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SOUND-PROOF PARTITIONS

BY

F. R. WATSON

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ENGINEERING EXPERIMENT STATION

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SOUND-PROOF PARTITIONS

AN INVESTIGATION OF THE ACOUSTIC PROPERTIES OF VARIOUS BUILDING MATERIALS, WITH PRACTICAL APPLICATIONS

BY

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ENGINEERING EXPERIMENT STATION

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SOUND-PROOF PARTITIONS

I. Introduction

1. *Purpose of Investigation.*—The demand for quiet rooms in hospitals, hotels, and office buildings, the desirability of insulating music studios and other rooms where disturbing sounds are produced, and the necessity for solving other problems for the control of noise have led to repeated requests from architects and builders for reliable information on effective methods for insulating sound. Although present knowledge of the subject is incomplete, nevertheless, on account of the pressing need for guidance in such matters, it is thought desirable to collect and present the available information in a systematic way, giving the methods and results of various investigations relating to the action of materials on sound, describing practical installations of soundproofiing, and setting forth in accordance with existing knowledge recommendations that may be applied where sound insulation is wanted.

Before 1915 little was known definitely about the subject and cut-and-try methods were used when soundproofing was desired. These cases were usually isolated and few published accounts are available, so that little progress was made. Since 1915 the problem has engaged the attention of scientists who have conducted investigations in the light of the known phenomena of sound and obtained results that are now being applied in practical constructions.

2. *Acknowledgments.*—In addition to the published accounts of investigations, to which proper reference will be made, acknowledgment is due to the Armstrong Cork Company, the United States Gypsum Company, and the Associated Metal Lath Manufacturers for their financial support and coöperation in the conduct of special investigations.

II. Action of Sound with Applications to Buildings

3. *Origin of Sound.*—Sound of a definite frequency consists of a regular series of alternate compressions and rarefactions generated by a vibrating body and progressing in spherical waves in the surrounding medium. Figure 1 pictures the waves in air sent out by the human voice through a megaphone.

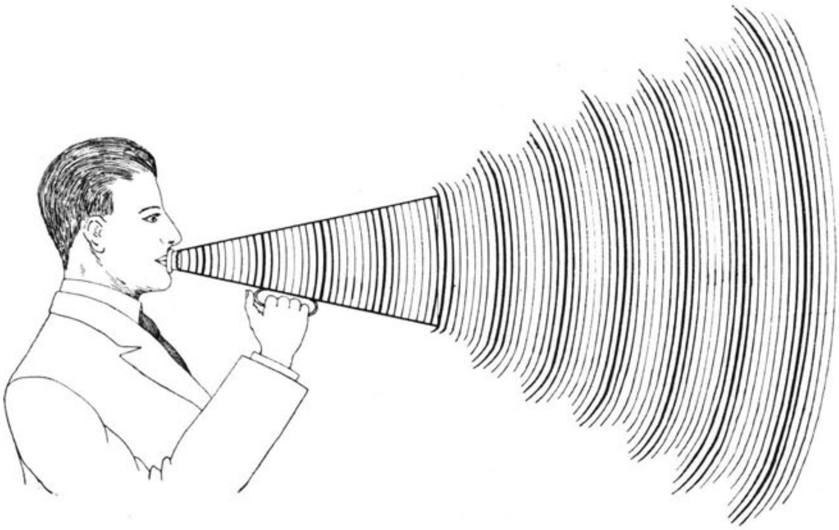

Fig. 1. Diagrammatic Representation of Compressions and Rarefactions (Sound Waves) Sent Out from a Source of Sound

The vibrations in this case are due to the vocal cords which are set into rapid oscillations by a stream of air from the lungs. An unbalanced motor may cause its supporting base to shake, thus imparting to the surrounding air small motions that are propagated as sound waves. A case for consideration in buildings is the generation of sound waves when a wall or floor is set in vibration by a motor, an elevator, or other agency.

4. *Amplitude of Sound Vibrations.*—The amplitude of vibration in sound waves is small, according to estimates varying from 0.00000005 in. for a sound barely audible to 0.004 in. for a loud

sound.* A very small motion of a building partition† will therefore be sufficient to generate in air a sound that may be detected by the ear. Thus one of the difficult problems in sound insulation of buildings is to reduce the motions of walls as far as possible.

5. *Propagation of Sound.*—Sound waves set up by vibrating bodies are propagated through the surrounding medium—solid, liquid, or gaseous—with a considerable velocity, v, depending on the elasticity, E, and the density, d, of the medium, according to the formula: $v = \sqrt{E/d}$. The values of the velocities for a few media are given in Table 1.‡

TABLE 1

VELOCITY OF SOUND IN VARIOUS MEDIA

Medium	Velocity of Sound at 0 Deg. C.
Air	1088 ft. per sec.
Water	4728 ft. per sec.
Pine Wood	10900 ft. per sec.
Brick	11980 ft. per sec.
Steel	16360 ft. per sec.

An inspection of the data given in this table shows that sound travels very fast, about one-fifth of a mile per second in air, and about three miles per second in steel. A sound traveling in the steel structure of a building 260 feet high would require only 260 ÷ 16360, or 0.0159 second to pass from the basement to the roof.

6. *Action of Materials on Sound.*—When sound waves in one medium encounter a second medium with a different elasticity or density, their regular progression is disturbed. Part of the energy is thrown back in the form of reflected waves, part is absorbed in the second medium, and part is transmitted—the relative amounts depending on the changes in elasticity and density of the second medium compared with the first, that is, in accordance with the change in the velocity of sound.¶ (See Fig. 2.)

* Shaw, P. E. "The Amplitude of Minimum Audible Impulsive Sounds." Proc. Roy. Soc., Vol. 76A, p. 360, 1905.

† Hall, E. E. "Graphical Analysis of Building Vibrations." Elec. Wld., Vol. 66, p. 1356, 1915.

‡ Smithsonian Tables, Tables 80 and 81.

¶ Rayleigh, Lord. "Theory of Sound." Vol. 2, Sections 270-272. Equations are given with discussions for different media.

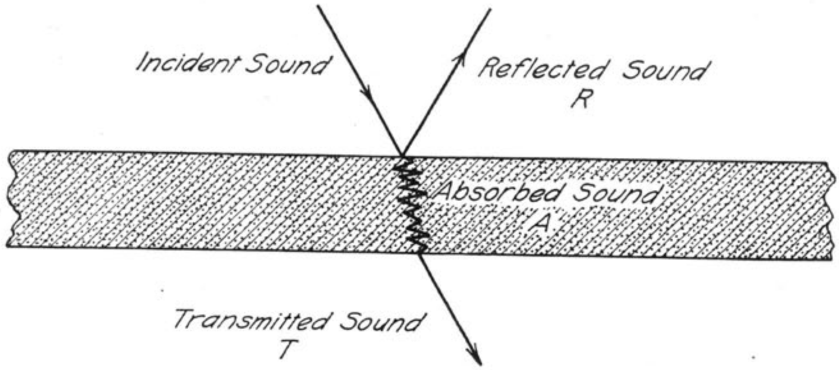

FIG. 2. REFLECTION, ABSORPTION, AND TRANSMISSION OF SOUND

A porous material like hairfelt presents little resistance to sound. The reflection is small, but the absorption in the porous channels may be quite large. What is not reflected and absorbed is transmitted. If the sound waves generated in a room meet solid plaster walls of sufficient rigidity they will suffer a reflection of over 99 per cent because of the large change in the elasticity and density between air and solids. If a ventilator opening is encountered instead of a wall there is no change in the medium and the waves progress with little hindrance through the continuous air passage, being confined in the ventilation duct by reflection from the metal walls. In a similar way sound vibrations generated in the solid matter of a building structure are confined to the structure by almost total reflection at the air boundaries and will pass with little interruption through the continuity of steel and concrete to distant parts of the building. These vibrations may be converted into sound waves in air where a wall or other structural member is set into sympathetic lateral vibration.

7. *Absorption of Sound.*—When air passages in which sound is passing become small in cross-section, friction that converts the wave energy into heat occurs between the sides of the passage and the oscillating air particles. Sound entering a small crack in a thick wall may be completely absorbed before emerging on the other side. The channels and interstices in carpets, hairfelt, and other porous materials, act in the same way in the absorption of sound energy.*

* Rayleigh, Lord. Behavior of Porous Bodies in Relation to Sound. "Theory of Sound," Vol. 2, Section 351.

The absorption and transmission of sound vary with the thickness of the absorbing material but not in direct proportion. For example, if 1 in. of hairfelt stops 10 per cent of the incident sound, 2 in. will stop 19 per cent, 3 in. 27 per cent, etc.; that is, the intensity of transmitted sound decreases according to the recognized exponential law: $i = i_0 a^{-x}$, where i_0 and i are the respective intensities of the sound that enters and is transmitted by the material, a is a constant, and x the thickness of the material.

The absorption of sound is an essential factor in the solution of sound insulation. It is not sufficient to reflect and scatter sound waves, for the energy cannot be destroyed in this manner; it must be absorbed, that is, converted by friction into heat energy.

8. *Transmission of Sound.*—Sound waves in air may be transmitted through an obstructing medium in three ways. First, they may pass through the air spaces of a porous material. Second, they may be transmitted by modified waves in the new medium. In this process sound compressions and rarefactions progress rapidly through the air, moving the molecules successively as they pass in somewhat the same way as a gust of wind blows the separate stalks in a wheat field. On reaching a solid partition the forward motion is hindered, particularly if the molecules of the new material are massive and resist compression. In this case most of the energy is reflected and only a small proportion progresses through the wall. On meeting a further discontinuity of material, such as wood or air, the waves are again affected, until finally a part of the energy emerges. Third, sound may be transmitted by setting a partition as a whole in vibration. The partition then acts as an independent source of waves, setting up compressions and rarefactions on the further side and giving a sort of fictitious transmission. If the partition is rigid and massive the vibrations are small and very little sound is transmitted; if the partition is thin and flexible a considerable amount of energy is transferred.* Usually in building constructions the partitions are complex, as for example plaster on wood lath and studding. In this case the plaster areas between the studding act in a manner similar to drum heads and transmit sound. Hard

* Rayleigh, Lord. "Theory of Sound." Loc. cit. See also:

Jäger, G. "Zur Theorie des Nachhalls." Sitzungber, der Kaisl. Akad. der Wissenschaften in Wien. Math. Natur. Klasse, Bd. CXX, Abt. 2a, 1911.

plaster on wire lath presents a different surface with a modified action on the incident sound.

The transmission of sound involves a number of phenomena and is not a simple matter. It depends essentially on the character of the structure through which sound is transmitted and can be calculated only for simple cases of homogeneous materials of known constants.

III. Insulation of Sound in Buildings

9. *Two Types of Sound in Buildings.*—Two types of sound should be considered in the problem of insulation in buildings. One type includes sounds that are generated in the air and that progress through the air to the boundaries of the room; the other is composed of compressions generated in the building structure by motors, elevators, and street traffic. The insulation of these disturbances is best accomplished by considering the actions of sound described in the preceding discussion. Several suggestions for soundproofing are given in the paragraphs immediately following.

10. *Insulation of Sounds in Air.*—Sounds of moderate intensity such as those generated by the human voice or a violin may be stopped with comparative ease if the walls of the room are continuous and fairly rigid. The more vigorous sounds of a cornet, trombone, etc. would require especially heavy walls or else double partitions. Any breaks in the walls for ventilators, pipes, or doors should be guarded by effective insulation.

11. *Insulation of Building Vibrations.*—Compressional waves generated in the building structure pass readily along the continuity of solid materials, and, as they have more paths for escape, are more difficult to insulate than sounds in air. Moreover, they may create trouble when they cause a wall or floor to vibrate. The insulation is based on the same procedure as that used for air sounds; namely, to interpose a new medium differing in elasticity and density. An air space in masonry would be effective if not bridged over by solid material, but since this is impossible for ordinary building constructions as the weight of bodies necessitates contact for support, an approximate insulation is sought by using air-filled substances like dry sand, ground cork, hairfelt, or flax, that possess but little rigidity but are capable of sustaining a floor or a partition that is not too heavy.

12. *Need for Experimental Data.*—The preceding discussion indicates from the standpoint of theory how sound waves will act under given conditions and how they may be controlled. Calculations may be made for a few simple cases of more or less homogeneous materials, but for the complex structures usually found in buildings

the present theory is inadequate to give trustworthy information. In view of this situation the procuring of data by direct experimental tests is quite desirable, particularly for the transmission of sound through materials both homogeneous and complex. Information about the absorption of sound is also needed. The following section gives in historical order descriptions of experimental investigations that have been completed or are now in progress.*

* See condensed account of experiments performed previous to 1909 in the article: "Schalleitung der verschiedenen Körper," in Winkelmann's "Handbuch der Physik," Vol. 2, pp. 554-562.

IV. Experimental Investigations of Action of Materials on Sound

13. *Conduction of Sound by Solids.*—Tyndall describes an interesting and instructive experiment on the conduction of sound. He writes,* "In a room underneath this, and separated by two floors, is a piano. Through the two floors passes a tin tube 2½ in. in diameter, and along the axis of this tube passes a rod of deal (wood), the end of which emerges from the floor in front of the lecture table. The rod is clasped by india-rubber bands which entirely close the tin tube. The lower end of the rod rests upon the sound board of the piano, its upper end being exposed before you. An artist is at this moment engaged at the instrument but you hear no sound. When, however, a violin is placed upon the end of the rod, the instrument becomes instantly musical, not, however, with the vibrations of its own strings, but with those of the piano. When the violin is removed, the sound ceases. . . . . What a curious transference of action is here presented to the mind! At the command of the musician's will, the fingers strike the keys; the hammers strike the strings, by which the rude mechanical shock is converted into tremors. The vibrations are communicated to the sound board of the piano. Upon that board rests the end of the deal rod, thinned off to a sharp edge to make it fit more easily between the wires. Through the edge, and afterwards along the rod, are poured with unfailing precision the entangled pulsations produced by the shocks of those ten agile fingers. To the sound board (of the violin) before you the rod faithfully delivers up the vibrations of which it is the vehicle. This second sound board transfers the motion to the air, carving it and chasing it into forms so transcendently complicated that confusion alone could be anticipated from the shock and jostle of the sonorous waves. But the marvelous human ear accepts every feature of the motion, and all the strife and struggle and confusion melt finally into music on the brain."

Hesehus† investigated the sound conductivity of various solids. The samples were shaped so as to be geometrically similar and placed

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* Tyndall, J. "Sound." Pp. 78-79.

† Hesehus, N. "Ueber das Schalleitungsvermögen der Körper." Jour. Russian Phys. Chem. Soc., Vol. 17, pp. 326-30, 1893. See also abstract in Fortsch. der Physik, Vol. 43, p. 542, 1893.

successively with the lower end resting on a resonating support. A vibrating tuning fork was then placed against the upper end and the relative conduction of sound was made manifest by the intensity of the resonance tone heard. He found that the conductivity for cylindrical bodies was directly proportional to the cross-section and inversely proportional to the length—the same relation that holds for conduction of heat and electricity. He found also that wood conducts sound much better parallel to the grain of the wood than at right angles. This fact suggests a construction for hindering the progress of sound waves, namely, a series of wooden slabs cut alternately parallel and perpendicular to the grain of the wood. If the slabs were separated by layers of felt and not nailed, the obstruction would appear quite efficient.

14. *Experiments by Tufts.*—The transmission of sound by porous materials was tested in 1901 by F. L. Tufts.* For the initial experiment the porous material consisted of lead shot piled in a tube. This was exposed to the action of sound through a metal gauze that supported the shot. A thin rubber membrane closed the bottom of the tube below the gauze and by the amplitude of its vibration gave a measure of the sound waves transmitted. Cotton batting, felting, and other porous materials were tested in the same manner. Tufts concluded that the resistance of a porous material to sound was in the same proportion as the resistance to air currents.

