RESEARCH IN APPLIED ACOUSTICS AT THE WALLACE CLEMENT SABINE LABORATORY

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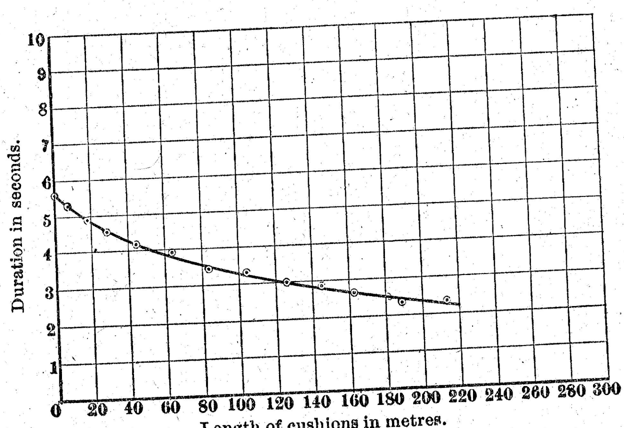
The problem of the behavior of sound within an enclosed space is as old as the art of public speaking. Vitruvius in his classic work on Architecture gives an admirable analysis of the conditions within an auditorium necessary for good hearing. Since that time it has been the subject of many opinions, enlightened and otherwise, as well as one of considerable popular interest. It is not too much to say, however, that it is one of the latest of physical problems to which the modern scientific method of exact quantitative experimentation has been applied. As a result the subject is even yet shrouded in mystery in the minds of many, and numerous false notions are still current.

The Wallace Clement Sabine Laboratory of Acoustics was built for the researches of the late Professor Sabine by his friend Col. George Fabyan. It is located at Riverbank, one mile from Geneva and thirty-seven miles west of Chicago. The work that is now being carried on there is a continuation of the Research in Architectural Acoustics begun in 1895, and carried on by Professor Sabine with remarkable skill and vigor up to the time of his death three years ago. A brief review of this earlier work constitutes a necessary introduction to an outline of the present activities of the new Laboratory.

These investigations had their inception in the necessity for correcting the acoustic properties of the Lecture Room of the then new Fogg Art Museum at Harvard University. The lines and proportions of this room corresponded very closely to those of Sanders Theatre, the large assembly room of the University, and were not in any marked degree different from those often found in theatre design. Although the volume of the new room was only one-fourth as great as that of the older room, yet it was found that its acoustic properties were such originally as to render it almost impossible of use as an audience room. The general problem then confronted was that of determining all the factors that enter into the acoustic merits or demerits of a room. Its complete solution should be quantitative, not qualitative merely, so that its application might be used to anticipate results, not merely to follow and explain them. Consideration of the examples just cited shows that shape alone is not a determinative factor. Further, size is not alone decisive, for we should expect conditions in the smaller room to be better than in the larger, whereas the reverse proved to be the case. The sequel showed that, in this particular case, the difference lay in the relative rates at which sound was absorbed by the walls, ceilings, and furnishings of the two rooms. Sound, once produced in a closed space, is a form of energy, filling the space, until converted into some other form of energy. Mere reflection from hard, rigid surfaces will diminish its intensity but very slightly. Only as the vibrations of the air particles constituting the sound energy do work against frictional and viscous forces is that energy absorbed and dissipated. It was in this particular that the two rooms differed most widely. In the first, a great deal of wood sheathing was used in the interior finish. The seats for some fifteen hundred persons were furnished with cushions, while aisles and open floor spaces were heavily carpeted. In the latter, walls and ceilings were of hard plaster, the seats were uncushioned and the floors uncarpeted. As a result, the rate of absorption in the second room was so small that a word spoken in an ordinary tone of voice persisted as audible sound for five or six seconds. Thus successive syllables, even when spoken most deliberately, were merged into the residual sound from many preceding syllables, and the result was a confusion of sound, amply loud, but one in which the separate elements of speech could be distinguished only by a distinct effort.

