AN INVESTIGATION

OF

ARCHITECTURAL ACOUSTICS

WITH AN ILLUSTRATIVE EXAMPLE

COMPRISING THE S. B. THESIS OF

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INTRODUCTION

This thesis is a brief discussion of that little-known science, acoustics; to be more exact, architectural acoustics,-the science applied to buildings. Practically no works on the subject have been published since the day when it was more a guessing game than a science. In the year 1898 appeared the first paper on acoustics written by the late Wallace Clement Sabine, Professor of Mathematics and Natural Philosophy at Harvard University. Since then several other papers, having been published in various magazines, his entire writings on acoustics have been collected and published in book form. These papers comprise the best treatment of the subject of which I know. I have studied them carefully and have used their material for a part of my discussion (that part dealing with the development of a method of acoustical investigation together with the evolution of formulas) but in no place have I transported any remarks or conclusions bodily from Professor Sabine's book to my thesis. To do so would have only produced confusion. In so brief a paper as this it has been necessary to condense everything atrociously, and I do not claim to have produced a work that will aid the specialist in acoustics, but only to have weeded out the true from the false in ideas about the science, comparing the old ideas with the new knowledge. The discussion has been written with the intention of making it intelligible to the ordinary reader. Such technical description as has been necessary I have made in very brief form. Unfortunately, any experimental research has been quite out of the question on account of the limited time at my disposal. My work has been confined to presenting the subject of acoustics in the light of an exact science, and to illustrating one of the principles involved by analytically solving a concert hall for its reverberation. I have not deemed it advisable to go into the minute detail of developing formulas or methods since such a discussion would have had to be the work of another, and would have been pure copying from a text. For example I have not discussed the significance of the number .164 , which is important in determining reverberation. It seems now to me that while this thesis extends over about fifty pages, it is a scanty showing for the preparation that preceded its writing, and a disgracefully slight topical outline of the subject of acoustics.

No library and no bookshop has been able to furnish me with any satisfactory text or reference book except the one by Professor Sabine. Many books published before 1898 , such as those mentioned in my bibliography, I have found to be vague and indefinite, and usually meaningless and worthless as far as actual investigation is concerned. Even to-day many persons who write on the subject are not sufficiently informed to make their work of any value. An article in the "Musical Quarterly" for the autumn of 1921, by a man who has written books about musicians, entered the field of acoustics and reverted to almost every former prejudice that has been discarded by recent investigation, begun by Professor Sabine.

It was my original intention to divide this thesis into two parts, the first concerned with acoustics, and the second with the design of a concrete arched roof for the concert hall solved in the first part. To the end that I might carry out my plan, I studied thoroughly the theory of concrete arches, in those books listed in the bibliography. Towards the end of this term however, it became evident that the concrete design could not be finished satisfactorily if the acoustics recived thir just attention. Wherefore having obtained the advice of Professor Lawrence, I decided to omit the second part of my original plan and to enlarge the first. I have finished the thsis according to this revised plan ,but I have decided to include two drawings made with the intention of using them in designing the arch. The first of these is a floor plan of Steinert Hall as it is to-daday; the other is the hall as I re-designed it with parallel walls to permit of a barrel vaulted ceiling.

Had I designed thevaulted ceiling a new acoustical problem would have been created whcih would have been difficult to solve, inasmuch as the action of vaulted ceilings is little known. Professor Sabines notes in his book one case of correcting the faults of a room which was roofed over in the manner I have described, and in which the sound was focussed in a line running up the centre of the room. Coffering the ceiling overcame the difficulty, and made the hall satisfactory acoustically (Yet Mt. Elson says that coffering in a ceiling is a bad thing anywhere) Be that as it may, it is obvious that had my original plan been followed, I would have been stranded with not one of my subjects completed.

The thesis as finally completed consists of two parts, one a general discussion of acoustics,and the other a solution of Steinert Hall for reverberation.

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PART ONE

GENERAL DISCUSSION OF ACCUSTICS

Architectural Acoustics may be defined broadly as the science of sound applied to buildings. Until recently, and even to-day not infrequently, architectsand engineers, as well as scientists and the public, have thought that nothing was quite so uncertain as the acoustic properties of a new auditorium or concert hall, and that the only plausible, if not the only possible solution is reference to previously built auditoriums known to be good. Such opinions were the result of deficient information or knowledge of the subject. Always had acoustical problems been attacked either quite blindly or with a purely theoretical scientific knowledge of sound itself but without any idea of its relation to buildings. When, however, a study was made starting at the right end, that is,-the building, and basing conclusions on observation combined with the knowledge of sound, it was speedily realized that acoustics could be treated as an exact science

The purpose of investigations of acoustics is to make possible the calculation before construction of the acoustic properties of any auditorium, and to remove the element cfguess ingwhich has so long been the best-known method . The best way to conduct such investigations is of course to make them in existing rooms, bad and good. It is certain that the science of acoustics is extremely complicated, but equally certain that it is an exact science. No simple rules can be made to govern the design of halls, but each one presents an individual case that requires individual solution. That is, it cannot be said that if a hall has the proportions 1:1:2 it will be good, or if it has plaster on tile it will be bad, or again, if it has an oval shape itwill have proper acoustics. No single factor determines the quality of a room. All the properties of a room affect its acoustical qualitiesin a greater or lesser degree. The shape no doubt is an important factor, though not nearly so important as commonly supposed.The construction, materials, ceiling, seats, heating and lighting, windows, stage, all have their effect, and must be considered.

In connection with the general rules that have in the past been followed in building auditoriums it is interesting to consider a few of the more important. First of all are asome Don'ts

Don't plaster on terra cotta, brick or stone.
Don't build spherical or conical domes in ceilings.
Don't build circular angles in corners.
Don't supply hot air in the center in large amounts.
Don't supply hot air through the ceiling in bulk.
Don'tput a ventilating shaft in the centre.
Don't put all the lighting in the centre.
Don't supply cold air through the floor.
Don't stretch wires across the ceiling or elsewhere.
Don't wax a hard floor.

Some of these warnings are most valuable and reasonable,but others have no meaning.

In connection with the heating of an auditorium it was held that to admit heat between the stage and the audience was very bad, since it formed a curtain of heat in the plane of the proscenium arch that could not easily be penetrated by sound waves issuing from the stage. To avoid this it was thought advisable to distribute the heating around the room as much as possible. Such an arrangement is indeed advisable. Heating should always be indirect,both for hygienic and acoustical resons. Direct heating as from steam radiators is not suitable for large rooms of any kind.

The effect of lighting on acoustics depends on the heat given off, wherefore the rules in use for heating hold for lighting as well. In addition it has been heldthat gas should be avoided and electricity employed . Particularly in footlights should any system that gives off much heat be avoided to prevent the formation of the curtain of heat mentioned above.

The shape of a room has always been held to be the most important factor in acoustics . This is a correct or nearly correct presumption, but it is not so simple a statement as it seem

A very good room may be of a condemned shape and one with the theoretically perfect egg-oval shape may be utterly worthless acoustically. Large halls cannot be treated as small ones, nor can a theatre audtiorium and a concert hall be considered in the same way. Some authorities, however were prepared to say with conviction that certain shapes gave good acoustics and certain other shapes gave bad. The following sketches furnish an example of supposedly good and bad rooms. The small circles indicate the position of the source of sound.

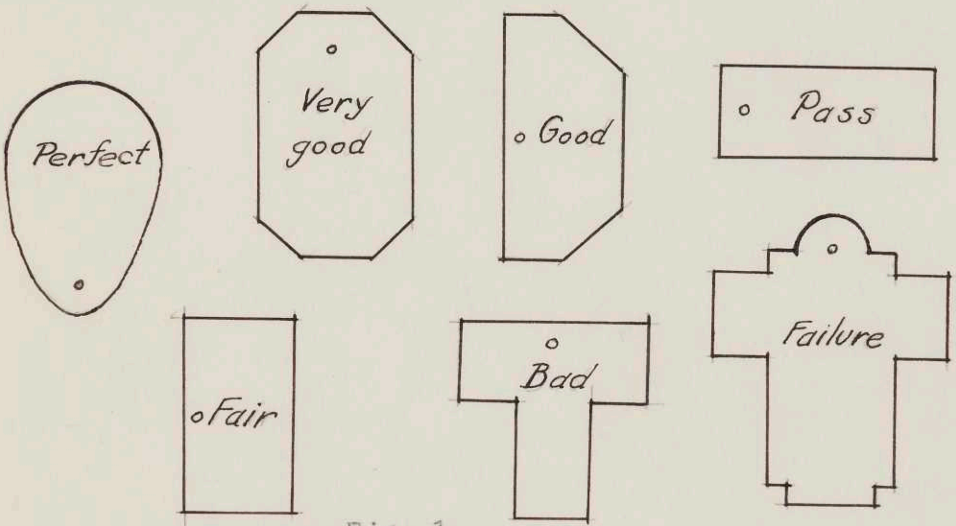
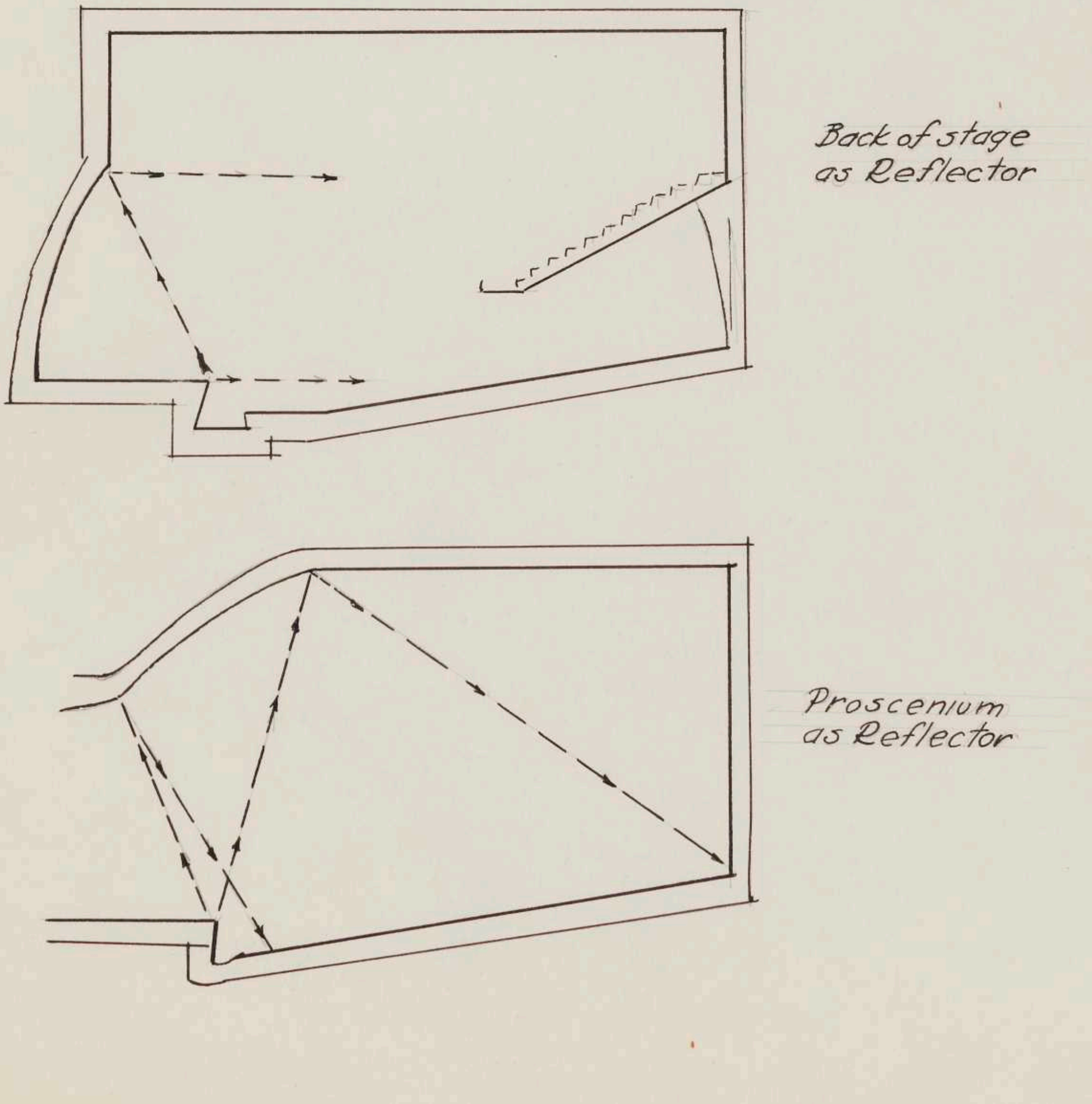


Fig. 1.

