Proceedings of the American Academy of Arts and Sciences.

Vol. XLII. No. 2. — June, 1906.

CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD COLLEGE.

ARCHITECTURAL ACOUSTICS.

- I. *INTRODUCTION.*
- II. *THE ACCURACY OF MUSICAL TASTE IN REGARD TO ARCHITECTURAL ACOUSTICS.*
- III. *VARIATION IN REVERBERATION WITH VARIATION IN PITCH.*

By Wallace C. Sabine.

CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY,
HARVARD COLLEGE.

ARCHITECTURAL ACOUSTICS.

Presented Dec. 13, 1905. Received March 22, 1906.

I. Introduction.

The problem of architectural acoustics requires for its complete solution two distinct lines of investigation, one to determine quantitatively the physical conditions on which loudness, reverberation, resonance, and the allied phenomena depend, the other to determine the intensity which each of these should have, what conditions are best for the distinct audition of speech, and what effects are best for music in its various forms. One is a purely physical investigation, and its conclusions should be based and should be disputed only on scientific grounds; the other is a matter of judgment and taste, and its conclusions are weighty in proportion to the weight and unanimity of the authority in which they find their source. For this reason, these papers are in two series. The articles which appeared six years ago began the first, and the paper immediately following is the beginning of the second.

Of the first series of papers, which have to do with the purely physical side of the problem, only one paper has as yet been published. This contained a discussion of reverberation, complete as far as one note is concerned. There is on hand considerable material for a paper extending this discussion to cover the whole range of the musical scale, and therefore furnishing a basis for the discussion of what has sometimes been called the musical quality of an auditorium. There has also been collected a certain amount of data in regard to loudness, resonance, interference, echos, irregularities of air currents and temperature, and the transmission of sound through walls and partitions, — all of which will appear as soon as a complete presentation is possible in each case. Each problem has been taken up as it has been brought to the writer's attention by an architect in consultation either over plans or in regard to a completed building. This method is slow, but it has the advantage of making the work practical, and may be relied on to prevent the magnification to undue importance of scientifically interesting but practically subordinate points. On the other hand there is the danger that it may lead to a fragmentary presentation. An effort has been made to guard against this, and the effort for completeness is the reason for delay in the appearance of some of the papers. Sufficient progress has been made, however, to justify the assertion that the physical side of the problem is solvable, and that it should be possible ultimately to calculate in advance of construction all the acoustical qualities of an auditorium.

Thus far it is a legitimate problem in physics, and as such a reasonable one for the writer to undertake.

The second part of the problem, now being started, the question as to what constitutes good and what constitutes poor acoustics, what effects are desirable in an auditorium designed for speaking, and even more especially in one designed for music, is not a question in physics. It is therefore not one for which the writer is especially qualified, and would not be undertaken here were it not in the first place absolutely necessary in order to give effect to the rest of the work, and in the second place were it not the plan rather to gather and give expression to the judgment of others acknowledged as qualified to speak, than to give expression to the taste and judgment of one. It is thus the purpose to seek expert judgment in regard to acoustical effects, and if possible to present the results in a form available to architects. This will be slow and difficult work, and it is not at all certain that it will be possible to arrive, even ultimately, at a finished product. It is worth undertaking, however, if the job as a whole is worth undertaking, for without it the physical side of the investigation will lose much of its practical value. Thus it is of little value to be able to calculate in advance of construction and express in numerical measure the acoustical quality which any planned auditorium will have, unless one knows also in numerical measure the acoustical quality which is desired. On the other hand, if the owner and the architect can agree on the desired result, and if this is within the limits of possibility considering all the demands on the auditorium, of utility, architecture, and engineering, this result can be secured with certainty, — at least there need be no uncertainty as to whether it will or will not be attained in the completed building.

The papers following this introduction will be: "The Accuracy of Musical Taste in regard to Architectural Acoustics," and "Variation in Reverberation with Variation in Pitch."

II. The Accuracy of Musical Taste in regard to Architectural Acoustics.

Piano Music.

The experiments described in this paper were undertaken in order to determine the reverberation best suited to piano music in a music room of moderate size, but were so conducted as to give a measure of the accuracy of cultivated musical taste. The latter point is obviously fundamental to the whole investigation, for unless musical taste is precise, the problem, at least as far as it concerns the design of the auditorium for musical purposes, is indeterminate.

The first observations in regard to the precision of musical taste were obtained during the planning of the Boston Symphony Hall, Messrs. McKim, Mead, and White, Architects. Mr. Higginson, Mr. Gericke, the conductor of the orchestra, and others connected with the Building Committee expressed opinions in regard to a number of auditoriums. These buildings included the old Boston Music Hall, at that time the home of the orchestra, and the places visited by the orchestra in its winter trips, Sanders Theatre in Cambridge, Carnegie Hall in New York, the Academy of Music in Philadelphia, and the Music Hall in Baltimore, and in addition to these the Leipsig Gewandthaus. By invitation of Mr. Higginson, the writer accompanied the orchestra on one of its trips, made measurements of all the halls, and calculated their reverberation. The dimensions and the material of the Gewandthaus had been published, and from these data its reverberation also was calculated. The results of these measurements and calculations showed that the opinions expressed in regard to the several halls were entirely consistent with the physical facts. That is to say, the reverberation in those halls in which it was declared too great was in point of physical measurement greater than in halls in which it was pronounced too small. This consistency gave encouragement in the hope that the physical problem was real, and the end to be attained definite.

Much more elaborate data on the accuracy of musical taste were obtained four years later, 1902, in connection with the new building of the New England Conservatory of Music, Messrs. Wheelwright and Haven, Architects. The new building consists of a large auditorium surrounded on three sides by smaller rooms, which on the second and third floors are used for purposes of instruction. These smaller rooms, when first occupied, and used in an unfurnished or partially furnished condition, were found unsuitable acoustically, and the writer was consulted by Mr. Haven in regard to their final adjustment. In order to learn the acoustical condition which would accurately meet the requirements of those who were to use the rooms, an experiment was undertaken in which a number of rooms, chosen as typical, were varied rapidly in respect to reverberation by means of temporarily introduced absorbing material. Approval or disapproval of the acoustical quality of each room at each stage was expressed by a committee chosen by the Director of the Conservatory. At the close of these tests, the reverberation in the rooms was measured by the writer in an entirely independent manner as described in the paper on Reverberation (1900). The judges were Mr. George W. Chadwick, Director of the Conservatory, and Sig. Oresti Bimboni, Mr. William H. Dunham, Mr. George W. Proctor, and Mr. William L. Whitney, of the Faculty. The writer suggested and arranged the experiment and subsequently reduced the results to numerical measure, but expressed no opinion in regard to the quality of the rooms.

The merits of each room in its varied conditions were judged solely by listening to piano music by Mr. Proctor. The character of the musical compositions on which the judgment was based is a matter of interest in this connection, but this fact was not appreciated at the time and no record of the selections was made. It is only possible to say that several short fragments, varied in nature, were tried in each room.

As will be evident from the descriptions given below, the rooms were so differently furnished that no inference as to the reverberation could be drawn from appearances, and it is certain that the opinions were based solely on the quality of the room as heard in the piano music.

The five rooms chosen as typical were on the second floor of the building. The rooms were four meters high. Their volumes varied from 74 to 210 cubic meters. The walls and ceilings were finished in plaster on wire lath, and were neither papered nor painted. There was a piano in each room; in room 5 there were two. The amount of other furniture in the rooms varied greatly:

In room 1 there was a bare floor, and no furniture except the piano and piano stool.

Room 2 had rugs on the floor, chairs, a sofa with pillows, table, music racks, and a lamp.

Room 3 had a carpet, chairs, bookcases, and a large number of books, which, overflowing the bookcases, were stacked along the walls.

Room 4 had no carpet, but there were chairs and a small table.

Room 5 had a carpet, chairs, and shelia curtains.

Thus the rooms varied from an almost unfurnished to a reasonably furnished condition. In all cases the reverberation was too great.

The experiment was begun in room 1. There were, at the time, besides the writer, five gentlemen in the room, the absorbing effect of whose clothing, though small, nevertheless should be taken into account in an accurate calculation of the reverberation. Thirteen cushions from the seats in Sanders Theatre, whose absorbing power for sound had been determined in an earlier investigation, were brought into the room. Under these conditions the unanimous opinion was that the room, as tested by the piano, was lifeless. Two cushions were then removed from the room with a perceptible change for the better in the piano music. Three more cushions were removed, and the effect was much better. Two more were then taken out, leaving six cushions in the room, and the result met unanimous approval. It was suggested that two more be removed. This being done the reverberation was found to be too great. The agreement was then reached that the conditions produced by the presence of six cushions were the most nearly satisfactory.

The experiment was then continued in Mr. Dunham's room, number 2. Six gentlemen were present. Seven cushions were brought into the room. The music showed an insufficient reverberation. Two of the cushions were then taken out. The change was regarded as a distinct improvement, and the room was satisfactory.

In Mr. Whitney's room, number 3, twelve cushions, with which it was thought to overload the room, were found insufficient even with the presence in this case of seven gentleman. Three more cushions were brought in and the result declared satisfactory.

In the fourth room, five, eight, and ten cushions were tried before the conditions were regarded as satisfactory.

In Mr. Proctor's room, number 5, it was evident that the ten cushions which had been brought into the room had overloaded it. Two were removed, and afterwards three more, leaving only five, before a satisfactory condition was reached.

This completed the direct experiment with the piano.

The bringing into a room of any absorbing material, such as these cushions, affects its acoustical properties in several respects, but principally in respect to its reverberation. The prolongation of sound in a room after the cessation of its source, may be regarded either as a case of stored energy which is gradually suffering loss by transmission through and absorption by the walls and contained material, or it may be regarded as a process of rapid reflection from wall to wall with loss at each reflection. In either case it is called reverberation. It is sometimes called, mistakenly as has been explained, resonance. The reverberation may be expressed by the duration of audibility of the residual sound after the cessation of a source so adjusted as to produce an average of sound of some standard intensity over the whole room. The direct determination of this, under the varied conditions of this experiment, was impracticable, but, by measuring the duration of audibility of the residual sound after the cessation of a measured organ pipe in each room without any cushions, and knowing the coefficient of absorption of the cushions, it was possible to calculate accurately the reverberation at each stage in the test. It was impossible to make these measurements immediately after the above experiments, because, although the day was an especially quiet one, the noises from the street and railway traffic were seriously disturbing. Late the following night the conditions were more favorable, and a series of fairly good observations was obtained in each room. The cushions had been removed, so that the measurements were made on the rooms in their original condition, furnished as above described. The apparatus and method employed are described in full in a series of articles in the Engineering Record and American Architect for 1900. The results are given in the accompanying table.

The table is a record of the first of what, it is hoped, will be a series of such experiments extending to rooms of much larger dimensions and to other kinds of music. It may well be, in fact it is highly probable, that very much larger rooms would necessitate a different amount of reverberation, as also may other types of musical instruments or the voice. As an example of such investigations, as well as evidence of their need, it is here given in full. The following additional explanations may be made. The variation in volume of the rooms is only threefold, corresponding only to such music rooms as may be found in private houses. Over this range a perceptible variation in the required reverberation should not be expected. The third column in the table includes in the absorbing power of the room (ceiling, walls, furniture, etc.) the absorbing powers of the clothes of the writer, who was present not merely at all tests, but in the measurement of the reverberation the following night. From the next two columns, therefore, the writer and the effects of his clothing are omitted. The remarks in the last column are reduced to the form "reverberation too great," "too little," or "approved." The remarks at the time were not in this form, however. The room was pronounced "too resonant," "too much echo," "harsh," or "dull," "lifeless," "overloaded," expressions to which the forms adopted are equivalent.

