use give better results.

One other point with regard to the exclusion of noise from rooms. Mr. West showed a slide of a method of silencing machines. Could the same scheme not be adopted in regard to windows that open on a noisy street? Could not a gap at the bottom of a window be used to allow the inlet of air without noise?

Dr. G. W. SUTTON :—

The summary of " factors affecting intelligibility of a telephone conversation " on page 15 omits what is, in my opinion, a most important point. I refer to the ratio of the level at which the listener hears his own side-tone to that at which he hears the received speech. Subsidiary to this is the extent to which the listener's circuit distorts the speech sounds heard as side-tone. The ratio of these levels depends, of course, on the type of telephone and on the line connection set up, but under present conditions it is by no means uncommon for the side-tone to be 20 db. louder than the received speech.

In my experience the high level of distorted side-tone in the present standard circuit temporarily deafens the listening ear and renders it quite unfitted to deal with the received level, especially in those only too numerous cases where the latter is already too low for comfort. This is particularly true when the listener makes some interjection, perhaps in an excited tone of voice. Should he happen to be on a short line the side-tone level may even approach the threshold of pain.

On page 16 the author states that " warble-tone " current was used for providing room noise. We also have found that noise records are inconveniently variable for such tests as those mentioned, but we would suggest that the " warble-tone " is a bad substitute owing to its lack of low-frequency components. The masking effect of low-frequency sounds is a well known and important factor in the effect of side-tone, and in the Telephone 162 the low-frequency " acceptor " circuit formed by the 2 $\mu$F condenser and the receiver make it even more important. For this reason we have been using the noise from a large machine-shop, picked up by a condenser microphone suspended in the roof, as our source of noise for such tests as are described by Mr. West.

There is one other point of considerable importance which I should like to raise. There is a strong tendency at the present day to add " db." of various quantities together in what appears to me to be a very haphazard manner, apparently because the quantities all happen to be recorded in db. In the present paper this is exemplified in Fig. 3. I should like to ask Mr. West if he would have added M.S.C. of junction attenuation to db. of noise with as little hesitation as he has added db. of attenuation, apart, of course, from the slight difference in size of the units? It may be that the experimental results justify the procedure he has adopted, but I would suggest that this should be most clearly stated if it is the case. It is a salutary warning, in this connection, to bear in mind that not even sending and receiving allowances can be added arithmetically—although they are both measured in db.

Mr. E. R. WIGAN :—

In section 6 of the paper, and the previous section, it is stated that the subjective method of testing loudness is uncertain by reason of the variation of the hearing loss in various individuals, yet three paragraphs later this variation is given in figures which show it to be no more than ±5 db. That this is a relatively small quantity is proved by the audiometer referred to in the paper being calibrated in 5 db. steps. The variation among the observers is therefore only twice the probable experimental error. Surely this is small enough to render the subjective method fairly accurate. Or are these figures exceptional?

From the description given in the paper no one would guess the chaotic state of noise measurement and noise units. The latter point is considered, but the relative merits of the subjective and objective methods of noise measurements are rather lightly touched on. I think it is not out of place to consider this matter in greater detail since only by the accurate measurement of a quantity like noise can we hope to make any headway in understanding its effects. At present there are three or four ways of measuring a noise and each of them gives as a rule a different answer. The fact that they all give their answers in decibels only adds to the confusion. Of these methods I have found the subjective masking method, using a tuning fork or an audiometer, to have much to be said for it. The tuning fork test is extremely simple and surprisingly consistent in its results. In the paper emphasis is laid on the necessity for an objective method for the measurement of noise. But the test gear usually recommended appears to me to be lacking in an important feature which the subjective test retains. In the latter method the ear itself is the indicator, and it must be remembered that the ear has a non-linear transmission characteristic. In the objective tests the amplifiers usually employed have linear transmission characteristics. By this I mean that these circuits are usually designed to give a measure of the pressure on the diaphragm of the associated microphone. If the pressure is multiplied by 1.000, the indication is increased 1,000 fold. In the ear, however, the ratio between the pressure transmitted to the inner ear and the external sound pressure is not a constant: it becomes greater as the amplitude of vibration of the ear-drum grows.