Now it is true that the qualities of auditoriums do follow to a certain extent thet tendencies indicated by these sketches, but it is probably due to the fact that a building of a peculiar shape has its own peculiar use and is usually constructed and finished off in the same way . For example, the last one here shown is that common to cathedrals, where the worst acoustics were generally found. Their acoustical failure is however as largely due to the presence of any sufficient absorbing material as it is to the actual shape of the builing. As will be seen later the acoustics of a room depend upon three things,-loudness, distortion,andconfusion. At present these terms have no exact meaning , but will be explained at the proper time

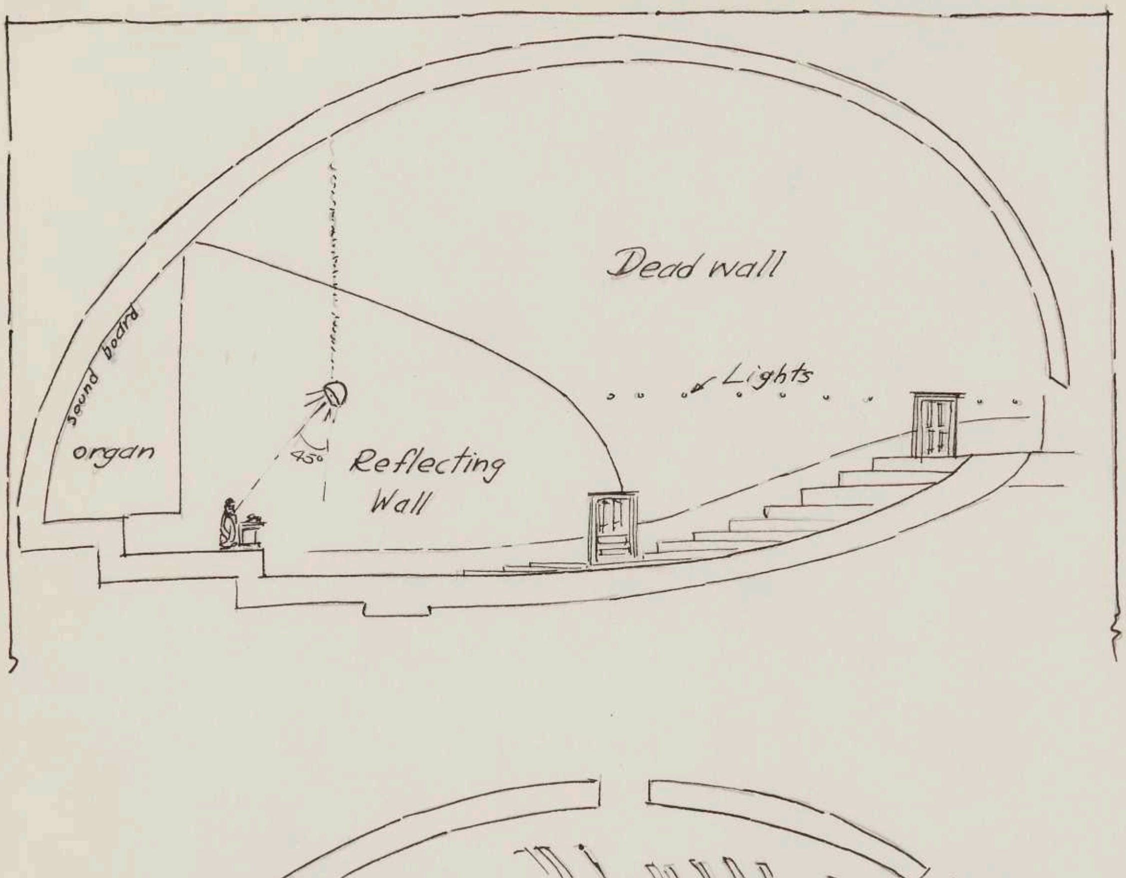
Sound reflectors have always been one of the first re sorts in acoustical difficulty,and have been considered very effectual. I am not prepared to confirm or deny this theory but it is certain that to be effectual they must be large and properly placed . Some of the types of reflectors in use are the Plano, COnvex, Concave, and Movable. The most common are the concave reflectors, which are made in elliptical, spherical and parabolic form.. Such sound-boards may form a part of the back ,f the stage ,the proscenium, the ceiling or the rear wall of a hall. The first two of these are shown in the sketches in Fig. 2. It is important to note that where sound reflectors are used there should be but one position of the source of sound. Otherwise they would have the opposite of the desired effect.

Fig. 2



Back of stage as Reflector

Proscenium as Reflector



An Ideal (?) Auditorium - Plan and Section

In conclusion of the discussion of former ideas on the subject of acoustical solution, it should be said that unvery recently the entire subject has been treated in an unfortunately one-sided fashion in that it has been considered as only qualitative. It should certainly be a quantitative problem as well. The following paragraphs will explain in some deatil how it can be so treated.

[Fig. 3 shows a supposedly ideal auditorium . No such place exists nor is likely to be built on accoubt of the displeasing aspect architecturally, so it cannot be said that the acoustics would be actually perfect. In fact it is in no way certain that they would be good without there being made a design of the auditorium which took into account the materials and construction .]

The manner of attacking acoustical problems to-day is largely the result of certain investigations carriedon by the late Professor W. C. Sabine of Harvard University. His solution of the problem was his own and it was as invaluable to the scientific world as it was unique and original. Instead of trying to reach some theoretical conclusions as to what makes an auditorium good, Professor Sabine made experiments in rooms needy of correction unticl he found out what improved them and therefore what was wrong with them. He found that one of the most important elements was the length of time required for a sound to become undiscernible. This property he called Reverberation.It is a phase of the property of Confusion. If the reverberation of a room is too great, confusion of articulate sounds is noticeable and frequently acoustically disastrous. If, on the other hand, it is too small, and the sound dies away too quickly, the voice of a speaker becomes indistinct, or music becomes dry and staccato. The decay of residual sound must take place in one of two ways, either it is telephoned to other parts of the structure or it is transformed into heat or mechanical energy by "absorption"by the materials of the room. It was upon the absorptive powers of various substances, including walls, furnishings and audiences that Professor Sabine made his first experiments.

Every material has some power of absorption of sound. Some have so slight powers that they are reflectors., In order to determine the relative absorptive powers of various substances, a method of comparison, or substitution, must be employed. By determining the reverberation of a room first with a known quantity of one material in it, and then with another, a relation can obviously be set up between their absorptions. The only remaining necessity is determining some standard . The open window is a perfect absorbent, and all other absorptive powers can be referred to it as coefficients, that of the open window being unity. The difficulty is in making experiments with open windows, on account of noises that enter on th most quiet of nights (daytime is altogether too noisy for experimenting.). As an alternative a medium can be used by means of which the absorption coefficients of substances may be found relative to the medium and then transformed in one set of expeiments to the open window standard. Felt cushions have been the most commonly used in this method.

The loudness of sound is another important property to be considered. It has been found that the loudness of any sound is inversely proportional to the absorption of a room . Since, starting at the source , sound is absorbed as it travels away, it is evident that it will sound less loud at a great distannce from the source than near it. Sound travels in every direc tion in a sphere. On a flat level plain, open an unobstructed, the intensity decreases as the hemi-sphere increaeses. An audience here would have to be close to the source in order to hear distinctly, for the sound, passing over those persons near at hand would be absorbed and those farther away would not receive any. In order to improve the hearing a sound board or wall might be erected behind the source , or the audience might be raised, or a roof might be built to enclose the plain, when it would become an auditorium, and the problem one of architectural acoustics. Thus in the modern theatre we find the floors sloping, balconies to bring the audience forward and sound reflectors to direct the waves in the desired paths. Loudness must not be confused with reverberation or with resonance. Reverberation has already been explained. Resonance is the growth of a vibratory motion of an elastic body under periodic forces timed to its natural rates of vibration. Resonance is closely akin to Interference, the phenomenon that is noticed when two trains of sound waves arriving at a point from two different sources, or in the case of reflection, of one train from a source and another from a reflecting surfacemin such a manner that a condensation and a rarefaction reach the point at the same instant. In this case there will be comparative silence due to "Interference". Interference is not so annoying, as resonancesince it does not change the amount of sound in a room,as resonance does, but merely alters the constitution of the sound.

Inorder that good acoustics are to be obtained in an auditorium, we observe that:-

1 Sounds must remain loud enough.

2 Simutaneous components of a complex sound must maintain their relative importance.

3 Successive sounds in rapid sequence of utterance must remain clear and articulate.

SECTION 2 Method of Accoustical Investigation and Solution

Those factors which must be considered in determining the reverberation of a room are theobjects that absorb the sound ,and those that reflect it. Since the reflection of sound is merely the opposite of its absorption it is possible to consider absorption only, leaving out of the discussion any reference to sound-boards, which are used as a corrective. The three chief absorbers of scynd in any room are the walls and ceiling and floor, the furnishings;and the audience. Any object brought into the room decreases the reverberation of the room in a greater or lesser degree, depending on the nature of the object. The method used in determining the absorptive power of a substance ,as I have explained previously, is one of substitution. If the reverberation of a room is found by experiment to be a certain number of seconds and after bri bringing into the room a known amount of say felt cushions, the reverberation is then found to be something less than the number of seconds first determined, the difference must have been due to the absortion of sound by the cushions. It is now simple to calculate the absorptive power of the material for a given unit, as for example a square metre.

Professor Sabine at Harvard University determined coefficients of absorption for many materials, spending every other night from twelve until five for several years. In th experiments he made he used organ pipes of the pitch 512 vibrations per second, or "violin C" . Listed below are some of the more common of these coefficients.