Room Number.	Volume.	Absorbing Power of Room.	Gentlemen Present.	Absorbing Power of Clothing.	Number of Meters of Cushions.	Absorbing Power of Cushions.	Total Absorbing Power.	Reverberation in Seconds.	Remarks.
1	74	5.0	0	0	0	0	5.0	2.43	Reverberation too great.
		"	5	2.4	0	0	7.4	1.64	Reverberation too great.
		"	"	"	13	12.8	20.2	.60	Reverberation too little.
		"	"	"	11	10.1	17.5	.70	Better.
		"	"	"	8	7.3	14.7	.83	Better.
		"	"	"	6	5.5	12.9	.95	Condition approved.
		"	"	"	4	3.6	11.0	1.22	Reverberation too great.
2	91	6.3	0	0	0	0	6.3	2.39	Reverberation too great.
		"	6	2.9	0	0	9.2	1.95	Reverberation too great.
		"	"	"	7	6.4	15.6	.95	Reverberation too little.
		"	"	"	5	4.6	13.8	1.10	Condition approved.
3	210	14.0	0	0	0	0	14.0	2.46	Reverberation too great.
		"	7	3.4	0	0	17.4	2.00	Reverberation too great.
		"	"	"	12	11.0	28.4	1.21	Better.
		"	"	"	15	13.7	31.1	1.10	Condition approved.
4	133	8.3	0	0	0	0	8.3	2.65	Reverberation too great.
		"	7	3.4	0	0	11.7	1.87	Reverberation too great.
		"	"	"	6	5.5	17.2	1.26	Better.
		"	"	"	10	9.1	20.8	1.09	Condition approved.
5	96	7.0	0	0	0	0	7.0	2.24	Reverberation too great.
		"	4	1.9	0	0	8.9	1.76	Reverberation too great.
		"	"	"	10	9.1	18.0	.87	Reverberation too little.
		"	"	"	8	7.3	16.2	.98	Better.
		"	"	"	5	4.6	13.5	1.16	Condition approved.

If from the larger table the reverberation in each room, in its most approved condition, is separately tabulated, the following is obtained:

Rooms.	Reverberation.
1	.95
2	1.10
3	1.10
4	1.09
5	1.16
	1.08 mean.

The final result obtained, that the reverberation in a music room in order to secure the best effect with a piano should be 1.08, or in round numbers 1.1, is in itself of considerable practical value; but the five determinations, by their mutual agreement, give a numerical measure to the accuracy of musical taste which is of great interest. Thus the maximum departure from the mean is .13 seconds, and the average departure is .05 seconds. Five is rather a small number of observations on which to apply the theory of probabilities, but, assuming that it justifies such reasoning, the probable error is .02 seconds — surprisingly small.

A close inspection of the large table will bring out an interesting fact. The room in which the approved condition differed most from the mean was the first. In this room, and in this room only, was it suggested by the gentlemen present that the experiment should be carried further. This was done by removing two more cushions. The reverberation was then 1.22 seconds, and this was decided to be too much. The point to be observed is that 1.22 is further above the mean, 1.08, than .95 is below. Moreover, if one looks over the list in each room it will be seen that in every case the reverberation corresponding to the chosen condition came nearer to the mean than that of any other condition tried.

It is conceivable that had the rooms been alike in all respects and required the same amount of cushions to accomplish the same results, the experiment in one room might have prejudiced the experiment in the next. But the rooms being different in size and furnished so differently, an impression formed in one room as to the number of cushions necessary could only be misleading if depended on in the next. Thus the several rooms required 6, 5, 15, 10, and 5 cushions. It is further to be observed that in three of the rooms the final condition was reached in working from an overloaded condition, and in the other two rooms from the opposite condition — in the one case by taking cushions out, and in the other by bringing them in.

Before beginning the experiment no explanation was made of its nature, and no discussion was held as to the advantages and disadvantages of reverberation. The gentlemen present were asked to express their approval or disapproval of the room at each stage of the experiment, and the final decision seemed to be reached with perfectly free unanimity.

This surprising accuracy of musical taste is perhaps the explanation of the rarity with which it is entirely satisfied, particularly when the architectural designs are left to chance in this respect.

III. VARIATION IN REVERBERATION WITH VARIATION IN PITCH.

Six years ago there was published in the Engineering Record and the American Architect a series of papers on architectural acoustics intended as a beginning in the general subject. The particular phase of the subject under consideration was reverberation — the continuation of sound in a room after the source has ceased. It was there shown to depend on two things, — the volume of the room, and the absorbing character of the walls and of the material with which the room is filled. It was also mentioned that the reverberation depends in special cases on the shape of the room, but these special cases were not considered. The present paper also will not take up these special cases, but postpone their consideration, although a good deal of material along this line has now been collected. It is the object here to continue the earlier work rather narrowly along the original lines. The subject was then investigated solely with reference to sounds of one pitch, C_4 512 vibrations per second. It is the intention here to extend this over nearly the whole range of the musical scale, from C_1 64 to C_7 4096.

It can be shown readily that the various materials of which the walls of a room are constructed and the materials with which it is filled do not have the same absorbing power for all sounds regardless of pitch. Under such circumstances the previously published work with C_4 512 must be regarded as an illustration, as a part of a much larger problem — the most interesting part, it is true, because near the middle of the scale, but after all only a part. Thus a room may have great reverberation for sounds of low pitch and very little for sounds of high pitch, or exactly the reverse; or a room may have comparatively great reverberation for sounds both of high and of low pitch and very little for sounds near the middle of the scale. In other words, it is not putting it too strongly to say that a room may have very different quality in different registers, as different as does a musical instrument; or, if the room is to be used for speaking purposes, it may have different degrees of excellence or defect for a whisper and for the full rounded tones of the voice, different for a woman's voice and for a man's — facts more or less well recognized. Not to leave this as a vague generalization the following cases may be cited. Recently, in discussing the acoustics of the proposed cathedral of Southern California in Los Angeles with Mr. Maginnis, its architect, and the writer, Bishop Conaty touched on this point very clearly. After discussing the general subject with more than the usual insight and experience, possibly in part because Catholic churches and cathedrals have great reverberation, he added that he found it difficult to avoid pitching his voice to that note which the auditorium most prolongs notwithstanding the fact that he found this the worst pitch on which to speak. This brings out, perhaps more impressively because from practical experience instead of from theoretical considerations, the two truths that auditoriums have very different reverberation for different pitches, and that excessive reverberation is a great hindrance to clearness of enunciation. Another incident may also serve, that of a church near Boston in regard to which the writer has just been consulted. The present pastor, in describing the nature of its acoustical defects, stated that different speakers had different degrees of difficulty in making themselves heard; that he had no difficulty, having a rather high pitched voice; but that the candidate before him, with a louder but much lower voice, failed of the appointment because unable to make himself heard. Practical experience of the difference in reverberation with variation of pitch is not unusual, but the above cases are rather striking examples. Corresponding effects are not infrequently observed in halls devoted to music. Its observation here, however, is marked in the rather complicated general effect. The full discussion of this belongs to another series of papers, in which will be taken up the subject of the acoustical effects or conditions that are desirable for music and for speech. While this phase of the subject will not be discussed here at length, a little consideration of the data to be presented will show how pronounced these effects may be and how important in the general subject of architectural acoustics.

In order to show the full significance of this extension of the investigation in regard to reverberation, it is necessary to point out some features which in earlier papers were not especially emphasized. Primarily the investigation is concerned with the subject of reverberation, that is to say, with the subject of the continuation of a sound in a room after the source has ceased. The immediate effect of reverberation is that each note, if it be music, each syllable or part of a syllable, if it be speech, continues its sound for some time, and by its prolongation overlaps the succeeding notes or syllables, harmoniously or inharmoniously in music, and in speech always towards confusion. In the case of speech it is inconceivable that this prolongation of the sound, this reverberation, should have any other effect than that of confusion and injury to the clearness of the enunciation. In music, on the other hand, reverberation, unless in excess, has a distinct and positive advantage.

Perhaps this will be made more clear, or at least more easily realized and appreciated, if we take a concrete example. Given a room comparatively empty, with hard wall surfaces, for example plaster or tile, and having in it comparatively little furniture, the amount of reverberation for the sounds of about the middle register of the double-bass viol and for the sounds of the middle register of the violin will be very nearly though not exactly equal. If, however, we bring into the room a quantity of elastic felt cushions, sufficient, let us say, to accommodate a normal audience, the effect of these cushions, the audience being supposed absent, will be to diminish very much the reverberation both for the double-bass viol and for the violin, but will diminish them in very unequal amounts. The reverberation will now be twice as great for the double-bass as for the violin. If an audience comes into the room, filling up the seats, the reverberation will be reduced still further and in a still greater disproportion, so that with an audience entirely filling the room the reverberation for the violin will be less than one third that for the double-bass. When one considers that a difference of five per cent in reverberation is a matter for approval or disapproval on the part of musicians of critical taste, the importance of considering these facts is obvious.

This investigation, nominally in regard to reverberation, is in reality laying the foundation for other phases of the problem. It has as one of its necessary and immediate results a determination of the coefficient of absorption of sound of various materials. These coefficients of absorption, when once known, enable one not merely to calculate the prolongation of the sound, but also to calculate the average loudness of sustained tones. Thus it was shown in one of the earlier papers, though at that time no very great stress was laid on it, that the average loudness of a sound in a room is proportional inversely to the absorbing power of the material in the room. Therefore the data which are being presented, covering the whole range of the musical scale, enable one to calculate the loudness of different notes over that range, and make it possible to show what effect the room has on the piano or the orchestra in different parts of the register.

To illustrate this by the example above cited, if the double-bass and the violin produce the same loudness in the open air, in the bare room with hard walls both would be re-enforced about equally. The elastic felt brought into the room would decidedly diminish this re-enforcement for both instruments. It would, however, exert a much more pronounced effect in the way of diminishing the re-enforcement for the violin than for the double-bass. In fact, the balance will be so affected that it will require two violins to produce the same volume of sound as does one double-bass. The audience coming into the room will make it necessary to use three violins to a double-bass to secure the same balance as before.

Both cases cited above are only broadly illustrative. As a matter of fact the effect of the room and the effect of the audience in the room is perceptibly different at the two ends of the register of the violin and of the double-bass viol.

There is still a third effect, which must be considered to appreciate fully the practical significance of the results that are being presented. This is the effect on the quality of a sustained tone. Every musical tone is composed of a great number of partial tones, the predominating one being taken as the fundamental, and its pitch as the pitch of the sound. The other partial tones are regarded as giving quality or color to the fundamental. The musical quality of a tone depends on the relative intensities of the overtones. It has been customary, at least on the part of physicists, to regard the relative intensities of the overtones, which define the quality of the sound, as depending simply on the source from which the sound originates. Of course, primarily, this is true. Nevertheless, while the source defines the relative intensities of the issuing sounds, their actual intensities in the room depend not merely on that, but also, and to a surprising degree, on the room itself. Thus, for example, given an eight-foot organ pipe, if blown in an empty room, such as that described above, the overtones would be pronounced. If exactly the same pipe be blown with the same wind pressure in a room in which the seats have been covered with the elastic felt, the first upper partial will bear to the fundamental a ratio of intensity diminished over 40 per cent, the second upper partial a ratio to the fundamental diminished in the same per cent, the third upper partial a ratio diminished over 50 per cent, while the fourth upper partial will bear a ratio of intensity to the fundamental diminished about 60 per cent. Quality expressed numerically in this way probably does not convey a very vivid impression as to its real effect. It may signify more to say merely that the change in quality is very pronounced and noticeable, even to comparatively untrained ears. On the other hand, if one were to try the experiment with a six-inch instead of with an eight-foot organ pipe, the effect of bringing the elastic felt cushions into the room would be to increase the relative intensities of the overtones, and thus to diminish the purity of the tone.