This is a most important difference and it seems to me that unless this non-linearity of the ear-drum system is simulated in the objective measurement no true indication of loudness can be given by the associated measuring instrument. It is usual to make allowance for the variation of the sensitivity of the ear over the audible range of frequency by giving the amplifier system a distorted frequency characteristic to fit the " equal loudness " curves shown in Fig. 4 of the paper. It is a mistake to suppose, however, that since these curves are marked " equal-loudness " the amplifier system will therefore give a true indication of loudness.

These " loudness contours " were obtained in the first place by comparing pairs of single pure tones, one of the frequency under consideration, and the other the standard 1000 cycle test tone. They do not necessarily apply to the case of a number of mixed tones, on account of the non-linearity of the ear. (Actually even the pure tone curves show signs of this non-linearity by their shape, at the higher levels of sound pressure). The fact is the ear mechanism produces a host of distortion tones, octaves, sums and differences of the tone sounds and it is these which in conjunction with the undistorted sounds ultimately affect the brain and produce the sensation of loudness. It seems reasonable therefore that an objective test should be designed to produce similar distortion terms for the indicating instrument to record, if it is intended to give a true measure of loudness.

Perhaps Mr. West has investigated the value of a stage of amplitude distortion in a noise-measuring system.

I am emphasising this point because I have found, and I believe many others have found that the various subjective methods of measuring noise do not agree among themselves, and until these matters are cleared up there will be more than a tinge of doubt about the meaning of any loudness value, read from a calibrated amplifier.

For example you may test the loudness of a complex noise produced by a loud-speaker by cutting down the current till the noise vanishes. The fall in current may be 80 db. The original noise level is then considered to be measured as 80 Sensation Units. If, however, it is measured by a masking test, such as by an audiometer or by Dr. Davis's method, the loudness may be recorded as 100 units. Thirdly, an amplifier system with a so-called " equal loudness " characteristic will probably give a reading either intermediate or agreeing with the first. Which is right? Twenty db. is a large quantity, even in noise units.

My third reason for a preference for the subjective loudness test is based on some work which very much resembles Mr. West's investigation of the relationship between articulation and noise. My work, some of which was drawn upon for the article on " Side-Tone " in the current issue of *The Post Office Electrical Engineers' Journal,* seems to show that if you measure noise by a masking, that is a subjective, method, you obtain results which are easily explained, whereas, if you use the rather unfortunately named Sensation Unit your results are extremely difficult to understand. I have applied this test to Mr. West's curves of Figs. 3 and 5 with some interesting results.

In Fig. A I have replotted his results. I wish to draw attention to the comparatively steep slope of the lines marked + 10, 0 and − 10. These curves have been drawn by plotting out the overall attenuation L against the noise level N, assuming that the two quantities are so adjusted that for every point on the curves shown, the articulation is kept constant at a value of 30%. I have assumed a reduction factor of 0.4, in taking the points off the curves of Fig. 5. At an articulation of 30%, intelligibility shows signs of deteriorating

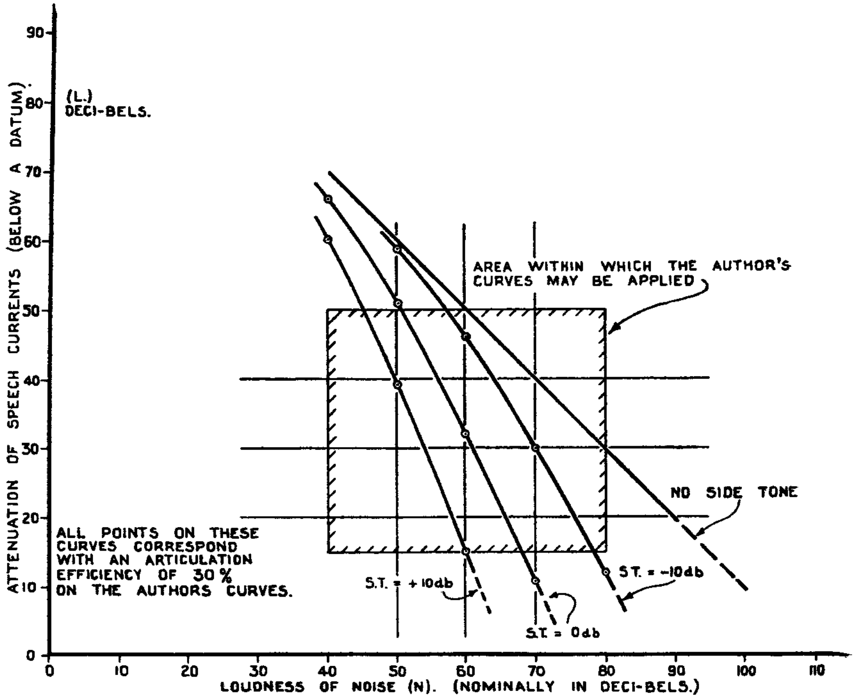


FIG. A.

