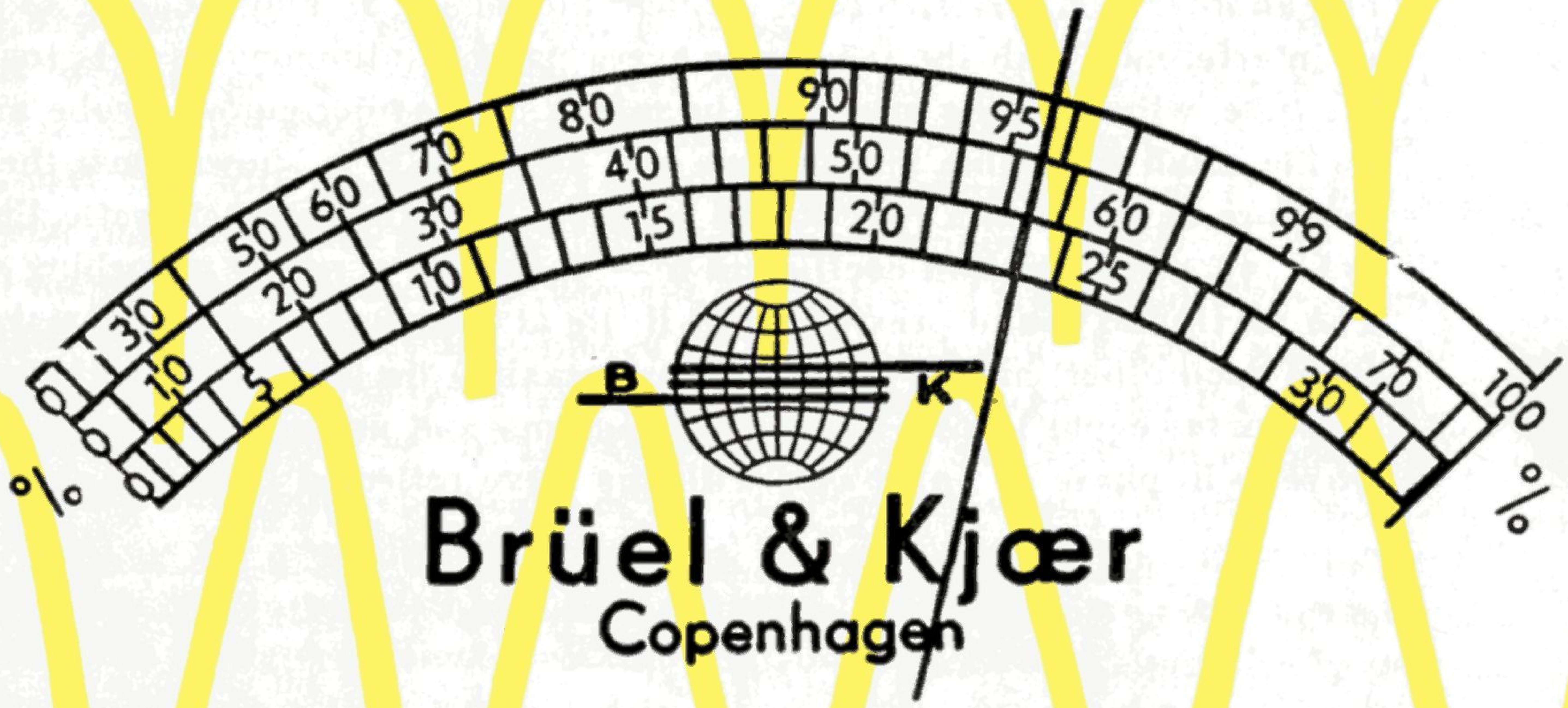
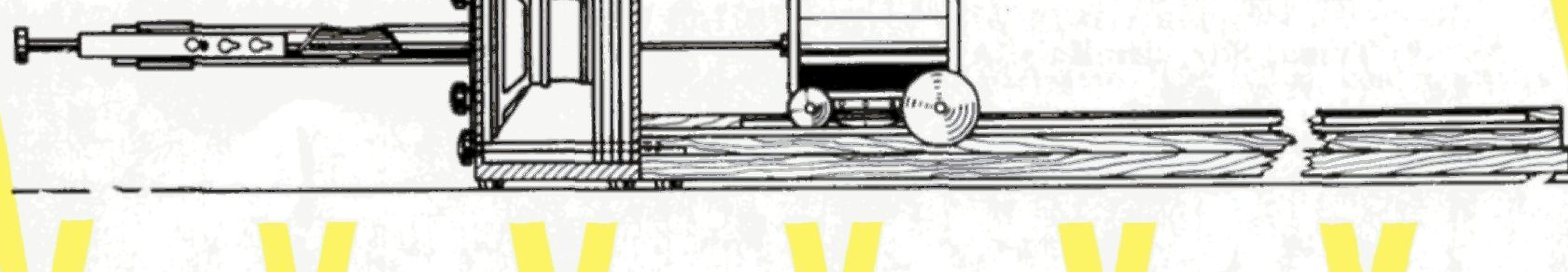
Brüel & Kjær

Technical Review

Teletechnical, Acoustical and Vibrational Research



STANDING WAVE APPARATUS



No. 1 January 1955

The Standing Wave Apparatus

by

Per V. Brüel. D. Sc.

As early as 1902 Tuma*) gave a method for measuring acoustic absorption coefficients by means of standing waves in a tube. This standing wave method has been considerably developed in the course of time, and has contributed greatly to the development of effective acoustic absorbents, which are the most effective weapon at the command of modern building technique in its fight against noise.

In fig. 1 a sketch of the principles of the apparatus is shown. Sound of pressure amplitude A is directed down the length of the tube by means of a loudspeaker at one end, to strike the sample placed at the other end. When the sound waves encounter the sample, part of the sound energy is absorbed and another part reflected back through the tube at an amplitude B. As a result of interference with the incident wave a partly stationary wave is formed in the tube, which can be measured by means of the microphone probe mounted in the small moveable microphone car. In fig. 2 it is shown how the sound pressure develops as a function of position, both for complete reflection, that is to say, an absorption coefficient $\alpha = 0$, and for a partly absorbing sample. The maximum sound pressures (A+B) lie at distances of one-half wavelength from each other, and in between these maxima lie the minimum points with amplitudes equal to (A—B). At such maxima and minima the incident sound wave is in phase or anti-phase with the wave reflected from the sample.

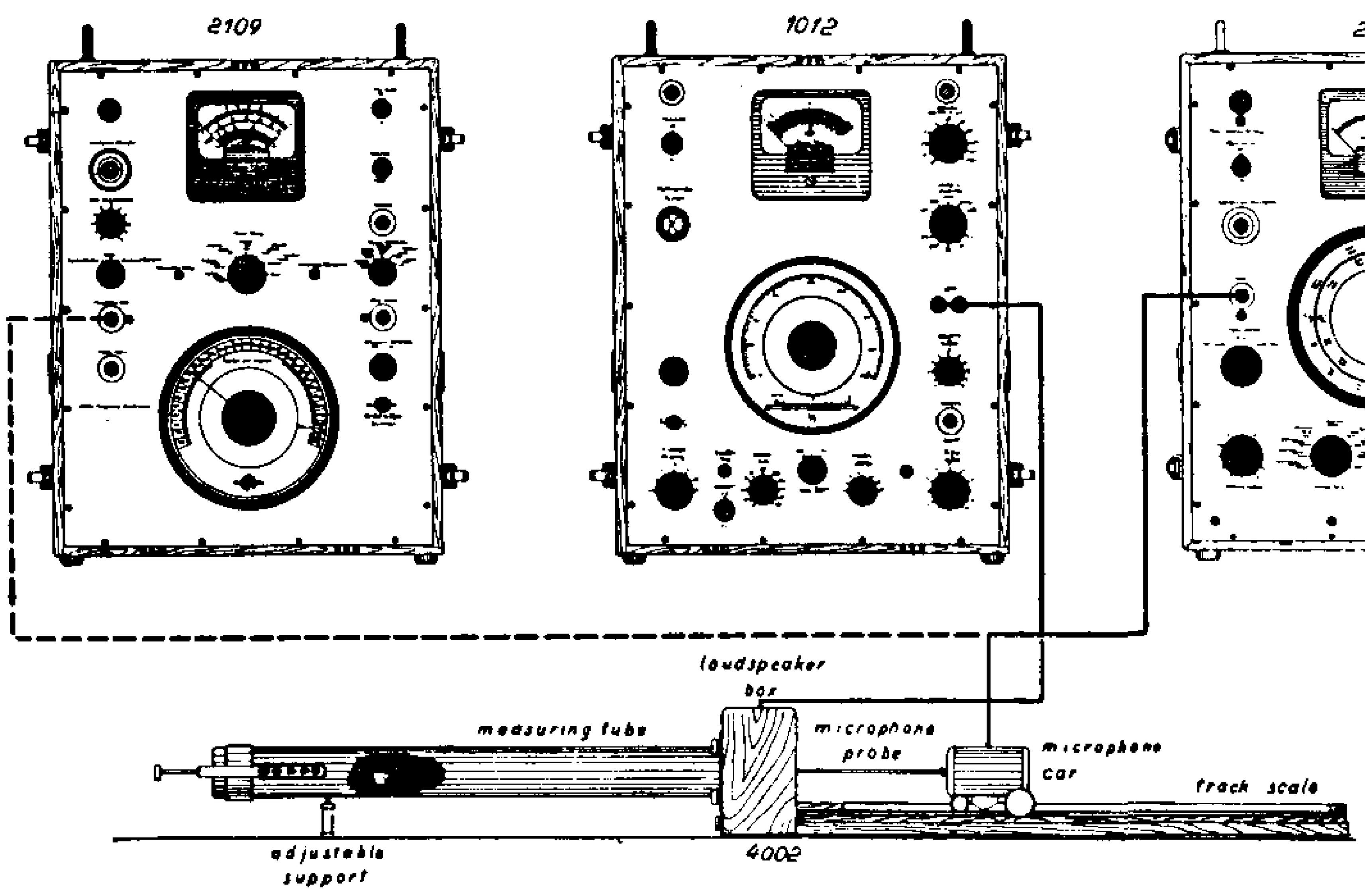


Fig. 1. Principle of the Standing Wave Apparatus for measuring acoustic absorption coefficients. The audio frequency generator used is the Brüel & Kjær B. F. O. type 1012, while as selective amplifier either Analyzer 2105 (adjustable to any frequency between 47 and 12,000 c/s) or Analyzer 2109 (for measurements at the standardized frequencies according to table I) may be used.

*) Tuma: Sitz. der Kais. Akad. der Wissenschaften, III 2 A, p. 402 (1902).

The measuring apparatus measures the relation n between the sound pressure maxima and minima in the tube

$$n = \frac{(A+B)}{(A-B)} = \frac{p_{max}}{p_{min}} .$$

The absorption coefficient of the sample is defined as the ratio between the energy absorbed by the sample and the total energy striking the sample. As the energy is proportional to the square of the sound pressure, we have

$$a = 1 - \frac{B^2}{A^2} = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4}{n + \frac{1}{n} + 2}$$

It is thus particularly easy to find the absorption coefficient, provided one knows the ratio between the maximum and minimum sound pressures. By means of a suitable construction of the electronic amplifying equipment the absorption coefficient can be read directly as a percentage on the instrument scale.

