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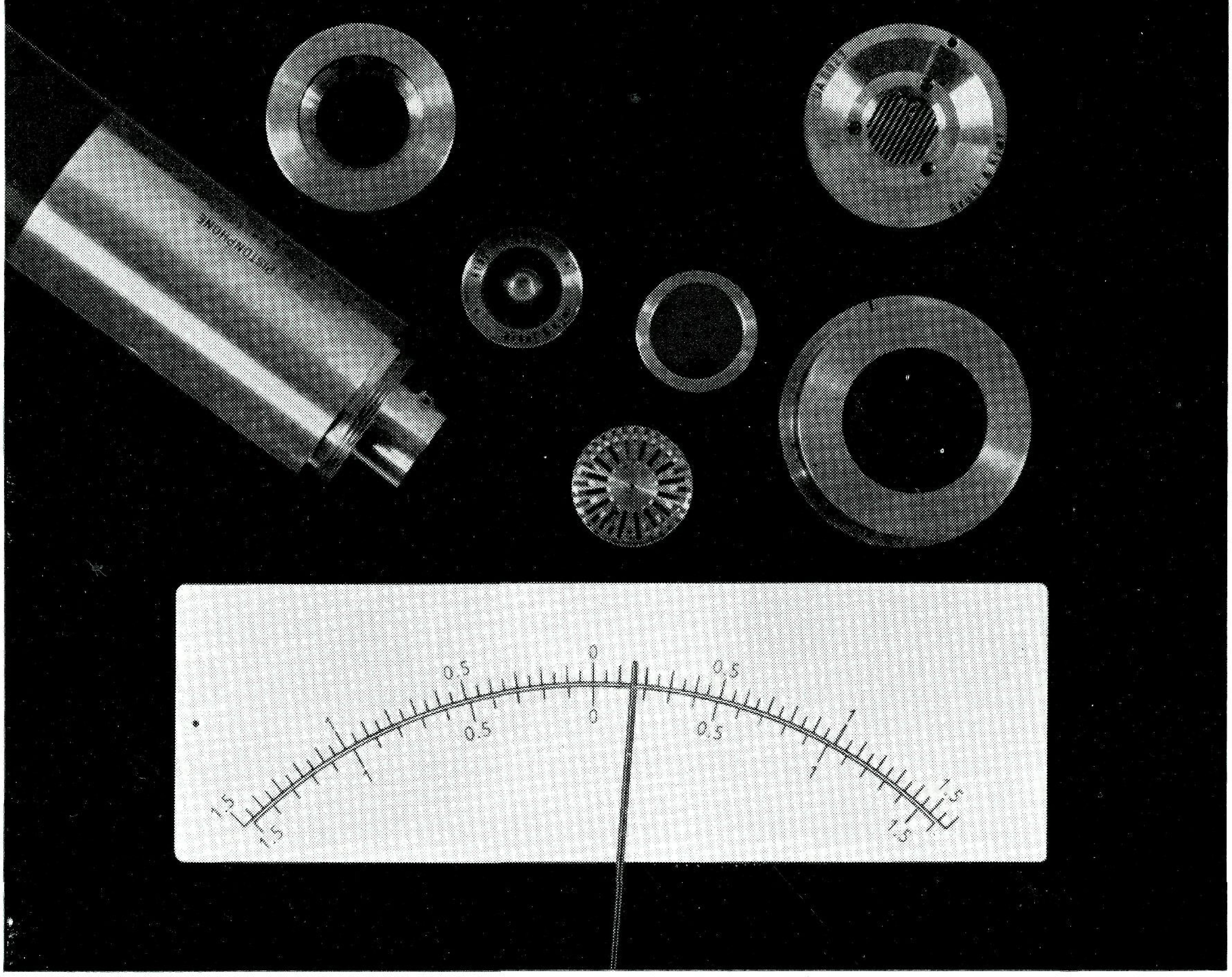
THE ACCURACY OF CONDENSER MICROPHONE CALIBRATION METHODS

PART I



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The Accuracy of Condenser Microphone Calibration Methods. Part I.

by

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ABSTRACT

The accuracy of nine different methods of sensitivity calibration of laboratory standard microphones are critically investigated. The results show that the reciprocity method is the most accurate when considering the absolute calibration of condenser microphone cartridges, but when dealing with the measurement of absolute sound pressure levels, the most accurate results are obtained when a double piston pistonphone is used as reference.

SOMMAIRE

La précision de neuf mèthodes différentes d'étallonnage de microphones étalons de laboratoire est examinée critiquement. Les résultats montrent que la mèthode de réciprocité est la plus précise, lorsqu'il s'agit de l'étalonnage absolu de microphones à condensateur, mais lorsqu'il est question d'une mesure absolue de niveau de pression sonore, les résultats les plus exacts sont obtenus en employant un pistonphone à double piston comme référence.

ZUSAMMENFASSUNG

Eine kritische Untersuchung 9 verschiedener Eichverfahren für Meßmikrophone zeigt, daß das Übertragungsmaß am genauesten mit Hilfe, des Reziprozitätsverfahrens bestimmt wird. Bei der Messung absoluter Schalldruckpegel erhält man jedoch beste Genauigkeit, wenn man ein Doppelkolbenpistonphon als Bezugsnormal verwendet.

Introduction.

It is the object of this investigation to try to find the accuracy, with which it is possible to calibrate standard microphones. The inaccuracy of the various methods can often be determined through a close investigation of the accuracy of the different elements of the whole test procedure forming the final result. In other words, if the inaccuracy of the applied barometers, voltmeters, amplifiers, attenuators, length gages, balances, resistors and capacitors, which are of importance for the measuring set-up is given, a calculation of the overall accuracy can be made.

In this way it should be possible to investigate critically every method of microphone calibration and give an exact figure for the accuracy obtained based on the known accuracy of the different elements.

To check this, let us say, calculated inaccuracy it is possible to make a relatively large number of measurements, particularly with different observers and under different temperature and pressure conditions, and from the spread in the results determine the standard deviation. The calculated inaccuracy and the measured standard deviation should be of the same order of magnitude,

but there is still a possibility of errors in the different calibration methods owing to direct errors in assumptions, in the limits of the formula or other fundamental errors which are made in the same way by each different observer. These errors can only be found by comparing the results of different calibration methods using the same condenser microphones as test objects. For the investigations described below therefore, two standard microphones of the type 4132, i.e. with a flat pressure response curve, and one type 4131 with a flat free field response curve were used. The microphones had been artificially aged and had then been used for more than a year before they were brought into this investigation. The microphones are very stable regarding temperature and humidity variations, and as all measurements have been carried out over a relatively short period of time and very constant temperature conditions, it can be assumed that the sensitivity of the cartridges has been practically unchanged during the test period.
It has only been the object to test the microphone sensitivity in a very limited frequency range. The problem of the accuracy of the frequency response will be left to a separate work.

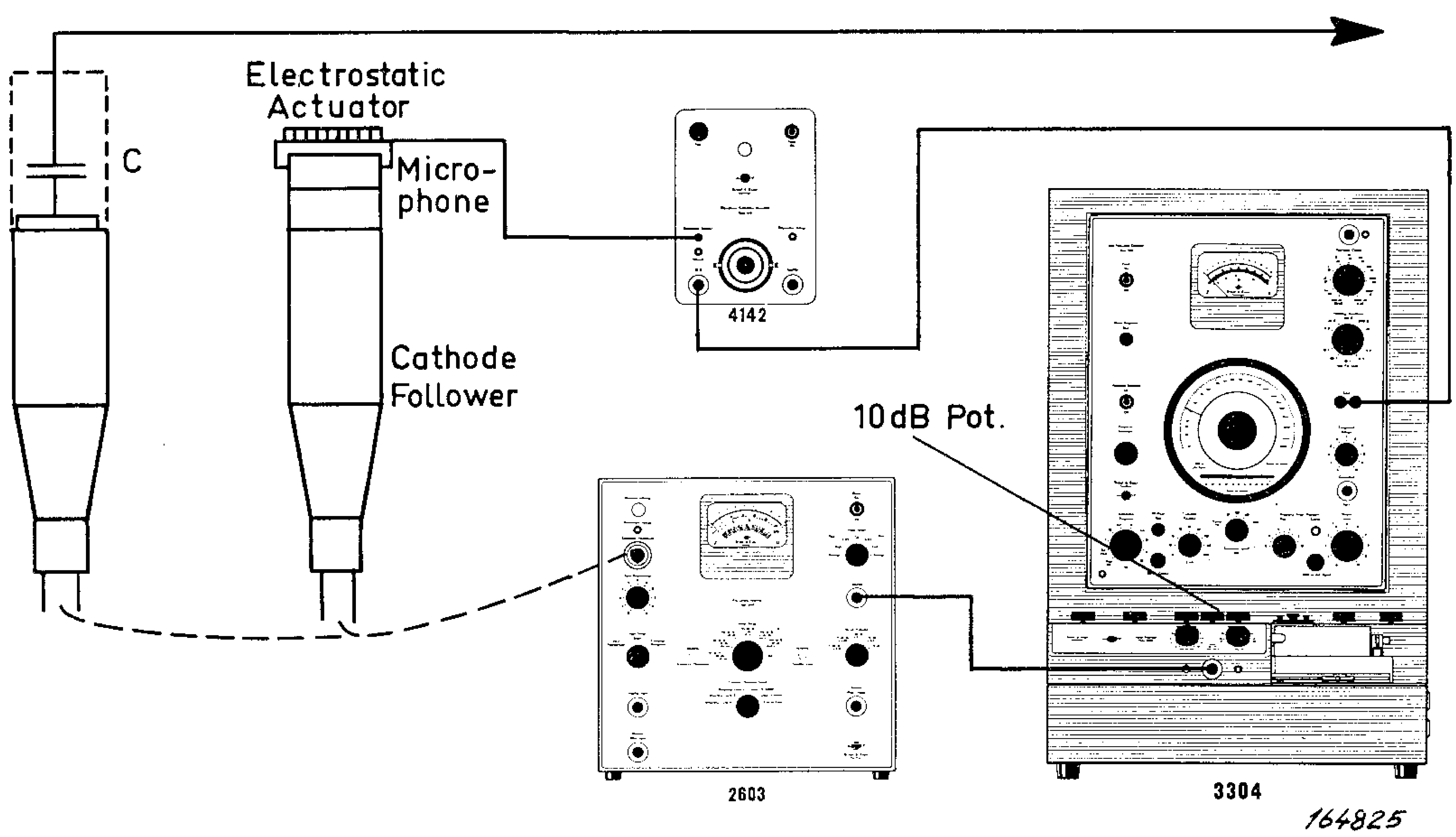


Fig. 1. Arrangement for the determination of the frequency response of condenser microphone cartridges. The Level Recorder is fitted with an accurate 10 dB potentiometer, and the amplification of the Recorder's DC amplifier is so high that the resolution of the system is ± 0.025 dB. A fine stylus, and wax paper, has been used together with a very accurate writing system.

Owing to the many different calibration methods used, the frequency range has been from 48 Hz (c/s) to 800 Hz (c/s) and it has been assumed that the relative frequency characteristic is flat within this frequency range. The relative frequency characteristics of the the three microphones were measured on the set-up shown in Fig. 1, where an electrostatic actuator was used and the Level Recorder was supplied with a 10 dB range potentiometer. The result is shown in Fig. 2, where the system response is also indicated. The response curves were taken twice, and between each measurement the cathode follower and the cartridge were completely dismounted and set up afresh. It can be seen that the accuracy with which the response curve is reproduced is very high, the linearity within the used frequency range is better than ± 0.025 dB, which is the limit for the total accuracy of the test procedure.

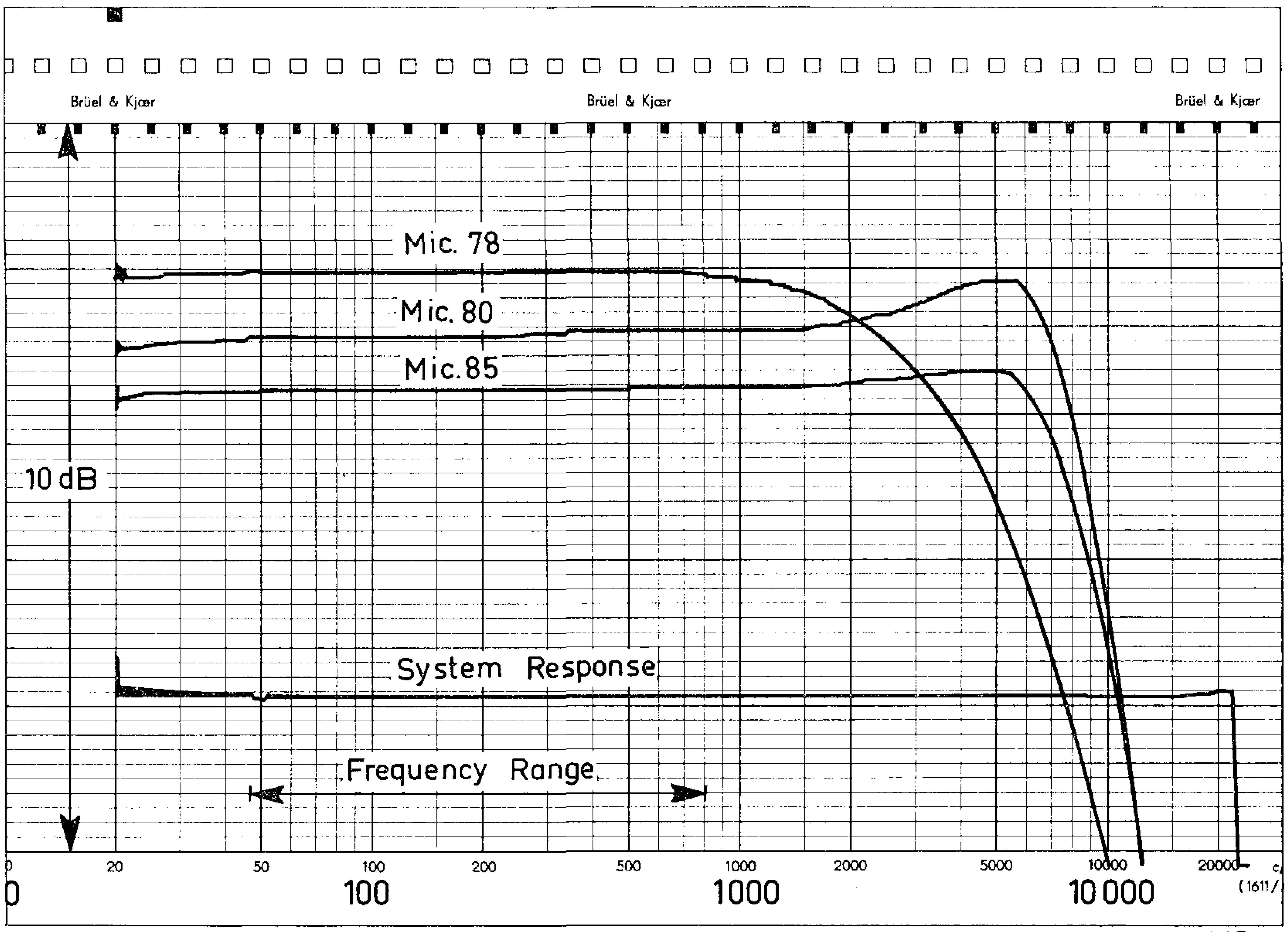


Fig. 2. Relative frequency response curves of the three microphones used throughout this investigation. Each curve was recorded twice, which shows the relative accuracy of the measurements.

