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Sound absorption balance in the acoustics of auditoriums[†]

By V. A. Schlenker*

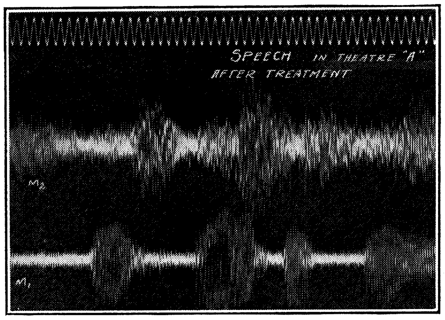

Fig. 2. Effect of reverberation on speech.

A REGRET expressed by engineers now delving into architectural acoustics is that the father of modern acoustics is no longer living. Professor Wallace Clement Sabine was never content to consider any phase of acoustics a closed book. He was always willing to re-open and continue with any investigation where there was hope of extending experimetal data in a practical way.

Unfortunately, many of his successors have shown a tendency to assume that his contributions were sufficient for the solution of practically all acoustical problems which the engineer encounters. Without detracting in the least from the monumental pioneer work of Professor Sabine, it can truthfully be said that his contributions are not entirely adequate to arm the present engineer to successfully cope with the acute conditions caused by sound pictures, radio, and television. Had Sabine lived he would no doubt still be the leader in experimental investigation with our present electro-acoustical instruments. That he was able to make such accurate and intricate measurements with the crude equipment available in his time is beyond the comprehension of most of us.

The most common assumption made by the young acoustician is that his job is done when he adjusts the reverberation of an auditorium to the so-called "optimum." Just what or why there is or should be an optimum period of reverberation has always been somewhat obscured with a veil of mystery. That music is enhanced with some reverberation is well known and it follows that a definite period, not too long and not too short, can be determined by the sensing of artists who react positively to the variation of the reverberation as it is adjusted. Professor Sabine reported that "a difference of five per cent in revereberation is a matter for approval or disapproval on the part of musicians of critical taste." (P. 80) Collected Papers on Acoustics.)

In the case of speech, however, it is not so simple. In a general way, the clarity should increase as the reberberation is reduced. At the same time the intensity at the ear of the listener is reduced by the introduction of acoustic absorption which is employed to reduce the reverberation. In small auditoriums the attenuation is not especially objectionable so long as the intensity is well within the limits of audibility. Therefore, if there are no other factors in control no optimum period of reverberation can be determined.

In the case of the large auditorium we have two essentially opposite effects on the quality of speech—one tending to increase, the other tending to reduce the reverberation. If there were no other important factors, naturally, a compromise or optimum would result.

It is quite apparent, in the small inclosure, at least, that some other important factor must be in control to

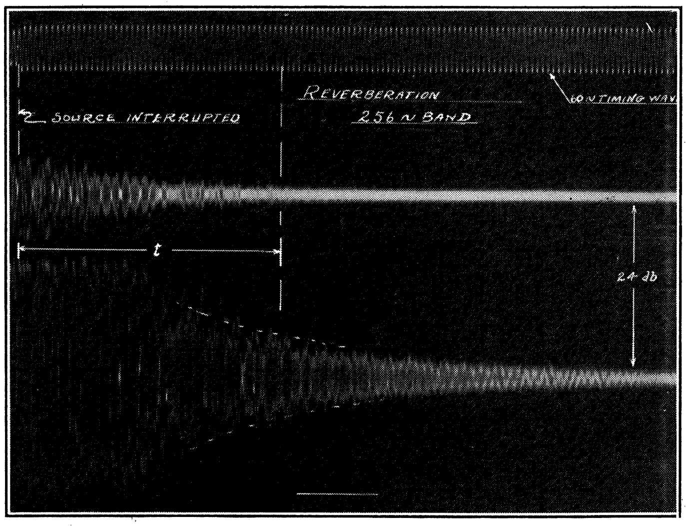

Fig. 1. Oscillographic trace of decay of sound.

[†] Presented before the Club, November 11, 1931.

