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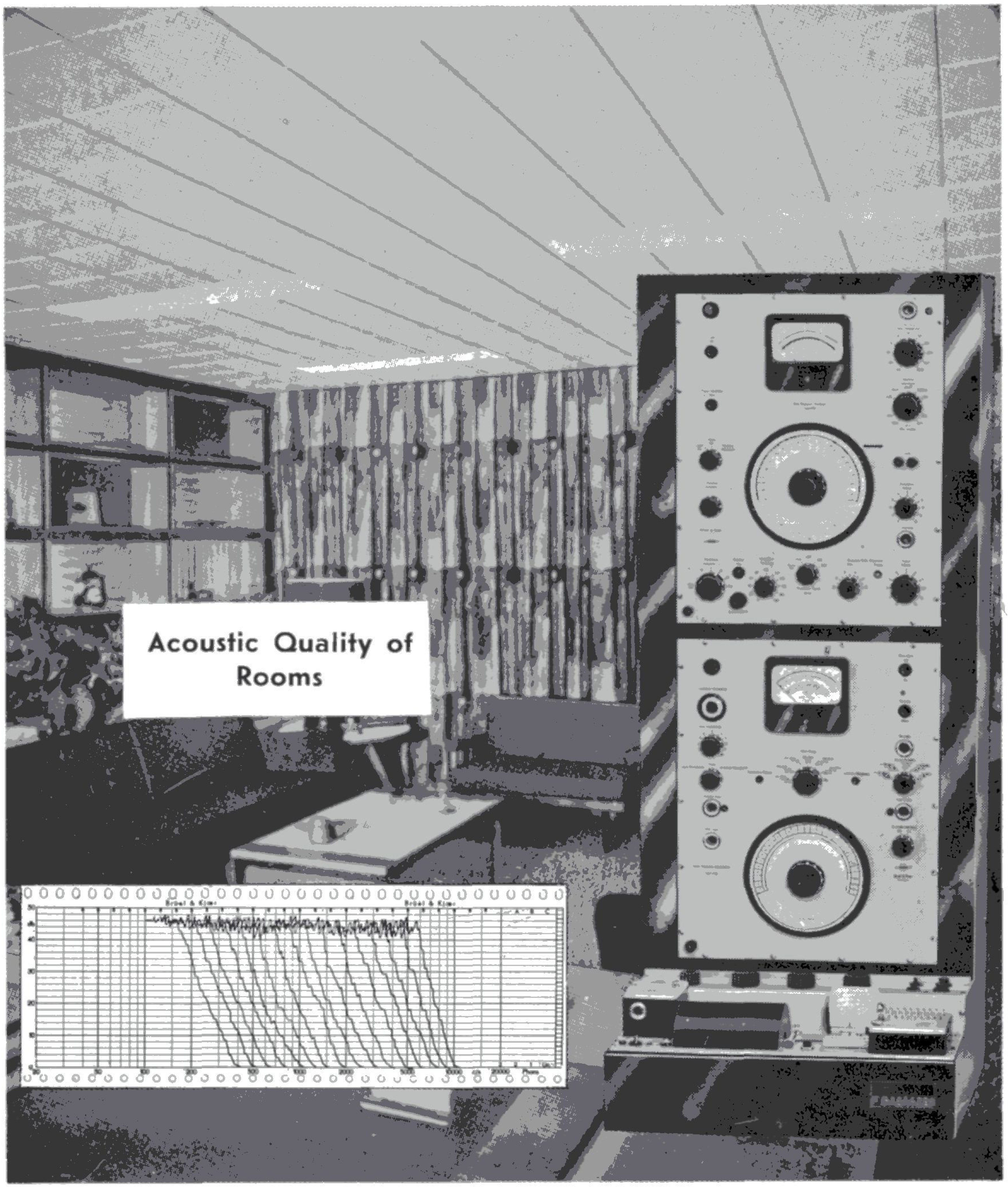

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Determination of Acoustical Quality of Rooms from Reverberation Curves

by

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The most important factor in the determination of the acoustical quality of a given room is the reverberation time, originally defined by W. C. Sabine.

Experience has shown that an optimum reverberation time exists for all rooms, and that it depends upon the purpose and size of the room. Fig. 1 shows the optimum reverberation times which are used as the design target by modern architects for different types and sizes of rooms.[1]) The curves shown are valid for empty rooms and a frequency range from 300 to 2000 c/s. A further requirement to be satisfied is, that the reverberation time should vary but little when measured as a function of the frequency.

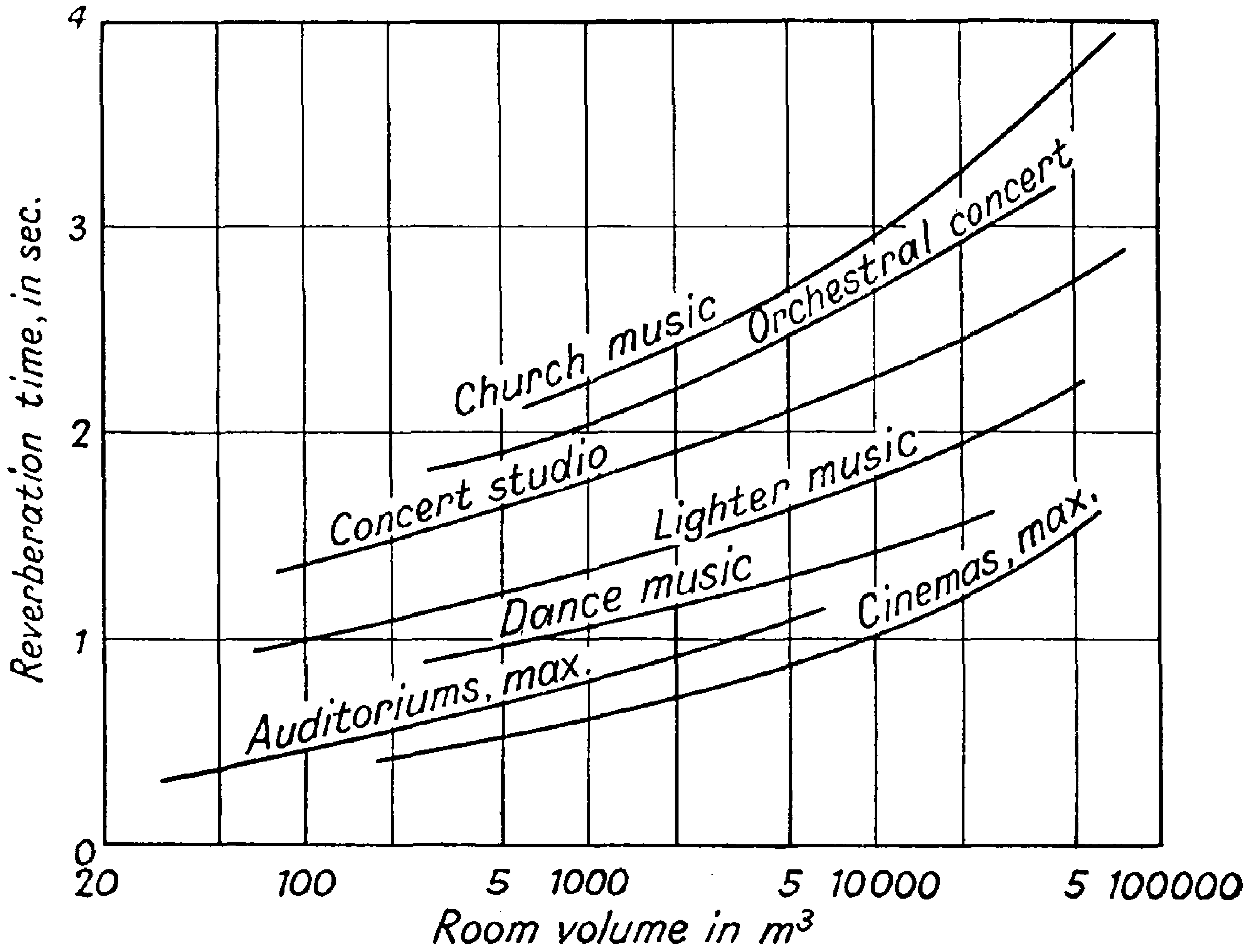

Fig. 1. Optimum reverberation times for different types of rooms, plotted against the room-size. The reverberation times indicated are valid for empty rooms.

Even though the reverberation time is an extremely important factor, the acoustical quality of a room can not be described only by means of its reverberation time.

Other requirements to be fulfilled before a room can be considered as acoustically good are that a diffuse sound field exists in the room, and that

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too large, or wrong time intervals are avoided between the reception of direct and reflected sound waves.

