A DIRECT METHOD OF FINDING THE VALUE OF MATERIALS AS SOUND ABSORBERS.

BY HAWLEY O. TAYLOR.

THE sound-absorbing quality of materials has been recognized for some time as having an important bearing upon architectural acoustics. In 1873, T. Roger Smith, M.R.I.B.A., a leading British architect, wrote:[1]

"Where there is too much resonance in a room, carpets or curtains may be advantageously employed to lessen it; in fact, to absorb the injurious excess of sound, and where there is an echo, a curtain judiciously hung will have the effect of deadening or stopping the sound before reaching the echoing surface. This expedient is well known, and often successfully employed; but carpets, as a remedy for excessive resonance, have perhaps not been so frequently made use of."

Since 1895, extensive investigations have been carried on at Harvard University by Professor Wallace C. Sabine[2] to determine some quantitative relations between the size, reverberation and sound-absorbing power of a room, and he placed his results in the well-known form:

$$a = \frac{.171\,V}{t},$$

where a is the absorbing power of a room of volume V, and t is the time of decay of the residual sound of an organ pipe whose intensity in terms of "minimum audibility" had been previously determined. As determined by Sabine, a room is most satisfactory for speaking purposes when t has a value of about 1.5 seconds, thus the proper amount of absorbing power, a, is limited. (The above equation does not apply to echoes and defects due to the shape of a room.) Since the sound-absorbing power of an auditorium is thus limited to a narrow range of values, the consideration of absorption is of great importance in auditorium design and construction.

The amount of absorption is equal to the sum of the absorbing powers of the different materials composing the bounding surfaces and the

[1] T. Roger Smith, "Acoustics of Public Buildings," p. 39.

[2] Prof. W. C. Sabine, Am. Arch., Vol. LXVIII., April 7, 21, May 5, 12, 26, June 9, 16, 1900.

furniture of the room; the absorbing power of the material is equal to the product of its area and the amount of sound absorbed by unit area. Sabine rated the amount of sound absorbed by unit area of open window as 1, then the amount absorbed by a material which reflects a part of it is always less than 1. This fraction is the coefficient of absorption of sound for a given material.

Besides the power of materials to absorb sound reflected from their surfaces, it is desirable also to know the power of materials to absorb sound transmitted through them. The application of this to architecture extends beyond the acoustics of a single room and has to do with the isolation of one room from sounds produced in another. The interior finish of rooms is of no consequence here, but the filling in the partitions and in the space under the floors is the important thing. The fraction of sound absorbed by unit thickness of a given material may be called the coefficient of absorption of the material for transmitted sound, or the insulation coefficient of the material for sound.

To find the coefficient of absorption of a material for sound reflected from it the method usually employed is to bring a known amount of the material in question into a room and make observations for the time of decay of the residual sound, applying the formula above stated. This may be called the reverberation method. The purpose of this investigation is to devise a direct method of finding the coefficient of absorption of materials for sound. Such a method is formulated and following is the theoretical basis:

When a train of progressive waves, P (Fig. 1), of amplitude, p, moves in the positive direction, say, then all points of the medium in the path of the waves move through a distance $2p$, as shown by the shaded portion of Fig. 1.

If the progressive waves strike an object, S (Fig. 2), and a portion of

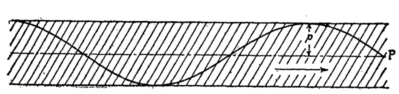

Fig. 1.

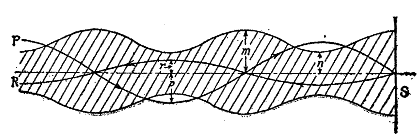

Fig. 2.

each is reflected, these reflected waves, R, of amplitude, r, will travel in the negative direction, and the two trains of waves will meet and combine. Some points of the medium will then move through a greater and others through a less distance than before, as shown by the shading in Fig. 2. The maximum amplitude (where crest meets crest and trough meets trough) will be $p + r$, and the minimum amplitude (where the crests of P meet the troughs of R, and vice versa) will be $p - r$.

A special case of this phenomenon is when the progressive and reflected waves have the same amplitude, p. The resultant maximum amplitude is then $2p$, and the minimum amplitude is zero. This is the ordinary stationary or standing wave. In order to have no motion at the nodes the two waves must be equal in amplitude, which is only the case when there is no absorption at the reflecting surface.