All tones below that of a six-inch organ pipe will be purified by bringing into the room elastic felt. All tones above and including that pitch will be rendered less pure. The effect of an audience coming into a room is still different. Assuming that the audience has filled the room and so covered all the elastic felt cushions, the effect of the audience is to purify all tones up to violin C_4 512, and to have very little effect on all tones from that pitch upward. On very low tones the effect of the audience in the room is more pronounced. For example, again take C_1 64, the effect of the audience will be to diminish its first overtone about sixty per cent relative to the fundamental and its second overtone over seventy-five per cent.

The effect of the material used in the construction of a room, and the contained furniture, in altering the relative intensities of the fundamental and the overtones, is to improve or injure its quality according to circumstances. It may be, of course, that the tone desired is a very pure one, or it may be that what is wanted is a tone with pronounced upper partials. Take, for example, the "night horn" stop in a pipe organ. This is intended to have a very pure tone. The room in contributing to its purity would improve its quality. On the other hand, the mixture stop in a pipe organ is intended to have very pronounced overtones. In fact to this end not one but several pipes are sounded at once. The effect of the above room to emphasize the fundamental and to wipe out the overtones would be in opposition to the original design of the stop. To determine what balance is desirable must lie of course with the musicians. The only object of the present series of papers is to point out the fundamental facts, and that our conditions may be varied in order to attain any desired end. One great thing needed is that the judgment of the musical authorities should be gathered in an available form; but that is another problem, and the above bare outline is intended only to indicate the importance of extending the work to the whole range of the musical scale, — the work undertaken in the present paper.

The method pursued in these experiments is not very unlike that followed in the previous experiments with C_4 512. It differs in minor detail, but to explain these details would involve a great deal of repetition which the modifications in the method are not of sufficient importance to justify.

Broadly, the procedure consists first in the determination of the rate of emission of the sound of an organ pipe for each note to be investigated. This consists in determining the durations of audibility after the cessation of two sounds, one having four or more, but a known multiple, times the intensity of the other. From these results it is possible to determine the rate of emission by the pipes, each in terms of the minimum audibility for that particular tone. The apparatus used in this part of the experiment is shown in Figure 1. Four small organs were fixed at a minimum distance of five meters apart. It was necessary to place them at this great distance apart because, as already pointed out, if placed near each other the four sounded to-

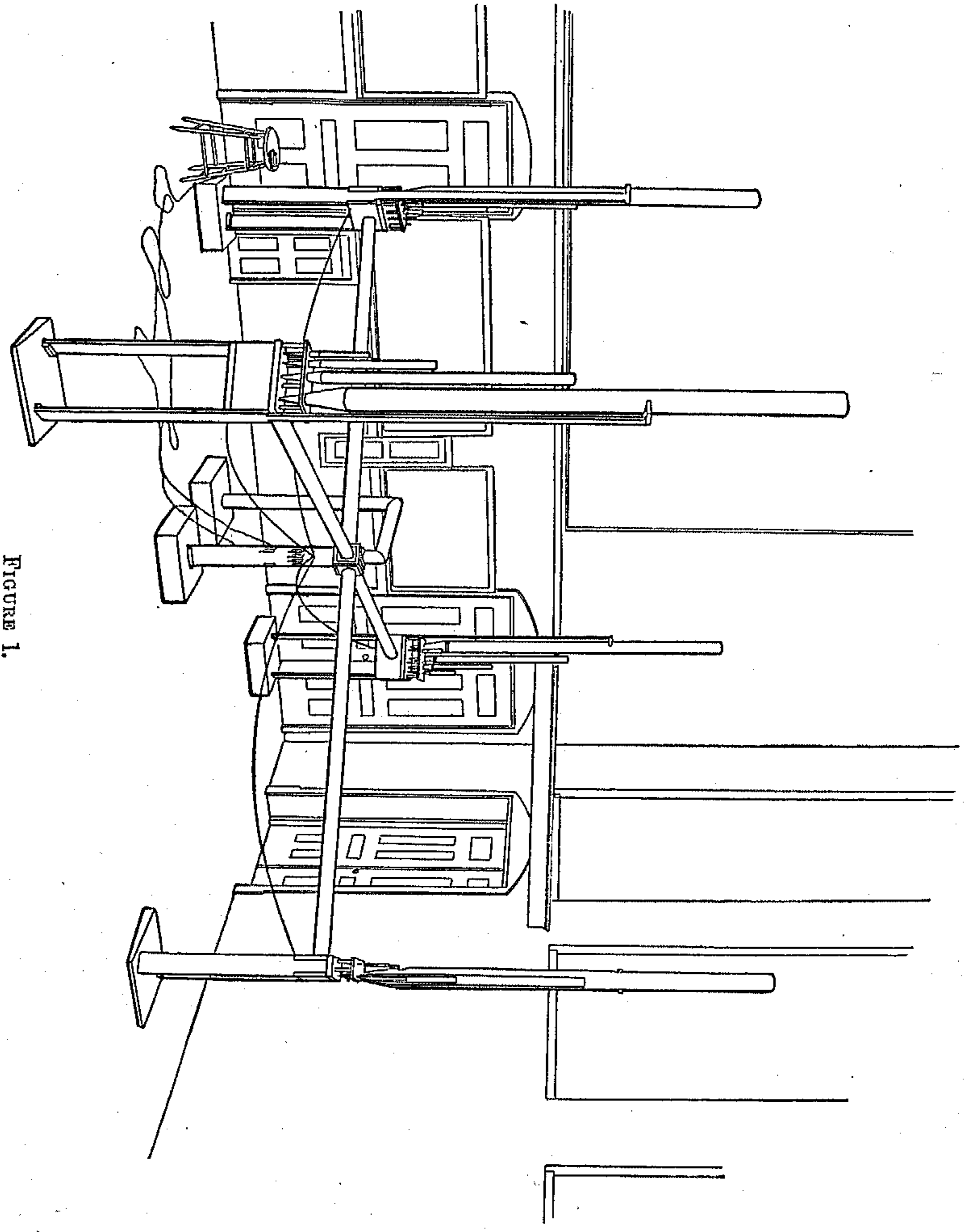

FIGURE 1.

gether do not emit four times the sound emitted by one. This wide separation was particularly necessary for the large pipes and the low tones; a very much less separation would have served the purpose in the case of the high tones.

From the point where the four tubes leading to the small organs meet, a supply pipe ran, as shown on the drawing, to an air reservoir in the room below. This was fed from an electrically driven blower at the far end of the building. The chronograph was in another room. The experiments with this apparatus, like the experiments heretofore recorded, were carried out at night between twelve and five o'clock.

The rate of emission of sound by the several pipes having been determined, the next work was the determination of the coefficients of absorption. The methods employed having already been sufficiently described, only results will be given.

In the very nature of the problem the most important data is the absorption coefficient of an audience, and the determination of this was the first task undertaken. By means of a lecture on one of the recent developments of physics, an audience was enveigled into attending, and at the end of the lecture requested to remain for the experiment. In this attempt the effort was made to determine the coefficients for the five octaves from C_2 128 to C_6 2048, including notes E and G in each octave. For several reasons the experiment was not a success. A threatening thunder storm made the audience a small one, and the sultriness of the atmosphere made open windows necessary, while the attempt to cover so many notes, thirteen in all, prolonged the experiment beyond the endurance of the audience. While this experiment failed, another the following summer was more successful. In the year that had elapsed the necessity of carrying the investigation further than the limits intended became evident, and now the experiment was carried from C_1 64 to C_7 4096, but including only the C notes, seven notes in all. Moreover, bearing in mind the experiences of the previous summer, it was recognized that even seven notes would come dangerously near overtaxing the patience of the audience. Inasmuch as the coefficient of absorption for C_4 512 had already been determined six years before in the investigations mentioned, the coefficient for this note was not redetermined. The experiment was therefore carried out for the lower three and the upper three notes of the seven. The audience, on the night of this experiment, was much larger than that which came the previous summer, the night was a more comfortable one, and it was possible to close the windows during the experiment. The conditions were thus fairly satisfactory. In order to get as much data as possible and in as short a time, there were nine observers stationed at different points in the room. These observers, whose kindness and skill it is a pleasure to acknowledge,

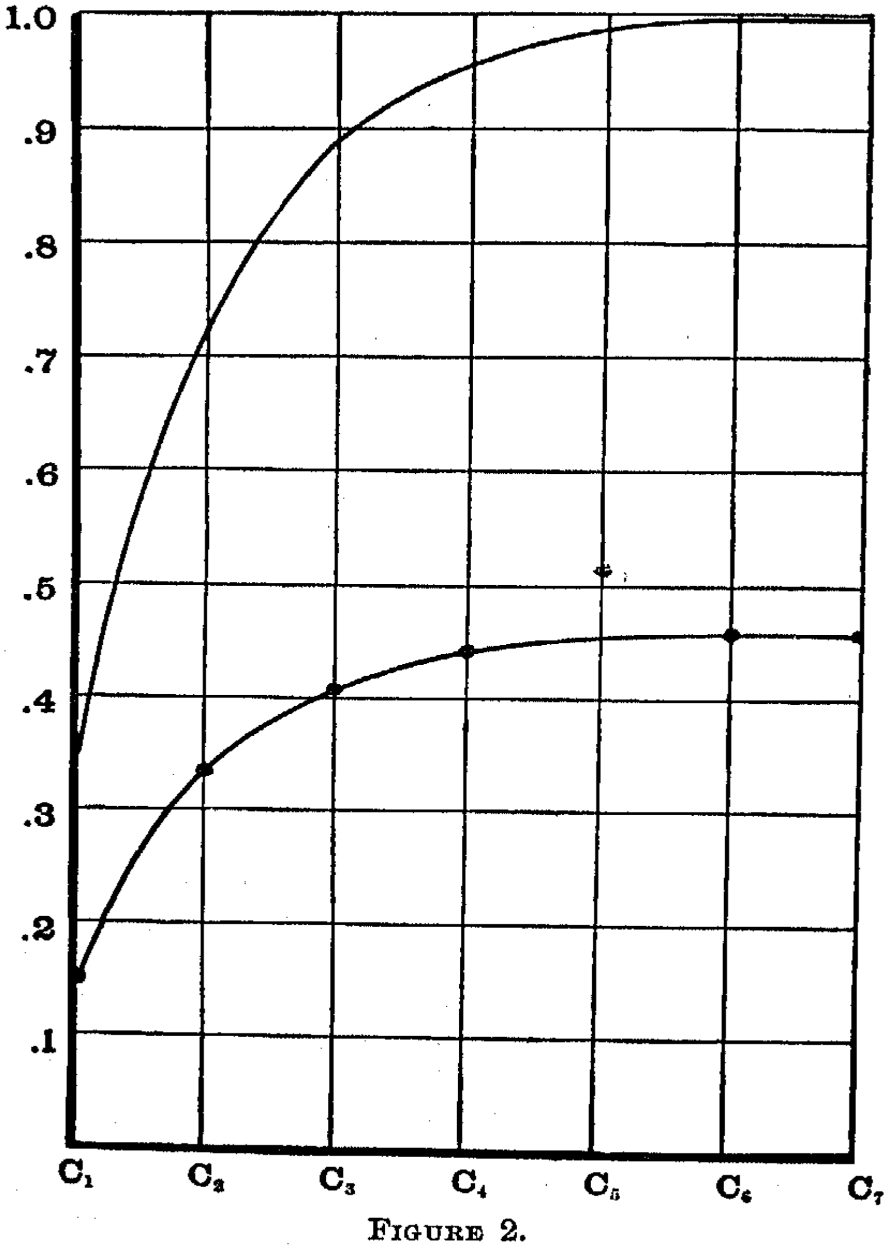

FIGURE 2.