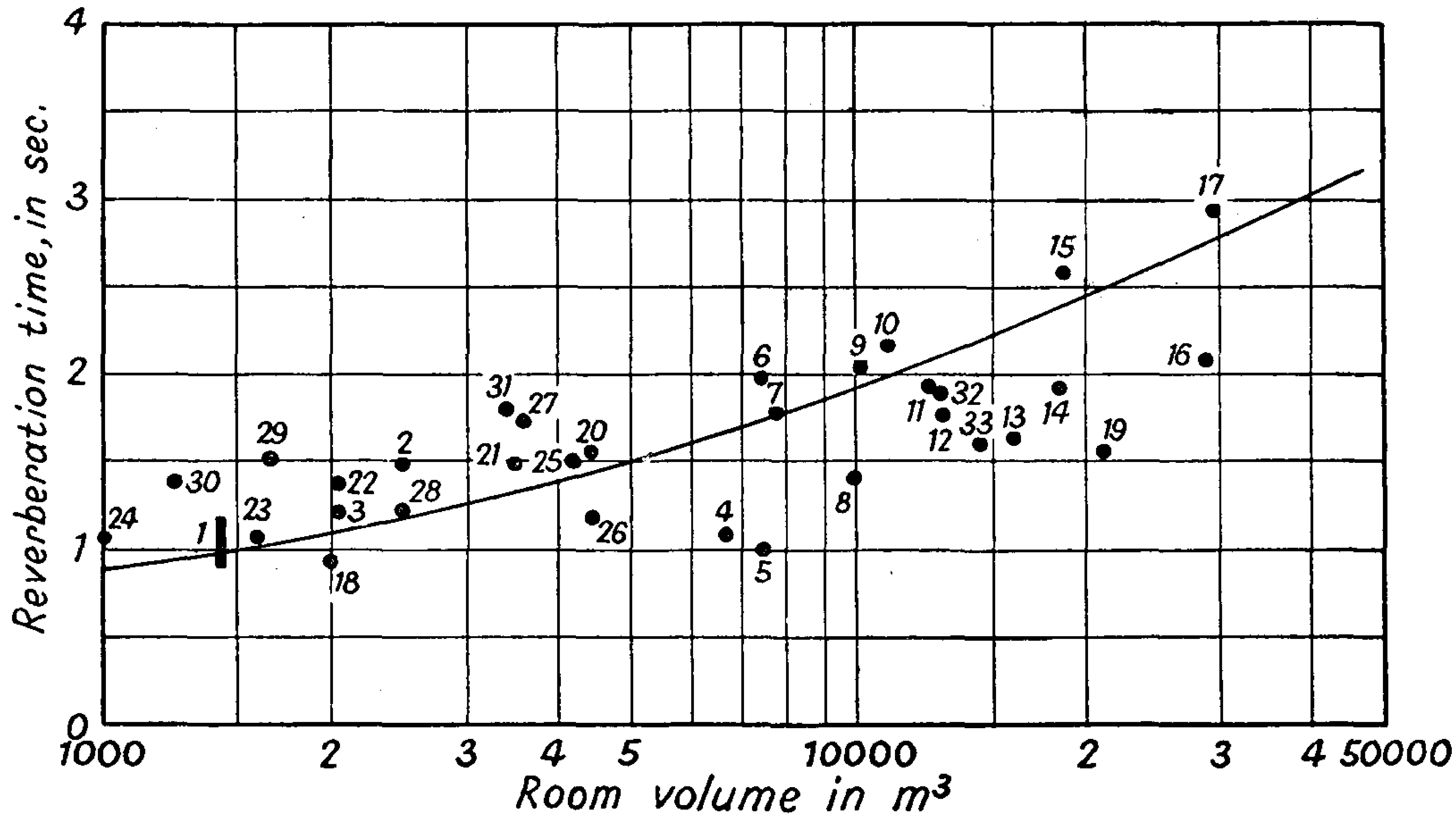


Fig. 2. Reverberation times at medium frequencies plotted against the room volume for a number of acoustically excellent rooms.

Fig. 2 shows the reverberation times for a number of concert halls and studios which are considered to be rooms of acoustical excellence. The rather large deviations in the reverberation times from the optimum values as indicated in fig. 1 are clearly noticed. On the other hand a number of rooms exist which have an exactly correct reverberation time, but which are considered as acoustically bad.

We therefore know at present, that to describe a room acoustically it is not enough only to know the reverberation time at different frequencies.

A conception will have to be found which, if possible should be expressed as a factor or be means of a well defined curve.

Several attempts have been made to find such a conception, which, together with the reverberation time, could give an indication of the acoustical quality of a room.

Bolt and Roop[2]) has defined the so-called Frequency Irregularity (F. I.), expressed in db per c/s, which should give a clear definition of the rather vague expressions known as "diffusion".

Measuring methods have been developed which are more or less able to automatically measure the F. I. as a function of frequency.[3]) However, comprehensive investigations made by Meyer, have shown that the F. I. of a room is so closely related to the reverberation time, that a measurement of the F. I. must be considered only as an extremely complicated method for the determination of the classical reverberation time.

Meyer has also, by means of directional loudspeakers and microphones mounted at different places in a room, tried to establish a sort of three-dimensional polar diagrams for different frequencies. This method gives a lot of interesting information as to the direction and magnitude of the basic reflections in a room. However, it is complicated and can only be carried out at relatively high frequencies. Apart from a rather clear picture which is obtained of the dominating reflections it is difficult to see how the result of such measurements can be formulated to give a practical concept of acoustical quality.

Sommerville[4]) has for some years worked on, and developed the so-called "Pulse Glide Method". This method is based on the use of pure tones which are applied to the room as impulses of short duration. The reverberation phenomena are then registered in such a way that the reverberation curves for the different frequencies are spaced close together See fig. 3.

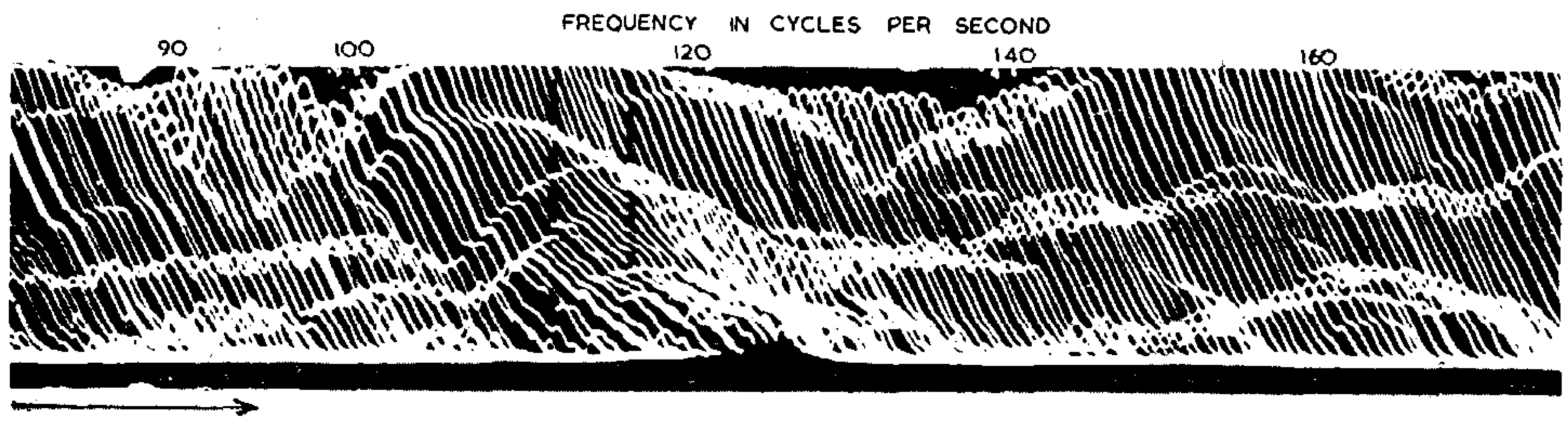


Fig. 3. Reverberation curves obtained from measurements with short lasting impulses of pure tones, employing the measuring device developed by Sommerville and his co-worker.

The frequency interval between two successive reverberation curves is extremely small, and the method of registration enables an immediate comparison of variations in the reverberation process for different frequency bands.

The BBC in London has designed an equipment consisting of a motordriven B.F.O. and a logarithmic microphone amplifier which is coupled together with a cathode ray oscilloscope.

The reverberation curve can then be viewed on the screen of the oscilloscope and photographed by means of a specially designed camera, in which the film runs in synchronism with the frequency drive of the B.F.O.

However, ordinary instruments such as the B.F.O. Type 1014 and Level Recorder Type 2304 may also be used in the "Pulse Glide Method". Fig. 4 shows an arrangement consisting of the B.F.O. and Level Recorder, both instruments being mechanically coupled together.

When the motor in the Level Recorder is started it will also drive the tuning capacitor of the B.F.O. the frequency range of which is thus traversed at a constant, predetermined speed. The recording paper on the Level Recorder is folded in a loop, enabling the reverberation curves to be recorded close together. For each revolution of the B.F.O. scalepointer a new reverberation curve is registered on the paper.