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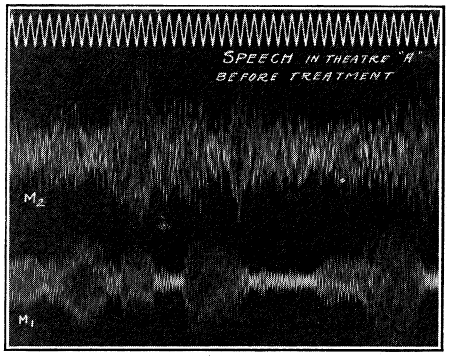


Fig. 3.

account for the optimum period of reverberation.

The reverberation of a room is usually measured by timing the decay of sound. Present methods involve a microphone to pick up the sound and a chronographic means of recording the time required for the sound intensity to drop a certain number of decibels. The number of seconds required for a 60 decibel reduction in level is universally designated as the period of reverberation regardless of frequency.

An oscillographic trace of such decay of sound can be seen in Fig. 1. The two traces are recorded simultaneously —the lower one is monitored on the upper channel electrically but set at an adjustable number of decibels above it in gain. In this particular case, the lower trace was recorded at 24 db. above the other. The distance between the points of equal amplitude on the two traces is a measure of the time for the sound to decay 24 db. By multiplying this figure by 2½ the period of reverberation is obtained. The difference of level chosen is determined by the noise level and the maximum intensity level of the test tone which is available.

The method just described was developed by the writer to avoid the possibility of error which is apt to enter when other methods are employed which involve the operation of marginal relays. Furthermore, the exact manner in which the decay takes place is at all times known when the oscillographic trace is made. This facility is very important for the research worker who must be on the look-out for new and unexpected phenomena.

The effect of reverberation on speech is shown in an interesting way in Fig. 2. In this case, two microphones were set up in a particular theatre. One was placed about four feet in front of the loudspeaker behind the picture screen giving the lower trace, while the other was positioned out in the auditorium, giving the upper trace. In this way a direct comparison between the sound as it comes out of the horn can be made with the sound as it is received by the listener out in the audience. The last three syllables are "VI-TA-PHONE."

Although the distortion is abundant because of reverberation it was worse before this house was acoustically treated, as will be seen in Fig. 3. The reverberation is so great that the individual syllables are scarcely discernible.

When the reverberation is measured in the auditorium the investigator at once discovers that there is a considerable variation, depending on the frequency. Some typical curves are given in Fig. 4. The curve marked T-1 has an excessive period of 4.0 seconds at 128 c.p.s., while at 4096 c.p.s. the period is only 1.5 seconds, which is a ratio of almost 2.7. The curve T-3 from a theatre which has been treated acoustically has a period of 3.5 at 128 c.p.s. and 1.0 at 4,096 c.p.s. Here the ratio is even greater—3.5. Curve T-2 has the smallest ratio—3.2 to 1.8 seconds, which is approximately 1.8.

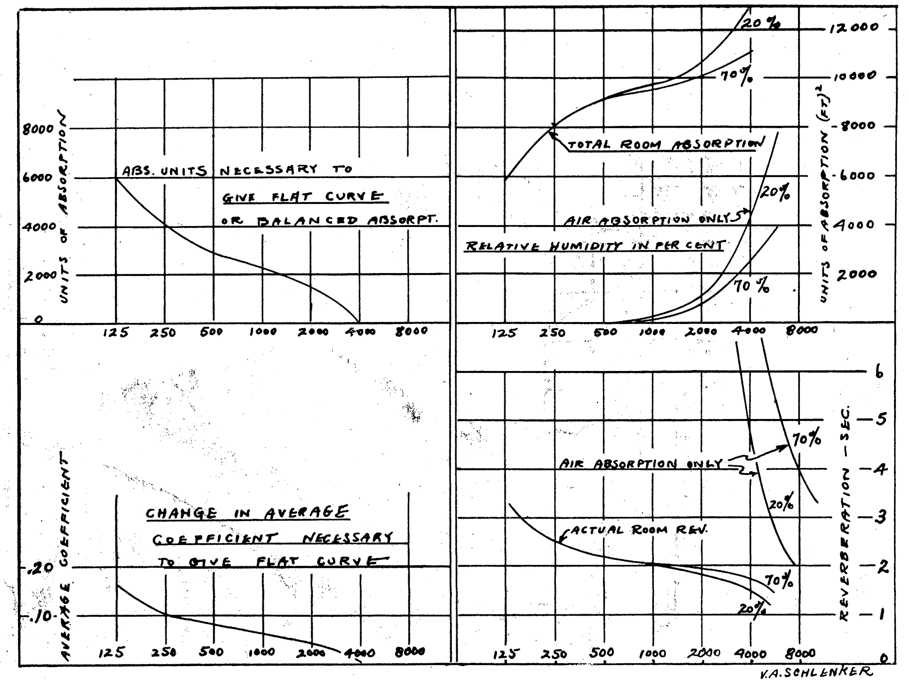


Fig. 5. Reverberation curves.