In a later experiment he measured the transmission of sound by materials impervious to air.† Two thin discs of such material closed the ends of a bifurcated tube. Sound pulses, caused by a metal ball dropped on a pine board, impinged on the discs so that the transmitted waves passed on through the tubes to a junction point, where an observer could compare the loudness of the two sounds by alternately closing one tube and then the other. The materials were tested in pairs, each sample being in the form of a disc, 10.5 cm. in diameter. Table 2 gives the results obtained.

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* Tufts, F. L. "The Transmission of Sound Through Porous Materials." Am. Jour. of Sc., Vol. 11, p. 357, 1901.

† Tufts, F. L. "Transmission of Sound Through Solid Walls." Am. Jour. of Sc., Vol. 13, pp. 449-454, 1902.

TABLE 2

TRANSMISSION OF SOUND BY MATERIALS IMPERVIOUS TO AIR

Material	Thickness in cm.	Rigidity*	Transmitted Sound
1. Lead	0.012	0.000106	Louder
Glass	0.012	0.000053	
2. Pine	0.65	0.000013	
Leather	0.65	0.000212	Louder
3. Reënforced brass	0.015	0.00008	Equal loudness
Two thicknesses of cardboard	0.44	0.00008	
4. 10 sheets cardboard	0.70	0.0002	Equal loudness
1 sheet cardboard	0.22	0.0002	
5. Reënforced brass	0.015	0.00008	
Brass with mass at center	0.015	0.0022	Much louder
6. Cardboard	0.22	0.0004	Louder
Cardboard with 34 gm. mass at center	0.22	0.0004	
7. 3 cardboards separated by air space	cardboards all cut from same sample	....	Louder
3 cardboards in contact			

*The numbers in the rigidity column represent the displacement of the discs for a pressure of 1 gm. per sq. cm., the smaller values thus indicating the greater rigidities.

A study of this table leads to the following conclusions:

1. The more rigid glass is the better insulator;

2. The more rigid pine is the better insulator;

3. For the same rigidity the cardboard, 30 times thicker than the brass, transmits the same amount of sound;

4. For the same rigidity 10 sheets of cardboard transmit the same sound as one sheet;

5. The more massive disc with smaller rigidity transmits more sound;

6. For equal rigidity the more massive disc is the better insulator;

7. The cardboards in contact gave a greater rigidity and cut off more sound. The air spaces are thus not as effective as was supposed.

Inspection of these results, therefore, shows that rigidity is the deciding factor, the amount of sound transmitted as an elastic wave being negligible compared with the to-and-fro vibration of the material. For instance in case 4, where the two discs possess the same rigidity, one would expect the transmission to be greater through the single thickness of cardboard than through the built up disc with many reflecting surfaces; but the transmitted sound is the same for the two constructions.

A few additional experiments were conducted using an organ pipe for the source of sound, thus giving a sustained series of alternate compressions and rarefactions instead of a single pulse. It was found that the results might be influenced by the pitch of the note used, so that, if a disc happened to be set into resonant vibration, it would transmit sound to a greater extent than without such resonance.

15. *Investigation by Weisbach.*—A tuning fork giving 236 vibrations per second was used as the source of sound and placed on one side of a wall. A telephone connected to a galvanometer was placed on the other side of the wall and served as a receiver for the sounds transmitted through materials installed over a small hole in the wall.* Weisbach found that metal, wood, etc. vibrated, whereas cloth and porous materials did not. When the disc was free from resonant vibrations the transmitted sound was proportional to the mass of the disc per unit area. When resonance occurred, the energy transmitted by the lateral vibrations was so great that it obscured the other effects, the results depending on the size, structure, and method of fastening the material. He concluded that sound is transmitted through the pores of materials, also by longitudinal vibrations (elastic waves) and by transverse vibrations of the materials.

16. *Tests by McGinnis and Harkins.*—In this investigation, the source of sound was an organ pipe of 768 vibrations per second, the measuring instrument being a telephone receiver in series with a crystal rectifier and a galvanometer.† The materials tested were clamped over an aperture ½ in. in diameter, through which the sound was transmitted. For porous materials such as calico and felt the investigators concluded that the amount of sound transmitted depended on the size and nature of the pores of the material, that is, on the true absorption. The non-porous materials like paper, oilcloth, and tin-foil transmitted less than one per cent of the incident sound when the lateral vibrations were eliminated. All the materials tested were quite thin and of small area.

17. *Work of Wallace C. Sabine.*—An investigation,†† fundamental and far-reaching in its scope, was inaugurated and partly

* Weisbach, F. "Versuche über Schalldurchlässigkeit, Schallreflexion und Schallabsorption." Annalen der Physik, Vol. 83, p. 763, 1910.

† McGinnis, C. S. and Harkins, M. R. "Transmission of Sound Through Porous and Non-Porous Materials." Phys. Rev., Vol. 33, pp. 128-136, 1911.

†† Sabine, W. C. "The Insulation of Sound." The Brickbuilder, Vol. 24, pp. 31-36, 1915.

carried out by the late Professor W. C. Sabine of Harvard University. A sound of measured intensity was generated in a room so that transmission took place through a partition under test. The sound was then reduced in intensity until an observer outside the partition could barely hear it. The test was repeated for other samples and comparative values deduced. The test rooms were especially adapted to confine the transmission of sound to the test material.

Table 3 gives results obtained in the preliminary investigation. Sheet iron and hairfelt were tested separately and in combination. The sheet iron because of its great rigidity and mass reflected much sound and transmitted but little. The reduction of transmission by the hairfelt was due largely to its absorbing power. The combination of the two in alternate layers gave the more effective insulation, the hairfelt serving to reduce further the small amount of sound transmitted by the iron.

TABLE 3

INTENSITY OF SOUND TRANSMITTED BY SHEET IRON AND HAIRFELT

Layers	Hairfelt	Sheet Iron	Sheet Iron and Hairfelt Combined
0	1 000 000	1 000 000	1 000 000
1	270 000	22 700	23 000
2	128 000	8 700	3 300
3	65 000	4 880	700
4	33 000	3 150	220
5	21 500	2 060	150
6	11 400	1 520	88

18. *Investigations by P. E. Sabine.*—Later experiments on sound transmission through windows and doors have been conducted by P. E. Sabine,* using methods similar to those of W. C. Sabine. He found that flexural vibrations play an important part in transmission. A plate of glass 3/16 in. thick transmitted less sound than a 3/16-in. composite structure of two 1/16-in. plates sealed together with a sheet of celluloid. Dead air spaces between double windows were not as effective as commonly supposed. The air space should not be bridged over by solid materials even at the edges of the glass. Inserting sound absorber between the glass plates increased the insulation. A steel door ¼ in. thick proved more effective than a solid oak door 1¾ in. thick or a refrigerator door 4 in. thick filled with heat-insulation material.

* Sabine, Paul E. "Architectural Acoustics." Am. Arch., Vol. CXVIII, pp. 102-108, 1920.

Additional experiments were conducted to test the transmission of sound through flexible materials.* Results were obtained to determine to what extent the damping of sound by such materials as hairfelt, sea-weed, and asbestos is an effective compensation for lack of mass and stiffness. Numerous curves are given showing the transmission of sound for a range of pitches. Further investigation was planned to test more rigid materials, including plaster walls.

19. *Sound Deadening in Hospitals.*—Richard E. Schmidt gives a discussion† of sound transmission in buildings, paying particular attention to the character of building materials with acoustic properties suitable for use in hospital construction. The article gives sketches of rooms and photographs of buildings in Chicago that have sound-proofing features.

20. *Sound-Proofing Tests Made in Chicago Music Building.*—Table 4 pictures the construction and relative sound-proof efficiency of various types of building constructions. This table appears in the 1911 catalogue of the Corrugated Bar Company. It has been impossible to locate any description of the tests other than the information given in the table, but the results set forth are so thoroughly in accord with the conclusions reached in other investigations that the data are included as additional information.

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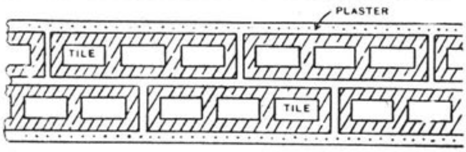
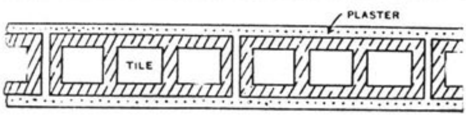
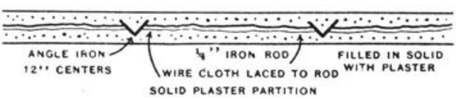
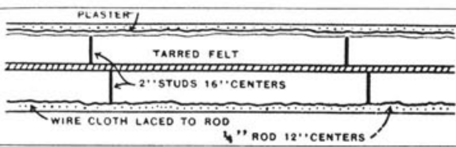
* Sabine, P. E. "Architectural Acoustics. The Transmission of Sound Through Flexible Materials." Am. Arch., Vol. 120, pp. 215, 266, 1921.

† "Sound Deadening in Hospitals." Surgery, Gynecology, and Obstetrics, Vol. XXXI, pp. 105-110, July, 1920.

TABLE 4

COMPARATIVE SOUND-PROOF TESTS MADE AT MUSIC BUILDING, CHICAGO, IN 1895.

<table>
<tr><th>TYPE OF PARTITION</th><th>Rank in Sound Proof Efficiency</th><th></th></tr>
<tr><td></td><td>1.</td><td>COMMON MORTAR (CEMENT)</td></tr>
<tr><td></td><td>2.</td><td>COMMON MORTAR (CEMENT)</td></tr>
<tr><td></td><td>3.</td><td>COMMON MORTAR (CEMENT)</td></tr>
<tr><td></td><td>4.</td><td>ROCK PLASTER
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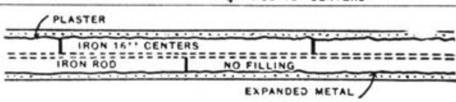
<tr><td></td><td>5.*</td><td>ACME PLASTER
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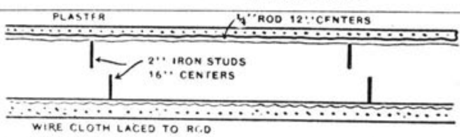
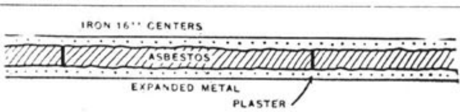
<tr><td></td><td>5.*</td><td>COMMON MORTAR (CEMENT)</td></tr>
<tr><td></td><td>5.*</td><td>ACME PLASTER
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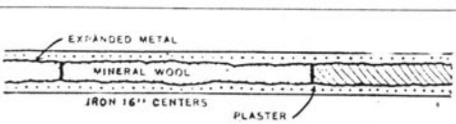
<tr><td></td><td>5.*</td><td>ACME PLASTER
COMMON MORTAR (CEMENT)</td></tr>
</table>

* Sound carried through due to metal connections.

V. Apparatus and Methods Used in Present Investigation

21. *General Methods and Apparatus.*—The experiments on which this bulletin is based have extended over a period of seven years, but have been confined largely to three periods. The method used remained essentially the same throughout, but the apparatus and conditions were improved greatly for the later tests. Materials tested had considerable area—at least 3 ft. by 5 ft.—and varied in structure

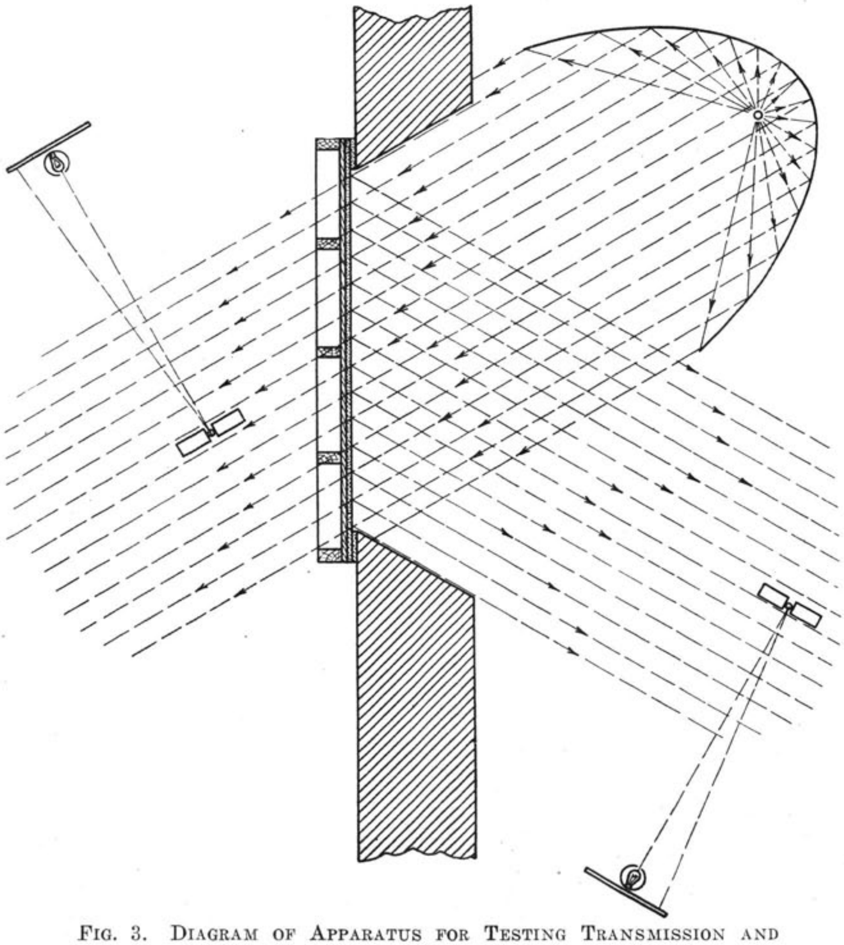


Fig. 3. Diagram of Apparatus for Testing Transmission and Reflection of Sound

from thin flax and hairfelt to solid plaster partitions. An adjustable metal organ pipe blown by air from a constant pressure tank served as the source of sound. This was mounted at the focus of a parabolic reflector 5 ft. in diameter (see Fig. 3), so that a large percentage of the generated sound was directed in a parallel bundle against the partition under test. The sound was partly reflected and partly transmitted, the amounts of transmission and reflection being measured simultaneously by Rayleigh disc resonators placed in the paths of the sound.

22. *The Rayleigh Disc Resonator.*—The simplest form of this instrument consists of a tube closed at one end and open at the other. (See Fig. 4.) Sound waves of suitable frequency, coming

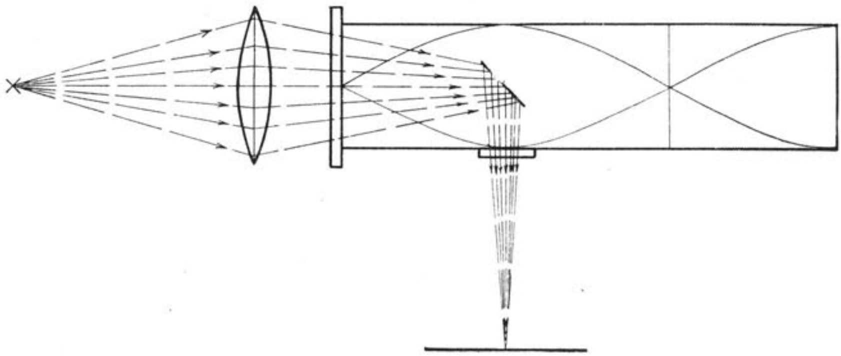


FIG. 4. DIAGRAM OF SIMPLE RAYLEIGH RESONATOR

to the instrument, set up standing waves in the tube with a considerable back and forth surging of the air at a "loop." A thin circular mica (or glass) disc suspended at this loop at an angle to the axis of the tube tends to turn flatwise to the alternating air currents. If a fine quartz thread is used to suspend the disc and the latter is placed at an angle of 45 deg. to the axis, a delicate means is provided for measuring sound, the amount of rotation of the disc varying from 0 deg. to 45 deg. depending on the intensity of the incident sound. This turning action is in accordance with the general principle that a flat object in a current tends to set itself flatwise to the current. Any turning of the disc is made visible by the movement of a beam of light reflected from its surface to a scale. Theory shows that the comparative intensities of two sounds acting separately on the instrument are given by the equation:*

$$\frac{I_1}{I_2} = \frac{\phi_1 \ sin\ 2\ (\theta - \phi_2)}{\phi_2 \ sin\ 2\ (\theta - \phi_1)}$$

where I_1 and I_2 are the intensities of the sounds, ϕ_1 and ϕ_2 the corresponding deflections of the disc, and θ (usually 45 deg.) is the angle between the normal to the disc and the axis of the tube.