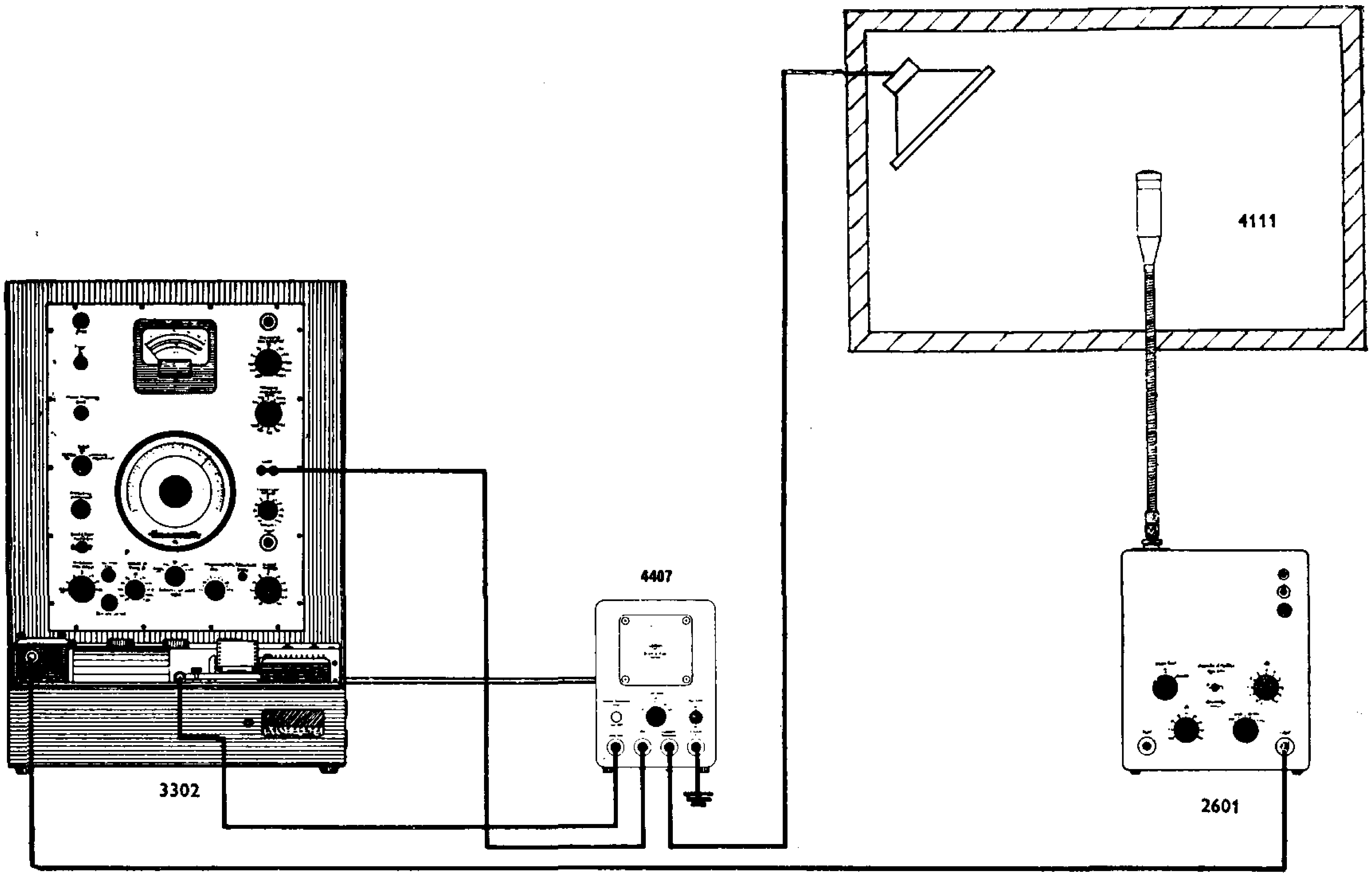


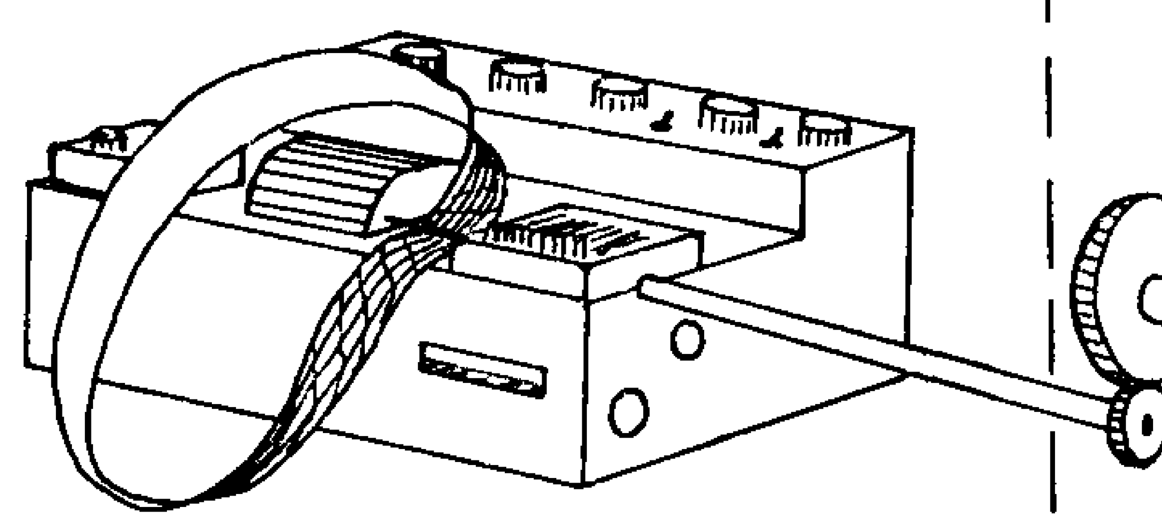
Fig. 4. Measuring arrangement consisting of B.F.O. 1014, Level Recorder 2304, Microphone Amplifier 2601, Condenser Microphone 4111 and the specially designed Reverberation Switch Type 4407 which controls both the loud-speaker and the recording system.

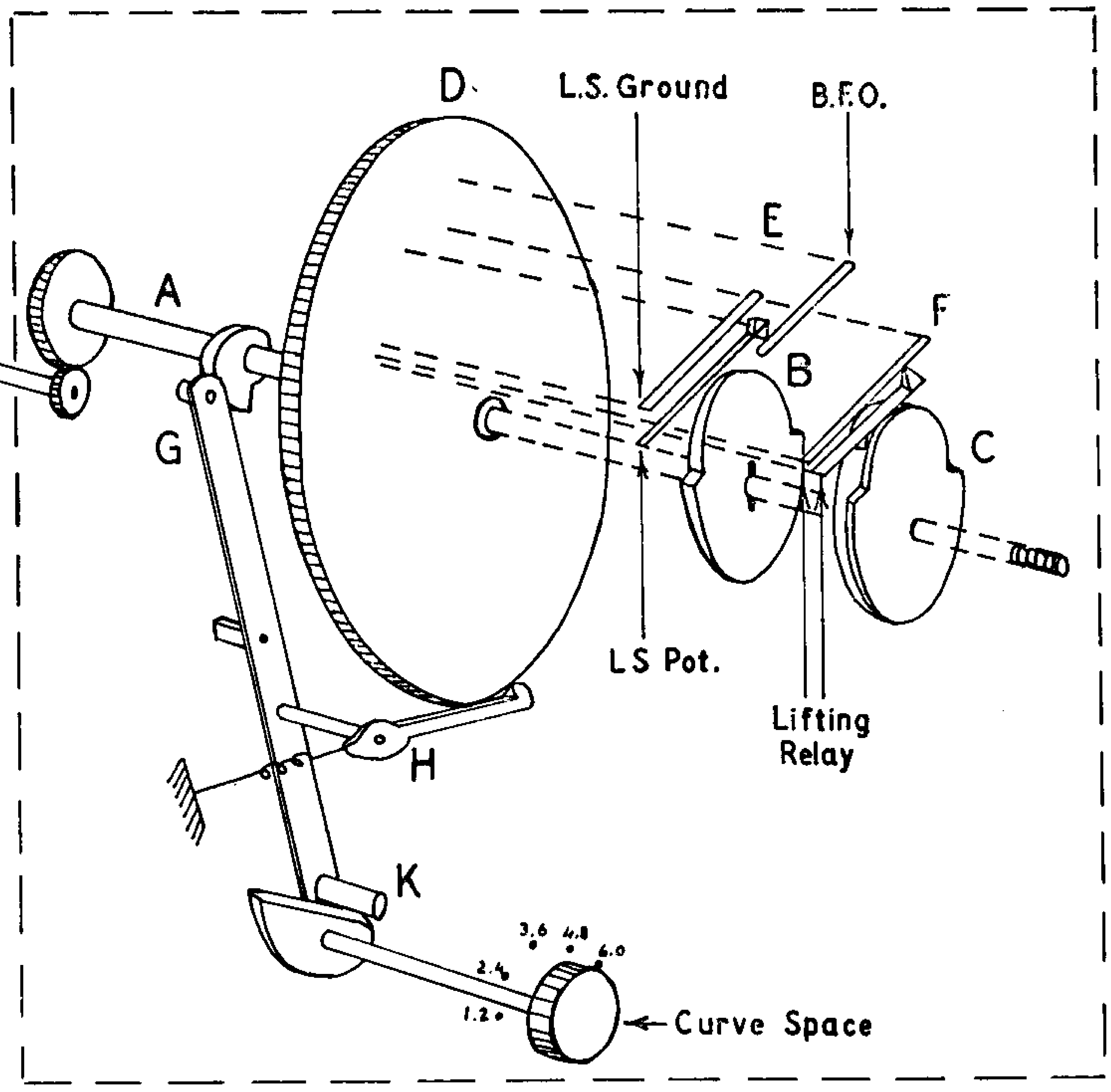
A further instrument employed in the set-up of fig. 4 is the Automatic Reverberation Switch (Universal Selector) Type 4407. This is mechanically coupled to the paper drive of the Level Recorder and serves the following purpose:

1) It connects the loudspeaker to the B.F.O. in such a way that an impulse of short duration is transmitted into the room.
2) It short circuits the loudspeaker during the period of time in which no impulses are wanted.
3) It controls the writing stylus on the Level Recorder by means of a specially designed lifting magnet, whereby only the reverberation process is registered on the recording paper.
4) It introduces a slight shift in the synchronization of the paper before each registration. The reverberation curves for different frequencies are thereby recorded on the paper with a constant spacing between the curves.