At once, one is led to the suggestion that perhaps the relative slope of the reverberation curve may be of considerable importance. In other words, the fact that low-frequency sound is absorbed less efficiently than the high frequency may be most valuable in determining the degree of intelligibility with which speech is understood.

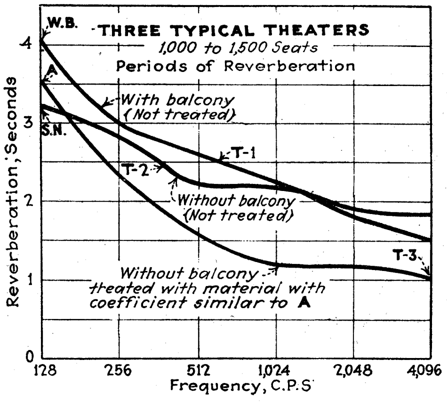


Fig. 4. Reverberation curves of three typical theatres with different acoustical treatment.

In Fig. 5 (lower right portion), is given the reverberation curve of a particular average theatre with a seating capacity of 1,800. It will be noted that the reverberation at the higher frequency depends upon the relative humidity of the air. Recent investigation by Dr. Knudsen and others have established the absorption of the air at different values of relative humidity. Their findings have been quite startling but entirely in accord with the experimental as collected by competent observers. Professor Sabine, himself, recognized the fact that the moisture content of the air is a factor in the dissipation of acoustic energy but he concluded that (to quote from p. 171 of his Collected Papers), "this form of dissipation instead of being an important factor, is an entirely negligible factor in any actual auditorium." If the bounding surfaces of this auditorium were perfect reflectors the reverberation at 4,000 c.p.s. would be 4.4 seconds due to the absorption of the air at a relative humidity of 20 per cent and room temperature of 70° F. On the other hand, if the humidity is 70 per cent the period is almost twice as great—the absorption at 4,000 c.p.s. being almost negligible for all practical purposes. In fact, this no doubt accounts for Sabine's failure to detect the effect of humidity, since he may have done practically all his work in humid air.

The effect of dry air must be taken into consideration since most of the theatres have very dry air in the winter time. I have been informed by the Carrier Engineering Corporation that the humidity will run as low as 25 per cent in the winter where no air conditioning is provided. The practical ideal for winter is 35 to 40 per cent as is maintained by the air conditioning equipment. It can be concluded that at frequencies above 2,000 c.p.s. the relative humidity must be considered in determining the acoustical absorption and its effect on reverberation.

In the upper right-hand portion of Fig. 5 is given the absorption as calculated from the reverberation given in the curve immediately below. It will be noted that the curve has an alarming slope at a relative humidity of 70 per cent. At an average humidity of 45 per cent the total absorption is 12,000 units at 4,000 c.p.s. and only 6,000 units at 125 c.p.s—a ratio of 2.0. For purposes of later consideration the units of absorption required to give a flat curve are given in the left portion. In other words, if a balanced condition is desired in this theatre the absorption must be added in largest amounts at low frequencies.

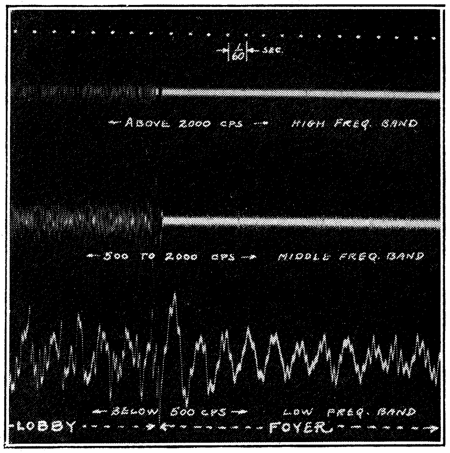


Fig. 7. Records of street noises.