The distance through which the medium moves varies from point to point, as represented by the amplitude of the envelope in Fig. 2. In the case of sound waves, this movement is the longitudinal vibration of the air particles, the intensity of the sound being greatest where the amplitude of vibration is greatest. The coefficient of absorption of sound is a function of sound intensity and therefore of the squares of the amplitudes of the progressive and reflected waves and of the resultant stationary wave (the envelope, Fig. 2). The intensity of sound in the progressive wave is $(kp)^2$, and the intensity of sound in the reflected wave is $(kr)^2$ (where k is a proportionality constant). This gives a coefficient of reflection,

$$\rho = \frac{r^2}{p^2}.$$

If the maximum intensity of sound (corresponding to the maximum amplitude of the envelope, Fig. 2) is called m, and the minimum intensity (corresponding to the minimum amplitude of the same envelope) is called n, then

$$m = (p + r)^2,$$

$$n = (p - r)^2,$$

from which

$$p = \frac{m^{\frac{1}{2}} + n^{\frac{1}{2}}}{2},$$

$$r = \frac{m^{\frac{1}{2}} - n^{\frac{1}{2}}}{2}.$$

Substituting these expressions for p and r in that for the coefficient of reflection of sound, we have

$$\rho = \frac{(m^{\frac{1}{2}} - n^{\frac{1}{2}})^2}{(m^{\frac{1}{2}} + n^{\frac{1}{2}})^2}.$$

The coefficient of absorption of sound, α, is the fraction of sound not reflected, or

$$\alpha = 1 - \rho = 1 - \frac{(m^{\frac{1}{2}} - n^{\frac{1}{2}})^2}{(m^{\frac{1}{2}} + n^{\frac{1}{2}})^2} = \frac{4}{m^{\frac{1}{2}}/n^{\frac{1}{2}} + n^{\frac{1}{2}}/m^{\frac{1}{2}} + 2}.$$

To find the coefficient of absorption, α, of a material, means must be provided (I.) for isolating a train of sound waves having a single period or pitch and a constant amplitude, (II.) for causing this train of waves to be reflected upon the surface whose absorption is desired, and (III.) for measuring the maximum and minimum intensities, m and n, of the resultant stationary wave.

Method of Procedure.

I. A tone of uniform intensity was produced by supplying an organ pipe with air from a pneumatic tank. This tank consisted of two sheet-metal cylinders closed at one end, the smaller of which was about 9 inches in diameter and 18 inches high and was placed, open end downward, into the larger which was half full of water. Air was drawn off by means of a faucet on top of the smaller tank and conducted to the organ pipe through ¼-inch tubing. The pressure of the air was regulated by adjusting a stop against which a rod soldered to the valve of the faucet would strike when the faucet was open the desired amount. The inner tank was weighed down by about 25 pounds of iron, thus making the pressure uniform for almost the entire air capacity.

To obtain a simple tone sound was passed through what might be called a tone screen which absorbed all the overtones leaving nothing but the fundamental. This tone screen is based upon Quincke's modification of Herschel's interference tubes described by Rayleigh.[1]

If CD, Fig. 3, is tuned to the pitch of sound waves traveling from A

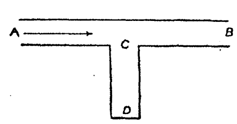

Fig. 3.

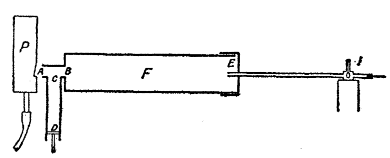

Fig. 4.

to B, and the opening at C is as large as the section of the tube AB, no sound will reach B—it is completely absorbed by the tube CD.

The truth of this was tested by taking a wooden flue, F (Fig. 4), of square cross-section 9 centimeters on a side and 115 centimeters long, placing a cap over end, E, through which projected a ½-inch glass tube from a sound-measuring instrument, I, and placing the interference tube or tone screen at end B. The tube AB was an inch hole bored in a block of wood 6 inches thick, and tube CD was a one-inch glass tube, the end D being a cork piston which allowed tuning of the tube. When the tube CD was removed, sound from the stopped organ pipe, P, passed through tube AB into the flue, F, and the measuring instrument indicated

[1] Lord Rayleigh, Theory of Sound, Vol. II., p. 210.

a large deflection. When the tube *CD* was in place and tuned to the organ pipe, the deflection of the measuring instrument was zero. (The tube *CD* was tuned to the fundamental of the organ pipe and hence also to its retinue of overtones, thus all of the sound of the organ pipe was absorbed.) When the tube was placed slightly out of tune with the organ pipe, a small deflection was obtained, and the deflection became larger as the dissonance was increased.

To isolate the fundamental tone of the organ pipe in the flue, *F*, four tubes similar to *CD*, tuned one to each of the first four overtones of the organ pipe, were placed around the passage *AB*. Since any overtones above the fourth for the organ pipe used were very weak if present at all, this constituted a very efficient tone screen. The tone in the flue was found to be simple by finding the sound intensity for each centimeter throughout the length of the flue and plotting a curve of intensity against distance. The curve was that of a simple tone.

A tone of uniform intensity having been obtained from an organ pipe, and its fundamental isolated in the flue, *F*, we must now ascertain whether or not the amplitude of the wave in the flue is constant throughout the length of the flue, as it is in Figs. 1 and 2. To this end, the first requisite is a flue of uniform cross-section to prevent the wave-front from spreading out and thus diminishing in amplitude. But if the flue lining absorbs the wave, the effect will be the same as a widening flue—the wave-front will spread out and both the progressive and reflected waves will diminish in amplitude as they advance.

Any detrimental presence of this lining absorption may be found by observing the maximum intensities all along the flue; they should be practically equal, otherwise the lining of the flue is absorbing sound.