The point thus arrived at was simply a qualitative explanation of why two rooms, similar in shape, may possess acoustical properties that are decidedly different by virtue of the difference in their sound absorbing powers. To be of practical value, it was necessary to know the relation between the time of reverberation and the various factors upon which it depends. Clearly this time will decrease as the area of the absorbing material is increased. Making a virtue of the defects of the room to be studied and corrected, Professor Sabine determined the general relation between the time of reverberation and the absorbing area. Cushions from Sanders Theater were brought into the room in varying amounts, and the time of reverberation from a selected organ pipe arranged to speak with uniform power was determined in each case by means of a chronograph. Figure 1 shows the reduction of this time from 5.5 seconds in the empty room to 2.14 seconds after 220 meters of the cushions were introduced. An analytical expression for this curve



Curve showing the relation of the duration of the residual sound to the added absorbing material.

Figure 1.

appears immediately when the data are plotted in a somewhat different way as shown in Figure 2. Here the ordinates are the reciprocals of the times. The upper scale represented the actual length of cushions introduced. The points so determined lie very close to a straight line so that we may write

$$\frac{1}{t} = [Lr + Lc]\, 1/k$$

Clearly Lr is the length of cushions that has an absorbing power equal to that of the empty room. If now, the origin of co-ordinates be shifted to the left by an amount

Lr and we use as our unit of absorbing power, the absorbing power of 1 meter of cushion, setting *a* equal to the total absorbing power of room and cushions, we may write

$$\frac{1}{t} = a\,1/k \qquad \text{or}$$

$$at = k, \text{ a constant quantity.}$$

This experiment yielded the important fact that in a given room, the time of reverberation of sound of a given

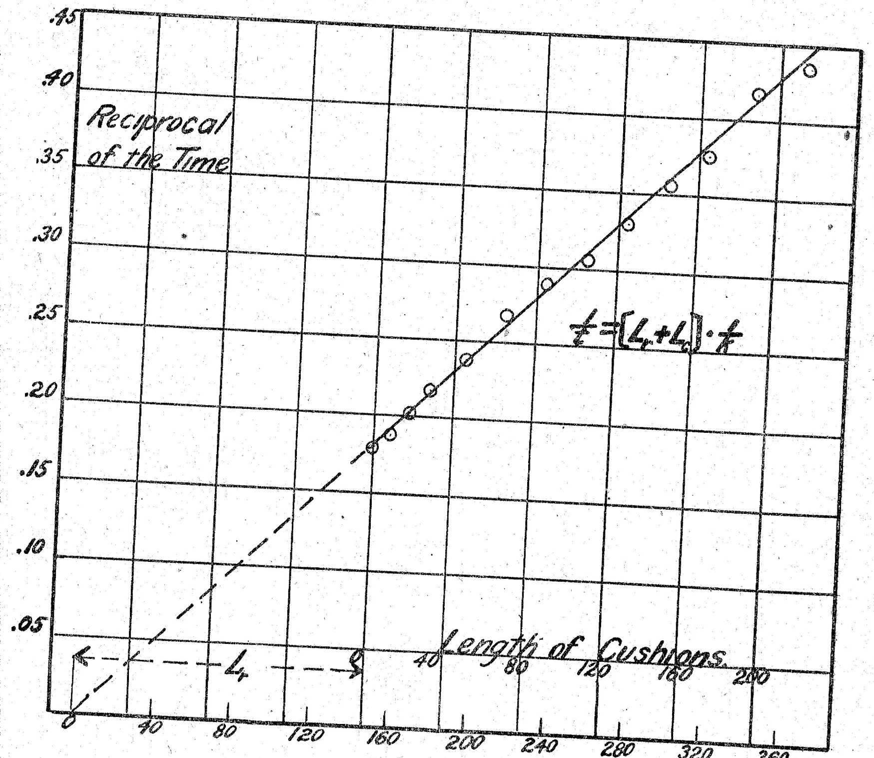


Figure 2.