When a sample of an acoustic absorbing material is investigated in a standing wave apparatus, the question arises as to what kind of absorption coefficient one is measuring. It is well known from the acoustic literature that different laboratories often measure widely different absorption coefficients for the same material, with the result that many manufacturers and users of acoustic material have a certain mistrust for acoustic absorption measurements. The usual method for measuring the acoustic absorption of a material is the room method, where the material is placed in an acoustically "hard" room. The reverberation time of the room is measured both before and after the material is placed in it, whereafter, by using the well known Sabine formula, one can calculate the absorption coefficient of the material by dividing the total absorption found, by the area of the test material: It must be pointed out that what is really being measured in this room method is the given material's **acoustic behaviour in the given room.** One can both theoretically and practically demonstrate that even with the very same test material the acoustic effect is different in different rooms, and again, in these rooms, is dependent on the placing of the material on the wall or ceiling. Furthermore, the acoustic effect (calculated as an absorption coefficient) is dependent on the superficial area of the test material in the room.

Thus, with the room method, it is in a way useless to speak of a definite absorption coefficient when, at the same time, one has not precisely specified the room's size and shape, and the material's superficial area and method of siting. The absorption coefficients measured by the room method are thus not only dependent on the physical constants of the absorption material, such as the mechanical construction, thickness, density, porosity, elasticity, homogeneity, etc., but also to a high degree influenced by the conditions under which the material is measured. This state of affairs is easily understood, when one considers that the absorption coefficients measured by the room method are not based directly on the definition of the absorption coefficient as the ratio between the energy absorbed by the sample and the total energy

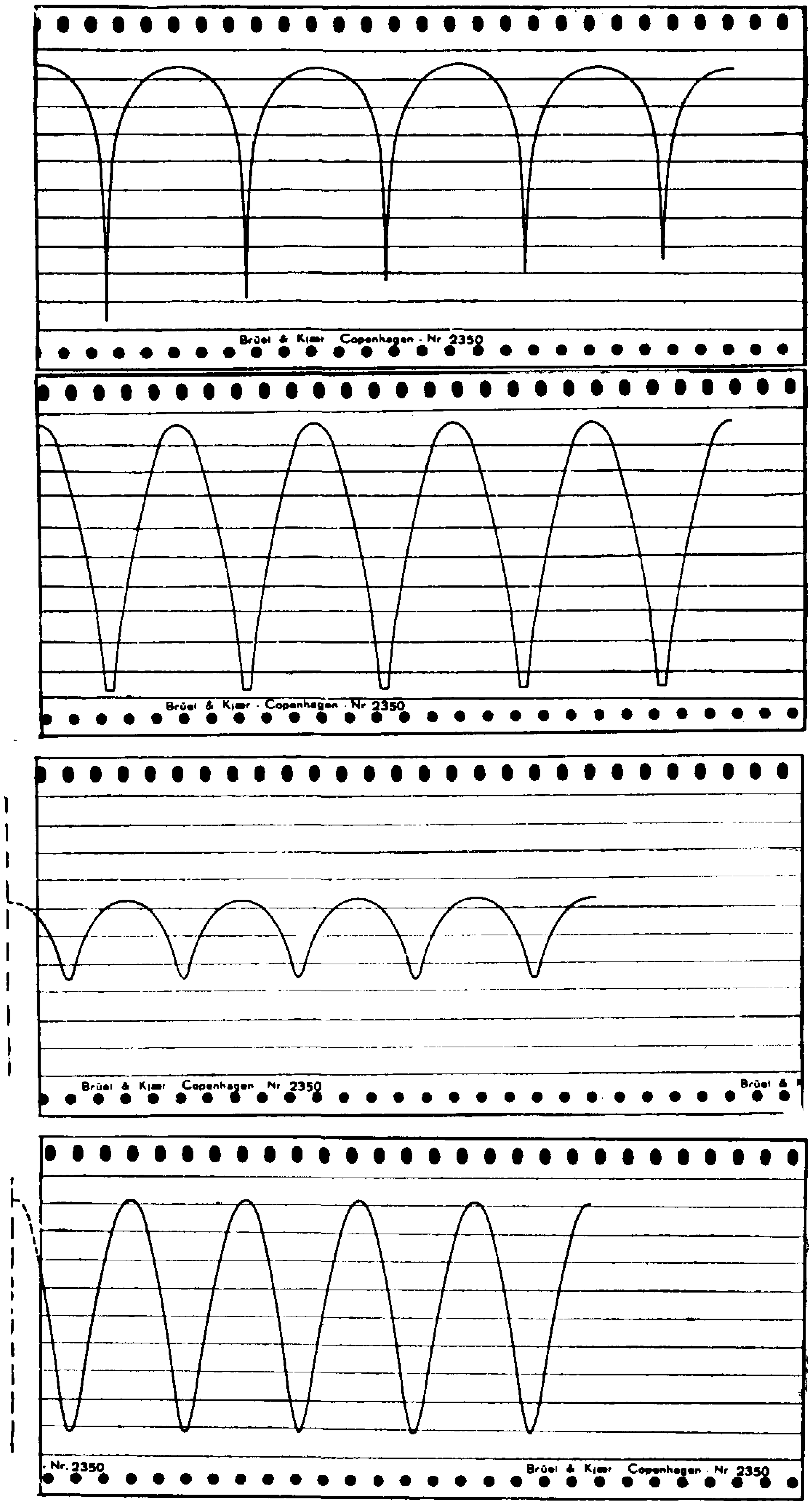


Fig. 2. Sound pressure as a function of the position of the microphone car, for different terminations. Test frequency 1000 c/s.

a) Hard termination. The sound pressure is depicted logarithmically. The difference between the 1st maximum and the 1st minimum is greater than 50 db, which corresponds to a zero absorption of the tube less than 1.3%

b) As a), with linear pressure scale.

c) With absorbent termination, logarithmic scale.

d) As c), with linear scale.

striking it, but only indirectly, in that, by means of Sabine's statistical reverberation formula (which postulates a series of conditions which no practical room can satisfy) a reverberation coefficient is *calculated.*

The matter is quite different when it comes to the Standing Wave Apparatus method. Here, the absorption coefficient is *measured* directly on the basis of its definition, so that it is only dependent on the physical constants of the material. This fact is again demonstrated if one sends different samples to different laboratories with the request that they be measured in a Standing Wave Apparatus. Provided the samples are uniform, and set up in the same way in the apparatus, the results obtained will be the same. The Standing Wave Apparatus is therefore eminently suited for the development of new absorption materials and for continuous production control.

In recent years, with various room acoustic problems, such as the investigation of troublesame flutter echoes and similar phenomena which can arise in radio studios, auditoria and so on, the sound waves in the room have been calculated by solving the so-called wave equation, in which, as a boundary condition for the room's limiting surfaces, the specific acoustic impedance of the wall coverings has been inserted. This is defined as the complex ratio between the sound pressure and particle velocity at the material's surface. The complex form of the impedance arises because there is a phase difference between the pressure and the particle velocity of the air at the surface. As a rule the impedance is expressed as a complex number $Z = R + jX = /Z/ \angle \phi$ The unit is the *Rayl*, which in the CGS system is g $cm^{-2}s^{-1}$, and in the MKS system is kg $m^{-2}s^{-1}$. It is possible to measure this complex impedance of an absorption material by means of the Standing Wave Apparatus, as will be described later.

Manufacturers and users of absorption material very often have use for a method of working out an absorbent which has a special absorption curve as function of frequency. If, for example, the frequency spectrum of the noise in a factory has been measured and found to be particularly accentuated for certain frequency bands, it would be natural to try to produce an absorbent for placing on walls and roof whose most powerful absorption lay just in the frequency bands in question, whereby the most effective and economic damping would be obtained. Very often, changes in the acoustic material, such as changing the air spacing between material and supporting wall, changing the degree of perforation, changing the thickness of the plate and so on, can shift the absorption maximum within very wide limits. The Standing Wave Apparatus is indispensable for the working out and checking of such investigations.

However, the Standing Wave Apparatus has also very great limitations. Thus, it is only possible to take measurements on very small samples, as it is a condition for the mode of operation of the apparatus that the diameter D be less than about half the length λ of the sound. Theoretically one can deduce that the condition $\lambda > 1.7$ D must be satisfied in order that plane sound waves exist in the tube. It is thus not possible to take measurements in the Standing Wave Apparatus on absorbents whose absorptive effect is based on the vibration of large surfaces as a whole. Similarly, the conditions under which the samples are set up can often cause difficulty, as it is easy when inserting the samples in the tube to produce stresses in the different layers of the material, and thus either change the resonance or even produce resonances which do not appear in larger surface areas. These limitations are of a fundamental nature, and in using the Standing Wave Apparatus one must bear them in mind at all times, as otherwise one is liable to obtain quite meaningless results.

What demands may one make of a practical Standing Wave Apparatus? The greatest possible frequency range is of course desired, but one is limited as far as the lower frequency limit is concerned by reason that the apparatus shall be a little more than a quarter wavelength long. That is to say, that if the apparatus shall be held within a reasonable length, one can hardly measure under 90—100 c/s. Upwards, one is limited by the necessity that the diameter of the tube shall be less than 0.586 λ, in that there is a possibility for a first transverse resonance at this wavelength. As the tube method presupposes a flat sound field in the measuring tube's cross section, transverse resonances can naturally not be allowed, as these would give rise to a varying sound pressure in the tube's transverse direction. To extend the frequency range, the apparatus in its later form has two measuring tubes, one for the lower frequency range of 95—1600 c/s, and one for the higher frequency range from 800—6500 c/s. Measurements above approx. 5,000 c/s have no significance whatever for the absorbents used in practice, as at these higher frequencies most materials have a more than sufficient absorptive capacity. To make do with a tube length of a little more than $^1/_4$ wavelength, it is a condition that the sound field be symmetrical throughout the whole length of the tube, i.e., that the sound source be placed quite symmetrically at one end of the tube. If this is not the case, it is necessary to extend the tube by at least a half wavelength, so as to give a sufficiently uniform transverse distribution of the sound pressure in that part of the tube in which the measurement is taking place. Another condition is that the measuring tube shall be sufficiently stiff, so that no damping worth mentioning arises when the sound waves move up and down in it. In practice, this means that the measuring tube must be circular, and not square in cross section, as is often constructed, as it is exceptionally difficult to make it so stiff that dangerous damping can be avoided. When the tube is terminated by means of a solid end holder, it should be possible to obtain a high ratio between maximum and minimum, which is a sign that there is no damping in the sides of the tube or the end holder. As the audio frequency oscillator used has often a quite weak 2nd harmonic, whose maxima will lie exactly over the minima of the fundamental, it is recommended in practice to use a selective amplifier for measuring the maximum/minimum ratio.