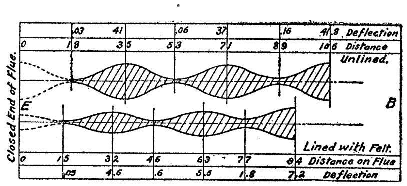

Fig. 5.

Following are some readings made with a wooden flue and with the flue lined with felt (Fig. 5).

Lining absorption occurs in both cases, but a marked diminution from *B* toward *E* is seen in the case of the felt. A smooth, painted wood lining shows practically uniform maxima.

In connection with flue lining, the table of observations indicates that the wave-length shortens as the lining absorption increases. This means a decrease in the velocity of sound with increase of absorption. That the velocity of sound in pipes is not a function of the properties of the gaseous medium only but also of the absorption of the lining of the pipe may be simply shown by placing a strip of carpet along one side of a middle *C* organ pipe and sounding the pipe. Upon sounding without the carpet the pitch is seen to rise nearly a semitone.

To bring out more clearly that sound absorption plays a part in changing the velocity of sound in a pipe, and that the phenomenon is not due entirely to the elastic properties of the walls of the pipe, the following experiments were made:

One side of an organ pipe was replaced by a removable trough, *AB* (Fig. 6), stopped at the ends and about an inch deep. The pipe was sounded with this trough in place and the tone identified by means of a cylindrical resonator held to the ear. Between the trough and pipe were placed successively a smooth sheet of cardboard and a heavy fibrous sheet like blotting paper, and the resulting pitches of the pipe were identified; then the trough was filled with hair felt covered successively with the materials above mentioned, and the resulting pitches of the pipe identified; the trough was then filled with a block of wood and the pitch of the pipe identified. The result is given in the following table (Fig. 7). (The order designated by the crosses from the top downward gives the order that the materials were used with the pipe from the inside outward.)

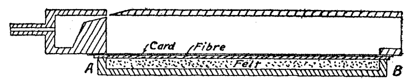

Fig. 6.

	No Response	Re_3^b		Re_3		Mi_3^b	Mi_3					Fa_3	
Card				X					X	X			
Fibre			X		X		X	X	X	X	X		
Card						X	X	X				X	
Felt	X				X	X		X		X			
Wood											X	X	X

Fig. 7.

When the felt, which is high in sound-absorbing quality and low in elasticity, is used alone, no tone could be produced. The absorbing power of the wall of the pipe decreases as we progress toward the right in the table, but it is seen that the elasticity of the surface exposed to the sound waves, and that of the under layers, has no regular change as we pass through this series. Take the tone mi_3, for instance: the elasticity of the wall consisting of fiber on wood is not the same as that of fiber on card over empty trough, and that of the latter is not the same as that of fiber on card on felt. For all of these combinations, however, the tone (and hence the velocity of sound) is the same.

An obvious relation between the elasticity and the sound-absorbing quality of a material is that, in general, as the former increases the latter decreases, but these phenomena lead to the conclusion that, while elasticity in the walls of a pipe may have some influence, direct or indirect, upon the velocity of sound in the air column, the velocity certainly decreases with increase of the sound-absorbing power of the walls of the pipe.

The influence on the velocity of sound in pipes due to a change in radius, elasticity and strength of wall, as well as the effect of compressibility and the temperature of the vibrating gas column, has been observed by Helmholtz, Kundt, Stokes, Schneebeli, Seebeck, Kirchhoff, Rayleigh, Korteweg, Dörsing, and others.[1] Korteweg's formula[2] for the velocity of sound in pipes,

$$c = c'\sqrt{1 + \frac{2}{CE} \cdot \frac{1}{e(1 - \frac{5}{6}e)}},$$

where c and c' are the velocities in free air and in a pipe, respectively, C is the compressibility of the fluid, E is the modulus of elasticity of the material of the walls of the pipe, and e is d/r, where d is the strength of the wall and r the radius of the pipe, gives a relation for the velocity of sound in the pipe to the radius.

This relation is shown by the following curve (Fig. 8), taking C equal to 10×10^{-7}, E equal to 10×10^{10} and d equal to 2.5.

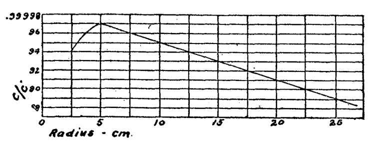

Fig. 8.

Except for tubes of very small diameter, this formula gives a decrease in velocity for an increase of radius. An increase in the radius of an organ pipe causes a lowering in the pitch of the pipe; also, from the experiment given above, an increase in the sound-absorbing power of the walls of a pipe causes a lowering of the pitch of the pipe, therefore, increasing the absorbing power of the pipe acts in the same way as increasing the radius of the pipe.

T. Boehm, in his book, "The Flute and Flute Playing" (translated by D. C. Miller), speaks[3] of the "flattening influence of the cork, mouth hole and tone holes." This flattening is undoubtedly an effect of the sound-absorbing power of the holes, or of that which covers them in playing.