Material	Absorptive power per square metre compared to open window
Open window	1.000
Wood (Hard pine)	..061
Plaster on wood lath	.034
Plaster on wire lath	.033
Glass	.027
Plaster on tile	.025
Carpet rugs	.20
Cretonne cloth	.15
Hairfelt 2.5 cm. thick	.78
Audience per person	.44
Isolated man	.48
Isolated woman	.54

It was desired early in experiments to determine some law that governed the decrease in duration of sound due to additional material material being brought into the room. By plotting the duration as ordinates against the amount of absorbing material units as abscissae a curve can be drawn which suggests the hyperbola. The equation of such an hyperbola as will represent the time of reverberation, the absortive powers of the walls and structural parts of a room and the absorptive power of objects brought in will be as follows:-

$$(a + x) t = k$$

In which a = absorption by extraneous objects

x = " by the room

t = duration of sound

k = the parameter

The value of k depends on the volume of the room under consideration. If we let $k = KV$ in which case K is a constznt for all rooms the value of K is for general purposes .171

By combining the factors for the absorptions by the r r,om and by the objects brought in, such as seats , audience, curtains, the formula reduces to

$$at = k$$

or

$$at = KV$$

and

$$t = \frac{K \times V}{a}$$

By means of this formula it is possible to calculate, without the necessity of experiments, the duration of residual sound in any room . The materials and audience of any new auditorium being known before construction , the reverberation can evidently also be computed. Some authorities say that if the duration of sound is less than two seconds or more than three the acoustics are pretty sure to be bad. This is a pure fallacy,as will be shown later . The size and use of a room determine the desirable reverberation and it may be anywhere from one second to four without any certainty of bad acoustics.

Without going into the details of the theory of exact acoustical solution used in determining absorptive powers of materials,I shall discuss briefly the main points upon which it is based.

It has been shown that the intensity of the source is dependent on not merely the mechanical profficiency of the device used to emit sound, but also on the absorptive power of the room, and that the intensity decreases as the absorption invreases. Thus in experiments it is necessary to have some standard of intensity, and it has been considered wise to choose the initial intensity which is 1,000,000 times theminimum audible intensity.

To determine the rate of decay of residual sound certain equations can be set up involving the formula $a = \frac{.171V}{t}$ and by means of the "mean free path" of the sound wavesb being reflected about the room = p an exact evolution of complicated formulae results..

It has been experimentally determined that the rate of decay of residual sound is proportional to the initial intensity, and as we have already seen, the total time required for complete absorption depends both upon the initial intensity of the sound and upon the volume of the room.

Experimenting with several sources of sound of equal intensity, (organ pipes are used because they give a constant emission and cease to sound as soon as the air is shut off), it has been found by plotting curves to represent the intensity of the sound at any instant after the source has ceased, as well as by comparing the values obtained for one two , three or more pipes, that the rate of decay is a logarithmic function of the initial intensity, that is, that the sound loses its intensity in a logarithmic curve. It is important to note that in making such experiments it is essential that the sound being emitted should reach a steady condition before shut off. In brief , if a case is considered in which several sounds of equal intensity are used and curves are drawn for the intensities at any instant the ordinates at the point where one dies away, of the others, will be multiples or submultiples of the initial intensity

Since the absorption of sound is proportional to the intensity (and therfore different at each instant after a source has ceased to emit, becoming less and less , it is evident that if

i = intensity at any instant
t = no. of seconds after source has ceased
I = the avg. intensity while the source is sounding
A = a constant of proprtionality

then

$$\frac{-di}{dt} = Ai$$

and $\log i + C = At$

the constant of integration being $\log I$

Thus from this equation we obtain

$$\log I - \log i = A t$$

by which formula it is possible to determine the intensity at any instant after the source has ceased.

It is necessary to fix upon a standard of inital intensity, in order that the law may fit any room. For this reason the value

$$I = 1{,}000{,}000\ i^1$$

where i^1 is the minimum audible intensity.

In approaching the exact solution by which it is possible to calcutlate the growth of sound , the absorptive power of objects, and the intensity at any instant it is necessary to consider the value p , the mean ffee path of reflected sound waves.

If A again = the rate of decay and v the velocity of sound; a the absortion and s the surface of the room; V its volume

$$\frac{av}{sp} = A$$

$$p = \frac{av}{As} = \frac{vkV}{Ast_1}$$

p is proportional to the linear dimensions of the room, and for any room of volume V the ratio

$$\frac{p}{\sqrt[3]{V}} = .62$$

Without explaining the processes involved in deriving them, I shall give certain formulas that can be used in the exact solution of the values mentioned above.

For the determination of the rate of growth of sound as it approaches a steady condition,

Total energy in the room when in steady condition

$$= \frac{pEs}{va} \qquad (1)$$

where E isthe rate of emission of energy from the source.

$$\text{and} \qquad E = VA \cdot \log^{-1} At$$

To determine K the factor of proportionality which we have heretofore considered as .171

$$K = \frac{13.8\,w}{V\,(A'' - A')}$$

where A' is the rate of deaay with windows closed and A" with them open. Here w is the absorbing power of a square metre o of open window minus its absorbing power when closed.

From this equation and the following,

$$a = \frac{A'\,w}{A'' - A'}$$

the useful equation (2) can be obtained

$$a = \frac{A'KV}{13.8} \qquad (3)$$

It should be noted that the values of A' and A" are found by means of formula

$$A = \frac{K \cdot I_1}{t_n - t_1}$$

this K <u>not</u> being the constant of proprtionality of absorption but the factor representing the number of time greater than th intensity of one pipe is the intensity of n pipes

There is no need to go into the details of the theory any further than to observe these formulas, as we have just done. For the investigator who is to make careful experiments or calculations in a theoretical and finished manner the equations are invaluable, but the present paper cannot cover any such wide purpose..

Up to the present I have considered only the physical aspect of the problem of acoustics. Not less important is the psychological side . What makes good acoustics ? We can now determine the reverberation, the intensity and the loudness of sound ,but what do these mean ? The answer is that these quantities must be given a qualitative meaning. When we say the reverberation is two seconds, that number should mean either good fair or bad, but in deciding we must ask what is the sound and what is the hall. Music and speaking are quite different in their needs, as anyone will attest who has entered a theatre. Speaking on the stage is usually heard distinctly anywhere, while music is generally indistinct, muffled or staccato. Music requires greater reberberation and LESS resonance than the speaking voice. Resonance is generally disastrous to polyphonic music.

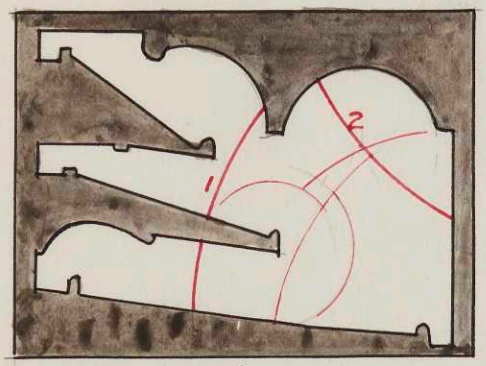
It is necessary to formulate some general rules for the desirable reverberation based on the reverberation in halls now in existence and known to be good. With the resulting figures in mind it is then a quantitaive problem ,how to get the proper value in a new hall.

The phenonmenon of reverberation is easy in this way to control. When we come to interference the problem is again both quantitative and qualitative. The problem is attacked in an entirely different way. Instead of mathematical solution there is in use a method as interesting as it is ingenious. That method is one which entails the construction of small models of a proposed hall , and photographing by electric spark the passage of sound waves sent out from a source in the position which it would occupy in the actual auditorium. Several of these photographs can be taken one after the other until a series will tell accurately the exact action of sound in the hall in any one plane section. Photographs can thus be made of reflection of sound in the vertical section or in the plan and any alteration that would diminish echos or improve the hall otherwise can be made with little or no coast.

I insert here a series, or two series of such photographs made of the Scollay Square Theatre in Boston. The left hand three represent the action of sound in an auditorium designed in a sketchy way, and the other three the action in the theatre as built, after improvements were made.In the original section it is easy to see the poor acoustics that would have resulted if the theatre had been built according to the plan. Sound wave 1 is the original wave from the stage source, and wave 2 is a reflection from the arched ceiling. By following these waves through the three diagrams it will be evident that an echo would occur in almost any part of the house, but worst of all in the first balcony, where the second wave would arrive just too late after the first to reinforce it, and yet still strong enough to be easily perceptuble as a distinct sound.. The other minor waves are also of a dangerous character since they would tend to produce a muddled sound of confusion, a series of slight echoes, perhaps.

As redesigned, the menacing arch was removed, and the effect is at once apparent.Wave number 2 is here an inconsequent little affair that is scarcely discernible from th other minor reflections that exist, and it would have no appreciable effect on the quality of the acoustics.

I regret that time has prevented my applying this method of determination to the hall I have chosen to solve, but have had to be content with solving the reverberation.



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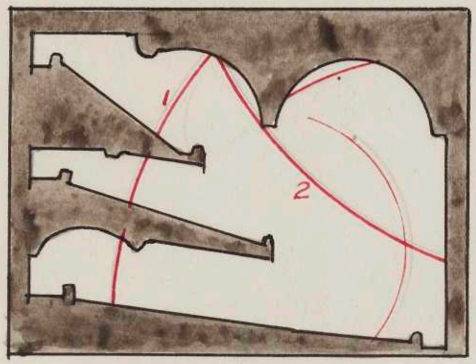

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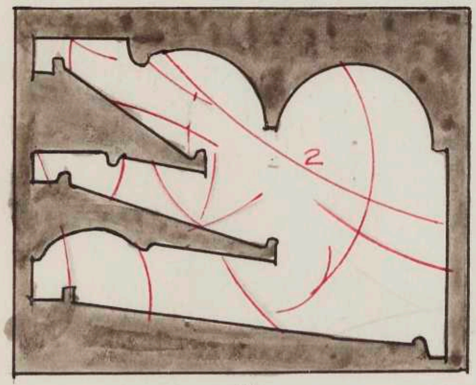

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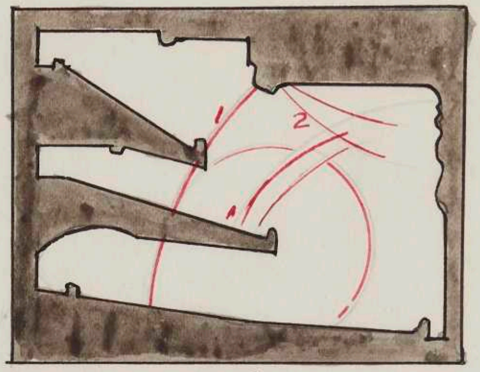

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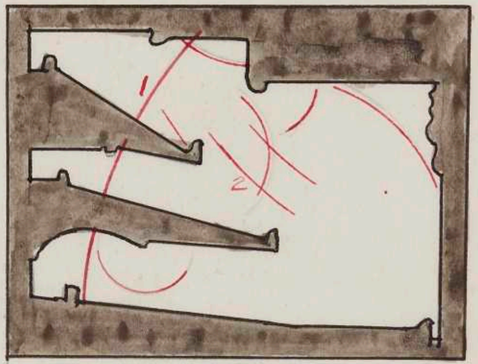

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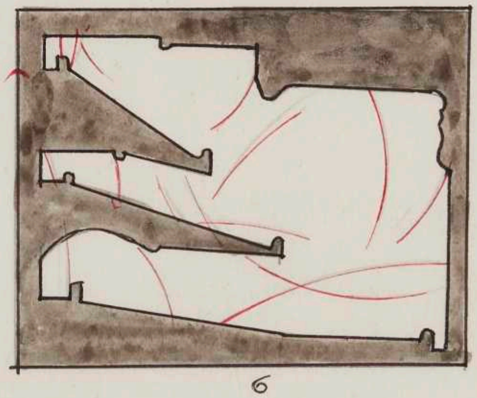

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In concluding the discussion it is intersting to observe that the intensity of sound itself from a given source is dependent upon the absorbing power of the room, and the absorbing power is dependent on the intensity, so that the two are inextricably intertwined.. The paramter of the hyperbolic law is (k) depends on the value of the intensity at any instant as well as on the initial intensity.

