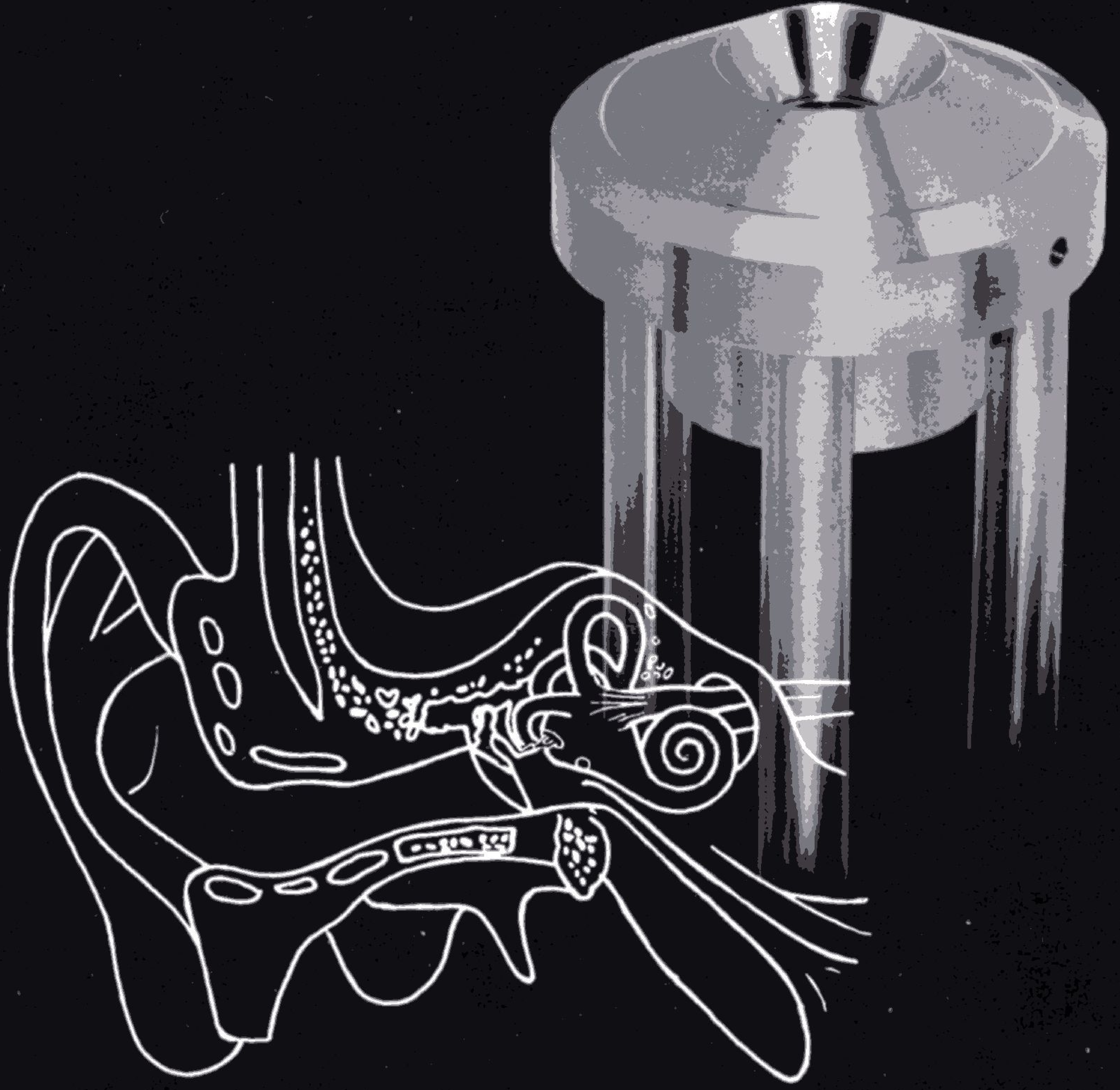
Brüel & Kjær

Technical Review

Teletechnical, Acoustical, and Vibrational Research

Artificial Ears



No. 4

1961

PREVIOUSLY ISSUED NUMBERS OF BRÜEL & KJÆR TECHNICAL REVIEW

1-1955	The Standing Wave Apparatus.
2-1955	Modern Accelerometers.
3-1955	Non Linearity of Condenser Microphones.
4-1955	A New Beat Frequency Oscillator Type 1014.
1-1956	Noise Measurements and Analyses.
2-1956	Use of Resistance Strain Gauges to determine Friction Coefficients.
3-1956	Determination of Acoustical Quality of Rooms from Reverberation Curves.
4-1956	Electrical Measurements of Mechanical Vibrations.
1-1957	Strain Gauge Measurements.
2-1957	Sound Analysis in Industrial Processes and Production.
3-1957	Measurement on Tape Recorders.
4-1957	Measurements of Modules of Elasticity and Loss Factor for Solid Materials. Surface Roughness Measurements.
1-1958	Measurement of the Complex Modulus of Elasticity.
2-1958	Vibration Testing of Components. Automatic Level Regulation of Vibration Exciters.
3-1958	Design Features in Microphone Amplifier Type 2603 and A. F. Spectrometer Type 2110. A true RMS Instrument.
4-1958	Microphonics in Vacuum Tubes.
1-1959	A New Condenser Microphone. Free Field Response of Condenser Microphones.
2-1959	Free Field Response of Condenser Microphones (Part II)
3-1959	Frequency-Amplitude Analyses of Dynamic Strain and its Use in Modern Measuring Technique.
4-1959	Automatic Recording of Amplitude Density Curves.
1-1960	Pressure Equalization of Condenser Microphones and Performance at Varying Altitudes.
2-1960	Aerodynamically Induced Noise of Microphones and Windscreens.
3-1960	Vibration Exciter Characteristics.
4-1960	R.M.S. Recording of Narrow Band Noise with the Level Recorder Type 2305.
1-1961	Effective Averaging Time of the Level Recorder Type 2305.
2-1961	The Application and Generation of Audio Frequency Random Noise.
3-1961	On the Standardisation of Surface Roughness

TECHNICAL REVIEW

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K. LARSEN & SØN - LYNGBY

Artificial Ears for the Calibration of Earphones of the External Type

by

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and

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ABSTRACT

In connection with the development of an artificial ear for audiometer use made for Working Group No. 11 under TC 29 at the International Electrotechnical Commission, some physical properties and limitations of such are discussed. The construction of a standard high impedance earphone (electrostatic type) with a flat frequency response curve over a large frequency range is described. A suggestion for an artificial ear which should be suitable as an international standard is given as a conclusion of the work. This artificial ear can be used over a large frequency range, gives highly reproduceable results, and is easy to make.

SOMMAIRE

L'établissement d'une norme internationale d'oreille artificielle pour essais d'écouteurs d'audiométrie placés contre l'oreille (et par extension d'écouteurs téléphoniques ordinaires) présente de nombreuses difficultés du fait de la complexité de l'oreille humaine et de la diversité des appareils déja en usage. L'article décrit des recherches entreprises sous l'égide de la Commission Electrotechnique Internationale (TC 29, groupe 11) dans le but de réaliser une oreille artificielle d'audiométrie susceptible de standardisation. Le point de départ de ces recherches fut une étude comparée détaillée des modèles d'oreille les plus généralement reconnus (modèles NPL anglais, CNET francais, PTT suisse, NBS. 9A et ASA. Z24.9 américains) après modifications nécessaires en vue de normalisation, c.à.d. remplacement des parties impossibles à définir géométriquement (genre feutre etc.) par des dispositifs métailliques de structure bien déterminée. Cette étude fut complétée par une série de mesures effectuées sur dix personnes différentes, de 50 Hz à 20 kHz. Un écouteur de référence consistant en une cartouche de microphone à condensateur de 12,7 mm (Type 4134) montée dans un pavillon de nylon dur a été employé pour les mesures. Ce dispositif simple possède une haute impédance acoustique et une réponse en fréquence plate jusqu'à 20 kHz. Alimenté par le Générateur Type 1014 il produit un niveau sonore suffisant avec une distorsion inférieure à 1 %.

Un prototype d'oreille artificielle synthétisant les résultats de ces recherches est présenté en fin d'article. La forme des cavités a été déterminée en particulier de façon à obtenir une réponse correcte dans toute la gamme acoustique. La construction est entièrement réalisée en matériaux durs amagnétiques. Pour déterminer avec quelle précision il est possible de reproduire pratiquement l'oreille étalon définie par ce prototype, il fut copié en trois exemplaires. Les courbes de réponse des trois copies se sont montrées identiques à ± 0.5 db près (± 1 db aux parties de pente forte).

ZUSAMMENFASSUNG

Einige physikalische Gegebenheiten und Grenzbedingungen werden in Verbindung mit der Entwicklung eines künstlichen Ohres für Gruppe No. 11 in TC29 des »International Electrotechnical Commission« besprochen. Ein Standard-Kopfhörer mit hoher Impedanz und sehr breitem Frequenzbereich ist beschrieben. Als Ergebnis der Arbeiten wird ein Vorschlag für ein künstliches Ohr gegeben, das als international Standard geeignet wäre. Dieses künstliche Ohr kann in einem weiten Frequenzbereich verwendet werden, gibt gut reproduzierbare Meßwerte und ist leicht herzustellen.

Introduction.

During the I.E.C. TC 29 Electro Acoustic Meeting in Rapallo in 1960 it was agreed that a new Working Group No. 11 should try to make international standards for artificial voices, mouths, and ears.

The working group dealing with hearing aids had already finished a specification for a 2 cm^3 artificial ear for insert type earphones, but also there was a need for an international artificial ear for earphones held outside against a human ear.

During a meeting in Liège on 8th November, 1960, a working programme was made up, and it was agreed for the moment *not* to try to make an ear where the main object was to test ordinary telephone receivers. It could be foreseen that a lot of difficulties would arise, if this was done, as practically every country has its own method of testing telephones, and very great economic interests were related to artificial ears for telephone testing. One therefore agreed to try to *suggest a specification for an international artificial ear to be used in connection with audiometers.* Of course, it was the hope that this new artificial ear also in the course of time would be used for testing ordinary telephones as it would be well suited for that purpose.

As the highest degree of reproducibility is necessary, it was agreed that in the design of an artificial ear only hard non-magnetic materials should be used and all leather, rubber, cotton, wool, and similar materials, which, from an acoustical point of view, are difficult to define, should be avoided.

Furthermore, if the new international artifical ear could be only a slight modification of an already existing widespread artifical ear or at least have characteristics which were not diverging too much from many already existing designs, this would be a great advantage.

It was therefore necessary very carefully to investigate the different artificial ears and couplers which were already in common use. The comparisons should be made with exactly the same measuring method and with the same earphones. Earphones with both high and low acoustical impedances should be used. It was also agreed that the same measuring microphone and amplifier equipment should be used throughout these comparison measurements in all the different ear models.

The following artificial ears and couplers should be used for these comparisons:

1) British NPL model modified to use a condenser microphone instead of a probe tube microphone.
2) French CNET model modified to hard material.
3) Swiss PTT model also modified to hard material.
4) USA NBS 9A 6 cm^3 coupler without modification.
5) USA ASA Z24.9 6 cm^3 coupler also without modification.

Brüel & Kjær consented to make these models and make the first test. Brüel & Kjær also agreed to try to make suggestions for models which could form the basis of an international artificial ear.

Requirements for an Artificial Ear.

In his book "Acoustical Measurements" L. L. Beranek has given a good description of an ideal artificial ear for earphone testing. An ideal artificial ear would fulfil the following requirements:

1. It would present to the earphone under test the same acoustic impedance as an average normal ear over the significant frequency range.
2. It would adequately simulate an effect of leakage between earphone and ear.
3. By means of a suitable microphone it would permit the measurements of the sound pressure at a point in the artificial ear, which gives a 1 : 1 correspondance with the sound pressure developed in the human ear over the significant frequency range.
4. Its performance would be stable.

Fig. 1 shows a simplified set-up for an artificial ear which basically consists of a cavity representing the volume between the diaphragm in the earphone and the ear-drum. From this cavity leads an opening which represents a leakage and compliance between the earphone and the ear. The sound pressure in the volume is measured by a condenser microphone connected to a suitable amplifier. The earphone is placed in the artificial ear, and to obtain a well defined frequency response, it is supplied with either a constant

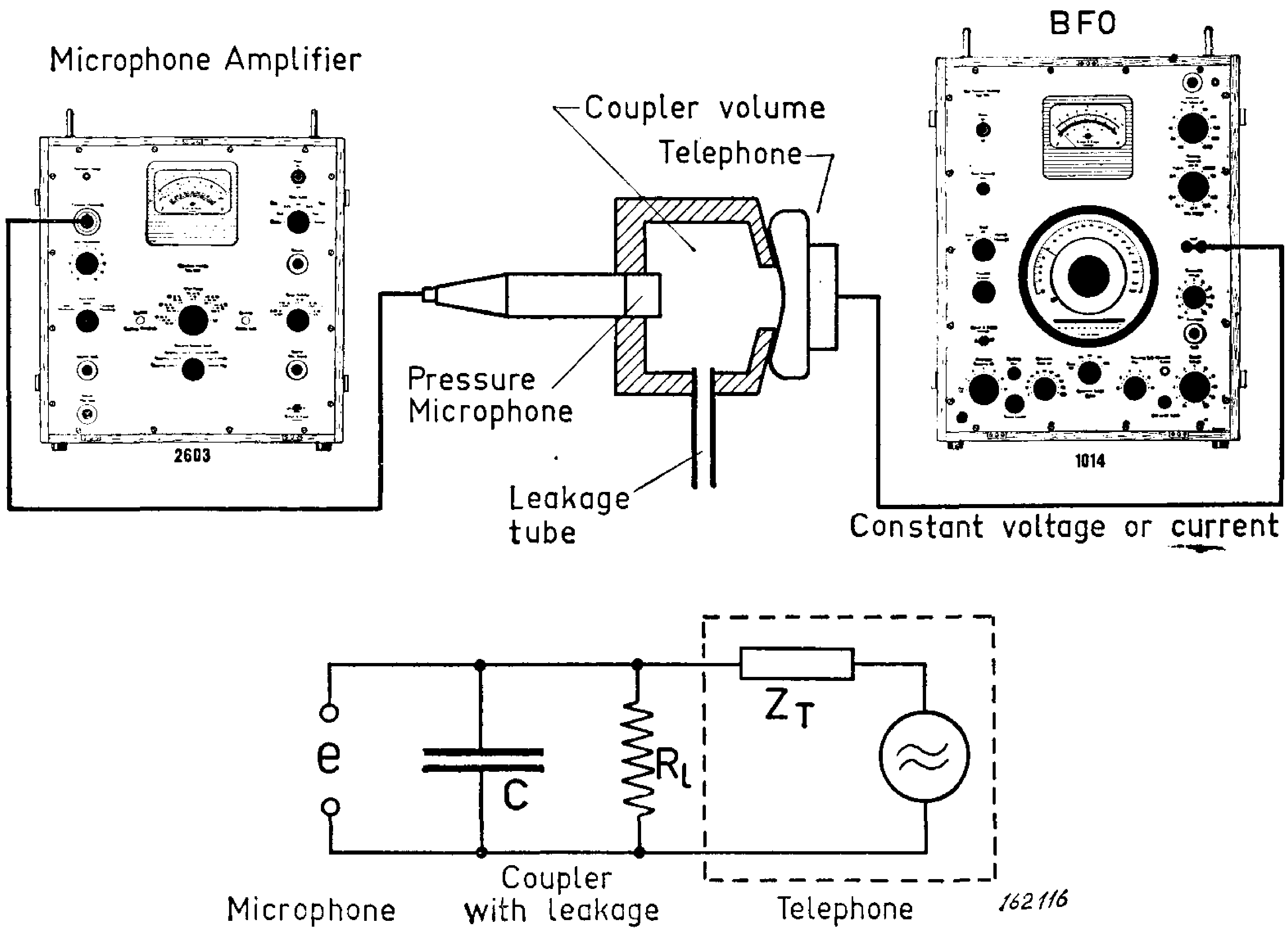


Fig. 1.
Above: Simplified set up for the testing of earphones.
Below: The equivalent electrical network.

voltage or a constant current vs. frequency.