Fig. 5 shows the principle of operation of the Reverberation Switch.

The frequency at which the reverberation measurement is carried out is not well defined due to the short impulses employed. On the other hand, the use of a warble tone is not necessary. In fig. 6 the result of measurements carried out according to the pulse glide method is shown. The measuring





A = Axle on which the camdiscs B and C are mounted
B = Camdisc which controls the on-off-switching of the loudspeaker.
C = Camdiscs for the control of the lifting relay
D = Ratchet wheel on which the contactors E and F are mounted. The movement of the wheel itself is controlled by the pawl H, and there is no direct mechanical coupling between the wheel and the axle A

E = Contact arms
F = Contact arms
G = Mechanism which determines the instant at which the wheel D is rotated a distance determined by the position of the "Curve Space"-mechanism K
H = Pawl which rotate the wheel D
K = Mechanism for the adjustment of the spacing between two adjacent reverberation curves on the rotating paper loop. The spacing between the curves is indicated on the switch

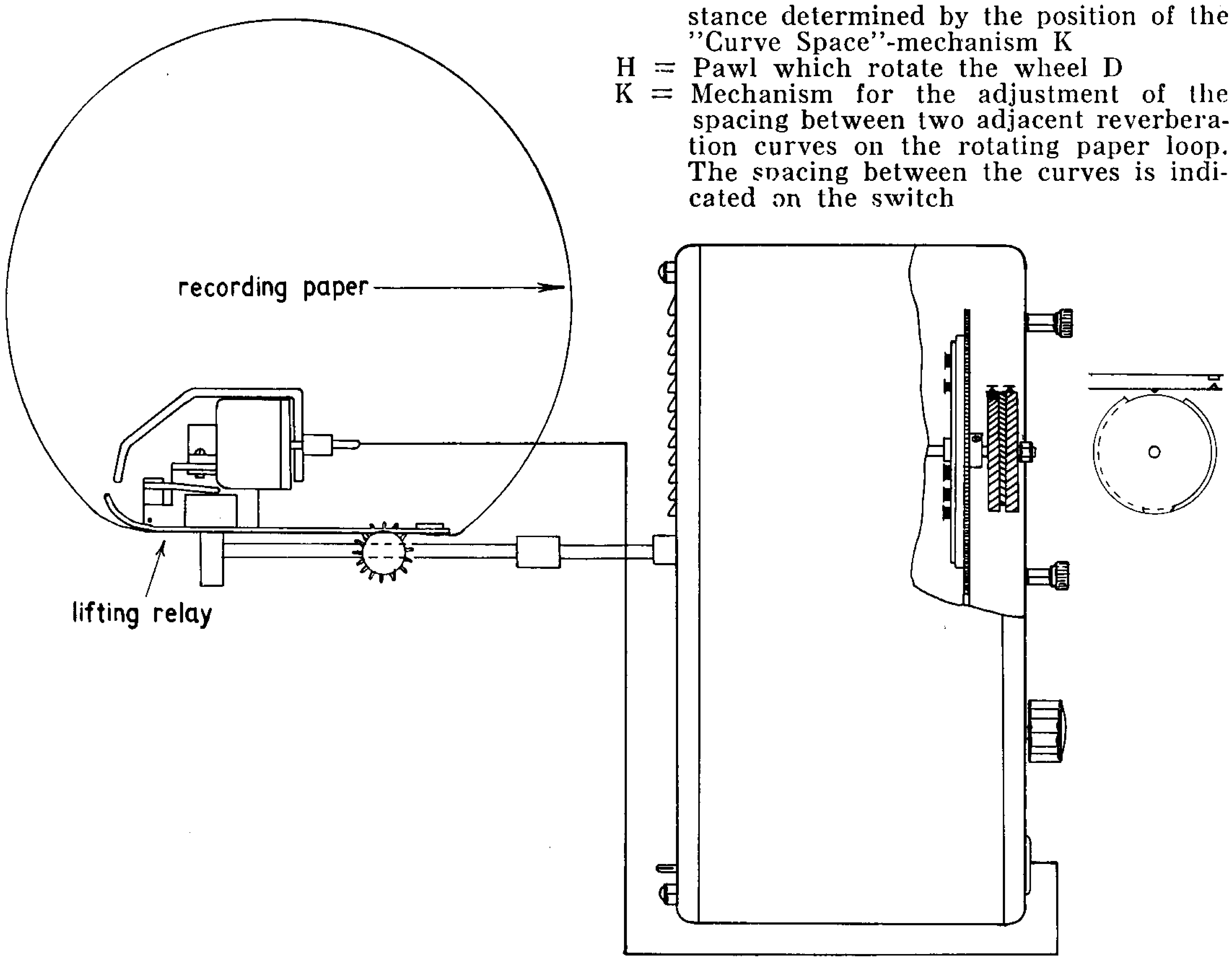


Fig. 5. Principle of operation of the Reverberation Switch 4407. A sectional view of the paper-drive and lifting magnet on the Level Recorder 2304 as well as the more important parts of 4407 is also shown.

arrangement of fig. 4 was employed. The acoustical quality of the room is now estimated from the irregularities of the different curves. To describe these irregularities Sommerville uses the word "Colouration", which does not give an exact definition of the room's quality, but describes the acoustical anomalies quite well. However, it is something of an art to extract the correct informations from the measurements.

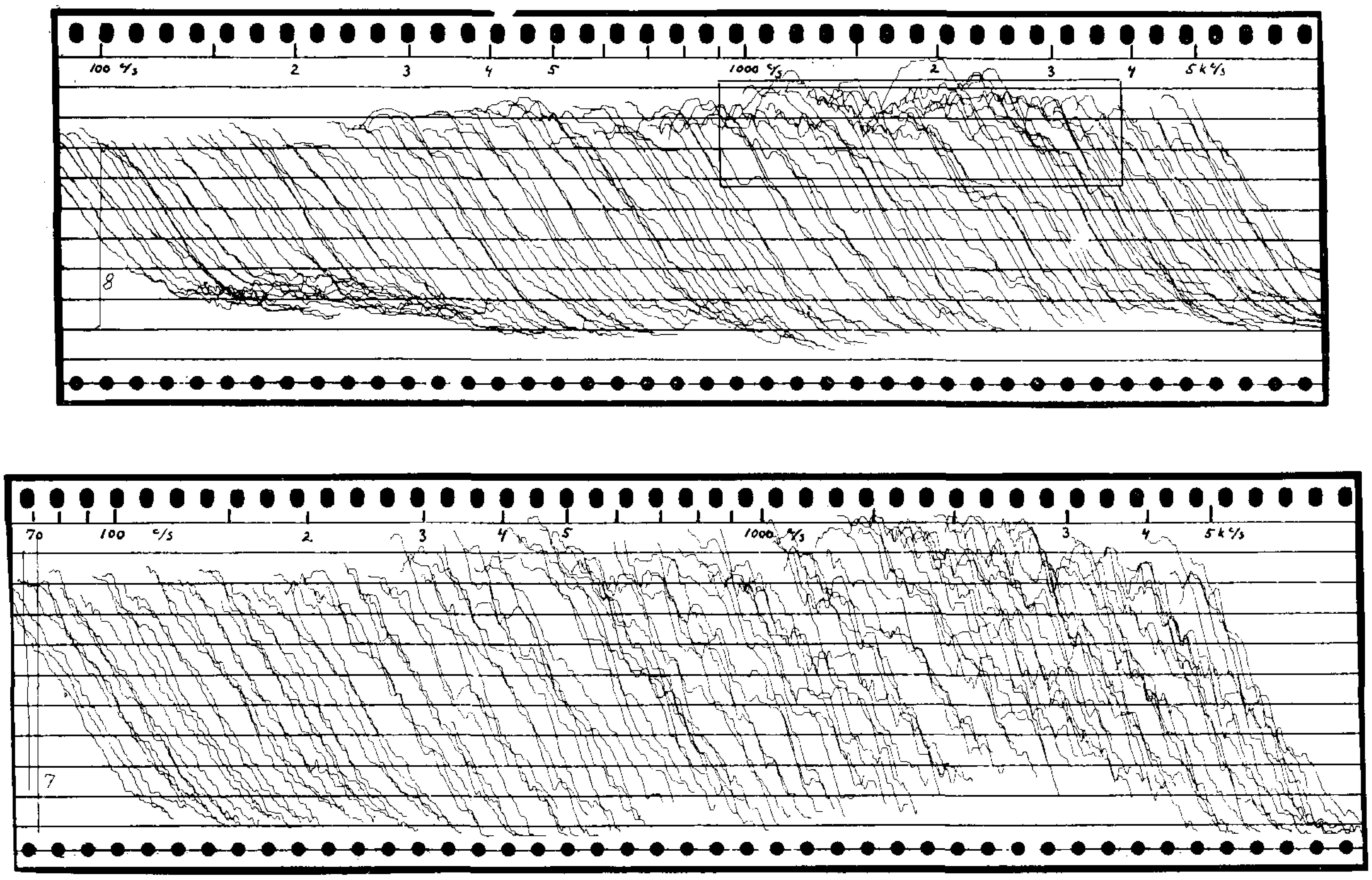


Fig. 6. Typical curves recorded with an equipment as shown in fig. 4 according to the pulse glide method. Note the exactly logarithmic frequency scale, the length of which can be varied by an adjustment of the spacing between adjacent curves. This adjustment is made by means of a knob on the front panel of the Reverberation Switch.