Since the intensities of the transmitted sounds varied over a wide range during the tests, several resonators of different sensitivity were required to obtain the measurements. For the faint sounds transmitted by solid plaster partitions, it was necessary to develop a sensitive double resonator† of the proper frequency to obtain measurements. (See Fig. 5.) This latter instrument measured sounds of "threshold audibility," that is, sounds so faint that they could barely be detected by the ear. The resonators are much more sensitive than the ear in measuring sounds of different intensities. This is evidenced by the need of several resonators of different sensitivity to measure the same range detected by the ear. The hearing sensation is proportional to the logarithm of the intensity and is therefore quite insensitive.

* Watson, F. R. "An Investigation of the Transmission, Reflection, and Absorption of Sound by Different Materials." Phys. Rev., Vol. 7, pp. 125-132, 1916.

† Rayleigh, Lord. "Note on the Theory of the Double Resonator." Phil. Mag., Vol. 36, pp. 231-234, 1918.

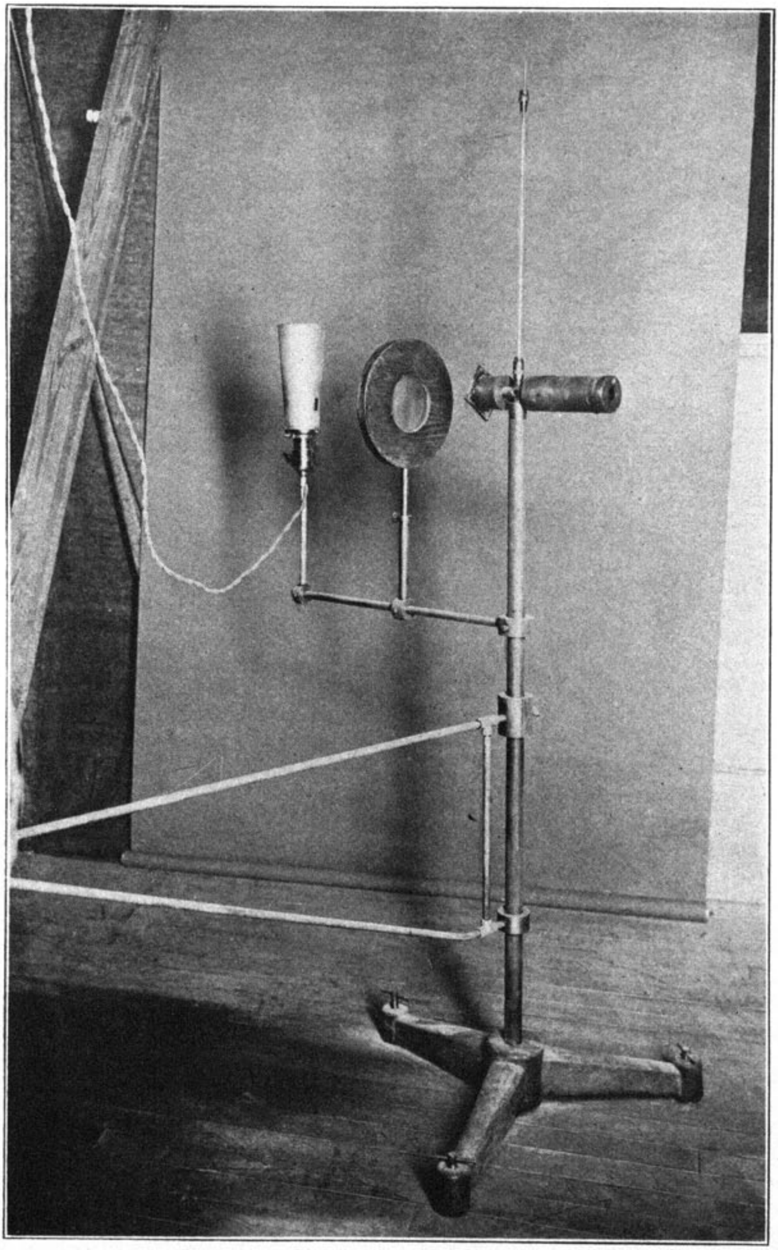


Fig. 5. Sensitive Rayleigh Resonator for Measuring Faint Sounds

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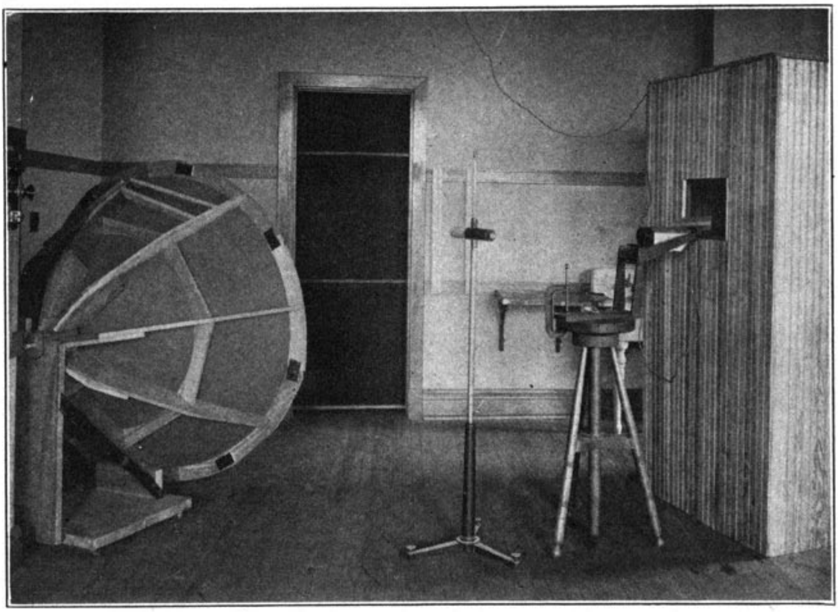

FIG. 6. APPARATUS USED IN INVESTIGATION

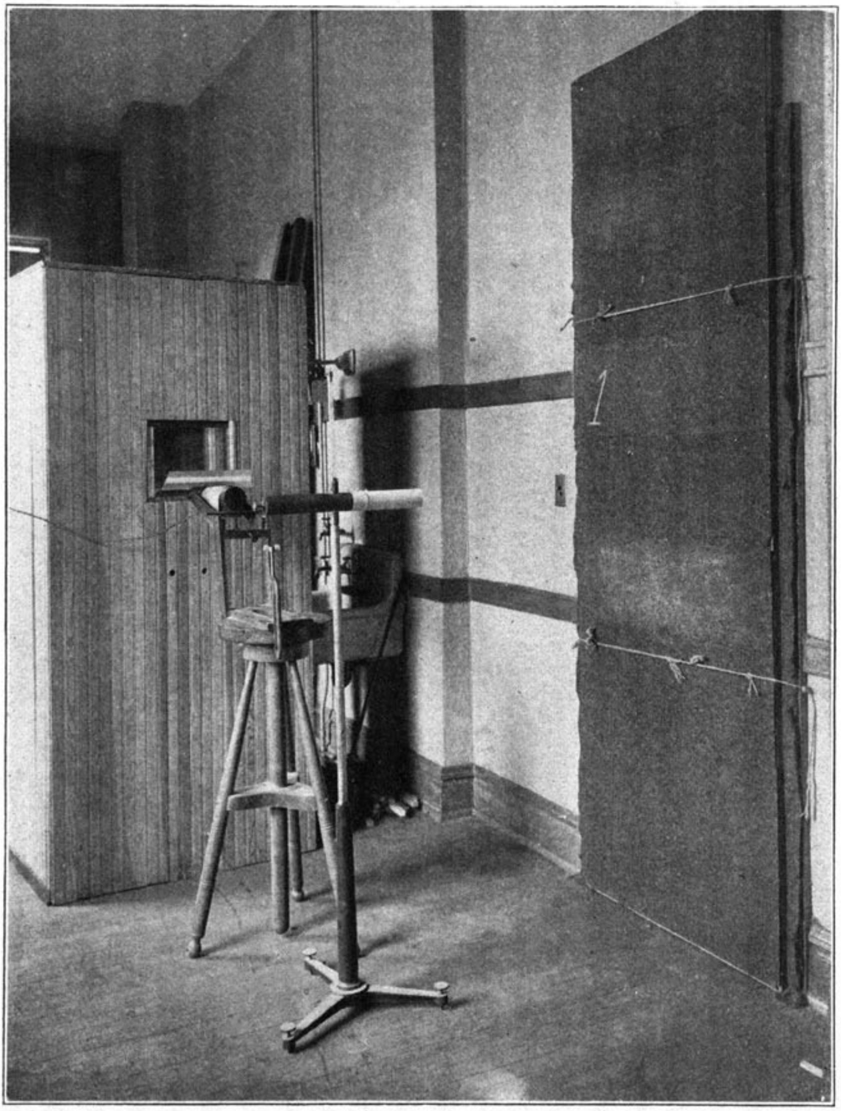

FIG. 7. APPARATUS FOR MEASURING TRANSMITTED SOUND

VI. Preliminary Investigation

23. *Arrangement of Apparatus.*—Figures 6 and 7 illustrate the conditions for the first test. An organ pipe blown steadily by constant air pressure generated a sound that was transmitted through a doorway into an adjacent room where a Rayleigh resonator measured the energy. Measurements were taken, first through the open doorway, then with one panel of the material over the doorway, next with two panels, and finally with three panels; the deflection of the resonator being noted for each case. Since the tests were comparative, all conditions were maintained as constant as possible. Every article in the room was left undisturbed so that the interference pattern due to reflection of sound from various surfaces would remain unchanged and not affect the readings of the resonator. To eliminate the effect of the observer, who necessarily must have some freedom of motion, a small booth was built with a glass window. The observer could shut himself in this compartment and take readings through the window. The samples to be tested were fastened on similar frames of 1-in. cypress and mounted over the doorway by two ropes. A strip of hairfelt was installed around the door frame to prevent leakage of sound at the edges.

24. *Experimental Results Obtained.*—Table 5 gives results for the reflection and transmission of sound.

Table 5
Transmission and Reflection of Sound

Material	Deflection of Resonator in cm.							
	Reflection				Transmission			
Thickness in layers	0	1	2	3	0	1	2	3
Open Doorway	3.9	......	......	......	39.4	......	......	......
½-in. Hairfelt	......	4.9	6.6	10.5	......	22.6	15.4	10.4
¼-in. Cork Board	......	15.7	22.0	22.6	......	7.9	3.75	2.9
¾-in. Cork Board	......	25.9	21.2	22.1	......	1.15	2.05	0.85
¼-in. Paper-lined Hairfelt	......	20.7	5.9	10.0	......	5.0	21.7	3.8
¾-in. Paper-lined Hairfelt	......	10.4	6.6	9.3	......	6.5	1.95	0.4
¾-in. Flax Board	......	22.5	20.0	20.0	......	2.25	0.55	0.1
¼-in. Pressed Fiber	......	23.2	......	......	......	0.32	......	......
¾-in. Pressed Fiber	......	......	......	......	......	0.2	......	......

25. *Discussion of Results.*—The results show the effects of different materials on sound waves. Porous hairfelt transmits con-

siderable sound, and the reflection is small. Other samples, impervious to air, reflect more and transmit less. A better conception of the results is obtained by considering the relative values of the transmission and reflection together with the absorption. Curves for these values may be plotted on the same scale by assuming that the open doorway transmits 100 per cent of the incident sound and reflects 0 per cent; also that the maximum reflection value (25.9 for the ¾-in. cork board) may be taken as 100 per cent. These assumptions are not rigorously correct, but they allow comparisons that are near the truth.*

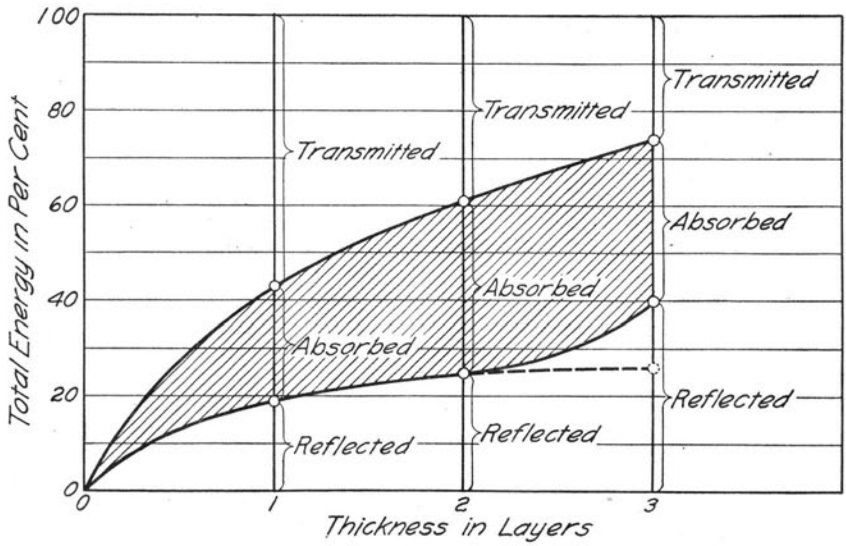

FIG. 8. RELATIVE AMOUNTS OF SOUND REFLECTED, ABSORBED, AND TRANSMITTED BY HAIRFELT

26. *Action of Porous Materials.*—Fig. 8 shows the results for ½-in. hairfelt. Due to absorption of energy in the pores of the material the transmission decreases with increasing thickness, according to the law stated in paragraph 7. The reflection increases with increasing thickness but tends toward a constant value, indicating that the reflection does not take place entirely at the surface of a porous material but requires a certain thickness to give the maximum value. The absorption also appears in this diagram because the

* Watson, F. R. Loc. cit.

incident sound ($I = 100$ per cent) is equal to the sum of the percentages reflected, absorbed, and transmitted.