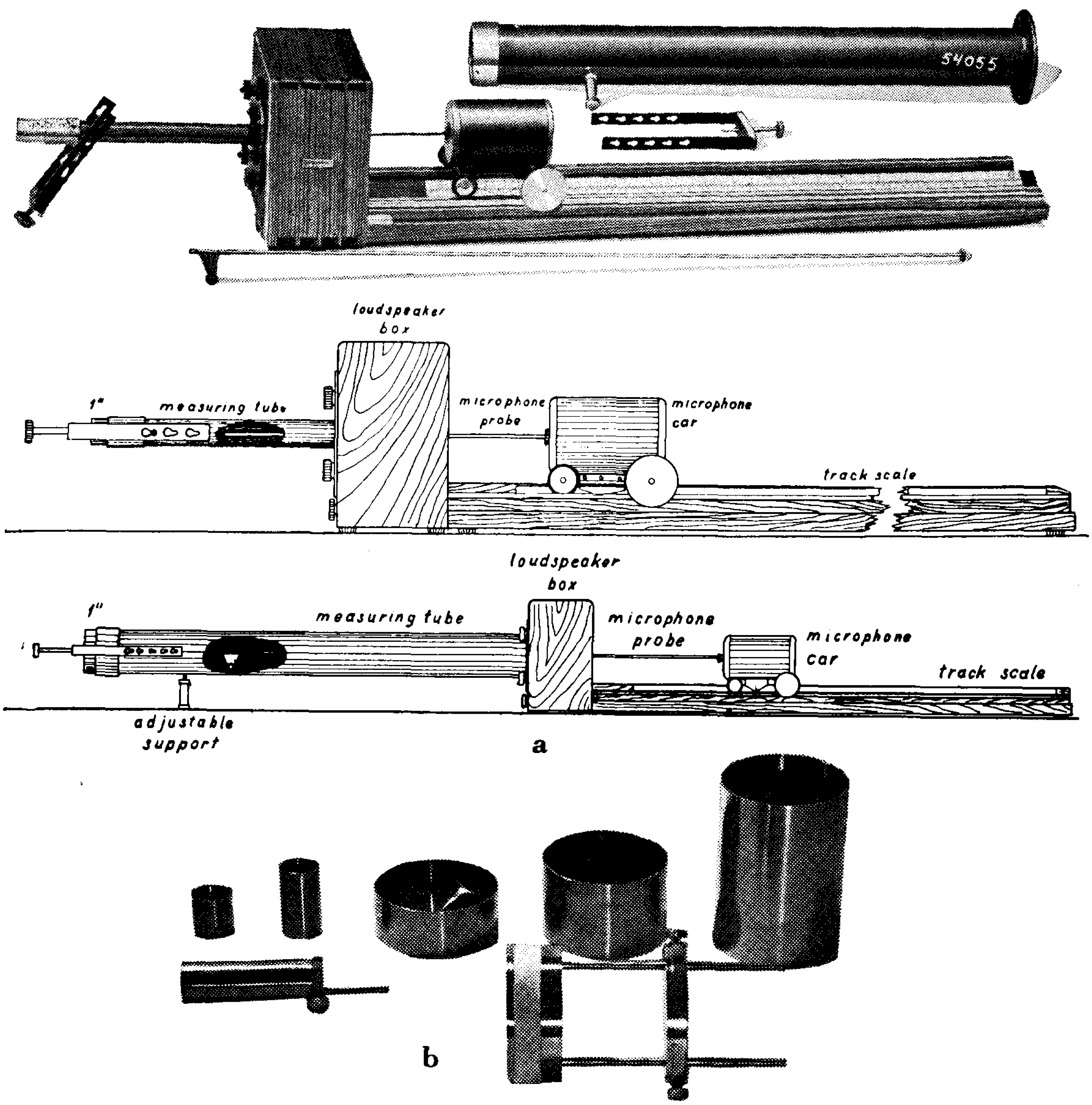
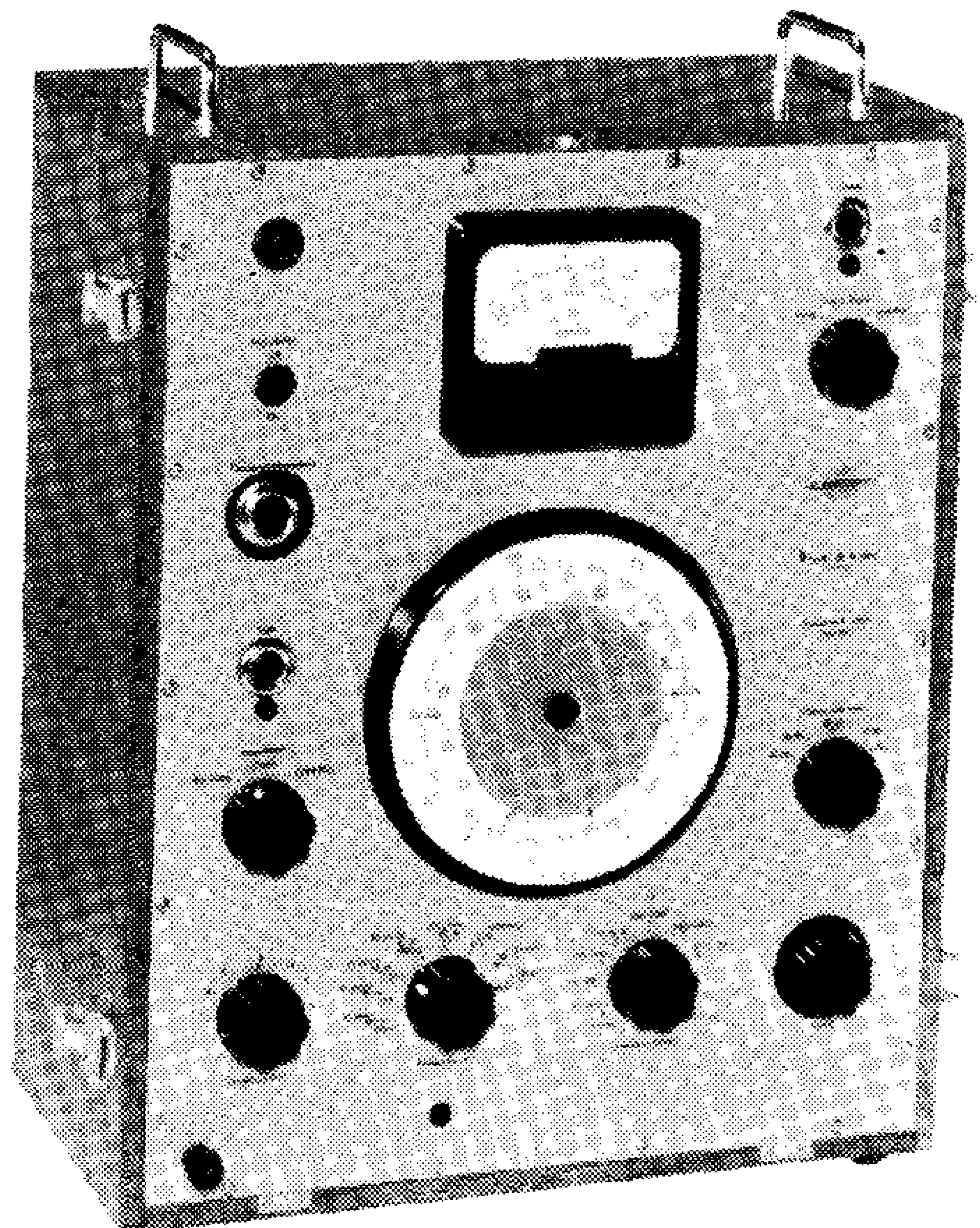


Fig. 3. a) Photograph and drawings of the Standing Wave Apparatus type 4002. b) Photograph of the six different sample holders belonging to the apparatus.

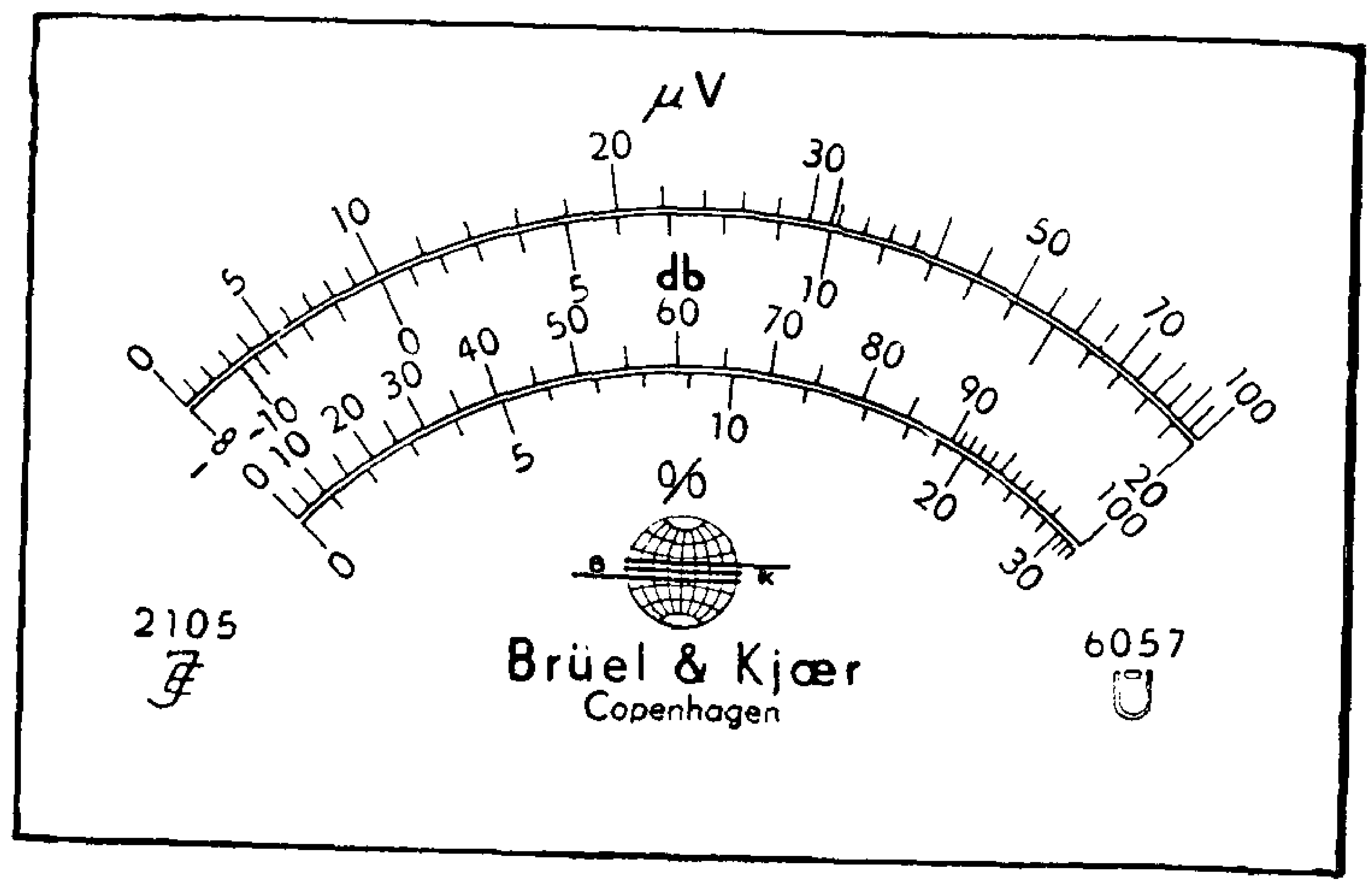
For the apparatus to be practicable in use, it is important that the samples can be set up in a simple manner, and that the holders, which are used to receive the samples and to terminate the tube, fit the tube hermetically.