II. If the flue, F (Fig. 4), were infinitely long, there would then be present in it a train of progressive sine waves, as shown in Fig. 1. Everywhere in the flue the sound would have the same intensity; there would be no reflected wave and, in the formula, m and n would be equal and α would be unity. Thus all sound is absorbed by an infinitely long flue.

If a surface (S, Fig. 2) be placed at the end, E, of the flue, F (Fig. 4), which reflects part of the sound, then the intensity throughout the flue

[1] Auerbach, Handbuch der Physik, Akustik, 1909, A. Winkelmann, pp. 539, 554; Theory of Sound, Rayleigh, Vol. II., pp. 29, 59, 317, 326.

[2] Auerbach, Handbuch der Physik, Winkelmann, p. 539.

[3] T. Boehm, "The Flute and Flute Playing," p. 18.

would no longer be uniform but would consist of maximum and minimum regions, as shown in Fig. 2. If the intensities, m and n, can be measured, then the coefficient of absorption, α, may be computed by means of the formula.

In using the flue in this way, the end where the absorbing material is placed must be closed air-tight with a cap in order not to have any "open end pipe" effect on the wave in the flue. If absorbing material has the inherent property of affecting sound waves as if the end of the flue were partially open (thus sending back waves with phase shifted one half wave-length), this interference would constitute absorption to the extent that it existed, and the material would behave to sound in this way wherever it was—whether it was stopping the end of a flue or decorating the wall of a room.

Any other "open end pipe" effect of the flue must be stopped. If the flue is a metallic cylinder, 4 or 5 inches in diameter, all crevices at the end, E (Fig. 9), may be done away with by means of the construction shown—a shrunk-on collar, s, over the finished surface of which the metallic cap, c, slides on and off. The absorbing material, S, is placed at the end of the flue, backed by any material, G, such as wood, that it is desired to use.

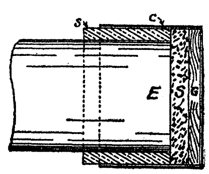

Fig. 9.

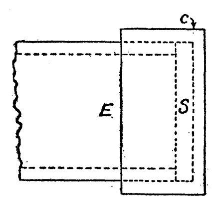

Fig. 10.

The flue used in the experimental work was made of wood of the dimensions already given. Its end, E (Fig. 10), was provided with a wooden cap, c, which served to hold the material, S, snugly against the flue and to close the end as nearly air-tight as possible.

III. In the search for means for measuring the intensity of sound tests were made of everything of any promise, and telephone receivers and transmitters,[1] strong and weak field galvanometers, molybdenite and silicon rectifiers, barretters[2] and microradiometers[3] all figured. The Rayleigh disc[4] was finally adopted as the most reliable and sensitive sound measuring instrument.

[1] Prof. G. W. Pierce, Proc. Am. Acad., Vol. XLIII., 13, p. 377, 1908.

[2] Prof. A. E. Kennelly, Trans. Internat. Elect. Cong. St. Louis, 1904, Vol. III., pp. 415–437, 1905; Bela Gati, Engr., 105, p. 24, Jan. 3, 1908.

[3] Prof. F. R. Watson, Phys. Rev., 28, p. 385, 1909.

[4] Lord Rayleigh, Phil. Mag., Vol. XIV., p. 186, 1882.

The disc used was made of mica, 1 cm. in radius, suspended on a quartz fiber about 10 cm. long, a small mirror being fixed to the top of it like the mirror of a D'Arsonval galvanometer, but when the disc was turned through an angle of 45°, the mirror faced the front. It hung in a little wooden box with a glass front and two one-inch glass tubes led into opposite sides of the box so that, virtually, the disc was suspended near the center of a one-inch glass tube. This tube was stopped at both ends with corks, and was of such a length as to be in resonance with the sound employed. A one-half-inch glass tube about three feet long (the length adjusted to resonance with the pitch employed) pierced one of the corks and served to deliver the sound energy to the disc. A sound at the end of the long tube causes the air in the tube to vibrate, and an antinode, or region of greatest velocity of air particles, is formed where the disc hangs. As is well known, the disc tends to set itself at right angles to the direction of motion of the air stream, and turns through an angle which is a measure of the intensity of the sound at the end of the long tube.

The equation of the torque acting upon the suspended disc, as worked out by W. König,[1] is

$$M = 4/3\rho r^3 v^2 \sin 2\theta,$$

where M is the moment of the couple due to the stream of density ρ, flowing with a velocity v, and r is the radius of the disc whose normal makes an angle θ with the direction of the undisturbed stream. In the case of the sound vibrations the velocity v would be alternating and the air particles would move with simple harmonic motion, thus the energy due to the vibrations would be proportional to the mean square velocity. W. Zernov has shown[2] that König's equation holds for sound vibrations in free air, the v^2 being proportional to the intensity of the sound and equal to the mean square velocity of the air particles.