The following fundamentally different test methods have been investigated and their uncertainties determined.

1. Rayleigh Disc in Wave Tube.
2. Classic Low Frequency Pistonphone.
3. Double Piston Pistonphone Type 4220.
4. Thermophone in closed chamber.
5. Smoke Particle Movements in Wave Tube.
6. Disc Lifting Method.
7. Electrostatic Actuator (Slotted and Solid models).
8. Reciprocity with Capacitor Shunt.

Apart from the eight different methods listed above the three microphones have also been checked against the following calibration methods by independent investigators.

9. Reciprocity with Resistor Shunt. (Danish Technical University Acoustics Lab.).
10. B & K Laboratory Standards including the results from I.E.C. Round Robin tests.
11. B & K Factory procedure.

The uncertainties for these last three methods are stated by the different laboratories involved and consequently, have not necessarily been determined in the same way as those for the methods investigated here.

The three microphones used are from different production batches and are therefore of different age. They are described in table I, where the full serial numbers are indicated as well as the type numbers used in this text. The sensitivity given when the microphone was manufactured is also indicated together with the results of rechecks made at a later date with the standard factory procedure.

Microphone Type	4131	4132	4132
Full serial no.	78606	80825	85800
No. Indication used here	78	80	85
Date of Manufacture	16.5.1962	21.12.1962	11.12.1962
Capacity in pF	68.1	58.0	61.4
Sensitivity at date of manufacture mV/μbar	4.68	4.32	3.94
Corresponding to dB re 1 V/μbar	—46.6	—47.3	—48.1
Checked February 25th 1964 dB	—46.1	—47.0	—47.7
Checked April 4th 1964 dB	—46.1	—47.0	—47.7
Sensitivity given by factory 4.4.1964 mV/μbar	4.95	4.47	4.12
Equivalent Volume cm^3	o.167	o.160	o.135

Table I. Description of the three microphones used in this text. The sensitivities given were checked with the normal factory test procedure.

It can be seen here that there is a slight difference between the sensitivity given when the microphones were first calibrated after production and the rechecks made at later dates. Checking the three microphones against the factory laboratory primary standards gave the results indicated in table II for both the absolute sensitivity and the equivalent volume.

Microphone No.	78	80	85
Sensitivity in dB re 1 V/μbar	—46.19	—47.02	—47.65
Sensitivity in mV/μbar	4.904	4.457	4.145
Equivalent Volume cm^3	o.160	o.143	o.122

Table II. B & K Laboratory check of the three microphones. Normal laboratory standard procedure against laboratory standard cartridges.

It should be emphasized that all the actual measurements using the different measuring methods were carried out by personnel having no knowledge of the final result or even of the sensitivity of the different microphones as given from the factory. This step was taken to ensure that no member of the test group could be mentally biassed towards certain results. The tests were made by one group while the results were calculated by another.
Even though the many calibration methods used are fundamentally different, there are certain inaccuracies common to all methods of determining the sensitivity of a microphone, such as the inaccuracies of the cathode follower, the preamplifier, the voltage read-off device, the stray capacitance and the polarization voltage. Fig. 3 shows the standard set-up used. The measuring amplifier Type 2603 is connected to a stabilized power supply, which in connection with the heavy feedback of the amplifier maintains constant amplification. To facilitate easier reading, the voltmeters used have large mirrored scales and suppressed zero points. The reading accuracy is better than 0.1 %.

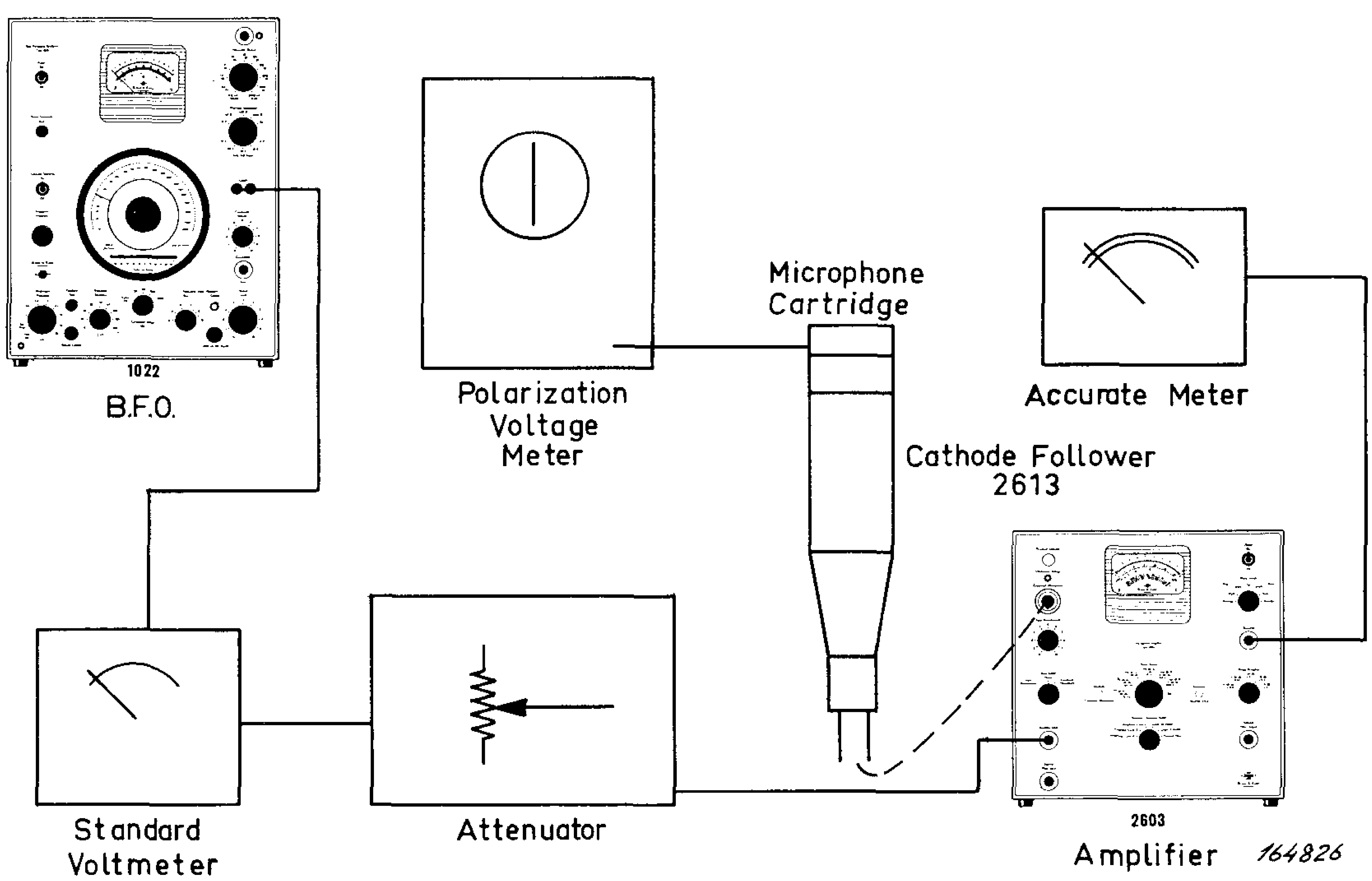


Fig. 3. Set-up for the accurate determination of the output voltage from cathode followers.

As a cathode follower is always used together with the condenser microphone cartridge then it is most practical to regard it as part of the microphone, and in the following text all statements of sensitivity will refer to the output voltage of the cathode follower. Only one cathode follower has been used, and therefore the inaccuracy arising from stray capacitance has been reduced practically to zero.

It should be emphasized that it is usual American practice to give the sensitivity of the microphone cartridge by the electromotive force of the microphone working into an infinite impedance. If an insert voltage technique is used the inaccuracy in determining both the stray capacitance and the gain of the cathode follower can, to a large degree, be eliminated.
From a manufacturing point of view it is maybe an advantage to give the electromotive force of the cartridge, as this figure is higher and gives a more impressive figure for the sensitivity of the microphone. If the voltage is referred to the output of the cathode follower, the sensitivity will generally be from 1.5 to 3 dB lower.

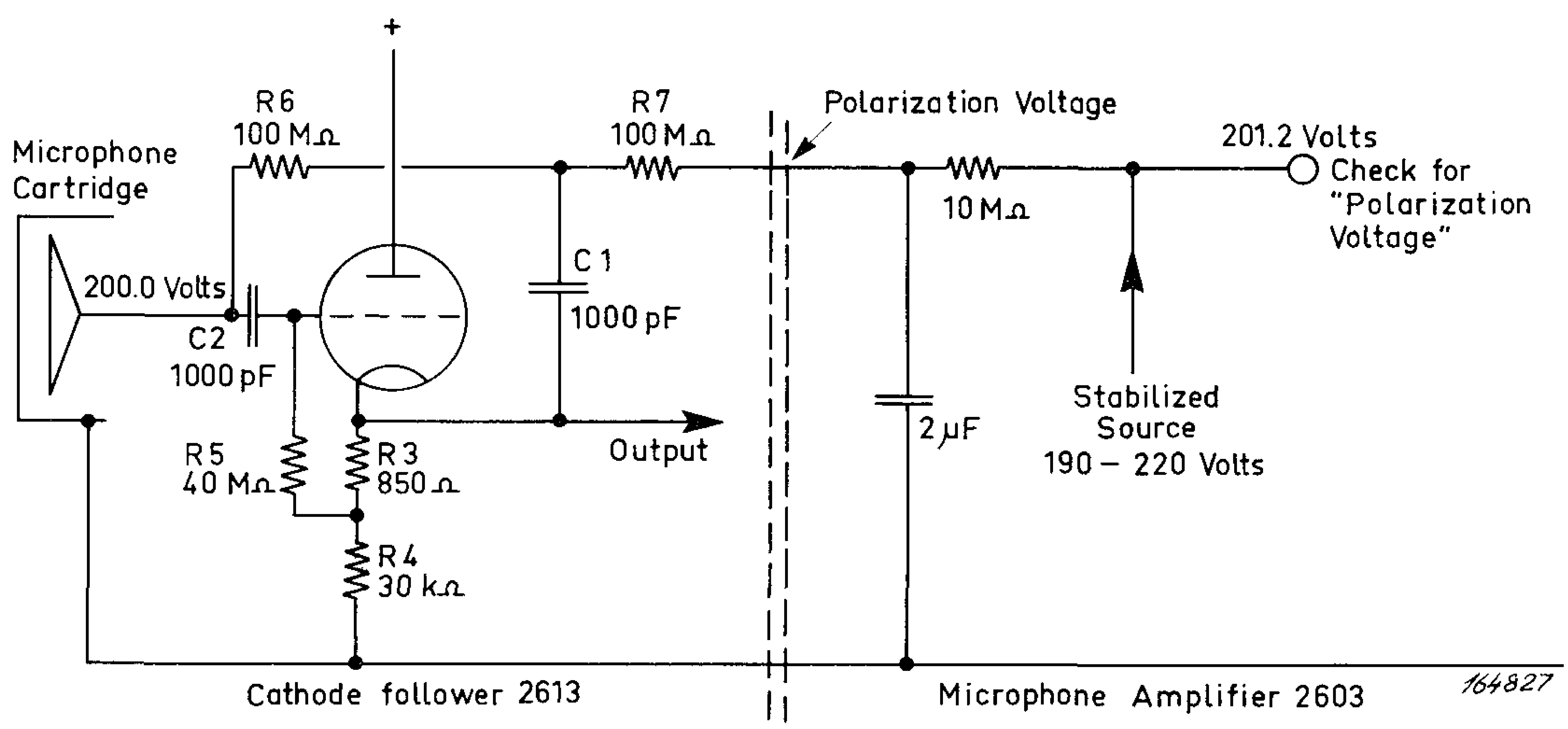


Fig. 4. Diagram of a Cathode Follower Type 2613 and the polarization voltage supply in a Microphone Amplifier Type 2603.

A diagram of the cathode follower used, a standard B & K Type 2613 where the input impedance has been increased by positive feedback, is shown in Fig. 4. This positive feedback is also used to increase the apparent impedance of the resistors, R6 and R7, feeding the polarization voltage to the cartridge. It can be seen that any leakage currents in the microphone cartridge, the capacitors C1 or C2 or in the general circuitry will result in lowering the polarization voltage of the cartridge. It is therefore very important that a possible voltage drop be minimized by ascertaining that the insulation resistance of the different components is sufficiently great. This can be carried out with a very sensitive, compensated voltmeter with a range from 195—205 V, and input impedance higher than 10^7 MΩ. A voltage drop between 1 volt and 1.4 volts was measured throughout these investigations.
The insulation resistance of the cartridge was greater than 5×10^8 MΩ and consequently had no influence on the leakage. The capacitors C1 and C2 are glass capacitors, the printed circuit is made on silicon treated goldplated glass laminate, and furthermore, it is possible to solder the components in the circuitry without flux. It seems to be difficult to do more to reduce the

leakage, and still the uncertainty of the exact value of the polarization voltage from one day to the other is ± 0.5 V. It is therefore very important to specify a certain cathode follower to a certain cartridge if a high degree of accuracy is required.
Consequently, if one wants to determine the sensitivity of a microphone cartridge with the highest degree of accuracy at a constant and known SPL the following uncertainties will be assumed, even when good laboratory instruments are used.