Looking at the reverberation process from a wavemechanical point of view, the reverberation curve of an acoustically lop-sided room will show two or more different inclinations. By an acoustically lop-sided room is meant a room in which two of the walls are furnished with sound absorbing material, and the remaining walls are acoustically hard.

The initial inclination of the reverberation curve is determined by the damping of the main group of eigentones, whereas the end inclination is mainly determined by the eigentones which move parallel to the absorbing material, and are thus damped to a smaller extent.

The relative magnitude of the above mentioned types of eigentones are of great importance with respect to the acoustical quality of the room.

In an acoustically good room the damping of the different eigentones should be approximately the same, i.e. the reverberation curves should show a constant inclination over a range of 35 to 45 db. When the measured results from the pulse glide method are estimated, the most important part of the estimation will therefore be to determine the irregularities in the inclinations of the reverberation curves. ,This then is the factor which gives a picture of the "Colouration".

To be able to judge as exactly as possible the acoustical anomalies of a room, a measuring method should be employed which gives a clear indication of the different damping of the eigentones in the frequency band under consideration. This means that the "bends" on the reverberation curves should

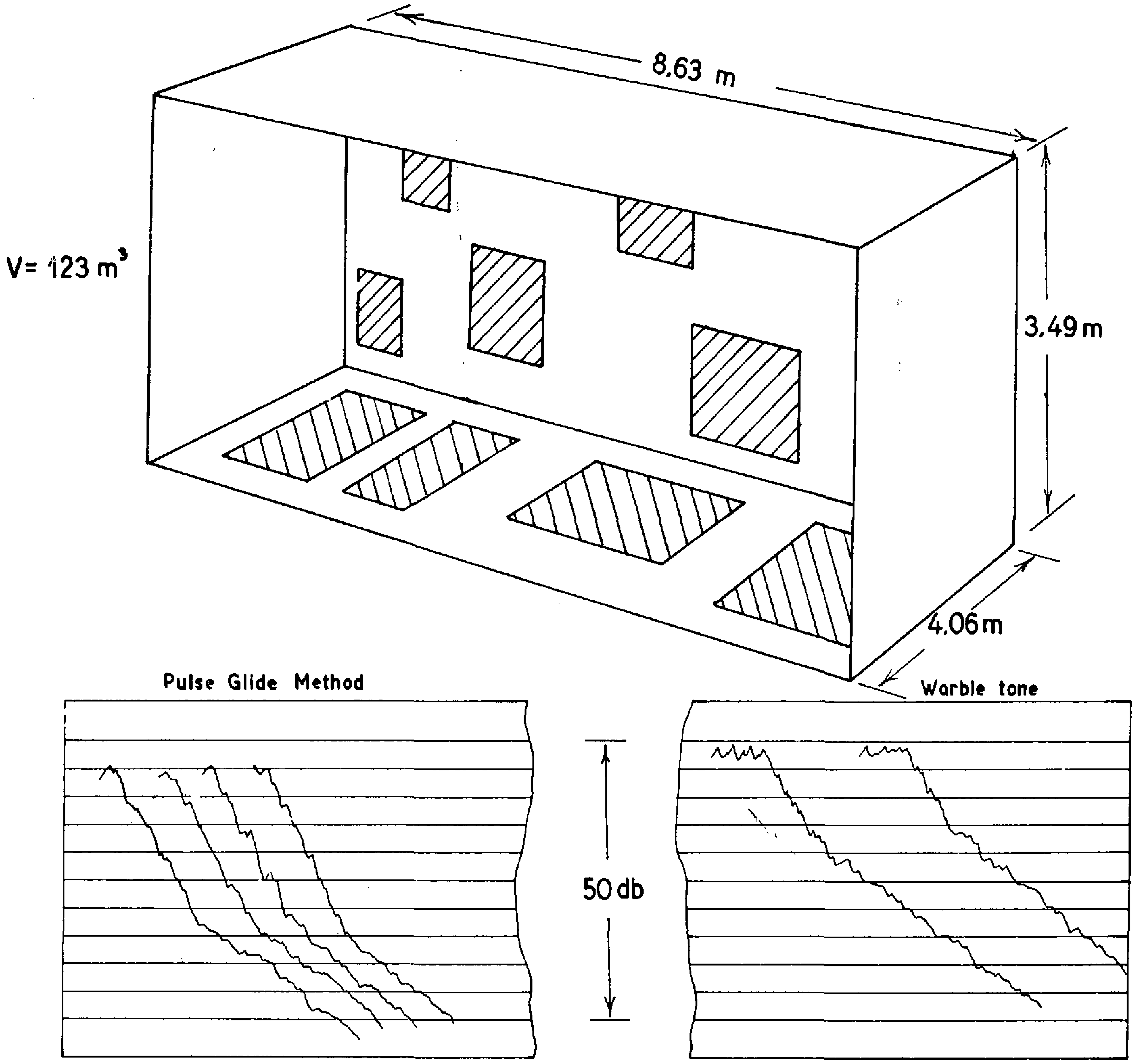


Fig. 7. Rectangular room ($V = 8{,}63 \times 4{,}06 \times 3{,}49 = 123\ m^3$) which is acoustically "bad", due to a too great sound absorption at two of the bounding surfaces. Reverberation curves obtained from measurements at 450 c/s in the above described room are also shown.
The curves shown to the left are recorded according to the pulse glide method, while the curves to the right are obtained from normal warble tone measurements (frequency swing ± 30 c/s).

take place as early as possible to reduce the undesired inaccuracy in reading caused by the effect of the noise level.

At the bottom of fig. 7 two recordings are shown, both being obtained from measurements in the same room.

One of the recordings is made in accordance with the pulse glide method, pulse length 180 milliseconds. The other recording is obtained from measurement with warble tone (frequency swing ± 30 c/s).

Both recordings show approximately the same initial and end inclination as well as the same fluctuations, but the "bend" on the curve is registered essentially earlier when warble tone is employed in the measurement than when the pulse glide method is used.

The reason for this difference in registration of the "bend" is the following:

The total quality factor (Q), for eigentones with a long reverberation time is higher than the "Q" for eigentones with normal damping (main group).

Therefore a short lasting impulse of 100—200 milliseconds duration will excite the eigentones having a smaller Q to a greater extent than it will excite the eigentones having a higher Q-value.

However, measurements with warble tone are normally carried out by transmitting the sound into the room for a longer period of time before the sound source is shut off. In this way eigentones with heigher Q will be excited to a level proportional to Q i.e. the initial level of the group of eigentones determining the end inclination of the reverberation curve will be higher than when the pulse glide method is used.

The acoustical anomalies of the room will therefore be more clearly noticed on reverberation curves obtained from measurements with warble tone than when short lasting impulses are employed.

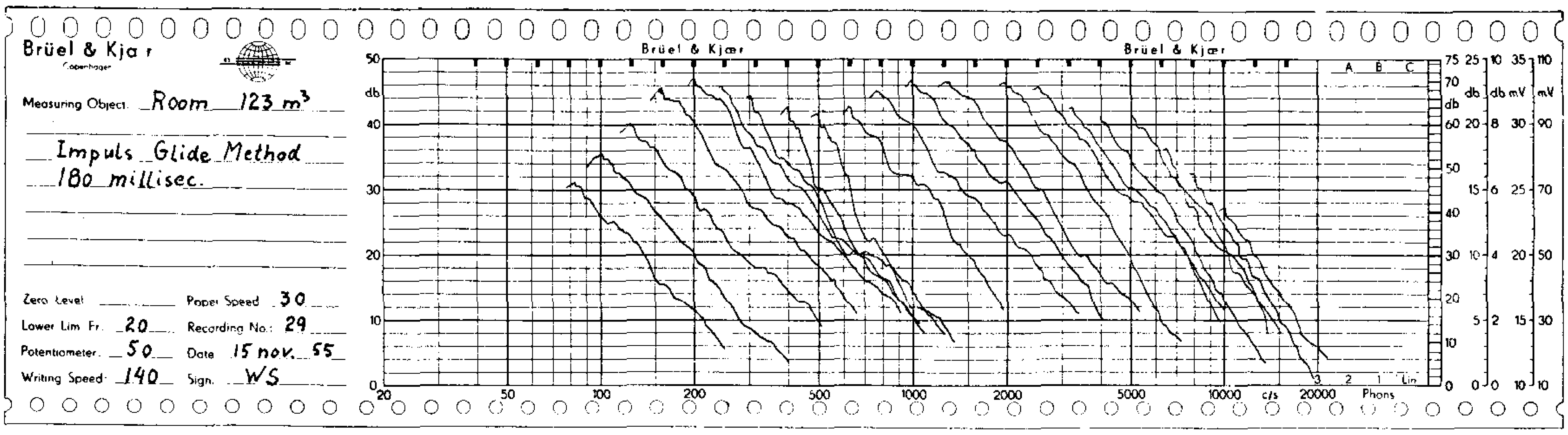
A further disadvantage of the pulse glide method is that the different decay curves do not start from the same level.

This difference in level is due to the loudspeakers used for the measurement which will not give the same response to all frequencies, whereby the evaluation of the measured results is made complicated.

As shown in fig. 10 it is possible when the warble tone method is used to utilize the automatic volume regulator of the B.F.O. Type 1014. By employing the regulator the sound level in the room is adjusted to the same value before the sound source is shut off. This is not possible when the pulse glide method is used. Fig. 8 shows the difference in recorded reverberation curves when the warble tone method employing automatic volume regulation is compared with the pulse glide method.