Variation in Reverberation, with Variation in Pitch.

It has been determined that the absorbing power of any substance varies with the pitch of the sound.In many cases it is greater for high pitches than for low.Thus the reverberation varies, and inversely as the absortion. For high notes, therefore, it will in general be less than for low, a fact which may account for the larger number of violins than double-basses in the orchestra.While their intensity may be the same, the violin tones are more quickly absorbed than the tones of the bass, and therefore seem lees loud.

There is no apparent law controlling the variation in absorption by all materials, each one following its own inclinations.At present there are no scientific means of determining the irregularities but experiments. Still this method is quite satisfactory, if tedious, and coefficients can be found in the same way as they were for the noteC=512 . Some substances, which may have a more or less regular surface, even such good absorbents as felt of cloth may act differently because sound waves are relected off in one reflection, while a person with clothing may absorb it much more quickly on account of the irregular surface of his clothing and the large numbr of small reflections that takeplace before the sound leaves the c clothing.

In Part II of this thesis I shall consider the matter of variation in reverberation fully in relation to the solution of Steinert Hall, and shall then give the necessary coefficients of all the materials used in that hall. It does not seem necessary to quote such others as are in general use

There are left a few factors that enter into an acoustical problem,which I shall treat very briefly here. One of these is the effect of air currents. It is certain that the attempt to send sound out to the audience by means of introducing ventilating openings at the front of a hall is of practically no effect.The effect of vertical currents caused by temperature difference will not be detrimental unless they are local and of a strong character. Uniform variation is not harmful. The row of lights that are used at the edge of the stage of a theatre are therefore likely to be a harmful factor.

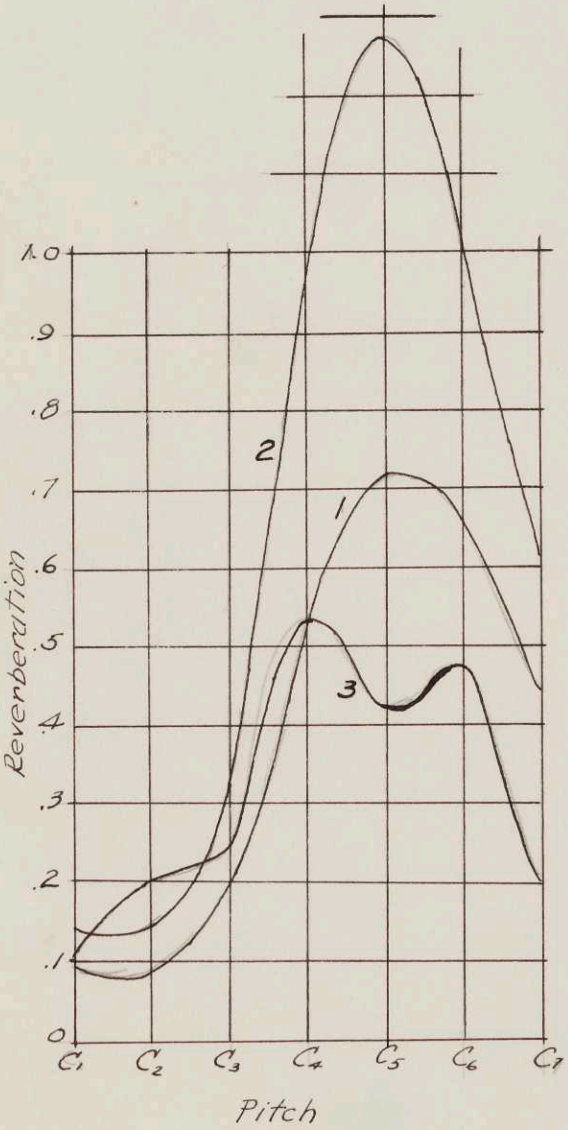
I have not treatdd theatre acoustics in themselves as separate from the science as applied to auditoriums in general. They do however present peculiar problems arising in the nature of their construction, the stage with its extremely high ceiling, if it can be called such, and the arrangement of the auditorium to permit the best seeing by the audience, as well zs many other characteristics make the acoustics of a theatre a difficult problem, and one seldom solved satisfactorily, if we compare them to concert halls.

A manner of the absorption of sound by the viscosity of the air has been shown to be a neglgible factor and needs no comment.

Sound is telephoned through a sturcture through its members, and is thus lost in mechanical energy. Many substances such as wood owe most of their absorbing power to the yielding of the body as a whole rather than to actual absorption into its fibers as heat This sort of absorption is obviously a transformation of sound into mechanical energy. Telephoning from one member to another or from a member such as a door to the surrounding air in an adjoining room is a subject little studied, and to my knowledge no published work contains anything available for use here.

The absorption of sound by a substance is not always independent of its position in a room. Felt cushions placed against the wall will not act the same as if spread out on the floor. The area exposed is also important, and that part of a cushion that is against another object cannot be included in any calculation. Still, the thickness of the samearea cushion will affect its absorption materially.

The position in a room sometimes affects the absorptio tion greatly . The accompanying graph illustrates this point vividly.



Curve 1 represents normal absorbing power of felt in a room with a barrel ceiling

Cureve 2, absorbing power im the centre of the room

Curve 3, absorbing power in sides of the room

It is very difficult to say whether or not any definite conclusions can be drawn from the discussion here terminated . In so brief form as the problem is treated in this thesis almost the entire subject matter is conclusion. But it is worth while summing up the principal methods of acoustic solution.

Before construction any auditorium can be determined with regard to

(1) Reverberation, by the formula $t = \frac{K \cdot V}{a}$

(2) Interference,confusion and reflection, with their tributaries,such as echo, by the photographing of models in two or more planes

In designing a concert hall or theatre ,its proportions and shape cannot be determined by any fixed rules at present. Reason and at least general reference to existing auditoriums are the only guides.It would be foolish to build a hall whose heighth exceeded its width in the ratio 6:1, but it cannot be said, on the other hand, that a hall 75 ft. wide must have a heighth of 50 ft.

In conclusion I shall quote literally a passage from a lecture given at the Sorbonne by Professor Sabine :-

"In no other domain (than acoustics) have physicists disregarded the conditions introduced by surrounding materials, b but in acoustics these do not seem to have recived the least a attention .If measurments are made in the open air, over a lawn as was done by Lord Rayleigh in certain experiments, is due consideration given to the fact that ~~certain~~ the surface has an absorbing power for sound of from 40 to 60 per cent ? Or, if inside a buiding, as in Wien's similar expreiments, is allowance made for the fact that the walls reflect from 93 to 98 per cent of the sound ? We need not be surprised if the results of these experiments differ from one another by a factor of more than a hundred.

" It would be no more absurd to carry out photometric measurements in a room where the walls, ceiling and even the floor and tables consisted of highly polished mirrors, than to make measurements on the intensity, or on the quantitative analysis of sound, under the conditions in which such experiments have almost invariably been made. It is not astonishing that we have been discouraged by the results, and that we may have despaired of seeing acoustics occupy the position to whcich it roghtly belongs among the exact sciences.

" The length of the waves of light is so small compared to the dimensions of a photometer that we do not need to concern ourselves with the phenomena of interference while measuring the intensity of light. In the case of sound, however it must be quite a difference matter.

" In order to show this in a definite manner, I have measured the intensity of sound in all parts of a certain laboratory room. For simplicity, a symmetrical room was selected, and the source, giving a very pure tone , was placed in the center. It was found that, near thesource, even at the source itself, the intensity was in reality less than at a distance of five feet from the source. And yet, the clever experimenter Wien, and the no less skillful psychologists Wundt and Munsterberg have assumed under similar conditions the law of variations of intensity with inverse square of the distance. It makes one wonder hoe they were able to draw any conclusions from the experiments.

" Not only do the walls reflect sound in such a way that it becomes many times more intense than it otherwise would be; and not only does the interference of sound exist to such an extent that we find regions of maximum and regions of minimum sound in a room; but even the total quantity of sound emitted by the source may be greatly affected by its position with regard to interference systems of the room.

" This will be more readily understood if illustrated by an incident drawn from the actual experiments. A special sort of felt, of strong absorbing power, was brought into the room and placed on the floor. The effect was two-fold. First, the introduction of the felt increased the absorption of the sound and thus tended to diminish the total intensity of sound in the room,theoreticaoly to a third of its previous value. But actuaally it had the contrary effect; the sound became much louder than before.The felt was so placed on the floor as to shift the interference system in the room, and thus the reaction of the sound vibrations in the room upon the source itself was ,odified. The source was a vibrating diaphragm at the base of a resonating chamber. In the first location the source was at the node of condensation, where the motion of the sound which had accumulated in the room coincided with that of the diaphragm. In the second case however, the vibrations of the two were opposite,the diaphragm was able to push upon the air, and although the amplitude of its motion was somewhat rduced by the reaction of the air upon it, the emmitted sound was louder.

" Naturally these two positions in the interfernece system were designedly selected, and they show exceptional reactions on the source. However, in the case of a very complex socund, a comparable divergence in the reactions of the room on the different components of sound would be probable.

"It is thus necessary in quantitative research in acoustics to take account of three factors: the effect of reflection by the walls on the increase in the total intensity in the room; the effect of interference in greatly altering the distribution of this intensity; and the effect of the reaction of the sound vibrations in a room upon the source itself..... "

\+ + + + + + +

Here we enter a field known to few and known by fewer. The development of acoustics as an exact science has just begun. I shall now proceed to examine and solve, so far as reverberation is concerned, a concert hall of known excellent quality Steinert Hall. I regret that time does not permit photographic investigation of the interference system.

PART TWO

THE SOLUTION OF THE ACOUSTICS OF A CONCERT HALL

The hall I have chosen to solve acoustically as an illustration of the methods explained in Part One of this thesis is one of the finest quality in both speaking and music. It is a small hall situated in the basement of the Steinert Building, known as Steinert Hall. This auditorium is fortunately protected from extraneous sounds by its situation under the street level.On the east side there is the basement of an office building, on the north is Boylston Street; opposite is nothing but an alley, while on the west the only possible disturbances are from the passage of wagons or trucks through a small side street paved with cobblestones. Such insulation gives any auditorium a great advantage in acoustics.

Above Steinert hall, on the first floor of the building is the piano and phonograph sales-room of M. Steinert & Sons. The framing of the floor is steel beams and girders . Between it and the ceiling of the auditorium is an air space and I believe, some insulating material, though I have been unable to determine certainly either its existence or its nature.