In an equivalent electrical network the volume will be represented by the capacity and the leakage as a resistor across the capacity, as shown in Fig. 1.

The earphone can be represented as a constant voltage source with a certain internal acoustic impedance. The sound pressure is thus simply represented by the voltage across the capacitor.

From this simple network it can be seen that if an earphone with an extremely low acoustic impedance is used, the variation in the output voltage will be practically independent of both coupler and leakage. In other words, for low impedance earphones a small variation in coupler size and leakage resistance will only have a minor influence on the pressure at the condenser microphone and consequently on the obtained response curve.

To effectively compare artificial ears it is therefore necessary to use a standard earphone which then must have a high acoustic impedance in order to clearly show the difference between the different artificial ears. Such an earphone would not be ideal for work such as audiometric testing where one would prefer a low impedance earphone in order to minimize the effect of variation in leakage, compliance and size of the enclosed volume.

Standard High Impedance Earphone.

The first task was therefore to make an earphone of a well defined shape, a high impedance, and a flat frequency response over a wide frequency range. For this purpose we followed the brief description outlined in ref. 1 by making "a flat rigid surface located over the auricula without causing

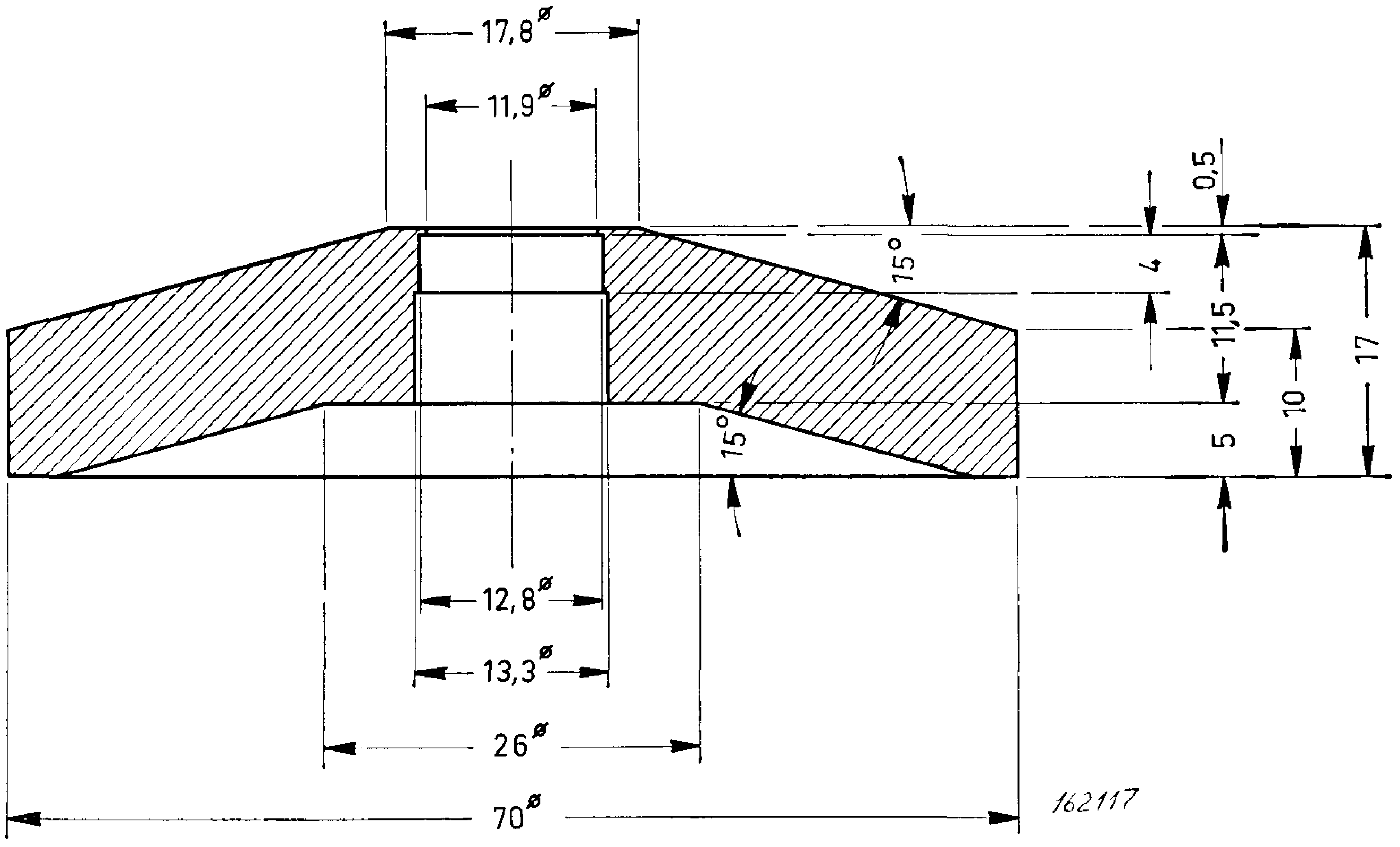


Fig. 2. Ear cap for use with a high impedance condenser transmitter. (Volume less than 0.01 cm^3 for B & K ½″ 4134 condenser microphone).

an uncomfortable depression in the flesh on the face side of the tragus and yet establishing a ring-shaped area of contact with the ear around the helix, the front of the tragus, and the lobe". We made up the ear cap shown in Fig. 2, and we tried to make it simple, well defined and reproducable, and still well adapted to an artificial ear and a human ear as well as the different national standard couplers. In order to obtain a very well defined source, we are using a condenser microphone as transmitter. Furthermore, we chose a small ½″ diameter type for reasons which shall be explained in the treatment of the high frequency range. The impedance of the transmitter should be as high as possible in order to avoid any influence on the ear impedance.

It is recommended to make the ear cap of an acoustically hard but lightweight material, for instance nylon. Furthermore, the ear cap shown in Fig. 2 is made so that the nylon piece can be used as holder for the earphone when placed on the artificial ear.

In most cases a certain mechanical load on the telephone under test is prescribed, and the nylon ear cap in connection with some spring arrangement can very easily give the necessary force.

When using the standard earphone, distortion is a very important factor. As will be seen from the following frequency response curves, practically all artificial ears have a very pronounced peak rising 25—35 db above the "standard" level at a high frequency. This peak is the resonance of the first natural modes in the coupler volume. The peaks cannot be avoided or damped. If, therefore, the telephone produces harmonics of some importance, the resonances will be excited, and when measured non-selectively will give rise to a small wiggle in the response curve at ½ and ⅓ of the resonant frequency (2nd and 3rd harmonic distortion). It is therefore important that both the BFO and the standard telephone have minimum non-linear distortion.

The force between the diaphragm and the back-electrode in the earphone cartridge can be determined from the following expression:

$$\text{Force} = \frac{S}{8\pi\, d^2\, 300^2}\left(E_o^2 + \frac{e_1^2}{2} + 2\, E_o e_1 \sin \omega t - \frac{e_1^2}{2} \cos 2\, \omega t\right) \text{ dynes} \quad \text{(I)}$$

where S is the effective surface area of the diaphragm and the back electrode in cm^2, d the distance between diaphragm and electrode also in cm, E_o is the polarization voltage in volts, normally 200 volts, and e_1 is the peak value of the alternating sinusoidal voltage impressed on the cartridge. The rms value of the alternating voltage is $e_{rms} = \frac{e_1}{\sqrt{2}}$

From this expression it is easily seen that the 2nd harmonic distortion is $\frac{e_1 \times 100}{2\, E_o} = 35{,}3\ \frac{e_{rms}}{E_o}\,\%$. If we require a distortion limit at 1 % and have a polarization voltage of 200 volts, the maximum rms alternating voltage voltage which can be used will be 5.6 volts. As the Beat Frequency Oscillator at high frequencies can have a distortion of up to 0.5 %, it is only possible in practice to use approximately 4 volts in order not to exceed the distortion limit of 1 % in the produced sound. The driving force will then be:

$$\text{Force} = \frac{S}{8\pi d^2 300^2}\ 2260 \text{ dynes}$$

It is possible to obtain a rather high sound pressure from a 1″ Cartridge Type 4132; however, it is our experience that the output from the ½″ cartridge is sufficient, and furthermore it is only in this way possible to include the higher frequencies in the measurements. A possible method of utilizing the ½″ microphone giving a higher sound pressure is described in the Appendix.

The Impedance of the Ear.

The impedance presented by the human ear to an earphone cap has been investigated very thoroughly by several laboratories during the last thirty years. After all there seems to be some agreement about the average values obtained.

One may divide the frequency range into three ranges each representing typical problems. The low (up to 700 c/s), middle (700—2000 c/s, and high (2000 c/s and up) frequency range.

The low frequency range below 700 c/s has been devoted a lot of attention in the literature and in the different artificial ear designs. In this range it is possible to obtain widely differing impedance information, although, by a close examination, it is possible to circle in some average values which are rather consistent. In some of the present national standards the problem has simply been bypassed by specifying a tight coupler of fixed volume, e.g. the American A.S.A. Z 24.9 specified coupler. If, however, the goal is to make a true artificial ear, it is necessary to introduce some acoustical impedance besides the capacity of the 6 cm^3 volume. In the literature most impedance values are averaged to be in the range 120 ohm to 150 ohm (see ref. 2—3—4—5) at low frequencies. The value depends to some extent on the experimental technique used. Some experimenters request the subject under test to adjust the receiver cap to obtain the maximum sensation from a certain tone impressed (ref. 2), others request the ear cap adjusted "as though listening to a marginal signal" (ref. 5).

Measurements have been carried out in order to determine the effect of more or less pressure by an ear cap against the ear (ref. 6 and 7), which all show that the impedance at low frequencies is not so much affected by the pressure as one should expect if the impedance was determined by a pure leakage, see Fig. 3. In fact the different sources which have measured and given average figures for the impedance at low frequencies with tight coupled ear caps are in surprisingly good agreement. This impedance will, of course, change with different ear cap shapes because of the alterations in volume both of the ear-cap and of the space left in the auricula, when the ear-cap is pressed against the ear, but these variations are not so big

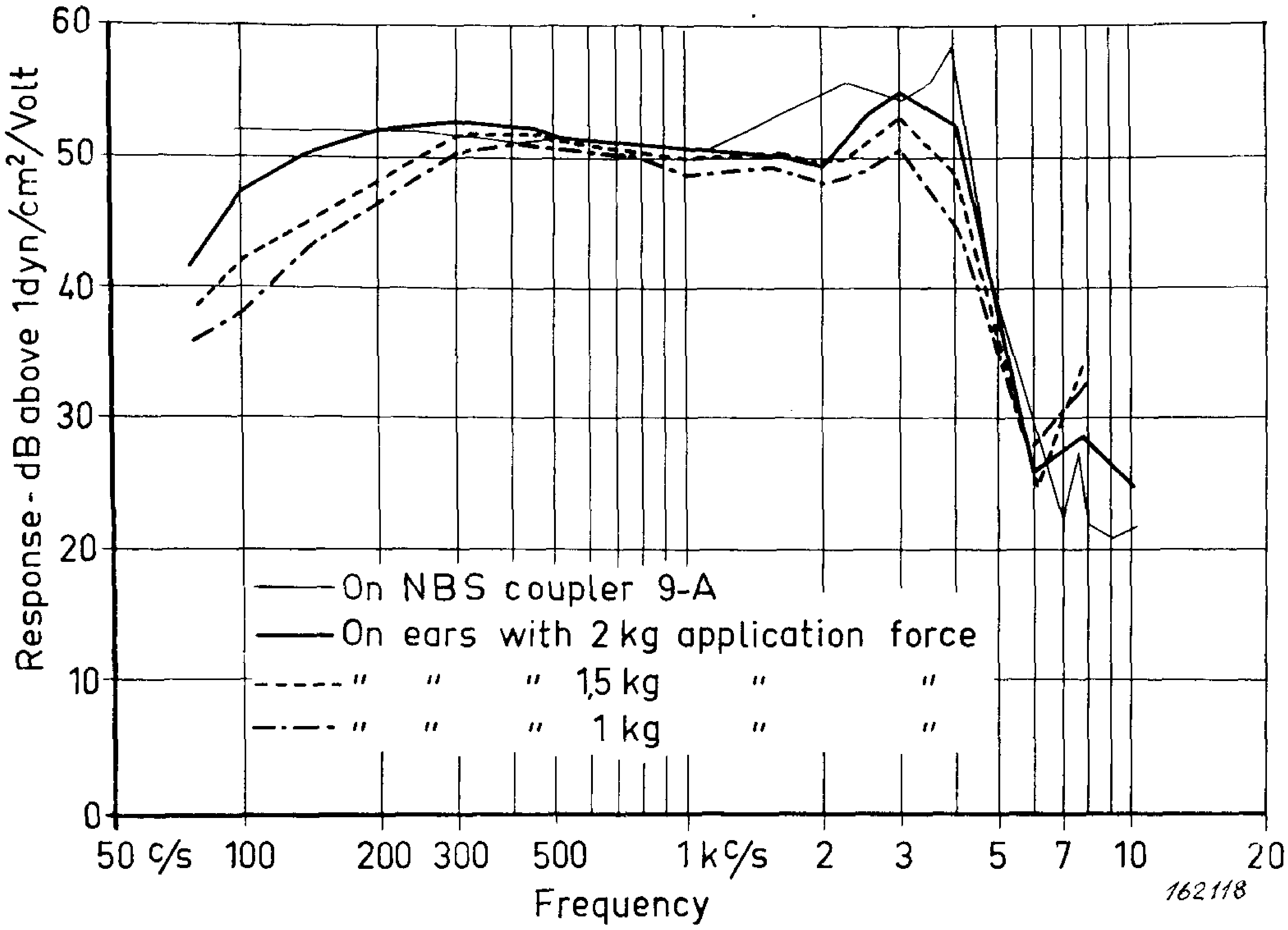


Fig. 3. Effect of earphone application force on earphone response for a Western Electric Type 705-A earphone. Force used to hold the earphone on the ear is the parameter yielding the separate curves. (After M. D. Burkhard and Edith Corliss ref. 6).

as one should expect if the impedance varied owing to a more or less casual leakage. In the works hitherto described the experimenters have all been using ear caps of different special makes, the dimensions of which are not shown in the papers. It is, of course, important to have a well defined ear cap to base the experiments on, if the results should be compared.