The absorbing power of an audience for different notes. The lower curve represents the absorbing power of an audience per person. The upper curve represents the absorbing power of an audience per square meter as ordinarily seated. The vertical ordinates are expressed in terms of total absorption by a square meter of surface. For the upper curve the ordinates are thus the ordinary coefficients of absorption. The several notes are at octave intervals as follows, C_1 64, C_2 128, C_3 (middle C) 256, C_4 512, C_5 1024, C_6 2048, C_7 4096.

had prepared themselves by previous practice for this one experiment. As in the work of six years ago, the writer's key controlled the organ pipes and started the chronograph, the writer and the other observers each had a key which was connected with the chronograph to record the cessation of audibility of the sound. The results of the experiment are shown on the lower curve in Figure 2. This curve gives the coefficient of absorption per person. It is to be observed that one of the points falls clearly off the smooth curve drawn through the other points. The observations on which this point is based were, however, much disturbed by a street car passing not far from the building, and the departure of this observation from the curve does not indicate a real departure in the coefficient nor should it cast much doubt on the rest of the work, in view of the circumstances under which it was secured. Counteracting the perhaps bad impression which this point may give, it is a considerable satisfaction to note how accurately the point for C_4 512, determined six years before by a different set of observers, falls on the smooth curve through the remaining points. In the audience on which these observations were taken there were 77 women and 105 men. The courtesy of the audience in remaining for the experiment and the really remarkable silence which they maintained is gratefully acknowledged.

The curve above discussed is that for the average person in an audience. An interesting form in which to throw the results is to regard the audience as one side of a room. We may then look at it as an extended absorbing surface, and determine the coefficient per square meter. Worked out on this basis the absorption coefficient is indicated in the higher curve. It is merely the lower curve multiplied by a number which expresses the average number of people per square meter. It is interesting to note that the coefficient of absorption is about the same from C_4 512 up, indicating over that range nearly complete absorption. Below that point there is a very great falling off, down to C_1 64. The curve is such as to permit of an extrapolation indicative of even less absorption and consequently greater reverberation for the still lower notes. Without entering into an elaborate discussion of this curve, two points may be noted as particularly interesting. The first is the nearly complete absorption for the higher notes, a result which at first sight seems a little inconsistent with the results which will be shown later on in connection with the absorption by felt. The inconsistency, however, is only apparent. The greater absorption shown by an audience than that shown by thick felt arises from the fact that the surface of the audience is irregular and does not result in a single reflection, but probably, for a very large portion of the sound, of multiple reflection before it finally emerges. The physical conditions are such that they obviously do not admit of analytic expression, but the explanation of the great absorption by an extended audience surface is not difficult to understand. In addition to the above there is another partial explanation which contributes to the results. The felt forms a perfectly continuous medium, and therefore offers a comparatively rigid reflecting surface. The comparatively light, thin, and porous nature of the clothing of women, perhaps more than of men, contributes to the great absorption of the high notes.

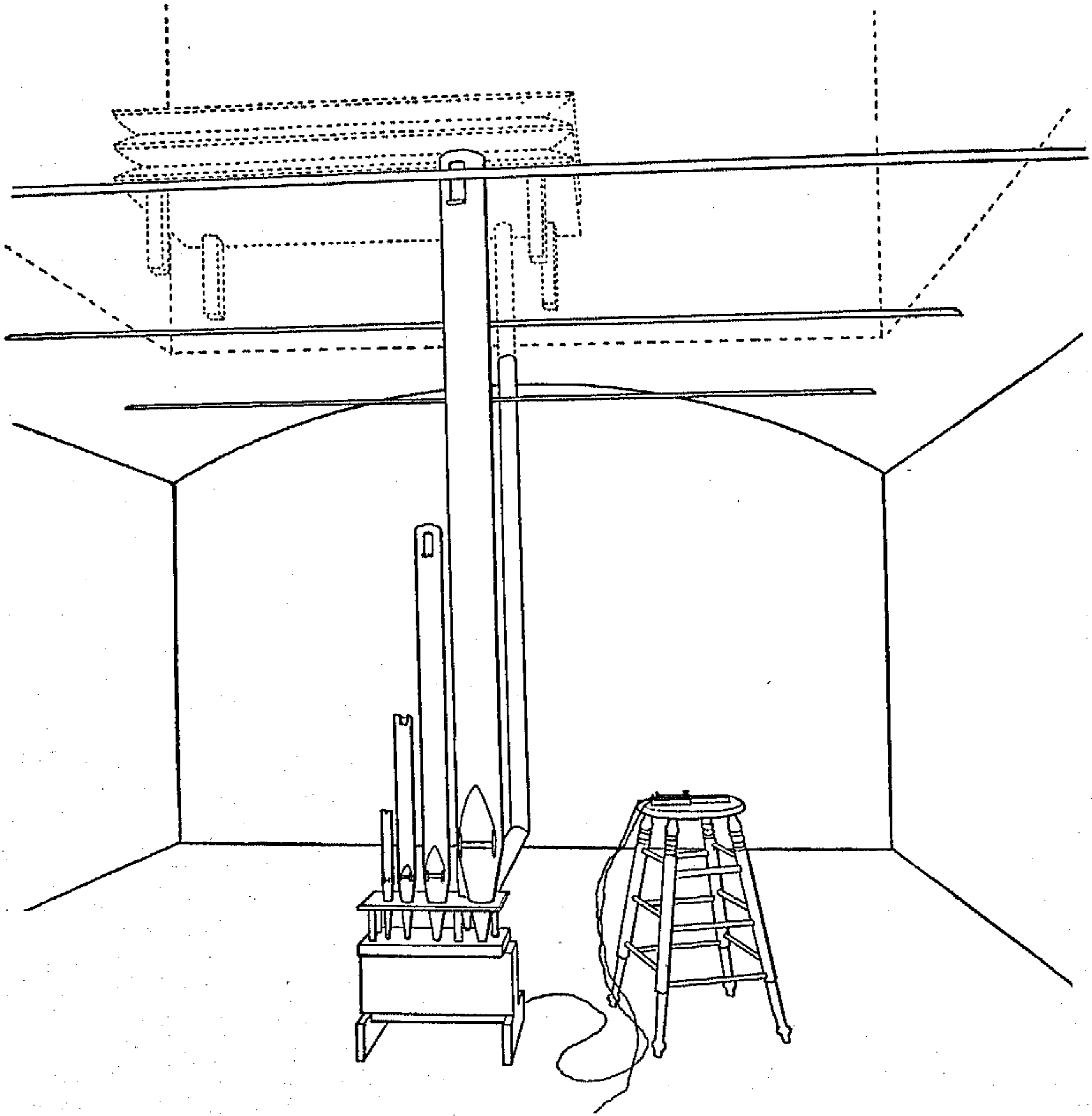

FIGURE 3.

The next experiment, taking them up chronologically, and perhaps next even from the standpoint of interest, was in regard to a brick

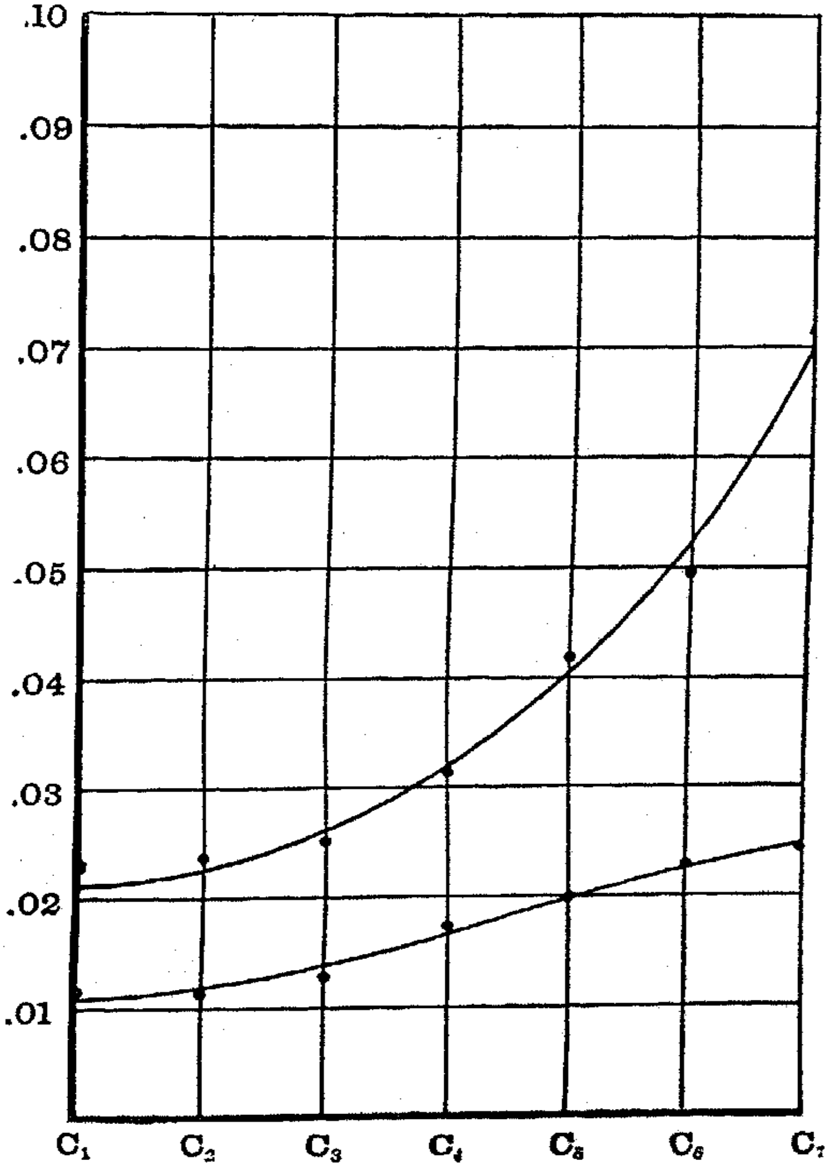

FIGURE 4.