Uncertainties of polarization voltage on the cartridge	0.3 %
Attenuator uncertainties including frequency errors	0.1 %
Scale errors for standard voltmeter including reading errors ..	0.2 %
Reference meter during work including reading errors	0.1 %
Uncontrollable variations of the gain of the cathode follower and input capacity variations	0.1 %
The total uncertainties for the electrical section of a laboratory precision set-up	0.4 %

Table III. Uncertainties in the electrical part of laboratory measurements.

With a less refined set-up as shown in Fig. 5, where no instantaneous check of the polarization voltage can be obtained, the uncertainties of the electrical part of the measurement from one day to another will be as follows:

Uncertainties from polarization voltage variations	0.5 %
Change of gain and capacity of cathode follower	0.1 %
Attenuator errors which are not known and compensated for ..	0.2 %
Reference voltage variation with temperature etc.	0.3 %
Variations of gain of amplifier with power line variations	0.1 %
Meter calibration errors	0.5 %
Reading errors	0.2 %
Total uncertainty on the electrical measurements with ordinary power line driven equipment	0.8 %

Table IV. Uncertainties in the electrical part when Microphone Amplifier Type 2603 is used.

With a battery driven precision sound level meter as for instance Type 2203 under the assumption that the polarization voltage and leakage attenuators, reference voltage and the output meter are controlled very carefully, the uncertainties from one day to another will be as follows:

The uncertainties of polarization voltage including time variation and the uncertainties of the adjustment (which is very difficult to carry out owing to the small current drain)	0.7 %
Uncontrollable amplifier gain variations with temperature, humidity etc.	0.6 %
Attenuator errors which are not known and compensated for ..	0.2 %
Reference voltage variations with temperature and wave form .	0.4 %
Instrument and scale uncertainties	0.7 %
Reading errors	0.4 %
The total uncertainty on the electrical section for a battery driven instrument	1.3 %

Table V. Uncertainties involved in the electrical part when battery driven amplifiers are used.

In the above estimation of the various uncertainties it is a condition that the signals are sinusoidal and continuous, and that the frequency range is between 45 and 1000 Hz and that the temperature and power line variations are reasonably small.

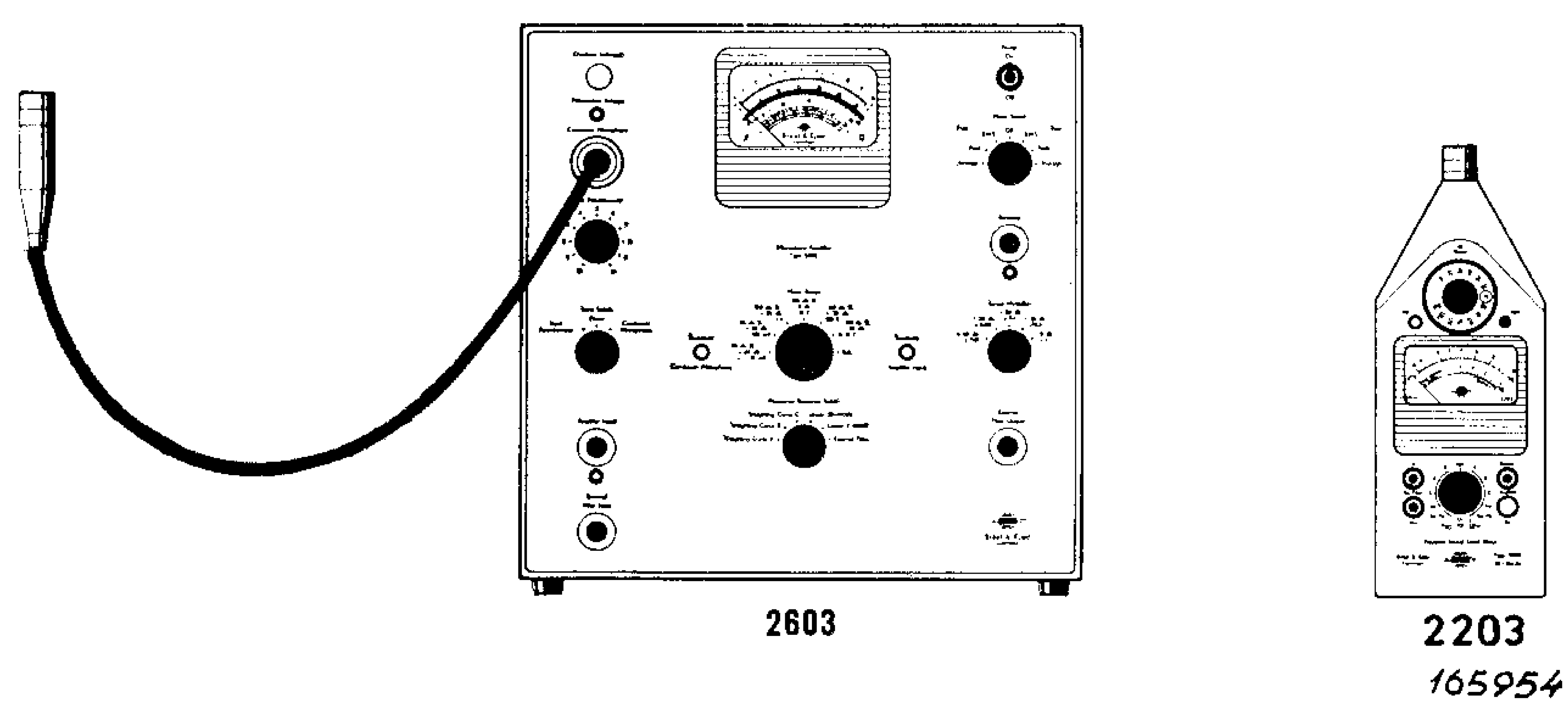


Fig. 5. Microphone Amplifier Type 2603 with cathode follower and battery driven Precision Sound Level Meter.

Uncertainties in General.

In calculating the uncertainties for many readings, $\Delta 1$, $\Delta 2$, $\Delta 3$, etc. are normally expressed in % of the total calculated uncertainties:

$$\Delta_{total} = \sqrt{\Delta_1^2 + \Delta_2^2 + \Delta_3^2 + \cdots} \;\%$$

In this way there is a probability of two thirds that the obtained value will be within the stated uncertainty limit. It is, naturally, a condition that all the uncertainties $\Delta 1$, $\Delta 2$, $\Delta 3$, etc. appear in the final formulae or results with the same order of magnitude. If some results are known with a high degree of accuracy compared to others, the very accurate results can be omitted in the calculation of the total uncertainties. Into such a calculation may also go the estimation of uncertainties of formulas, unknown conditions etc. which will give a constant error but not a spread in the measured results. When a series of n different measuring results is given, X1, X2, X3, etc. the average is calculated simply by

$$\text{Average } M = \frac{X_1 + X_2 + X_3 + \cdots}{n}$$

To check the consistency and the spread in the measured results the standard deviation is used, which is given by

$$S = \sqrt{\frac{(M - X_1)^2 + (M - X_2)^2 + (M - X_3)^2 + \cdots}{n - 1}}$$

The standard deviation can be given either in the measured units or as a percentage standard deviation given by

$$\sigma = \frac{S \times 100}{M} \%$$

In the following check of the different absolute calibration of microphones a thorough investigation was first made of the methods, the conditions for the used formulae and all possible errors which may have an influence on the final result plus the uncertainty of the instruments employed. In this way the total calculated uncertainty for the various methods can be obtained.

Later on a series of measurements are carried out and the standard deviation is determined from the measurements. If there are no systematical errors included, which are of the same order of magnitude as the random errors the calculated uncertainties and the final measured standard deviation shall be of the same order of magnitude.

If there is a spread in the final results greater than the standard deviation it is an indication that some systematical error in the set-up must exist. By using the same three microphones to check all nine different calibration methods it is possible to get a rather clear indication of both random uncertainties and systematical errors.

Rayleigh Disc.

In the early days the Rayleigh disc was used extensively for the absolute calibration of microphones, and the British Post Office has developed this method to a high degree of sophistication. Actually they have used the Rayleigh disc in standing wave tubes for many years as a primary standard for microphone calibration.

The principle of the Rayleigh disc is described in several publications 1)—6). For this experiment a slightly modified B & K Standing Wave Apparatus Type 4002 was used, with the microphone and glass scale for zero calibration mounted at the end of the tube as shown in Fig. 6. The Rayleigh disc was suspended from the roof of the tube at a given distance from its end, by a single glass fiber through an arrangement permitting accurate angle alterations and measurements.

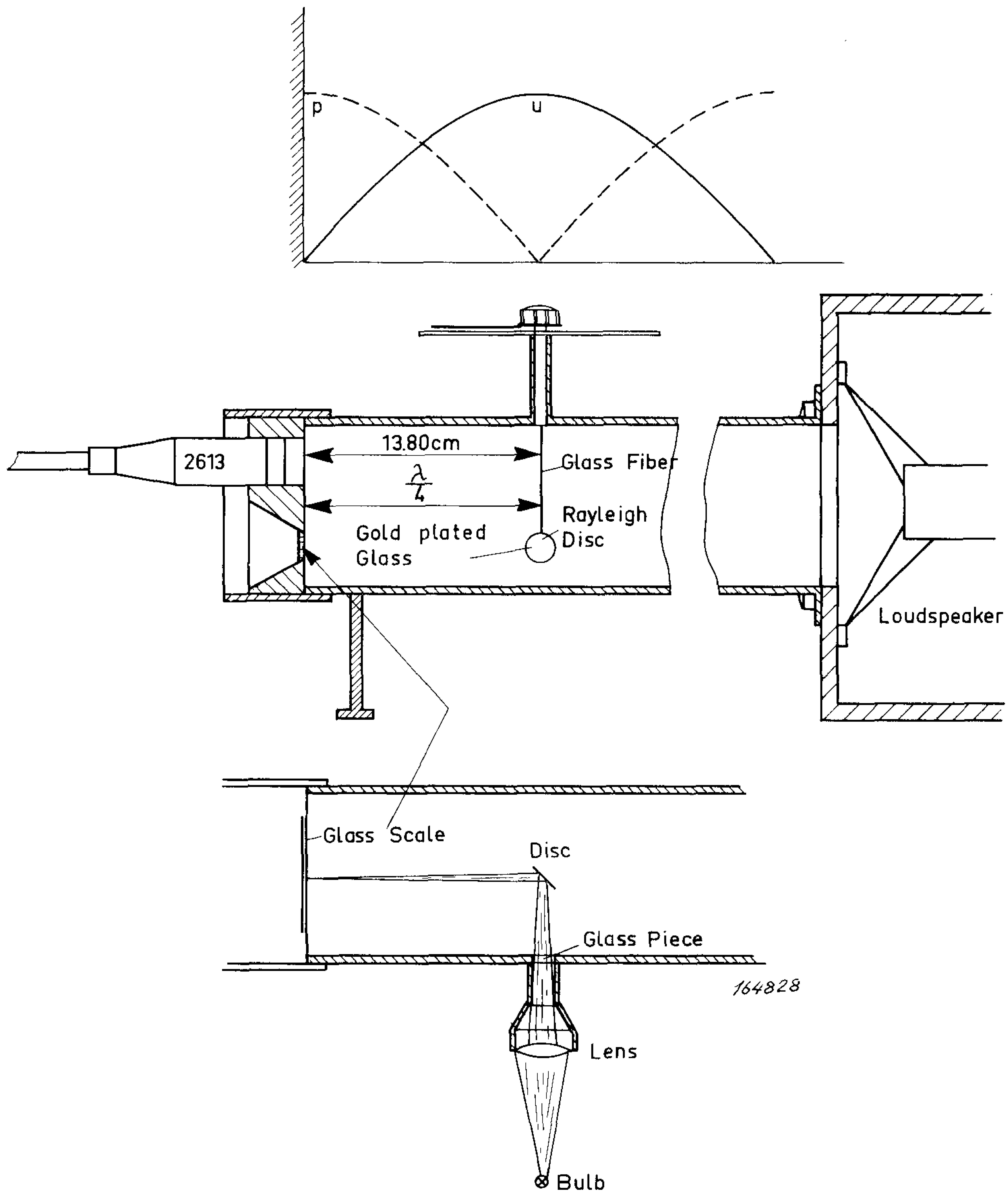


Fig. 6. Rayleigh Disc in Standing Wave Apparatus Type 4002.

The Rayleigh disc itself is made of thin goldplated glass. The light enters the tube from the side, and is reflected by the disc and focused on the glass scale. When the air particle velocity turns the disc, an opposite torque is applied bringing the light back to the zero point on the glass scale. In this way it is ensured that the disc will always have en angle of 45° to the velocity direction thus assuming maximum torque and no correction for angle. With this arrangement the distance between the microphone and the Rayleigh disc is fixed, allowing only one frequency to be used, as there should be exactly one quarter of a wave length between microphone and Rayleigh disc, in this case 625 Hz. However, by applying a simple correction it is possible to vary the frequency within some limits and thereby make measurements over a larger frequency range. Here frequencies between 500—800 Hz have been used. The simple correction is indicated in Fig. 7.