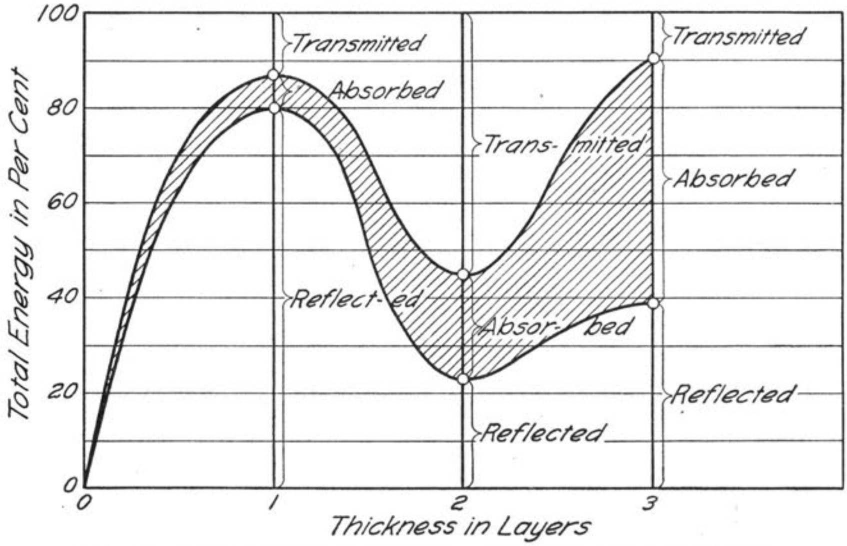

FIG. 9. TRANSMISSION, REFLECTION, AND ABSORPTION OF SOUND BY VIBRATING PARTITION

27. *Action of Materials Impervious to Air.*—Fig. 9 shows results that at first were quite puzzling. Two layers of paper-lined felt transmitted *more* sound than one layer; also, the reflection was *less* for two layers than for one. The explanation is easily seen when the transmission and reflection are plotted together. The two layers *vibrated* under the action of the sound so that the transmission was disproportionately large. An extreme case of this kind would exist if a material vibrated exactly as the air would if the material were not present. There would then be no resistance to the sound waves, hence no reflection, and all the sound would be transmitted.

28. *Conclusions.*—The information given in Figs. 8 and 9 is quite vital in the consideration of sound-proof structures. Fig. 8 shows the normal reflection, absorption, and transmission to be expected for compressional waves passing from one medium through another. Fig. 9 shows the anomalous effects set up when a layer of material vibrates as a whole. This is the usual case in building constructions where partitions vibrate more or less under the action of sound and give unexpected results. The obvious procedure to avoid this complication is to use rigid partitions and minimize the vibration.

VII. Investigation of Thin Plaster Partitions

29. *Arrangement of Apparatus.*—This set of tests was conducted in two basement rooms separated by a double wall consisting of two 9-in. brick partitions with separating air space. The walls enclosing the rooms were of heavy brick construction, the ceilings consisted of 4-in. concrete slabs, and the wood floors rested on concrete. A window cut through the double wall between the rooms was lined with cement plaster and allowed the sound generated in one room to pass directly to the partition under test. (See Figs. 3 and 10.) The reflected sound and the sound transmitted into the neighboring room were measured by Rayleigh resonators. The source of sound was an adjustable Edelmann pipe giving about 630 vibrations per second. The double doors connecting the rooms were padded with felt and arranged to shut as tightly as possible. The arrangements proved to be quite satisfactory for the experiments. Air currents were eliminated and disturbing outside sounds were reduced to a minimum. Any transmission of sound from one room to the other was thus confined to the sample under test.

30. *Materials and Method of Measurement.*—The materials tested varied in structure from porous hairfelt to plaster coating on wood lath. Since the measurements were to be comparative all conditions were maintained as constant as possible, the only changing factors being the samples under test. When taking measurements, the observer entered a small booth built for the purpose and closed the door. Each panel had the same size, 3 ft. by 5 ft., and was clamped in place over the window in the same manner by a wooden frame with iron bars and tightening nuts. Collapsible samples were held in place by wire netting. The range of intensities of sound transmitted was so great that two Rayleigh resonators of different sensitivity were used, intermediate values being taken by both resonators to give continuity of results. The reflected sound was measured simultaneously with the transmitted sound, thus giving check measurements, since any variation in conditions affected both the transmission and the reflection.

31. *Results Obtained.*—The plaster samples were constructed by an expert workman and allowed to dry before testing. They were

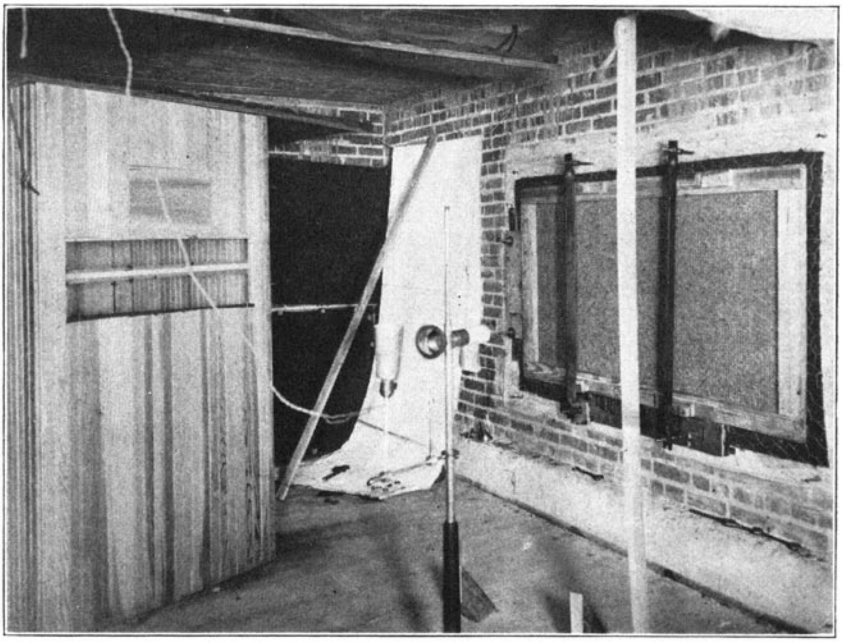

Fig. 10. View of Test Room, Showing Sample Partition Clamped over Window

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then tested one after the other under conditions kept as uniform as possible. The measurements were repeated five times, thus giving six observations for each result noted. In some cases of doubt, further measurements were taken. Table 6 indicates the results obtained. The first column of figures gives the actual deflections observed for transmitted sound, the three Sackett boards being tested by both resonators to establish the connecting ratio between the two sets of readings. The second column gives relative transmission values for the entire set of materials. These values were obtained by reducing proportionately the numbers in the second set so that the readings for the Sackett boards were the same in both sets. The third column gives deflections for the reflected sound, the same resonator being used throughout for these measurements.

32. *Discussion of Results.*—The results show that the porous, burlap-lined flax and the hairfelt transmit considerable sound and reflect little. Paper-lined materials—the Keystone Hair Insulator and Cabot Quilt—transmit less and reflect more. The Sackett boards are the most efficient sound insulators of the thinner samples, while in the plaster panels those containing gypsum plaster appear to be more effective in stopping sound. This is probably due to the fact that gypsum produces a stiffer, more rigid structure. Some estimation of the absorption of sound may be formed by remembering that the sum of the transmitted, reflected, and absorbed sound equals the constant incident sound. If the transmission and reflection are both small, as with the mineral wool for example, the absorption is correspondingly large. Thus with the plaster panels the reflection is extremely large, and the transmission and absorption correspondingly small.

TABLE 6

DEFLECTIONS OF RESONATOR FOR TRANSMITTED AND REFLECTED SOUND

Material	Transmission		Reflection
½-in. Flax, burlap-lined	69.4	69.4	5.2
½-in. Hairfelt	59.7	59.7	6.0
¼-in. Paper-lined hairfelt	35.2	35.2	14.7
¼-in. Cabot Quilt single ply	34.3	34.3	15.6
⅛-in. Building paper	12.7	12.7	32.3
½-in. Flax board	6.5	6.5	26.2
¼-in. Sackett board	0.36	0.36	41.9
⅜-in. Sackett board	0.26	0.26	42.2
½-in. Sackett board	0.15	0.15	42.7

TABLE 6 (CONTINUED)

TRANSMISSION OBTAINED WITH MORE SENSITIVE RESONATOR

Material	Transmission		Reflection
¼-in. Sackett board	28.3	0.36	....
⅜-in. Sackett board	23.4	0.26	....
½-in. Sackett board	9.4	0.15	....
2-in. Mineral wool	18.5	0.22	16.9
2-in. Gypsum furring strips	6.1	0.073	45.8
PLASTER PANELS			
Lime base, gypsum finish	5.2	0.062	45.2
Sanded gypsum base, lime finish	6.5	0.078	45.1
Sanded gypsum base, gypsum finish	3.5	0.042	45.8
Wood fiber base, gypsum finish	3.0	0.036	46.0
Wood fiber base, lime finish	1.8	0.022	46.1

Since the materials in this series of tests were compared under circumstances maintained as uniform as possible, the results obtained are valuable for guidance when selecting material and constructions for sound-proofing purposes.

VIII. Miscellaneous Transmission Tests

33. *Test Rooms and Apparatus.*—The apparatus and arrangements for these tests were quite similar to those used in the previous ones. (See Fig. 11.) The apparatus was rearranged for convenience

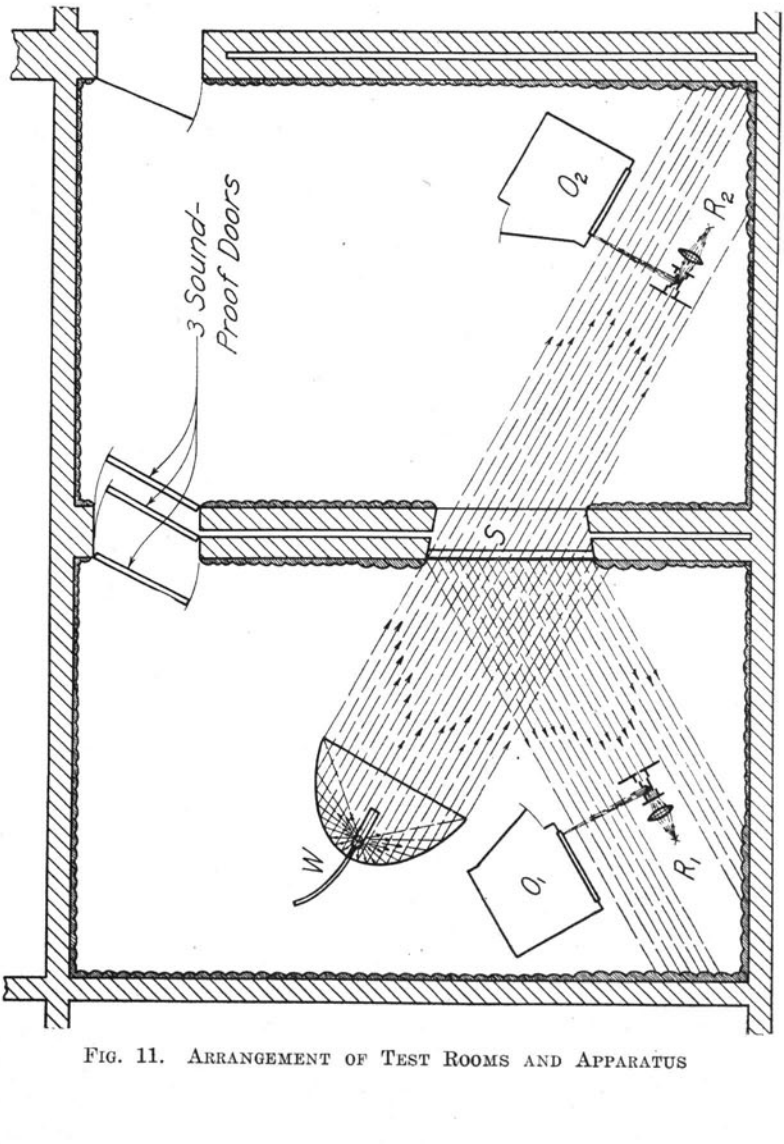

Fig. 11. Arrangement of Test Rooms and Apparatus

and to guard the sensitive resonators from disturbance when workmen were about. The source of sound was an adjustable metal organ pipe designed for the tests and arranged to give 512 vibrations per second, this being considered an average pitch for sounds ordinarily met with in buildings. The organ pipe was blown by air from a constant pressure tank so that throughout the tests the pitch was maintained at 512 vibrations per second, with a maximum variation of 3 vibrations per second as shown by comparison with a standard tuning fork at different times. A double Rayleigh resonator developed to a high degree of sensitivity served to measure the faint sounds transmitted by the thicker wall. (See Fig. 5.) It gave responses for sounds that could barely be detected by the ear, thus furnishing a desirable instrumental substitute for the hearing, because the ear is untrustworthy in its quantitative comparison of sounds of different intensity.

34. *Further Details of Arrangements.*—The amount of sound transmitted was small, so special care was taken to minimize the effect of any leakage of sound. As already explained, the bulk of the sound was directed by means of a reflector against the partition under test. The reflected sound was then largely absorbed by padding, especially by additional layers hung on the walls first struck by the reflected waves. Figs. 12 and 13 show the details.

The doorway between the rooms received special attention. Two sound-proof doors were installed in the wall of the inner room, the door casing cracks being stopped by hairfelt and plaster of Paris. These proved sufficient for the preliminary tests, but when the thicker plaster partitions were tested a small transmission of sound became noticeable. A third sound-proof door was therefore mounted in the second brick wall, after which no leakage of sound through the door could be detected by the ear.

The sound transmitted by the test partition passed directly to the Rayleigh resonator, where it produced its effect, and after this it was absorbed by padding as in the other room. Investigation with the ear verified the actions just described. It showed that an intense sound was directed to the partition and that it was then reflected strongly, the paths of the waves being as shown in Fig. 11.

Since the measurements were to be comparative, the effort was made, as in the previous tests, to maintain constant conditions. Articles of furniture and draperies in the rooms were kept fixed in position so that the interference pattern would remain unchanged. The observer placed himself in a small booth where he could take