In order to confirm our findings in the literature by self-experience, we made measurements on both ears of 10 different persons, using the standard ear cap shown in Fig. 2. All the curves show a variation in impedance in the low frequency range which was more consistent than should be expected if the impedance were only determined by casual leakage. In that case we should expect any condition between effective tightness and very open channels between the ear and the ear cap. In order to determine the conditions for a completely tight ear, we arranged the measuring set-up as shown in Fig. 4. The ear cap was sealed against the ear by generous use of vaseline and the tightness determined by arranging a slight overpressure of a few mm of water. The pressure was checked right before a measurement and right after, and the tube for the pressure measurement was closed close to the earphone cap

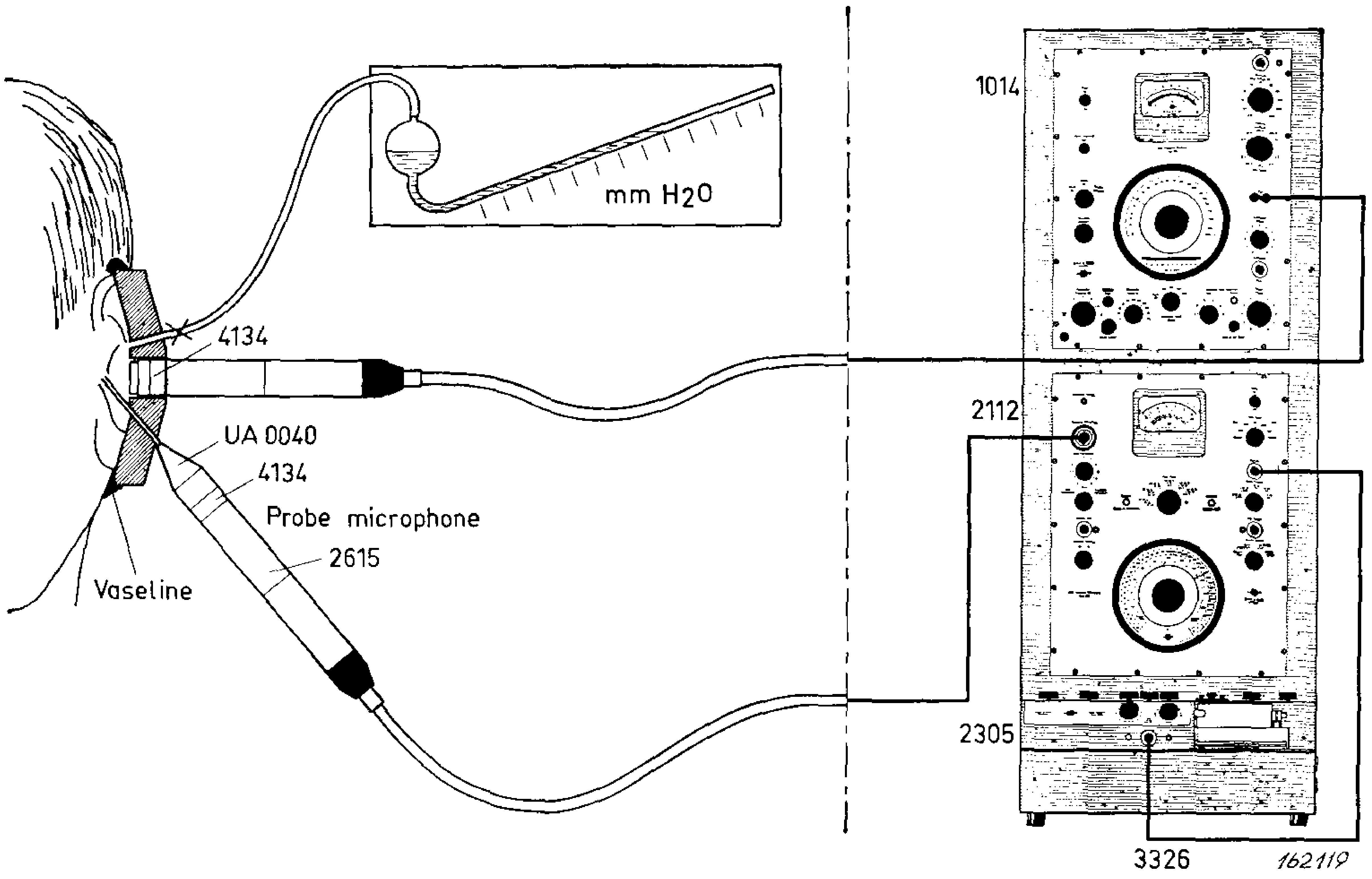
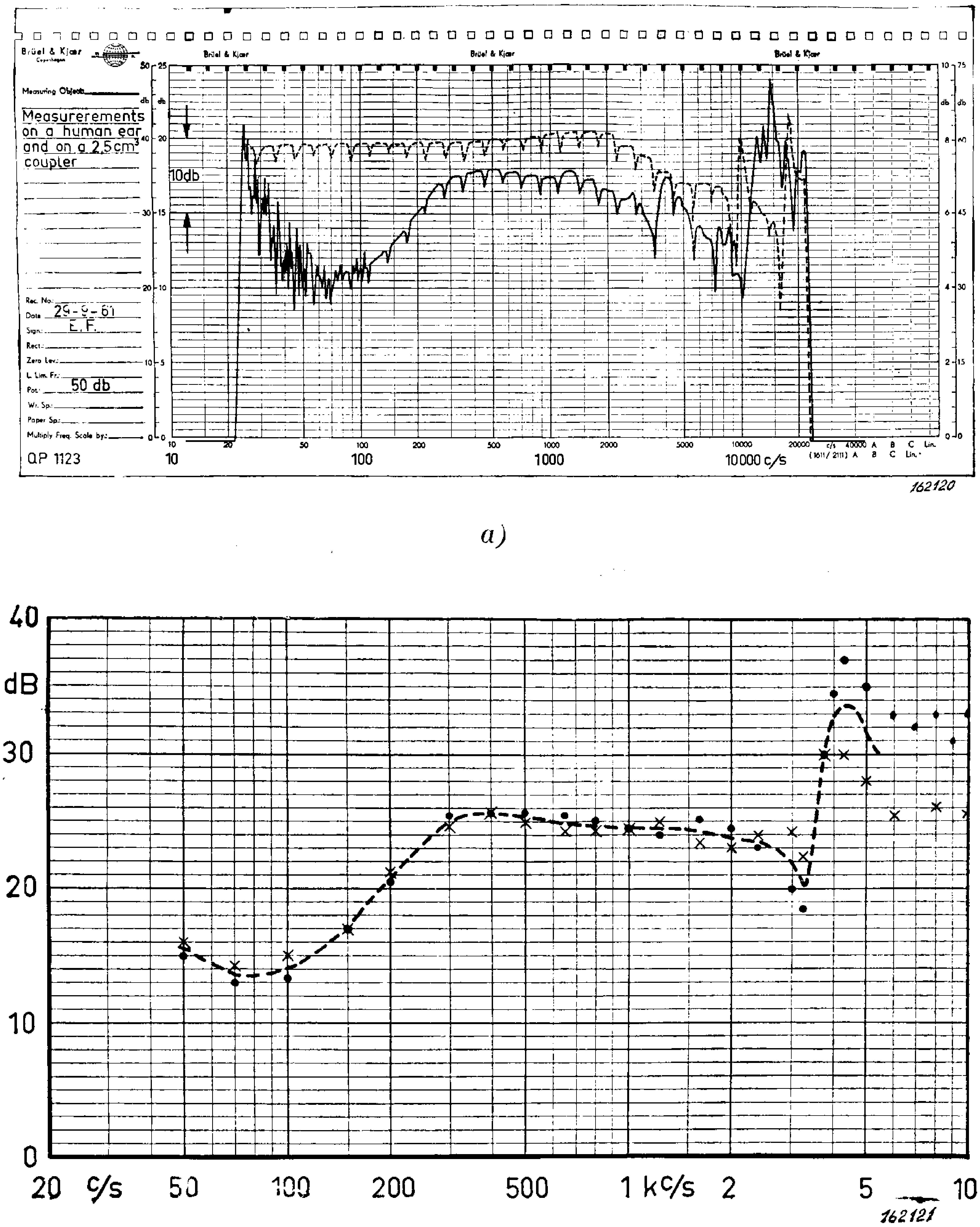


Fig. 4. Measuring set up for the measuring of the sound pressure at the ear channel entrance using the condenser transmitter and the probe tube microphone as receiver.

in order to avoid the influence of the compliance of the tube. The actual measurement was carried through in 18 sec. To cut down the effects of ambient noise and pressure variations due to small unintentional movements of the subject under test, the signal from the probe microphone was filtered through a third octave analyzer synchronized with the B.F. Oscillator feeding the "transmitter". The signal was finally recorded on a level recorder. In order to obtain a reference for the complete set-up, the receiver, including probe microphone and pressure measuring arrangement, was transferred to a 2.5 cm^3 coupler right after the ear measurement and a new curve recorded. Two typical recordings obtained in this way are shown in Fig. 5. Measurements were carried through between 50 c/s and 20 kc/s. It is interesting to note the trough in the curve at 70 c/s. Most experimenters stop their investigations at 100 c/s, however, in ref. 6 some data are given also at 70 c/s, which show a somewhat similar tendency as we found. This trough may be explained as a resonance in the outer ear. It is interesting too to note how well the slope of the curve below 300 c/s corresponds with those shown in some of the earlier works carried out with relatively high impedance microphones. In the middle frequency range there is a good agreement between the different experimental results as to the impedance value. The volume enclosed by the ear will of course depend on the shape of the cap. A well designed ear cap intended for wide frequency range use will have as small a volume enclosed as possible. The normal value cited in the literature is 5—6 cm^3. The extreme values are 3.6 and 7.2 cm^3, see



a)

b)

Fig. 5.

a) Typical recording as obtained on a human ear (full line) and on a 2.5 cm^3 coupler as reference (dotted line). Recorded by the set up shown in Fig. 4.

b) Typical average curve for right and left ear of one of the subjects tested.

ref. 8. It is undoubtedly possible to obtain a value of 3.6 cm^3 with an ear cap which fits well to the ear and partly fills out the auricle, and also a volume of 7.2 cm^3 may be found for a very deep ear cap. The A.S.A. standard prescribed a matching of the 6 cm^3 coupler to the ear cap so that the 6 cm^3 volume is maintained independent of the shape of the ear cap. This method, of course, gives full credit to the driving system when comparing receivers. However, it does not give any idea of the care by which the ear cap is designed and how the driving system is placed in the ear cap, this being especially important at high frequencies.

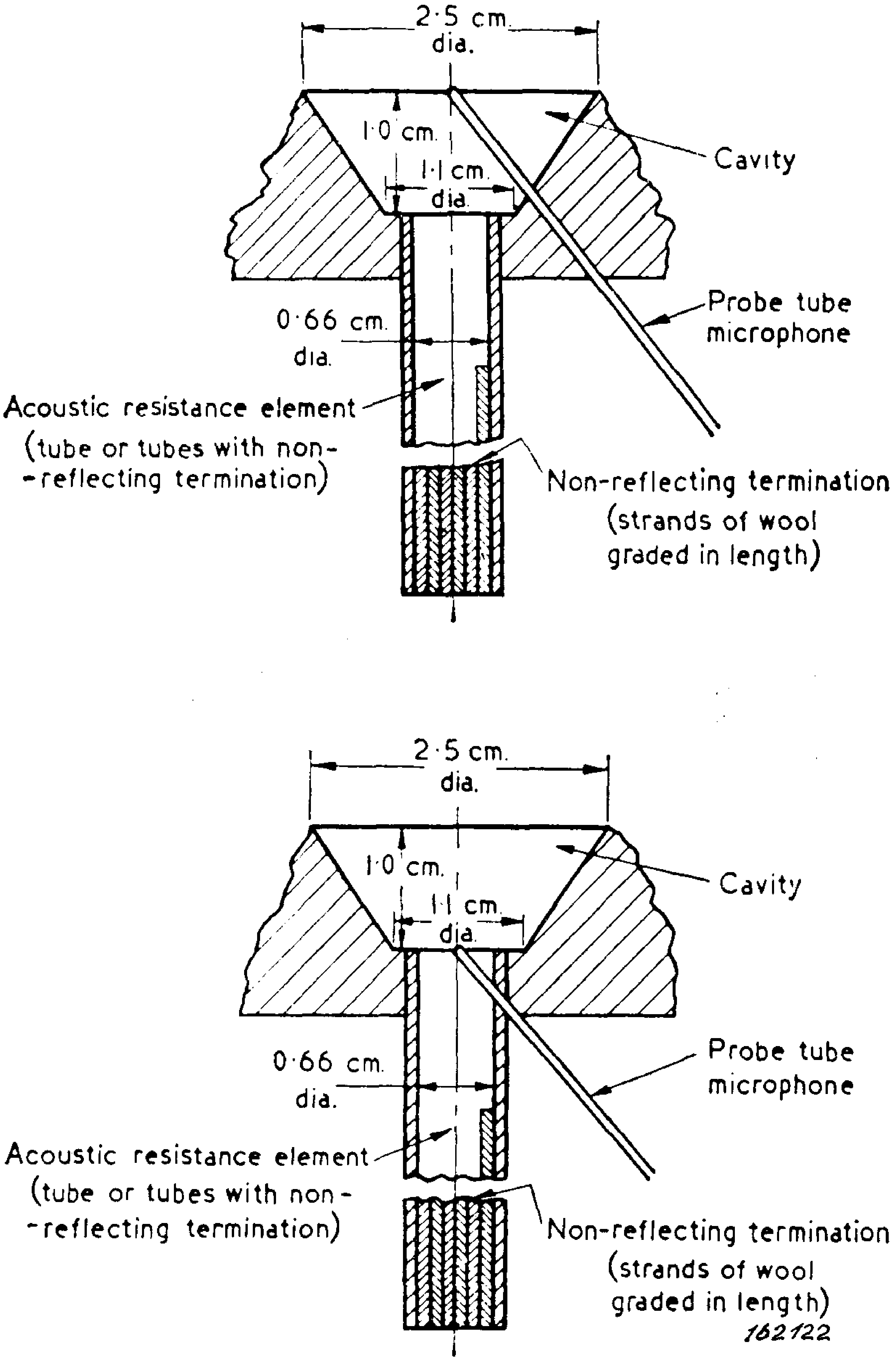


Fig. 6. Specified drawing of the British Standard artificial ear with probe tube microphone. British Standard 2042 : 1953.

Regarding the high frequency range above 2000 c/s there is in most works a tendency to bypass the troubles obtained in silence. However, it is clearly shown in several works that the volume reactance changes rather sharply between 2000 and 3000 c/s. In general the change is comparable to the change between a 4.5 cm^3 and a 2.5 cm^3 volume, thus we may regard this change as being caused by the mass inertance in series with the volume reactance of the ear channel + the equivalent volume of the ear drum. In the electrical equivalent diagram, Fig. 28, is shown in detail the circuit and the frequency response in that range. The dip in the response is caused by the series resonant circuit and the succeeding parallel resonance causes the peak. The steepness of the slope is determined by the value of the resistance. The impedance variations in this range are also described in ref. 2, as well as an artificial ear including an acoustical compensation network. Also in the Swiss PTT coupler an acoustical network is included for the same reasons.

At frequencies above 5000 c/s very little information is available in the literature except for the work done by S. C. Dalsgaard, ref. 9. In order to cover the frequency range above 5000 c/s in the best possible way one should have a small coupler volume and a correct shaped one. Also the microphone used is very important. This is discussed later in the article.