Steinert Hall was constructed in an endeavor to obtain perfect acoustics, and as far as I have been able to find out from any sources whatever, received no exact or approximate solution before it was built. It was, then, designed with all the existing ideas upon the problem in mind, and as for its success,I have been told that Professir Sabine, who made experiments in it at different stages in construction stated that it was the second best auditorium in existence. Whether these words are the ones used by him is doubtful, but I am inclined to believe that the quotation has gained much in enthusiasm since its utterance. Professor Sabine was not given to making over-assertive statements. Still, there is no denying the merits of the hall. It has been my own experience that there is no defect in its acoustics either in speaking, or in any kind of music that it can be used for. The piano and the string quartet can be enjoyed to the fullest extent and singing is unusually pleasing in the now famous hall. One of the most fortunate features of the acoustics is the absence of any need for one's ears to become " acclimated " to the sound before it can be enjoyed. I can perhaps make my meaning more clear by mentioning the condition that has possibly been noticed by many persons in Symphony Hall, in Boston, that makes it necessary to listen to a violoncello for ten or fifteen minutes before the ear becomes able to appreciate its tone. (This is also true to a lesser degree in the case of a solo violin, and even a piano.) In Jordan hall, a similar difficulty exists to a slight degree. But in Steinert Hall the difficulty is absent.

The auditorium is of the egg-oval shape, but the rear is continued in rectangular form beyond the limit of the curved portion. As can be seen from the accompanying drawings the oval is formed by two circles or semi-circles of 15'-5" and 18'-6" radii with their centers 18'-8" apart on the longitudinal axis of the hall. The rear portion is enclosed in walls tangent to the 18'-6" circle but slightly converging so as to preserve to some degree the general oval shape. This convergence is made possible without any waste of space by the acute angle between Boylston and Carver Streets. The stage is at the smaller end and is semi-circular of radius 7'-0"; its ceiling is more nearly an ellipsoid than a hemisphere and serves to reflect the sound that strikes it in straight lines to the auditorium.

From the rear wall to the back of the stage is 83 feet. The greatest width measures 42 feet, while the height is, at the front, 26'-6". The proprtions are then roughly 1:2:3 taking the height zs unity. The height at the rear is three feet less than in front, or about 23-7.

A single balcony begins at the circumference of the rear semicircle that forms the outline of the main floor,the front of the balcony being semicircular in outline of radius 18'-6". The balcony extends to the rear wall,and is entered by doors, one at each side. Despite the comparatively low ceiling of the balcony, and a deep beam that runs across the entire front edge, the hearing in this part of the hall is as good as anywhere.

The hall is entirely finished in plaster. The walls are painted a light color and around their base runs a hidh pannelled motive meant to look like white enamelled wood. The deception is so well handled that it is necessary to touch the substance to believe it is plaster. The white paint is also applied with equal force to a series of shallow pilasters, fluted, and topped with, I presume, a representation of the Corinthian capital. On each side of the hall are three semicircular niches of four foot radius that serve as boxes but on the east side one of these is increased in size and transformed into a rectangular room originally intended to hold a small pipe-organ. Doors lead from either side of the stage into the back entrance. Over these doors hang heavy velour curtains that have been in use since the dedication of the hall, twenty-six years ago.

The main floor, which pitches one foot in twenty-five, is of hard pine, and is single. Beneath it is a plenum chamber for ventilation. Under the legs of every chair of the main floor have been bored three small holes . Throught them all the heat and air enters the auditorium. Small gratings are provided om the sides of the chair-legs and the air comes in very gently in order that no draft may be noticed by the persons occupying the seats. The air entering is at the proper temperature for both heating and ventilating purposes. Anyone who is familiar with Steinert Hall will testify that there is never any discomfort there on account of stuffiness or bad air-draughts. The circulating system is by a large fan that draws outside air to the heating aparatus and forces it subsequently into the hall. A second fan was installed to extract the air but it was found to be not only unnecesszry but undesirable, and is never used. The balcony is not supplied with the ventilating system of the main floor, but is so small that it needs no more than the natural air currents.

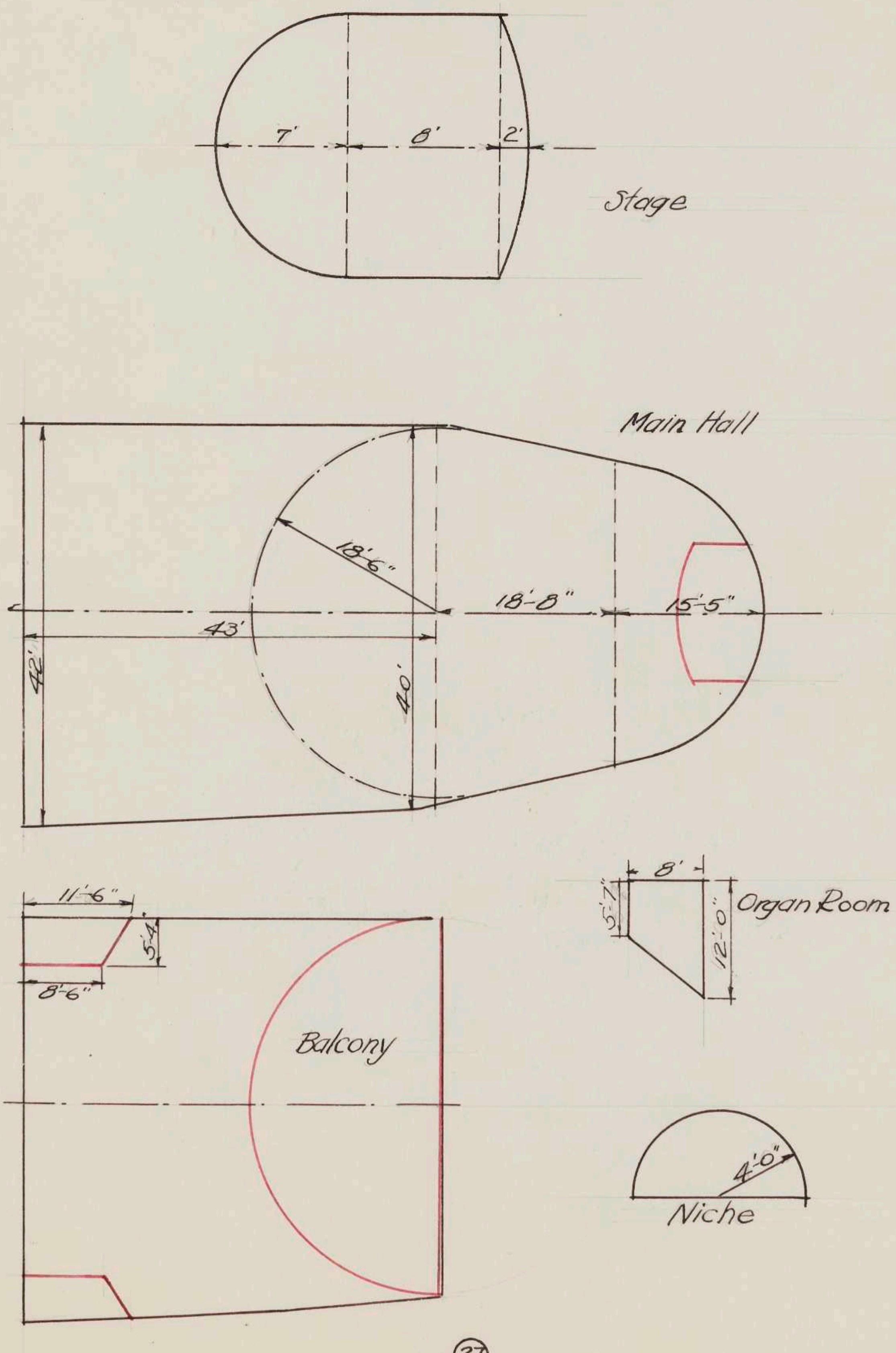
The hall is, then, a clean-cut auditorium with no important obstructions, of a good shape, and with only three important absorbing elements, plaster, wood, and seats. It will be seen later that the most important is the last-named. When filled with people, they take the place of the seats and it is not necessary to consider them.

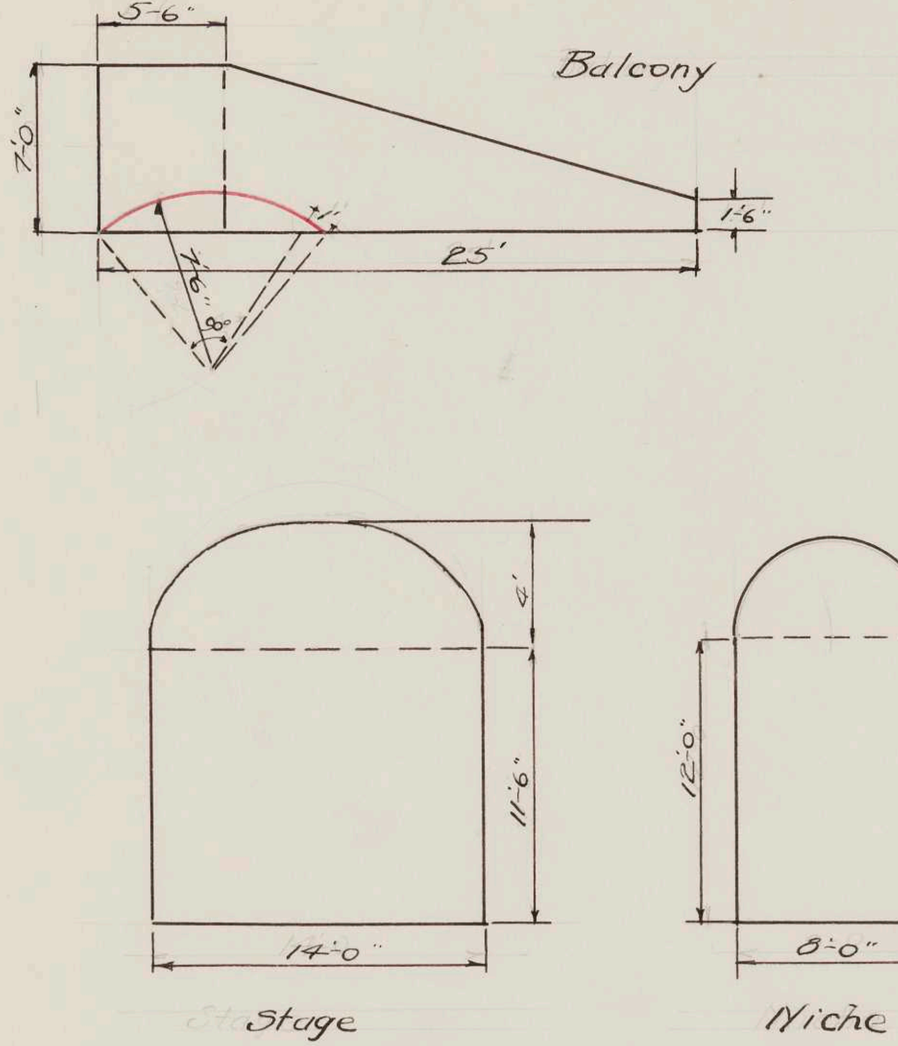
The architect in order to preserve the spirit of the design but four large columns to hold up the balcony. They appear on the plans as 18" colums, but Mr. Richard Newman assures me that they are no more than small brick piers inside. To so disguise the situation is, leaving out of the question acoustics, pretty poor architecture, but in addition the columns might seriously break up the sound as it reached t them and prevent any hearing in the rear of the hall. That they do not is good fortune.

Lighting is indirect. Around the top of the mouldings of the auditorium near the ceiling are rows of electirc lamps that cannot be seen from the seats and obviously cannot affect the air currents below. A few footloghts have been installed s since the extension of the stage but not enough to injure the acoustics, and since there is really no proscenium arch, no curtain of heat could be formed.