For use in measuring sound intensity, the Rayleigh disc is suspended in a resonance tube. It has been shown by Stewart and Stiles[3] that the intensity of sound in a resonance tube is proportional to the intensity of the exciting sound in the free air at the mouth of the tube. The following simple experiment also brings out this fact: A disc was hung near the mouth of a tube and a source of sound (an organ pipe) placed near the end of the tube (Fig. 11). A stop at d made the tube a resonator for the sound and deflections were made for several different distances of the organ pipe from the tube. The stop was then moved to d' thus

[1] W. König, Wied. Ann., XLIII., p. 51, 1891.
[2] W. Zernov, Ann. der Phys., XXVI., p. 79, 1908.
[3] Stewart and Stiles, PHYS. REV., April, 1913, p. 309.

throwing the tube out of resonance. The sound vibrations which affected the disc were then not due to resonance but were of the character of reverberation in a room and the disc responded as in free air. Deflections were again taken for the same distances of the organ pipe from the end of the tube. Following is the result — showing the same law to hold in both cases:

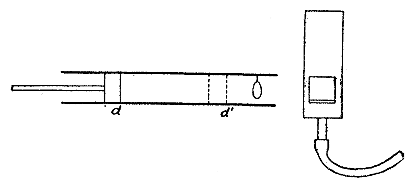

Fig. 11.

Case of Reverberation:

Organ Pipe Distance.	Deflection.
1 cm.	20.1
2 cm.	10.2
3 cm.	6.0

Case of Resonance:

Organ Pipe Distance.	Deflection.
1 cm.	36.0
2 cm.	18.4
3 cm.	10.8

The similarity in the behavior of the disc in the two cases is clearly shown by the similarity in the shape of the curves (Fig. 12).

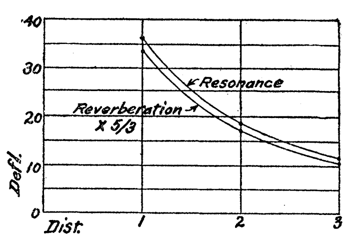

Fig. 12.

Thus the intensity of sound in a resonance tube is proportional to the intensity of the sound in free air at the mouth of the tube, and the deflections of a disc in a resonance tube are a measure of the intensity of the sound at the mouth of the tube.

With König's equation as a basis, the calibration of the disc for sound intensity may be worked out as follows:

When responding to sound, the disc turns through an angle which we will represent by ϕ. Since the apparatus was so constructed that $\theta = 45^\circ$ when there is no sound, then $\phi = 45^\circ - \theta$, and $2\phi = 90^\circ - 2\theta$. When the return torque of the suspending fiber is balanced by the couple acting on the disc due to sound vibrations, then

$$L\phi = M = kv^2 \sin 2\theta,$$

where L is the moment of torsion of the suspending fiber, and $k = 4/3\rho r^3$. (ρ, the density of the air, is a constant at an antinode of sound vibration.)

$$\cos 2\phi = \cos (90^\circ - 2\theta) = \sin 2\theta,$$

therefore

$$L\phi = kv^2 \cos 2\phi = qi \cos 2\phi,$$

where i (the intensity of the sound) is proportional to v^2, q being equal to k times the proportionality factor.

Then

$$i = \frac{L\phi}{q \cos 2\phi} = \frac{b 2\phi}{\cos 2\phi},$$

where

$$b = \frac{L}{2q}.$$

Since the deflection, δ, on the scale is equal to $s \cdot \tan 2\phi$, where s is the distance of the mirror from the scale, then $2\phi = \tan^{-1} \delta/s$, and

$$\begin{aligned} i &= \frac{b \cdot \tan^{-1} \delta/s}{\cos (\tan^{-1} \delta/s)} = \frac{b \cdot \tan^{-1} \delta/s}{s/(\delta^2 + s^2)^{\frac{1}{2}}} \\ &= \frac{b(\delta^2 + s^2)^{\frac{1}{2}} \tan^{-1} \delta/s}{s} = h(\delta^2 + s^2)^{\frac{1}{2}} \tan^{-1} \delta/s, \end{aligned}$$

where $h = b/s$.

For small deflections, δ^2 may be neglected in comparison with s^2, and the angle and its tangent may be considered equal, then the intensity of sound is proportional to the deflection of the disc, or

$$i = k\delta.$$

The error involved in using this approximate formula may be brought out by the following example:

Let the distance from mirror to scale, s, be 100 cm. and two deflections be $\delta_1 = 40$ cm. and $\delta_2 = 0.87$ cm.

Using the exact formula for computing relative sound intensity:

$$\frac{i_1}{i_2} = \frac{h \cdot 107.71 \cdot 21.8\pi/180}{h \cdot 100.004 \cdot \pi/360} = 46.96.$$

Using the approximate formula involves merely a comparison of the deflections:

$$\frac{i_1}{i_2} = \frac{40}{.87} = 45.84.$$

Thus the percentage error is $\dfrac{46.96 - 45.84}{46.96} \times 100$ or 2.2 per cent.—the approximate formula giving the smaller value for the louder sound.