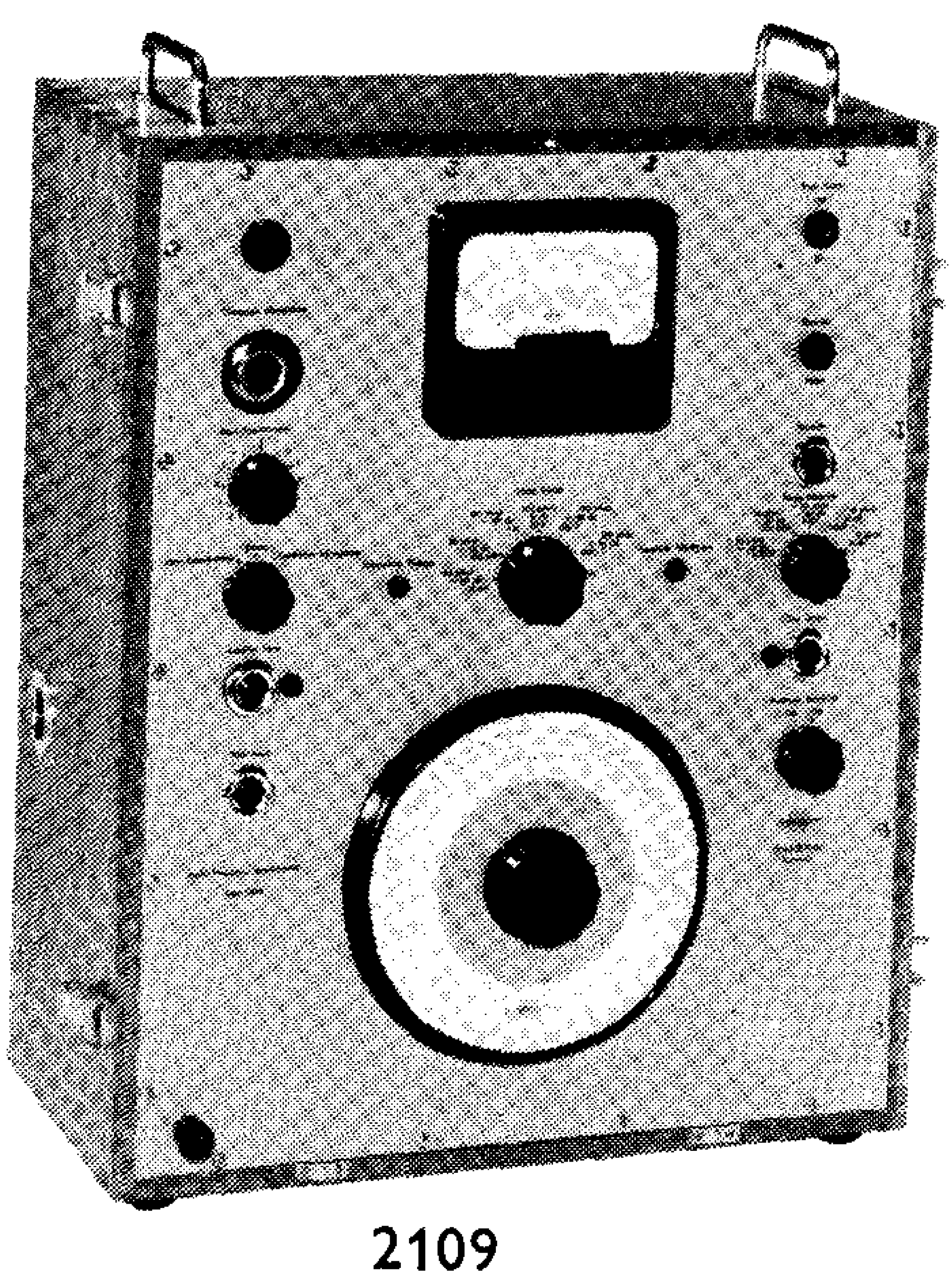
Description of the Standing Wave Apparatus type 4002.

Fig. 3 shows a photograph and drawings of the commercial form of the Standing Wave Apparatus, which consists of two measuring tubes with diameters of respectively 10 and 3 cm, covering a frequency range from 95 to 1600 c/s and from approx. 800 to 6500 c/s. These measuring tubes can be screwed to a loudspeaker case which is placed symmetrically with respect to the measuring tube, so that the sound field is plane at the start. A probe microphone is inserted in the measuring tube, the microphone itself being placed in a good insulated moveable measuring carriage, running on rails. The position of the probe can be read off on a scale, parallel to the rails. The probe itself, which protrudes from the measuring carriage into the measuring tube, is a thin brass tube, running down the centre of the measuring tube and going through the loudspeaker's centre mandrel. There are two measuring probes, one for the small tube for the high frequencies and one for the large tube. There are three sample holders to each measuring tube. One has a depth of 25 mm (1"), the next has a depth of 50 mm (2"), and



2105





2109

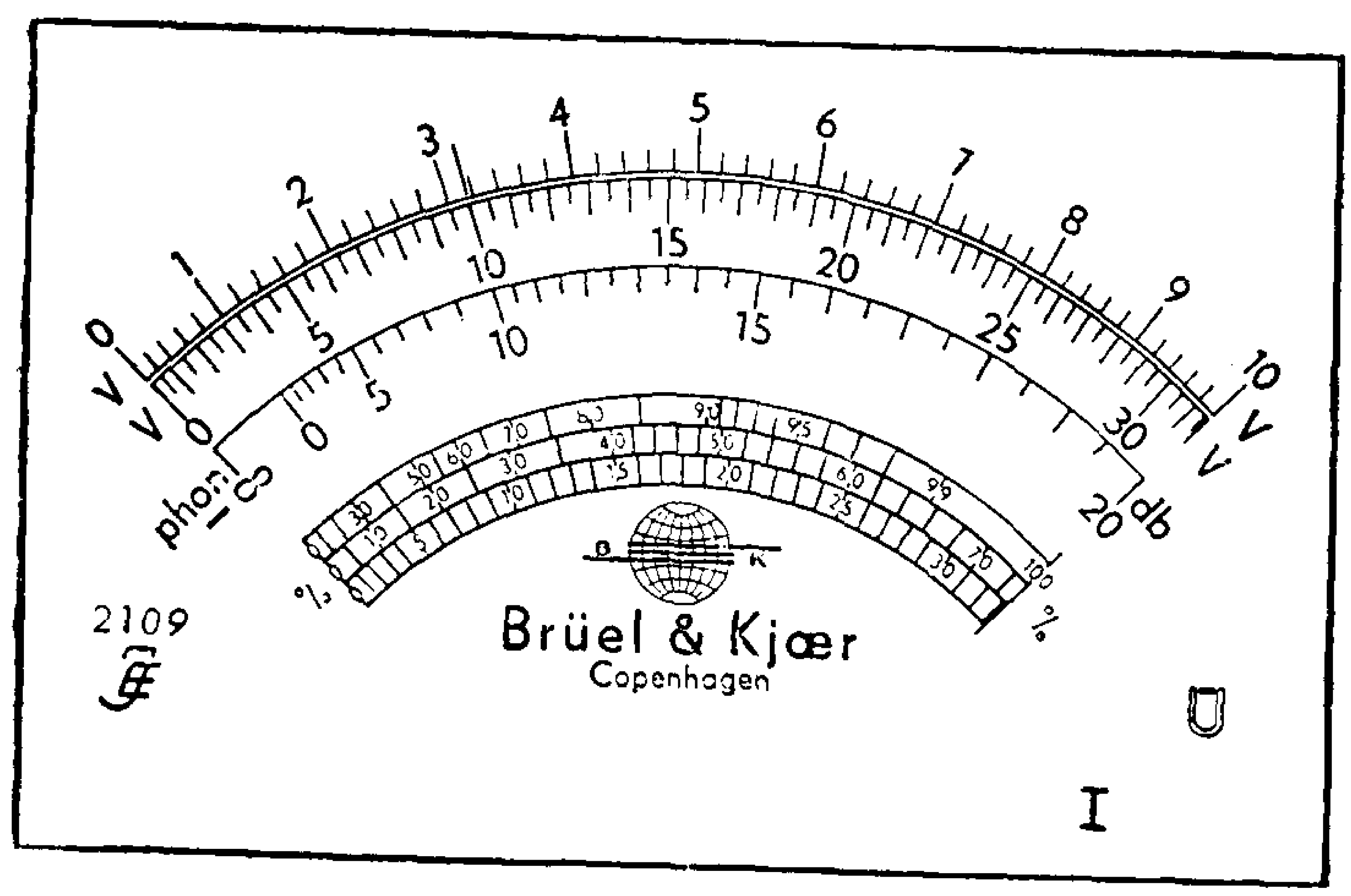


Fig. 4. Frequency Analyzer type 2105 and Audio Frequency Spectrometer type 2109, both suitable as amplifiers for the Standing Wave Apparatus type 4002. The meter scales of these instruments, showing the special calibration for reading absorption coefficients direct in %, are shown enlarged.

the third consists of a 15 cm tube with a sliding piston with airtight packing One can thus obtain any desired depth in the sample holders from 0—10 cm. The Standing Wave Apparatus type 4002 is intended for operation from an Audio Frequency Oscillator, for example the Beat Frequency Oscillator type 1012, and as measuring amplifier either the Frequency Analyzer type 2105 or Audio Frequency Spectrometer type 2109 should be used. Fig. 4 shows both these analyzers, with their meter scales. At the bottom of these scales the calibration, which allows the direct reading of absorption coefficients in percent, can be seen.