The absorbing power of a 45 cm. thick brick wall. The upper curve represents the absorbing power of an unpainted brick surface. The bricks were hard but not glazed, and were set in cement. The lower curve represents the absorbing power of the same surface painted with two coats of oil paint. The difference between the two curves represents the absorption due to the porosity of the bricks. In small part, but probably only in small part, the difference is due to difference in superficial smoothness. C_3 (middle C) 256.

wall surface. This experiment was carried out in the constant temperature room mentioned in the previous papers. The arrangement of apparatus is shown in Figure 3, where the air reservoir in the room above is shown in dotted lines. In many respects the constant temperature room offered admirable conditions for the experiment. Its position in the centre of the building and its depth underground made it comparatively free from outside disturbing noises, — so much so that it was possible to experiment in this room in the earlier parts of the evening, although not, of course, when any one else was at work in the building. While it possesses these advantages, its arched ceiling, by placing it in the category of special cases, makes extra precaution necessary. Fortunately, at the beginning of the experiment the walls were unpainted. Under these conditions its coefficient of absorption for different notes was determined. It was then painted with an oil paint, two coats, and its coefficient of absorption redetermined. The two curves are shown in Figure 4. The upper curve is for the unpainted brick; the lower curve is that obtained after the walls were painted. The difference between the two curves would, if plotted alone, be the curve of absorption due to the porosity of the brick. It may seem, perhaps, that the paint in covering the bare brick wall made a smoother surface, and the difference between the two results might be due in part to less surface friction. Of course this is a factor, but that it is an exceedingly small factor will be shown later in the discussion of the results on the absorption of sound by other bodies. The absorption of the sound after the walls are painted is, of course, due to the yielding of the walls under the vibration, to the sound actually transmitted bodily by the walls, and to the absorption in the process of transmission. It is necessary to call attention to the fact that the vertical ordinates are here magnified tenfold over the ordinates shown in the last curve.

The next experiment was on the determination of the absorption of sound by wood sheathing. It is not an easy matter to find conditions suitable for this experiment. The room in which the absorption by wood sheathing was determined in the earlier experiments was not available for these. It was available then only because the building was new and empty. When these more elaborate experiments were under way the room had become occupied, and in a manner that did not admit of its being cleared. Quite a little searching in the neighborhood of Boston failed to discover an entirely suitable room. The best one available adjoined a night lunch room. The night lunch was bought out for a couple of nights, and the experiment was tried. The work of both nights was much disturbed. The traffic past the building did not stop until nearly two o'clock, and began again about four. The interest of those passing by on foot throughout the night, and the necessity of repeated explanations to the police, greatly interfered with the work.

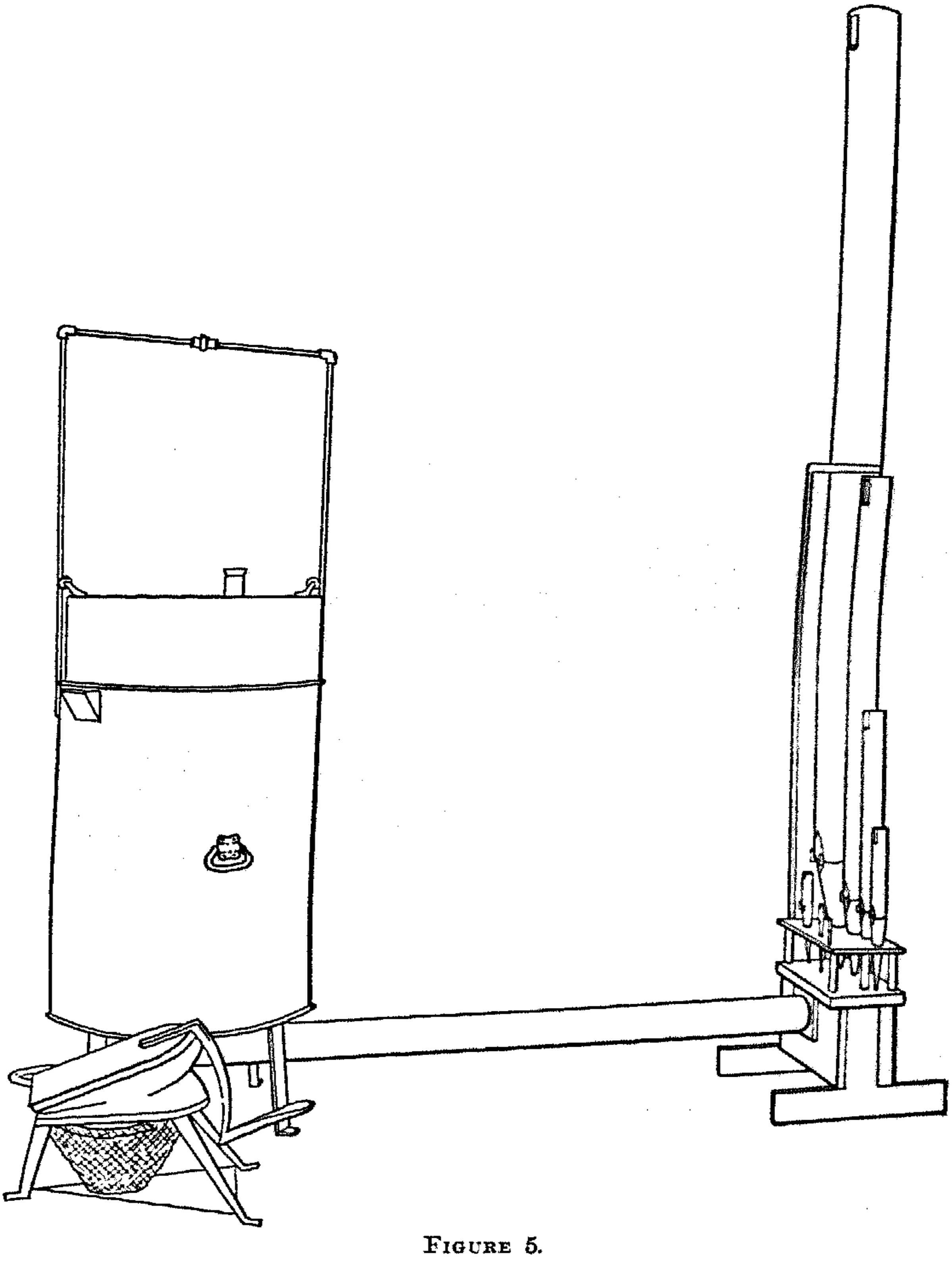

FIGURE 5.

This detailed statement of the conditions under which the experiment was tried is made by way of explanation of the irregularity of the observations recorded on the curve, and of the failure to carry this particular line of work further. The first night seven points were obtained for the seven notes C_1 64 to C_7 4096. This work was done by means

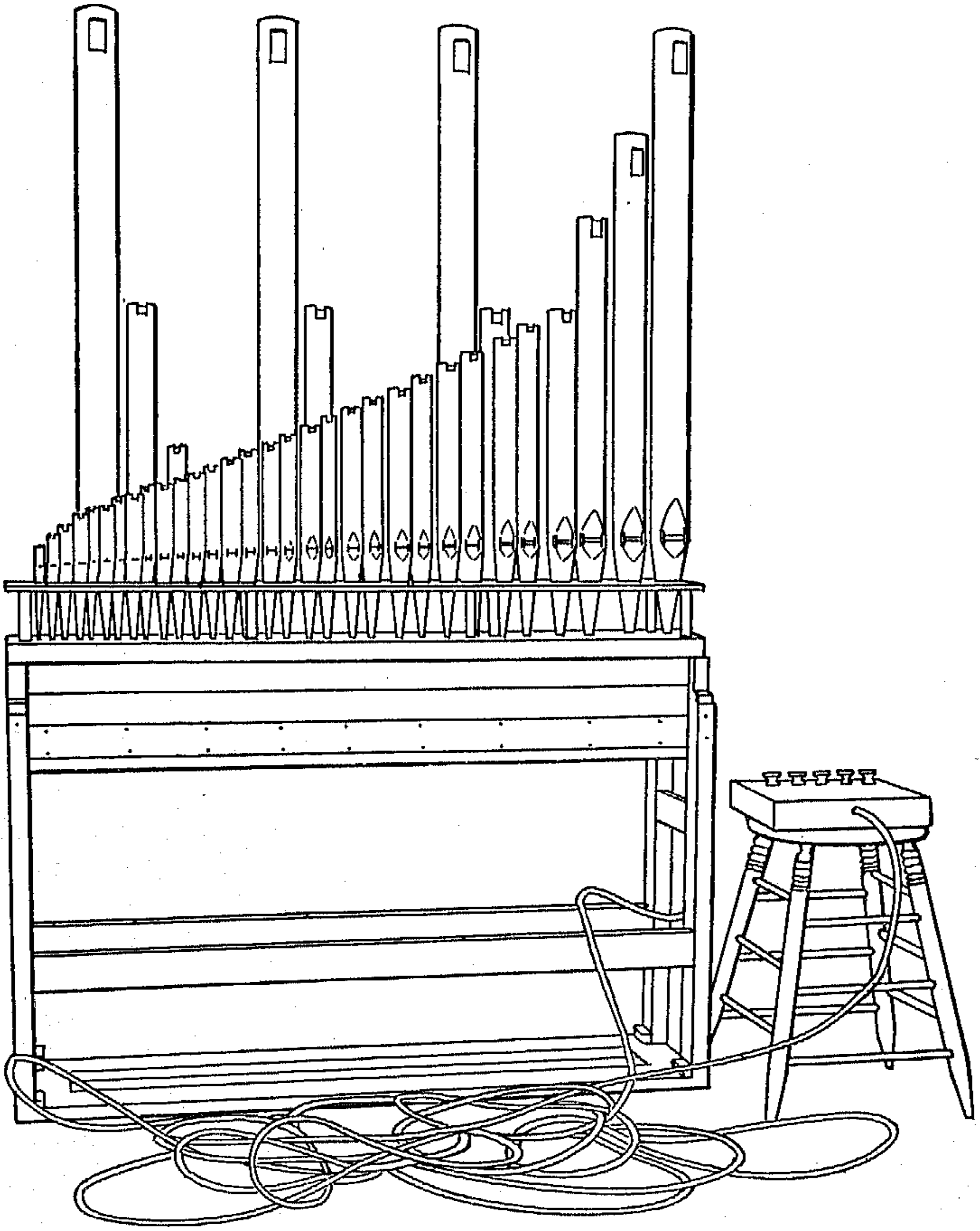

Figure 6.