rapidly. One might expect therefore that on these graphs an increase of the noise level N would always be combined with an approximately equal decrease of attenuation L in order to maintain the intelligibility at the threshold value. This would doubtless be true if the noise were measured in actual *loudness* units. The lines on the diagram would then all slope at something less than 45 degrees. The only one which does so, corresponds to zero side-tone. The fact that the lines corresponding to the various side-tone levels + 10, 0, − 10 have about twice this slope suggests that the method of measuring the loudness of the noise is not beyond suspicion.

I have found that similar curves, obtained in a slightly different manner in my own work, had the same excessive slope until I had re-assessed the noise levels by a "masking" test instead of in terms of sensation units. When they were corrected in this way they showed a slope at all points less than 45°, and gave excellent agreement with the Weber-Fechner law of sensation, when the influence of the two ears was allowed for.

In this way the masking method of measurement was checked from two points of view. It seems to me that any objective measurement should pass a similar test before it can be accepted as measuring the same quantity as is heard by the ear. Meanwhile a number of different ways of measuring noise are in general use, all of them employing decibels as units, and each apparently recording different values. When the long overdue move is made to co-ordinate these tests I submit that the masking or disturbance effect of the noise should be made the criterion in determining loudness.

If this is done the measurement of loudness will give results which, as I have shown, do agree with the deductions made from the known laws governing the behaviour of the ear, and so far as we are concerned with the matter as telephone engineers, it is the ear's point of view which should influence us in our choice of units of measurement.

Capt. N. F. CAVE-BROWNE-CAVE :—

For the non-expert, though all the main points in the paper are very clearly brought out, some of the terms used could perhaps have been a little plainer. Mr. West mentions, for example, the " magnitude " of noise, of sound and of tones; the " volume " of sound, of speech and of received speech; and the " loudness " of noise. He uses the terms " volume efficiency " and " receiving volume efficiency " in a way which is no doubt quite familiar to experts. But the non-expert finds it difficult to understand how, (as in Fig. 3), we can add together volume efficiency L and Noise Level N; and how, (as in the last para. of Section 16), " if the Volume Efficiency is L = 30 " it can happen that " the volume efficiency *is reduced to* L = 40." Actually L seems to be a measure of the attenuation of the original speech, and I feel sure that the non-expert will more clearly understand Sections 16 and 17 and Fig. 3 if he everywhere substitutes " Volume Level " in place of " Volume Efficiency."

The general utility of the paper would be increased for many of us if he would add two appendices giving :—

(1) The absorption coefficients of the usual components of a Switch Room, and also of some recognised practical absorbents suitable for use therein, and

(2) The noise levels actually measured in several Switch Rooms of different type, and also what may be regarded as acceptable noise levels therein.

The provincial Engineer wants to be able to measure noise levels and reverberation times cheaply and easily without having to go to Dollis Hill to be personally calibrated. Would it be possible to produce a series of charts, suitable for engineers with different hearing powers, such charts to be used in the organ-pipe test which is described by Mr. West? The individual engineer would himself select his appropriate chart by aid of the tuning fork test—apparently a very easily applied means of calibration.

I am convinced that, for many of the complaints of reverberation in Switch Rooms, all that is necessary is to persuade or coerce the operators not to speak loudly. If they speak too loudly to the subscriber, the receiver ought to howl in their ear; if too loudly to a neighbouring operator, an alarm should indicate this fact to the Supervisor. If, in spite of such precautions, reverberation still gives trouble, then surely the floor should receive attention before unsightly sheets are strung up. Strips of perforated absorbent floor covering, not too big to be raised for cleaning, should be cheap and effective. If the Traffic Staff object, because they like a nicely polished floor, then they should have to endure the reverberation.

Three examples which bear on reverberation problems may be of interest.