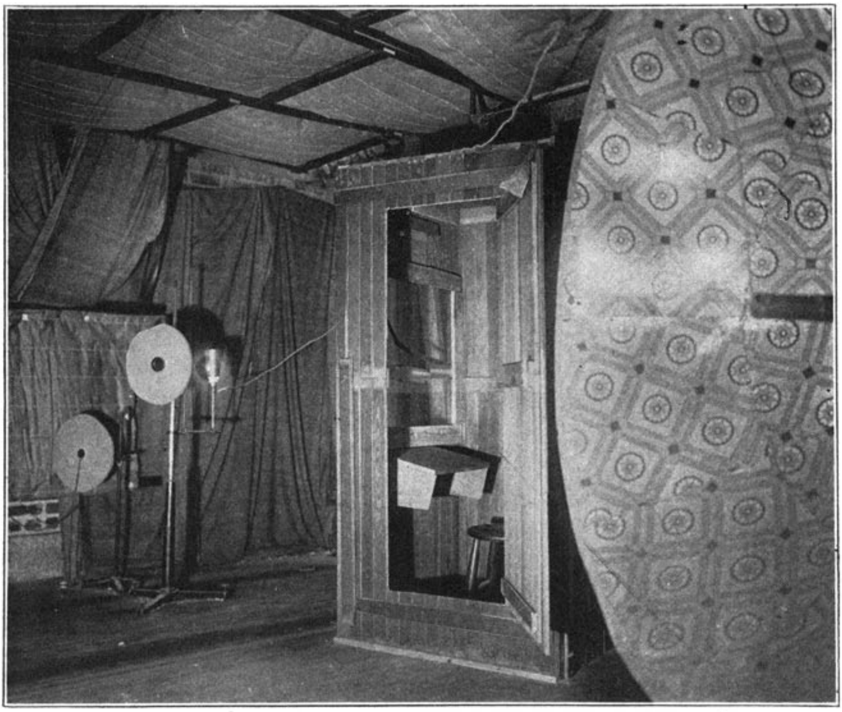

Fig. 12. View of Test Room, Showing Rayleigh Resonator and Booth for Observer

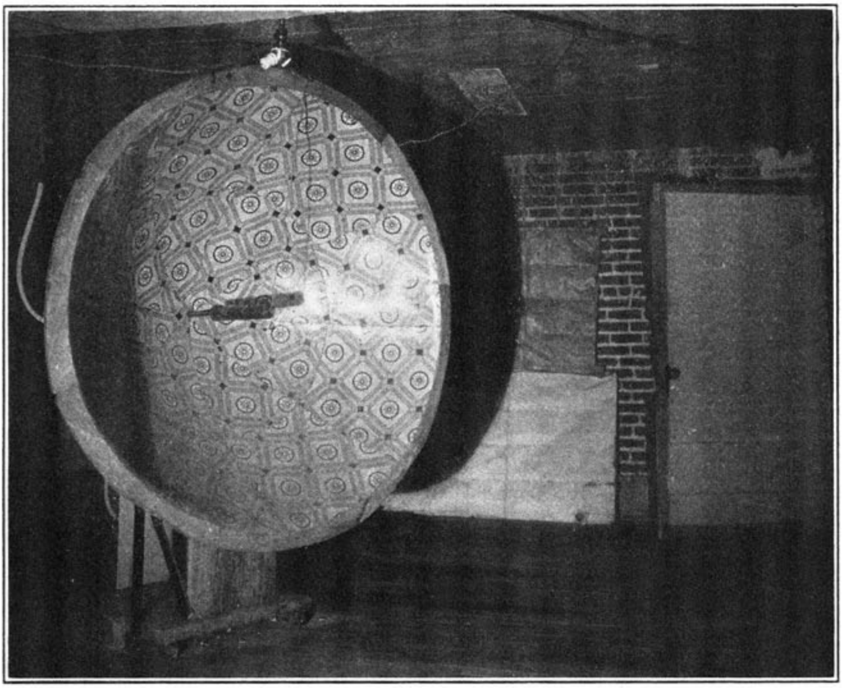

Fig. 13. View of Test Room, Showing Parabolic Reflector Lined with Linoleum

readings through a glass window without disturbing the action of the sound. After the initial adjustments the organ pipe and resonator were not modified. The pressure tank and the pipe connections were set up permanently at the beginning of the experiments. Changes were made only when one partition was taken out and its successor built in the wall in the same position. Where the partitions were of equal thickness the measurements were strictly comparable. The tests were conducted as rapidly as was consistent with accuracy in order to secure fairly uniform conditions of temperature and humidity, the chief delaying factor being the time required for the plaster coats to dry. The tests on the plaster walls were made during the months of June and July, 1919.

Additional measurements were taken throughout by methods other than the one described. While these extra measurements are not considered as reliable as those given by the Rayleigh resonator, they are in the same order and thus furnish an independent check on the results.

35. *Preliminary Test on Transmission of Sound Through Outing Flannel.*—It was the intention in this test to make certain that the apparatus and method would be applicable to plaster partitions, particularly those of some thickness. It was planned also to establish if possible the law connecting the intensity of the transmitted sound with the thickness of the partition. For this latter purpose a preliminary experiment was performed on the transmission of sound through outing flannel. One, two, three, four, five, and six layers of this material were mounted in succession over a metal lath core installed in the opening between the two rooms, the transmitted sound for each case being measured by a Rayleigh resonator. The results are shown graphically in Fig. 14, where the intensities of the transmitted sound are plotted against the respective thicknesses. If this were a case of pure absorption, expressible by the equation $i = i_0 a^{-x}$, as in paragraph 7, the logarithms of the intensities plotted against the thicknesses would give a straight line. The logarithms plotted for this case are shown in Fig. 14, the small departure from a straight line being explained simply by the fact that the reflected sound was not constant, but became greater with increasing thicknesses, so that the intensity of the transmitted sound fell off more rapidly than it would by absorption alone. The success of this experiment verified the various assumptions concerning the method and apparatus and gave confidence for further tests with denser walls.

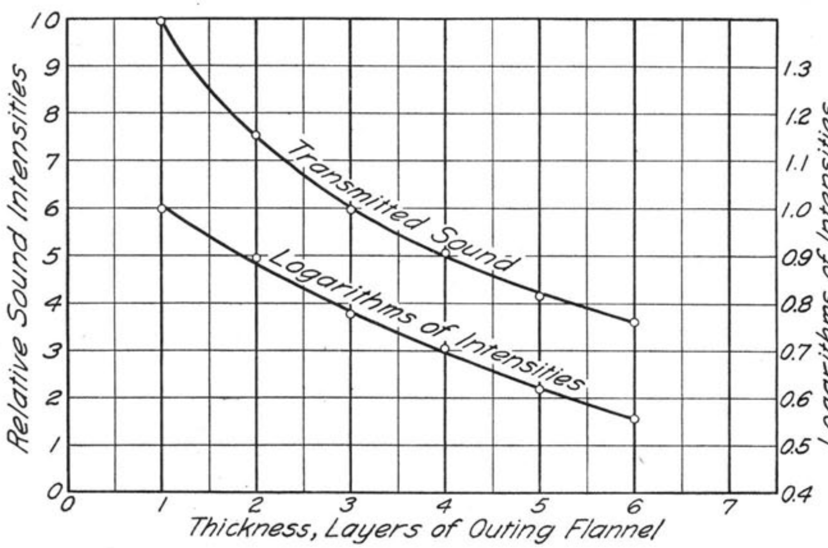

FIG. 14. TRANSMISSION OF SOUND BY OUTING FLANNEL

36. *Transmission Through Thin Plaster Partition.*—Plaster was then applied in place of the outing flannel (see Fig. 15), and it proved to be so much more effective in stopping sound that the resonator used with outing flannel gave no readable deflection, making it necessary to install one much more sensitive—the resonator pictured in Fig. 5—before a reading could be obtained. Measurements were taken on this panel for a week, until the plaster dried. More plaster was then applied with a brush to the back of the panel in order to fill the holes between the keys, thus producing a fairly uniform thickness of about ½ in. For this increased thickness the resonator gave a deflection about one-sixth as great as for the thinner layer. Further measurements were then taken for nine successive days, the results being shown graphically in Fig. 16, which displays some interesting features. The transmission increased during the second and third days after the first coat of plaster was applied, due probably to some change in the plaster as it set and dried. This phenomenon is shown for the second coat of plaster also.

37. *Effect on Transmission of Sound When Pressure is Applied to a Thin Partition.*—Finally, the transmission of sound was measured when this panel was subjected to successively increasing pressures until it broke. The pressures were applied by a 2-in. board and two

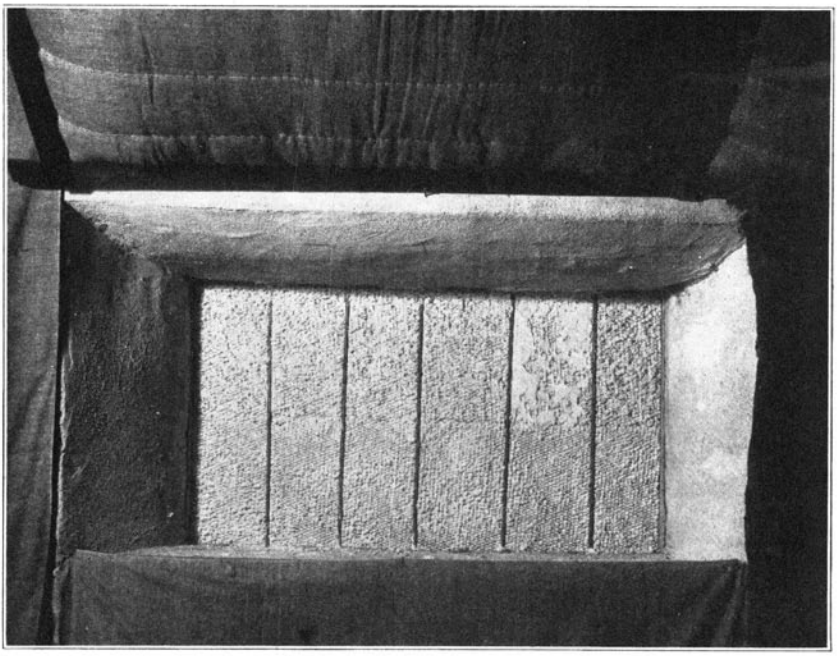

FIG. 15. EXPERIMENTAL PARTITION FORMED BY A COAT OF GYPSUM PLASTER ON METAL LATH

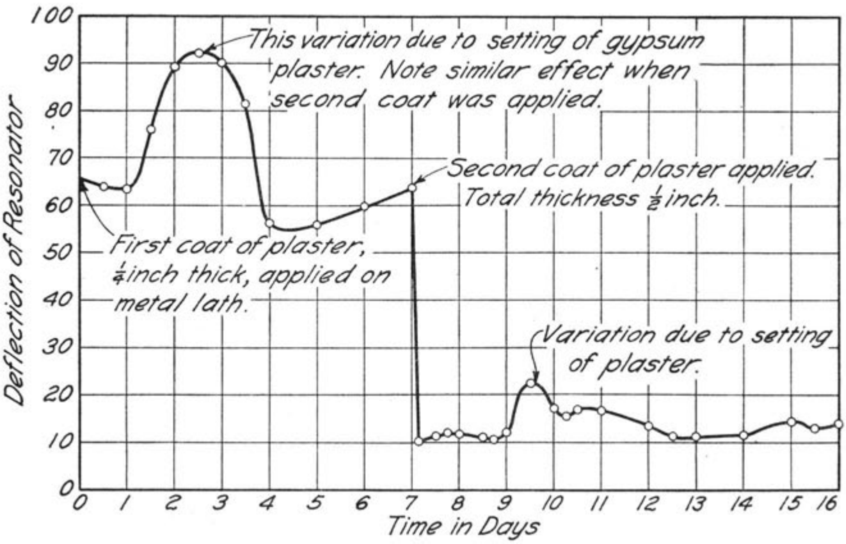

FIG. 16. TRANSMISSION OF SOUND BY PLASTER PARTITIONS OF TWO DIFFERENT THICKNESSES

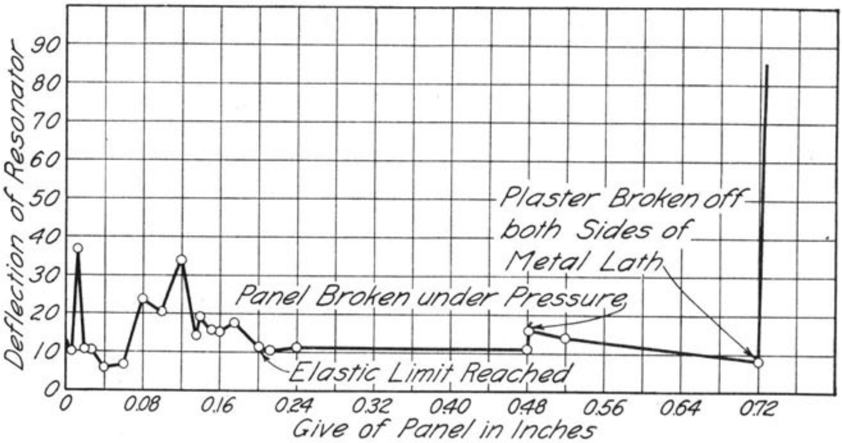

FIG. 17. TRANSMISSION OF SOUND BY PLASTER PARTITION UNDER PRESSURE

iron bars. Turning the nuts on the bolts supporting the iron bars gave successive increases in pressure. Under this treatment the panel acted very much like a drumhead, transmitting more sound when tuned up and less when something in the panel gave way and relieved the tension. Additional pressure tightened it again and the transmitted sound was increased, etc., until finally it passed the elastic limit and gave way like putty under the increases of pressure. No great amount of sound was transmitted in any case until plaster was knocked off both sides of the metal lath, thus leaving an open passage about 6 in. long. Fig. 17 gives the details.

38. *Effect of Pressure on a Thick Plaster Partition.*—The foregoing experiment was repeated with a 2-in. solid plaster board and plaster partition. A 4-in. wooden block was pushed with successively increasing pressures against the center of the partition and measurements of transmission taken at successive stages until cracks of some size were developed. The amounts of sound transmitted were not large, probably because of the friction between the rough walls of the cracks and the vibrating air particles. Figs. 18 and 19 show photographs of the partition, while Fig. 20 gives the transmission measurements.

39. *Transmission of Sound Through Threshold Apertures.*—In order to test the transmission through threshold apertures, a door was built into a 2-in. solid metal lath and plaster partition as shown in Fig. 21. The door was constructed of 2-in. wooden planks and was carefully fitted into the opening. Door stops were used on the side opposite the source of sound except at the threshold aperture. The relative intensities of sound calculated from the resonator readings are as follows:

2-in. metal lath partition, before insertion of door	0.93
With door installed with $\frac{3}{16}$-in. threshold opening	7.3
With door installed with ½-in. threshold opening	11.7

While the results probably do not express exactly the intensities of the transmitted sound because of the diffraction effects by the narrow opening, they give relative values of the effect of threshold openings. These openings are equivalent to wide cracks.