The arch under the rear part of the balcony has no apparent effect on hearing in that part of the hall. It is small and its effect would have to be purely local, such as focussing the sound on a single row of seats, but even this condition does not prevail. The absence of any obstructions the plain nature of the surfaces and the few absorbing factors all make for good acoustics; and one other good feature in the design is the lack of doors or other openings into the hall except from the rear. Thus air currents from cracks cannot furnish interference. The only air entering the room is through the ventilating system.

Diagrammatic plans to show dimensions of the hall used in computations





Diagrammatical Elevations showing dimensions of the hall used in computations.

Calculations for finding the areas of the various parts of the hall.

1. The stage. Wooden floor.

Circular part $A = 1/2 \cdot \pi 7^2$ = 77 sq ft
Front rect. part 8 × 14 = 112
Front segment $1/2 \cdot 2 \times 14$ = 14
203 sq ft

2. Other wooden parts

Main floor
Front semicircle $1/2\ \pi 15.4^2$ = 373 — 373
Central trapezoid 1/2 (18.5 +15.4)×18.67
= 633 — 633

Rear trapezoid $1/2(40 + 42) \cdot 43$ = 1756 — 1756
Organ room floor $1/2(12 + 5.6) \cdot 8$ = 70.4
Corner $1.5 \cdot 3$ = 4.6
85.0 — 75

Niches $5 \times 1/2\ \pi 4^2$ = 126. — 126

Balcony floor Trapezoid $1/2(40 + 42) \cdot 43$ = 1756
Deduct circle $1/2\ \pi\ 18.5^2$ = 537
Deduct side juts $1/2(11.5 + 8{,}5) \cdot 5.3$ = 106
Net 1113 sq ft — 1113

Deduct intersection of Stage with hall 126

4076
-126

3950

STAGE above of Maple 203

4153

Doors as follows:
Main floor 2-3.5×7 = 49
1-5 × 7 = 35
Balcony 2-5 × 7 = 70
Stage 1-5 × 7 = 35
Boxes (niches) 40 approx. Total 229 — 4374

Areas in Plaster

Main Ceiling

Front circular part	373	
Front trapezoid	633	
Rear trapezoid	1756	
	2762	2762

Deduct twice cross section of balcony

$7 \times 5.5 = 38.5$

$4.25 \times 20 = 85.1$

Add sector due to arch under balcony

$A = 1/4\ \pi 7.5^2 = 44.1$

and a $\Delta\ 1/2 \cdot 11 \cdot 5 = 27.5$

Net deduction = 106 — 106

Ceiling under balcony

Gross circ. + trap. area 1756

Deduct semicircle $1/2\ \pi\ 18.5^2 = 537$

ADD area due to arch, as greater than flat ceiling

cylindrical area $= 1/2\ \pi \overset{\times 7.5}{42} + 42 \cdot 1 =$ 537

Flat area $11 \times 42 =$ 462

Add.... 76 u

Net ceiling area is therefore

$2762 + 76 - 106 =$ 3951 sq ft

<u>Walls</u>

Stage Cylindrical $7 \cdot \pi \cdot 11 =$ 242

Spherical $\pi \cdot 7^2 =$ 154

396

Main walls

Front circualr part $\pi r h = \pi \cdot 15.5 \times 26.5 =$ 1290

Deduct intersection with stage

$$\frac{2\pi r\ 67\ h}{360} =$$

$$\frac{2\pi \times 15.5 \times 67 \times 16}{360} = 289.5$$

Deduct part of one niche

Deduct part of one niche

rectang. 6.5 × 8 = 52

circ. $1/2\ \pi\ 4^2$ = 25

Deduct organ room 8×14 = 112

circ. $1/2\ \pi\ 4^2$ = 25

Deduct 2 doors 2.5×7 = 35

Total deductions from wall circular part

529 sq ft

Main walls, trapezoidal part front

19.5× 26.3 × 2 = 1025

Deduct 4 niches 4× 77 = 308

717

Trapezoid, rear part of hall

44× 25.6× 2 = 2254

Deduct cross section of balcony twice

106 × 2 214

2040

Back wall 42× 24.5 = 1030

Deduct balconuy intersection 6.7 × 42 = 282.

also 5 doors 154

balcony windows 7× 3.5 24

460

Net back wall area ... 570.

Other areas.

5 Niches cylindrical $\pi r h = \pi \cdot 4 \cdot 12$ = 151

spherical πr^2 16π = 50

201

5× 201 = 1005 1005

Organ room walls

perimeter = 25' "= 25 ×26.5= 640

Organ room ceiling 75

2-18" columns 21.5'

2- 22.0 $\pi 1.5(44+43+21)$ 510

2- 10.5

Beam at edge of balcony $4\pi\cdot 18$ approx 225

Deduction, door to niche west side front

$3 \times 7 = 21$

OTHER MATERIALS.

Heavy velour curtains over doors by stage

2-7 × 2.5 curtains 3ft a= 42 sq ft

Glass, balcony windows 24

Addenda, Plaster 2 juts in balcony 6×8 96

Deduct stage door 35

Summary of areas of various materials

Plaster	10,920	sq ft
Wood, pine and maple	4,374	
Velour	42	
Glass	24	

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CALCULATION OF VOLUME OF THE HALL.

Stage cylindrical part 11.5× 77 = 886.0 cu ft

spherical part $4/3\pi 3.5^2 \times 1/2 =$ 44.9

931.-

Main part of Hall

Front semicircular part 373×26.5 = 9900.

Front trapezoidal 633 × 26.3 16660 (see note)

Rear trapezoid 1756 × 25.6 = 45000

Deduct volume of balcony abt 106×42 = 4490

front part $.25\times 18.5^2\times 1/2 \times 2$ =268.5

Total balcony vol. 4222 + cu ft

Volumes of niches

h of cylinders = 12' r = 4'

cyl. $V = 1/2\ \pi\times 4^2\times 12 = 301$

spher $= 4/3\times\pi\times 4^3 = 67$

368

5× 368 = 1900 cu ft 1900

Organ room

Volume = 75 × 27.5 = 2065

Deduction, juts on sides of balcony
V= 106 × 8.5 = 900

Summary of Volumes.

Main Hall		
Front semi circular		9900
Front trapezoid		16660
Rear trapezoid		45000
Stage		931
Niches		1900
Organ room		2065
		76,456
Deductions		
Balcony	4222	
" side	900	
	5122	5,122

Total net Volume........71, 334 cu ft

Volume = 71334 ×.02832 = 2020 cubic metres.

CALCULATION OF ABSORBING POWERS

These coefficients of absorption, per square metre, the open window taken as a standard , will be used

Wood	.061
Plaster	.033
Velour	.23
Glass	.027

The hall contains seats for 573 persons, 400 of which are in the main floor and 173 in the balcony

For plain ash seats the coefficient .0077 is generally used, and for upholstered seats the value .28. The seats in Steinert hall areneither the one nor the other , but are half way between, wherefore it is reasonable to compute a coefficient half way between these twp. The coefficient thus obtained is .16 .

The calculations of the duration of residual sound based on the above values will be made for the hall empty, full and two-thirds full. The results obtained will show th reverb beration for one pitch only, that of C above middle C, or C of 512 vibrations per second. The absorbing powers of mater ials varying greatly with the pitch, as explained heretofore, it will then be necessary to make new calculations for every note desired. I shall make the computations for seven notes, the seven C's from C_1 64 to C_7 4096.

Below are the absorptions of the materials present in Steinert Hall when empty:-

Wood .061 × 496.5 = 24.8
Plaster .033 × 1015.0 = 33.5
Velour .23 × 3.9 = .9
Glass .027 × 2.23 = .06
Seats .16 × 573 = 91.8

From these values by the formula $t = \frac{K \cdot V}{a}$

it is possible to determine the reverberation for the hall for the pitch c= 512

The table below shows in detail the method used to solve the hall for the pitch C=512

Material	Sq Ft	Sq M	Coeff.	Absorption
Wood	4374	406.5	.061	24.8
Plaster	10920	1015.0	.033	33.5
Velour	42	3.9	.23	.9
Glass	24	2.23	.027	.06
Seats	573seats		.16	91.8
				151.0

$$t = \frac{K \cdot V}{a} = \frac{.164 X\ 2020}{151.0} = 2.20 \text{ seconds}$$

Had we comsidered that the plaster was on tile rether than on wire lath, its coefficient would have been.025 and the total absorption= 25.4. In this case the hall would have had an absorption of 142.9

$$t = \frac{.164 \times 2020}{142.9} = 2.32$$

It is unlikely that this condition exists, and my conclusion is borne out by the close proximity of the t: 2.20 to the time experimentally determined by Prof, Sabine, of which experiments I have already spoken.

The above calculations are here varied by assuming the hall full of people. I shall hereafter neglect the absorption by glass as inconsequential. With the hall full, it is reasonable to consider some of the floor covered so as to cut down its absorption materially. Therfore I shall take into account only 2100. square feet as having any effect on the reverberation. In making the calculations for the hall it is evident that it will be within the limits of the accuracy of these computations to use the same value, since it is more than likely that it has been observed before now that the audience is the most important absorptive agent in any hall. This is the more true the larger the hall; in Symphony hall, the absorption due to the audience is 25 times that of the next largest absorbing material in the hall.

Reverberation with the Hall filled.

Material	Sq. Feet	Sq. M.	Coeff.	Absorption
Wood	2100	195	.061	11.9
Plaster	10920	1015	.033	33.5
Velour	42	3.9	.23	.9
Audience	573 persons		.44	252.0
		TOTAL		298.3

Reverberation with hall two-thirds fileed

Wood	21oo	195	.061	11.9
Plaster	10920	1015	.033	33.5
Velour	42	3.9	.23	.9
Audience	382 persons		.44	168.0
Seats	191 seats		.16	30.6
		TOTAL		244.9

The values of t for the above cases are:

hall filled $t = 1.111$
two-thirds: $t = 1.353$

There is so slight a difference between these two values as to insure good acoustics even when the hall is only partially filled. The ear of critical musical observers or listeners detect a difference of a tenth of a second or less, but this does not mean that such persons would call the one condition good and the other bad. Indeed, one might be neither better nor worse than the other.

Variation in reverberation with pitch.

Since, as I have explained, the absorptive power of any substance varies with the pitch of the sound, it is desirable to calculate the effect on the reverberation in Steinert of this phenomenon. I shall tabulate below the coefficients and absortions of the several factors previously considered for the single note C=512, for seven C's from C=64 to C=4096, taking three separate cases, (1)the hall empty (2) the hall full of people and (3) the hall two-thirds full of people.

The pitches of the seven notes to be considered are as follows:-

C_1= 64 vibrations per second
C_2= 128
C_3= 256
C_4= 512
C_5= 1024
C_6= 2048
C_7= 4096

Table I. Hall empty.