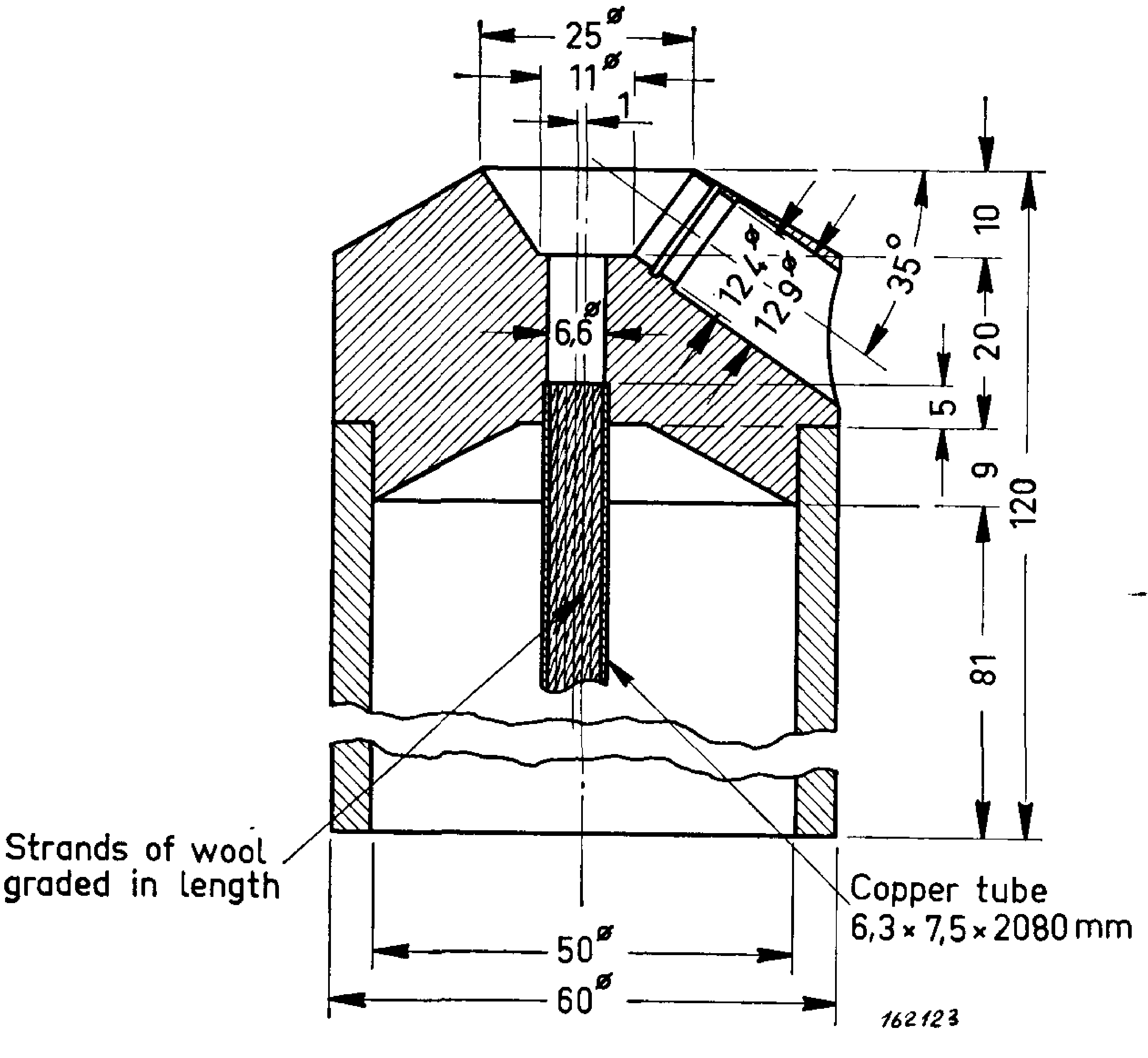
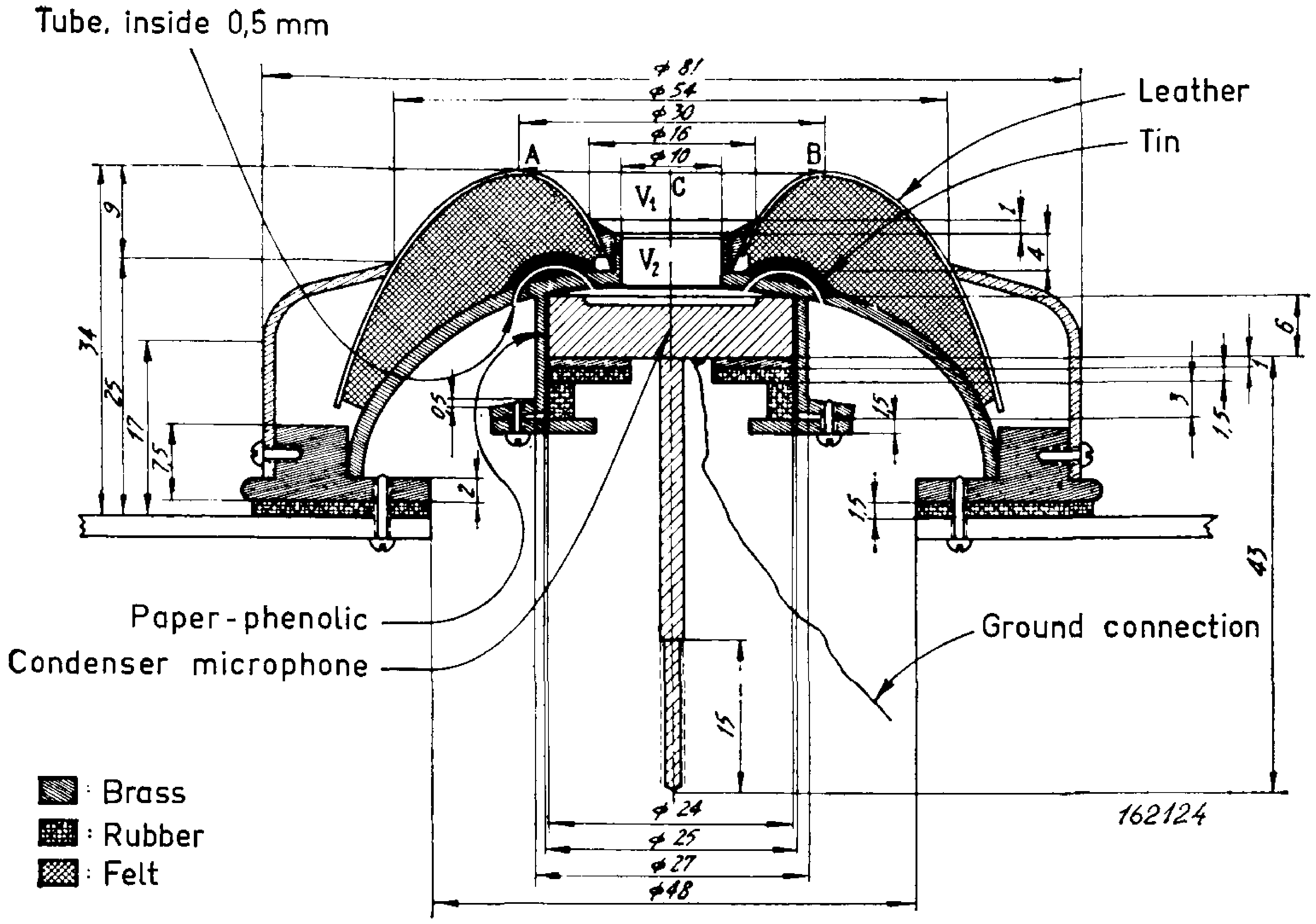
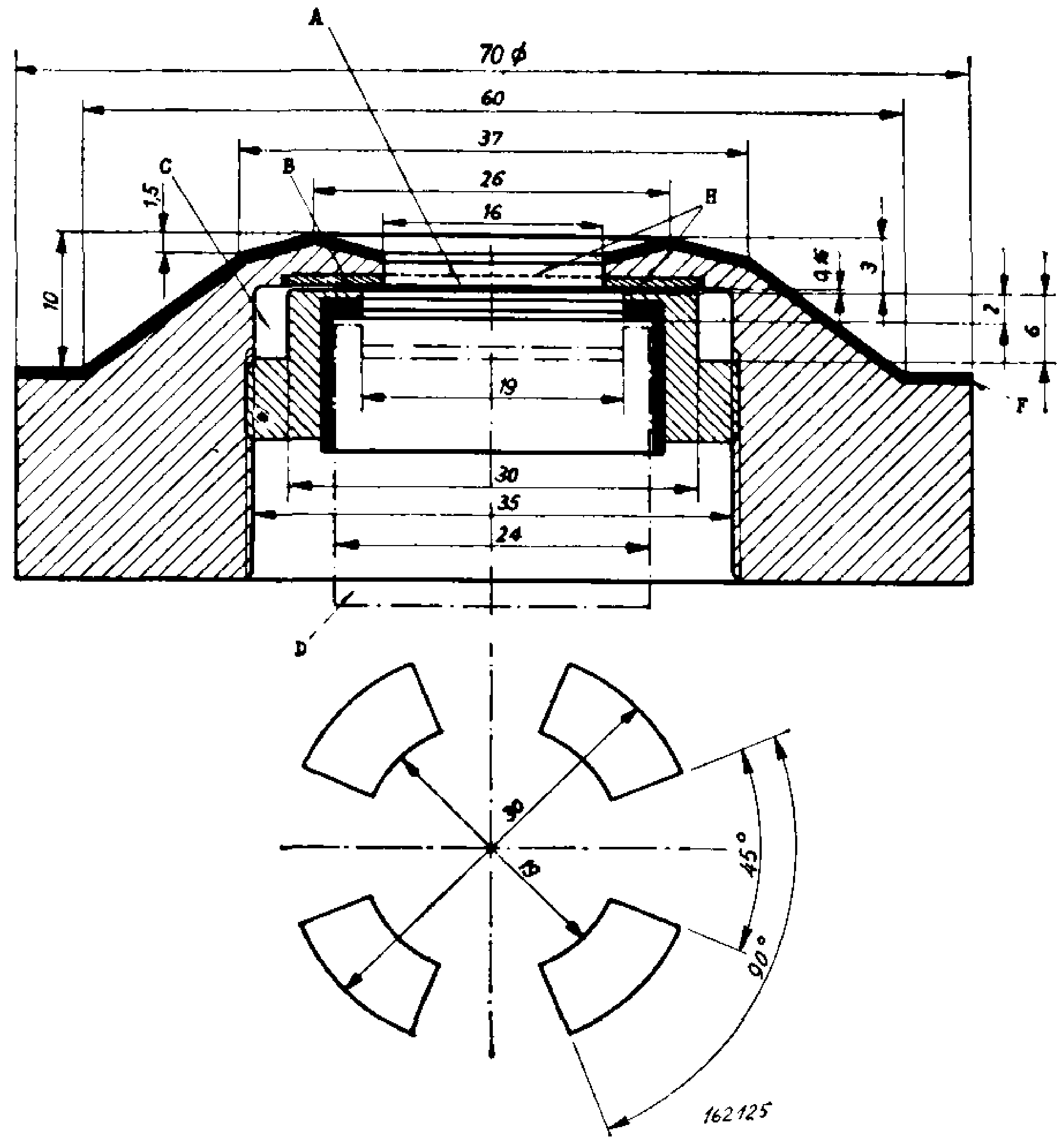


Fig. 7. British Standard artificial ear made up to BS 2042, but using a ½″ condenser microphone instead of probe tube microphone described in the standard.



a)



b)

Fig. 8.

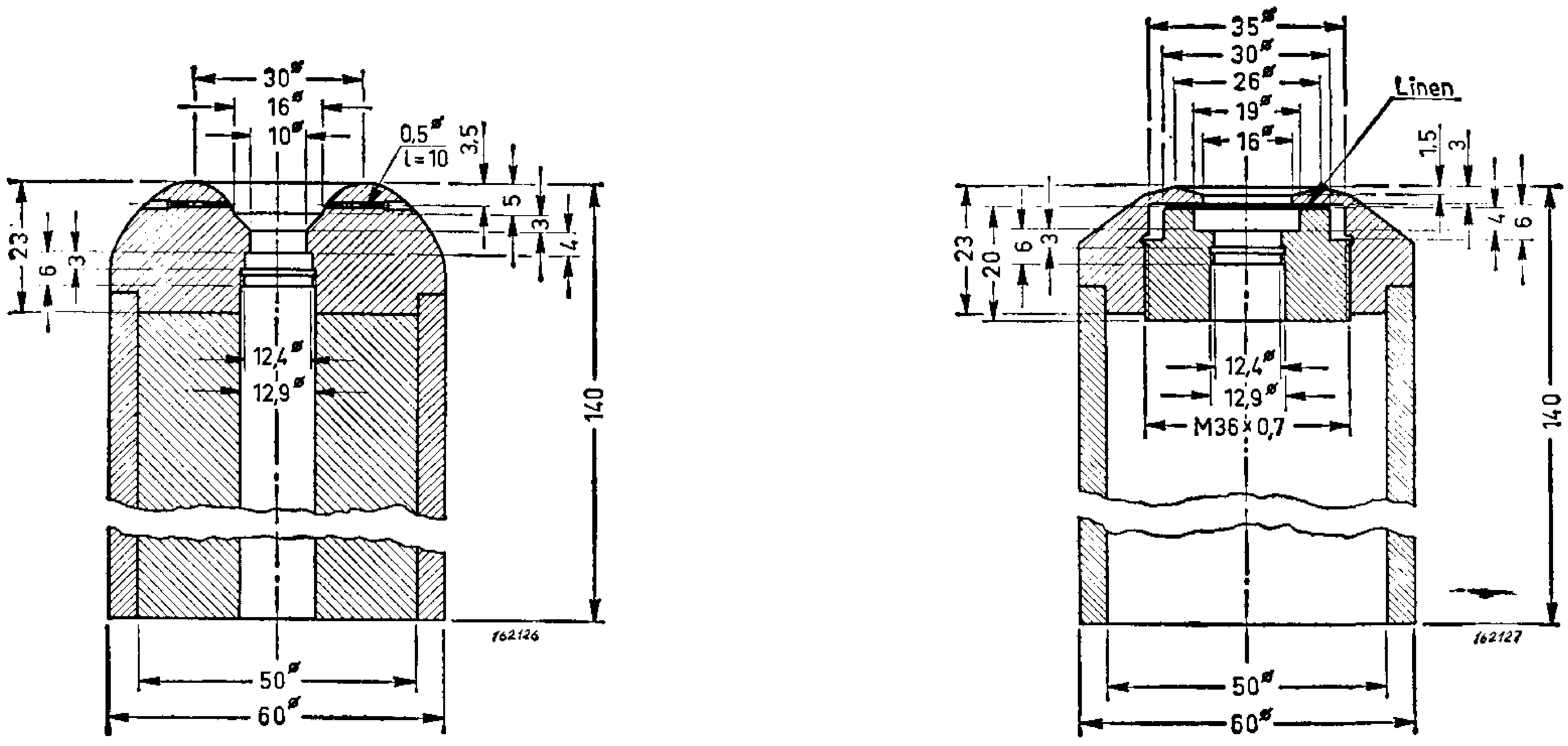
a) Specified drawing of the French artificial ear made by CNET.
b) The Swiss ear made by the Swiss P.T.T.

Existing Artificial Ears.

Fig. 6 shows the original English NPL models in two versions, where the leakage is represented by a pure resistance of 120 acoustical ohm. The volume is around 2½ cm^3. As this volume is rather small, and as at the time when this ear was designed it was difficult to obtain small microphones, a probe microphone is used in the British NPL model. The use of probe microphones, especially at high frequencies, is difficult, and since there now exist small condenser microphones, it was suggested that the probe microphone should be replaced by a condenser microphone.

In Fig. 7 this modified British artificial ear is shown.

The French CNET model is shown in Fig. 8 together with the Swiss PTT design. Both these ears contain materials which cannot be regarded as acoustically hard materials. The French model has some gaskets made up of felt and leather and the Swiss model uses cloth as damping material between the two cavities and on the top. Modified models of both CNET and Swiss PTT artificial ears were made up as shown in Fig. 9. The soft materials used for the CNET ear undoubtedly correlate very well with the compliance of the human skin, but it is not easy to reproduce, and it is also in disagreement with the requirement about acoustically hard materials. However, other properties of these artificial ears are very useful for the establishment of an I.E.C. artificial ear.



a) *b)*

Fig. 9.

a) The CNET type modified to use only hard material.

b) The Swiss P.T.T., as original except for the outer lining, which had been avoided, and the use of the same ½″ microphone as used for the other ears.

In Fig. 10 the two U.S. 6 cm^3 couplers are shown, the NBS 9A coupler, which has a very useful and practical form, and the ASA coupler, described in Z 24.9, which has a somewhat larger internal diameter. The latter model has the advantage that the first mode of resonance both in the longitudinal direction and in that parallel to the diaphragm occurs at the same frequency, with the result that the pressure at the diaphragm will be constant even at frequencies rather close to the resonance frequency. This is not the case with the NBS coupler (see Fig. 16).