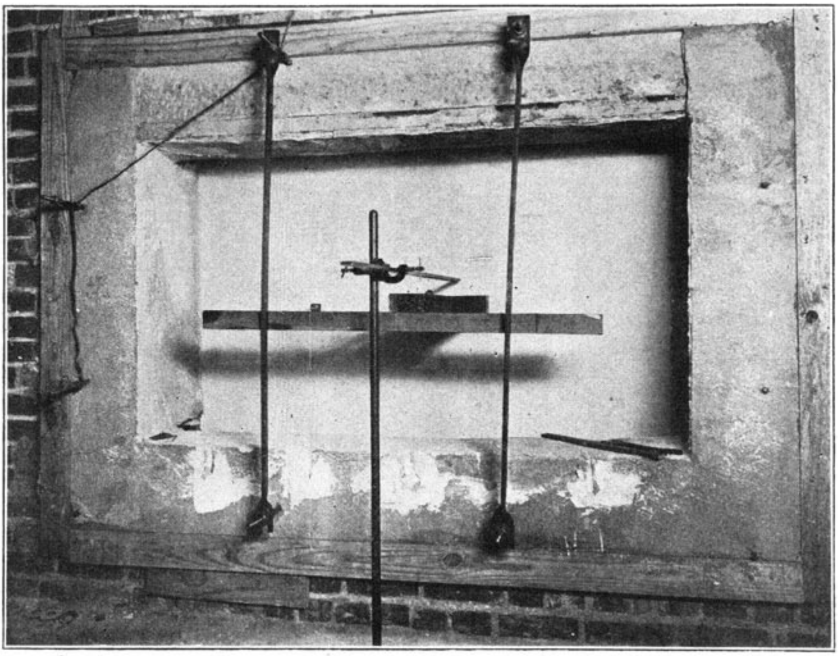

Fig. 18. Method of Applying Pressure to Partitions

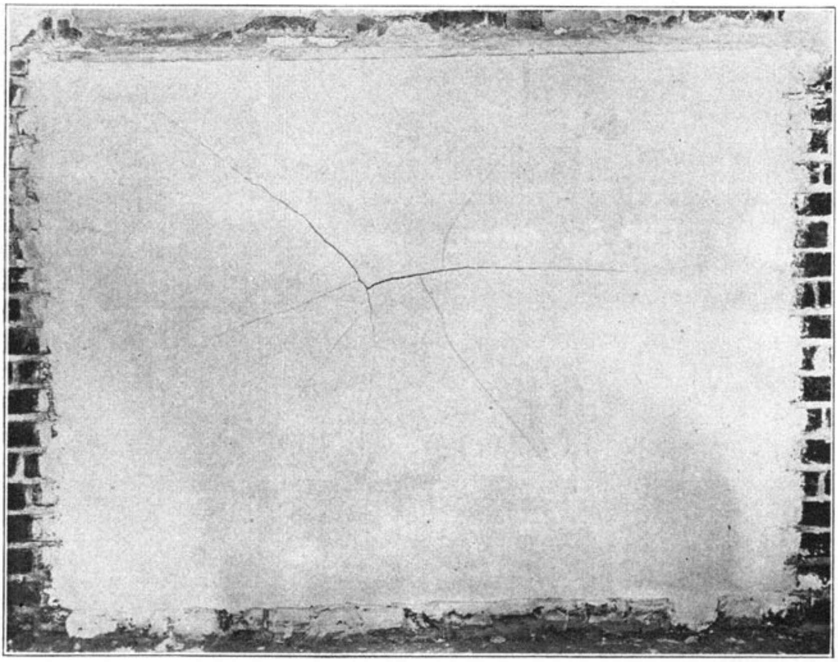

Fig. 19. Cracks Developed in Solid Plaster Board and Plaster Partition

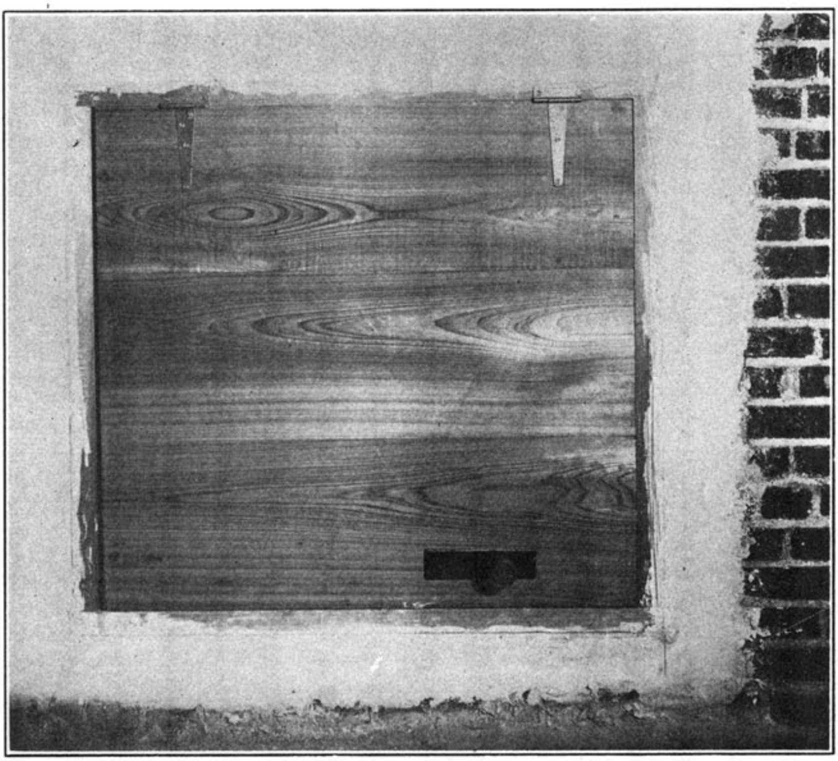

FIG. 21. DOOR INSTALLED IN 2-IN. METAL LATH AND PLASTER PARTITION

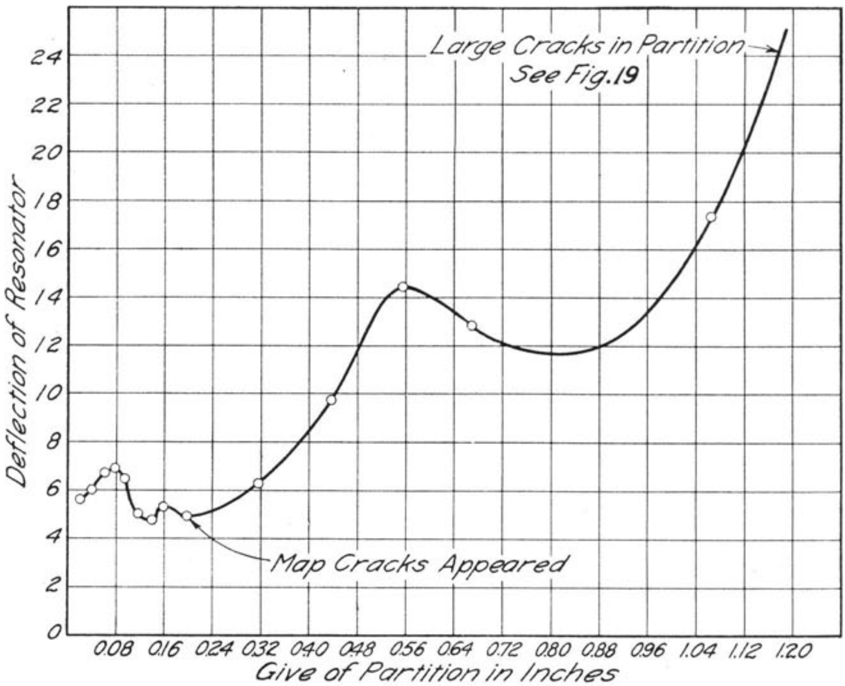

FIG. 20. TRANSMISSION OF SOUND BY PLASTER PARTITION WHEN CRACKS DEVELOP

IX. Transmission of Sound by Solid Plaster Partitions

40. *Introductory Statement.*—The preceding tests showed that the method could be applied to solid plaster partitions as well as to outing flannel and thin partitions, and that the instruments were sensitive enough to measure the fainter sounds transmitted by thick plaster. The way was now open to test thicker plaster partitions. According to the method described comparative measurements on the intensity of transmitted sound were made on the following constructions:

2-in. solid metal lath and plaster partition;
2-in. plaster board and plaster partition;
3-in. plaster block partition plastered on both sides;
3-in. plaster block partition plastered on both sides with the air holes in the plaster block filled with plaster.

The partitions, 49 in. by 64 in. in area, were erected by an expert journeyman plasterer according to the usual practical methods. All materials were purchased by a local contractor in the open market. The same kind of plaster was used on all partitions.

41. *Case for 2-in. Solid Metal Lath and Plaster Partition.*—The partitions were built solidly into the wall nearest the source of sound, the plaster coats being applied successively according to standard specifications. Instead of waiting until the partition was completed, measurements on transmission of sound were taken for each thickness, thus giving some idea of the effect of increasing thicknesses of plaster in stopping sound. Table 7 gives details of results for the metal lath partition and indicates the procedure followed for the other partitions tested for which only the essential records are shown. Each measurement recorded is the average of two measurements in most cases, in others of three.

Fig. 23, Curve 1, shows the deflections of Fig. 22 plotted against the increasing thicknesses of the partition. The transmitted sound decreases rapidly until the thickness of the wall increases to about ¾ in., after which the decrease is slower. The thicknesses for the various layers were measured when the partition was torn down, average values of several broken pieces being taken.

TABLE 7

READINGS OF RAYLEIGH RESONATOR FOR SOUND TRANSMITTED BY A 2-IN. METAL LATH AND PLASTER PARTITION*

Date	Hour	Conditions
June 24	A.M. 8.00	First coat of plaster applied on metal lath
	P.M. 2.00	72.5 cm. deflection of resonator
	4.30	68.0 cm.
June 25	A.M. 8.30	87.7 cm.
	11.30	89.7 cm.
	P.M. 1.00	second coat of plaster applied
	3.00	10.2 cm.
	4.00	9.4 cm.
June 26	A.M. 8.30	14.6 cm.
	11.30	16.2 cm.
	P.M. 1.00	third coat of plaster applied
	2.30	7.3 cm.
	8.30	5.4 cm.
June 27	A.M. 8.30	4.3 cm., drying fans put on
	P.M. 1.00	both finish coats applied
	3.00	3.8 cm., transmitted sound very faint
	8.00	3.6 cm.
June 28	A.M. 8.30	3.0 cm.
	11.30	2.8 cm.
	P.M. 4.30	1.2 cm.
June 29	1.30	3.4 cm., Sunday, quiet
June 30	A.M. 8.30	2.2 cm.
	P.M. 1.00	2.6 cm.
	5.00	2.6 cm.
July 1	A.M. 8.30	3.6 cm.
	P.M. 1.00	3.8 cm.
	7.30	3.7 cm.
July 2	A.M. 8.30	3.4 cm.
	P.M. 5.00	3.6 cm., plaster wet on surface
July 3	A.M. 8.30	3.2 cm., drying fans on
	P.M. 4.30	3.9 cm.
July 4	A.M. 8.30	3.4 cm.
	P.M. 8.00	3.5 cm.
July 5	A.M. 8.30	3.4 cm., partition dry except one spot
	P.M. 5.30	3.6 cm.
July 6	1.30	3.6 cm.

*The data for the metal lath partition are shown graphically in Figure 22, where the deflections of the resnonator due to the transmitted sound are given for successive days as additional coats of plaster were applied.

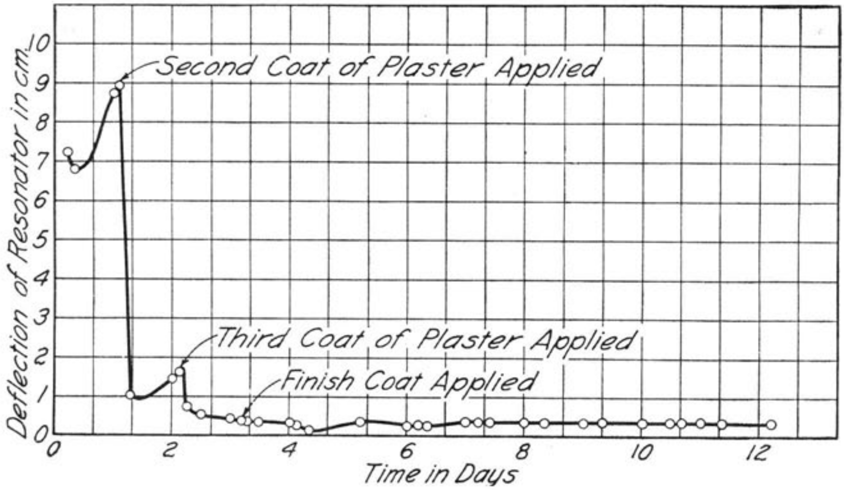

FIG. 22. TRANSMISSION OF SOUND BY PLASTER PARTITION AS SUCCESSIVE COATS OF PLASTER ARE APPLIED

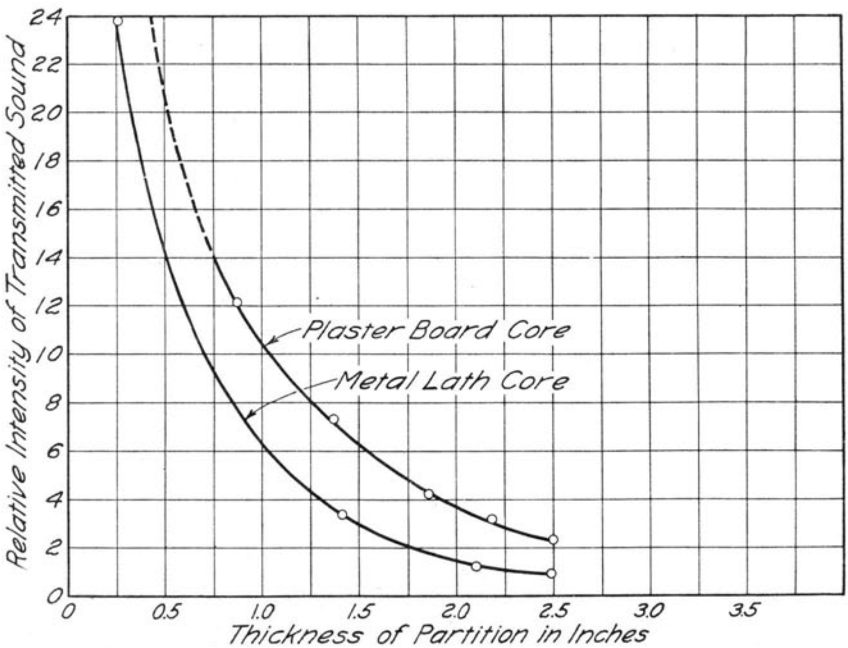

FIG. 23. EFFECT OF INCREASING THICKNESS OF PARTITION ON TRANSMISSION OF SOUND

42. *Comparative Tests of 2-in. Solid Plaster Partitions.*—A similar set of readings was taken for a 2-in. plaster partition with plaster board core. (See Fig. 23). The comparative efficiencies of the finished partitions are given in Table 8, the deflections of the resonator noted being the average of all the measurements taken after the finish coats were applied, and the intensities of the transmitted sound being calculated by using the relation given in paragraph 22.

TABLE 8

TRANSMISSION OF SOUND BY SOLID PLASTER PARTITIONS

	Average Deflection	Relative Transmission
2-in. solid metal-lath and plaster partition	3.35 cm.	0.93
2-in. plaster-board and plaster partition	8.52 cm.	2.35

43. *Comparative Transmission of Sound by 3-in. Plaster Block Partitions.*—The partitions tested are described as follows:

(a) 3-in. plaster block partition plastered on both sides, giving a total thickness of 4 in.

(b) 3-in. plaster block partition plastered on both sides with the air holes in the plaster blocks filled with plaster, giving a total thickness of 4 in.

The measurements were taken in the same manner as for the 2-in. partitions. The plaster blocks for test (b) were filled with plaster and allowed to dry before erection into the partition. The results obtained are as follows:

	Average Deflection	Relative Transmission
Partition (a)	13.9 cm.	3.85
Partition (b)	4.23 cm.	1.16

44. *Effect of a Rigid Plaster Partition on Sound.*—The transmission of sound through a plaster partition appears to depend on its rigidity and mass. Thin partitions transmit considerably more sound than thick ones, largely because they are less rigid, and vibrate more easily. Vibrations are set up which may become quite large when the natural frequency of the partition is in tune with the incident sound. Thick partitions on the other hand are more rigid and vibrate less, so that they stop sound largely in proportion to their mass.

Sound in a room may be transmitted through the partitions with more or less difficulty, depending on the qualities of the structure. Thus, the *inertia* of a partition plays an important part. On striking the heavy partition particles, the air particles of small weight are thrown back in much the same way that a tennis ball would be, on striking a cannon ball. Fig. 24 pictures a conception of this idea.

The partition particles are moved back and forth slightly by the incident pressures and rarefactions, so that sound waves greatly diminished progress through the partition. Since the latter is thin compared with the wave length of the sound, all the particles in it may be thought of as moving simultaneously in the same direction; that is, the partition may be considered to move back and forth as a unit. This motion is carried to the air on the further side where diminished waves, constituting a faint sound, are set up.