In the last analysis of the acoustic problem, the final judge which must be satisfied is the human ear. It is well known that the ear is limited in tonal range or frequency. It is also limited in the range of intensities. The very faintest sound is sensed at the "threshold of audibility" while the very loudest sound is sensed at the "threshold of feeling." Both the frequency and intensity ranges can be represented on a chart by a certain area as shown in Fig. 6.

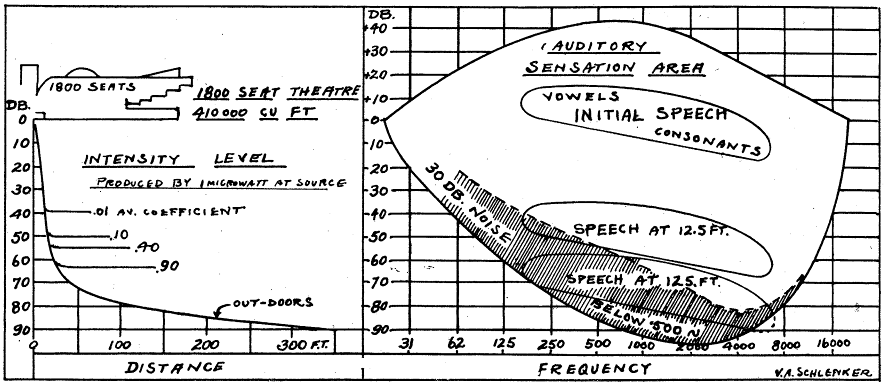


Fig. 6. Frequency and intensity ranges.

A smaller area can be used to represent average or normal speech. The average extends from 200 c.p.s. to 8,000 c.p.s. for the important components. The speech area, then, will extend from 200 to 8,000 along the frequency axis and about 25 decibels along the intensity axis. The speech area can be further divided into the vowel and consonant portions. The vowels occupy the region of low frequency and high intensity while the consonants are found in the region of high frequency and low intensity.

Taking the total speech power as 10 microwatts for average speech (p. 67, Fletcher, "Speech and Hearing"), the speech intensity is 1 microwatt per square centimeter at a distance of one-half inch from the mouth of the speaker, since the power is divided over the 10 sq. cm. of surface of the hemisphere whose radius is .5 inch. The intensity of 1 microwatt per sq. cm. is taken as zero level.

If sound continues to radiate into unconfined space the intensity will diminish according to the inverse square of the distance. At a distance of 12.5 feet the intensity will be 50 db. lower than the "initial level" which is taken at a distance of .5 inch by definition.

On the auditory chart the effect of the listener moving from .5 inch to 12.5 feet can be represented as a 50 db. vertical drop of the speech area. When the listener moves to a distance of 125 feet a further drop of 20 db. is experienced. At this distance, the speech area is then touching the minimum audibility level.

Some idea of what this means in terms of the dimensions of a theatre can be gained by the curve and sketch shown in the left portion of Fig. 6. It will be seen that if a person spoke on the stage with a speech power of 1 microwatt, it would be just audible in the rear of the theatre, assuming that no reflections took place from the walls, ceiling, and floor. If there is noise present a portion will be masked. In the shaded portion of the auditory sensation area is represented the space occupied by a 30 db. level of noise which has its components below 500 c.p.s. The masking extends well up in the higher frequency range as has been determined at the Bell Telephone Laboratories. If this noise were present as is frequently the case, the speaker could not be heard in the remote portion of the balcony. In other words, the one microwatt voice with an initial intensity level of —10 db. would have to be raised 30 db. to 1,000 microwatts to give an initial level of +20 db. This would insure a —50 db. level at a distance of 125 feet without the aid of reflections.

In the actual theatre the reflections raise the level of sound, immensely. For the purpose of comparison the intensity levels have been calculated for different absorption conditions. For an average coefficient of absorption of 0.10 the intensity level of approximately 50 db. below 1 microwatt per sq. cm. (zero level) would be established by a sustained sound.