		C_1		C_2	
Material	Sq. M.	Coeff.	Absorp.	Coeff.	Absorp.
Wood	406.5	.064	26.0	.098	39.8
Plaster	1015.0	.048	48.7	.020	20.3
Velour	3.9	.23	.9	.23	.9
Seats	573 seats	.14	80.2	.14	80.2
TOTALS			155.8		141.2

	C_3		C_4		
Material	Coeff.	Absorp.	Coeff.	Absorp.	
Wood	.08	32.5	.061	24.8	
Plaster	.024	24.4	.033	33.5	
Velour	.23	.9	.23	.9	
Seats	.15	86.0	.16	91.8	
TOTALS		143.8		151.0	

Table I continued

	C_5		C_6		C_7	
Material	Coeff.	Absorp.	Coeff.	Absorp.	Coeff.	Absorp.
Wood	.081	32.9	.082	33.4	.113	46.0
Plaster	.030	30.5	.028	28.4	.043	43.6
Velour	.23	.9	.23	.9	.23	.9
Seats	.17	97.5	.19	119.2	.21	120.4
TOTALS		161.8		181.9		210.9

Table II. Hall full of people.

Material	Sq. M.	C_1		C_2		
		Coeff.	Absor..	Coeff.	Absorp.	
Wood	195.	.064	12.5	.098	19.1	
Plaster	1015	.048	48.7	.020	20.3	
Velour	3.9	.23	.9	.23	.9	
Audience	573 persons	.16	91.8	.332	190.4	
TOTALS			153.9		230.7	

Materials	C_3		C_4		C_5	
	Coeff.	Absorp.	Coeff.	Absorp.	Coeff.	Absorp.
Wood	.08	15.6	.061	11.9	.081	15.8
Plaster	.024	24.4	.033	33.5	.030	30.5
Velour	.23	.9	.23	.9	.23	.9
Audience	.395	226.5	.44	252.0	.455	260.6
TOTALS		267.4		298.3		307.8

	C_6		C_7		
Materials	Coeff.	Absorp.	Coeff.	Absorp.	
Wood	.082	16.0	.113	22.1	
Plaster	.028	28.4	.043	43.6	
Velour	.23	.9	.23	.9	
Audience	.460	261.5	.460	261.5	
TOTALS		306.8		328.1	

Table II. Hall two-thirds filled

Materials	Sq. M.	C_1		C_2	
		Coeff.	Absorp.	Coeff.	Absorp.
Wood	195.0	.064	12.5	.098	19.1
Plaster	1015.0	.048	48.7	.020	20.3
Velour	3.9	.23	.9	.23	.9
Audience	383 persons	.16	61.1	.332	125.8
Seats	191 seats	.14	26.8	.14	26.8
TOTALS			150.0		193.9

Materials C_3 C_4

Materials	C		C_4		C_5	
	Coeff.	Absorp.	Coeff.	Absorp.	Coeff.	Absorp.
Wood	.08	15.6	.061	11.9	.081	15.8
Plaster	.024	24.4	.033	33.5	.030	30.5
Velour	.23	.9	.23	.9	.23	.9
Audience	.395	151.0	.44	168.0	.455	174.0
Seats	.15	28.6	.16	30.6	.17	32.5
		220.5		244.9		253.7

Materials	C_6		C_7		
	Coeff.	Absorp.	Coeff.	Absorp.	Coeff.
Wodd	.082	16.0	.113	22.1	
Plaster	.028	28.4	.043	43.6	
Velour	.23	.9	.23	.9	
Audience	.46	175.8	.46	175.8	
Seats	.19	36.3	.21	40.1	
TOTALS		257.4		282.5	

Taking the coefficient of the velour as constant is a feasonable approximation, since its effect on thr reververation is almost negligible, and to comput different values for each pitch would be a needless waste of time.

The following table collects the total absorptions of the hall for the seven notes, and by the formula

$$t = \frac{K \cdot V}{a}$$

the reverberation is calculated for each note.

Table IV Reverberations

Hall Empty

Pitch	Absorption	t in seconds
C_1 64	155.8	2.125
C_2 128	1141.2	2.345
C_3 256	143.8	2.304
C_4 512	151.0	2.195
C_5 1024	161.8	2.048
C_6 2048	181.9	1.822
C_7 4096	210.9	1.570
	Hall filled with people	
C_1 64	153.9	2.154
C_2 128	230.7	1.435
C_3 256	267.4	1.240
C_4 512	298.3	1.111
C_5 1024	307.8	1.075
C_6 2048	306.9	1.080
C_7 4096	328.1	1.010

Table IV continued

Hall two-thirds filled

Pitch	Absorption	t in seconds
C_1 64	150.0	2.208
C_2 128	193.9	1.710
C_3 256	220.5	1.503
C_4 512	244.9	1.353
C_5 1024	253.7	1.308
C_6 2048	257.4	1.288
C_7 4096	282.5	1.162

I have construcred three curves to give a graphical representation of the conditions just determined, and it will be readily seen that the points fall pretty generally on smooth curves. The peculiarity of the curve for the hall empty is that it has the lowest reverberation, and correspondingly, the highest absorption of sound not at C_1 but at C_2. This surprising irregularity is not a freak with this auditorium, but is characterisic of many others. I shall insert here a graph of the reverberation experimentally recorded for the Jefferson Physical Laboratorym in which it is easy to see a like peculiarityi in the curve for hall when empty. To dtermine the cause, we may consult the table of absorptions, Table I. Here it is at once evident that, the absorption due the seats remaing practically constantfor the first three notes, that of the walls decreases sharply from C_1 to C_2 and the effect on the reverberation would be far greater were it not for the fact that at the same time the absorption by the floors and other wooden parts of the hall increases rapidly, tending to counteract the effect of the plaster.

I wish to return for a moment to the subject I briefly mentioned ealrier on this paper, which is the desirable reverberation in an auditorium. I said that some authorities claim that if the duration of residual sound be more than three seconds or less than twoy the acoustics are likely to be bad. The

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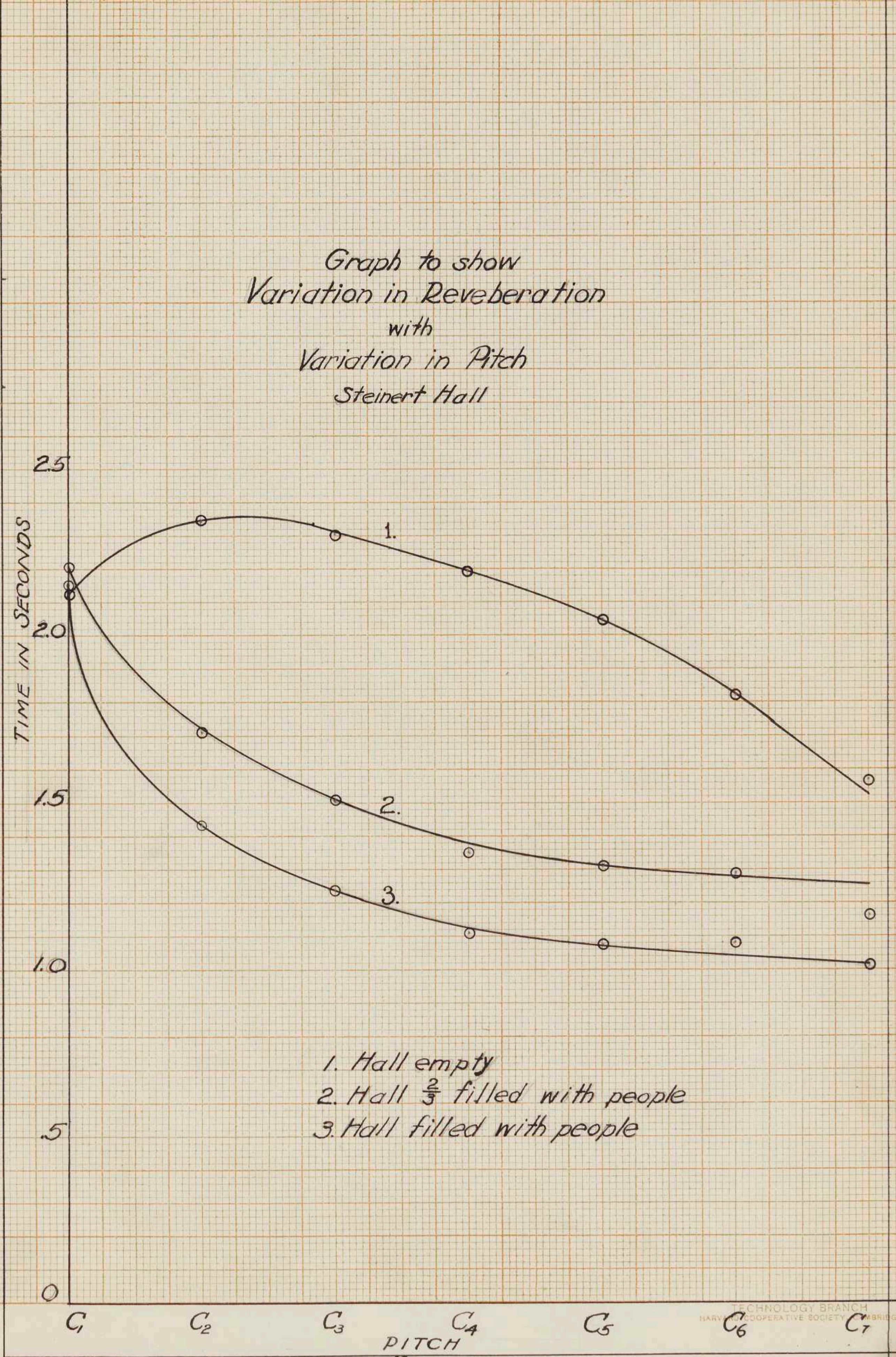
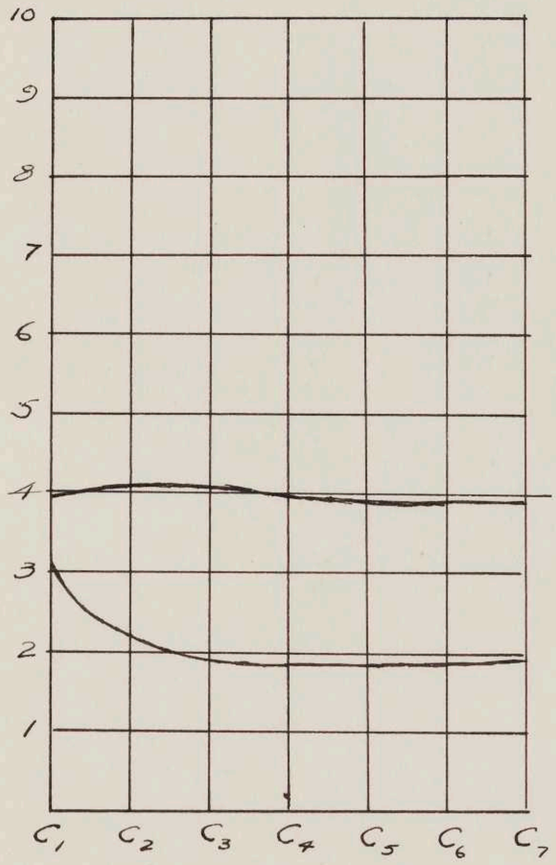


Graph to show
Variation in Reveberation
with
Variation in Pitch
Steinert Hall



Graph showing the reverberation in th Jefferson Physical Laboratory at Harvard University for seven notes, as determined experimentally. The upper curve is for the empty room, while the lower one is for the room with an audience filing it. The lower curve represents a satisfactory condition, and it will be noted that most of the line is below the two second mark.

results here obtained, in the calculations for a hall known to be of the highest quality would seem to refute any such calim. In all probability the claim was made with a special case in mind. Of course the problem of desirable reverberation is one of critical taste, and not of phsical solution. To say what is desirable one must first ask many questions such as," What is the size of the hall ? What isthe use to which it is to be put,-is it speaking or music ? If music, what kind, piano, chamber, orchestra, choral,or organ, and in addition, is it Classical,Modern, or Italian Noise-Makers' music? " And there is no end of questions that must first be a answered before deciding upon the desirable reverberation.