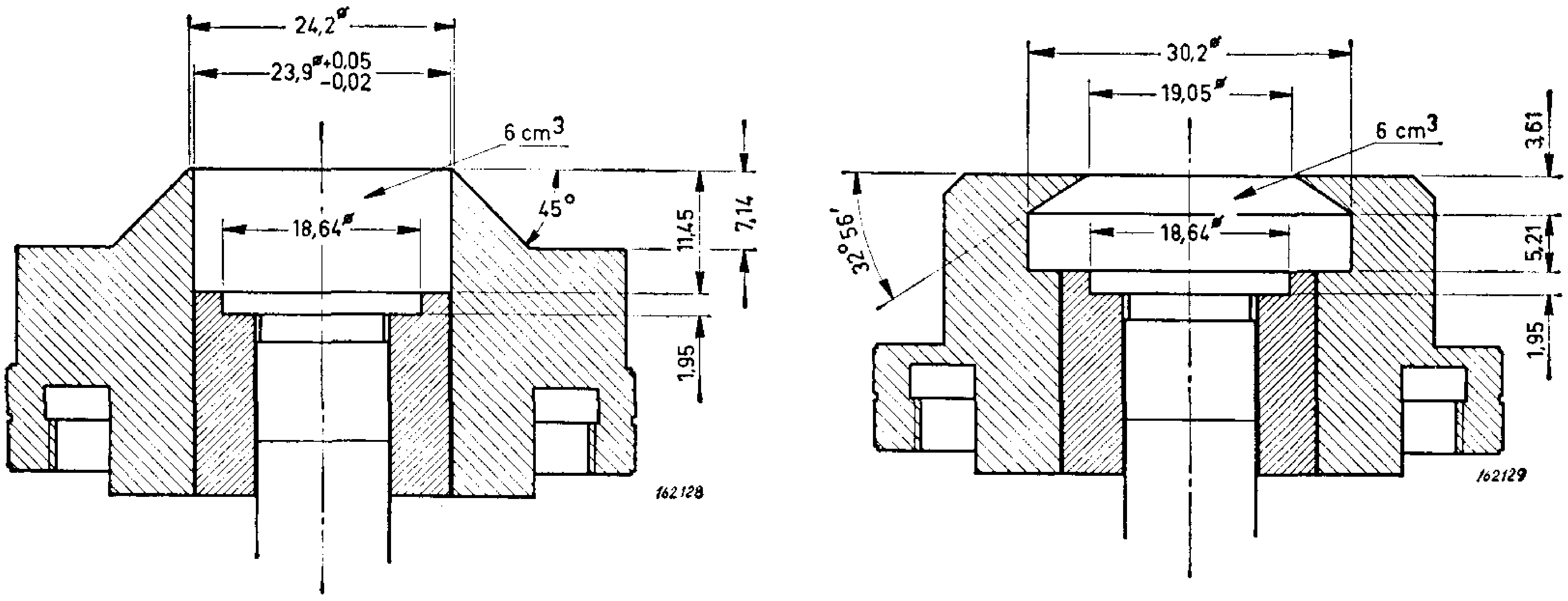


Fig. 10.

a) The National Bureau of Standards Coupler 9-A. See also A.S.A. standard 24.5. 1951.

b) The A.S.A. standard 24.9. 1949 Type-1 coupler.

It should be noted that the U.S. 6 cm^3 coupler is somewhat larger than the British, French, and Swiss couplers, and that the U.S. coupler has no leakage. This gives a very flat response and high sensitivity at low frequencies, practically the correct response in the middle frequency range, but unfortunately too low a sensitivity at high frequencies as compared with the average human ear. Another disadvantage with the 6 cm^3 coupler is that the large volume will effectively limit the upper frequency where this artificial ear can be used, as the first mode of resonance in the coupler is primarily determined by the volume. In practice it can be stated that it is not possible with a large volume to make an artificial ear which can be used for the desired high frequency range up to 12500 c/s.

As mentioned in the introduction to the A.S.A. standard Z 24.9-1949. "It must be emphasized that the relationships which are established between subjective and physical calibration will vary with the physical constants of the earphone unit. It is necessary, therefore, that correlation between subjective performance and coupler performance be established separately for each earphone design."

The scope of this work is to bypass the difficulty by making such transfer measurements. It has been proposed to modify the A.S.A. coupler by introducing a small spacing of 0.001″ between the coupler surface and the ear cap (ref. 5). However, this method does not satisfy the requirement also given in the A.S.A. standard that 6 cm^3 should be the total volume of the ear cap and coupler, which should be modified to include eventual cavities in the ear cap.

Fig. 11 shows the frequency response of the British NPL model in the version where the condenser microphone is used instead of probe microphones, but apart from that, everything is practically unchanged.

The curves are taken with the standard earphone containing a 1″ cartridge and corrected for the frequency response of the cartridge.

In connection with the British NPL model it is rather difficult to hit exactly the 120 ohm and adjust the length of the tube so that no ripple comes up in the curve. By using a somewhat larger tube the ripple in the low frequency end could be avoided.

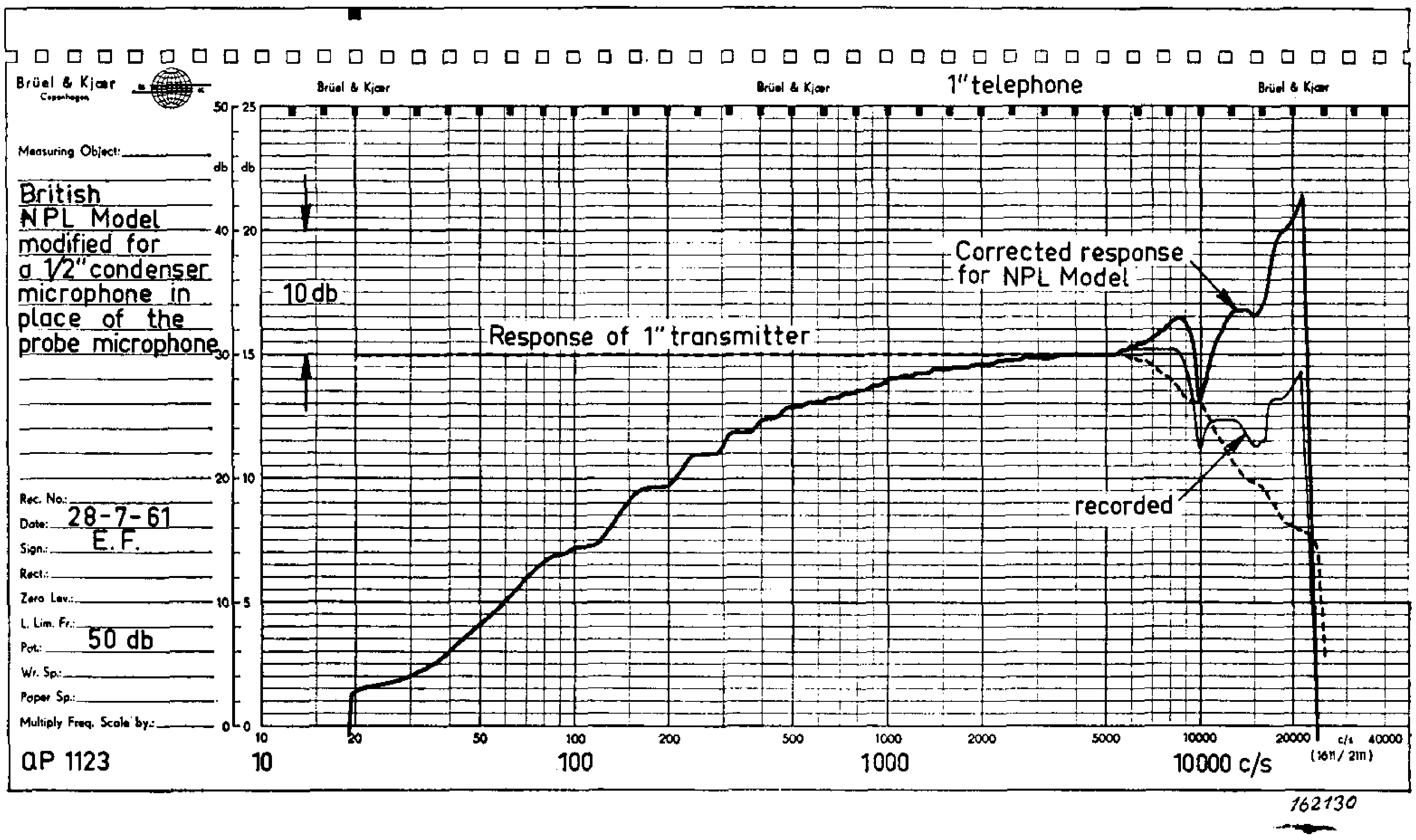


Fig. 11. Response of the coupler shown in Fig. 7. A flat earcap with a 1″ condenser transmitter driving system was used. The volume in cm^3 is only 2.5 + 0.2 (equivalent volume of the condenser transmitter). Hence the half power point will be placed at a rather high frequency due to the low impedance of the leakage tube.

Fig. 12 shows the frequency response for different damping materials in the long leakage tube. Wihtout any damping material an extraordinarily high ripple is obtained, as seen in Fig. 12a. In Fig. 12b some attempts to terminate the leakage tube by a well defined impedance at the end of the tube are shown, but far the best results were obtained, as in the original NPL, by using some woollen wires drawn through the tube. It was not possible with the NPL model to fulfil the requirements of using only hard material in the construction if the length of the leakage tube should be within reasonable limits. Fig. 13 shows the NPL model with one tube and a modification with four tubes.

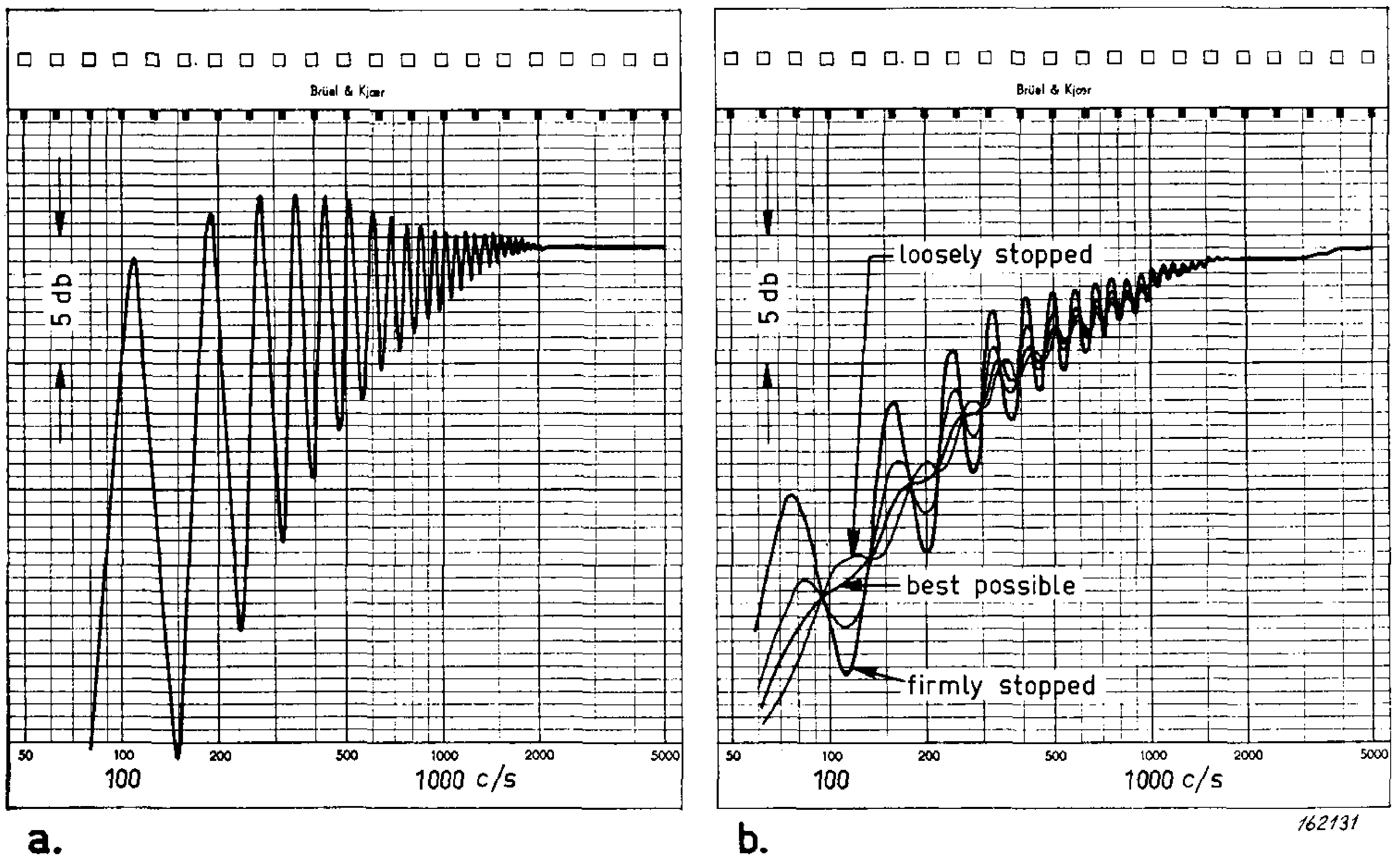


Fig. 12. Frequency response of the ear shown in Fig. 7.
a) Without damping material in the tube.
b) Damping carried out by stopping the far end of the tube with steel wool instead of cotton in order to obtain a standing wave cancellation in the low frequency region by proper choice of impedance.

Fig. 14 shows the response curves for the French modified model, where the shape is exactly like the original CNET design and with two leakage tubes. The frequency characteristic below 5000 c/s is measured with the standard earphone with 1″ cartridge and above 5000 c/s with the ½″ cartridge in the earphone.

As will be seen from the curve, and owing to the very small leakage, this coupler has a rather flat response between 150 and 4000 c/s. Above that frequency some different resonances occur. At lower frequencies a "normal" slope of 6 db/octave in the curve is found.