The nature of the room noise which is ever present should be known with some degree of accuracy. Not only the intensity should be known, but its frequency distribution as well. Fig. 7 gives a record of the street noise which filtered into the theatre which we have

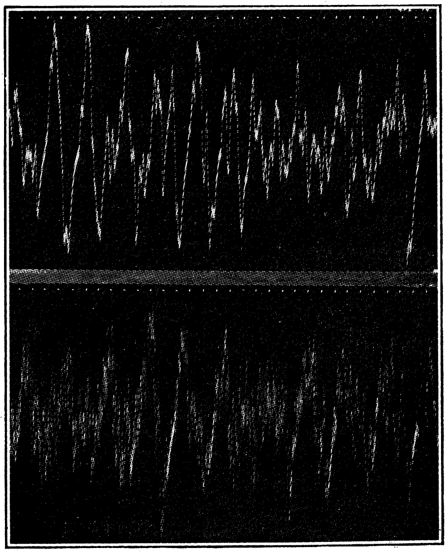
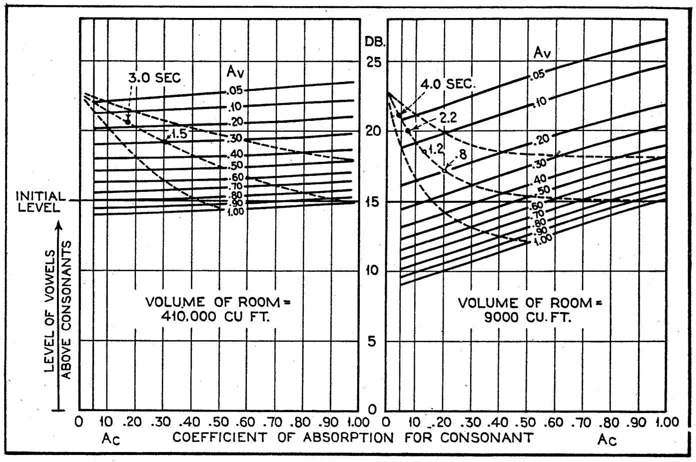


Fig. 8. Traces made in an acoustically treated theatre.

been considering as typical. The electrical circuits were arranged with special filters so that the entire frequency range was divided into three bands—low, middle, and high. The distribution of the noise is fairly uniform over the three bands when picked up on the street. After finding its way into the lobby the middle and high frequencies are attenuated somewhat as can be seen in the left half of the traces. A special switching device automatically switches the circuits over to another microphone located in the foyer. This switching is accomplished in much less time than it takes the sound to travel from one microphone to the other. The traces from the noise in the foyer show an entirely different distribution of energy over the three bands. In the foyer, which is really a part of the orchestra itself, the noise is almost entirely made up of frequencies below 500 c.p.s. This fact is important in determining the characteristics of any acoustical treatment which is prescribed for noise abatement. The type of auditory masking which it causes is also determined by its frequency characteristics.

Fig. 8 shows an interesting comparison of two traces which were taken in a studio which was heavily treated acoustically. The upper trace shows the room noise which runs as low as 30 c.p.s. up to 200 c.p.s. The lower trace shows the same room noise with high frequency noise of a motion picture camera superposed. These traces were taken separately but within 15 minutes of each other. Once more the room noise is found to be made up of low frequency components.

Fig. 10. Intensity level of vowel above intensity level of consonant:
tv = .30 sec.
tc = .05 sec.



It has been noted how multiple reflections build up the sound intensity when a single tone is sustained long enough for a steady state condition to be established. In dealing with speech, however, the duration of the individual component is very short. The time of the average vowel is 0.3 second while the average consonant can be taken as 0.05 second. Inasmuch as the vowels and consonants are entirely different in frequency, duration, and intensity, it seems reasonable that each should be considered separately. For purposes of diagnosis, the writer has developed an electrical syllable which can be used to simulate a component of speech. If its frequency is set at, say, 250 c.p.s. with a length of 0.30 second, it will represent a vowel. If its frequency is set at, say, 4,000 c.p.s., with a length of 0.05 second, it will represent a consonant.

In this way an auditorium may be tested by acoustically projecting the vowel and the consonant separately and recording the sound as it is picked up in various parts of the house by a microphone.