The error involved in using the approximate formula for the computation of the coefficient of absorption, α, may be shown by using these results in the formula for α already derived:

For the correct ratio of sound intensities, $m = 46.96$, and $n = 1$; then

$$\alpha_0 = \frac{4}{m^{\frac{1}{2}}/n^{\frac{1}{2}} + n^{\frac{1}{2}}/m^{\frac{1}{2}} + 2} = \frac{4}{6.8527 + 0.1459 + 2} = \frac{4}{8.9986} = 0.4445.$$

For the approximate ratio of sound intensities, $m = 45.84$, and $n = 1$; then

$$\alpha_1 = \frac{4}{6.7702 + 0.1447 + 2} = \frac{4}{8.9179} = 0.4485.$$

The percentage error for the coefficient of absorption is

$$\frac{0.4485 - 0.4445}{0.4445} \times 100 = 0.9 \text{ per cent.}$$

As the ratio of sound intensities approaches unity, the percentage error decreases, therefore, for the computation of the coefficient of absorption, the approximate formula for relative sound intensity is close enough for material of high absorbing power but should not be used when the absorbing power is less than 0.20.

In agreement with the above calibration of the disc deduced from theoretical considerations, the result of the following experiment may be cited.

The disc was suspended in a resonance tube an inch in diameter and ¾-wave-length (about 30 cm.) long, closed at both ends except for four small glass tubes of one-eighth-inch bore lying across one end, each tube pierced with a little hole which opened into the resonance tube (Fig. 13). The tubes were mounted in a wooden cap which fitted nicely over the end of the resonance tube, and the whole arrangement constituted an adaptation of Quincke's interference tube. A sound passing through one or all of the four little tubes would be swallowed up by the resonance tube, if its pitch is that to which the latter is tuned. One end of each of these four tubes was fitted into the wooden cap closing end, E, of the wooden flue already described which served as a horn to catch the sound from an organ pipe placed at the end, B, and four little wooden rods were made of such a size as to slip into the glass tubes and stop all sound from coming into them.

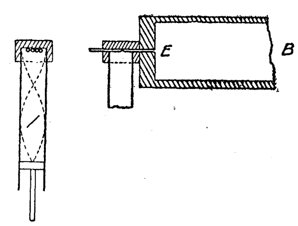

Fig. 13.

With one rod removed, the organ pipe was sounded and a deflection of the disc was noted. The resonance tube in which the disc hung had absorbed all of the sound which was passing through one little tube, and the disc felt the impulse of the sound vibration. The same was done with two tubes open, then three and then all four. The following is a sample of the deflections received:

Number of Tubes.	Deflection.
1	.12
2	.46
3	.98
4	1.96

The deflections are seen to run about in the following proportion: 1 : 4 : 9 : 16. Variations may be due to slight differences of bore in the tubes. The sound in the first tube produced a certain amplitude in the resonance tube; the sound in two tubes gave twice as great an impulse or produced twice the amplitude in the resonance tube, etc. All of the sound delivered to the resonance tube was very weak and could produce no great crowding of air particles, and so the amplitudes were able easily to be superimposed one upon another without loss of motion, and since the intensity of sound varies as the square of the amplitude, it would vary, also, in this case, as the square of the number of tubes delivering sound to the resonance tube. The resulting deflections very nicely confirm this, and since the deflections were all small they would come within the approximation made above which gave the final calibration formula, $i = k\delta$, deduced from König's law of the Rayleigh disc. Thus, for the Rayleigh disc, it is theoretically and experimentally established that, for small deflections, the intensity of sound varies as the deflection; for large deflections, the intensity may be computed from the more extended formula,

$$i = h(\delta^2 + s^2)^{\frac{1}{2}} \tan^{-1} \delta/s.$$

The calibration of the Rayleigh disc provides the necessary means for measuring the ratio of the maximum and minimum sound intensities in the sound flue (Fig. 4) and makes possible the calculation of the coefficient of absorption of sound by the use of the formula:

$$\alpha = \frac{4}{m^{\frac{1}{2}}/n^{\frac{1}{2}} + n^{\frac{1}{2}}/m^{\frac{1}{2}} + 2}.$$

When the Rayleigh disc is used to measure sound intensity the range of pitch is limited by the fact that the disc must lie in an antinode, and density variation of the air must be absent. For very short waves the disc would swing out of the region of constant density and thus complicate the calculation of sound intensity. For very high pitches, therefore, very small discs must be used. For a disc one millimeter in diameter there would be no great error when used with a wave two centimeters long, which would correspond to a frequency of about 16,500 vibrations per second, or a pitch of about C_9—six octaves above middle C (C_3—256 vibs./sec.). An octave and a half above this would take us to the upper limit of audibility, showing that the apparatus is applicable to any probable range of pitch.