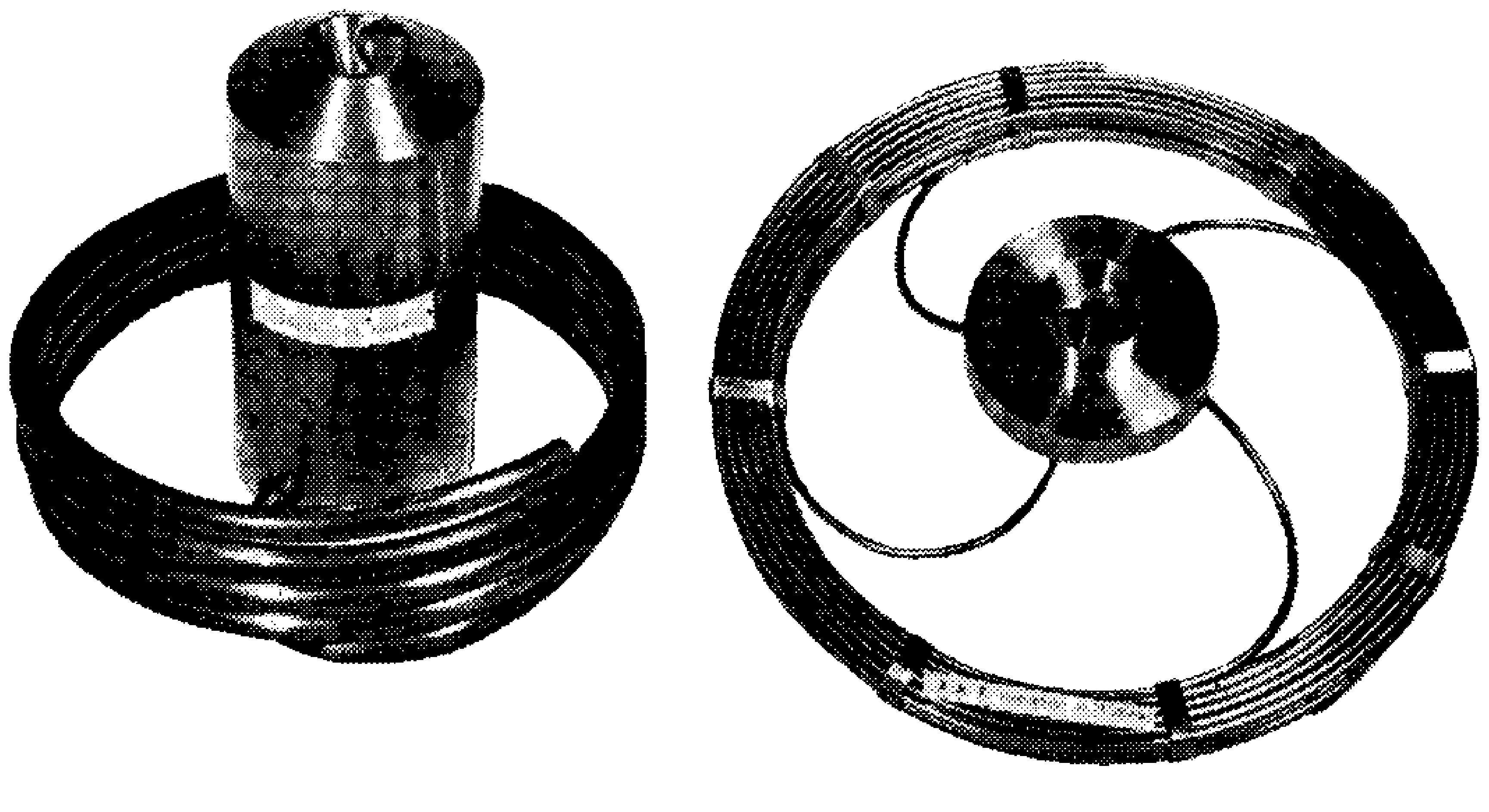


Fig. 13a. The British NPL model in two versions. With one leakage tube and, on the right, with four leakage tubes arranged symmetrically around the microphone.

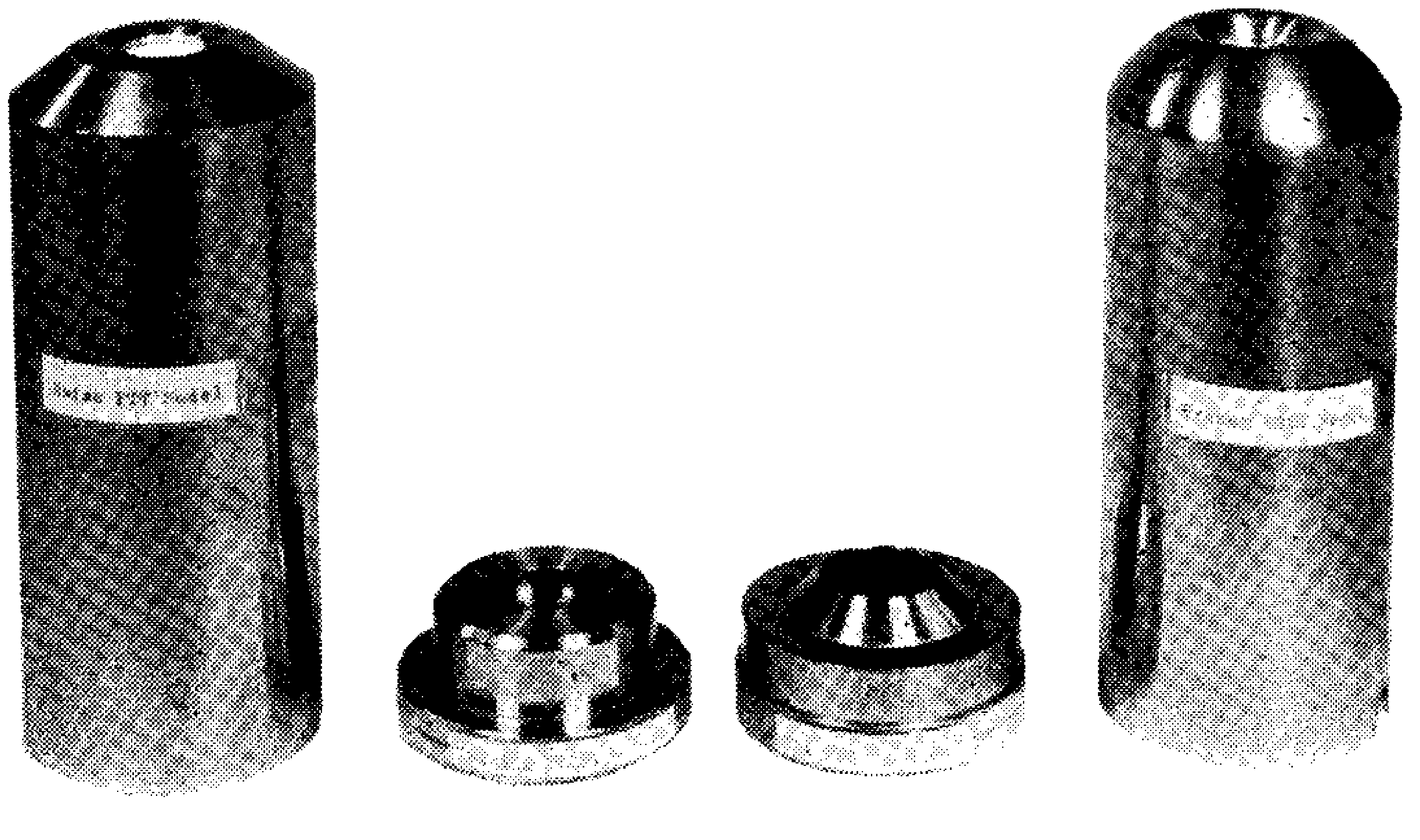


Fig. 13b. From left to right are shown:
The Swiss P.T.T. model
A.S.A. 24.9. 1949, 6 cm^3 coupler
USA N.B.S. Type 9A, 6 cm^3 coupler
French CNET model

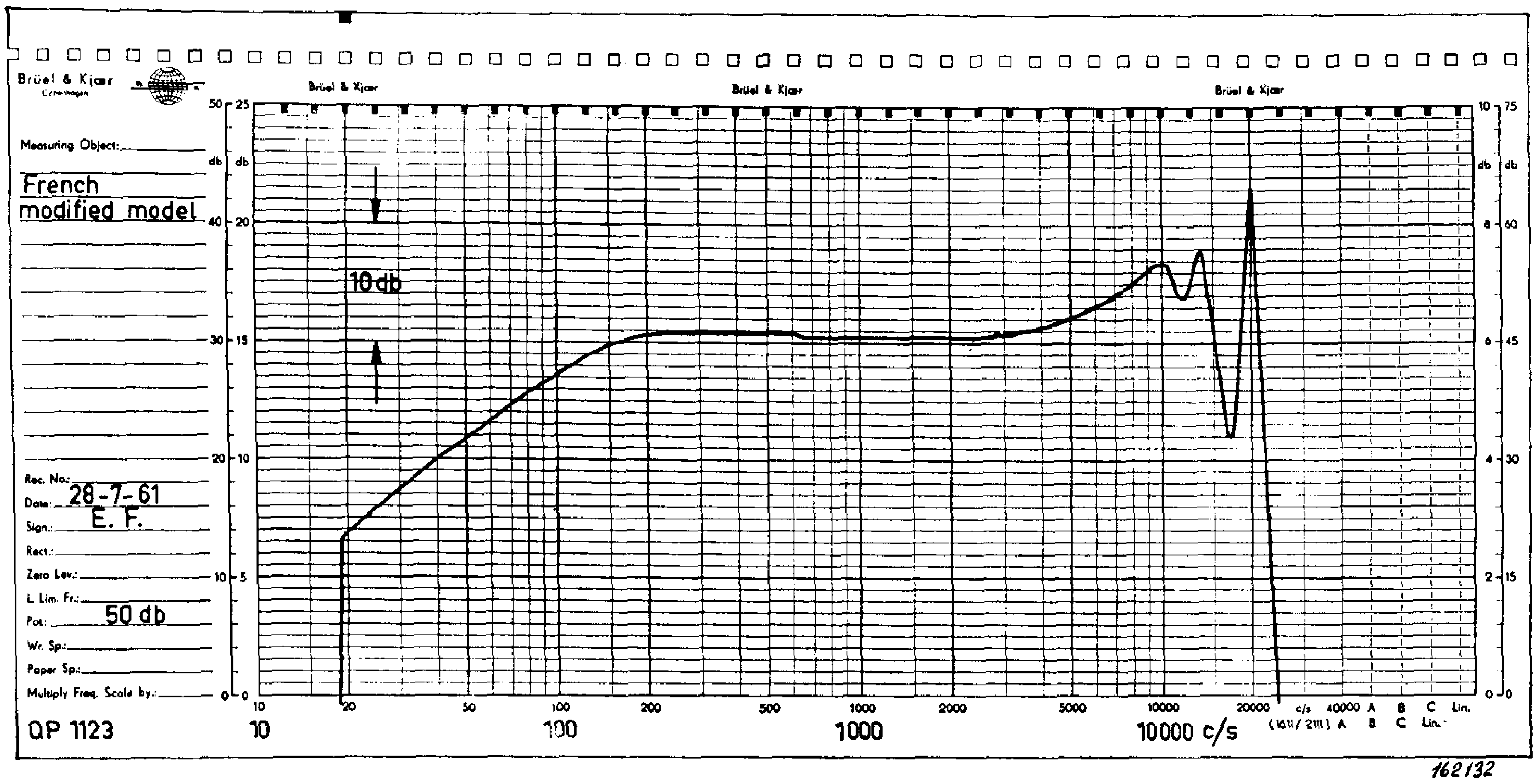


Fig. 14. Frequency response curve for the French modified model. The shape of the artificial ear is like the original CNET. However, the material used is hard and the compliance and, thus the performance, is changed as compared to the original CNET ear.

In Fig. 15 the curves for the Swiss PTT coupler are shown. As the coupler has no leakage to the outside, (the textile prescribed on the top could not be used for this purpose) but has two cavities coupled together through a damping material made of textile, the result is that for frequencies below

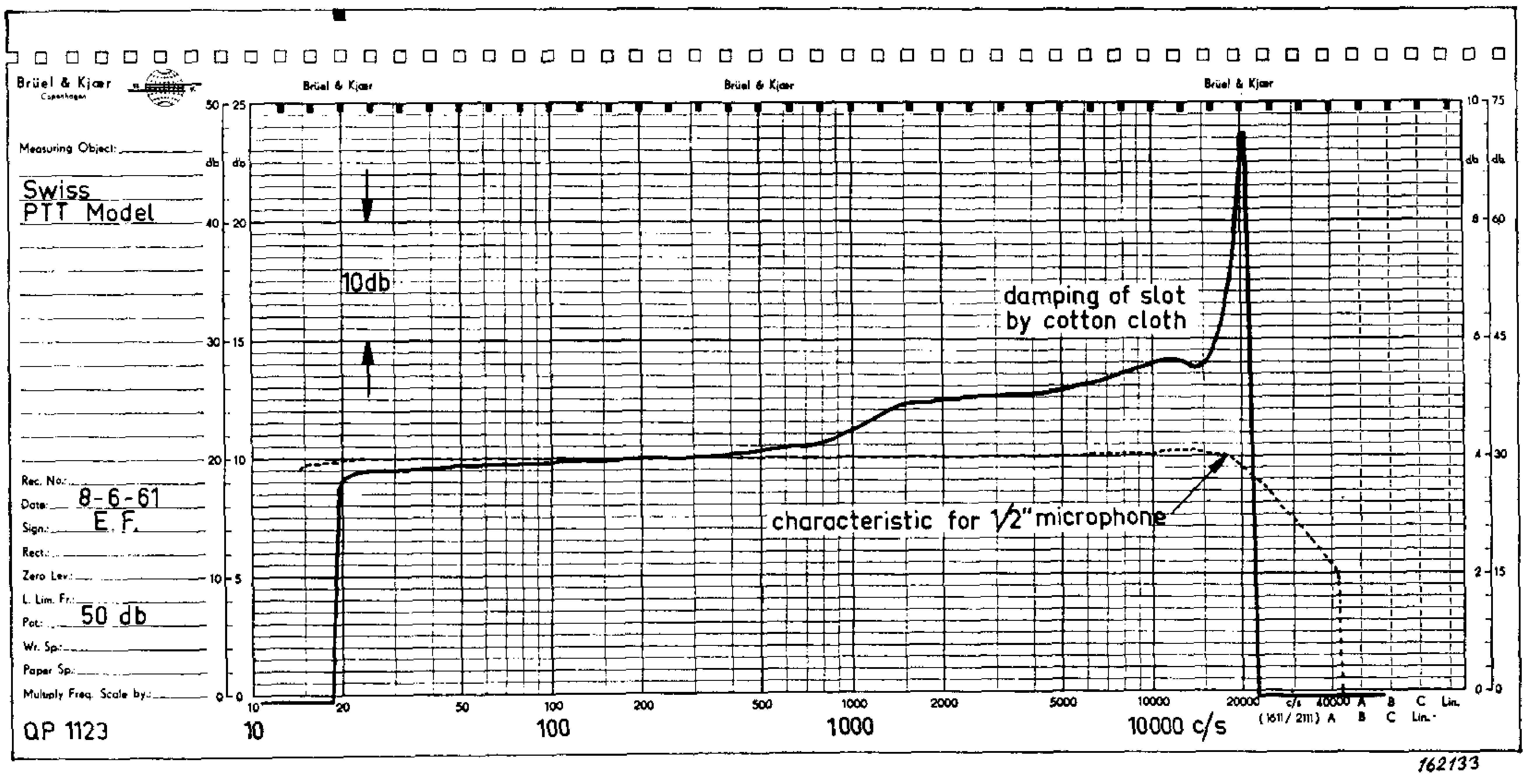


Fig. 15. Frequency response for the Swiss P.T.T. artificial ear version. The ear shown in Fig. 9b was used, and the earcap employed for testing was made up with a ½″ condenser transmitter, the response of which is shown by a dotted line.

300 c/s the curve is absolutely flat as the whole coupler is working as one closed cavity. Between 500 and 2000 c/s there is an increase in the response owing to the coupling effect between the two cavities, and for the very high frequencies only one cavity is in operation. This cavity is only 1.5 cm^3 and naturally the first resonance frequency will be in the region around 20,000 c/s.