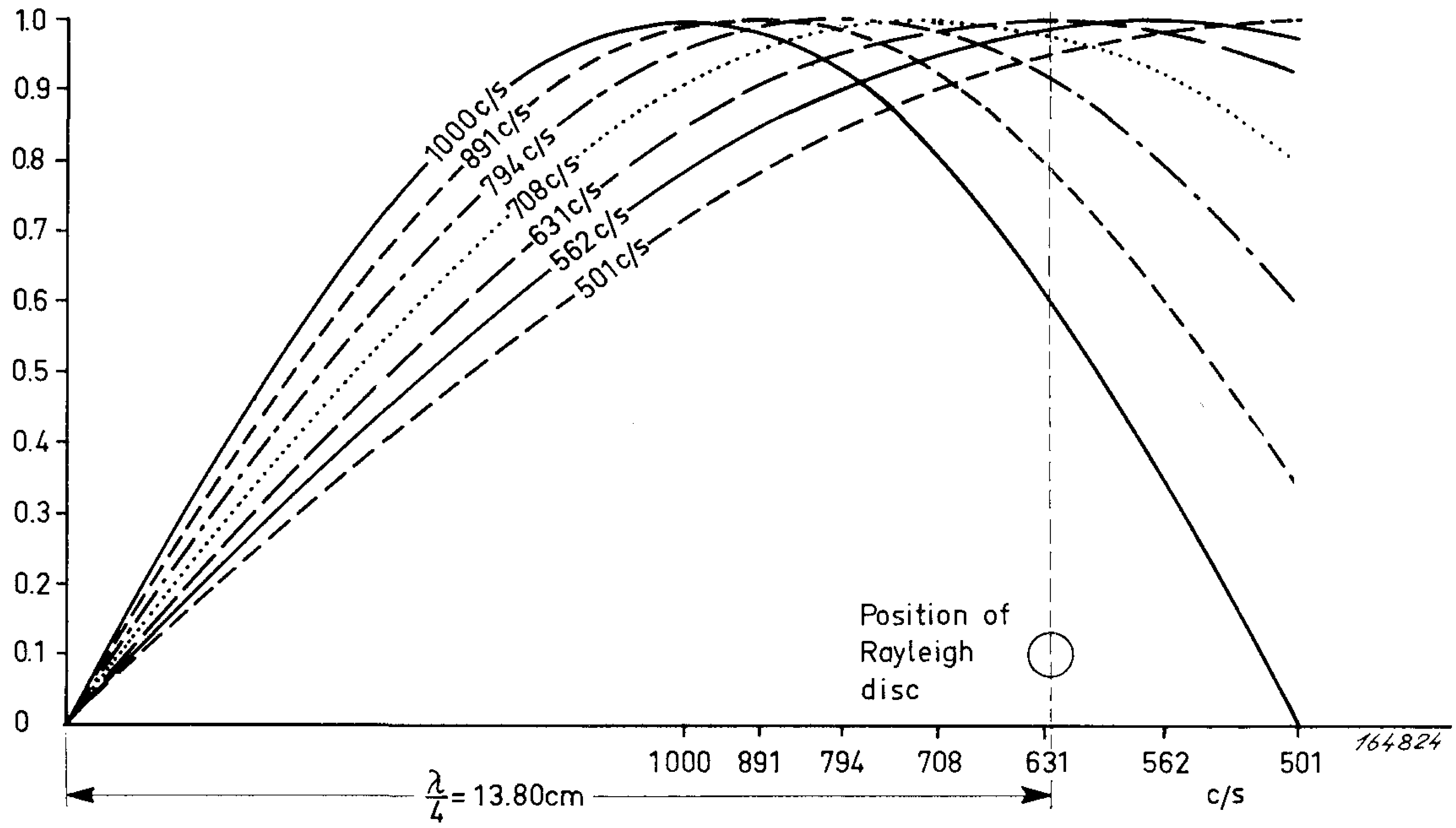


Fig. 7. Sound velocity in standing wave tube as function of distance and frequency. This graph can be used for making the correction when the Rayleigh disc is placed at other than the 1/4 wavelength point.

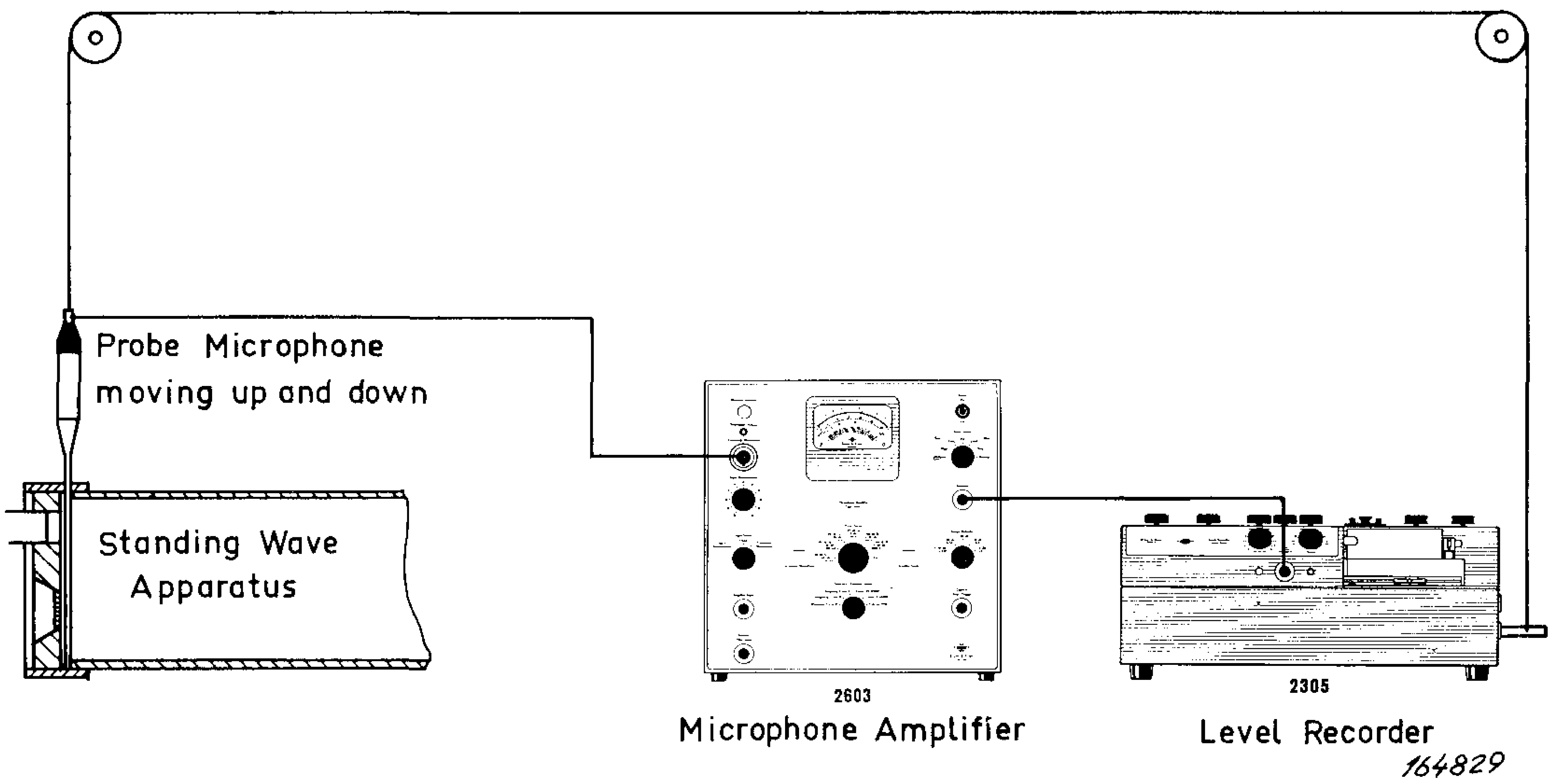


Fig. 8. Set-up for checking the sound pressure distribution in the standing wave tube.

This method will be correct only if the wave length is considerably greater than the diameter of the tube. To ascertain that a completely constant sound pressure distribution existed over the whole diameter of the tube a test was made with a probe microphone, Fig. 8. The result of this test where a 10 dB potentiometer was used in the Level Recorder is shown in Fig. 9.

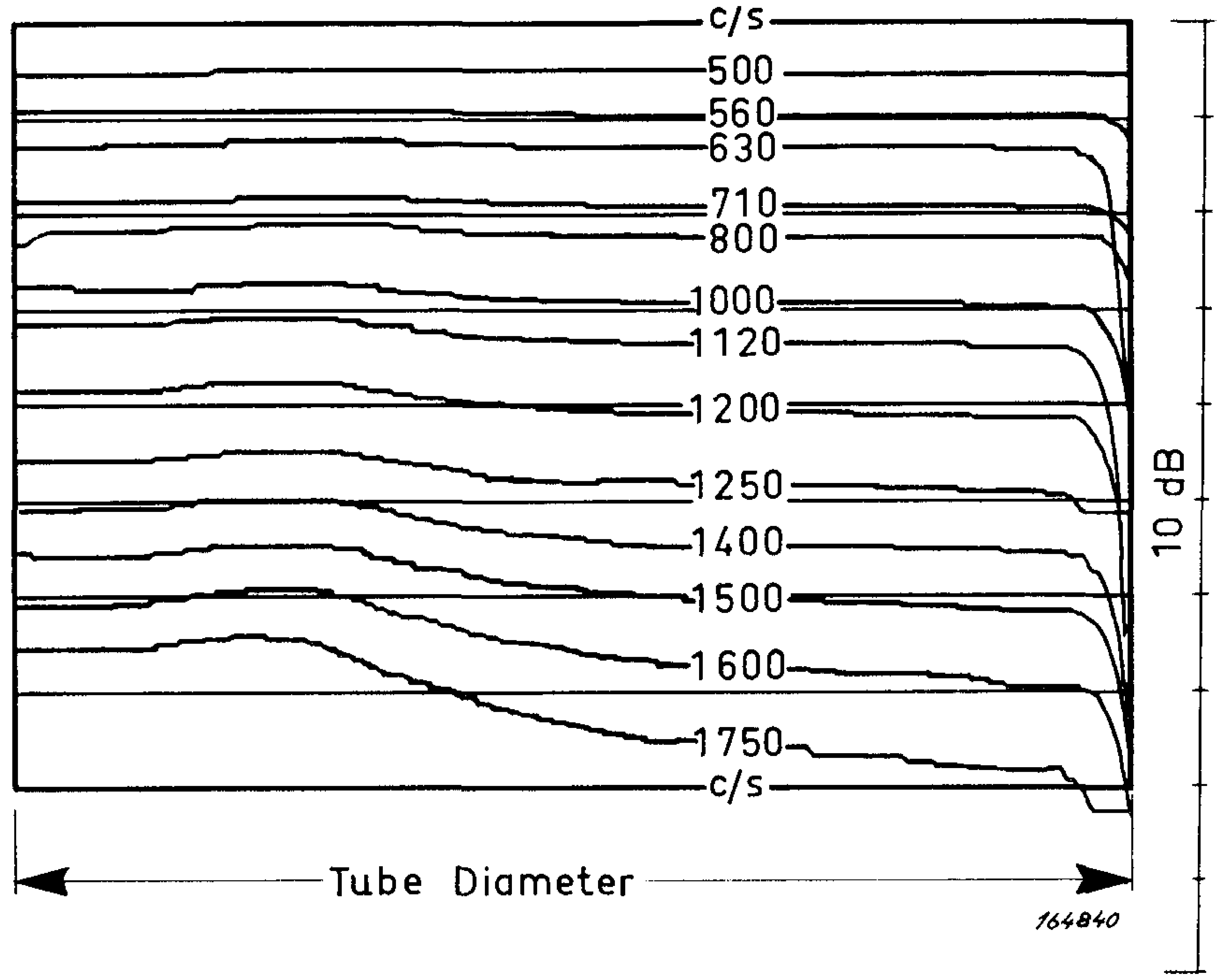


Fig. 9. Recorded graph of sound pressure over the tube diameter.

It can be seen from the graph that the method functions with an accuracy which is within a tenth of a dB up to 800 Hz. At 1600 Hz errors up to 1 dB can be found owing to the unequal sound distribution.
The sound pressure is determined by a formula given by L. V. King:

(1) $$p^2 = \frac{(\varrho_0 c)^2 \times 8\ \pi^2}{T^2} \times \frac{(I_1 + I_0)\ (m_1 + m_0)}{m_1 \times m_0} \times \Theta\ \text{dyn}^2/\text{cm}^4$$

This formula can, if the disc is small as is the case here, be reduced to

(2) $$p^2 = \frac{(\varrho_0 c)^2 \times \pi^2 \times m_1 \times 3}{T^2 \times \varrho_0 \times a \times 4} \times \Theta\ \text{dyn}^2/\text{cm}^4$$

Table VI gives the nomenclature to the different terms, units and the actual values in which the different constants are going into the measurements, and the uncertainty related to the values.
As well as the uncertainties given in Table VI, there is also the uncertainty of the formulae (1) and (2) and listed below is a series of corrections which according to taste can either be applied or ignored.

a. According to Scott (ref. 2) the torque will be increased when the disc cannot be regarded as infinitely thin in relation to the diameter. The ratio was for the present measurements 0.6×10^{-2}.
b. Owing to the vortex motion around the edge of the disc the torque will also increase according to Merrington and Oatly (refer 3). In this case the

Letter	Description	Unit	Value	Uncertainty in %
$\varrho_0 c$	Specific acoustic impedance	rayl	41.50	o.2
ϱ_0	Density of air	g/cm^3	o.001195	o.3
m_1	Mass of disc	g	125×10^{-3}	o.5
a	Radius of disc	cm	o.996	o.1
I_1	Moment of Inertia of disc = $1/4\, m_1 a^2$	g/cm^2	30.6×10^{-3}	o.5
m_0	Hydrodynamic mass of disc $8/3\, \varrho_0\, a^3$	g	3.2×10^{-3}	2.5
I_0	Hydrodynamic inertia of disc $2/15\, m_a\, a^2$	g/cm^2	$o.42 \times 10^{-3}$	2.0
Θ	Angular rotation of disc suspension	radians		1.5
T	Period of oscillation	sec.	5.56	o.8

Table VI. The constants used for the Rayleigh Disc. During the measurements the static pressure P_0 = 1023 mbar and the temperature = 298° K.

particle velocity is rather small so that the vortex motion correction should be negligible.

c. The torque should increase somewhat because the diameter of the Rayleigh disc is not infinitely small in comparison with the diameter of the tube. According to Scott this correction should in the present measurement be about o.5 %.

d. As the Rayleigh disc is not infinitely heavy it will oscillate slightly in response to the air particle movement. This results in a decrease in the measured torque.

e. In the neighbourhood of the natural resonance of the disc rather significant variations in the torque can be noticed. Here, however, the lowest resonance of the disc was 1850 Hz.