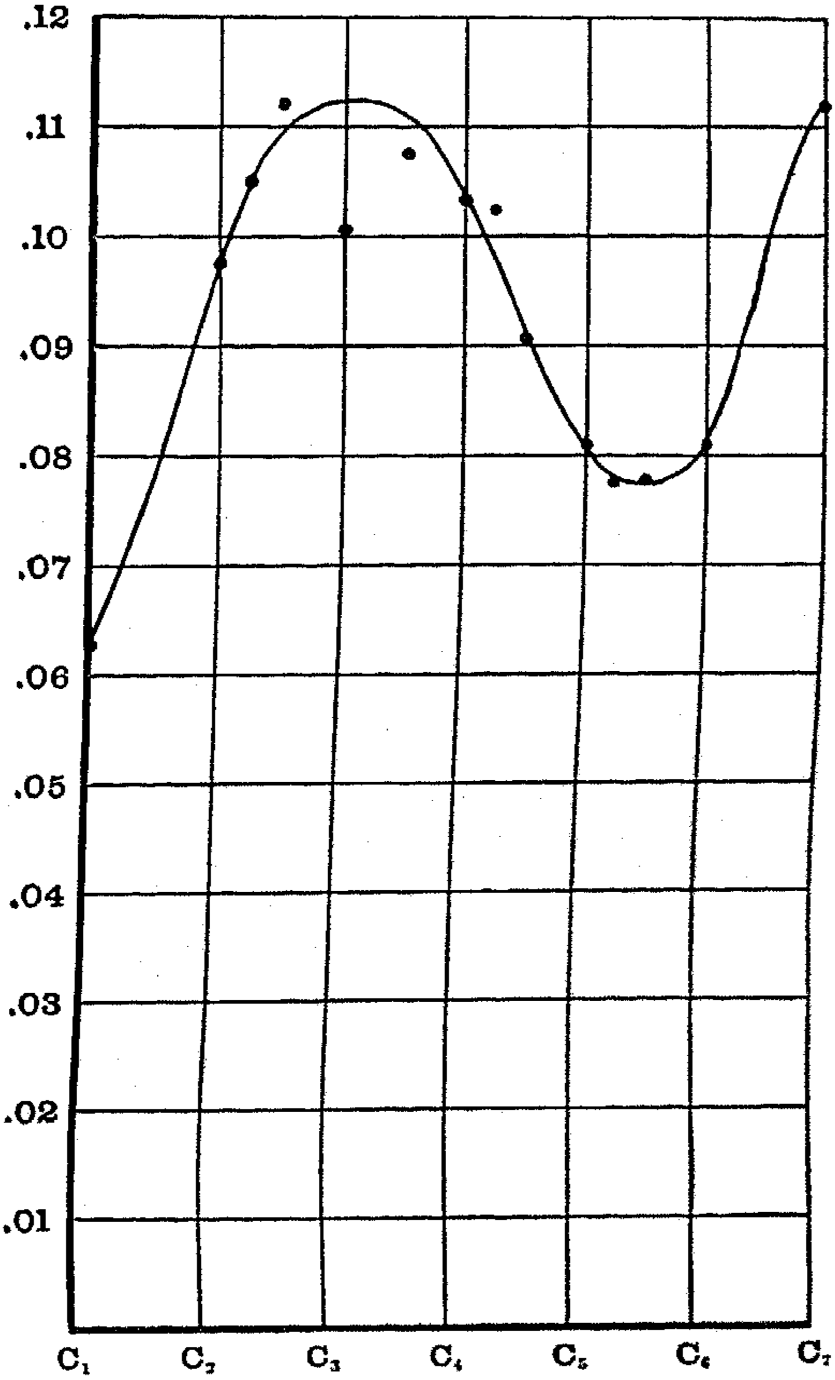

FIGURE 7.

The absorbing power of wood sheathing, two centimeters thick, North Carolina pine. The observations were made under very unsuitable conditions. The absorption is here due almost wholly to yielding of the sheathing as a whole, the surface being shellacked, smooth, and non-porous. The curve shows one point of resonance within the range tested, and the probability of another point of resonance above. It is not possible now to learn as much in regard to the framing and arrangement of the studding in the particular room tested as is desirable. C_3 (middle C) 256.

of a portable apparatus shown in Figure 5. The reduction of these results on the following day showed variations indicative of maxima and minima, which to be accurately located would require the determination of intermediate points. The experiment the following night was by means of the organ shown in Figure 6, and points were determined for the E and G notes in each octave between C_2 128 and C_6 2048. Other points would have been determined, but time did not permit. It is obvious that the intermediate points in the lower and in the higher octave were desirable, but no pipes were to be had on such short notice for this part of the range, and in their absence the data could not be obtained. In the diagram, Figure 7, the points lying on the vertical lines were determined the first night. The points lying between the vertical lines were determined the second night. The accuracy with which these points fall on a smooth curve is perhaps all that could be expected in view of the difficulty under which the observations were conducted and the limited time available. One point in particular falls far off from this curve, the point for C_3 256, by an amount which is, to say the least, serious, and which can be justified only by the conditions under which the work was done. The general trend of the curve seems, however, established beyond reasonable doubt. It is interesting to note that there is one point of maximum absorption, which is due to resonance between the walls and the sound, and that this point of maximum absorption lies in the lower part, though not in the lowest part, of the range of pitch tested. It would have been interesting to determine, had the time and facilities permitted, the shape of the curve beyond C_7 4096, and to see if it rises indefinitely, or shows, as is far more likely, a succession of maxima. The scale employed in this curve is the same as that employed in the diagram of the unpainted and painted wall surfaces. It may perhaps be noted in this connection that at the very least the absorption is four times that of painted brick walls.

The experiment was then directed to the determination of the absorption of sound by cushions, and for this purpose return was made to the constant temperature room. Working in the manner indicated in the earlier papers for substances which could be carried in and out of a room, the curves represented in Figure 8 were obtained. Curve 1 shows the absorption coefficient for the Sanders Theatre cushions, with which the whole investigation was begun ten years ago. These cushions were of a particularly open grade of packing, a sort of wiry grass or vegetable fiber. They were covered with canvas ticking, and that in turn with a very thin cloth covering. Curve 2 is for cushions borrowed from the Phillips Brooks House. They were of a high grade, filled with long curly hair, and covered with canvas ticking, which was in turn covered by a long nap plush. Curve 3 is for the cushions of Appleton Chapel, hair covered with a leatherette, and showing a sharper maximum and a more rapid diminution in absorption for the higher

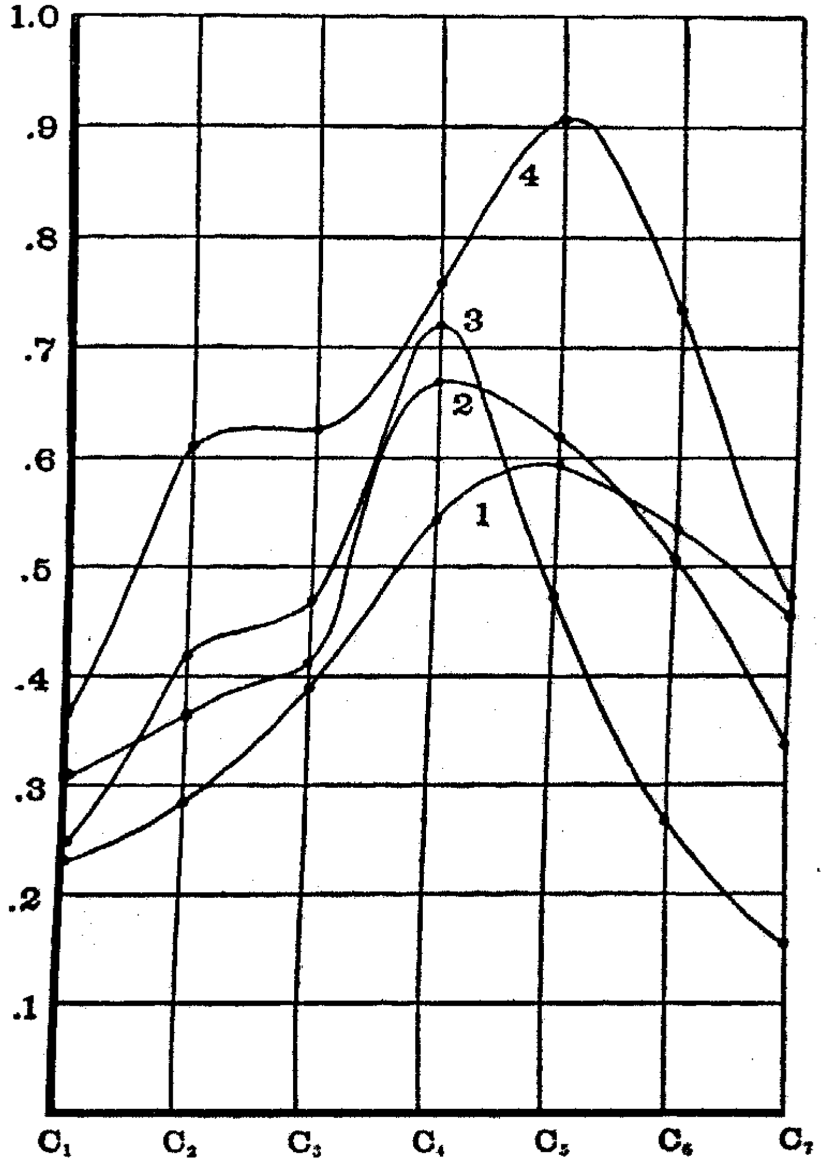

FIGURE 8.

The absorbing power of cushions. Curve 1 is for "Sanders Theatre" cushions of wiry vegetable fibre covered with canvas ticking and a thin cloth. Curve 2 is for "Brooks House" cushions of long hair covered with the same kind of ticking and plush. Curve 3 is for "Appleton Chapel" cushions of hair covered with ticking and a thin leatherette. Curve 4 is for the elastic felt cushions of commerce of elastic cotton covered with ticking and short nap plush. The absorbing power is per square meter of surface. C_3 (middle C) 256.

frequencies, as would be expected under such conditions. Curve 4 is probably the most interesting, because for more standard commercial conditions. It is the curve for elastic felt cushions as made by Sperry and Beale. It is to be observed that all four curves fall off for the higher frequencies, all show a maximum located within an octave, and three of the curves show a curious hump in the second octave. This break in the curve is a genuine phenomenon, as it was tested time after time. It is perhaps due to a secondary resonance, and it is to be observed that it is the more pronounced in those curves that have the sharper resonance in their principal maxima.

Observations were then obtained on unupholstered chairs and settees. The result for chairs is shown in Figure 10. This curve gives the absorption coefficient per single chair. The effect was surprisingly small; in fact, when the floor of the constant temperature room was entirely covered with the chairs spaced at usual seating distances, the effect on the reverberation in the room was exceedingly slight. The fact that it was so slight and the consequent difficulty in measuring the coefficient is a partial explanation of the variation of the results as indicated in the figure. Nevertheless it is probable that the variations there indicated have some real basis, for a repetition of the work showed the points again falling above and below the line as in the first experiment. The amount that these fell above and below the line was difficult to determine, and the number of points along the curve were too few to justify attempting to follow their values by the line. In fact the line is drawn on the diagram merely to indicate in a general way the fact that the coefficient of absorption is nearly the same over the whole range. A varying resonance phenomenon was unquestionably present, but so small as to be negligible; and in fact the whole absorption by the chairs is an exceedingly small factor. The chair was of ash, and its type is shown in the accompanying sketch, Figure 9.

The results of the observations on settees is shown in Figure 11. Those plotted are the coefficients per single seat, there being four seats to the settee. The settees were placed at the customary distance. Here again the principal interest attaches to the fact that the coefficient of absorption is so exceedingly small that the total effect on the reverberation is hardly noticeable. Here also the plotted results do not fall on the line drawn, and the departure is due probably to some slight resonance. The magnitude of the departure, however, could not be determined with accuracy because of the small magnitude of the total absorption coefficient. For these reasons and because the number of points was insufficient, no attempt was made to draw the curve through the plotted points, but merely to indicate a plotted tendency. The

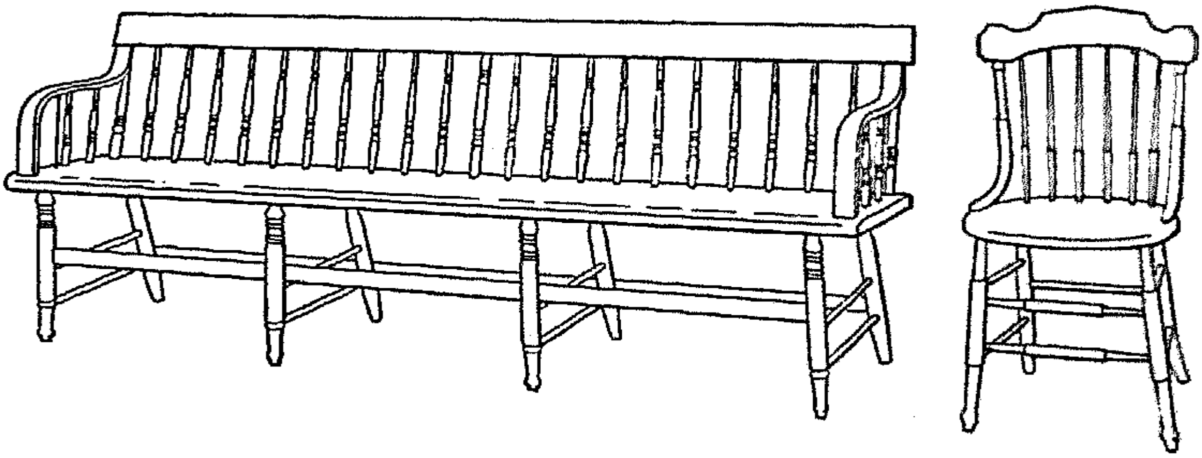

FIGURE 9.

