The Acoustics of Buildings.[1]

By Dr. G. W. C. Kaye.

In view of the examples of acoustically defective halls which abound in our towns and cities, it is the more surprising to find that the fundamental principles of architectural acoustics were clearly appreciated nearly a century ago in Great Britain by a number of workers. Then, as now, it was realised that the two defects most frequently met with in large auditoriums are (1) echoes and (2) excess of reverberation; that is, the tendency of an arrested sound to persist unduly by multiple reflection at the boundaries, owing to their deficient absorptive properties.

So long ago as 1835, at a meeting of the British Association at Dublin, we find Reid recognising reverberation as a prevalent acoustic defect and suggesting remedies in the shape of more absorbent walls by increasing their roughness or irregularity, or by hanging draperies. He also stressed the advantage of excluding superfluous space.

Dickens's acoustic powers of observation are exemplified in "Martin Chuzzlewit," written in 1843. In Chap. ix., in describing the houses in the neighbourhood of Todger's boarding-house, he relates how

"these mansions, now only used for storehouses, were dark and dull, and, being filled with wool, and cotton, and the like—such heavy merchandise as stifles sound and stops the throat of echo—had an air of palpable deadness about them."

Roger Smith, in his "Acoustics of Public Buildings" (1861), remarked that: "In empty houses a great reverberation is perceptible which diminishes as the floors are covered with carpets and the rooms filled with furniture." Tyndall, in 1868, in evidence before a Select Committee of the House of Commons, stressed the value of a low ceiling as a reinforcing device, and the influence of an audience and of draperies in quenching the after-sound. During the proceedings of this committee, it was elicited that flock paper applied to the walls of a reverberant room had proved an effective remedy.

Again, Johnstone Stoney (1885) described how he tested a room which had its walls papered over a lining of canvas, the canvas being a short distance in front of the framework over which it was stretched. From his experiment he inferred that concert halls or public rooms could be effectually freed from echo effects by the simple expedient of lining the walls and ceiling in such a manner.

Rayleigh, in the second edition of his "Theory of Sound" (1896), gave the first mathematical treatment of the absorption of sound waves by porous rigid bodies. He clearly recognised the inevitability of reverberation in large rooms with non-porous boundaries, and suggested a remedy in the shape of thick carpets, curtains, etc.

The ground would seem to have been well prepared for a systematic investigation on auditorium acoustics in England, but it was not forthcoming, and it is to the pioneer work of the late Prof. W. C. Sabine, of Harvard University, that we must turn for the first elucidation of the main practical problems, particularly as regards reverberation. His "Collected Papers on Acoustics" extend over the period from 1900 to 1915, and his work and that of others has attracted considerable attention both in the United States and Germany.

As a consequence, although much remains to be done, there is now sufficient volume of experience to enable the main acoustic requirements of a building to be satisfactorily met before the erection of the building is even commenced.

The principles are simple and straightforward, but much scepticism and apathy will have to be dispelled in Great Britain to prevent a repetition of the acoustical failures conspicuous in a number of modern halls. The Press reflects the view commonly held that architectural acoustics is a gamble. For example, the *Times* on July 24, 1922, remarked that: "Broadly speaking, it may be said that the acoustic qualities of a hall or room cannot yet be predicted"; and again in its issue of Oct. 19, 1926, it was stated that "there is no means of studying the acoustic properties of a building which does not exist, or exists only on paper."

However, within recent years the subject of applied acoustics, as a quantitative science, has become the object of study at a number of centres in England, notably the Signals Experimental Establishment at Woolwich, the National Physical Laboratory at Teddington, and the Building Research Station at Watford.

We may proceed to review some of the acoustical characteristics of a building.

Echoes.

As regards echoes, it is found that an echo becomes noticeable when the reflected sound lags behind the direct sound by more than about $\frac{1}{15}$ second. If the lag is less than this, the reflected sound will serve to reinforce the direct sound. This is an argument in favour of limiting the heights of the ceilings of council chambers and the like to not more than about 35 ft., as the ceiling is the only reinforcer common to every speaker no matter what his location. The House of Commons serves as an illustration.

Thus the question of echoes will not arise except with large halls, though even a slight echo may contribute to poor hearing. The effect is not likely to be pronounced in the absence of smooth concave surfaces, such as a dome or barrel vaulting, which lead to uneven sound distribution and are definitely inimical to good acoustics. Such surfaces should be broken up, for example, by coffering, and the objectionable reflections absorbed by suitable means. A satisfactory distribution of sound may normally be anticipated within a hall of approximately rectangular section. Furthermore, inter-

[1] Abstracted from three Tyndall Lectures delivered at the Royal Institution in November 1926.

ference phenomena are not likely to be of any moment, particularly in the case of speech.