The different parts of the apparatus used for making observations for sound absorption have already been described. The parts were assembled as shown in Fig. 14. The flue, *F*, moved along a graduated

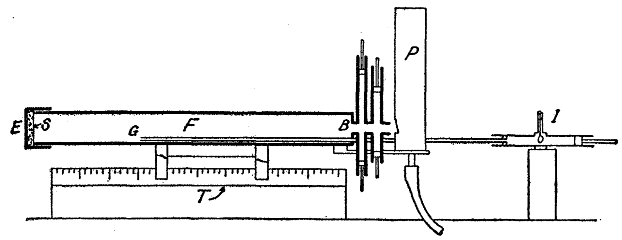

Fig. 14.

track, *T*. The one-half-inch glass tube, *IG*, from the suspended disc passed through the tone screen at *B* and projected into the flue. The intensity of sound at the end, *G*, of this tube causes the air in the tube to vibrate and this in turn produces a deflection of the disc.

In taking observations, the flue, *F*, with the organ pipe, *P*, attached to it was moved along the track, *T*, in steps one centimeter long. Observations for intensity were made at each step, and at the region of maximum and minimum intensities for shorter steps, and thus the maximum and minimum intensities, m and n of the formula, were found. Applying these values in the formula, the coefficient of absorption of sound for the material, *S*, closing the end, *E*, of the flue, *F*, was calculated as already shown by an example.

Following is the coefficient of absorption of a few materials computed by using the approximate formula:

Material.	m	n	α
Smyrna Rug	6.55	.04	.26
Brussels Carpet	7.30	.03	.23
Hair felt (1-inch thick)	24.70	.78	.51
Ceilinite ($\frac{1}{2}$-inch thick)	57.50	.22	.25
Asbestos roll fire felt ($\frac{3}{4}$-inch thick)	54.50	.30	.26
Compressed cork ($1\frac{1}{2}$-inch thick)	27.00	.25	.32

The last four materials were kindly furnished by the Johns-Manville Co. of New York. The values of the absorbing power given here for the first three materials check fairly well with values obtained by the reverberation method.

The absorbing power of material is increased by increasing the space between it and the wall behind it. This may be explained by considering sound absorption as a retardation of the motion of the vibrating air particles; hence, by placing the absorbing material out a little from the wall (where the air is at rest) it becomes more effective in retarding motion and thus more efficient as a sound absorber. Following are the coefficients for compressed cork taken for several different distances between it and the board behind it:

Compressed Cork.

Distance from Board.	m	n	α
2 mm.	25.00	.25	.34
5 mm.	25.50	.34	.38
10 mm.	18.30	.46	.47
20 mm.	13.70	.74	.61

The relation is also shown by the curve (Fig. 15):

An important application of the flue to auditorium acoustics is the following: Sabine has found[1] that the reverberation of a room varies for different parts of the musical scale. To correct the acoustics of a room, therefore, absorbing material must be so applied as to make the reverberation for each tone normal. Since the absorbing power of a material varies with its distance from the wall, and this distance varies for the maximum absorption of each tone, it is possible to so graduate the distance of the material from the wall as to make the reverberation of the room for each tone of the entire musical scale normal. The flue makes the determination of the absorbing power of materials for variation of tone and distance from wall a simple matter.

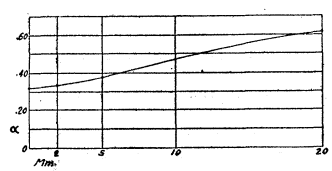

Fig. 15.

The flue method of finding the value of a material as a sound absorber eliminates the effect of the interference system of a room on the absorbing power of the material. As shown by Sabine[1] a material of high absorbing power placed in a room where, due to interference, the intensity of sound, or sound pressure, is very small would have little effect on the sound in the room, but if placed in a region of large relative sound pressure it would diminish the sound perceptibly.

If the absorbing power of this material were obtained by the reverberation method in this room in the first position mentioned, it would be found to be relatively small, and in the second position, relatively large. If one of these is the correct absorbing power, the other is not, and the probability is that neither is correct.

[1] Prof. W. C. Sabine, Arch. Quar. of Harvard Univ., March, 1912, p. 20.

Conversely, if the correct absorption of a material is found by means of the flue, and this material is used to reduce the reverberation of an auditorium, its value will depend somewhat upon its position in the room. Thus the true power of absorption of a material will be useful in connection with auditorium acoustics only when used with due precaution—and then it is of much value. It is useful also as an index to give the material a rating with relation to other sound absorbing materials.

The power of materials to absorb sound transmitted through them was found as follows:

The wooden flue already described (Fig. 4) was stopped at end, E, by a board one-half-inch thick, through the center of which passed a one-half-inch glass tube from the Rayleigh disc, I (Fig. 16). The tone screen was removed from end B of the flue, and a closely fitting tin box slipped into the end. The two opposite ends of this box, through which the sound must pass to enter the flue, were made of cheese cloth and their distance apart was adjustable.

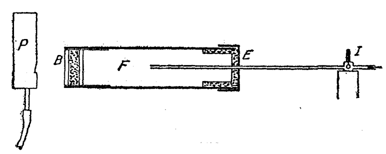

Fig. 16.