initial intensity is inversely proportional to the total absorbing power of the room and its contents. Further, it suggested a means by which the absorbing efficiencies of different materials may be compared quantitatively with that of some standard material. Thus by substituting for the cushions, a known area of heavy rugs, let us say, and noting the duration of audible sound under these conditions, the ratio of the efficiencies of rugs to cushions may be determined. Naturally, the next step in the investigation was the determination of the absorbing power of the cushions in terms of some more universally accessible and more permanent unit. Viewed from the standpoint of reverberation, it is immaterial whether the sound energy is dissipated as heat, as is the case in true absorption, or escapes from the room through an opening. Experiments in rooms with a large number of windows showed that open windows are also effective in reducing the time of reverberation. The relative efficiencies of cushions and open windows were determined in the manner indicated above. Assuming that the latter acts as a perfect absorber*, the absorption co-efficients of a large number of materials that are used in the interiors of auditoriums were measured as outlined above, and have been published from time to time in Architectural and Scientific Journals.

Extending the experiments to a large number of rooms of different volumes, it was shown that the constant product of absorbing power and time of reverberation is directly proportional to the volume of the room. Using sources of different acoustical powers, the times of reverberation were found to be proportional to the logarithms of the initial intensities.

In the foregoing, we have gone somewhat in detail into these first experiments merely to illustrate the method by which quantitative sound measurements have been made with apparatus no more complicated than a stop watch and the unaided ear. Pursuing this method through a course of the most careful investigations covering a period of more than twenty years, Professor Sabine secured data, and developed a complete theory of auditorium acoustics, which makes the remedy of faulty conditions entirely possible, and, what is practically more

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* Recent experiments show that this assumption is true only in special cases. Theoretical considerations indicate that the fraction of the sound that passes through an opening is not in general unity, and that a portion of the incident sound energy is reflected. The relation between the reflected and the transmitted portions depends upon the dimensions and the shape of the opening as well as upon the wave length of the sound. It is to be said that later work is not based upon this assumption.

useful, enables the architect to provide in advance of construction for acoustic conditions, with the same assurance as he provides for lighting and ventilation. Finally, the progress of the investigation developed an extremely useful means of making acoustical measurements, which may be called the Sound Chamber method. Having established the relation existing between the time of reverberation, the absorbing power and the volume of the room, and the acoustical power of the source, it is possible to compute the intensity in terms of minimum audible intensity at any time after the source has ceased. The only other physical factor upon which this time depends, the acuity of hearing of the observer, enters into the problem in such a way that the results are independent of its absolute value. Hence, although this threshold intensity may vary widely with the pitch of the sound, and be markedly different for different individuals, yet measurements made by different observers prove to be quite consistent.

The Laboratory at Geneva was built primarily for the purpose of applying this method of acoustical measurements to the study of the transmission of sound through building constructions. Figure 3 shows the arrangement for measuring the transmission of sound by standard types of partitions as well as by any other construction or material. The Sound Chamber is an empty room 27 x 19 x 19 feet, with walls of brick, eighteen inches in thickness. As shown, there is no structural connection between this room and the rest of the building. The arrangements for excluding sound from without is such that observations requiring complete silence in the room can be made while others are at work in the building. Openings into three smaller rooms called Test Chambers are made in the walls of the Sound Chamber. In these openings, which are of different sizes, the largest being 6 x 8 feet, the partitions to be studied are built. Heavy steel doors can be closed over these openings, so that it is possible to restore the room to standard conditions whenever control experiments are necessary.

The source of sound is a complete organ of seventy-two pipes, voiced so as to give as nearly pure tones as possible. The wind pressure for the organ is supplied by an organ blower driven by an electric motor placed just outside the Sound Chamber The acoustic insulation between the blower and the organ is so good, that although there is a direct air passage between the two, the noise