The procedure is as follows: The microphone measuring carriage is placed on a maximum as close to the sample as possible, which as far as the lowest frequencies are concerned is that maximum which lies in the immediate vicinity of the sample. For frequencies above 200 c/s that maximum which lies approx. $^1/_2$ wavelength from the sample should be used. The analyzer is now adjusted in its selective position to the frequency of the BFO, and the BFO and analyzer amplification so adjusted that a full deflection (100 %) is obtained on the analyzer meter. The microphone carriage is then moved to a minimum position, and the absorption coefficient read off direct on the scale. If the absorption coefficient is so small that this reading is not accurate enough

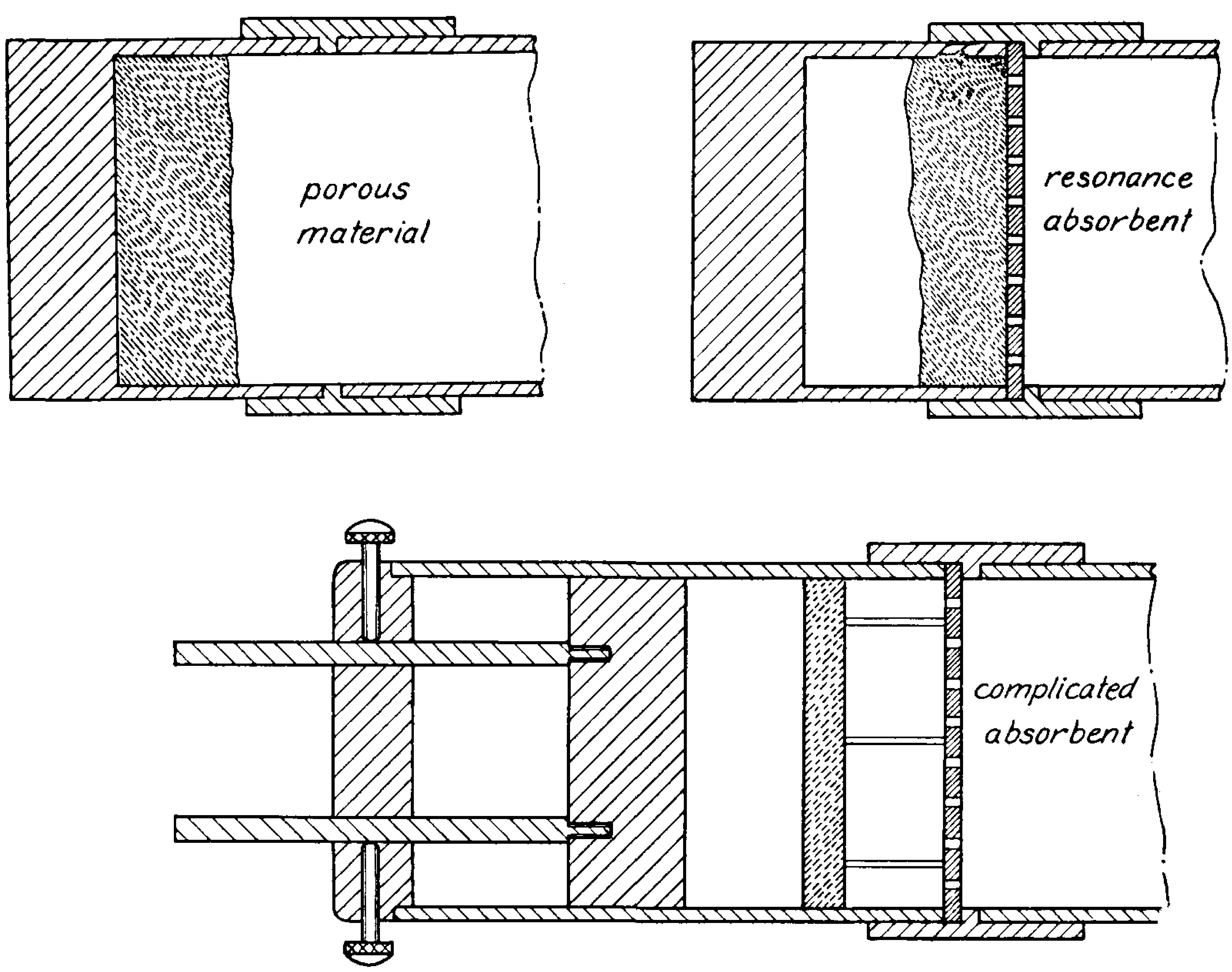
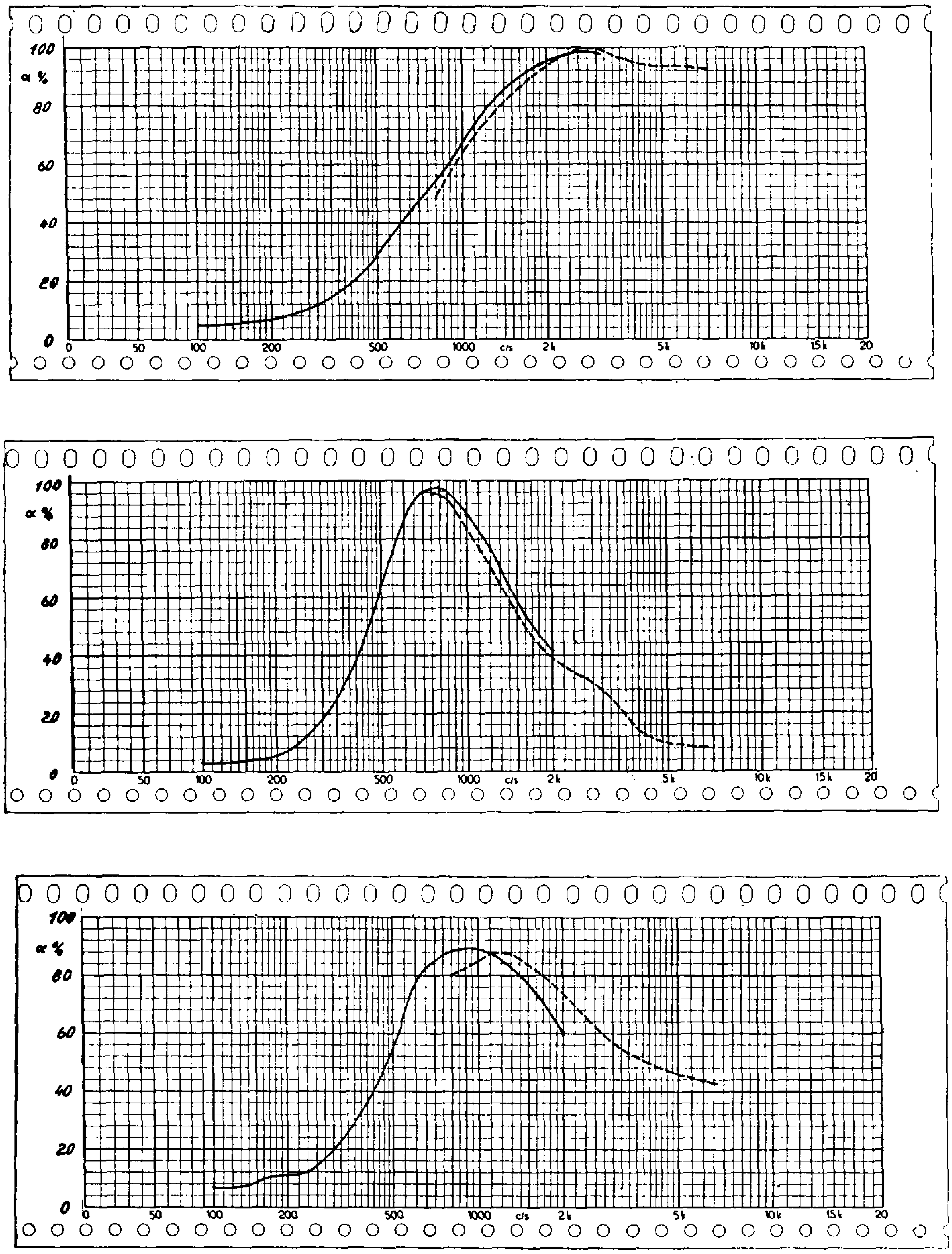


Fig. 5. Insertion of the samples in the apparatus. On the left, the insertion of a porous absorbent in the holder. On the right, the insertion of a resonance absorbent with perforated front plate, and below, a complex absorbent inserted in the variable holder.



a
b
c

Fig. 6. Absorption curves of three typical absorbents: **(a**)*a porous material,* **b)** *a membrane absorbent and* **c)** *a resonance absorbent with damping material.*

the amplification can be increased by 20 db (x10) to achieve a sure reading of the minimum. The lowest absorption scale on the meter should then be used which ranges from 0—30 %. With type 2109 it is possible to increase the amplification $\sqrt{10}$ times, i. e., 10 db, and in that case the middle absorption scale on 2109 should be used, ranging from 0—70 %.

Fig. 5 shows some typical set-ups of absorption material in the material holders. Porous materials such as rockwool, glass wool, wood fibre board, acoustic plaster and such like are placed in the base of the material holders, provided the materials are to be used normally set up directly in contact with a hard back wall. The holder with the porous material is placed in the Standing Wave Apparatus, taking great care that the edge of the container is quite clean, so that there is complete tightness between container and measuring tube. If the degree of tightness is not sufficient, possibly because the container edge is damaged, it should be made tight by means of a little vaseline. Leakages will give rise to measurements of too high absorption at the lowest frequencies.

An acoustic absorbent is often constructed of a perforated hard plate set up on wood laths, usually 1" or 2" thick, so that there is a space between the perforated hard front plate and the back wall. The space in between can then be partly filled with a porous material to increase the resistance part R of the impedance Z of the total construction. Such an absorbent is easiest inserted in the apparatus by cutting the hard plate to a diameter just equal to the holder's outer diameter. By using respectively the 1" or 2" holder the same result will be obtained as if the hard, perforated plate had a spacing of respectively 1" and 2" from the back wall. If a damping matting is used, inserted behind the perforated plate, it should be cut to a diameter corresponding to the holder's internal diameter and carefully inserted into the holder.

With more complicated constructions, for example when there are several layers in sequence, the variable holder is as a rule used. To obtain the correct measurements, it is important that the different sections fit tightly to the edge, so that the air particles cannot be set in motion in the space between the material and the inner side af the holder. Thus, the samples should be prepared with precision, and set up in the Standing Wave Apparatus without strains arising in them, or any considerable degree of packing in the case of soft materials.

Another important detail with measurements of materials where the surface is perforated, is that the sample should have the same percentage of perforations as is the average for a large area. Particular care should be taken when cutting out samples for the small measuring tube, where the area is small.

One often finds absorption material which is packed in paper or plastic. and in this case it is very important when taking tube measurements that the paper be not only cut precisely, but also glued internally to the holder, in such a way that it is impossible for air to get past the edge. The acoustic resistance of paper is often very great, so that even a very slight leak at the edge of the paper will cause considerable changes in the conditions of absorption.

Fig. 6 shows three typical absorbents, with their absorption curves measured as function of frequency. The different absorbents are: 1) Porous materials, which have poor absorption at low frequencies, but high at higher frequencies. 2) Membrane absorbents, consisting of the same porous material, but covered with a thin plastic membrane. Here it is seen that the absorption is

Standard frequenciec	American $^1/_3$ - octave bandnumber
100 c/s	20
125	21
160	22
200	23
250	24
315	25
400	26
500	27
630	28
800	29
1000	30
1250	31
1600	32
2000	33
2500	34
3150	35
4000	36
5000	37
6300	38

40-series	20-series	10-series	5-series	Exact Value	Mantissa
1	1	1	1	10000	000
1.06				10593	025
1.12	1.12			11220	050
1.18				11885	075
1.25	1.25	1.25		12589	100
1.32				13335	125
1.4	1.4			14125	150
1.5				14962	175
1.6	1.6	1.6	1.6	15849	200
1.7				16788	225
1.8	1.8			17783	250
1.9				18836	275
2	2	2		19953	300
2.12				21135	325
2.24	2.24			22387	350
2.36				23714	375
2.5	2.5	2.5	2.5	25119	400
2.65				26607	425
2.8	2.8			28184	450
3				29854	475
3.15	3.15	3.15		31623	500
3.35				33497	525
3.55	3.55			35481	550
3.75				37584	575
4	4	4	4	39811	600
4.25				42170	625
4.5	4.5			44668	650
4.75				47315	675
5	5	5		50119	700
5.3				53088	725
5.6	5.6			56234	750
6				59566	775
6.3	6.3	6.3	6.3	63096	800
6.7				66834	825
7.1	7.1			70795	850
7.5				74989	875
8	8	8		79433	900
8.5				84140	925
9	9			89125	950
9.5				94406	975

Table I. Standard frequencies which should be chosen when taking measurements in the apparatus. The frequencies are based on the R_{10} series of the international "Preferred Numbers". A complete table of these socalled "standardized Renard numbers" dividing a decade into 10 equal logarithmic steps is shown at the right.

now higher at the lower frequencies and lower at the higher frequencies. Finally, we have 3) resonance absorbents, built up of a perforated plate, simply placed in front of the porous material. Here one notes a peak on the absorption curve, so that there is powerful absorption at a medium frequency range and lesser absorption at both lower and higher frequencies. By changing the size of the holes, air separation behind the hard plate, distance between holes and the thickness of the hard plate, it is possible, within wide limits, to alter the frequency characteristic entirely as one desires.