The rather large variation in "Starting Level" due to the non linear frequency response of the loudspeaker is clearly noticed. By using pre-printed, frequency calibrated paper *and employing the automatic volume regulator* it is possible to obtain a frequency calibrated recording of the different reverberation curves.

The curves will then be spaced at a distance of $^1/_3$ octave.



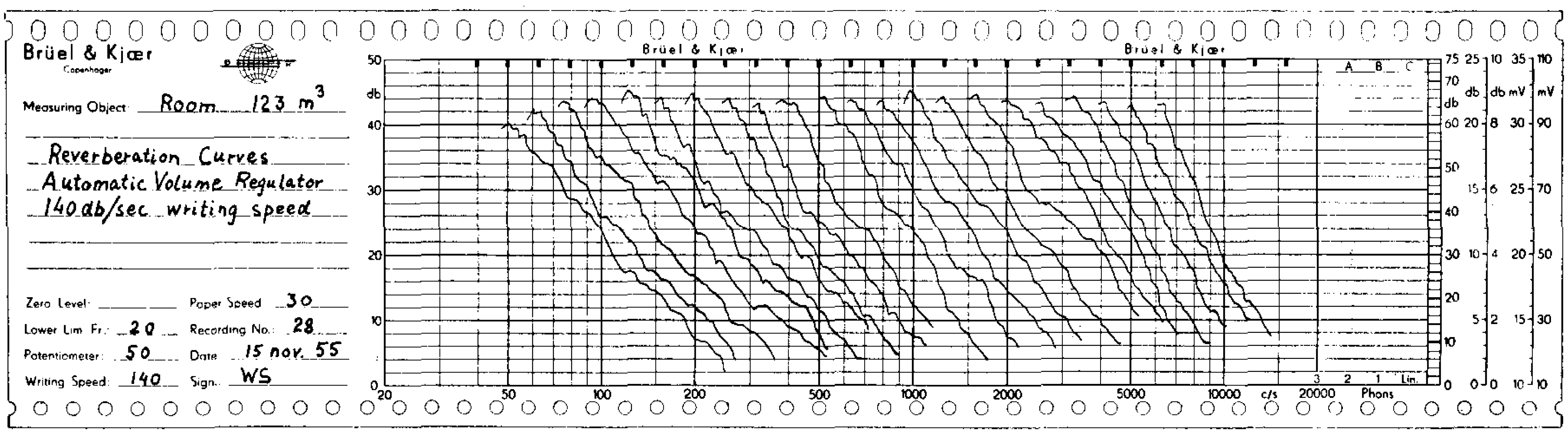


Fig. 8. Reverberation curves obtained from measurements with warble tone, using automatic volume regulation. Reverberation curves obtained from measurements in the same room according to the pulse glide method are also shown. The deviation in "Starting Level" for the different curves when the pulse glide method was employed is clearly seen.

To obtain a detailed picture of the acoustical quality of a room it is necessary to investigate the slope of the reverberation curves over a wide level range, at least 45—50 db. It is not only difficult, but also rather expensive to drive the loudspeakers with more than 3—10 watts (100 watts will only give a 10 db higher intensity level than 10 watts) and the only remaining solution to the problem of obtaining a wide level range is therefore

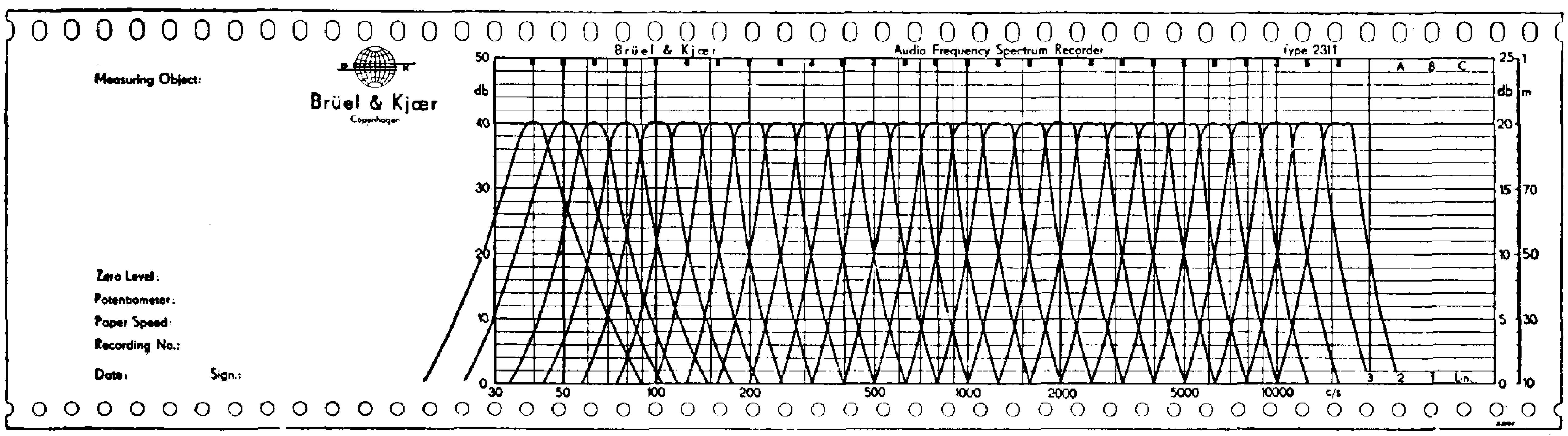


Fig. 9. Filter Curves for the selective microphone amplifier (Spectrometer) Type 2109. The shifting from one filter to the next can be carried out automatically, and brough into complete synchronism with the frequency sweep of the B.F.O. Type 1014.

to reduce the noise level. This can be accomplished by employing a selective microphone amplifier, with a bandwidth of, for example, $^{1}/_{3}$ octave. The amplifier (or rather analyzer) must then be driven in sychronism with the tuning of the Oscillator.

In this way all frequencies outside the passband of $^{1}/_{3}$ octave are heavily attenuated, and the noise level will be reduced by approx. 20 db. A detailed analysis of the end inclinations of the reverberation curves is thus possible.

An effective noise reduction is, of course, only obtained when the characteristic curves of the filters employed show steep slopes outside the pass-band. A steepness of the slope of 80 to 120 db/octave is preferable. Fig. 9 shows the filter characteristics of a suitable selective amplifier.

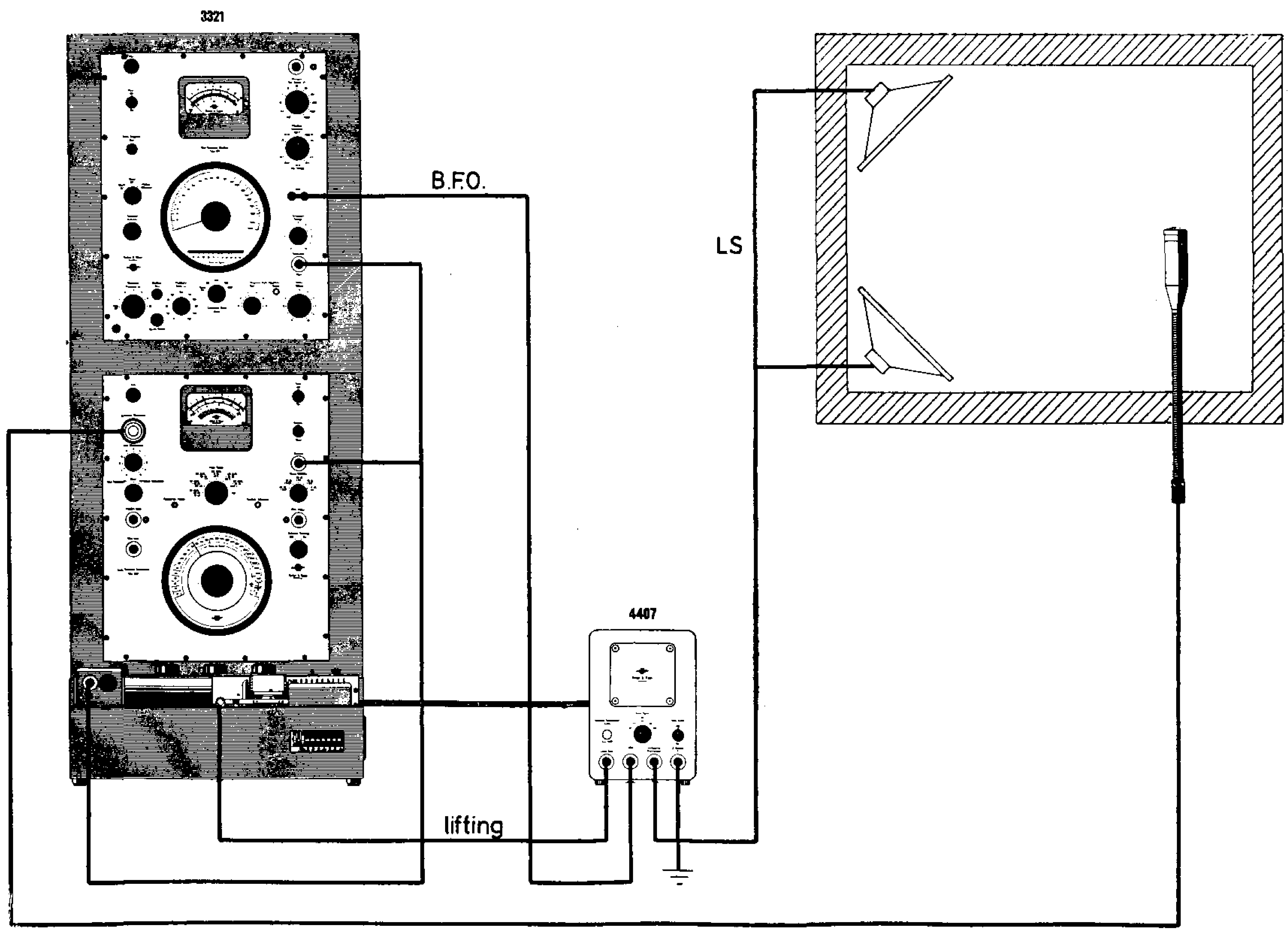


Fig. 10. Measuring arrangement for recording reverberation curves automatically. The arrangement consists of Beat Frequency Oscillator Type 1014 containing automatic volume regulation, selective microphone amplifier (Spectrometer) Type 2109 and the High Speed Level Recorder Type 2304, all instruments mechanically coupled together in one single unit, namely the A.F. Response and Spectrum Recorder Type 3321. Further instruments employed in the set-up are the Reverberation Switch Type 4407, Condenser Microphone Type 4111 and the cables necessary for the electrical connections of the arrangement.