(1) A few years ago the reverberation in York Minster was so bad in places, even with (or because of) the elaborate loudspeaker system installed, that no single word of the lessons or sermon could be understood, though the volume of sound was considerable. This applied to a seat about two-thirds of the length of the Minster back from the speaker.

(2) It is understood that the British Broadcasting Corporation Engineers, when broadcasting gramophone records, have reverted to the audible reproduction of such records in their studios, microphones being used in the normal way. Previously they

could dispense with microphones by using electrical pick-ups working direct into the output system. They have made this change because they can now enormously improve the general tone and volume effect of, at any rate, the cheaper orchestral records, by utilising reverberation effects introduced from their " Echo Room." Reverberation is by no means always an enemy.

(3) The sensations that one experiences in the Research Section sound-proof room, where there is no reverberation, are very wierd and unpleasant to strangers, who are thankful to get outside again. " Silence " inside it is unbelievably silent.

We amateurs must not overlook the important difference between articulation efficiencies, as referred to by Mr. West, and the intelligibility of ordinary speech. Fifty per cent. articulation conditions give about 90% intelligibility. In intelligibility figures the context greatly assists the listener to fill in missing words unconsciously; but speed of recognition is introduced as an additional factor which is largely excluded in articulation tests.

Finally, as regards noise in phonogram rooms, I am not clear whether side tone effects are serious or not. If they are, could not a simple foot or knee switch be provided to cut out the transmitter when desired? Have tests been made in these rooms with earpieces large enough to cover the ears entirely and padded so as to exclude room noises? The construction would have to be such that one earpiece only would be in use at a time, the other one resting on some other part of the head; and such that a change from one ear to the other could be easily and quickly effected. Published tests go to show that noises, if not excessively loud, which are received in the *free* ear—*i.e.*, the ear with which the desired speech is not being listened to—have very little, if any, effect on intelligibility.

Mr. G. SPEARS :—

*Re* the noise indicator. I think Capt. Cave struck the real idea behind the development of this device, since it was introduced to give an indication to supervisors when the room noise due to operators talking was above a certain level. It was intended that a lamp should be fixed on the supervisor's or monitor's desk to indicate when the noise exceeded a predetermined level, and thus indicating when steps should be taken to quieten things down.

With regard to the circuit. In the original model it was found necessary to use a thermal relay, which would delay the signal about 1½ to 2 seconds. This was necessary in order to avoid signals due to accidental noises caused by the movement of furniture, etc., which could not be controlled by the supervisor. The noise therefore had to be more or less sustained before any indication was given. I should like to know why it has been found necessary to cut that facility out. Rectified reaction was used, because it offered a ready means of causing a relay to operate without the use of a large number of valves; it simplified the apparatus as a whole, and made the device fairly compact.

As to absorbing materials, there is a great deal of difficulty in meeting all the requirements of materials for treating switchrooms, and a number of the requirements are conflicting in nature. We have to consider the absorption coefficient; ease of fixing (which is of importance in modern buildings with concrete ceilings); tendency to harbour dust and vermin; fire resistance; reflection of light; and last but most important, cost.

Mr. West has devised a treatment using strips of building board with a paper backing, and this treatment costs roughly one third that of other proprietary materials considered so far and is satisfactory otherwise.

The question of ventilation. Mr. West pointed out that in cases where a room was subject to street noise, the only satisfactory remedy was to block up the windows and introduce a ventilating system. As a matter of interest, some figures which were got out by the Bell Laboratories are quoted. It was found that a 15 db. reduction was obtained in the noise picked up by a microphone placed 21″ from a window simply by closing it. The best result obtained by the use of sound absorbent in a room, was a reduction of 11.0 db. Therefore, the act of simply shutting a window produced a better result than an expensive absorption treatment.

I think Mr. West mentioned the point that acoustic treatment should be applied during the erection of buildings, and there is no doubt this is the correct course to adopt.

We have tried practically all the materials he has on view on the table, and we have considered the opinions expressed by people occupying rooms treated with these materials and made tests of reverberation time before and after treatment.

As to the table on page 23, I am afraid these figures are rather on the high side. I have figures here for two cases, which were actually measured by Mr. West. In the first case, Dudley Exchange, the volume of the room concerned is 25,000 cu. ft. Mr. West's figures indicate that 2.5 seconds is an adequate figure for the reverberation time, but in actual fact the staff occupying the room were not quite satisfied when it was reduced to 2.2 seconds. At Walton Exchange, the second case, the volume is 9,000 cu. ft. The initial period in this room was 2.1 seconds which is less than Mr. West's proposed optimum of 2.2 seconds for a room of this size, but we got it down by ceiling treatment to 1.2 seconds which was considered satisfactory.