In fig 6, a, b and c, the results of the absorption measurements carried out on both the big and the small tube are given. The continuous curve is valid between 100 and 1800 c/s, the dotted curve between 800 and 6500 c/s. With the glass wool sample of fig. 6 a and the glass wool covered with plastic of fig. 6 b, the overlapping of the two domains is quite satisfactory. This is however far less the case with fig. 6 c, due to the fact that in order to obtain the same percentage perforation for the panel used in both measurements, only 3 holes were allowed in the small measuring tube sample. With a hole diameter of 4 mm and a rectangular spacing of 13 mm it was impossible in this case to give each hole the same kind of back volume as the average hole had in the bigger sample. However, even in this extreme case both measurements give an idea of the absorption qualities of the given material in the complete frequency range from 100 to 6500 c/s.

When making tube measurements, the absorption coefficient or impedance should be determined at a series of different frequencies. For ordinary routine investigations of absorbents, it is recommended to take readings at frequency intervals of $^1/_3$ octave. It is most convenient to use the so-called preferred numbers, which are now standardized in most countries. In normal cases the R10 series can be used (see table I), for more exact measurements the R20 series or the R40 series. When the analyzer 2109 is used as a selective amplifier, the R10 series in fact corresponds to the middle frequencies of the $^1/_3$ octave filters in that analyzer.

An absorbent whose acoustic impedance is real, i.e., where there is no phase difference between the pressure and the particle velocity at the surface of the absorbent, will have a pressure maximum exactly at the surface of the material, and a pressure minimum exactly a quarter wavelength away.

If the sample provides a complex impedance, of which one wishes to find both the real and imaginary parts, one must first measure the ratio $n = \frac{p_{max}}{p_{min}}$. One then measures the distance Δ by which the minimum has been displaced with respect to that position it would have had if the measuring tube has been terminated by a hard surface. The distance Δ can be found in two ways. 1) First, find the minimum position with the absorption material in the holder, then removing the holder with absorption material, replace it by an empty holder, reversed in position and find the new minimum position, taking into account the difference in position which can arise between the surface of the absorption material and the hard surface of the holder. The difference between the minima positions gives Δ . 2) By measuring $\lambda/2$ between two minima and then calculating Δ as the difference between

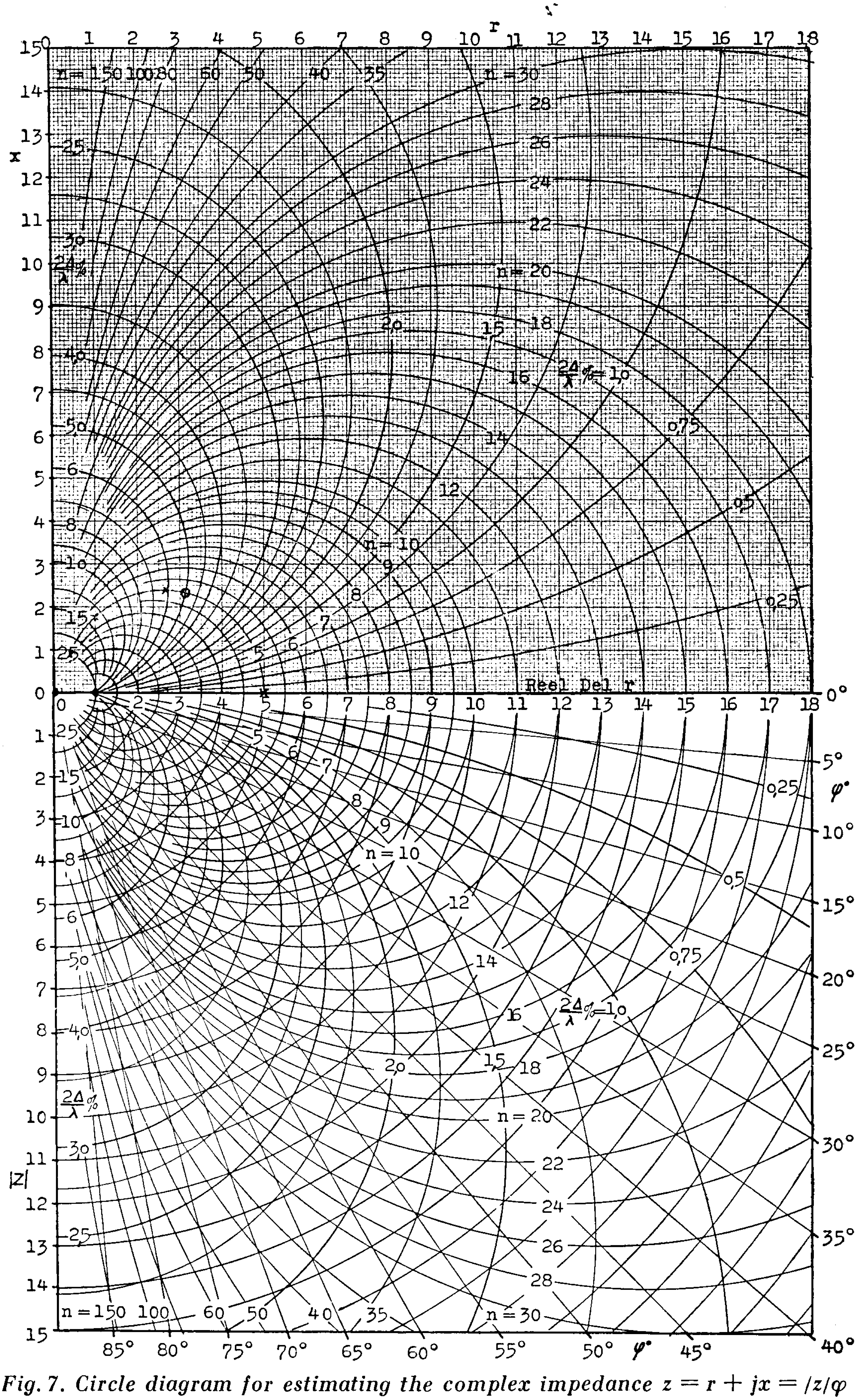
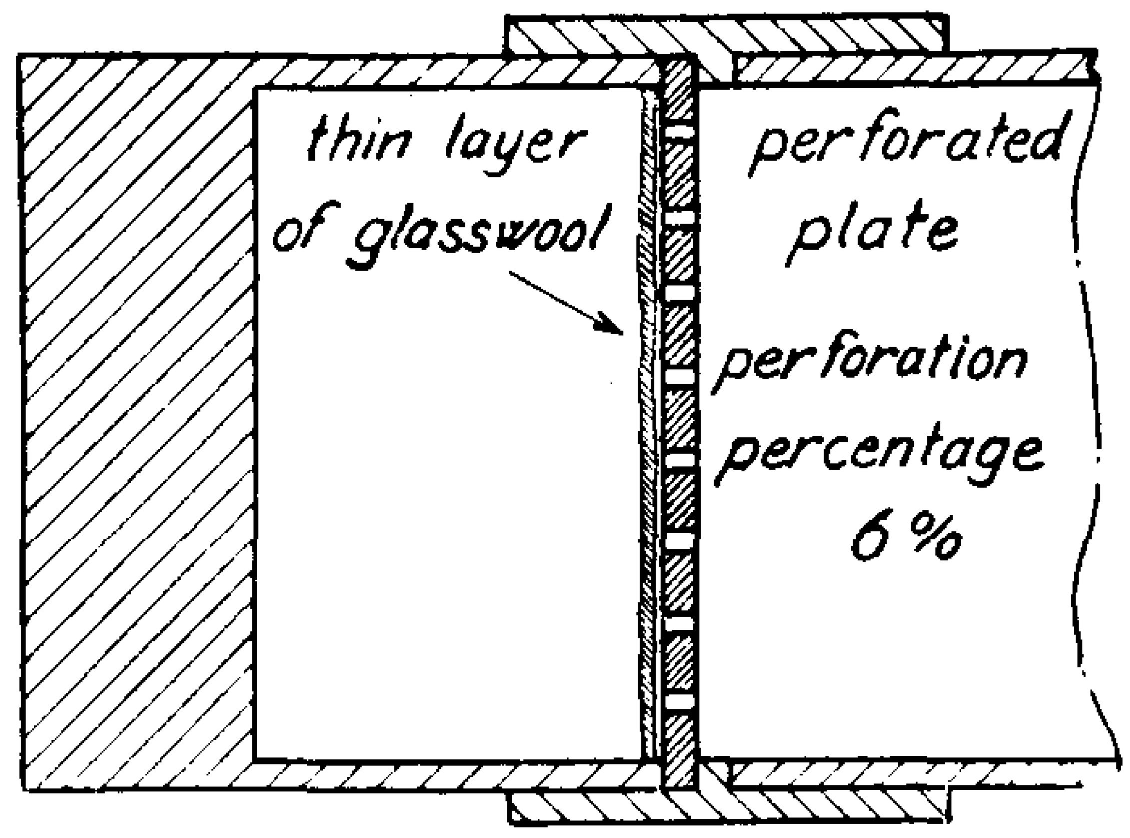


Fig. 7. Circle diagram for estimating the complex impedance $z = r + jx = /z/\varphi$ from the measuring results $n = \frac{\max}{\text{pmin}}$ and $\frac{2\triangle}{\lambda}$ 100 % obtained in the



v c/s	a %	n	Δ cm	$\lambda/2$ cm	$\frac{2\Delta}{\lambda}$ 100%	r	x	|z|	φ
100	5½	70	÷ 2,1	170,0	÷2,5	2,5	÷12,3	13,0	÷80°
125	4	100	÷ 4,9	136,8	÷ 3,6	0,7	÷8,9	9,0	÷85°
160	6	65	÷ 4,4	107,2	÷ 4,1	0,8	÷7,7	7,9	÷84°
200	8	48	÷ 5,0	86,8	÷ 5,8	0,4	÷5,6	5,7	÷84,5°
250	10½	36	÷ 6,0	68,7	÷ 7,3	0,4	÷4,3	4,3	÷84,5°
315	17½	21	÷ 5,5	53,7	÷10,2	0,3	÷3,0	3,0	÷83,5°
400	33	10	÷ 5,9	43,0	÷13,7	0.3	÷2,2	2,2	÷82°
500	57	4,8	÷ 6,5	34,7	÷18,8	0,7	÷1,2	1,5	÷54°
630	87	2,1	÷ 7,1	27,0	÷26,2	0,8	÷0.5	1,0	÷37°
800	96	1,5	+10,1	21,6	+46,5	0,8	+0,2	0,7	+ 5°
1000	88	2,0	+ 4,6	17.4	+26,2	0.7	+0,6	0,4	+40°
1250	69	3,5	+ 2,6	13,6	+19.0	0.8	+1.2	1,5	+56°
1600	47	6.3	+ 1,3	10,8	+12,0	0,8	+2,1	2,4	+69°
2000	32	10,4	+ 0,9	8,6	+ 9,5	1.8	+2,9	3,1	+72°

Fig. 8. A resonance absorbent with a table of standard frequencies, with the values of the absorption coefficient α, $n = \frac{p_{max}}{p_{min}}$ Δ' , $\lambda/2$ *and r and x of the complex impedance* $z = r + jx$, *all at the standardized frequencies.*

the distance from the absorption material to the first minimum and the value $\lambda/4$. For these measurements the millimeter scale placed on the microphone carriage track can be used. It is important, when inserting absorption material in the apparatus, to first adjust the microphone probe by screwing it further in or out of the microphone carriage, so that it is just touching the surface of the absorption material.