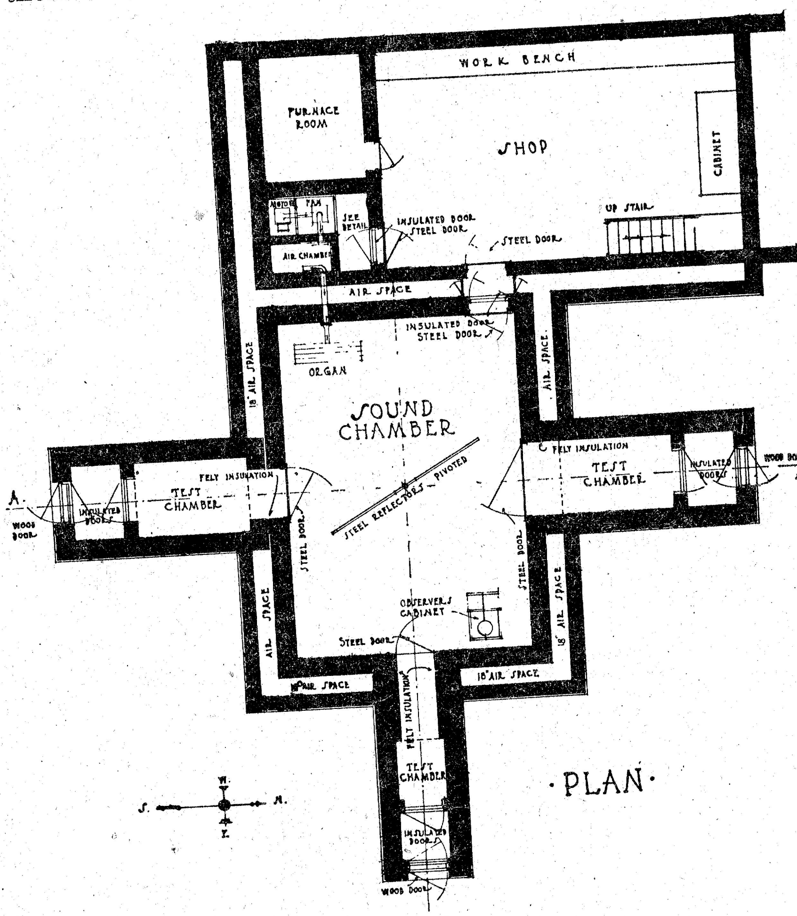

Figure 3.

from the blower is entirely inaudible in the Sound Chamber. The organ is operated from four different keyboards, one in each of the Test Rooms and one in the Sound Chamber. By means of a specially designed stop-watch chronometer, the duration of audible sound in the larger room, and as heard in the smaller rooms through the partitions being studied, can be measured with a high degree of accuracy.

From these measurements, the relative intensities of the sound upon opposite sides of the partition being studied are easily determined. Seated in the Sound Chamber, the observer causes any desired pipe to speak. A single electric contact stops the sound and starts the chronometer. This contact is maintained as long as the sound is audible and is broken the instant the sound ceases to be heard, the time being automatically recorded. This operation is repeated in the test chamber, with the partition to be studied intervening. Now it has been shown that although at any one point the sound fluctuates through maximum and minimum values as it dies away, yet on the average taken throughout the room, the intensity decreases according to a logarithmic law, that is, the average intensities at successive equal intervals bear a constant ratio to each other. Hence the logarithms of the ratio of the intensities on the two sides of the partition is proportional to the difference of the times during which the sound remains audible in the Sound Chamber and in the Test Chamber. The factor of proportionality involves only the absorbing power of the Sound Chamber, its dimensions and the velocity of sound. The first of these is known from an initial calibration, made with sources of sound of known acoustical outputs. Illustrative of the general method, the computations are given for a wall made of two inch solid gypsum block plastered on both sides. (Figure 4.)

Calculation of Relative Intensities of Sound, pitch 512 d. v., on opposite Sides of a Wall made of 2″ solid Gypsum Block, plastered on both sides with Gypsum Plaster.

I_1 = Intensity inside
I_2 = Intensity outside
t_1 = time of residual sound inside = 13.48 seconds
t_2 = time of residual sound outside = 8.44 seconds
a = absorbing power of room = 4.40

$$\log_{10}\frac{I_1}{I_2} = .126a\,(t_1 - t_2) = .126 \times 4.40 \times 5.04 = 2.80$$

$$\frac{I_1}{I_2} = 631$$

Fig. 4.