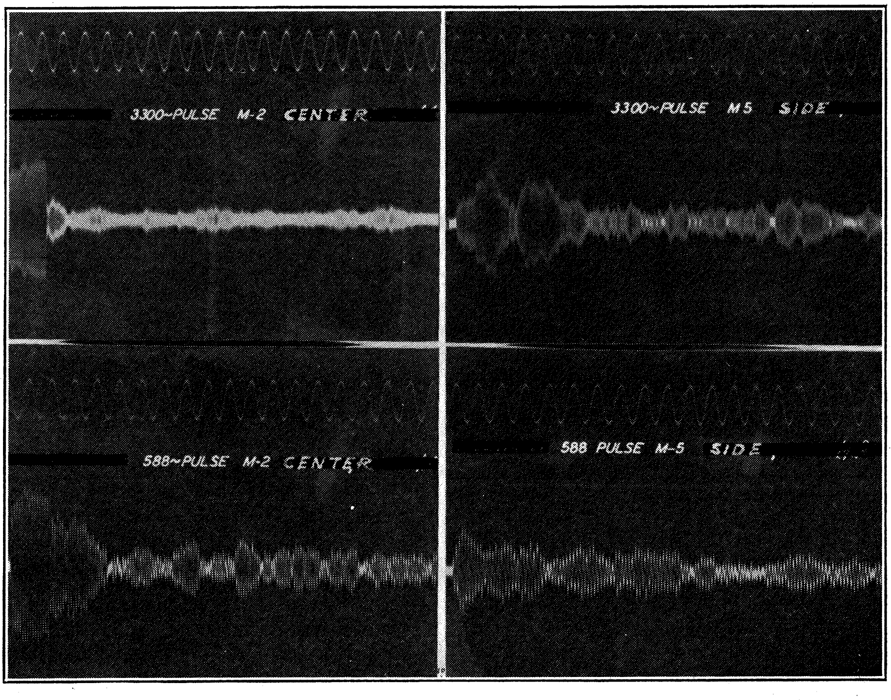


Fig. 9. Traces made in an acoustically treated theatre.

Four different oscillograms are reproduced in Fig. 9. These were taken as suggested in the last two paragraphs. In fact, they were all taken in the same theatre but in different positions. The traces on the left were taken in the center of the orchestra while the ones on the right were taken on one side of the orchestra. Space will not permit more than a glance, but it is obvious that a great wealth of information may be gained from a careful study of such soundings in an auditorium. The particular orientation of the horns will also control to some degree whether the high frequency projection will "clean cut" like the one at "M-2" or ragged like the one at "M-5."

After a careful consideration of the properties of speech and its interpretation by the ear, the writer has finally concluded that the true relation between reverberation and articulation can be traced to the short length of the fundamental speech sounds. If the vowels are assigned a duration of 0.3 second and the consonants 0.05 second with a difference of 15 decibels in power we will have a good average representation. The vowel can have a frequency of 250 c.p.s. while the consonant can be assigned 4,000 c.p.s. The intensity to which each will build up can then be calculated where the average coefficient of absorption of the room is known for each frequency. It is at once apparent that the consonant will build up to only a small fraction of the steady state value because it is so short in duration. On the other hand, the vowel which is six times longer will attain a much greater fraction of its steady state value.

As has been seen, the vowels are about 15 db. higher than the consonants. One can then proceed to calculate the difference in level as determined by the duration of the sound, the absorption at the particular frequency of the vowel or consonant, the volume, and total surface of the room.

Fig. 10 shows the results when all the possible coefficients of absorption are assigned to the vowels and consonants, respectively. The true vertical distance represents the intensity level of the vowel above that of the consonant for any particular value of the consonant coefficient. For example, take the point marked 0.8 second on the chart for the room with a volume of 9,000 cubic feet. This represents a consonant with a coefficient of 0.20 and a vowel with a coefficient of 0.20 also; the level of the vowel being 17 db. above the consonant. The 0.8 second is the reverberation for this particular coefficient. The dotted line passing through this point is a locus of all conditions in which the vowels and consonants have the same coefficient. In other words, this line represents a balanced absorption with respect to frequency.