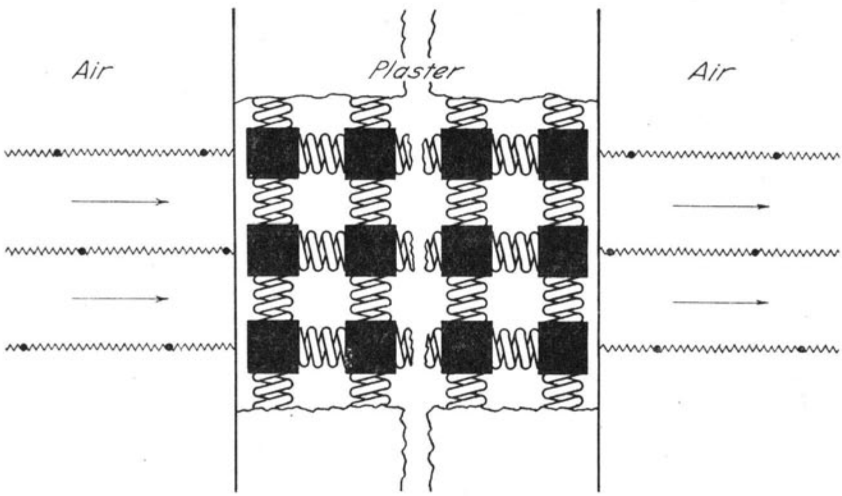

FIG. 24. DIAGRAM ILLUSTRATING TRANSMISSION AND REFLECTION OF SOUND WAVES BY A SOLID PARTITION

Theory shows that the sound in air reflected from a rigid material is given by the expression:*

$$-\frac{\pi \rho_1 l/p \lambda}{\sqrt{1+\pi^2 (\rho_1 l/p \lambda)^2}}$$

where ρ is the density of air, ρ_1 that of the material, λ is the wave length of sound, and l the thickness of the material. Calculations

* Rayleigh, Lord. "Theory of Sound." Vol. 2, Sec. 271, Equation 11.

from this expression show that the sound reflected from a rigid gypsum wall 2.5 in. thick is 99.99968 per cent where the incident sound is taken equal to 100 per cent. The transmitted sound is the difference between these quantities, or 0.00032 per cent, giving approximately a transmission of 3 parts in 1 000 000 assuming that no sound is absorbed in passing through the wall or lost in any other manner. The determining factor in the reflection is the ratio of the density of air compared to that of plaster; that is, the wall behaves like a rigid body and acts mainly because of its inertia. It is quite unlikely, however, that such a partition will be absolutely rigid, particularly if it has some area; therefore, some sound will be transmitted because of vibrations.

45. *Effect of a Flexible Plaster Partition on Sound.*—In case the partition is limited in extent and fastened at the edges, as it must be in any form of partition construction, the sound pressures must overcome not only the inertia of the plaster but also its *rigidity* or resistance to being distorted. A sound pressure applied perpendicularly to the surface causes a small displacement, greatest at the center and zero at the edges, so that the partition becomes slightly bulged, with a small increase in area. The less a wall gives under such a force, the more efficiently will it stop sound. An inspection of Figs. 24 and 25 in this connection give some idea of the strains set up by a

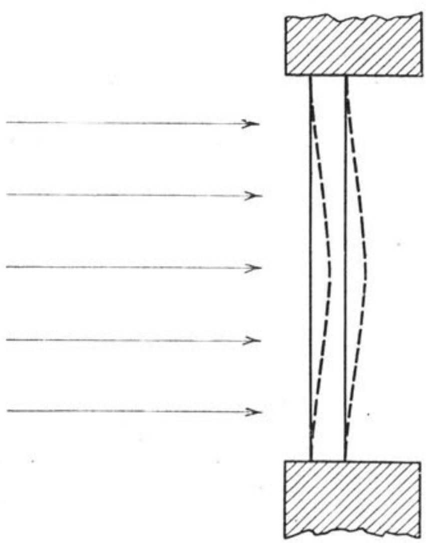

FIG. 25. HOW A PARTITION IS BULGED BY PRESSURE OF SOUND

bulging force. It should be remembered that the pressures due to sound are not static but are rapidly alternating pressures and rarefactions of very small amplitude.

The transmission of sound depends on the vibration of the partition, which acts in this regard like a thick elastic plate. The rapidly alternating pressures and rarefactions of the sound waves set the partition in minute motion and thus create corresponding pressures and rarefactions (sound waves) on the farther side of the partition. The effect is intensified and the transmitted sound increased in volume if the natural period of the partition is in tune with the sound waves. The vibrations for ordinary sounds and partitions are usually small, probably not exceeding 1/100 in. in amplitude. Other factors being the same, they decrease in intensity in walls of greater rigidity.

For a rectangular partition fixed at the edges the period of vibration, N, is deduced from the equation:*

$$N = \frac{\pi h}{2}\left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)\sqrt{\frac{q}{3^3\,(1-\sigma^2)}}$$

where q is Young's modulus of elasiticity, ρ the density of the partition, σ is Poisson's ratio of lateral contraction to longitudinal extension, a, b, and $2h$ the length, breadth, and thickness of the partition, and m and n whole numbers depending on the mode of vibration. This equation shows that thick elastic partitions vibrate quickly, but massive partitions of some dimensions vibrate more slowly.

46. *Effect of the Structure of Plaster Partition.*—Another factor affecting the transmission of sound through a partition is the character of the structure. Compared with a thin partition a thick, homogeneous structure has the advantages of greater inertia and rigidity. The use of an air space completely separating two members of a rigid, non-vibrating double partition would have a marked action on sound, and, according to theory, a partition of this construction would stop many times more sound than a similar single partition whose thickness equals the sum of the thicknesses of the two members of the double partition. This is due to the abrupt change in elasticity and density

* Barton, E. H. "Text Book of Sound." Sec. 226, Equation 11.
Rayleigh, Lord. "Theory of Sound." Vol. 1, Sec. 225.

from plaster to air and from air to plaster as the sound strikes the second member. In case the air space is bridged over, as in practical constructions is usually the case at the ceiling, floor, and other points, this theoretical efficiency is greatly diminished because the vibrations travel easily along the paths afforded by the continuity of solid materials. Thus the bridged over partition should be considered as a unit instead of two separate members, and its efficiency in stopping sound judged mainly on its weight and rigidity.

The core of a partition is another feature of structure that affects the transmission. It may be of such a nature as to increase the strength of the partition, it may be simply the central part of a homogeneous medium, or it may so separate the partition into two parts that the structure is weaker than a homogeneous unit. A partition with increased strength due to the core, such as a steel reënforcement, would be more rigid than an equally thick homogeneous partition and would stop more sound. The homogeneous partition in turn would be more efficient in stopping sound than the double partition weakened by the core. The latter, however, has some possible advantage in reflecting sound because of the change in elasticity and density in the core. An extreme illustration of this kind would be the case where the core consists of hairfelt, so that its action in stopping sound would be analogous to that of an air space. If the core consists of a sheet of thick paper, making, without air space, a continuous contact with plaster on both sides, this efficiency is largely lost and the small gain due to reflected sound would appear to be overcome by the loss in rigidity of the structure.

47. *Discussion of Experimental Results Obtained with Solid Plaster Partitions.*—The experimental results obtained in the tests appear to be in accord with these theoretical considerations. Thin partitions vibrated under the action of sound waves, as could be ascertained by touching the surface of the plaster. The vibrations (and transmitted sound) were more vigorous for the proper coördination of the elasticity of the partition and the frequency of the sound as shown by the data pictured in Fig. 17. Thick partitions transmitted but little sound. They were quite rigid because of their small area and considerable thickness, and also because they were mounted solidly in a double brick wall. Their action in stopping sound must have been due largely to their rigidity and mass.

It should not be concluded from these tests that partitions of similar construction in buildings will all have exactly the same sound-proof qualities; larger area of building partitions, resulting in lessened rigidity, will allow a greater transmission of sound. The value of the results obtained in the tests lies in the fact that they were obtained by direct comparison under identical surroundings, rather than by tests on different types of partitions in different buildings, with varying floor and ceiling constructions, unequal sizes of rooms, uncontrolled extraneous sounds, etc. The results thus give information for guidance in the choice of materials and constructions where sound insulation is contemplated.

X. Examples of Sound-Proof Rooms

48. *Preliminary Statement.*—In order to supplement the information given in the previously described experiments examples of soundproofing should be included in the discussion. These examples are mostly practical constructions in buildings with walls of greater size than could be tested conveniently in laboratory experiments, and with additional complexities such as a ventilation system, pipes for steam, water, and wires, etc. An account of such constructions, together with the results of the previous tests, allows more definite conclusions to be drawn concerning the general procedure in sound insulation.

The illustrations chosen for discussion concern two types of installations; first, single rooms that are soundproofed for experimental purposes, and second, entire buildings where sound insulation was needed. A detailed description of all the examples available would involve too long an account; therefore, several typical cases are selected for discussion and references are given for the others.

49. *Sound-Proof Rooms for Acoustic Experiments.*—A small laboratory building containing a number of rooms for acoustical experiments was designed by W. C. Sabine according to his extensive experience in architectural acoustics.* The essential construction was simple yet effective. Heavy brick walls served to give sufficient rigidity to reduce vibrations to a minimum. The weight of these walls together with an air space between them presented a decided hindrance to the transmission of sound waves. (See Fig. 26.)

* Sabine, P. E. "Wallace Clement Sabine Laboratory of Acoustics." Am. Arch., Vol. 116, pp. 133-138, 1919.

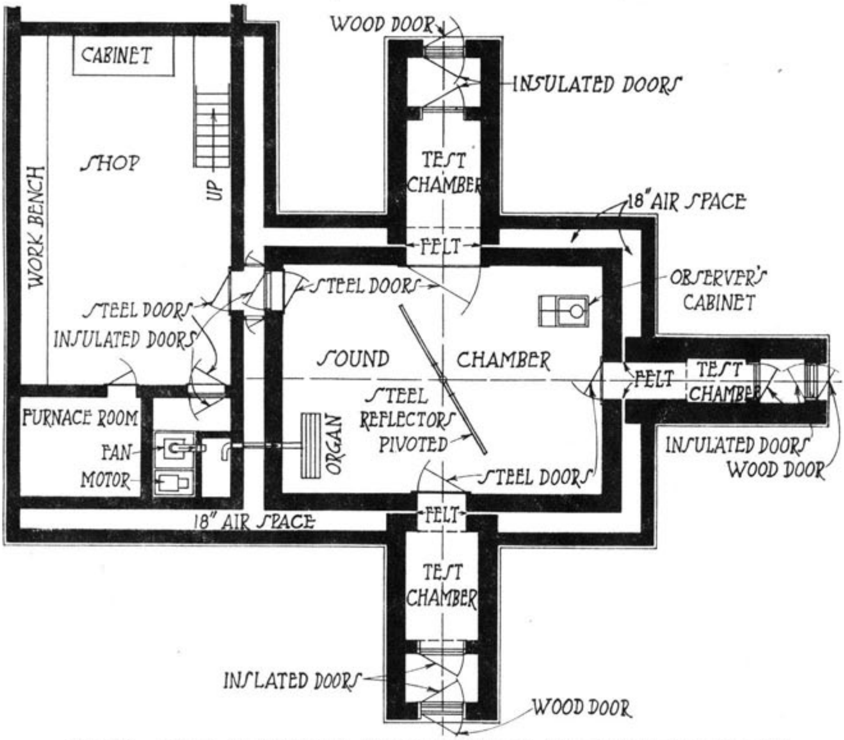

FIG. 26. PLAN OF WALLACE CLEMENT SABINE ACOUSTICAL LABORATORY

(This laboratory was built and is maintained by Colonel George Fabyan at Geneva, Illinois, because of his interest in scientific work and his personal regard for Professor Sabine. Since the death of the latter the investigational work has been conducted by Dr. Paul E. Sabine, a cousin of Professor Sabine.)

50. *Sound-Proof Constant-Temperature Room.*—The structure illustrated in Fig. 27 is a small building constructed primarily for securing constant temperature. It appears also to be an excellent sound-proof structure. The description* is as follows:

* "Results of Observations made at the Coast and Geodetic Survey Magnetic Observatory at Cheltenham, Maryland, 1901-1904." Dept. of Commerce and Labor, U. S. C. and G. S., pp. 11-13, 1909.

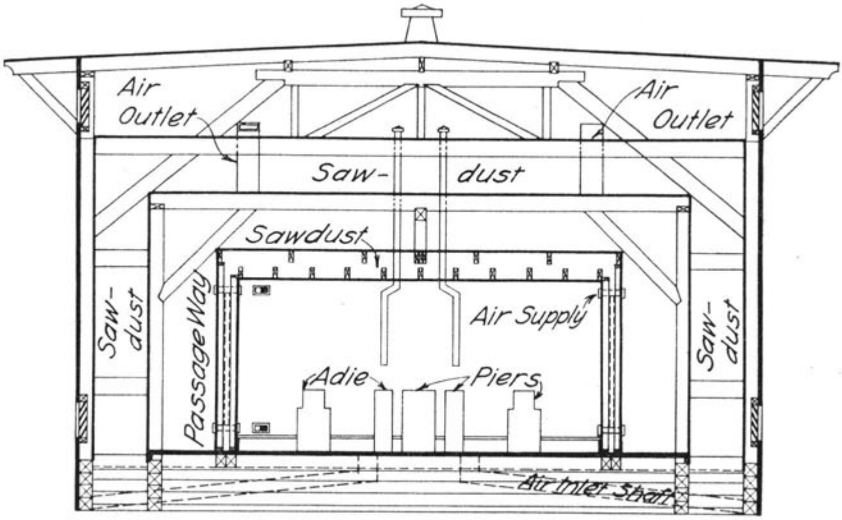

FIG. 27. VERTICAL CROSS-SECTION OF SOUND-PROOF CONSTANT-TEMPERATURE ROOM

"The variation observatory is essentially two small buildings inclosed by a third larger one. The outside dimensions of the variation observatory are 36 by 56 by 24 ft., with a vestibule 10 by 13 ft. The inner rooms are each 16 by 19½ ft. inside measure, separated from each other by a passageway 5½ ft. wide. The wall insulation is as follows (see Fig. 27); beginning at the outside, pine weather-boarding, 8-ply building paper, 1-in. pine sheathing, 8-in. air space, 1-in. pine sheathing, 8-ply paper, 3 ft. pine sawdust, 8-ply paper, ⅞-in. pine sheathing, 3 1/16 ft. air space (passageway around inner rooms), ⅞-in. pine sheathing, 8-ply paper, 1 ft. pine sawdust, 8-ply paper, ⅞-in. pine sheathing. Beginning at the roof and going down: gravel and asphalt-pitch roof, 1-in. pine sheathing, 3 2/3 ft. air space, 1-in. rough pine floor, 3 ft. pine sawdust, 8-ply paper, ⅞-in. pine sheathing, 3 ft. air space above inner rooms, 1-in. rough pine floor, 1½ ft. pine sawdust, 9-ply paper, ⅞-in. ceiling. Insulation from bottom of foundation is 2 2/3 ft. earth, 6 to 8 in. layer of gravel, 3 ft. sawdust, 1-in. pine floor, ⅞-in. matched pine floor. The 8-in. air space next to the outside of the building is provided with slat ventilators at top and bottom, which when open permit a free circulation of air up the sides of the building and out through the ventilators in the roof. By the use of tight-fitting shutters it can be converted into a practically air-tight space. By this arrangement of alternating air spaces and sawdust packing the variation in the temperature is kept within the desired limits without the aid of heating apparatus. The daily range is kept down to almost nothing and the annual range to only a few degrees Centigrade."

Mr. W. W. Merrymon, one of the magnetic observers, stated that the room was so sound-proof that he thought he would be unable to make outsiders hear in case he were in distress—from lightning or other causes. Trial by loud shouting within the room gave almost no sound outside, and this faint sound appeared due to the passage of sound through the air ducts in the floor. By closing these the room would doubtless have been made "sound-proof."