I have concluded that for my own enjoyment, judging from the point of view of a critical appreciator without, however any extensive grammatical or rhetorical training, that the reverberation should be greater in large halls than in small (which condition generally prevails), and that for music it should be much greater than for speaking. For speaking there is no low limit except the time necessary to prevent destroying the rich quality of the voice, and of course, it must not be so short that ~~it~~ the sound does not reach the ear in its entirety.

To say what is the relative desirable reverberation for various kinds of music is difficult in that individual taste is the only criterion .In any case it should be sufficient to give that rich quality of tone without which any music seems dry, brittle and lifeless. It is certain that too short a reverberation leads to more disastrous results in the case of a piano than in the case of an orchestra,because of difference in the nature of the sounds each goves forth,-the piano a quickly,disappearing,percussion tone, and the orchestra one sustained. It is this contrast in tone that makes the effect of a piano playing against a large orchestra one of the most interesting and pleasing combinations in music, and one which has led many of the greatest writers to do their best work in piano concertos. Yet I am sure a hall cannot have at the same time,t two different reverberations for the same pitch. Since all the exact experiments that have been made have employed the organ pipe it is impossible to say with certainty whether a percussion tone has a different treatment by the hall than one of sustained vibration,but it is not unlikely. Of cousre the piano string continues to vibrate for a short time after the key returns to position, as well as the body of the instrument, and it is partly due to this peculiarity that a lower reverberation is desirable in the case of piano music.

Some interesting experiments were performed at the New England Conservactory of Music in small rooms,used by instructors for piano lessons. The results showed that in the unanimous opinion of several accurate critics the best time for th duration of residual sound is in the neighborhood of one second. The variation in five rooms was between .95 seconds and1.16. It should be understood that the rooms were small and the music a solo piano. On the other hand the reverberation in Sanders Theatre, Cambridge is 3.42 seconds. In this hall the Boston Symphony Orchestra plays to the greatest advantage. The music takes on a rich mellow tone without any blurring. Only this season I experienced the unprecedented enjoyment of the performance of the greatest piece of Spanish music ever put on paper, Ravel's Spanish Rhapsody .The same piece had been performed in Symphony hall with equal artistry but the impression was not the same. I do not mean by this that Symphony Hall is anything but a first-rate concert hall,but it does not compare in acoustics to Sanders Theatre. In Symphony Hall there are certain seats or, indeed certain sections, where hearing is extremely bad(for music) In one of these, Floor seat K28 or thereabouts the tone of a piano is very feeble, and against an orchestra is at times almost submerged, and undiscernible. It is difficult, if not impossible, to say what is the cause of such "pockets", for the hall is of a simple plan with no freak shapes or juts in it, and with a regular ceiling. If the proportions of the hall cause them on account of the manner in whic sound wave trains are reflected from the walls (so as to cause two trains to meet and destroy each other at one point and reinforce each other at another point) no remedy could be found without great expense if it could at all. Prbably photographic investigation of a model would clear up the question.

The reverberation in the halls mentioned in this thesis are here noted for comparison, together with a description of the hall and its uses.

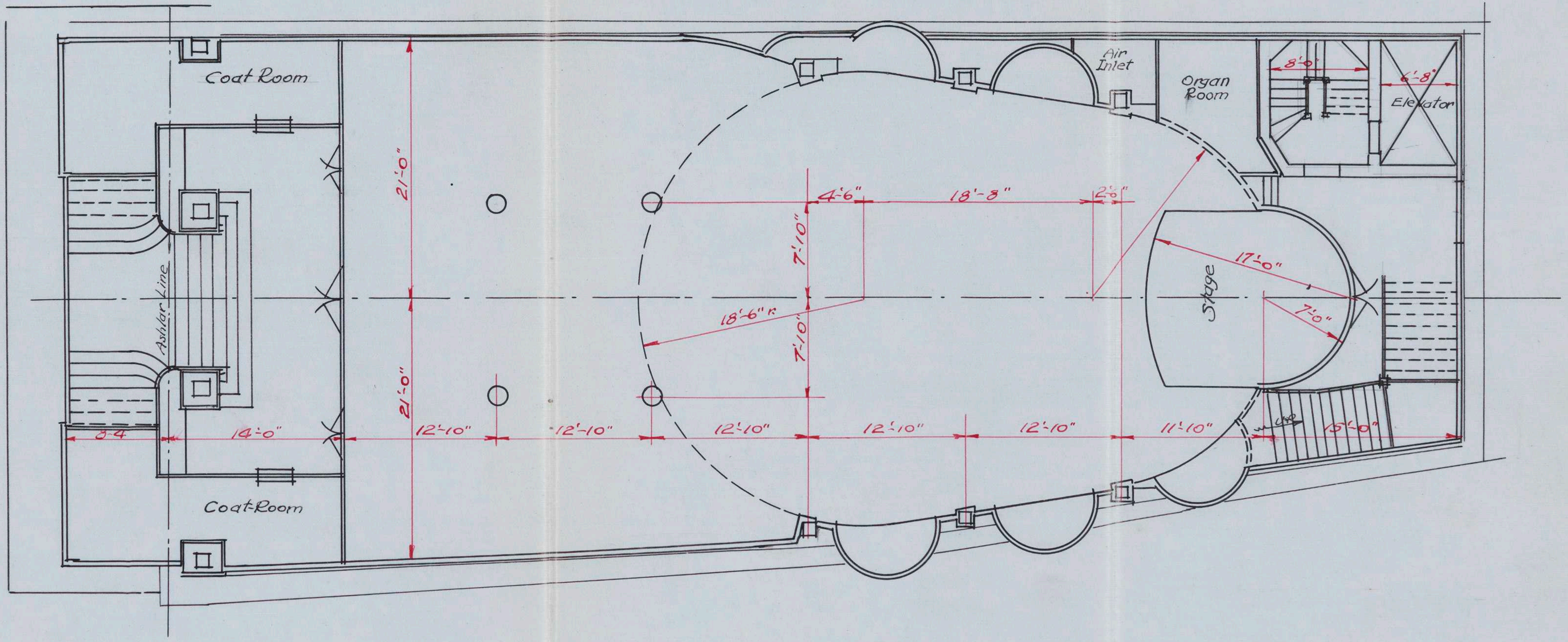
1. Steinert hall- this case has been considered fully heretofore. The hall is used for recitals by solo pianists, violinists or even singers and unpretentious speakers; it is commonly employed by chamber music organizations. The reverberation for C-512 is(hall filled with people) 1.11 seconds For the hall empty 2.20 seconds.

2. Symphony Hall. This hall is used by the Boston Symphony Orchetrsa, by choral societies, and by great or popular artists in recital. Speakers use it to their disadvantage and to that of their hearers. The reverberation for the hall filled is2.31 seconds, a very good figure for orchestral music. The hall is large, seating 2579 persons and having these dimsnsions length 130 feet, breadth 75 feet and heigth 59 feet.

3. Sanders Theatre. The hall is largely of wood, of a semicircular shape .It is used for all kinds of musical and other events . The reverberation empty is 3.42 seconds.

Like Symphony hall in design and acoustics are two halls; the old Boston Music Hall and the Leipzig Gewandhaus. Their reverberations zre repsectively 2.44 and 2.31 seconds.

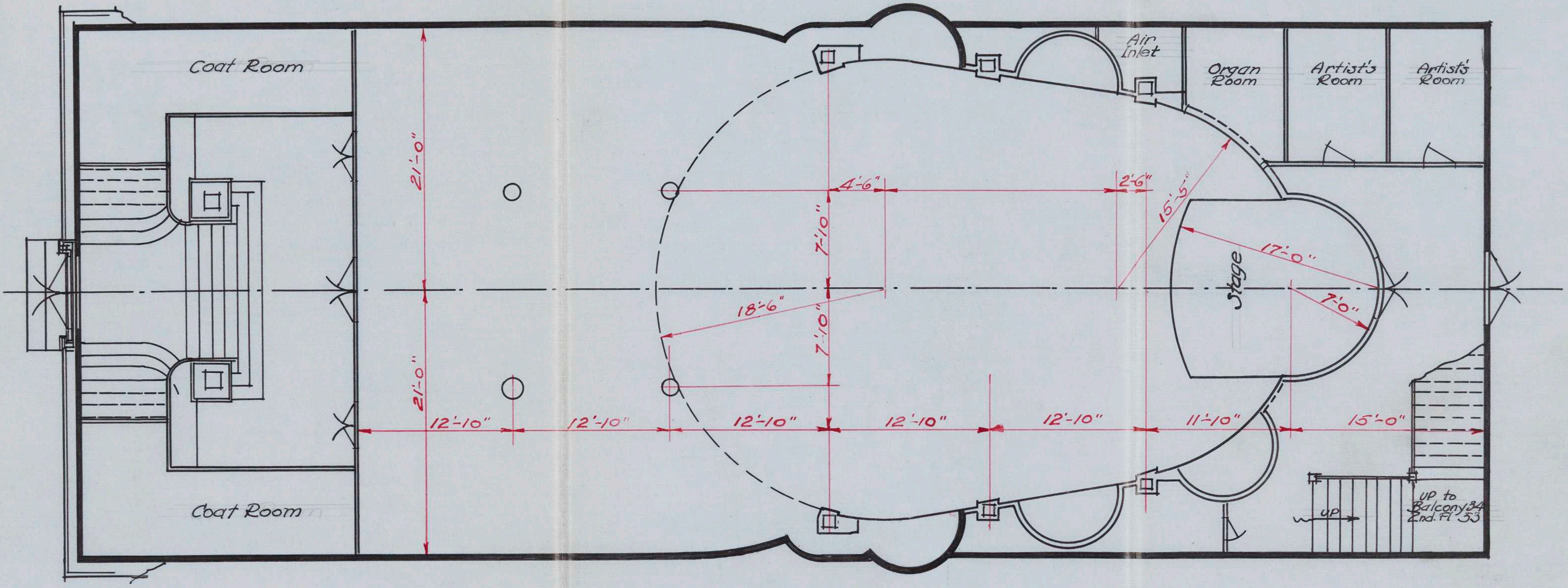
I have not considered interference in Steinert because, as I have previously stated, the method to be used is long and delicate in performance. Such an investigation might easily tell why the hall is so good, and what effect the various parts of the hall have,-as for example the niches, whcih would seem at first glance to furnish a needless temptation for the sound waves to reflect into the auditorium in a disturbing manner. As a matter of fact they do not have any such effect, possibly because of their small size, but more likely because the body of sound waves passing out from the st stage passes by them parallel to the plane of their opening. This is due to the shape of the hall. . The general idea that an egg-oval is the ideal shape for an auditorium is thus supported, but Sanders Theatre is even superior to Steinert Hall and has an entirely different shape.



STEINERT HALL

ORIGINAL PLAN
Scale $\frac{1}{8}$"=1'-0"

Drawing No. 1 for S.B. Thesis
R. W. Reno



STEINERT HALL

REVISED PLAN

Scale $\frac{1}{8}$"=1'-0"

Drawing No. 2 for S. B. Thesis
R. W. Reno