As these corrections in any case are fairly small but given with a high degree of relative uncertainty, it was here chosen not to apply any correction, hoping that the corrections in a positive and negative way will somewhat compensate for each other.

In the calculation of the uncertainties it was chosen to give formula (2) an uncertainty of 5 %. In this case the uncertainty of the formula will be by

Frequency c/s	Measurem.	Correction for Velocity	Microphone 78				Microphone 80				Microphone 85			
			$\alpha°$	p μbar	mV	mV/μbar	$\alpha°$	p μbar	mV	mV/μbar	$\alpha°$	p μbar	mV	mV/μbar
501	1	1.053	42.1	186	921	4.95	43.7	189	880	4.65	49.1	201	874	4.34
	2		54.4	211	1068	5.05	61.1	224	1051	4.70	72.5	244	1059	4.33
562	1	1.011	49.0	192	962	5.01	55.1	205	941	4.59	61.7	216	930	4.31
	2		60.5	214	1080	5.05	67.4	226	1049	4.63	75.5	239	1030	4.31
631	1	1.000	50.8	194	953	4.91	50.0	193	881	4.57	56.1	204	871	4.27
	2		55.8	204	1017	4.97	63.9	218	1001	4.59	66.1	222	946	4.26
708	1	1.020	43.9	183	900	4.92	49.3	195	881	4.52	56.0	208	862	4.15
	2		57.0	210	1040	4.96	66.2	226	1031	4.56	70.6	232	982	4.11
794	1	1.094	40.1	189	927	4.90	46.7	204	932	4.56	51.2	213	891	4.19
	2		55.1	221	1099	4.97	62.5	236	1081	4.57	64.7	239	1016	4.25
Average Sensitivity in mV/μbar						4.97				4.59				4.25
Standard Deviation in mV/μbar						0.054				0.052				0.078
Standard Deviation in %						1.1%				1.1%				1.9%

Table VII. Final measuring results obtained by using the Rayleigh Disc method.

far the biggest contribution to the uncertainty of the whole measuring set-up. By applying the constants given to formula (2) the sound pressure can be expressed as

$$(3) \qquad p = 27.2 \sqrt{\alpha^\circ} \ \mu\text{bar}$$

where α° is measured in degrees.

The uncertainty of the sound pressure measured with the Rayleigh disc in the standing wave tube can be calculated to

$$(4) \qquad \sqrt{0.2^2 + 0.8^2 + 0.3^2 + 0.1^2 + 1.5^2 + 5^2} = \pm 5.2\ \%$$

In Table VII the final measuring results are given for each frequency and each of the three microphones as two different measurements made at two different levels. Five different frequencies have been used, thus giving ten different sensitivity measurements for each microphone. At the bottom of the table the average sensitivity is calculated and the standard deviation is found in both mV/μbar and %. It is seen that the standard deviation is much smaller than calculated in formula (4), but the very high uncertainty given to formula (2) will of course not appear in this measurement as the formula uncertainty given will probably be one-sided and consequently go into all the measured results with the error in the same direction.
If we calculate the uncertainty on the measurements alone without taking the formula uncertainty into consideration the calculated uncertainty will be

$$\sqrt{0.2^2 + 0.8^2 + 0.3^2 + 0.1^2 + 1.5^2} = 1.7\ \%$$

where it will be seen that this is in the same order as that measured. In other words, the actual measurements with Rayleigh disc can be carried out with a repeatability of $\pm$ 2 %, but the unknown factor is still the validity of the formula used for determining the torque of the Rayleigh disc which in our opinion brings the total uncertainty of the Rayleigh disc method up to more than $\pm$ 5 %.

Classic Pistonphone.

A simple and accurate method of obtaining a known sound pressure is to use a mechanical pistonphone. This method has been used for many years and consists in general of either a motor driven or an electrodynamically driven piston, operating into a volume in which the microphone under test is placed.
A drawing of the pistonphone that was used here is shown in Fig. 10.
The piston was chosen to have a rather small diameter, only 2 mm, so that the stroke could be relatively long, since the main difficulty with pistonphones is to measure the stroke sufficiently accurately. Beside the small diameter it was an additional advantage that no bearing was necessary between the piston and the connecting rod thus eliminating any bearing slip which might otherwise have been introduced.

Letter	Description	Measured value	Unit	Uncertainty %
$\varkappa$	Ratio of specific heats for air at 26°C and 65 % humidity	1.402	ratio	o.01
P_0	Atmospheric pressure 26.7.63	1013.4×10^2	dyne/cm^2	o.1
A_p	Effective area of piston $\pi/4d^2$	3.142×10^{-2}	cm^3	o.5
l	Length of main cylinder	8.60	cm	o.15
D	Diameter of main cylinder	9.188	cm	o.10
V	Volume of main cylinder $\pi/4lD^2$	570.10	cm^3	o.2
	Volume before microphone	1.69	—	3
	Volume in microphone cavity	o.45	—	3
	Equivalent volume of microph.	o.16	—	5
	Total volume in cavity	572.40	—	o.2
s	Peak amplitude of piston from waxed paper	o.526	cm	2.0
S	Internal surface area in vol.	385^2	cm^2	1
α	Thermal Wave number	29.4	cm^{-1}	20
η	Correction for non-adiabatic compression	99.54	%	2.0
Total uncertainty for Sound Pressure $= \sqrt{o.1^2 + o.5^2 + o.2^2 + 2^2 o.15^2 + o.1^2 + o.2^2}$				2.1

Sound pressure

$$p = o.9954 \frac{1.402 \times 3.142 \times o.4916 \times 1013.4 \times 10^3}{10^2 \times 572.40 \times \sqrt{2}} = 28.95\ \mu\text{bar}$$

Table VIII. Dimensions for the classic pistonphone together with indications of the obtained uncertainty for the different parts.

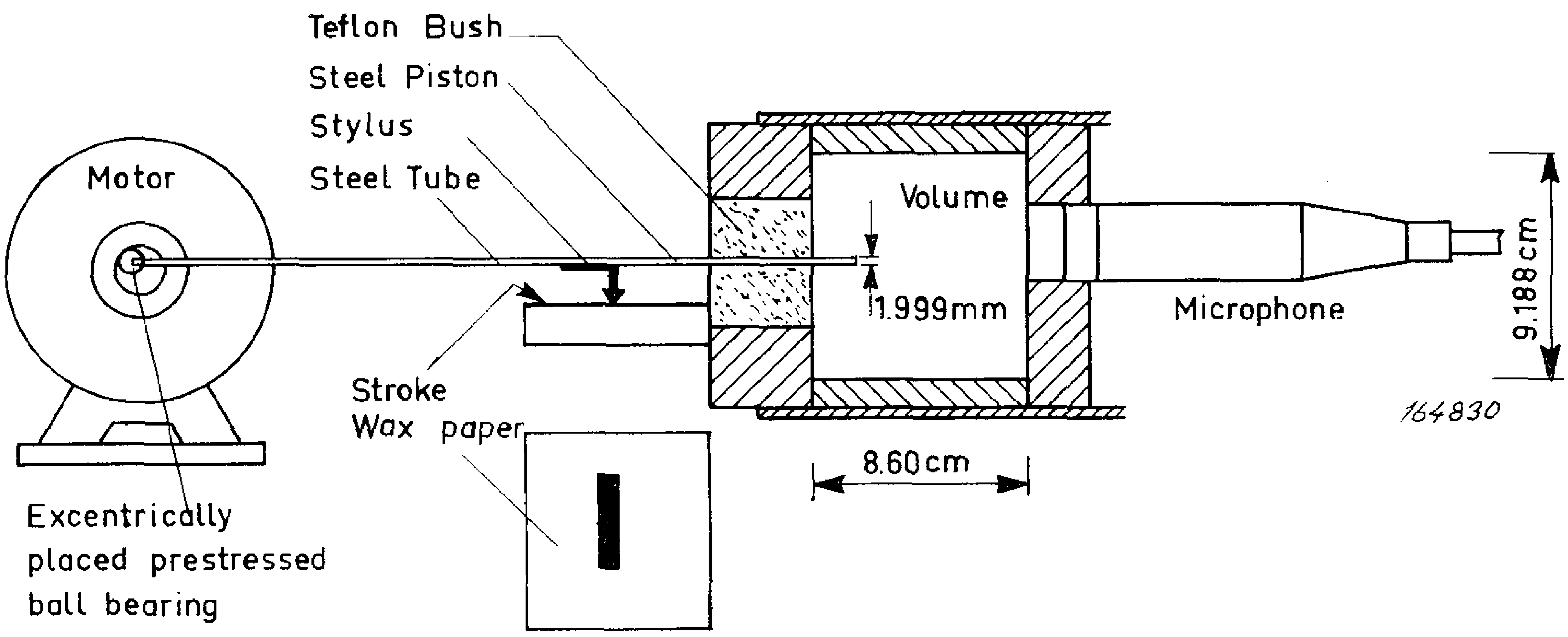


Fig. 10. The classic pistonphone running at a frequency of 49.8 Hz, where the measured relative stroke is recorded on waxed paper.

Owing to the vibration always present in such a relatively large mechanical set-up, it is necessary to measure the stroke when the machine is running. Many people have used a measuring microscope to measure the movement of a small mark on the connecting rod, but even with a stroboscope light it is difficult to get an accuracy better than 3 % of the amplitude. As it is the relative movement between the piston and main body which is important, a very simple method has been developed. As indicated in Fig. 10 a small diamond stylus fastened to the connecting rod scratched the relative movement onto waxed paper which was held close up to the body of the cylinder. In this way only the stroke was recorded independent of other vibrations. The measurement of the stroke was made with an estimated uncertainty of around 2 %.

The physical dimensions of both volume and piston can be measured with a much better accuracy, so that the total inaccuracy of the method is about 2 %.

The sound pressure in the volume is determined by

$$p = \eta \frac{\varkappa \times P_0 \times A_p \times S}{V \times \sqrt{2}} \text{ dynes/cm}^2 \qquad (3)$$

where the quantities for the classic pistonphone used here are defined in table VIII together with the calculations of both the sound pressure and the total obtained uncertainty.

Non-adiabatic Compression.

In the equation it is assumed that adiabatic compression exists in the volume or in other words there is no heat exchange between the air in the volume and the surface of the container. This phenomenon has been very carefully studied by Golay (ref. 7) and Daniels (ref. 8), and the result is a correction curve which has been redrawn in Fig. 11 valid for normal atmospheric air with room temperature and for cylindrical volume form, where the ratio between length and diameter is between 0.5 and 2.

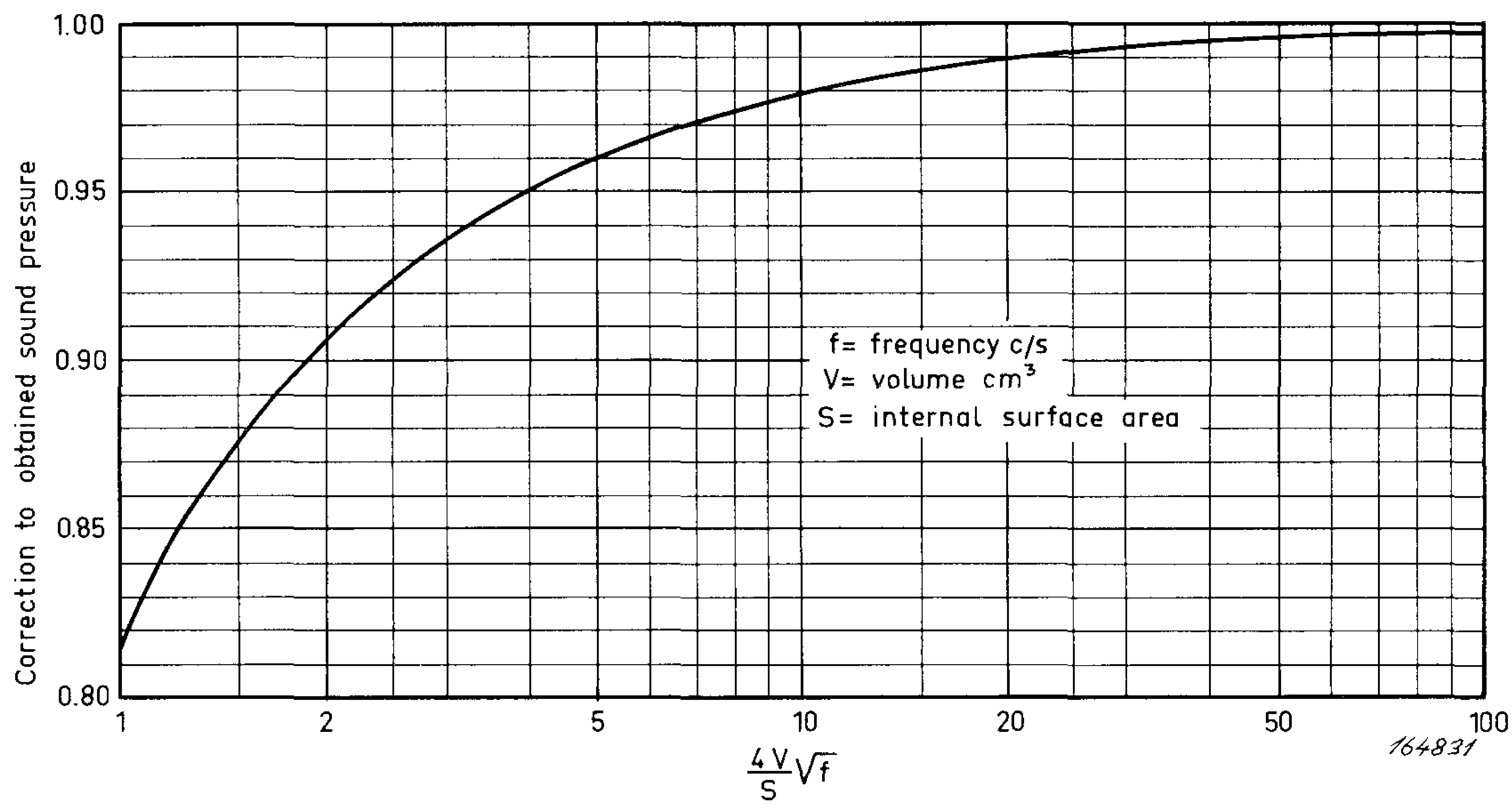


Fig. 11. Correction factor for non-adiabatic compression in a cylindrical volume.