The real part R and the imaginary part X of the complex acoustic impedance can then both be calculated with the aid of n and Δ. The half wavelength $\lambda/2$ must also be known, and the ratio $\frac{2\Delta}{\lambda}$ expressed in percent. The upper half of the diagram shown in fig. 7 will immediately give the impedances r and x if the values of n and $\frac{2\Delta}{\lambda}$ % are marked off. The lower half of the diagram gives the complex acoustic impedance expressed by the modulus /z/ and the angle $\varphi°$. The figures given in the diagram are the so-called reduced impedances, which are non-dimensional. To find the impedances expressed in Rayls ($gcm^{-2}\,s^{-1}$), the values found must be multiplied by the acoustic impedance of air. $\varrho c = 42$ Rayls.*) Lastly the positive or negative sign of x (i.e. whether the reactance of the impedance can be assumed to be a mass or a compliance) follows from the sign of Δ. With the distance sample to first minimum $> {}^1/_4\lambda$, Δ and x will be positive, when $< {}^1/_4\lambda$, Δ and x will be negative.

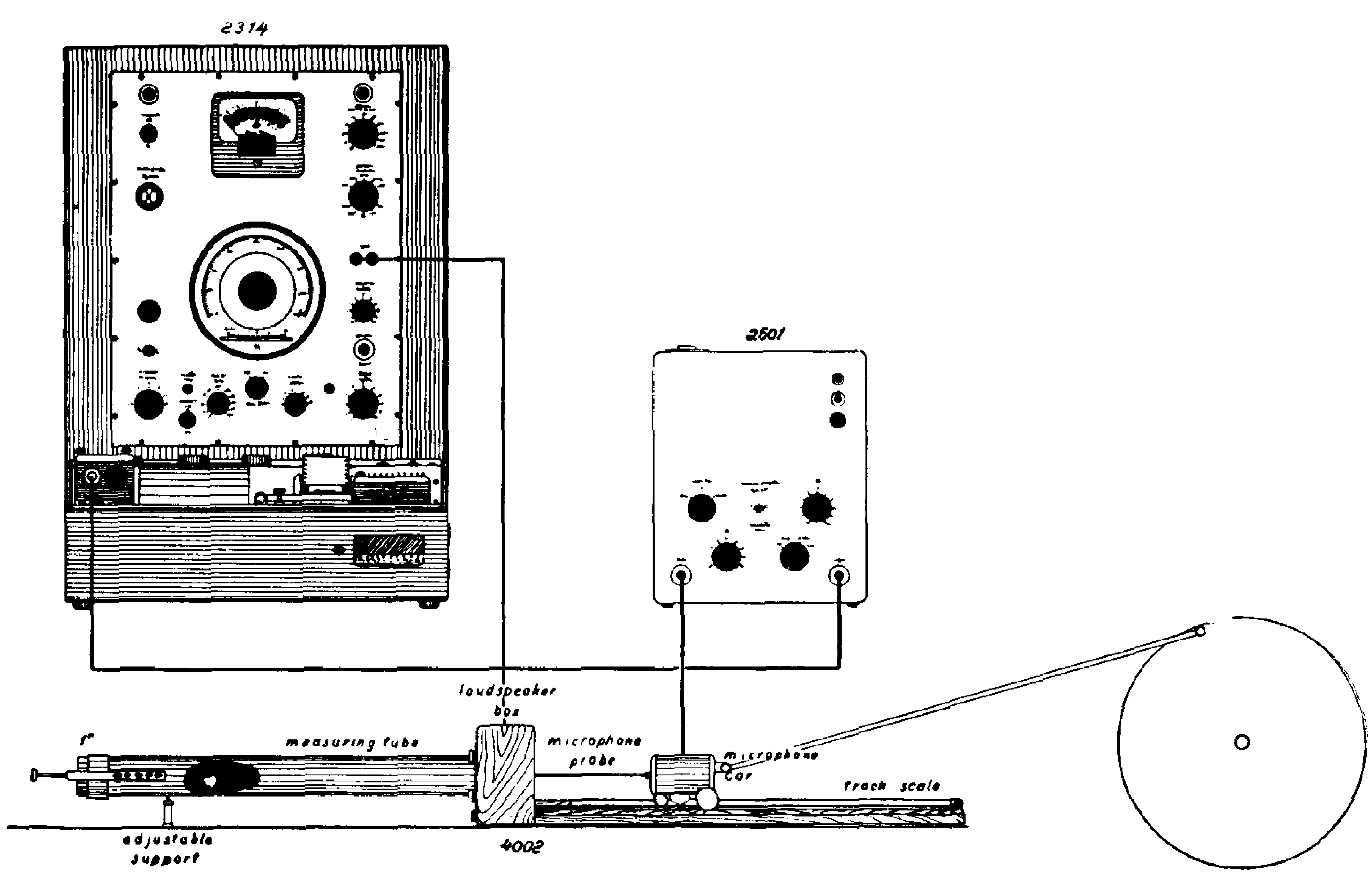


Fig. 9. Set up for the automatic measurement of the absorption coefficient with the aid of the Automatic Frequency Response Recorder type 2314, consisting of the BFO 1012 and the High Speed Level Recorder 2304. The Microphone Amplifier type 2601 has been used here as a linear amplifier. Frequency range 200—2000 c/s.

*) For the derivation of fig 7 see Per V Brüel: Sound Insulation and Room Acoustics, p. 56-63, Chapman & Hall, London 1951.

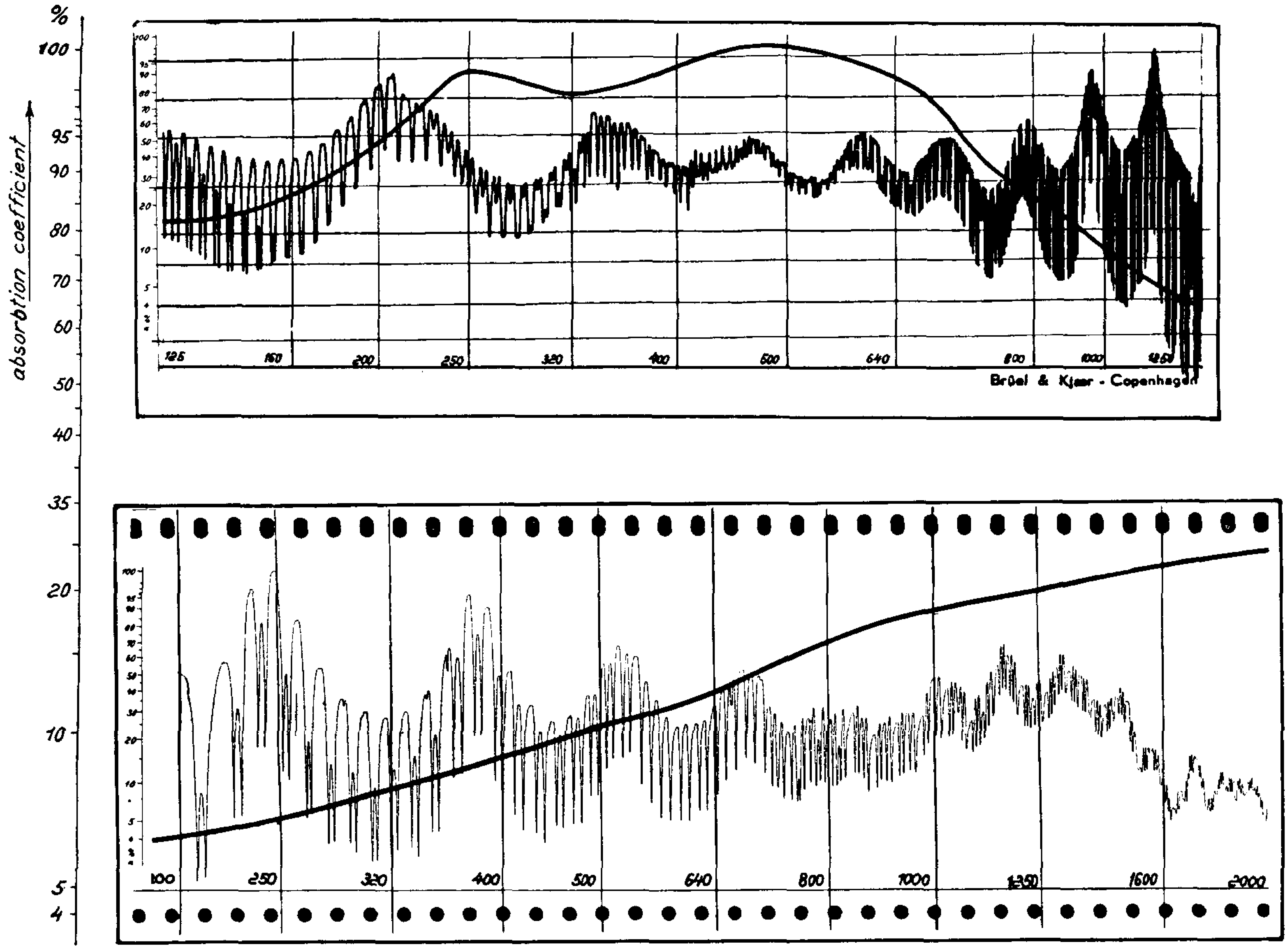


Fig. 10. The result of an automatic measurement-carried out on the set-up of fig. 9. The special scale for direct estimation of the absorption coefficient from the recording diagram is inserted in both diagrams and shown enlarged at the left side. The scale is effective for a 50 db potentiometer.