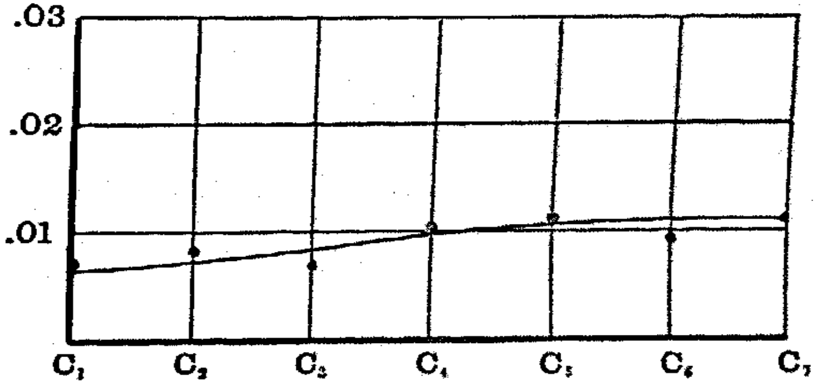

FIGURE 10.

The absorbing power of ash chairs shown in Figure 9.

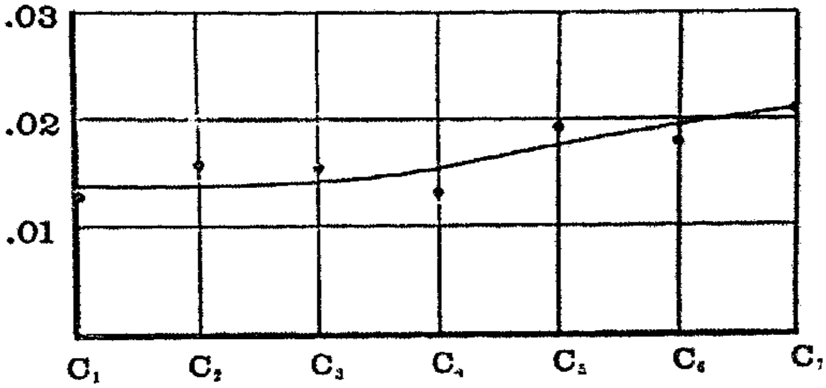

FIGURE 11.

The absorbing power of ash settees shown in Figure 9. The absorption is per single seat, the settee as shown seating five.

settees were of ash, and their general style is shown in the accompanying sketch.

An investigation was then begun in regard to the nature of the process of absorption of sound. The material chosen for this work was a very durable grade of felt, which, as the manufacturers claimed, was all wool. Even a casual examination of its texture makes it difficult to believe that it is all wool. It has, however, the advantage of being porous, flexible, and very durable. Almost constant handling for several years has apparently not greatly changed its consistency. It is to be noted that this felt is not that mentioned in the papers of six years ago. That felt was of lime-treated cow's hair, the kind used in packing steam pipes. It was very much cheaper in price, but stood little handling before disintegrating. The felt employed in these experiments comes in sheets of various thicknesses, the thickness here employed being about 1.1 cm.

The coefficient of absorption of a single layer of felt was measured for the notes from C_1 64 to C_7 4096 at octave intervals. The experiment was repeated for two layers, one on top of the other, then for three, and so on up to six thicknesses of felt. Because the greater thicknesses presented an area on the edge not inconsiderable in comparison with the surface, the felt was surrounded by a narrow wood frame. Under such circumstances it was safe to assume that the absorption was entirely by the upper surface of the felt. The experiment was repeated a great many times, first measuring the coefficient of absorption for one thickness for all frequencies, and then checking the work by conducting experiments in the other order; that is, measuring the absorption by one, two, three, etc., thicknesses, for each frequency. The mean of all observations is shown in Figure 12 and Figure 13. In Figure 12 the variations in pitch are plotted as abscissas, as in previous diagrams, whereas in Figure 13 the thicknesses are taken as abscissas. The special object of the second method will appear later, but a general object of adopting this method of plotting is as follows:

If we consider Figure 12, for example, the drawing of the line through any one set of points should be made not merely to best fit those points, but should be drawn having in mind the fact that it, as a curve, is one of a family of curves, and that it should be drawn not merely as a best curve through its own points, but as best fits the whole set. For example, in Figure 12 the curve for four thicknesses would not have been drawn as there shown if drawn simply with reference to its own points. It would have been drawn directly through the points for C_1 64 and C_2 128. Similarly the curve for five thicknesses would have been drawn a little nearer the point for C_2 128, and above instead of below the point for C_1 64. Considering, however, the whole family of curves and recognizing that each point is not without some error, the

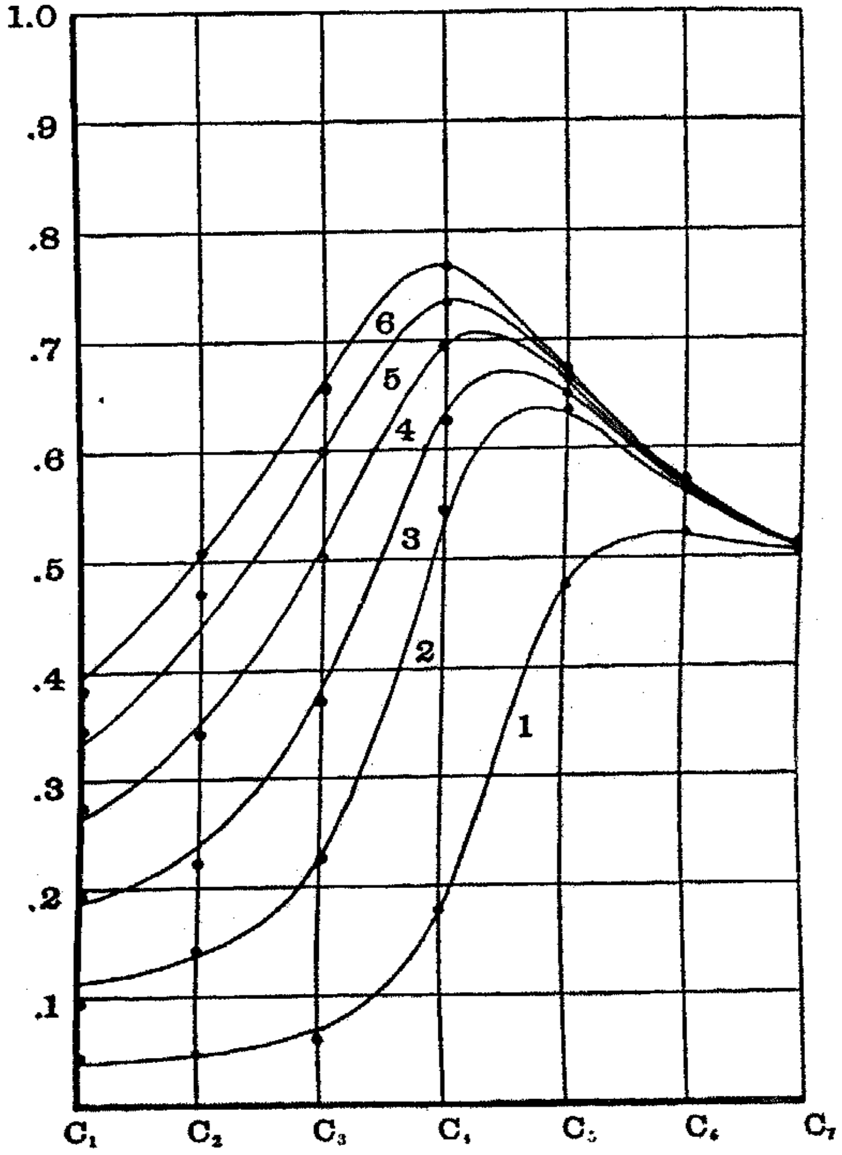

FIGURE 12.

The absorbing power of felt of different thicknesses. Each piece of felt was 1.1 cm. in thickness. Curve 1 is for a single thickness, curve 2 for two thicknesses placed one on top of the other, etc. As shown by these curves, the absorption is in part by penetration into the pores of the felt, in part by a yielding of the mass as a whole. Resonance in the latter process is clearly shown by a maximum shifting to lower and lower pitch with increase in thickness of the felt. C_3 (middle C) 256.

curves as drawn are more nearly correct. The best method of reconciling the several curves to each other is to plot two diagrams, one in which the variations in pitch are taken as abscissa and one in which the variations in thickness of felt are taken as abscissas; then draw through the points the best fitting curves and average the corresponding ordinates taken from the curves thus drawn; and with these average ordinates redraw both families of curves. The points shown on the diagram are of course the original results obtained experimentally. In general they fall pretty close to the curves, although at times, as in the points noted, they fall rather far to one side.

The following will serve to present the points of particular interest revealed by the family of curves in Figure 12, where the absorption by the several thicknesses is plotted against pitch for abscissas. It is to be observed that a single thickness scarcely absorbs the sound from the eight, four, and two foot organ pipes, C_1 64, C_2 128, and C_3 256, and that its absorption increases rapidly for the next two octaves, after which it remains a constant. Two thicknesses absorb more — about twice as much — for the lower notes, the curve rising more rapidly, passing through a maximum between C_4 512 and C_5 1024, and then falling off for the higher notes. The same is true for greater thicknesses. All curves show a maximum, each succeeding one corresponding to a little lower note. The maximum for six thicknesses coincides pretty closely to C_4 512. The absorption of the sound by felt may be ascribed to three causes, — porosity of structure, compression of the felt as a whole, and friction on the surface. The presence of the maximum must be ascribed to the second of these causes, the compression of the felt as a whole. As to the third of these three causes, it is best to consult the curves of the next figure.