Dr. Kjerbye-Nielsen (ref. 10) has given new formulae for the calculation of the correction factor for the sound pressure in a pistonphone which is in complete agreement with that given in Fig. 11.
The formula is as follows, where the numbers inserted are valid for the pistonphone used here:

$$\eta = \frac{1}{1 + \frac{(\varkappa - 1)\,S}{2\,\alpha\,V}} = \frac{1}{1 + \frac{0.402 \times 385}{2 \times 29.4 \times 572}} = 0.995$$

The thermal wave number is

$$\alpha = \sqrt{\frac{\varrho \times \omega \times C_p}{2\,K}} = \sqrt{\frac{1.2 \times 2\,\pi \times 50 \times 0.24 \times 10^5}{10^3 \times 2 \times 5}} = 29.4\ \text{cm}^{-1}$$

where C_p = the specific heat of the air at constant pressure = 0.24 cal/g°C
K = the thermal conductivity of the air = 5×10^{-5} cal/cm sec°C
thus giving

$\alpha = 4\sqrt{f}\ \text{cm}^{-1}$ when the units of the C.G.S. system are used.

It should be noted that with the classic pistonphone used here the correction is only 0.5 %, which means that the sound pressure calculated from formula 3 should be reduced by 0.5 %. Being a very small correction, even a large uncertainty on this correction has only very little influence on the final result.

Beranek (ref. 9) gives a curve for non-adiabatic compression which is based on Daniels' work, but the correction is only given with half the actual values. These values only have validity as correction in reciprocity chambers and cannot be used for pistonphones without doubling.

The measured results, taken on two different days having different barometric pressures, are given in Table IX. The standard deviation of the measurements is also indicated.

Microphone No.	Date	Sound Pressure μbar	Millivolts	Sensitivity mV/μbar	Average mV/μbar
	26/7	28.95	143.6	4.96	
78	—	28.95	143.8	4.96	4.98
	27/7	29.05	146.1	5.03	
	26/7	28.95	131.4	4.54	
80	—	28.95	131.2	4.53	4.52
	27/7	29.05	130.3	4.49	
	26/7	28.95	118.2	4.09	
85	—	28.95	120.6	4.16	4.18
	27/7	29.05	124.1	4.28	
Standard deviation for all three microphones:					1.2 %

Table IX. Sensitivity determined using the classic pistonphone together with the elaborate set-up shown in Fig. 3.

A series of measurements taken with the classic pistonphone, where different amplifiers and power supplies have been used, is given in Table X. The standard deviation has been calculated and it is seen that the measured deviation is much smaller than the anticipated deviation. This is naturally due to the fact that working with only one pistonphone it is not possible experimentally to judge systematic errors with a certain machine.

Microphone No.	78		80		85	
2603 - 110134	o.148	o.143	o.134	o.134	o.1212	o.121
2603 - 110200	o.152	o.149	o.137	o.131	o.123	o.123
2603 - 110197	o.140	o.139	o.127	o.126	o.122	o.120
2603 - 110202	o.145	o.143	o.130	o.129	o.118	o.120
2603 - 110153	o.141	o.141	o.129	o.129	o.118	o.118
Average voltage	144.3 mV		130.8 mV		120.4 mV	
Standard deviation s	4.4 mV		3.3 mV		2.0 mV	
Percentage s %	o.30 %		o.25 %		o.17 %	
Sensitivity of Mic.	4.98 mV/μbar		4.52 mV/μbar		4.15 mV/μbar	

Table X. The classic pistonphone used in connection with five different amplifiers of the type 2603. Two measurements were taken for each microphone.

Double Piston Pistonphone.

This is a precision sound source where the high degree of precision is obtained by incorporating two symmetrically mounted pistons with a floating retaining spring arrangement which eliminates shaft eccentricity and backlash from bearings.

The principle of the Pistonphone Type 4220 is shown in Fig. 12, where a section of the volume through the two pistons is shown to the left. The

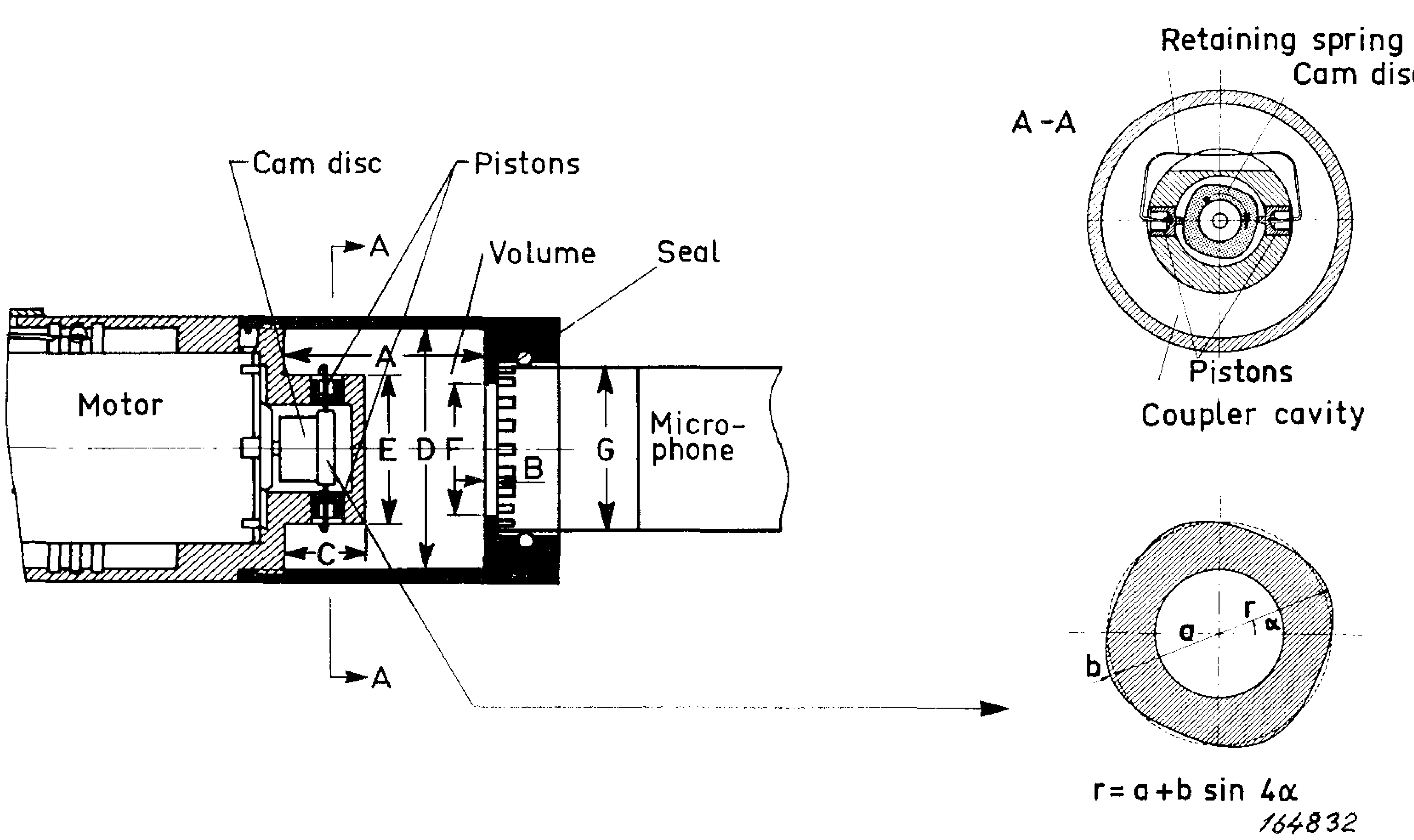


Fig. 12. Section through a double piston pistonphone with indication of principle and dimensions. The form of the cam disc is shown to the right.

pistons are driven by a cam disc of a battery driven miniature motor. The microphone is placed in the volume in which the small pistons generate the sound pressure. The cam, which is made of specially selected tempered steel, can be machined to a high degree of accuracy, in such a way that a sinusoidal sound pressure is obtained. The cam disc is formed as shown to the right in Fig. 12 so that the frequency is equal to 4 times the speed of rotation. The sound pressure will be according to formula 3 (Classic Pistonphone section) with the only difference that in this case there are two pistons, so that formula 3 has to be multiplied by a factor of 2. The correction for non-adiabatic compression is, in this case where the frequency is 250 Hz

$$\eta = 0.992$$

Another possibility for error exists if the volume housing is not stiff enough. A rough calculation made out on a simple volume is indicated in Fig. 13 showing that the equivalent volume for the movement of the wall is less than 10^{-3} cm^3 and consequently without any importance regarding the accuracy.

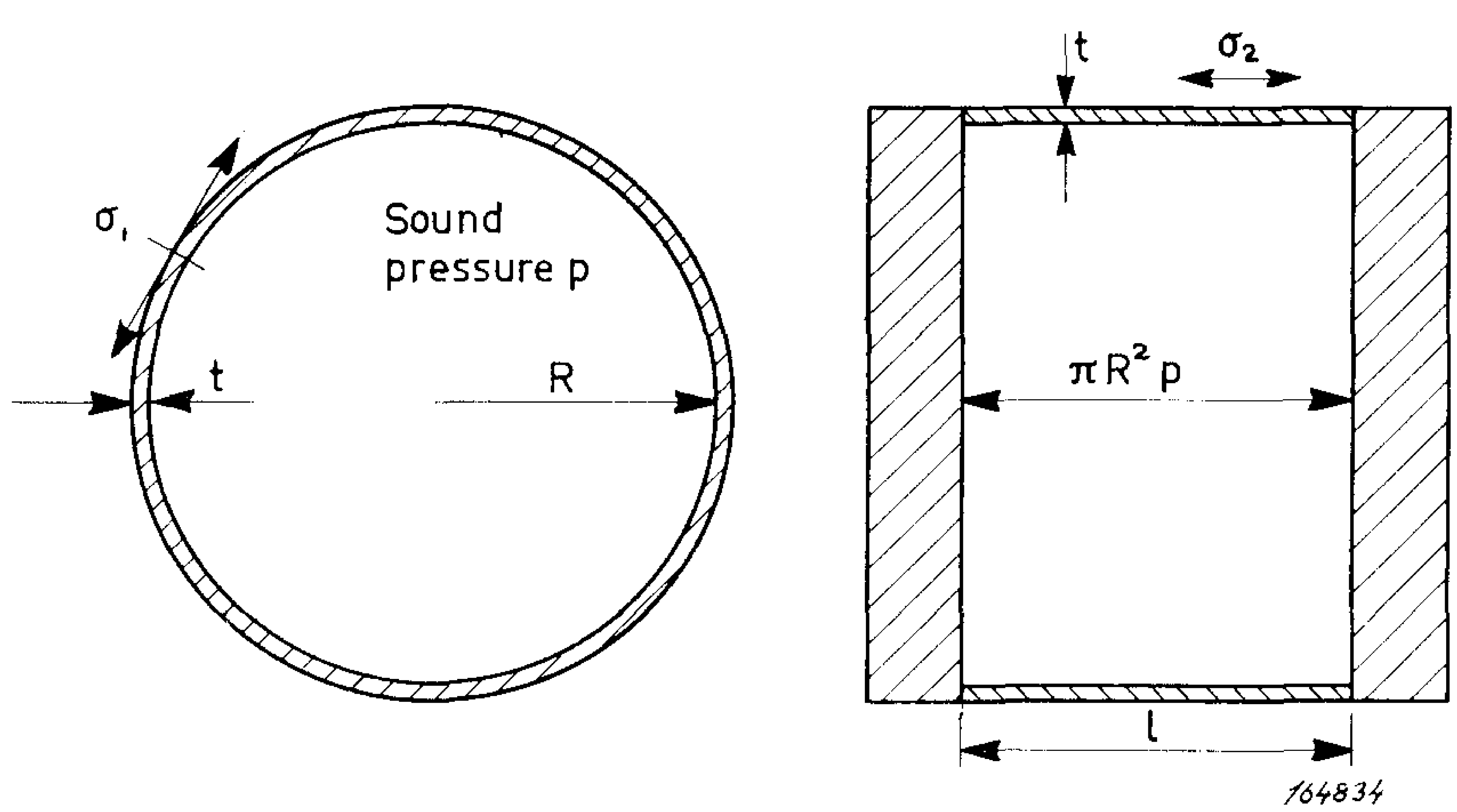


Fig. 13. Sketch from which the stiffness of cavity walls is calculated. The simple calculation involved is not given here.

In older types of pistonphones, where the volume was made of a plastic material with a modulus of elasticity of only 3×10^9 dyn/cm^2, the equivalent volume is 0.2 cm^3. This rather large equivalent volume has to be taken into account in very precise measurements.

In Table XI length and diameter measurements are shown for 3 different pistonphones. In order to determine the volume with the greatest possible accuracy Johansson's measuring blocks were used extensively, with the result that the uncertainty on the length and diameter measurements is 0.05 %. The volume is then calculated as shown in the table. It can be seen that due to the fact that the form of the volume is rather complex both positive and negative volumes appear in the table.