In Fig. 16 the frequency response curves of the two U.S. standard 6 cm^3 couplers are shown. It will be seen that the frequency response of the NBS 9A coupler starts to increase at about 4000 c/s, reaching the first maximum at about 14 kc/s, while the ASA coupler has a more flat response up to about 8000 c/s, where it starts first to drop in an anti-resonance and

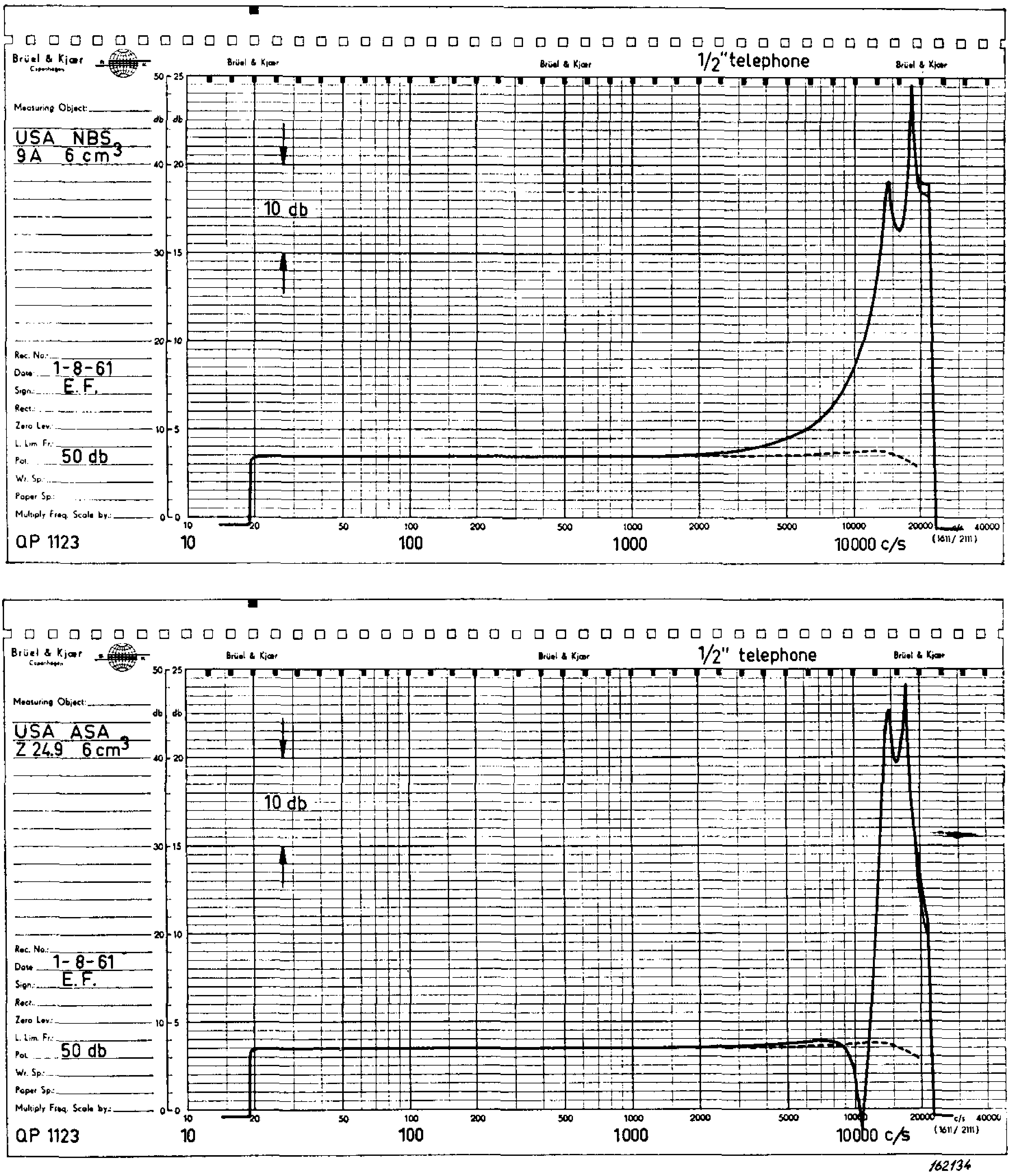


Fig. 16. The frequency response of the 6 cm^3 NBS — 9A and the A.S.A. 24.9 couplers as obtained with a ½″ condenser microphone transmitter and receiver.

then rapidly increases to a resonance at 14 kc/s.

The remarkable difference between these two curves for closed couplers both with a volume of 6 cm^3 can be explained by their difference in shape (the location and size of the receiver and transmitter diaphragm also play an important role. The first longitudal mode of vibration will produce a rise in pressure at the diaphragm of the microphone. On the other hand, the first transverse mode will produce a drop in pressure. If, therefore, the shape of the cylindrical coupler is made so that the natural frequencies of these two modes of vibration coincide, the effect will be that the two modes will cancel each other to some extent over a fairly large frequency range. To obtain this effect it is necessary that both the microphone and the transmitter have symmetrical characteristics. This example shows that the form of the cavity is very important. With a cylindrical form it is rather easy to calculate the ratio between diameter and height to obtain this cancellation effect, but for a conical shape it is more difficult and therefore some experiments have been carried out in order to try to measure the effect of other physical shapes, all with a volume of about 2½ cm^3.

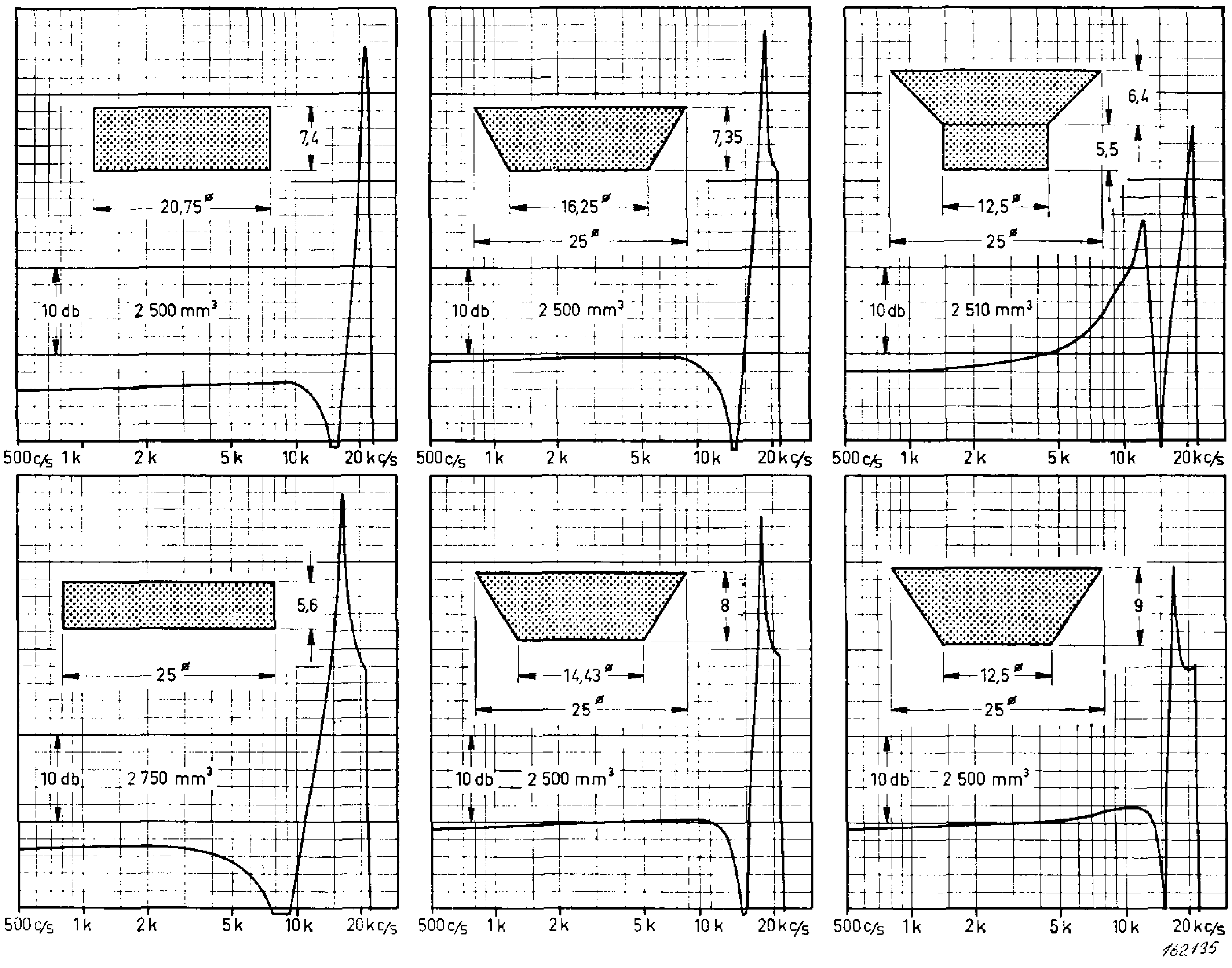


Fig. 17. Frequency response obtained by a ½″ condenser microphone receiver and transmitter mounted concentrically in the top and bottom of the differently shaped coupler volumes. Valid for the range 500—20,000 c/s. All coupler dimensions are given in millimeters. Vertical scale 2 db per line, 50 db full scale.

On Fig. 17 are shown all the different shapes with dimensions that have been tested and the corresponding frequency response curves, all taken with a 50 db range potentiometer on the level recorder, a ½″ transmitter and a ½″ condenser microphone receiver. A very pronounced difference is noticable for the two rectangular shapes, and also the conical shapes are rather different. As is seen from the curves, it is possible to make the frequency response curve very flat over a wide frequency range. However, the disadvantage is that the anti-resonance will be rather sharp and occur at a relatively low frequency. To obtain the widest possible frequency range, it is advantageous to choose a shape that will give a slight increase in the response at high frequencies with the result that the anti-resonance will move further up in the spectrum and be less steep. In this way the useful range for the artificial ear can be extended up to about 14 kc/s. It can be obtained with the coupler, which is 25 mm in the top and 13.4 mm at the bottom end, and 8.4 mm high. This shape is very close to that of the British NPL model and also close to the shape of the volume in the French CNET model and may be considered a simplified shape of the auricle of a human

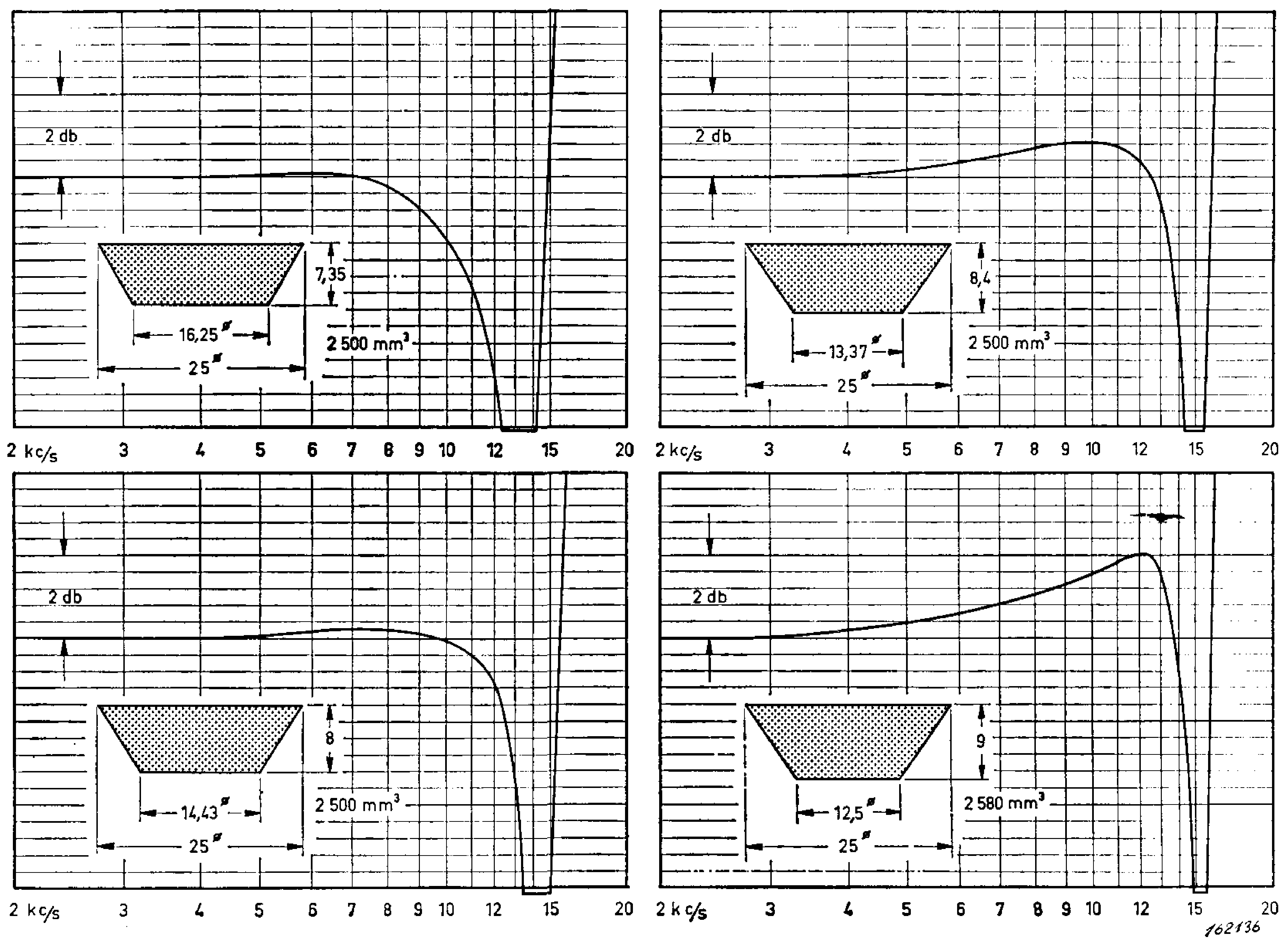


Fig. 18. Detailed measurements to determine the optimum dimensions for the best possible linearity over the widest frequency range. 10 db full scale.

ear. For the further work with artificial ears this shape of coupler was chosen. Also the importance of having the sensitive part of the receiving microphone placed symmetrically in the coupler and having a well-defined sensitive diaphragm area should be stressed at this point as being very important at higher frequencies (see ref. 9). The conical shape chosen will allow a microphone with a sensitive area equal to the entrance of the ear channel to be mounted close to the entrance of the real ear. The coupler combining a cylindrical and conical shape gives very unsatisfactory results.

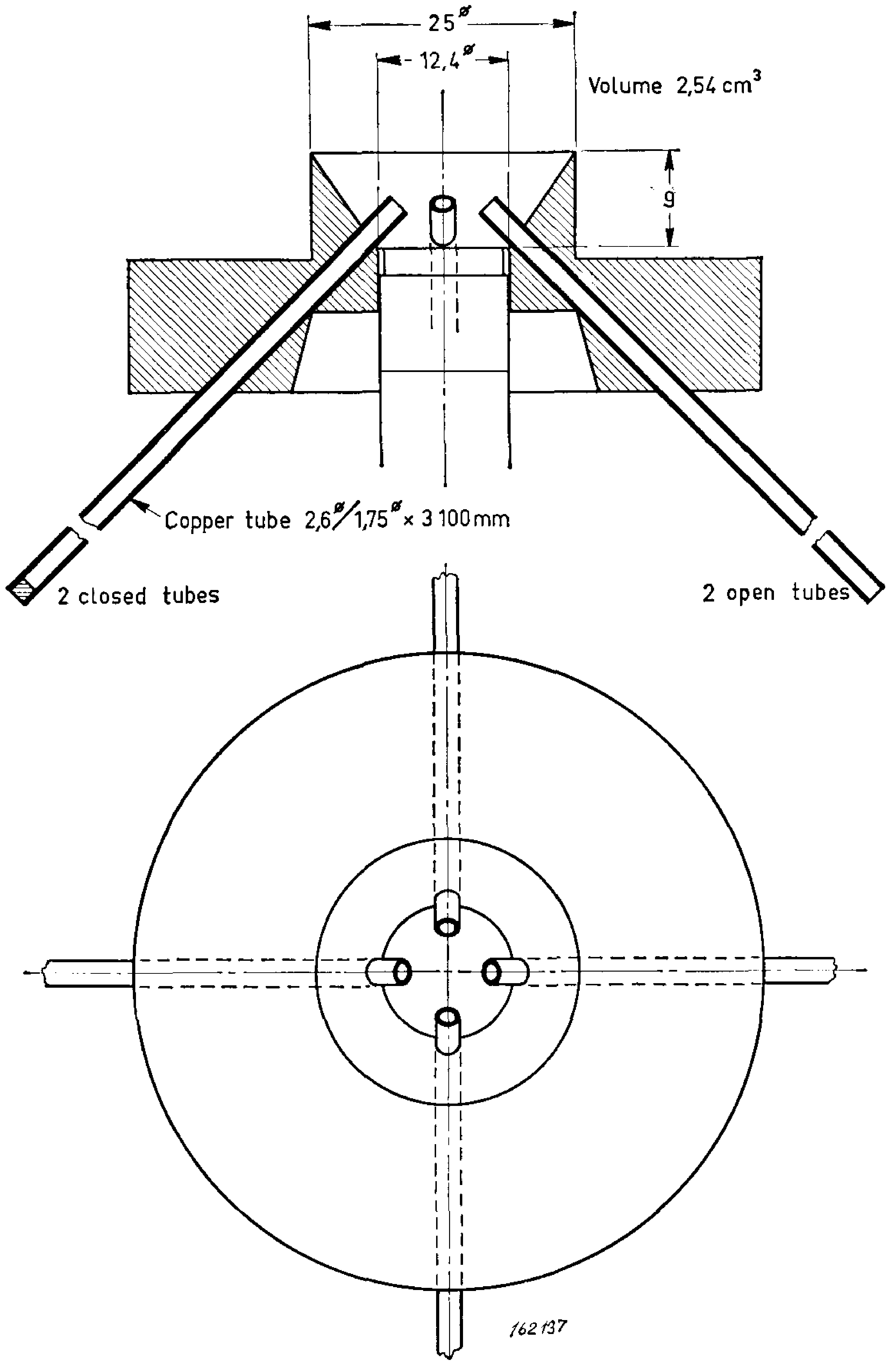


Fig. 19. A version of the British artificial ear made up with four leakage resistance tubes arranged symmetrically around the microphone. See also the photo in Fig. 13.