In this way, the study of a large number of materials as well as of various structural units has been made. It is important to bear in mind the different processes by which the vibrations set up by any source of sound in one room may result in aerial vibrations in an adjoining room. If the vibrating source is in solid connection with the floor or wall, these vibrations may be conducted directly along timbers or beams to the floors or walls of adjacent rooms. Probably the greater proportion of the sound from a piano, cello, or any stringed instrument resting on the floor, as well as the hum of motors or machinery, is transmitted through buildings in this way. Thus far, no attempt has been made to deal with this aspect of the problem. In the case of sound of the voice or from an organ pipe, the alternating pressures in the aerial sound wave in one room produce vibrations of walls or partitions, which in turn communicate their motion to the air of the adjoining room. In the case of porous materials, such as felts or fabrics, the motion of the air may be communicated directly through the pores of the material, with little or no motion of the partition itself. The problems so far studied all come under the last two heads.

The case of solid impervious partitions is illustrated by doors and windows. Here the partition acts as a heavy plate, having its own natural frequencies of vibration. Its response to tones having these frequencies will theoretically, at least, be much greater than to other tones. Hence we should expect the sound transmitted to vary widely with the pitch. The experiments amply justify this conclusion, so that a complete study of the transmission of sound by a single partition involves measurements for a large number of tones covering the entire musical range. The results here presented are for six or seven tones, at octave intervals, covering the entire musical range from 64 to 4096 vibrations per second.

Figure 5 shows the effect of both stiffness and mass upon the transmission of sound by glass windows. The ordinates of the curves give the logarithms of the reduction of intensity of tones given on the horizontal scale.

The lowest curve shows the reduction produced by a window with panes 3/16 of an inch thick, composed of two thin sheets of glass with an intervening sheet of celluloid. Curve 2 is for a similar window with panes of solid plate glass of the same thickness. The effect of the greater stiffness of the solid glass pane in producing a greater reduction in the intensity of the transmitted sound is shown. Curve 3 is for an identical window using plate glass ¼ of an inch thick. Translating the logarithmic reductions into numerical ratios, the curves for the heaviest window show a reduction in the ratio of 100 to 1 at middle C and a reduction of about 500 to 1 for tones in

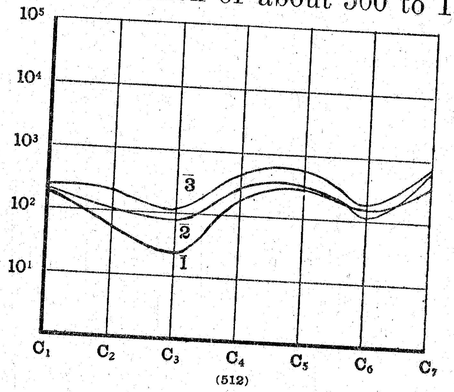

Figure 5.
Curve 1. Reduction produced by triplex glass. Curve 2. By 3/16″ plate. Curve 3. By ¼″ plate.

the second octave above middle C. In Figure 6, is shown the relative transmissions of sound by a single and a double pane window. The lower curve gives the reduction produced by a window of lighter glass than those shown in Figure 5. Curve 2 is for a double glass window, the panes being set in putty upon opposite sides of the sash, with an intervening air space of 1¾ inches. The third curve is for the same window, the panes being set in felt rather than in putty. As is shown, the merit of the double glazed over the single glazed construction is slight for the lower tones, but the former produces a somewhat higher reduction for the upper tones. Similarly, the effect of the felt in reducing the transmitted sound is negligible for the lower tones, but does produce a marked effect in improving the sound insulating properties for higher tones. Similar tests conducted upon a number of window units of various types justify the

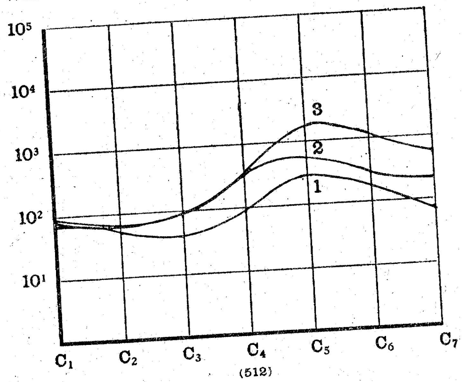

Figure 6.