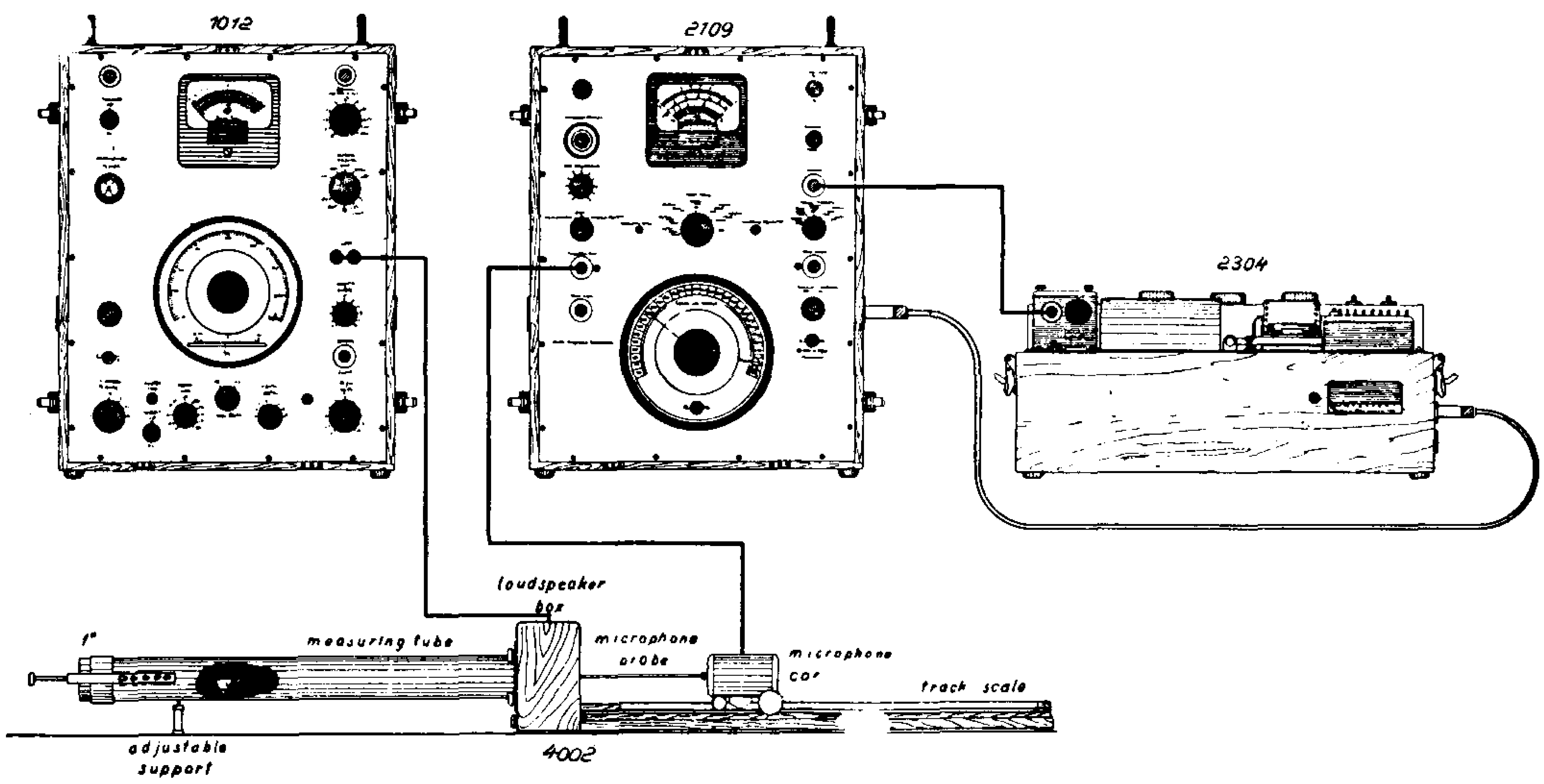
Fig. 8 shows a resonance absorbent as well as a table of the results measured at the standardized frequencies 100—125—160—200 etc., for the absorption coefficient α, n. Δ and $\lambda/2$ and acoustic impedance $z = r + jx$. Between 100 and 250 c/s the values of $\lambda/2$ and therefrom Δ followed with this measurement according to the first method described on p. 13; from 250 to 2000 c/s the values follow from the distance measurements of the first and second minima. The latter method should be regarded as the more accurate of the two, as one uses the same setting of the B.F.O., etc.

When developing new absorption materials one has often to carry out a long series of measurements, often within a certain frequency range only. If, in addition to a BFO 1012 and Analyzer 2105 or 2109, one has also access to a Level Recorder 2304, it is practicable to be able to carry out the measurements more or less automatically. Fig. 9 shows such a set-up, where a special motor slowly moves the microphone carriage back and forward by means of a simple connecting rod arrangement. The total range of movement of the microphone carriage is approx. 50 cm.

The Level Recorder is connected to the BFO, so that the BFO's frequency changes quite slowly at the same time as the paper moves on the Level Recorder in synchronism with the frequency traverse of the BFO. When the frequency has to change over a wide range, it is impossible to work with a selective amplifier, unless one uses type 2109, synchronized with the BFO and Level Recorder. In these measurements one therefore uses a linear amplifier, e.g. the Microphone Amplifier 2601 or uses the linear frequency range of Analyzer 2105 or 2109.

A logarithmic potentiometer of for example 50 db is used in the Level Recorder, whereby the ratio between pressure maxima and pressure minima can be read off directly from the recording paper. For these measurements it is possible to construct a scale as shown in fig. 10, left, from which the absorption coefficient can be read off directly when the scale is placed over the recorded curve. On account of resonance phenomena in the measuring tube, loudspeaker and microphone, the absolute amplitude will naturally vary very much, as can also be seen in the examples shown in fig. 10. It is therefore advantageous to use a 75 db potentiometer on the recorder when making this measurement, so as to be able, without changing the amplification, to carry out absorption measurements over a greater frequency range, with of course a consequent increased inaccuracy in the reading of the absorption coefficients from the special scale.

Another way of recording the absorption coefficient semi-automatically is shown in fig. 11. Here, the Level Recorder with logarithmic potentiometer of 50 or 75 db is mechanically coupled to the 1/3-octave Analyzer 2109. Each time the Analyzer switches to a new filter the BFO is set manually to the mid-frequency value of that filter. The max./min. ratios are then recorded by moving the microphone carriage slowly by hand a few times up and down



11. Set-up for the semi-automatic measurement of the absorption coefficient with the aid of Level Recorder 2304 mechanically coupled to the ⅓-octave Analyzer 2109.

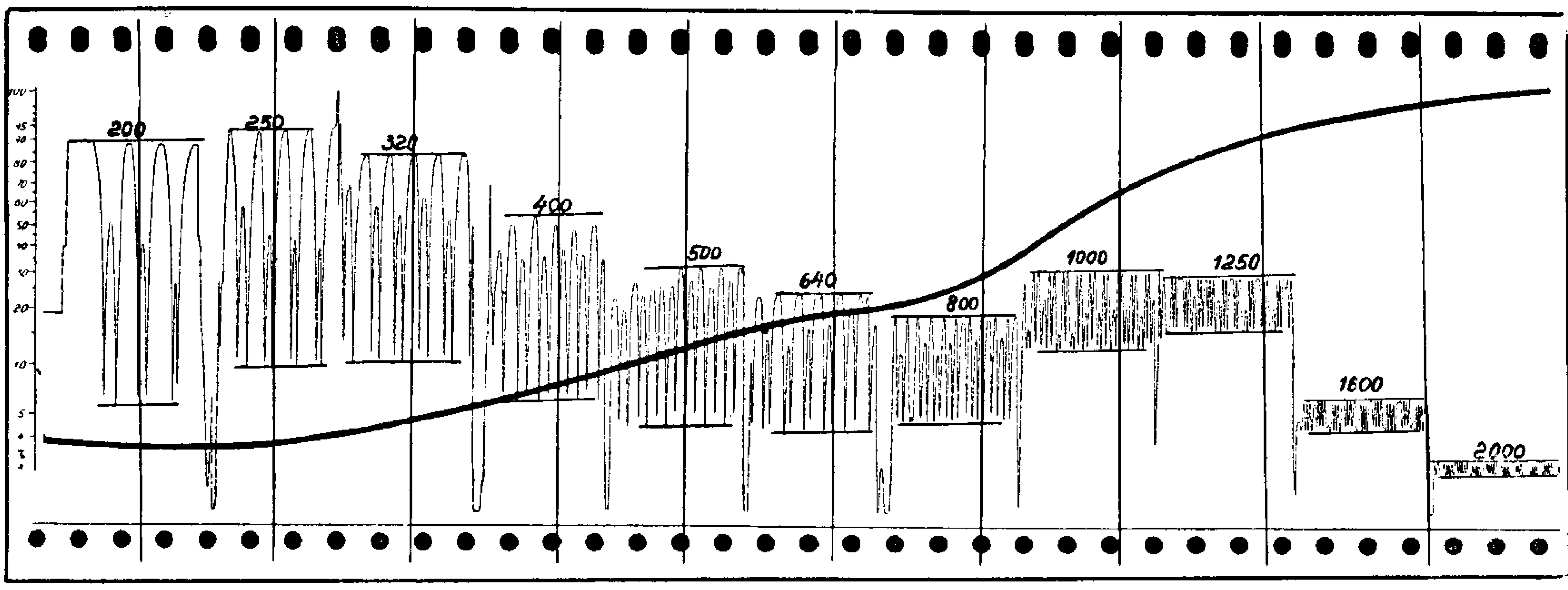


Fig. 12 Result of a semi-automatic measurement according to fig. 11.

for each filter, while the paper passes through the recorder at an appropriate speed. The special scale of fig. 10, left, can then again be used to determine the absorption coefficient at the standardized frequencies. The advantage, compared with the foregoing method is that the measurement is carried out selectively, which in principle is the only correct measuring procedure. However, for a preliminary investigation the difference between both procedures,

	Selective measurement with Analyzer 2109		Linear Measurement with Microphone Amplifier 2601 or Analyzer 2109 on "linear"	
v c/s	$\frac{p_{max}}{p_{min}}$	a	$\frac{p_{max}}{p_{min}}$	a
200 c/s	30 db	12,5 %	29 db	16 %
250 c/s	27 db	17 %	25 db	20 %
320 c/s	24 db	23 %	21 db	30 %
400 c/s	21 db	30 %	18 db	39 %
500 c/s	18 db	39 %	16 db	48 %
640 c/s	16 db	48 %	14 db	55 %
800 c/s	12 db	64 %	10 db	73 %
1000 c/s	9 db	77 %	8 db	82 %
1250 c/s	6 db	88 %	6 db	88 %
1600 c/s	4 db	95 %	4 db	95 %
2000 c/s	1,5 db	99 %	1,5 db	99 %

Table II. Comparison of measuring results of the two measurements of absorption coefficient according to fig. 10 and 12.

especially with higher absorption coefficients, is rather small. The higher the absorption, the smaller the difference between max. and min. pressure in the tube, and the less the influence of the higher order modes which are also excited. The results, as shown in figs. 10 and 12, of the measurements carried out according to figs. 9 and 11 on the same sample of glass wool, are repeated below in tabular form to indicate the difference. Attention should be paid to having the right matching impedance (6 Ω) for the connection to the loudspeaker, so as to give minimum distortion, especially with the method of fig. 9. Further, in both methodscare should be taken that the writing speed of the level recorder is high enough, and the speed of rotation in the motor of fig. 9 or the manual speed of the movement in fig. 11 slow enough, to allow the correct recording of the pressure drop at the minima (see the logarithmic representation of pressure versus distance in the tube in fig. 3 a). With the microphone car crossing the minima too quickly, the minima will be recorded too high, and an erroneous absorption coefficient will be obtained. A check at the lower frequencies that the minima are actually passed is the recording of the double minimum for only one maximum. This double tail (see figs. 10 and 12) only results if the probe really passes a minimum twice in one up and down movement.

Brüel & Kjær

ADR.: BRÜEL & KJÆR
NÆRUM - DENMARK

TELEPHONE: 800500
BRUKJA, Copenhagen

Printed in Copenhagen, Denmark