The upper dotted line represents the condition in which coefficient of absorption for the vowels (Av) is only one-half that for the consonants (Ac). Likewise, the lower dotted curve contains all the points in which the vowel absorption is twice that for the consonant. In brief, the area above the middle dotted line represents unbalanced absorption of the usual kind while the area below represents a reversed absorption unbalance which is most unusual.

Many interesting deductions can be made from this chart. Perhaps the most interesting thing to note is that the condition of unbalanced absorption causes the vowels to rise far above the normal level for initial speech which is bound to decrease the articulation. On the other hand, the reversed unbalance causes the vowels to be much lower in level and in some cases to be below the normal level. Further experiment will show that the articulation will be improved in a corresponding way.

The effect of the size of the room is strikingly shown when the same calculations are made for a room with a volume of 410,000 cubic feet. Here there is less opportunity to keep the level of the vowels at or below the normal level of initial speech. However, the reversed absorption condition is far superior to even the balanced condition.

In the application of acoustical treatment, one must not lose sight of the fact that coefficients of absorption which are available, are painfully limited. Practically all the materials on the market have absorption curves similar to those which are shown in Fig. 11. The slopes of these curves are of special interest in view of the data given in the chart presented. The absorption at high frequencies which controls the consonants is between twice and three times that at low frequencies which controls the vowels. These curves have the usual unbalance which results in the vowels being intensified in excess of the consonants. The net effect is to lower the articulation.

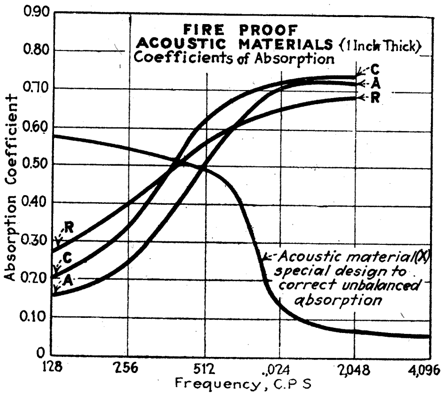


Fig. 11. Coefficients of absorption curves of well known materials for different frequencies, also one material of special design to correct unbalanced absorption in acoustic treatment.

The new acoustic treatment which is indicated by the curve "X" in this figure is designed to aid in the correction of the unbalanced condition. The cost of treatment which will give the extreme slope of one-fifth is considerably more than a modified treatment on the same principle which has a slope of one-half.

Referring again to Fig. 10, the smaller room gave an articulation of 79 per cent when the reverberation was adjusted to a period of 1.2 seconds for a sensation level of 72 db. (J. C. Steinberg, J. A. S., Oct., 1929). In this room (whose dimensions were 20 x 30 x 15 feet), the coefficients Av and Ac were approximately equal to 0.12. Reading the chart, it will be noted that the vowels are about 3 decibels above the normal, or a total of 18 db. above the consonants. If this room were treated with the new material with a reversed absorption curve, the average coefficient for the vowels Av could be adjusted to 0.30 keeping the A c at 0.12. The result would be to bring the vowel level completely down to the normal for initial speech, thereby enhancing the intelligibility.

In conclusion, the method of acoustic treatment of auditoriums which employ a new material with maximum absorption at low frequencies has unusual possibilities for improving the articulation of speech. That there is a sound scientific basis for such a conclusion in addition to experimental confirmation is most reassuring to the engineer who desires to determine the specifications of acoustic treatment to give a certain percentage of articulation at a prescribed acoustic intensity level.

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Club Notes

Harry W. Houck has joined the Kolster Radio Corp. as assistant chief engineer, after having been connected with the Dubilier Condenser Corp. and its predecessor for ten years. He will be stationed at the Kolster Company's engineering laboratories in Newark, New Jersey.

C. E. Brigham, chief engineer of Kolster Radio, Inc., Newark, N. J., has been appointed director of the engineering division of the Radio Manufacturers' Association. Mr. Brigham is chief engineer of Kolster Radio, Inc. He is a Fellow and a Member of the Board of Directors of the Radio Club of America, a member of the Institute of Radio Engineers and on the Committee of Papers and Standardization of the I. R. E.

Homer G. Tasker, now connected with United Research Corp., 41-39 38th Street, Long Island City, N. Y., as chief engineer. Formerly in sound department of Warner Bros. Pictures, Inc., Hollywood, California.