Curve 1. Reduction produced by single glazed window 3/16" plate. Curve 2. By double glazed window, with panes set in putty. Curve 3. By double glazed window, panes set in felt.

statement that the sound-insulating properties of such constructions depend upon the mass and stiffness of the entire unit rather than upon the properties of the materials used.

Figure 7 presents the reduction of sound intensity produced by doors of various types. Curve 1 is for a light

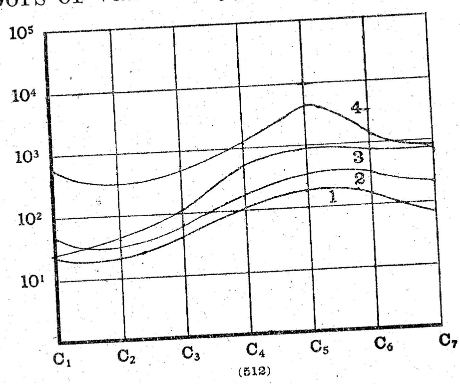

Figure 7.

Curve 1. Reduction produced by door of ¼" steel. Curve 2. By ¼" plate glass with cross bracing. Curve 3. By ¼" plate without cross bracing. Curve 4. By 3/16" small leaded panes. Curve 5. By ⅛" panes 10" x 19".

four panel door of birch veneer. Curve 2 is for a solid oak door, 1¾ inches thick. Curve 3 shows the reduction produced by a double walled "ice box" door, made of heavy pine, the intervening space being filled with heat insulating material. Interestingly enough, it was found that a solid steel door, ¼ of an inch in thickness, was much more effective in reducing the amount of the transmitted sound than were any of the other door constructions tested. Curve 4 indicates that, in general, only about 1/1000 of the sound was transmitted by this door. The net results of these investigations point to the conclusion that the highest degree of sound insulation is in the use of materials having the greatest mass and stiffness, rather than in those in which the natural damping is greatest.

It has been generally supposed that soft flexible materials possess great virtues in preventing the passage of sound. This opinion, no doubt, arises from their known value as insulators for heat, as well as to their property of being highly absorbent of sound. Our experiences in the use of such materials in securing the necessary sound insulation in the laboratory led to serious question as to the validity of this belief. Accordingly a study of a number of materials of this general character has been made. Due to its wide spread use as a sound absorbent for the reduction of reverberation, uncovered hair felt was the first material tested. In Figure 8, the logarithmic reductions of intensity of transmitted sound produced by different thicknesses of this material are shown. The point of most practical significance is the relatively small reduction of intensity of the transmitted sound as compared with material such as glass and steel. For all but the highest tones, four inches of this material is less effective than one-fourth of an inch of plate glass. It will be further noted that the sound insulating efficiency rises rapidly with rising pitch. If the logarithmic reduction be plotted against the thickness of the material as in Figure 9, the relation is seen to be linear, that is, each succeeding layer reduces the intensity of the transmitted sound by a constant ratio. This leads to the conclusion that the reduction of intensity by such a material is a pure absorption process, and makes it possible to express the insulating efficiency in terms of the thickness and two experimentally determinable coefficients. The extension of the study to a large number of materials of the same character leads to the general conclusion that their insulating efficiencies follow the order of their densities.

Another, somewhat different application of the Sound Chamber method has been an experimental study of the