Dim. Letter	Description	Unit	Pistonph. 4220 serial No.			Uncert. %
			47147	85428	85459	
A	Length of main volume	mm	26.78	26.83	26.83	0.05
B	Length of coupler opening	mm	1.05	1.03	1.015	0.2
C	Length of pistonph. house	mm	11.01	11.00	11.00	0.05
D	Diameter of coupler	mm	32.059	32.029	32.024	0.05
E	Diam. of pistonph. house	mm	20.011	20.019	20.033	0.05
F	Diam. of coupler opening	mm	18.08	18.00	18.00	0.05
V_1	Calculated main volume	cm^3	21.617	21.617	21.611	
	V in coupler opening +		0.279	0.262	0.258	
	Piston house —		21.896 3.463	21.879 3.462	21.869 3.467	
	Total volume to microphone plane	cm^3	18.433	18.417	18.402	
V_2	Volume in front of microphone with adaptor ring		0.729	0.279	0.279	
V_3	Difference betw. adaptor ring and normal grid		0.609	0.609	0.609	
V_4	Equivalent vol. of mic. 78		0.160	0.160	0.160	
V	Total measured volume	cm^3	19.481	19.461	19.450	0.10
$V_1 + V_2$	Volume measured by weighing Hg + V_4				19.440	0.03
Ap	Effective area of pistons	cm^2	12.56×10^{-2}	12.56×10^{-2}	12.56×10^{-2}	0.1
S	Peak amplitude of one piston	cm	2.495×10^{-2}	2.490×10^{-2}	2.475×10^{-2}	0.15
P	S.P.L. with 760 mm Hg and microphone 78		320.2	319.3	318.7	0.2

Table XI. Determination of volume, piston area, and stroke for three pistonphones of the type 4220. The volume of serial No. 85459 was also checked by weighing the equivalent volume of mercury. The sound pressure level was determined with normalized static pressure.

As the pistonphones are normally used with microphones fitted with the standard protection grid, the volume of these complicated grids and the volume down to the sealing gasket are taken into consideration together with the equivalent volume of the microphones. A drawing of the protecting grid is shown in Fig. 14.

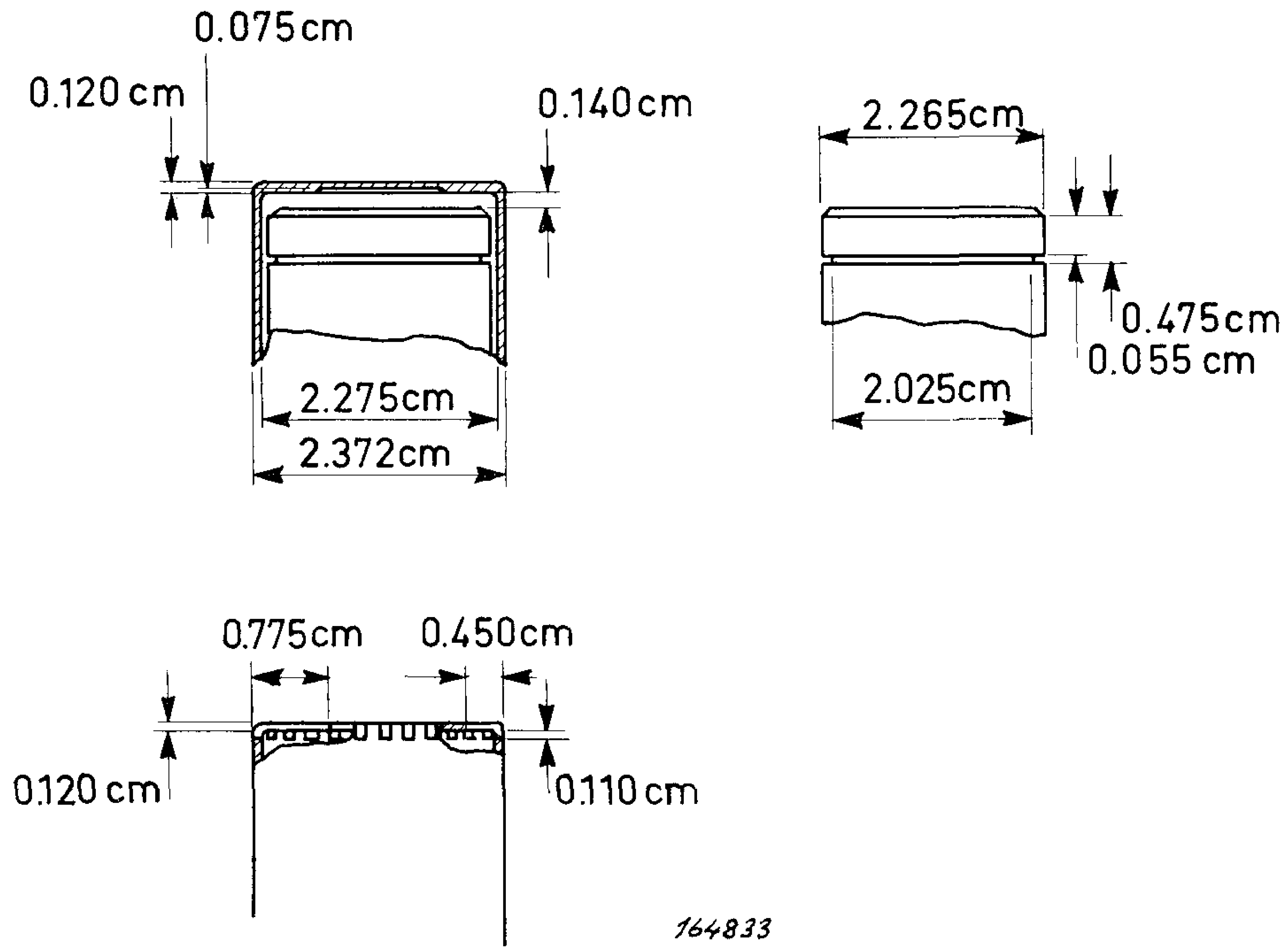


Fig. 14. Drawing and dimensions of the standard protecting grid used over the microphones when tested in the Pistonphone Type 4220.

Finally, the total volume can be determined with an overall accuracy of 0.10 %. To check the measured volume one of the pistonphones with serial No. 85459 was controlled by weighing the equivalent volume of mercury. A small hole was drilled in the side of the pistonphone so that it was possible to pour mercury into the volume. A dummy microphone with the equivalent volume cavity was inserted, and in this way the total volume including protecting grid, sealing volume and the main volume could be weighed out with an accuracy of about 0.03 %. This accuracy could very easily be controlled by jigging the mercury a little to and fro and keeping track of the mercury lost in the whole process.

All the measurements were repeated by different people at different times, which gives a good picture of the uncertainty of the measurements.

The effective area of the pistons is determined as the average of the outside diameter of the pistons and the internal diameter of the holes. As the pistons are running dry, there is in fact only extremely small clearance between pistons and wall. The peak amplitude of the pistons is determined with a high degree of accuracy from measurements of the cam disc, but still

it can be seen from the table that these measurements involve the greatest uncertainty on the whole sound pressure determination.
The sound pressure level under standard static pressure conditions and a microphone with equivalent volume of 0.16 cm^3 is given in the table.
The total uncertainty of the sound pressure, which is indicated in the table, is only 0.2 %.
For the determination of the sensitivity of a microphone cartridge the set-up shown in Fig. 15 is used, where all efforts to cut down the uncertainty of the electrical measurements are made. The three cartridges which have been used here were then all measured with the pistonphone 85459, which under standard conditions produces 318.7 μbar.
Shown in Table XII are the results of a series of measurements taken on

Date	Unit	Microphone Output Voltage with 318.7 μbar		
		Microphone 78	Microphone 80	Microphone 85
April 14	dB re 1 volt	3.91	3.10	2.38
— 14	—	3.91	3.04	2.34
— 15	—	3.90	3.05	2.34
— 15	—	3.84	3.02	2.40
— 17	—	3.86	3.03	2.40
— 17	—	3.84	3.05	2.37
— 22	—	3.91	3.02	2.34
— 22	—	3.90	3.08	2.35
— 23	—	3.91	3.07	2.33
— 25	—	3.92	3.08	2.34
— 25	—	3.91	3.08	2.38
— 29	—	3.86	3.01	2.36
Average dB	—	3.89	3.05	2.36
Deviation s	dB	0.03	0.03	0.025
Deviation s	%	0.33	0.33	0.28
Output	volts	1.563	1.420	1.311
Sensitivity	mV/μbar	4.91	4.46	4.11
Standard Deviation	%	0.37	0.37	0.34

Table XII. Sensitivity of the three microphones determined with the double piston pistonphone No. 85459. Standard deviation on both the electrical measurement, and the sensitivity determination is found.

different days, but all reduced to standard static pressure, and taken with a chosen cathode follower with a standard 0.8 dB attenuation and 3 pF input impedance. The output voltage is given in dB with reference to 1 volt. The average value is calculated and the sensitivity determined. The table also gives an estimate of the obtained accuracy, which of course is somewhat higher than the directly measured spread in results.
To give an indication regarding the spread in results from standard instruments a number of microphone amplifiers were taken from the store, and the three microphones were measured using pistonphone 85459 as sound source (Table XIII).
All the measurements were carried out on the same day so no correction for difference in static pressure was necessary. All amplifiers have been carefully adjusted as to internal reference voltage before use.
The results show a standard deviation in readings up to 1.5—2 %, which seems to be the best accuracy obtainable with standard mains operated instruments, but it can also be seen that all the inaccuracy in sound pressure measurements with condenser microphones is in the electrical end of the measuring system.

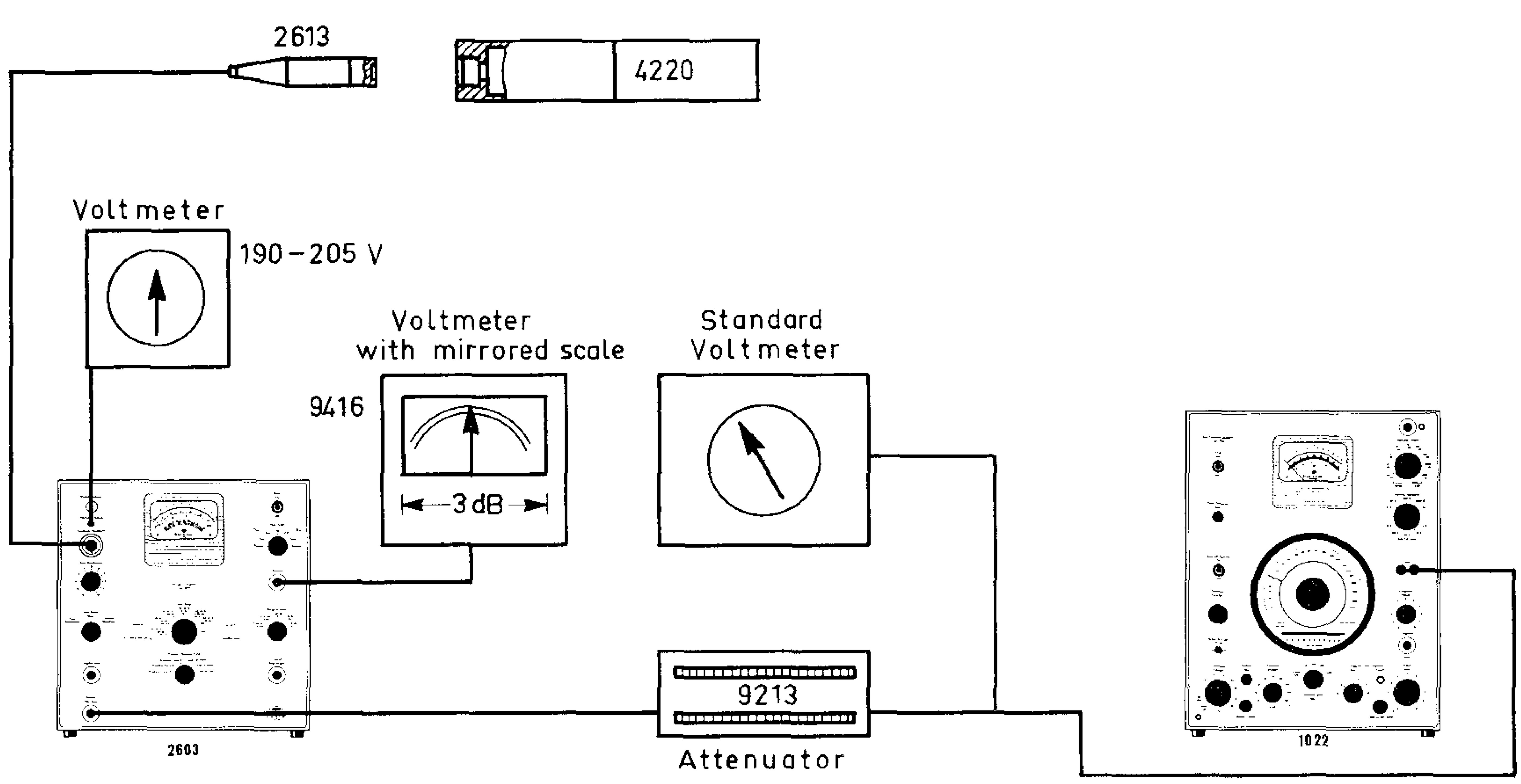


Fig. 15. Set-up for accurate sensitivity calibration using pistonphones.

April 10, 1964 Pistonphone 4220 No. 85459 Static Pressure 758 mm Hg			
Amplifier	Microphone 78	Microphone 80	Microphone 85
2112 - 107377	1.57 volts 1.56 —	1.35 volts 1.39 —	1.28 volts 1.29 —
2603 - 110202	1.58 — 1.57 —	1.39 — 1.42 —	1.30 — 1.33 —
2603 - 110197	1.54 — 1.56 —	1.39 — 1.45 —	1.29 — 1.28 —
2603 - 110200	1.55 — 1.61 —	1.41 — 1.43 —	1.30 — 1.36 —
2603 - 110134	1.58 — 1.55 —	1.48 — 1.40 —	1.31 — 1.34 —
2603 - 110153	1.529 — 1.54 —	1.39 — 1.41 —	1.31 — 1.29 —
2107 - 94692	1.58 — 1.56 —	1.43 — 1.42 —	1.31 — 1.33 —
Average	1.562 —	1.410 —	1.308 —
Sensitivity mV/μbar	4.90	4.44	4.11
Standard Deviation %	1.4	1.5	1.9

Table XIII. Sensitivity measurements for the three microphones using the very accurately calibrated pistonphone 85459 together with a series of standard amplifiers. The given standard deviation consists entirely of uncertainties in the electrical system.