From the foregoing it is seen that *selective amplification should be employed both when the pulse glide method is used and when normal reverberation measurements are takenn.*

A measuring arrangement which satisfies the above requirements is shown in fig. 10. In a single unit, namely the A.F. Response and Spectrum Recorder Type 3321 both Oscillator 1014 (supplied with automatic volume regulator) selective microphone Amplifier (Spectrometer) 2109 and Level Recorder 2304 are contained, all instruments being mechanically coupled together enabling synchronous drive. The frequency range of the instruments can be swept totally or partly with 9 different speeds to be selected within wide limits.

The recording paper is folded in a loop with a total loop length of 48 cm, exactly as with the pulse glide method, and the Automatic Reverberation Switch 4407 is used to control the loudspeaker on-off switching, the writing stylus on the Level Recorder, and the slight shifting of the recording paper.

A group of reverberation curves recorded in a set-up as shown in fig. 10 and described above, gives a lot of valuable information, not only regarding the reverberation time of the room at a number of different frequencies, but a detailed study of the separate reverberation curves or groups of curves is possible.

To obtain an idea of the difference between an acoustically "good" and an acoustically "bad" room, different rooms of the same size which had approximately the same reverberation time at all frequencies, were investigated. However, the sound absorbing material was placed in such a way that one of the rooms was judged as acoustically "good", while the other was found to be acoustically "bad" when judged subjectively. The reverberation curves of the acoustically "good" room GA are shown at the top of fig. 11, and the reverberation curves of the corresponding acoustically "bad" room DA are given in the middle of the figure.

At the bottom of fig. 11 the reverberation time as a function of the frequency is shown for both rooms. The rooms were rectangular, with a volume $V = 8{,}63 \times 4{,}06 \times 3{,}49 = 123\ m^3$, both being furnished with "normal" furniture. In room DA most of the sound absorbing material was situated at the ceiling, the rest being furniture and carpets placed on the floor. In room GA the absorbing material was more uniformly spread all over the bounding surfaces of the room. From the reverberation curves the essentially more irregular slopes of the curves obtained from measurements in the acoustically "bad" room is clearly noticed, even though the size of the rooms, their form, furnishing and measured reverberation times are almost equal in the two cases.

A second pair of rooms were also investigated, the dimensions of the rooms being $6{,}10 \times 6{,}20 \times 3{,}82 = 144\ m^3$, and the number and sort of furniture being almost equal in both rooms.

However, the sound absorbing material was again differently placed.

Room GB was subjectively judged as acoustically "good", room DB as

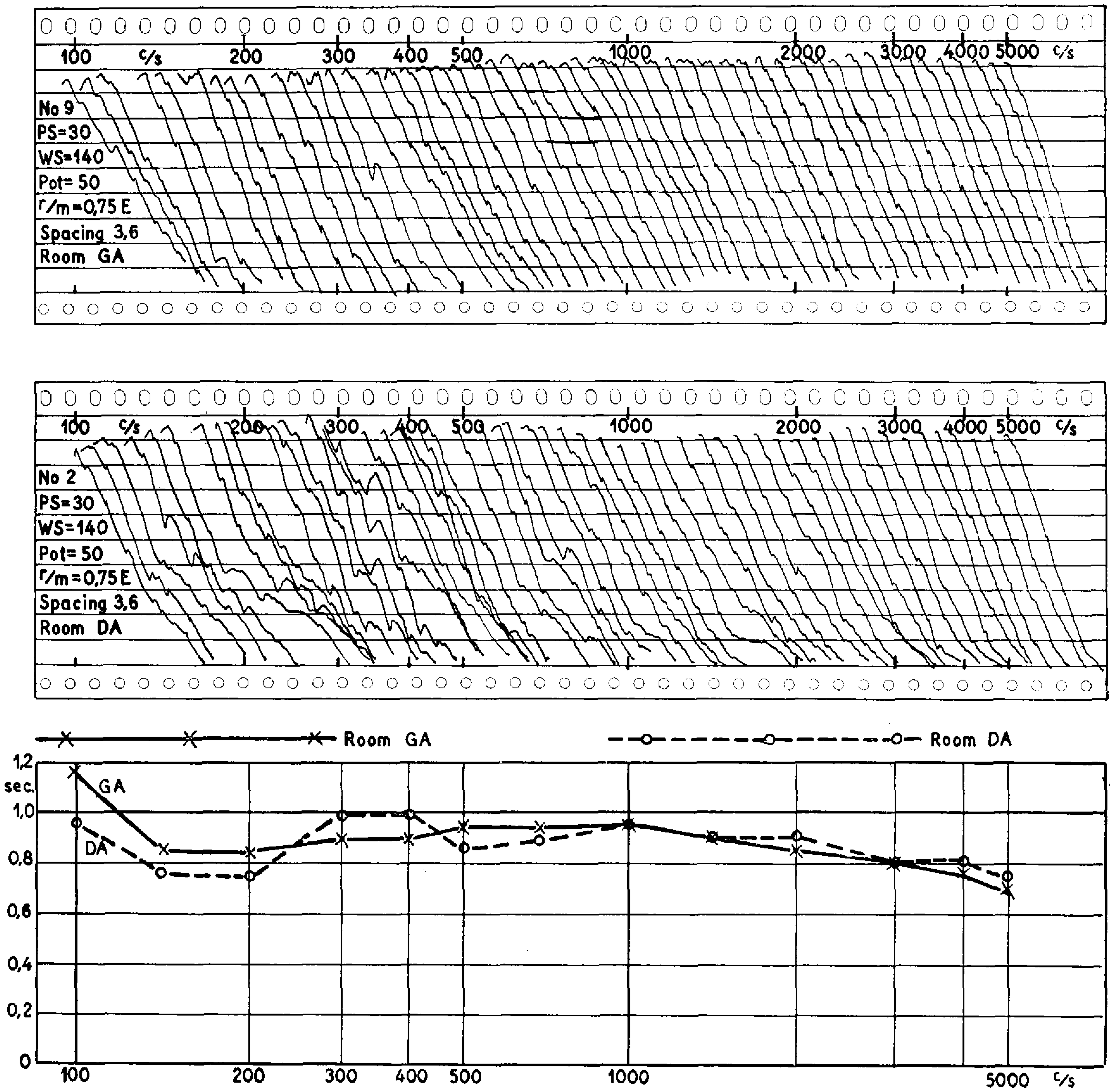


Fig. 11. Reverberation curves obtained with the measuring arrangement shown in fig. 10. The measurements were carried out both in an acoustically good room GA (above) and in an acoustically bad room DA, of the same dimensions and furnished with the same type and quantity of furniture. Below is shown the reverberation time as a function of frequency for the two rooms. The frequency scale is valid for the starting points of the curves.

acoustically "bad" or "mediocre". In the subjective judgement of the two rooms, the slightly greater damping effect in room GB relative to room DB must be taken into account. The far greater irregularities in the reverberation curves measured in room DB than those measured in room GB is clearly seen from fig. 12. All reverberation curves shown in fig. 12 are taken with the same paper-speed, writing speed, frequency scanning, spacing etc. The frequency scale indicated is valid for the starting points of the curves.