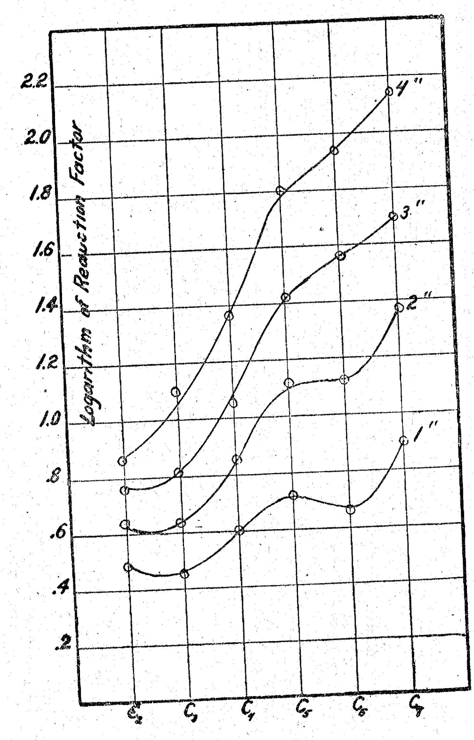

Figure 8.
Reduction of Intensity of Sound transmitted by Hair Felt of varying thickness, plotted as a function of the pitch.

sound amplifications produced by various hearing devices. The actual effectiveness of artificial aids to defective hearing has never been the subject of any more precise determination than the opinion of their users. Accordingly, an investigation was conducted to determine the efficiencies of a number of the more commonly used devices for the aid of the deaf. The eleven different instruments tested may be classified as "Sound Collectors", "Sound traps", speaking tubes, and telephones. Under the first group may be included all the modifications of the simple conical horn. The observations were made by a deaf observer, Mrs. M. H. Liddell, of Lafayette, Ind., whose skillful aid it is a pleasure to acknowledge. They consisted in timing the duration of audible sound, with the instrument held to the ear, and without. From the difference of these times, the amplification of sound is computed as in the case of reduction by parti-

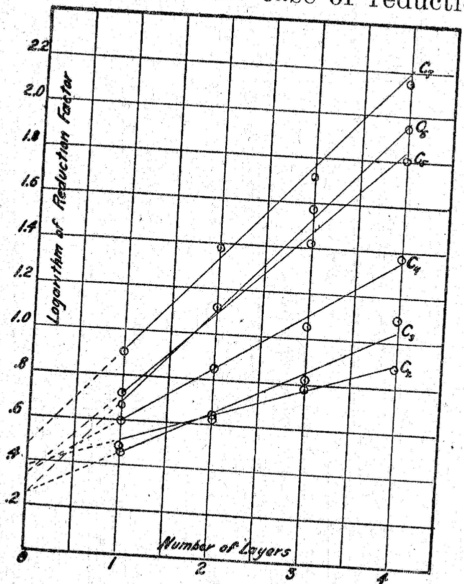

Figure 9.
Reduction of Intensity of Sound of different pitches transmitted by Hair Felt, plotted as a function of the thickness.

tions. The results showed that the order of amplifications produced followed that of the relative sizes of the instruments. The largest one tried produced a magnification of some twenty fold. It is of interest to note that simply holding the hand to the ear was as effective an aid as any but the largest of the ear trumpets. The instruments which I have denoted as sound traps are modifications of the open horn, obviously designed to secure magnification of sound intensity by reflection and focusing of the sound by curved surfaces. That such effects are not produced was evidenced by the fact that devices of this character were no more effective than the open horn of the same dimensions. To reflect sound as a mirror reflects light, the dimensions of the reflecting surface must be large as compared with the wave length of the sound. When it is recalled that the wave lengths of tones in the middle register are of the order of several feet, it is apparent that any amplifying device based upon such a principle must of necessity be prohibitively large as a portable instrument. Hence there is no virtue in such instruments when small, other than that of their simple action as resonators.

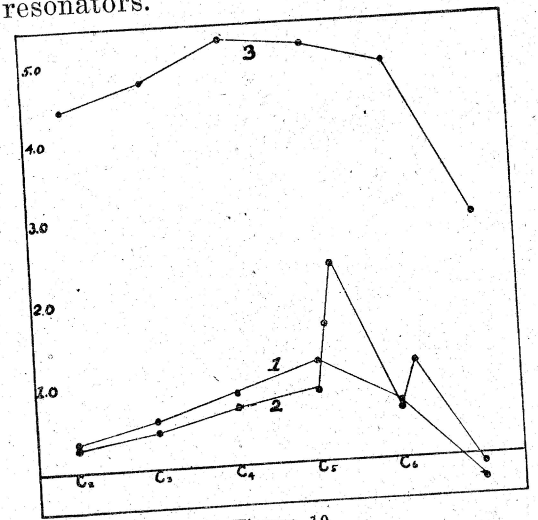

Figure 10.
Logarithmic amplifications of Sound intensities produced by artificial aids to hearing. See Text.