51. *Sound-Proof Room for Psychology Tests.*—Concerning this room, Dean C. E. Seashore of the State University of Iowa writes: "Our experience in building the sound-proof room in psychology would not be of any great help in the soundproofing of a music building, since all the precautions that we have taken are such as could be taken for a small cage room." The description* of the room is as follows:

"The construction of the observing room deserves especial mention. To make a dark room impervious to external light is a matter presenting no serious difficulty. To make a room impervious to external sound or wholly free from the jarring from surrounding rooms or adjacent streets is a problem which has not yet been solved and of course never will be. We made the attempt to approach a little nearer to this end than has hitherto been done. The result is a room as free from external disturbances as is needed in any experiments in which it is necessary to control visual, auditory and tactual stimuli. So far as this has been accomplished, the credit is largely due to the architects, Messrs. Proudfoot and Bird, who worked out many of the details of construction. The position of the observing room is central, occupying a place not otherwise desirable from lack of light. The room rests on an independent foundation, having no solid connection with the rest of the building either below, above, or on the sides. The superstructure which supports the room rests upon a sand bed and a second sand bed at a higher level still further assists in eliminating possible jarring or sound which might be communicated from the ground. The walls of the room itself, inside the main partitions, which separate the whole space from the surrounding apartments, are made of two four-inch walls of hollow tiles separated by an air space and each covered with a thick insulating material made of sea-weed. Inside of all, the walls are plastered and then lined throughout with black broadcloth. The inside room is divided into the main observing room 12 ft. 2 in. by 12 ft. 7 in., and a vestibule, 4 ft. by 12 ft. 7 in. The room is entered through five doors, the outer one being an ordinary oak door and the other four especially constructed tight fitting cedar doors, covered with black cloth on the sides and edges. The doors close with strong springs and are held open by automatic catches. The floor is made of Tennessee red cedar and covered with linoleum painted black. The room is heated and ventilated by means of hot air introduced not directly

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* Studies in Psychology, Vol. III, pp. 132-143; State Univ. of Ia., Bul., New Series, No. 49, May, 1902.

but from the attic through cedar shafts provided with overlapping cloth partitions which admit the air but help to exclude sound. For very fine experiments the ventilating shaft may be closed and the room ventilated during intermissions. The room may be lighted by gas or electricity, the former being introduced through rubber tubes. The furnishing consists of black tables and chairs and a telephone connected with the measuring room. In the exclusion of sound and vibration, as well as in other respects, the room has proved to be a complete success. The loudest stentorian shouting just outside the doors is absolutely unheard within.''

52. *A Noiseless Room.*—A noiseless room for sound experiments was built in Utrecht, Holland.* Figs. 28 and 29 show the complicated details. The room was about 7 ft. by 7 ft. by 7 ft., and the walls were 11 in. thick. A person in this room could hear his heart beat.

53. *A Group of Sound-Proof Rooms.*—Norton† tested five small rooms whose walls were specially constructed of different materials. The tests were not strictly comparative because three of the rooms had one thin side that vibrated under resonance and transmitted sound to adjacent sides; also there was some leakage of sound through the doors and ceiling. Observations were taken by the ear, and different partitions rated by estimation. The results show that increasing the thickness of the walls promoted sound insulation; also, that double partitions with air space and enclosed sound absorbing materials are more effective than single partitions.

54. *Room Soundproofed for Machine Gun.*—During the war a room about 12 by 14 by 12 ft. was designed to insulate the explosive sounds of machine guns when these were being tested. The room occupied one corner of a larger room. The walls of the insulating room were brick on two sides—those of the larger room—and wood on the other two sides. Four inches of ground cork lined the wood walls, being held in place by metal netting nailed to 2 in. by 4 in. wood studding. A double layer of flax boards lined the ceiling. A pile of sand into which the bullets were fired assisted in the absorption of sound. People across the street from the room were unaware of the machine gun operation until the observer forgot to close the double windows after opening them to let the powder smoke out.

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* Franz, S. I. "A Noiseless Room for Sound Experiments." Sc., Vol. 26, pp. 878-881, 1907.

† Norton, C. L. "Sound-Proof Partitions." Insur. Eng., Vol. 4, p. 181, 1902.

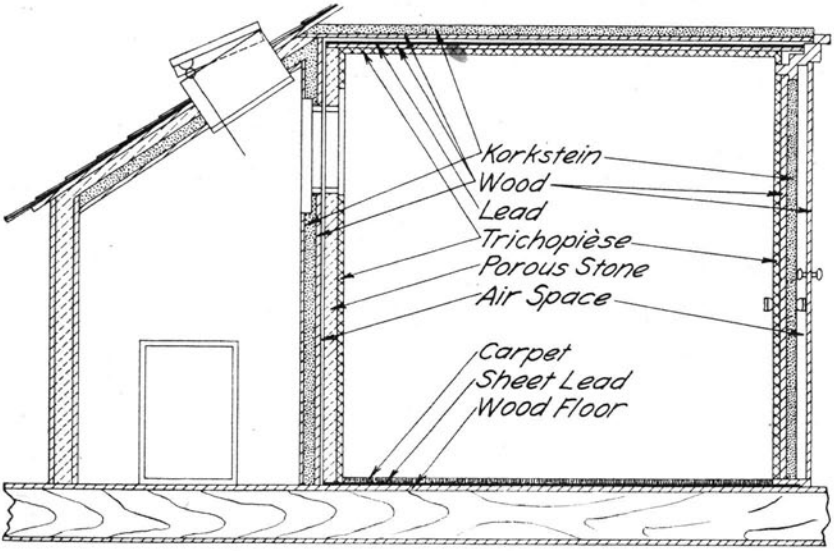

FIG. 28. VERTICAL CROSS-SECTION OF NOISELESS ROOM

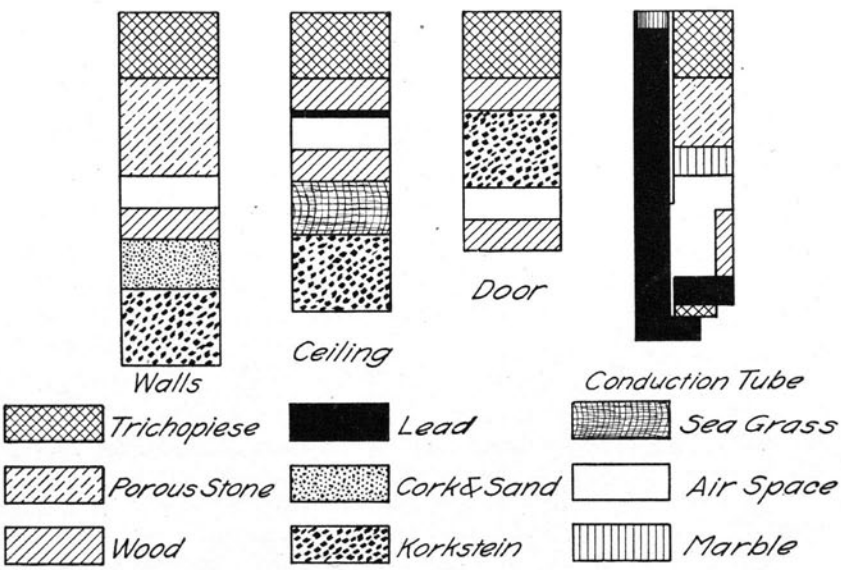

FIG. 29. DETAILS OF CONSTRUCTION OF NOISELESS ROOM

FIG. 30. SOUND-PROOF BOX TO REDUCE NOISE OF BRICK RATTLER

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55. *Soundproofing a Noisy Machine.*—A brick rattling machine, used by the Highway Engineering Department at the University of Illinois, was extremely noisy, so that suggestions for a method of minimizing the disturbance were requested. The machine was mounted on a platform and enclosed first in a sheet iron covering which served to prevent the escape of dust as well as sound. (See Fig. 30.) A larger, double walled wooden box, having the interspace filled with saw-dust, and being equipped with a hinged cover, was built to give further insulation. Without the covers, the machine is so noisy that one person cannot be heard by another without shouting loudly into his ear. With the covers on, the noise is greatly reduced and conversation is possible. This matter has its economic side, because, with noisy machines, the hearing and therefore the efficiency of employees becomes affected.

XI. Sound-Proof Buildings

56. *The Smith Music Building.*—An increasing number of buildings with soundproofing features have been constructed in the past few years. F. R. Watson, in collaboration with Architect James M. White, incorporated a number of soundproofing constructions in the Smith Memorial Music Building at the University of Illinois.* This problem was more complex than soundproofing a single room. It involved the sound insulation of some fifty small practice rooms, twelve studios, and the larger concert hall, besides the acoustic control of sounds of motors, fans, and elevators.

Since the possibility of transmission of sound was greatest between adjacent rooms, each dividing wall, ceiling, or floor was made double, with air space containing absorbing material, and was left entirely unbroken. All pipes, conduits, ventilator ducts, doors, and windows were specially placed in outside or corridor walls where the leakage of sound would be less harmful. This systematic construction *throughout* the building meant that a sound generated in a room must penetrate the insulation to escape. To enter another room, it must pass a second time through a special insulation. When traversing the building structure, a sound would continually meet hindrances that would either stop or absorb it.

Fig. 31 pictures some of the features that were adopted to control sound. The concrete floor, 12 in. thick, was broken in its continuity by the form planks that were purposely left in place. Walls between rooms were constructed of two 3-in. gypsum partitions insulated at the bottom by machinery cork and at the top and sides by hairfelt. "Insulite" was installed in the air space between the gypsum partitions, to absorb sound and also to present a barrier in case cracks developed in the gypsum. The finish floors were floated on a 1-in. layer of dry sand in order to break the continuity of material and thus stop the progress of vibrations.

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* Watson, F. R. "Sound-Proofing a Building." Arch. For., Vol. 35, pp. 178-182, Nov., 1921.

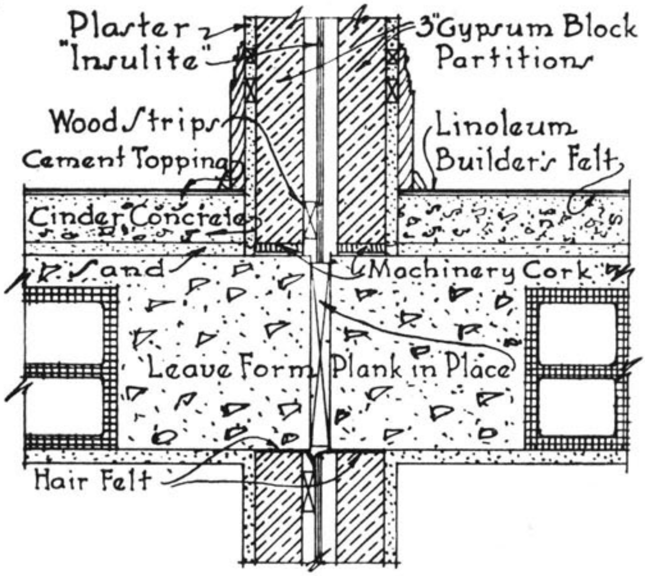

FIG. 31. DETAIL OF FLOOR AND PARTITION CONSTRUCTION IN SOUND-PROOF BUILDING

Experiments conducted in the building after its completion show that a measure of success attended the design and construction. Loud speaking and shouting in the practice rooms can hardly be heard outside. Music, however, penetrates the insulation more easily, so that sound, largely diminished, may be heard in adjacent rooms. This leakage of sound, however, does not appear of great disadvantage. Students use adjacent rooms for singing practice, and for piano, violin, and other instrumental drill, without serious disturbance to each other.

The ventilation system is not as sound-proof as desired, and appears to be the greatest drawback in the control of sound. Each room was equipped with a separate inlet and outlet duct. Four independent ventilating systems furnished air to four groups of rooms in order to lessen the chance for transfer of sound from one group to others. The ventilation system is now under investigation with a view to improving the insulation.

The building is not absolutely sound-proof nor does this appear necessary for practical purposes. The sounds that leak through the insulation are greatly diminished in intensity and therefore of minor importance compared with the sounds generated in the room containing the observer.

57. *Other Buildings with Soundproofing.*—Music buildings with soundproofing features have been erected at other institutions, and, from the reports received, appear to give satisfaction. The constructions involve double walls with absorbing material, and more or less attention has been given to the design of the ventilation.

XII. Conclusions

58. *Summary of Conclusions and Recommendations.*—The information in this bulletin was drawn from three sources; the theory of the behavior of sound waves, experimental investigations of the effect of materials on sound, and examples of sound-proof installations. The details of this information, while drawn from different sources and apparently unrelated, coördinate in a satisfactory way in setting forth similar conclusions.

Some of the more general principles and recommendations are stated in the following paragraphs, but the details and comments necessary for a more comprehensive conception of the problem of soundproofing are to be found in the descriptions throughout the bulletin.

Sound may be transmitted from one side of a partition to the other in three ways; it may progress through continuous air passages, it may pass as an elastic wave through the solid structure of the partition, or, by setting the partition in vibration, it may originate sound waves on the further side.

These actions are quite readily understood by remembering that sound consists of a series of compressions and rarefactions that progress rapidly through a medium without interruption unless they meet a new medium with a different elasticity or density. For instance, sound waves in air proceed without hindrance through air passages, such as ventilation openings in a partition. If, however, the passages are small in cross-section, as in the case of a porous material, the progress is hindered and a certain amount of absorption of the energy takes place, due to the friction set up between the vibrating air column and the sides of the pores.

In case the partition is impervious to air, the direct progress of the waves is interrupted. A thin partition is set in vibration and thus orginates new waves on the side opposite the incident sound. For a thicker, more rigid partition, the vibrations are smaller and a very considerable part of the energy is reflected. The transmission in this case takes place by compressional waves communicated to the solid material of the partition. The amount of energy thus transmitted is usually quite small.

In view of these considerations a sound-proof partition should be as rigid and free from air passages as possible. For effective soundproofing of a group of rooms, the partitions, floors, and ceilings between adjacent rooms should be made continuous and rigid. Any necessary openings for pipes, ventilators, doors, and windows should be placed in outside or corridor walls where a leakage of sound will be less objectionable.

In case the sound is generated in the building structure, as the vibrations set up by a motor fastened to the floor, the compressional waves proceed through the continuity of solid materials. In order to stop them, it is necessary to make a break in the structure so as to interpose a new medium differing in elasticity and density. For instance, the vibrations of a motor may be minimized by placing a layer of hairfelt, or similar air-filled material, between the supporting base and the floor. Where the machine is quite heavy, footings may be made of alternate layers of asbestos, lead, and leather. Bolting through this material will reduce the insulation, because the vibrations in this case will pass easily through the bolts to the floor. The insulation should thus be left without any bridging over of the discontinuities. Air gaps in masonry will be effective if the air space is not bridged over at any point. A floor floated on sand, sawdust, or hairfelt would approximate this condition. The edges of the floor should be insulated from the walls by felt or similar material.

Especial attention should be paid to the ventilation system. All effective sound-proof constructions either omit entirely a ventilation system or else construct it in some special manner to avoid transmission of sound. In some buildings air is supplied and withdrawn from rooms by individual pipes that are small in diameter and extend without break from the air supply chamber to the rooms. This results in considerable friction between the walls of the pipes and the air, with a resultant weakening of the sound waves. Without some efficient control of the transference of sound through the ventilation system it is a waste of effort to construct sound-proof walls, double doors, and other contrivances for insulation.

When soundproofing a building all details should be considered with respect to the likelihood of transmission of sound. Each room, as far as possible, should be made an insulated unit by means of air spaces or air-filled materials that separate it from surrounding walls. Pipes and ventilators should be so installed as to minimize the chance of transfer of sound. Patent doors are now available that will close the door space at top, sides, and bottom. In case a troublesome sound is generated in the room, it may be minimized by installing absorbing material on the walls.

The absorption of sound is an essential feature for soundproofing. Reflecting sound and scattering it still leaves it with energy. It must be absorbed; that is, converted into heat energy by friction, before it is eliminated as sound. This means that carpets, furniture, draperies, etc. should be present, or if greater absorption is desired, hairfelt or similar materials must be installed.

The insulation of sound is a complex problem and a successful solution is obtained only when all the possibilities of transfer of sound are anticipated and guarded against. While many things may be learned from further experience and much may be gained from additional theory, enough has been revealed to give encouragement to the belief that soundproofing may be prescribed in the future with some of the certainty that now attends the acoustic design of auditoriums.

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