Mr. J. Hedley (*Chairman*) :—

Before calling on Mr. West to reply, perhaps a little history might be interesting.

With regard to noise in phonogram rooms, originally phonogram circuits were fitted in silence cabinets. The next move was that they were taken out of the cabinets and placed in message stalls. The technical instruction of over 20 years ago stated that all such rooms should be away from noisy streets. Then they were put in the open switchrooms. As a consequence there was room noise and reverberation, so valve amplifiers and volume control were tried.

I am in sympathy with Capt. Cave because, in the Provinces it is very difficult to deal with transmission complaints —as at present they have no means of testing at their disposal. It is not only a question of just treating the wall ; in some cases the position of the existing exchange is such that some other alteration may be required. My own view is that the improvement demanded during the last few years is due largely to the influence of broadcasting.

There is a very good example of the lack of interest which is taken in this question of reverberation. A beautiful paper used to exist on the walls of the G.P.O. (N) Refreshment Club before the walls were painted. Now it is almost impossible to hear people speak because the paper has gone, and there is a big room noise. With regard to the noise level indicator, in connection with an investigation relating to a transmission complaint it was found that general room noise existed which was largely caused by the operating staff in the switchroom and that the supervisor did not appear to appreciate when this was abnormal. These conditions influenced Capt. Lucas to such an extent that he suggested and developed proposals for a noise indicator. Personally I think this apparatus will be very useful to the Department.

It has generally been recognised that the right way of dealing with the noise problem is to attack it at its source. At present there is no accepted standard method of eliminating the trouble, and it is a question of gaining experience from field experiments.

When we are in a position to issue a technical instruction on the matter, the number of transmission complaints should be reduced, and there should be a big improvement in telephone service.

Mr. W. West (*in reply*):—

In connection with possible future telephone developments, Captain Cohen has drawn attention to the important and unfortunate tendency for a microphone to exaggerate the effects of room noise and reverberation. No single explanation seems quite satisfactory, so that it would appear that a number of causes contribute, possibly both physical and psychological. My own impression is that distortions by the microphone and associated apparatus play some part in manifestations of this tendency. The transmission or reproduction of room noise by high quality systems does not sound quite natural, and the systems are incapable of dealing faithfully with the extreme variations of volume to which the ear can respond. In the paper cited in the conclusion, Ashbridge says: " It would seem that the ear has the power of subconscious rejection of the unwanted sounds when listening directly in a concert hall, which it does not possess to the same degree when listening to a loud-speaker in a small, quiet room."

The articulation tests recorded in sections 16 and 17 represent transmission in one direction only; as Mr. Fairbairn has clearly deduced, the effects of room noise at one end only of a telephone conversation all combine to the disadvantage of the listener at the noisy end We may therefore be prepared for the apparently paradoxical conclusion that, in such circumstances, the introduction of equal room noise at the quiet end might produce an over-all improvement. In any case, concentration of attention on the listening conditions at a noisy end—as described in the paper—seems to be justifiable. Possibly the repetition rate method of test, to which Captain Cohen has alluded, may supply satisfactory quantitative data regarding the effects of room noise and side-tone where both-way transmission is concerned.

That an increase of side-tone tends to cause a speaker to lower his voice is indeed the case, and the tests which Mr. Fairbairn has quoted provide an interesting example to show that the effect can be measured. It can thus be included in the over-all sending efficiency of the circuit. That telephone users are accustomed to side-tone is a matter of habit and no inherent necessity for side-tone on this account can be deduced. Hence, in my opinion, the desirable extent of side-tone reduction is a problem in costs the solution of which can be based on the curves shown in Fig. 5.

I agree with Mr. Fairbairn that the principle illustrated in Fig. 6 for the reduction of noise penetration can be applied to window openings, but the constructional difficulties would justify the classing of such a scheme as special ventilation.

The omission to which Dr. Sutton refers relates partly to the effect of side-tone on the loudness at which the speaker talks into the transmiter—a factor which is included in my list. It seems unlikely that a speaker would permit his own voice to create an uncomfortable volume of sound in his own ear; rather would he speak more quietly, or further from the transmitter.