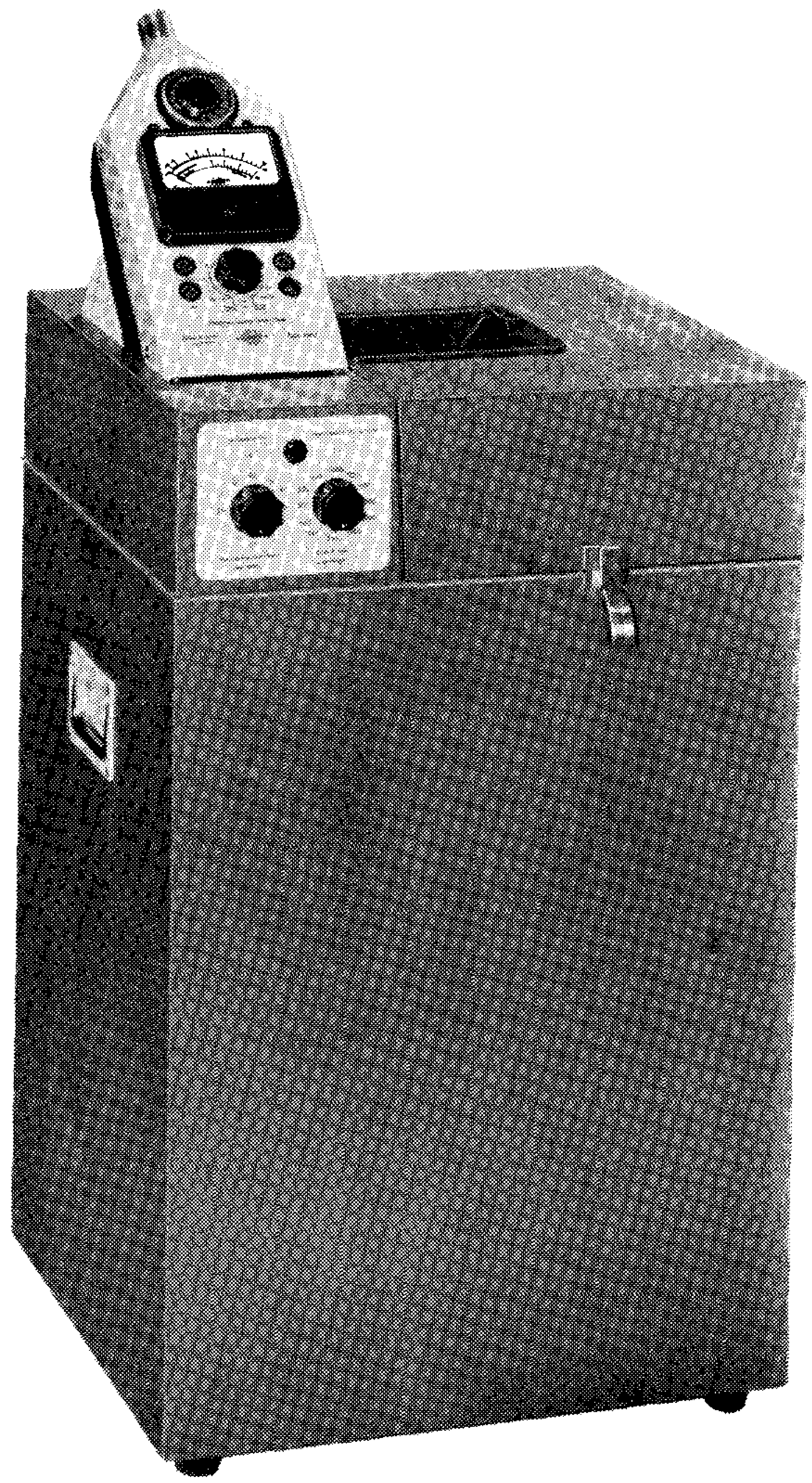
(Article to be continued in T.R. No. 1—1965)

Selected References.

1. L. V. King: "On the Theory of the Inertia and Diffraction Corrections for the Rayleigh Disc." Proc. Royal Soc., London, A153 p. 17—40 (1935).
2. R. A. Scott: "An Investigation of the Performance of the Rayleigh Disc." Proc. Royal Soc., London, A183 p. 296—316 (1945).
3. A. C. Merrington and C. W. Oatly: "An Investigation of the Accuracy of König's Formula for the Rayleigh Disc." A171 p. 505—524 (1939).
4. L. L. Beranek: "Acoustic Measurements", Chapman & Hall, Ltd. London (1956) p. 148.

5. W. König: "Theory of the Rayleigh Disc." Wied. Ann. Vol. 43 (1891) p. 43—60.
6. P. V. Brüel: "Sound Insulation and Room Acoustics." Chapman & Hall, Ltd. London (1951) p. 63.
7. M. J. E. Golay: "Theory of Pneumatic Detector". Rev. Sci. Inst. 18, p. 347 (1947).
8. F. B. Daniels: "Acoustical Impedance of Enclosures". J.A.S.A. 19, p. 570 (1947).
9. L. L. Beranek: "Acoustic Measurements". John Wiley N. Y. p. 145, and p. 173 (1949).
10. A. Kjerbye Nielsen: "Microphone Measurements" (in Danish), Copenhagen, p. 40 (1949).

News from the Factory



Type 4217.

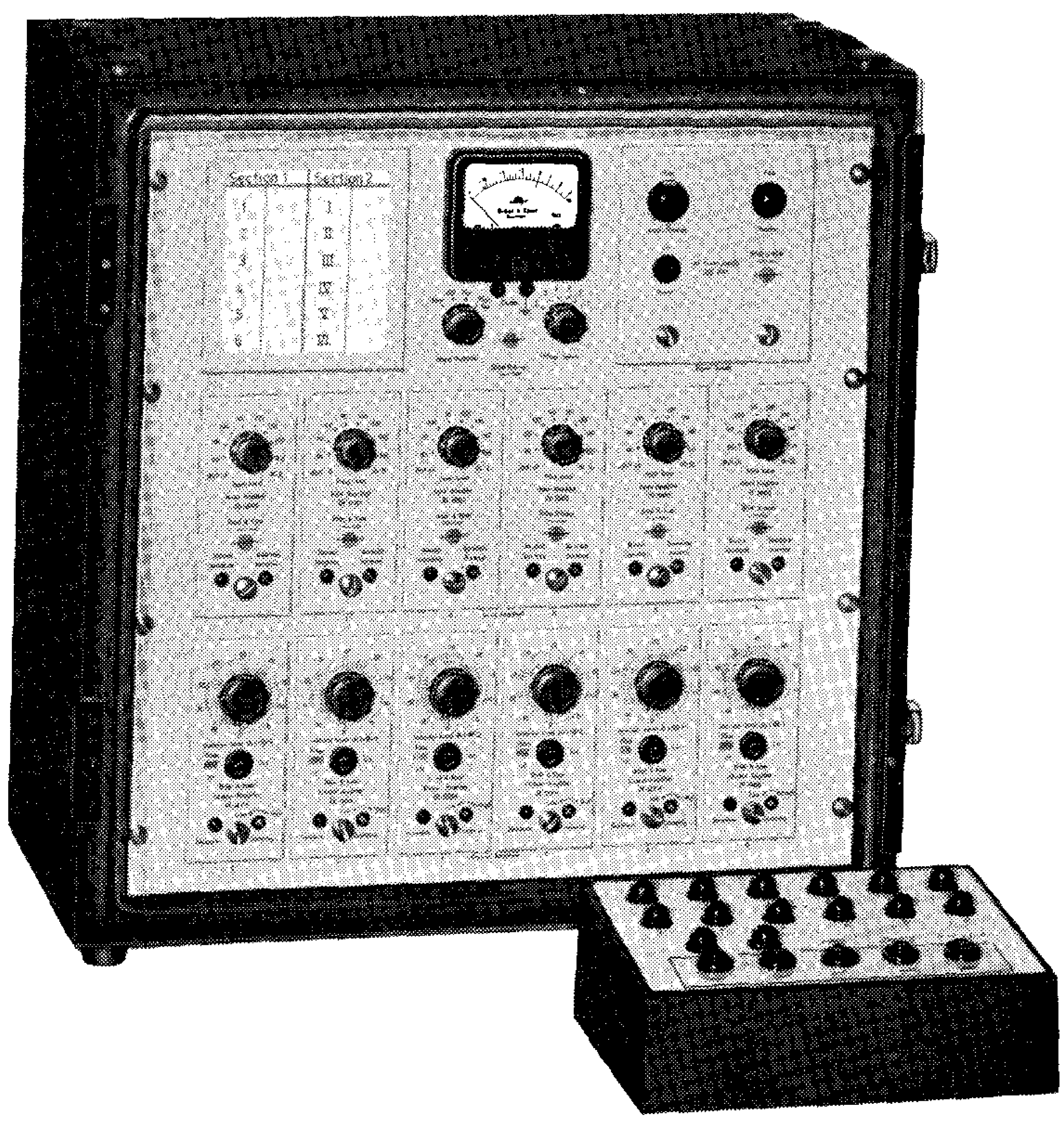
New Hearing Aid Test Box Type 4217.

This box has been designed to allow hearing aid dealers, doctors and technical hygienists to perform relatively inexpensive, complete tests on hearing aids. The only accessories necessary to perform these tests are the Precision Sound Level Meter Type 2203 (and possibly the Octave Filter Set Type 1613), which can also be used to investigate noise complaints.

The Test Box consists basically of a small anechoic enclosure with built-in loudspeaker, oscillator and amplifier covering the frequency range from 200 Hz to 5000 Hz by means of 15 fixed frequencies spaced corresponding to the internationally standardized 1/3 octaves.

The anechoic enclosure provides a reproduceable sound field, and presents free field conditions similar to those of the widely used Test Box Type 4212. At the various frequencies the output level can be individually adjusted. The maximum sound level which can be obtained at the measuring object is above 90 dB. A built-in attenuator allows variation of the sound pressure level in 5 dB steps over 40 dB, allowing a 50—90 dB range to be covered. Built-in potentiometers enable further reduction in the SPL to be made.

It is also possible to connect a tape-recorder, microphone etc. to the amplifier in the Test Box which is of specific interest in speech audiometric measurements etc.

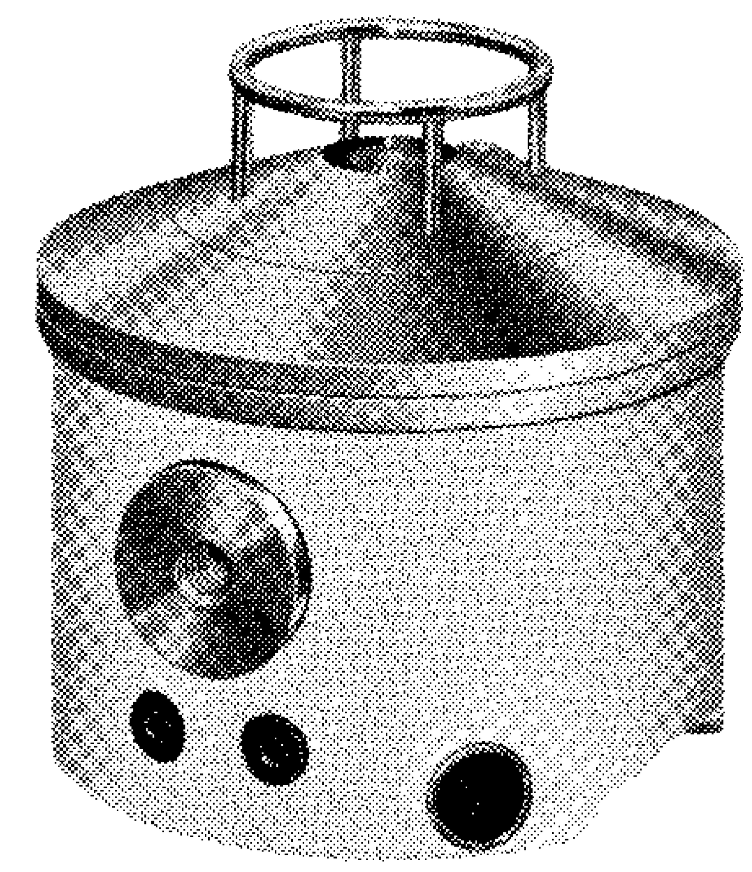


Type 2212.

New Noise Limit Indicator Type 2212.

The Noise Limit Indicator Type 2212 is an instrument designed to provide a rapid and accurate indication when a certain noise and/or vibration level is exceeded at several places, up to 2×6 places, simultaneously. It has been designed to offer the utmost simplicity in operation, and after the initial setting-up an unskilled operator can easily interpret the indicating panel. When the pre-set noise or vibration level is exceeded at one of the measuring positions a red indicating or warning lamp will light up, and in this way the possibility of confusion or errors from meter readings is completely eliminated. Due to its design even great distances can be used between the actual measuring position (position of microphone or accelerometer) and the Noise

Limit Indicator itself, which can thus be placed wherever it is found most convenient for the operator.
A typical field of application for this instrument is as Airport Noise Monitor. When used as such it is a special advantage that the output signal from each channel can also be fed into for instance a tape recorder. By later analyzing the tape the PN dB-value of the noise can thus be determined.



Type 4216.

New Artificial Mouth Type 4216.
New Artificial Mouth Type 4216 is a complete redesign of the Artificial Mouth Type 4215 and is intended for use in laboratories and for quality production control where a well defined sound source is required, as it is often more convenient to use an artificial mouth rather than the human voice for research or test purposes.
The Artificial Mouth produces a reproduceable and well defined sound field, and it covers the frequency and pressure ranges that are normally produced by the human voice.
Provision is made for automatic regulation of the sound level so that the Artificial Mouth can produce a constant sound pressure level. It should be noted, however, that the regulation is performed with the aid of a **1/2″ Microphone Type 4134 + 2615.**
The apparatus is of a cylindrical shape and consists of a small loudspeaker mounted in a metal housing, a coupler, a retaining ring and sockets for the mounting of the regulating microphone and cathode follower.
On the coupler is mounted a lip ring which may serve as a useful reference plane (acoustic center*) for the measurement of distance between the artificial mouth and the object under test. This lip ring can be removed, when pressure measurements are desired.

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*) The acoustic center is defined as the point from which the sound appears to be coming when the sound source is observed from a point in the far field.

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