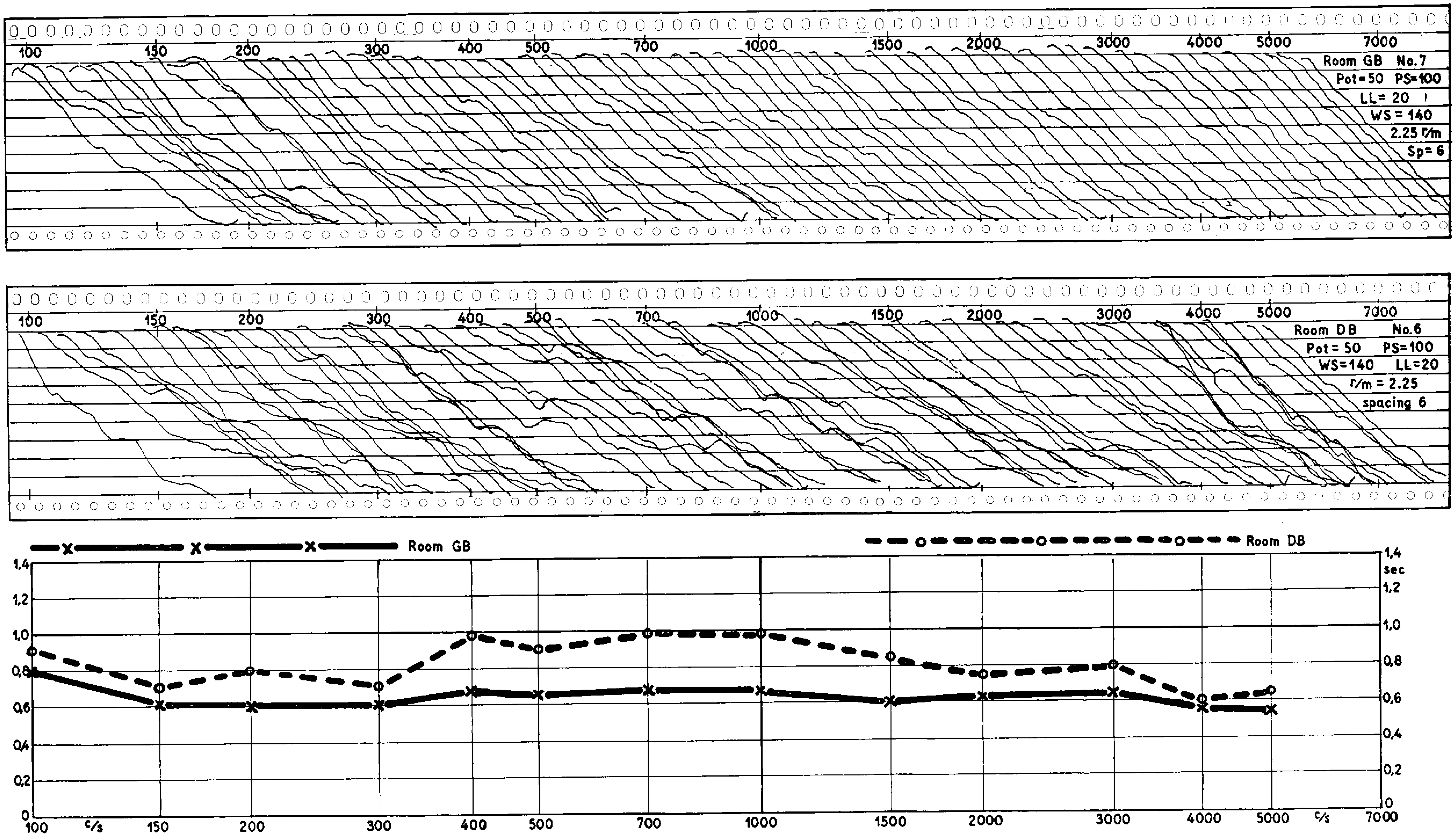


Fig. 12. Reverberation curves obtained from measurements in two acoustically differently treated rooms of the same size ($V = 144\ m^3$). GB was judged subjectively to be acoustically good, DB to be acoustically bad. Below is shown the reverberation time as a function of frequency.

When reverberation measurements are carried out in a room, the reverberation curves should be recorded by means of an arrangement as shown in fig. 10, which gives the following advantages when compared with the conventional method where each reverberation curve is measured separately.

1) In addition to the determination of the reverberation time, an impression of the acoustical quality of the room is obtained which is in agreement with the subjective judgement.
2) The measuring method gives, without difficulty or a great consumption of recording paper, a large number of curves measured at different frequencies.
3) The measurements can be carried out automatically, whereby time is saved both when the measurements are taken, and, which is even more important, when the measured results are evaluated.
4) It is easy to take copies of the curves, whereby the original reverberation curves can be kept at hand. A copy of the recordings should be included with every report on reverberation measurements so .nat the originally measured results can always be checked and discussed.

It might be possible in some way or other on the basis of curves such as those shown in fig. 11 and 12, to express the acoustical quality of a room by means of a formula in which, for example, a relationship between the initial inclination T_1, and the end inclination T_2 of the reverberation curves, together with the spacing d in db between the starting point of the curves to the cross-over point between the initial- and end inclination is employed.

A possible formula is (see fig. 13):

$$\text{Acoustical Quality } AQ = \frac{T_1}{(T_2 - T_1)\, d}$$

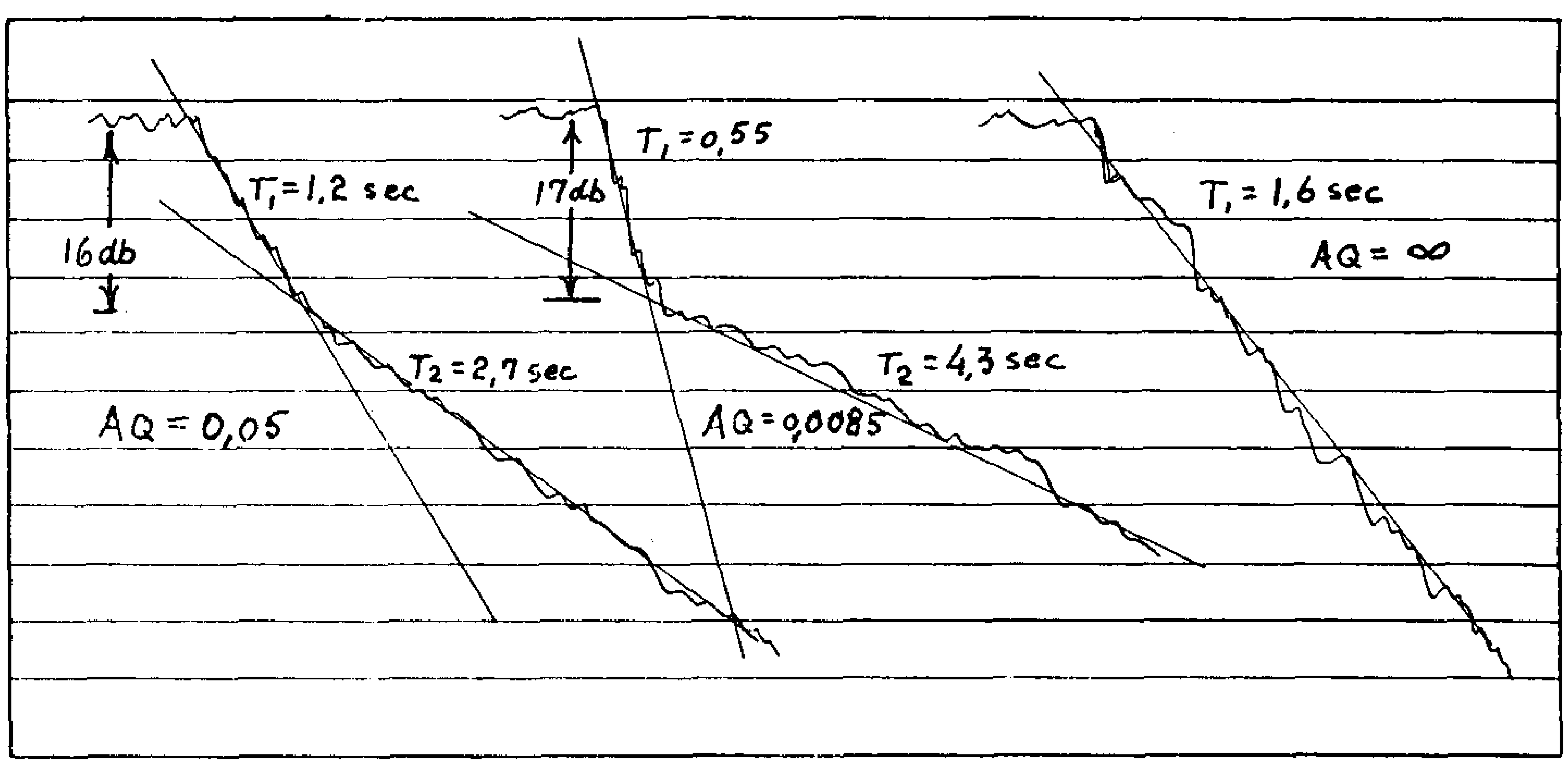


Fig. 13. Examples of the determination of acoustical quality AQ according to to the formula:

$$AQ = \frac{T_1}{(T_2 - T_1)\, d}$$

For the curves shown in fig. 13 the quality is determined by means of this formula and indicated on the figure.[5]) However, defining a relationship for the determination of acoustical quality as in the above given formula is not possible until this or a similar formula has been tried on a great amount of material available from different reverberation measurements.

Such a work is based on, that when a room is described acoustically, not only the reverberation time as a function of the frequency should be given (which has been normal practice up to now), but the reverberation curve itself should also be published.

References.

[1]) Fig. 1 and Fig. 2 see also Per V. Brüel: Sound Insulation and Room Acoustics (Chapman & Hall, London, 1951) p. 179 and 180.

[2]) R. H. Bolt and R. W. Roop: Frequency Response Fluctuations in Rooms. J. A. S. A., Vol. 22 (1950) p. 280.

[3]) Per V. Brüel: Automatic Recording of Frequency Irregularity in Rooms. B. & K. Technical Review, No. 3, 1953.

[4]) T. Sommerville and G. L. S. Gilford: Composite Cathode Ray Oscillograph Displays of Acoustic Phenomena and their Interpretation. The B.B.C. Quarterly, Vol. 7 (1952-53) p. 41.

[5]) A somewhat similar attempt to find an expression for the acoustical quality of a room has been made by Sommerville. See also T. Sommerville: An Empirical Acoustic Criterion. Acoustica, Vol. 3 (1953) p. 365.

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