The extent to which a listener is temporarily deafened immediately after hearing a loud sound is, I believe, an unknown though not perhaps an unimportant quantity. I have made some tests of the effects of loud " clicks " in a telephone receiver on the acuteness of hearing; observers' thresholds of hearing were measured by an audiometer immediately before and after a succession of clicks due to a condenser of 2 $\mu$F discharging from a p.d. of 50 volts through a receiver held to the ear. It required about 15 seconds to obtain the second measurement of the threshold, and in no case was any deafening effect observed. On the other hand, an increase in the just perceptible change of intensity of a pure tone, due to previous stimulation by a loud tone at the same frequency, has been observed (J. F. Allen, " Phil. Mag." vol. 9, page 834, 1930).

Dr. Sutton's criticism that the type of noise used did not satisfactorily represent average room noise could probably have been applied to any artificially controlled noise. The warble-tone appeared to the ear to be more normal in tone than a reproduction of actual room noise from a gramophone record, which was the available alternative. It has been used with success for simulating speech in routine testing of telephone instruments.

Although it is not disputed that the curves of Figs. 3 and 5 have an essentially empirical basis, there is nothing haphazard in the method of plotting. It is reasoned that the articulation reduction factor due to noise should depend mainly on the available range in the auditory sensation area (Fig. 2) between the levels of the wanted (speech) sound and of the masking noise reaching the listening ear. If there is no side-tone the masking noise reaches the ear by various paths of mechanical transmission, and it is supposed that it is proportional to the room noise level. On this argument, therefore, the sum of L + N, both expressed in db., is a measure of the available range, also in db., in the auditory sensation area. That the articulation reduction factor is entirely independent of the position of this available range is not to be expected, but that the test results show that substantially it is so within the moderate range of magnitudes stated is, I think, hardly surprising.

The effect of side-tone is an addition to the masking noise. It is purely a matter of convenience that the amount to be added should be ascertained as an arithmetic addition to the quantity N; it depends only on the side-tone and the room noise level. These considerations explain the manner in which the curves of Fig. 5 are plotted, and the test results supplied the necessary data.

It may be noted that if the side-tone is reduced beyond about 20 db. less than standard there is practically no increase in the masking level due to side-tone and, in fact, when two masking noises are present simultaneously, one being much weaker than the other, the weaker is itself masked.

In Mr. Wigan's reference to section 6, the measurement of the threshold of hearing, there appears to be a misunderstanding of the two separate stages involved. First, an average must be taken of the readings obtained from a considerable number of observers to obtain the normal; individuals with apparently normal hearing may differ by as much as 20 db. This is a purely subjective test and it illustrates the importance of obtaining subjective measurements in terms of the average from several observers. Next the sound pressure at the average reading must be measured—an objective test. In the last paragraph of section 6 it is the latter measurement that is referred to. It is, of course, possible that different investigators, using different observers, may strike a different average; it is equally possible that, using different methods of objective measurement, they may obtain different results on the same average—due to the difficulties of such tests and to differences in the acoustical conditions under which they can be made. Discrepancies of this kind have been encountered in the absolute calibrations of microphones.

The whole subject of noise measurements and units is still in an experimental stage and awaits standardization, but it need not be regarded as " chaotic "—it is noise itself which is indeed a state of chaos. Perhaps it is unfortunate that the same word " measurement " is used for exact determinations, *e,g.*, of time or space, as for the estimation of a single value to express an average aural sensation resulting from the complex and continually changing vibrations which generally constitute noise.

In choosing our noise units and the method of their measurement the purpose for which they are intended should be borne in mind; the same qualification applies also to the degree of accuracy which is desirable or attainable from the measurements. If we wish to define noise in terms of its effect on hearing—as, for the purpose of this paper, I have done—then the function of hearing enters as an integral part of the measurement, and the tests have necessarily a subjective basis, the accuracy available being largely controlled by the number of observers used.