The reflecting characteristics of the boundaries of an auditorium may, with a little experience, be approximately appraised from a geometrical study of sections based upon the optical laws of reflection. Two other methods are available for use with scale-models. In one, first used by Sabine in this connexion in 1913, the progress of an actual sound-pulse in the model is displayed by the well-known method of spark illumination. In the other, use is made of the analogy between water ripples and cylindrical sound waves, a method which appears to have been first suggested by Scott Russell at a meeting of the British Association in 1843. Each method has its advantages, and both give results which, although predictable in the main by geometrical methods, show also the spreading of waves by diffraction beyond the optical limits. Incidentally, either of the experimental methods is more convincing than the geometrical when for any reason it is desired to provide ocular demonstration of the acoustic properties of a particular architectural design.

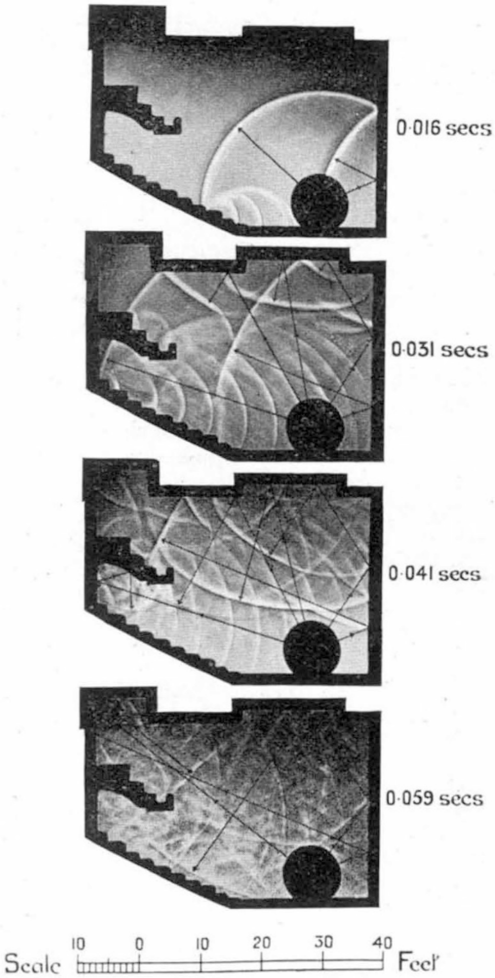

FIG. 1.—Sound-pulse study of the lecture theatre at the Royal Institution.

Fig. 1, taken at the National Physical Laboratory by Mr. Fleming, shows the progress of a sound-pulse in a central vertical section of the theatre of the Royal Institution, which was erected in 1800 and is of acknowledged acoustical excellence—a view subscribed to by Faraday in evidence before a Select Committee in 1835. In the figure, arrows drawn from the position of the source show the tracks of certain selected wave fronts.

REVERBERATION.

As already remarked, the common defect of large auditoriums is undue reverberation. Rigid non-porous walls have, on Rayleigh's estimate, a higher reflecting power for sound than the best mirrors have for light. Thus, unless absorptive materials in some form are provided, the rate of dying away of a sound in a large hall will normally be so protracted as to cause confusing overlapping of successive sounds or syllables emitted at ordinary rates.

It was primarily the work of Sabine that has made it possible to measure the proportion of incident sound energy absorbed by a material (that is, the absorbing power), or to predetermine the amount of absorbent necessary to ensure acceptable reverberation in a hall. If a steady source of sound in a room is suddenly stopped, then Sabine showed that the duration of audibility (when determined under proper conditions) is an important acoustical characteristic of the room. He established the relation that this reverberation period (as it is called) is proportional to the volume of the room, and inversely proportional to the total absorbing power of the boundaries and contents. If we work in square feet and seconds, the constant of proportionality is $\frac{1}{20}$. It may be noted that the relative linear dimensions of a room are not now regarded as material, except perhaps for extreme shapes.

The degree of reverberation is all-important. A certain amount is pleasing and helpful; excess leads to greater loudness but increased confusion; insufficient results in enfeeblement and staccato effects which are displeasing to hearers and, furthermore, impart a sense of deadness or absence of power to a speaker or singer. A great variety of observations have been carried out on the optimum reverberation periods to suit different conditions. Briefly, it may be said that for speech in relatively small halls (up to, say, 50,000 cubic feet) a period of about one second is preferred, the value increasing up to about two seconds for the largest halls. Cultivated musical opinion agrees in preferring rather longer periods for music, depending on its character and volume.

It may be remarked that in large cathedrals and churches, reverberation periods up to six or seven or more seconds are common, a condition which dates back to medieval times and is responsible for certain features of the services—the characteristic choral and organ music, the intoned liturgy, and the frequent inaudibility of the speaking voice.