With this box in the end of the flue, F, and an organ pipe, P, placed immediately behind it, the first reading was made giving the intensity of the sound in the flue when end, B, was not closed with the material whose absorption was wanted. Then the cheese cloth ends of the tin box were adjusted for several different distances apart and for each one the box was filled with absorbing material and slipped into the end of the flue for a reading. Following are the readings made for water glass crystals loosely shaken down but not packed, the organ pipe sounding the note *si* (240 vibs./sec.):

Thickness. cm.	Deflection. δ.	Fraction of Sound	
		Transmitted.	Absorbed.
0	44.20	1.000	0.000
2	24.90	.564	.436
4	15.50	.352	.648
6	11.50	.260	.740
10	5.50	.124	.876
16	1.10	.025	.975
20	.53	.012	.988

The intensity of sound varies as the deflection, $i = k\delta$. If I represents the sound intensity transmitted through zero thickness of the material, and i the intensity transmitted through thickness, t, then i/I is the fraction of sound transmitted through thickness, t, and $1 - i/I$ is the fraction absorbed by thickness, t. The following equation gives the relation, when t is small:

$$i/I = (1 - \beta)^t,$$

where β is the fraction of sound absorbed by unit thickness (1 cm.) of the material. This fraction is the insulation coefficient for sound for the material.

The insulation coefficient for three materials follows:

Material.	β
Water Glass Crystals	.211
Hair Felt	.226
Compressed Cork (1-inch thick)	.500

The curve between observed thickness and sound transmitted shows the experimental relation (Fig. 17):

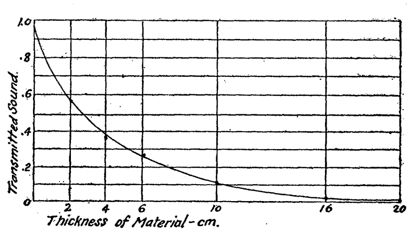

Fig. 17.

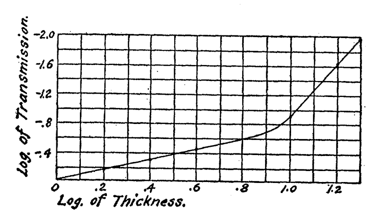

Fig. 18.

The curve between the logarithm of the fraction of sound transmitted and the logarithm of thickness shows that the logarithmic relation holds only when t is small, and that a distinct change occurs in the law of absorption in a certain region (Fig. 18):

The absorbing lining at the end, E (Fig. 16), of the flue makes internal reflection in the flue impossible. When sound strikes the outer surface of the material at the end, B, it is, in general, partially reflected, thus the amplitude of the wave which actually enters the material is not that of the incident wave. The coefficients given above express the relation between the incident and transmitted sound. Architecturally, this coefficient would probably be more useful than the coefficient based upon the sound which actually enters the material, since it is the intensity present in a room and incident upon a wall that one hears, and the wall is constructed to isolate this sound from adjoining rooms. Thus this is properly the insulation coefficient of a material for sound.

The intensity of sound which actually enters a material may be obtained by finding the coefficient of reflection, ρ, of the material when it is in place at the end, B, of the flue, F, and taking the product of this and the first deflection, δ_0, in the above table; δ_0 is proportional to the incident sound, therefore $\rho\delta_0$ is proportional to the reflected sound, and $\delta_0 - \rho\delta_0$ is proportional to the intensity of the sound entering the material. Simplifying, we have $\delta_0(1 - \rho) = \delta_0\alpha$, since $1 - \rho = \alpha$; therefore the intensity of the sound actually entering the material is proportional to the product of the deflection when no material covers the end, B, of the flue and the coefficient of absorption of the material when it is in place at the end of the flue with a column of air behind it. The fraction of sound transmitted when $\delta_0\alpha$ is used as a basis may properly be called the transmission coefficient of the material for sound, and it may be computed by using $\delta_0\alpha$ in place of δ_0 in the computations for $(1 - \beta)$.

Reflection from the outer surface of the material at the end, B, of the flue may be prevented by a covering of acoustically black material—loose felt. The sound transmitted by this covering may be found by making observations with it alone, and $\delta_0\alpha$ thus obtained experimentally.

The methods for finding the absorption of sound as outlined above may be applied in a number of ways; following is a partial list of suggestions:

(*a*) Determining the relation between the absorbing power of a material and its distance from the wall behind it.

(*b*) Determining the relation between the absorbing power of a material and pitch of sound.

(*c*) Determining the relation between the absorbing power of a material for transmitted sound and the thickness of the material.

(*d*) Determining the relation between the absorbing power of a material for transmitted sound and pitch of sound.

(*e*) Determining the relation between the absorbing power of a material and its composition or texture for a range of different pitches of sound.

(*f*) Determining the relation between the sound absorbing quality and elasticity of a material.

(*g*) Determining the absorbing power of materials by means of the effect of absorption upon the pitch of an organ pipe.

The Rayleigh disc may be used:

(*h*) For the detection of the presence of overtones in a sound by suspending it in a tube tuned to the pitch of the overtone.

(*i*) To bring psychological observations of ear accommodation up to a greater degree of completeness and accuracy.

PHYSICAL LABORATORY,
CORNELL UNIVERSITY,
May 26, 1913.