There is neither mention nor inference in the paper of any necessity for an objective method for the measurement of noise. The two kinds of test, objective and subjective, are complementary; the functions of one cannot wholly be fulfilled by the other. Objective measurement is required for analysis (*e.g.*, of the frequency contents), and for providing an exact quantitative basis, as in the case of the measurement of the normal threshold. Objective apparatus can also be used to obtain subjective measurements—if it has been calibrated against noises which have been measured by subjective tests. The particular characteristics of the apparatus are of minor importance if the noise is similar in kind to that used for calibrating; otherwise it is desirable to imitate, as far as possible, the characteristics of the ear in those of the apparatus. As Mr. Wigan points out, it is not logical to stop at the matching of the frequency characteristic.

With objective measurements we can work to a system of mechanical units which have long been standardized, but subjective units are not in so fortunate a case. There is, of course, an unlimited number of possible ways of defining subjective units, and an indiscriminate use of these definitions—or of the same name applied to different definitions—only leads to confusion.

For the purpose of this paper, therefore, I have stated and used as few units as are necessary, and these are rigidly defined in accordance with the oldest and most established practice available. Mr. Wigan's contention appears to be that the loudness unit I have used is incorrect, but my view is that, in the absence of an accepted standard in this country, I have stated exactly what is meant in this paper by " loudness units," so that the question of correctness does not arise. It is perhaps more usual to speak of loudness levels rather than loudness units, but if there is no ambiguity it is reasonable to accept the convenience of using either term.

In Mr. Wigan's valuable contribution to the subject of side-tone,* he makes use of the masking method for gauging the magnitude of a noise. He is, of course, free to call his results " loudness units," but in doing so he is, I believe, creating a precedent; moreover, he does not define specifically what he means by the term. There are other words available—such as " masking " or " deafening " levels—which can be used for the results of such measurements, and, to avoid confusion, I will refer to them as " masking levels," as does Dr. Kaye in the article cited in section 16.

I think there is room for both masking and loudness levels and I have sometimes used both in making measurements of noise. Before the adoption of loudness levels for the tests mentioned in section 16, the following points received consideration :—

(1) The two other units used, L and S, were both measured by a subjective, balancing method—as are loudness levels.

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* Journal P.O.E.E., Vol. 25, p. 197, 1932.

(2) Although for a regular kind of noise the masking test is the easier, it is, in my experience, the more difficult for many noises as actually encountered. This is due to the fluctuations in the noise level, which the ear cannot average in assessing a masking level so easily as it can when making an estimate of equality with the standard tone.

(3) The standard tone was applied by a telephone receiver, so that for a masking test the receiver must be spaced a certain distance from the ear to allow the masking noise to enter. This distance introduces a somewhat arbitrary quantity into the measurement.

(4) While it is the masking effect that is of importance in impairing hearing, this is not the masking level that is measured; the ear is not free (as when making the measurement), but is covered by a receiver which itself produces some of the masking sound if there is side-tone. Hence loudness levels are just as applicable as masking levels as noise units for the purpose under consideration.

In obtaining the curves of Fig. A from my curves of Figs. 3 and 5, Mr. Wigan has in view a comparison with his own test results (*e.g.*, Fig. 2 in his paper, cited above). His method is simple and ingenious; instead of making articulation tests, he increases the attenuation in the junction until the conversation ceases to be intelligible. This method of test should have many useful applications, but presumably it requires delicate handling because both the intelligence of the listener and the difficulty to him of the ideas transmitted are included—factors which are avoided in articulation testing.

If we might expect that " an increase of the noise level N would always be combined with an approximately equal decrease of attenuation L in order to maintain intelligibility at the threshold value," then surely we should expect a slope of approximately 45 degrees for all curves plotted as in Fig.A. Actually those in this figure show a slope of 45 degrees with no side-tone and, when there is side-tone, a tendency towards that slope at low noise levels, but a greater slope at higher noise levels, while Mr. Wigan's curves show a slope of 45 degrees only for a side-tone condition at high noise levels, and otherwise a slope less than 45 dgrees.

In both cases there is evidence of lack of uniformity as between the effects of low and high noise levels, but why, when the magnitude of the wanted sound is plotted vertically and that of the masking sound horizontally, should it be logical for this lack of uniformity to appear as a slope less than 45 degrees at low noise levels, but illogical for it to appears as a slope greater than 45 degrees at high noise levels?

The case which Mr. Wigan has stated so emphatically against the loudness units used in the paper is, I think, based too much on reasoning which is inadequately informed. Both the performance of a carbon transmitter and the hearing of an observer are involved in tests covering a wide range of difficult listening conditions, and our knowledge of both of these is very limited. The Weber-Fechner law is mentioned, for example, but the validity of this psychological law, as applied to audition, has been disputed, and it would seem that it is only approximately true even under normal listening conditions and for moderate changes of the stimulus.