The remedy for excessive reverberation in a room is either to reduce the volume, if practicable, say, by lowering the ceiling and partitioning off unnecessary large recesses, or to increase the sound-absorbing power of its surfaces by the use of absorbents such as felt, quilting, wood-wool, aerated plaster, fibre board, carpets, curtains, upholstery, etc. In some cases the disposition and shape of such absorbents can be so chosen that they will also serve to suppress undesirable reflections.

In passing, it may be added that there does not appear to be any recorded scientific evidence that stretched wires exert any beneficial effect in auditorium acoustics, though examples may still be found.

Loudness.

In addition to the defects of echo and reverberation, the question of inadequate loudness will almost certainly arise in a large building, particularly in the case of speech. Experience agrees that the range of the unassisted speaking voice of average strength is of the order of 50 feet, that is, provided the hearer is so situated as to receive a direct 'ray' of sound. At greater distances it becomes necessary to provide reinforcement, either by reflection from suitable surfaces, or by an electrical loud-speaker system. In view of the increasing use that is being made of public address systems, it should be realised that their main office in a large hall is to provide adequate loudness in the remoter parts. Further, by placing the loud-speakers in suitably high positions, troublesome ceiling echoes may sometimes be obviated. The system is not a remedy for excessive reverberation; on the contrary, the increased loudness adds to the confusion. The system may be a valuable corrective when steps have been taken to reduce reverberation by introducing absorbent material—a procedure which of itself unfortunately decreases the volume of sound. It has, of course, to be recognised that in some cases the rendition of an amplifier and loud-speaker may not be wholly acceptable to a cultivated ear. The amplification should not be excessive or unnatural effects will result, nor should the different loud-speakers be widely separated or effects of repetition akin to echo will be produced. In Great Britain the system has so far been installed notably in large cathedrals, *e.g.* Liverpool Cathedral, Westminster Abbey, and Bath Abbey. An alternative method of amplification is employed in the House of Lords, where certain seats are equipped with ear phones, for the purpose of affording assistance to individual auditors who suffer from deafness.

Absorption Coefficients.

We see that for a room to attain its optimum reverberant condition, it is necessary to arrange that the various exposed surfaces shall possess in the aggregate the requisite absorbing power. We thus require to know the absorption coefficient or the absorbing power of unit area of each material present.

Various methods have been employed for measuring this coefficient of absorption for building and other materials. One method is to measure the change in the reverberation period in a calibrated test chamber when a known and suitably large area of the material is introduced under proper conditions. In a second method, a beam of sound is directed towards a test specimen mounted as a panel in an aperture in a sound-proof wall, and the proportions of the incident sound which are reflected or transmitted are measured. Fig. 2 illustrates the use of this method by Dr. Davis and Mr. Littler at the National Physical Laboratory. In the case of small samples, another method is available for measuring the reflecting power. This is based upon measurements of the ratio of the intensities at the nodes and antinodes of the stationary waves in a tube, one end of which is closed by the test material.

Figures for the absorption coefficients of a number of materials have been determined by

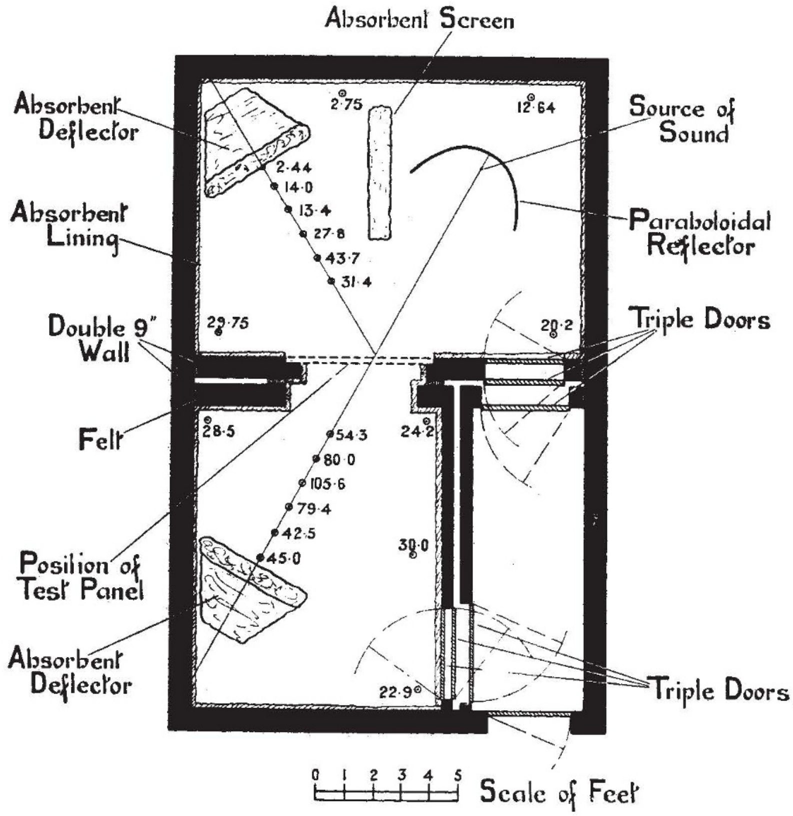

Fig. 2.—Sound-proof rooms at the National Physical Laboratory, Teddington, for measurement of transmission and reflection coefficients.