In Fig. 18 is shown a detailed curve over a limited frequency range, measured with high accuracy. A 10 db range potentiometer was used on the level recorder.

As there were such great difficulties in obtaining the correct damping in the single leakage tube of the English version, this tube was divided into a number of smaller tubes so that the natural damping in the tube should be sufficient to give the required acoustical resistance and diminish the reflection from the termination of the tube.

This model consists of 4 tubes of equal length, as will be seen from the drawing in Fig. 19, which are used as leakage resistance. By having two of the leakage tubes open and two closed a very nice cancellation of the end effect of the tube can be obtained. From a mechanical point of view it is thus rather easy to give this version a nice and smooth frequency response curve, Fig. 23, whereas it is rather critical to ensure the correct termination at the end in the models with one leakage tube of limited length only.

It can be seen that the response in the frequency range between 1000 and 5000 c/s is not flat, and that the slope towards the lower frequencies is not following the usual curve for a simple RC network. The same is also the case for the NPL model, Fig. 11, and is an indication that the leakage tubes do not function as a pure resistance only, as required in the British Standard, but that they also contain a small acoustical reactance, which may be undesired and at least rather difficult to make reproduceable.

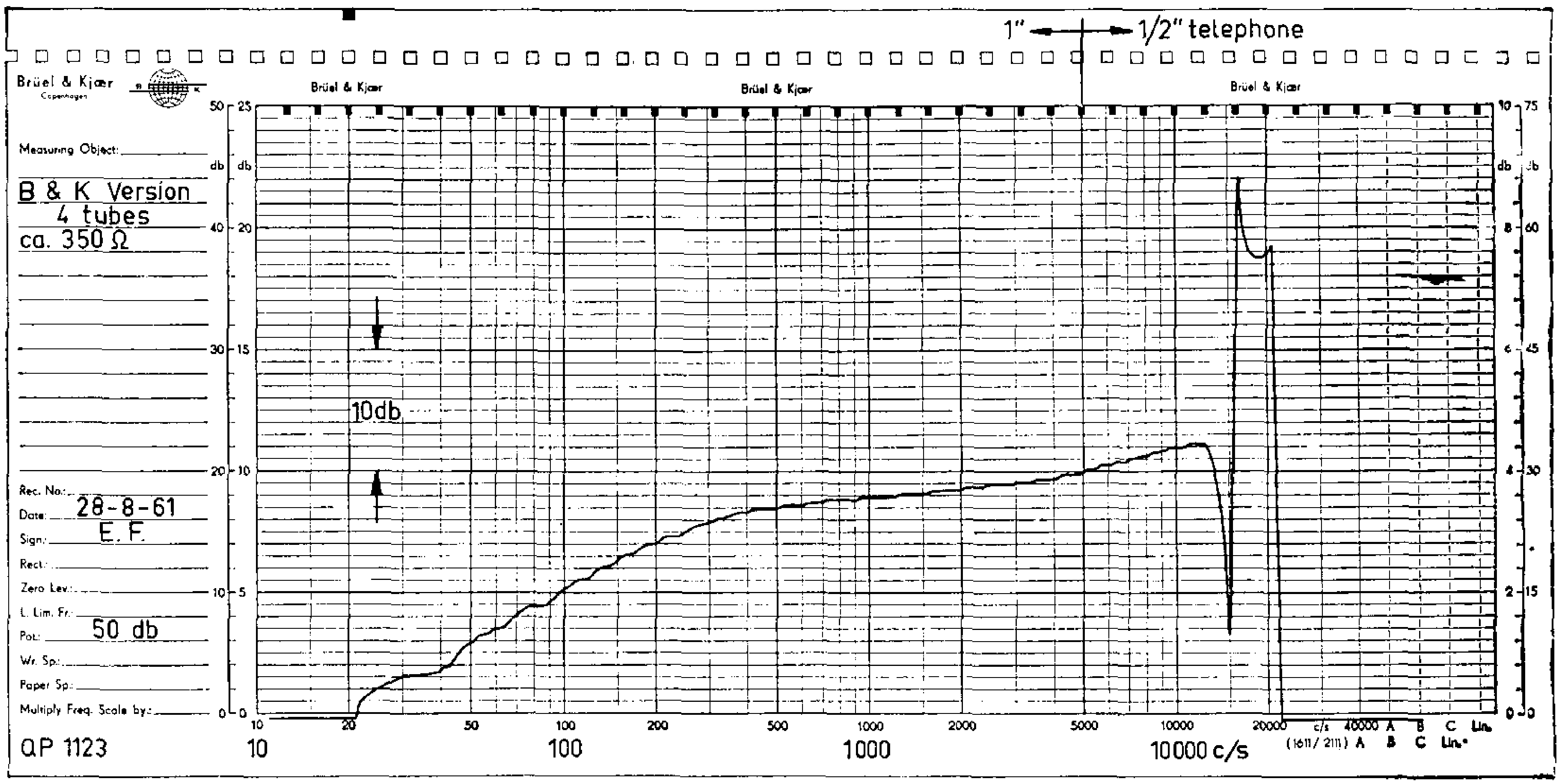


Fig. 20. Frequency response of the four leakage tube version.

One method of obtaining a pure resistance in the leakage of an artificial ear is to use a great number of very small and short tubes of such dimensions that the total resistance will be correct. In Fig. 21 such a version is shown, where a great number of very small holes are filled with needles of a somewhat smaller diameter. The dimensions are chosen so that the total resistance is measured to 120 ohm, just as required in the British Standard. The advantage of this system is obvious, as there is practically no volume in the leakage device, and consequently no resonances can occur from the leakage tubes. The system is also in practice possible to adjust as the holes just have to be carefully drilled when the dimensions of the needles are known, or the holes can be drilled first, as the diameter of the needles can easily be adjusted by a simple plating technique.

Another advantage of this system is that the acoustical resistance can be determined with a simple D.C. measurement, i.e. by measuring the flow of air with a given pressure difference, or it can be measured dynamically by determining the 3 db point of the frequency response at lower frequencies.

In the version shown in Fig. 21 the required 120 ohms are obtained and the response, Fig. 22, of the whole artificial ear shows no irregularities at all except at the resonance frequencies of the cavity at high frequencies.

Notice the correct reactance-free resistor controlling the low frequency range.

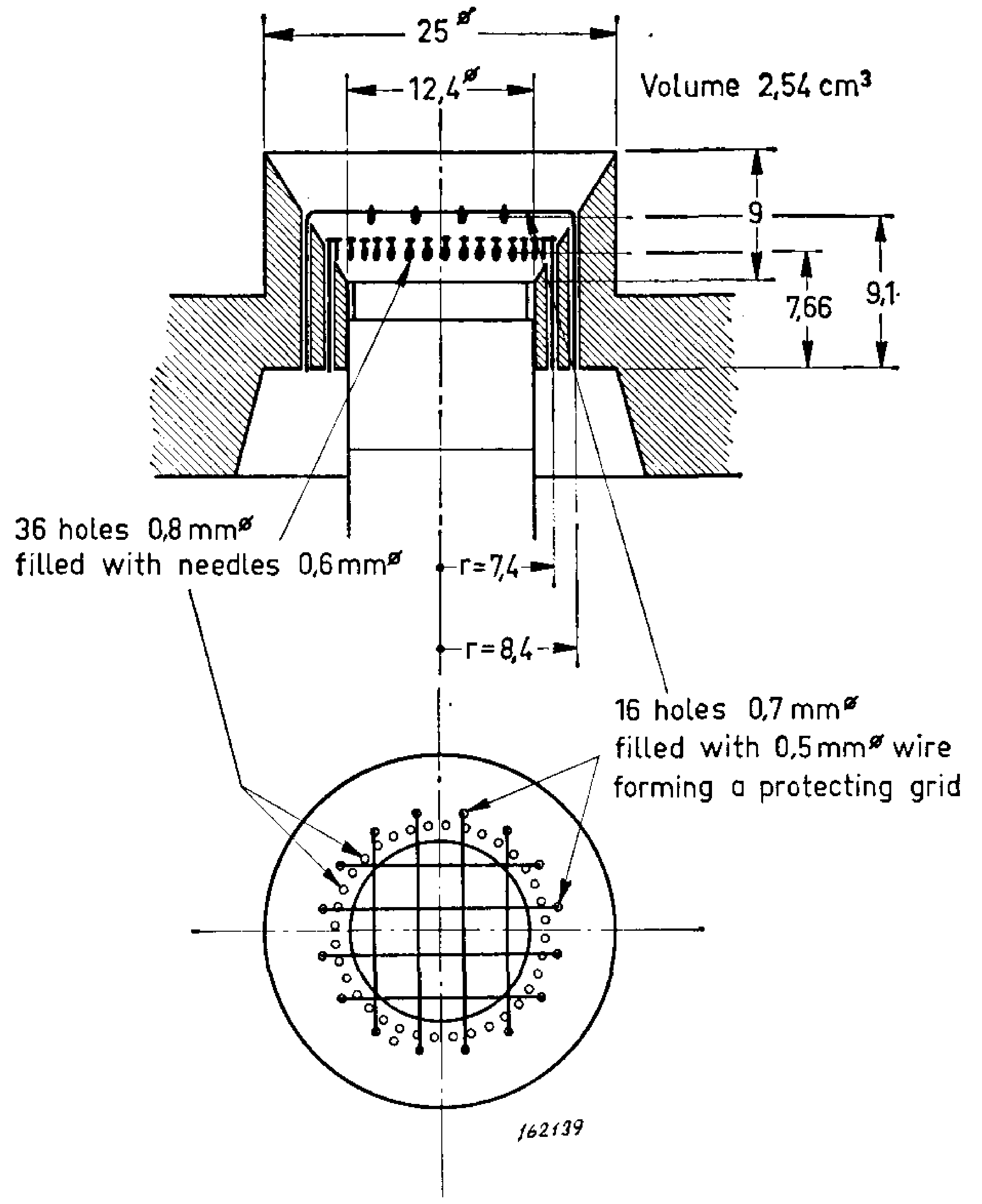


Fig. 21. A version of the British artificial ear. Leakage resistance of 120 Ω made up by holes partially filled out with needles.

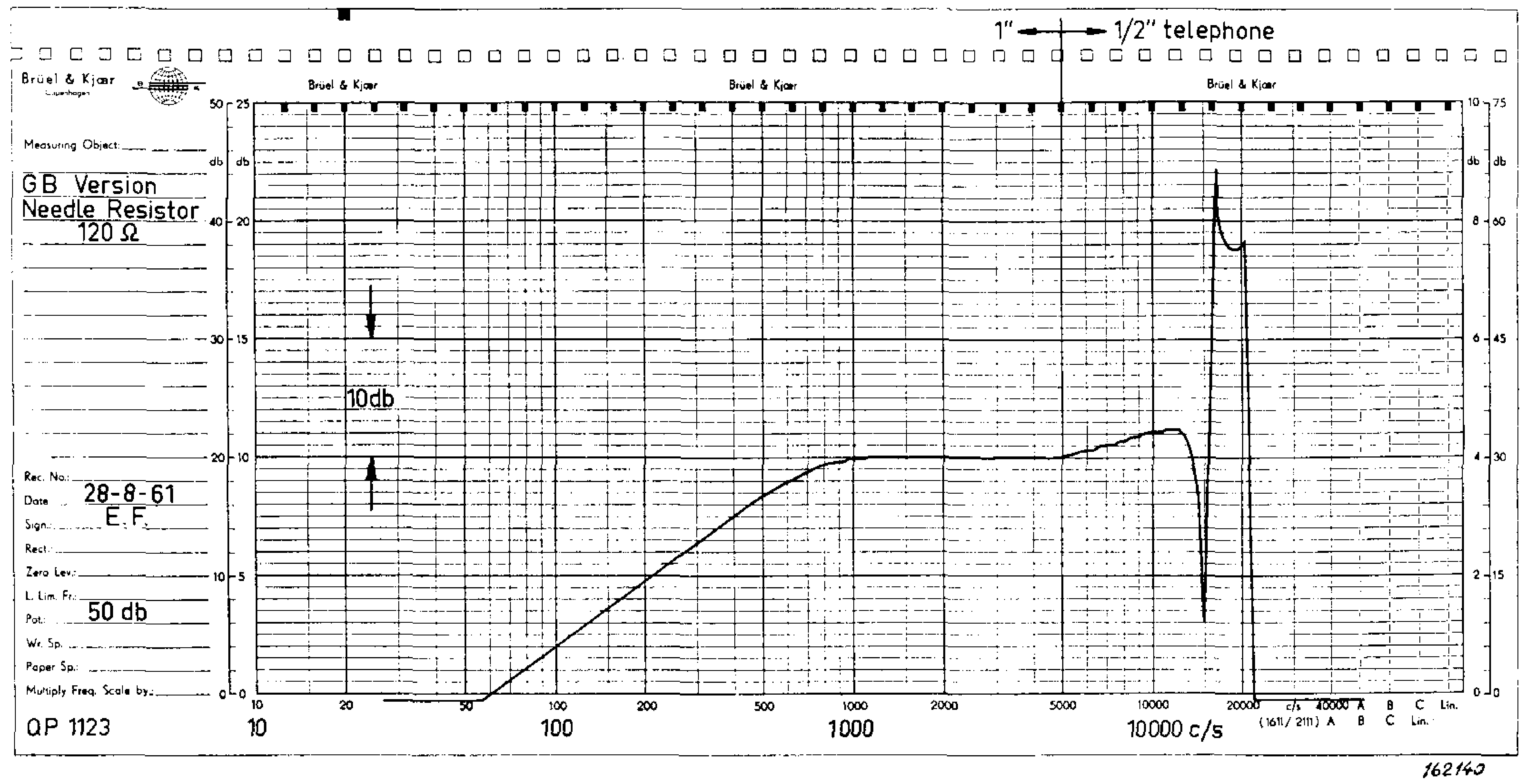


Fig. 22. Frequency response of the needle resistor version.

This article will be continued in no. 1/1962.

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