Although the points raised by Mr. Wigan have led to a discussion of differences of opinion on the units involved, we should not overlook the very substantial agreement that exists between our test results where they cover similar ground. We have both found, for example, by entirely different methods, that side-tone conditions such as are quite usual can, when there is also room noise such as is fairly average for city offices, create an impairment of telephone reception equivalent to an attenuation of the order of 20 db.—a figure which, in quite noisy situations, may even be doubled.

The addition of the appendices suggested by Capt. Cave would undoubtedly be of value, and I had considered the insertion of a table of absorption coefficients. More complete information would, however, be obtainable by reference to a text-book on Architectural Acoustics. The Research Section is not equipped with a reverberation laboratory such as is necessary for measuring absorption by large surfaces.

From the data available from publications by the N.P.L. and other sources it appears that whereas the ordinary wall, ceiling and floor surfaces of a switchroom would have absorption coefficients of the order of one per cent., good acoustic tiles and plasters have 20 or 30 per cent. and special treatments, such as Paxfelt, Acousti-celotex and the building board strips with paper backing, about 60 per cent. Floor coverings of lino or cork carpet are only very slightly absorbing, a thick pile carpet is much more effective.

With regard to what is acceptable in the way of noise levels in switchrooms, there is room for wide difference of opinion. Noise levels greater than 70 have been tolerated in certain rooms, but I regard this level as excessive. In one switchroom a reduction of 10 noise units has resulted from a ceiling treatment of Paxfelt.

Capt. Cave suggests reducing the noise reaching the operators' ears by cutting out side-tone and providing noise-excluding ear-caps. It seems that side-tone effects are not generally serious on operators' circuits and that, though a satisfactory noise-excluding ear-cap could be designed for an individual, a design for universal fit is very liable to introduce reception loss. The difficulty may, however, not be insurmountable.

Mr. Spears has stated the specific use for which the apparatus shown in Fig. 1 was primarily designed, namely, as an aid to supervision in the control of the noise level in a switchroom. For this purpose additional apparatus is required to introduce delay before the signal is made by lighting a lamp, and the whole outfit is termed a Noise Level Alarm. The most suitable amount of delay has not yet been ascertained. Obviously the circuit as illustrated need not be restricted to this particular use and only the parts of general interest to the question of objective measurement have been included.

The experiment which Mr. Spears has quoted to show the relative noise reductions obtained by closing the window and by introducing sound absorbent to the room provides a good example of the limitations of the latter method in cases of penetration of external noise.

While I agree with Mr. Spears that the proposed specification in section 20 for the maximum permissible reverberation is, from the acoustical point of view, too high, I doubt if there is sufficient justification for the cost that would be involved in reducing it further. In any case Mr. Spears has not, I think, quite correctly interpreted the intention, which is that the specification should apply to the bare, unfurnished room—as handed over by the builders. The object is to simplify the acoustical specification and calculations for the builder and architect by eliminating from consideration the unknown and variable contributions to absorption by the furniture and staff. In neither of the cases, Walton or Dudley, does the measured reverberation time apply to the bare room. At Walton there was a large curtain in the room when the test was made; it had been fixed as a temporary draping and could not readily be removed, so it was rolled up for the test. The reverberation time of the room without curtain, furniture and staff would certainly have been greater. At Dudley the absorbing treatment was not correctly applied, with the result that the final coat of paint re-introduced some of the reverberation which the previous stages of the treatment had removed. Since the staff were present during all the stages, the effect of the painting naturally left an unfavourable impression.

Both the Chairman and Captain Cave have referred to the question of the provision of acoustical testing equipment for use in the districts. In addition to the noise level alarm a portable audiometer for subjective noise measurement has been designed. At the same time it is reasonable to point out the limitations to the usefulness of such measurements; they indicate neither the causes nor the effects of noise; they cannot alone be relied upon to decide whether noise reduction is imperative or justifiable, nor to indicate how it may be effected. In so far as the effects of noise are psychological, they probably depend more on the listener than on the noise itself. This does not mean that noise measurement has no uses, but that the results may be meaningless or even misleading, unless the tests are made as part of a carefully considered plan.

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