Telephonic devices proved to be much more efficient as sound amplifiers than the simpler ear trumpets. In instruments of this type, however, the maximum amplifications are limited to a small range of tones in the neighborhood of the natural frequencies of the transmitter and receiver diaphragms. The logarithmic amplifications produced by the largest of the ear trumpets [curve 1] and by one of the better known telephonic devices [curve 2] are shown in Figure 10. The upper curve shows the amplification necessary to enable the deaf observer to hear sounds as faint as those that can be heard by normal ears. Expressed in terms of physical intensity, the amplification required to produce normal sensitivity for this observer is of the order of 100,000 fold. The best of the ear trumpets produced a magnification of some twenty fold, while the telephone at the frequency for which it was most efficient magnified the intensity some two hundred fold.

Study of the ear, regarded simply as a piece of physical apparatus, has been a field of investigation sadly neglected by physicists. What is known of the performance of the ear in a quantitative way is lamentably small. Otologists readily admit that the physical methods they are forced to employ for want of better are deplorably inadequate, as compared with similar methods employed in the diagnosis of defects of vision. A program of investigation in this field has been begun. The first problem attacked has been that of the determination in absolute units of the minimun sound intensity that will produce the sensation of sound. The results of previous investigations on this question have shown enormous differences. Thus Wien, working in Germany, obtained results indicating a sensitivity of normal ears for tones in the middle and upper registers 10,000 times as great as that determined by Lord Rayleigh. In our Laboratory, Mr. F. W. Kranz has spent almost two years upon this problem. Using a number of methods, results have been obtained, discordant at first, but now showing satisfactory agreement, as sources of error have been eliminated one after another. The energies to be measured are extremely small, and the experimental difficulties are great. Perhaps the most striking of the results is the wide variation of apparently normal hearing. Of the twenty normal ears examined, the least sensitive required for the perception of the tone 512 vibrations, 100 times that required by the most sensitive. At a pitch two octaves above this, the maximum variation of sensitivity was by a factor of 1,000. In general, the range of tones for which the ear is most sensitive is the third octave above middle C, where the sensitivity is about 10,000 times as great as for the octave below this tone. In the region of maximum sensitivity, Mr. Kranz' measurements indicate that amplitudes of vibration of the same order as atomic dimensions, namely 10^{-8} cms., produce the sensation of sound. The extension of the method to other problems of audition promises to yield much valuable information upon a subject in which such knowledge is badly needed.

These are some of the problems that have been attacked and partially solved during the three years of the Laboratory's existence. Beginnings have been made upon others, and there is still a large group for the study of which the Laboratory affords most excellent facilities. One of the most fundamental of these is the development of standard sources of sound of easily measurable acoustical output. An equally fundamental desideratum for acoustical measurements is a means of measuring sound intensity as energy, simply, independently of its pitch. All of our sound measuring devices give readings that are functions of both pitch and intensity, so that both of these factors must be taken into account in acoustical measurements as now made. The status of our present investigational methods is that which existed in the measurement of radiation before the development of the bolometer and the sensitive thermo-couple. Rapid advance in the quantitative study of acoustical problems awaits the development of corresponding means for sound measurement. The measurement of noise, which is sound without definite pitch characteristics, is at present impossible.

One of the outstanding lessons of the war was the discovery of the military and naval possibilities of acoustical methods. Equally impressive was the discovery of the entire inadequacy of our quantitative knowledge of this branch of Physics. The control and reduction of sound becomes one of vital importance in view of the multiplication of sources of noise in this mechanical age and the increasing congestion of living and working conditions of modern life. Hence research in Acoustics offers a pleasant prospect of contributions of practical value to scientific knowledge, and a laboratory devoted to this purpose should fill a useful place in the scheme of things scientific.