Sabine and others. Per square foot, they range from 1·0 for an open window, 0·5 for hair-felt one inch thick, to about 0·01 for plaster or glass. Each isolated member of an audience is equivalent in absorbing power to about 4½ square feet of open window. In the majority of cases the audience constitutes the most absorbent feature in a hall, so that the reverberation period is markedly responsive to the size of the audience.

SOUND-PROOFING.

The question of sound-proofing is often of great practical importance. As regards the transmission of air-borne sounds, they are best arrested by having the walls sufficiently massive and rigid. In the case of structure-borne sounds, it is necessary for effective insulation to interrupt the continuity of the structure. For example, a sound-proof room may well be constructed like an inner box which is floated on insulators on the structural floor, and everywhere insulated from the structural walls and ceiling.

To conclude what is only a partial survey of the subject, it is evident that neglect of the established principles may lead to defective acoustic conditions which may prove to be incurable after a building is erected. Preventive treatment is preferable to curative, and architects should be prepared to allow acoustic requirements some share in influencing their designs.

Lister and Physiology.[1]

By Sir C. S. SHERRINGTON, O.M., G.B.E., F.R.S.

IT is indeed fitting that we should recall on this commemorative occasion the contributions made by Lister to physiology. His very earliest scientific papers were all physiological. He may be said to have entered by way of physiology his surgical researches which were to achieve so much. His first paper was entitled "The Contractile Tissue of the Iris." It was work done by the microscope, which he used for the study of function rather than of form alone. It appeared in 1853, in the first number of the first volume of the now well-known *Quarterly Journal of Microscopical Science*. Lister was then twenty-five years of age. That the microscope should be his instrument for his maiden voyage of discovery was but natural in the son of his father, Joseph Jackson Lister, that remarkable man, who leaving school early for the business he conducted so successfully, yet found time to cultivate optics to such purpose as to devise and give to the world the achromatic microscope. Lister's earliest paper, this on the iris, supplied the first full and correct description of the radiating muscle dilating the pupil of the eye. It thus made a lasting mark upon its subject.

Lister's second paper, of a few months later, dealt likewise with involuntary muscle; this time in the skin, where had been recently discovered the arrector muscles of the hairs; a discovery which Lister confirmed and in several respects extended.

We may be struck by the remoteness of these Lister's first themes both from surgery and indeed from actual practice—they are frankly academic. I think we have to picture him a young man to whom the thing that really mattered was to engage at once upon research, caring less what in particular the research might be; a young man so ardently curious about Nature, especially animate Nature, that he turned enthusiastically to the problem that came first to hand. These papers in the simplicity of their text seem to reflect the Quaker upbringing of Lister's home. There is already that sobriety of expression which, characteristic of Lister all his life, made yet the more impressive his own self-restrained statements of his great results later on. No man in his career had more excuse for, more justification for, hyperbole of phrase than had Lister, and no man ever indulged in hyperbole less than did he. It is therefore of significance when the young author allows himself an expansive adjective, as when he writes "the grand discovery of plain muscle-cells," "the beautiful muscle of the iris." We feel these expressions to be, from him, not mere phrases. An abiding interest of these youthful papers is their revelation of attributes in Lister's, so to say, original nature. Any reader of them must be struck by his power of penetrative and faithful observation, his patient enthusiasm, a restless testing of authority by observed fact, and an unhesitating self-submission to wherever the truth might lead.

His third paper, still physiological and on the same theme, smooth muscle, followed some four years later. The cellular nature of that tissue had been denied; Lister returned to its further proof. He furnished it overwhelmingly. Forty years afterwards the then foremost authority on this tissue wrote of this paper of Lister's as being still not only abreast but in several respects ahead of other subsequent papers on its subject.

This work proved, however, to be Lister's farewell contribution to that particular theme. To him by then much had happened and was happening to compel his main interest elsewhere. His scientific enthusiasm had indeed definitely orientated itself towards a chosen quest in the great field of the unknown. His spirit of inquiry had found a direction of overpowering interest to it. In his own words, written to his father, he had fallen in love with surgery; and with that widely detailed and highly technical art and calling prospectively spread before him, the genius within him impelled him to study not so much this or that particular skill or difficulty, but the fundamental and all-pervading process of inflammation itself as being for him the one prime and central problem for investigation.

[1] Discourse delivered in the Robert Barnes Hall of the Royal Society of Medicine on April 6.