The following facts are rendered particularly evident by the curves of Figure 13. For the tones emitted by the eight-foot organ pipe, C_1 64, the absorption of the sound is very nearly proportional to the thickness of the felt over the range tested, six thicknesses, 6.6 cm. The curves for notes of increasing pitch show increasing value for the coefficients of absorption. They all show that were the thickness of the felt sufficiently great, a limit would be approached, — a fact, of course, self-evident, — but for C_5 1024 this thickness was reached within the range experimented on; and of course the same is true for all higher notes, C_6 2048 and C_7 4096. The higher the note, the less the thickness of felt necessary to produce a maximum effect. The curves of C_1 64, C_2 128, C_3 256, and C_4 512, if extended backward, would pass nearly through the origin. This indicates that for at least notes of so low a pitch the absorption of sound would be zero, or nearly zero, for zero thickness. Since zero thickness would leave surface effects, the argument leads to the conclusion that surface friction as an agent in the absorption of sound is of small importance. The curves plotted

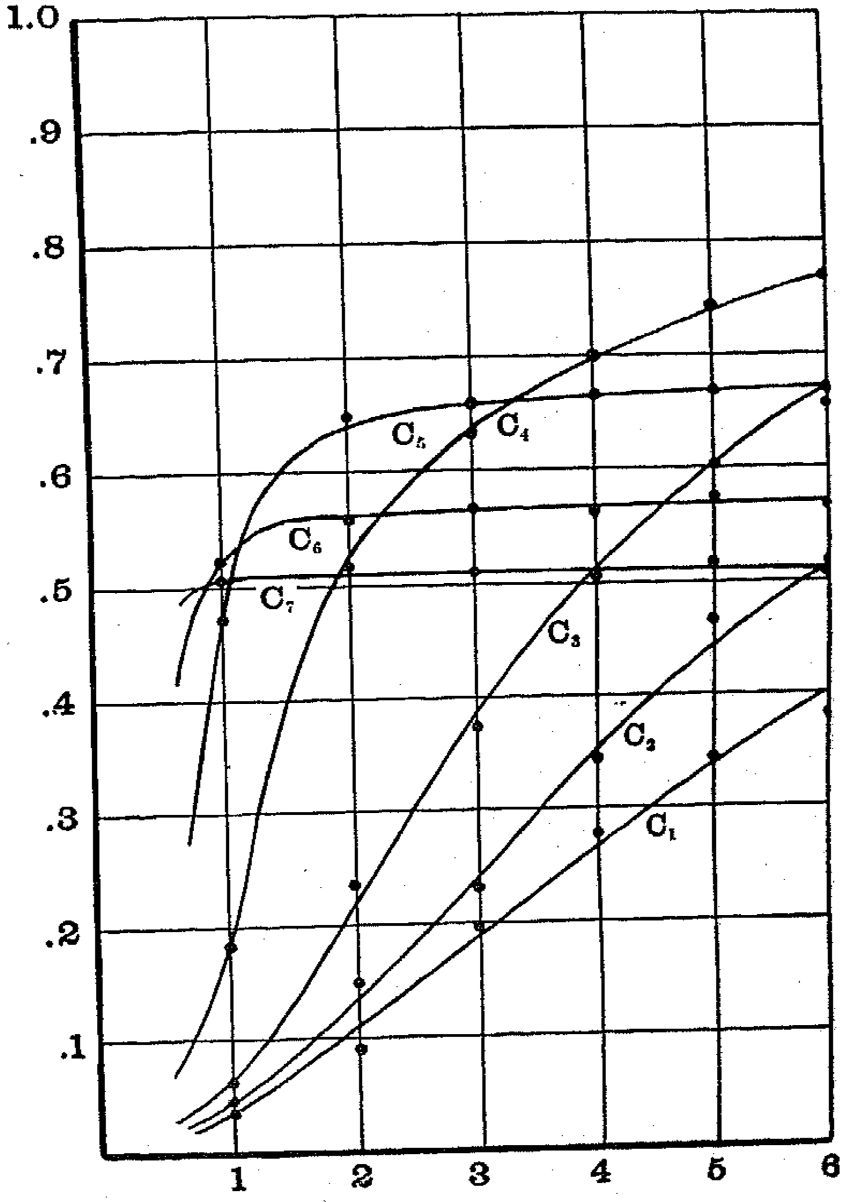

Figure 13.

The absorbing power of felt of different thicknesses. The data, Figure 12, is here plotted in a slightly different manner, — horizontally on plotted increasing thickness, — and the curves are for notes of different frequency at octave intervals in pitch. Thus plotted the curves show the necessary thickness of felt for practically maximum efficiency in absorbing sound of different pitch. These curves also show that for the lowest three notes surface friction is negligible, at least in comparison with the other factors. For the high notes one thickness of felt was too great for the curves to be conclusive in regard to this point. C_3 (middle C) 256.

do not give any evidence in this respect in regard to the higher notes, C_5 1024, C_6 2048, and C_7 4096.

It is of course evident that the above data do not by any means cover all the ground that should be covered. It is highly desirable that data should be accessible for glass surfaces, for glazed tile surfaces, for plastered and unplastered porous tile, for plaster on wood lath and plaster on wire lath, for rugs and carpets; but even with these data collected the job would be by no means completed. What is wanted is not merely the measurement of existing material and wall surfaces, but an investigation of all the possibilities. A concrete case will perhaps illustrate this. If the wall surface is to be of wood, there enter the questions as to what would be the effect of varying the material, — how ash differs from oak, and oak from walnut or pine or whitewood; what is the effect of variations in thickness; what the effect of panelling; what is the effect of the spacing of the furring on which the wood sheathing is fastened. If the wall is to be plaster on lath, there arises the question as to the difference between wood lath and wire lath, between the mortar that was formerly used and the wall of to-day, which is made of hard and impervious plaster. What is the effect of variations in thickness of the plaster? What is the effect of painting the plaster in oil or in water colors? What is the effect of the depth of the air space behind the plaster? The recent efforts at fireproof construction have resulted in the use of harder and harder wall surfaces, and great reverberation in the room, and in many cases in poorer acoustics. Is it possible to devise a material which shall satisfy the conditions as to fireproof qualities and yet retain the excellence of some of the older but not fireproof rooms? Or, if one turns to the interior furnishings, what type of chair is best, what form of cushions, or what form of upholstery? There are many forms of auditorium chairs and settees, and all these should be investigated if one proposes to apply exact calculation to the problem. These are some of the questions that have arisen. A little data have been obtained looking toward the answer to some of them. The difficulty in the way of the prosecution of such work is greater, however, than appears at first sight, the particular difficulties being of opportunity and of expense. It is difficult, for example, to find rooms whose walls are in large measure of glass, especially when one bears in mind that the room must be empty, that its other wall surfaces must be of a substance fully investigated, and that it must be in a location admitting of quiet work. Or, to investigate the effect of the different kinds of plaster and of the different methods of plastering, it is necessary to have a room, preferably an underground room, which can be lined and relined. The constant temperature room which is now available for the experiments is not a room suitable to that particular investigation, and for best results a special room should be constructed. Moreover, the expense of plastering and replastering a room — and this process, to arrive at anything like a general solution of the problem, would have to be done a great many times — would be very great, and is at the present moment prohibitive. A little data along some of these lines have been secured, but not at all in final form. The work in the past has been largely of an analytical nature. Could the investigation take the form of constructive research, and lead to new methods and greater possibilities, it would be taking its more interesting form.

The above discussion has been solely with reference to the determination of the coefficient of absorption of sound. It is now proposed to discuss the question of the application of these coefficients to the calculation of reverberation. In the first series of papers, reverberation was defined with reference to C_4 512 as the continuation of the sound in a room after the source had ceased, the initial intensity of the sound being one million times minimum audible intensity. It is debatable whether or not this definition should be extended without alteration to reverberation for other notes than C_4 512. There is a good deal to be said both for and against its retention. The whole, however, hinges on the outcome of a physiological or psychological inquiry not yet in such shape as to lead to a final decision. The question is therefore held in abeyance, and for the time the definition is retained.

Retaining the definition, the reverberation for any pitch can be calculated by the formula

$$T = \frac{K V}{a},$$

where V is the volume of the room, K is a constant depending on the initial intensity, and a is the total absorbing power of the walls and the contained material. K and V are the same for all pitch frequencies. K is .164 for an initial intensity 10^6 times minimum audible intensity. The only factor that varies with the pitch is a, which can be determined from the data given above.

In illustration, the curves in the accompanying Figure 14 give the reverberation in the large lecture room of the Jefferson Physical Laboratory. The upper curve defines the reverberation in the room when entirely empty; the lower curve defines this reverberation in the same room with an audience two thirds filling the room. The upper curve represents a condition which would be entirely impractical for speaking purposes; the lower curve represents a fairly satisfactory condition.

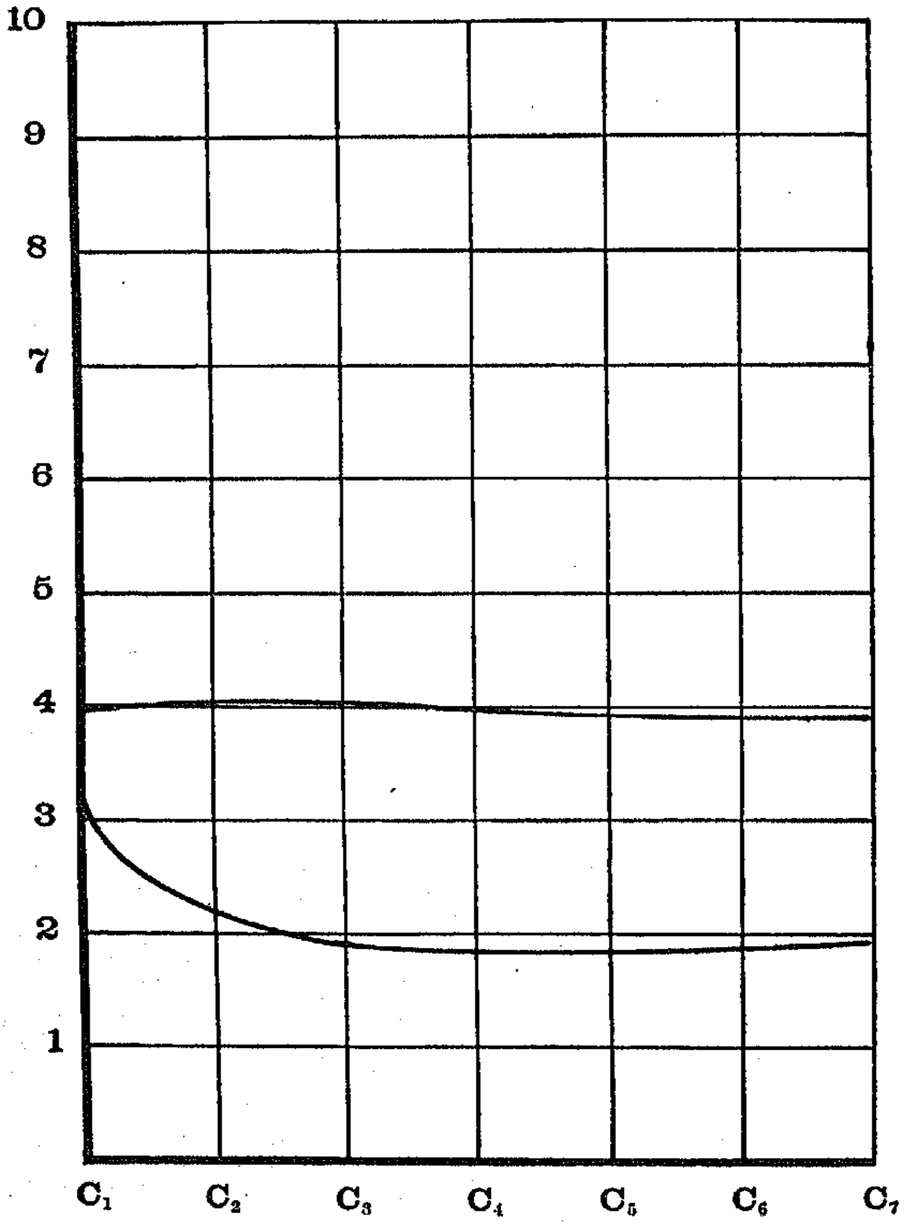

FIGURE 14.

Curves expressing the reverberation in the large lecture room of the Jefferson Physical Laboratory with (lower curve) and without (upper curve) an audience. These curves express in seconds the duration of the residual sound in the room after the cessation of sources producing intensities 10^6 times minimum audible intensity for each note. The upper curve describes acoustical conditions which are very unsatisfactory, as the hall is to be used for speaking purposes. The lower curve describes acoustically satisfactory conditions. C_3 (middle C) 256.