TEMPERATURE AND HUMIDITY EFFECTS ON LOUDSPEAKER CONE PERFORMANCE

by

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BACHELOR OF SCIENCE

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ABSTRACT

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Viscoelastic measurements were carried out on formed paper and polypropylene speaker cone materials using an Instron tensile tester and a Rheovibron dynamic viscoelastometer under various conditions of temperature and humidity. The paper cones showed little sensitivity to temperature and considerable sensitivity to humidity variation. A characteristic parameter of fibrous polymers is identified, the glass transition humidity. Polypropylene cones showed limited response to temperature and no response to humidity variation.

Acoustical frequency response plots were obtained from assembled loudspeakers using paper and polypropylene cones under conditions from 70°F., 36% relative humidity to 90°F., 95% relative humidity. Strong correlations were found between the modulus, mass density, and loss tangent of the cone materials and the position and intensity of the frequency response aberrations due to cone resonances.

Thesis Supervisor: David K. Roylance

Title: Associate Professor of Materials Engineering

ACKNOWLEDGEMENTS

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I. INTRODUCTION

The conical diaphragm, moving coil loudspeaker has been the most often employed transducer design since the inception of electrically powered sound reproduction systems. The goal of an acoustic transducer is to convert an electrical signal into a movement of the adjacent air molecules which corresponds exactly in frequency, amplitude, and phase to the original signal. These local pressure variations then propogate as pressure waves which, in the ideal case, are indistinguishable from those produced by the recorded event. Figure 1 shows the general features of this class of loudspeakers.

Most analyses of speaker cone performance have assumed totally rigid materials. This assumption had to be made because of the numerical complexity involved in analyzing a flexible, damped cone driven from a truncated end. Because of this analytic simplification, the speaker designer's choice of cone materials has usually been guided by trial and error, guesswork, and some luck. Pressed paper is the most commonly used cone material, often felted on one or both sides. Paper has many desirable characteristics including low cost, high stiffness in some of its available forms, and easy adhesion to typical surrounds and voice coil former materials.

Cone loudspeakers only exhibit piston-like behavior over a narrow region of their range of acoustic output. Above this frequency range of ideal behavior standing waves develop on the cone . These standing waves can reinforce or reduce the output of the speaker at a given frequency depending on their

positions on the cone surface. Peaks and dips in the loudspeaker's frequency response result from these resonances above the piston range. This series of peaks is superimposed, in the case of a low or mid-frequency driver, on the response characteristic of the next higher frequency range driver. In two-driver designs the transition region between the woofer, or low driver, and the tweeter, or high driver, is usually between 1,000 and 3,000 Hz. (cycles per second). The response peaks and dips for most woofers used in such systems also occur in this range, which contains the fundamental frequencies of many instruments and much of the energy of the human voice. The ear is most sensitive to level variations in this midrange region, so any shifts in the midrange response become readily noticeable.

Frankort (1) published an analytic treatment of loudspeaker cone behavior. Computer-aided finite element analysis was employed to correlate the cones' resonant behavior with material parameters such as modulus, loss tangent, and cone density. Takeo Shindo et al (2) developed an extended numerical analysis of loudspeaker behavior, also using the finite element approach. Several cone geometries were considered, as well as the influences of the voice coil and surround on acoustic output.

Speaker designers have realized for some time that paper cones change their behavior significantly in differing humidity environments. Some loudspeakers have been designed using other materials such as bextrene or polypropylene to combat humidity sensitivity. These materials, on the other hand, vary their

behavior with temperature. To my knowledge, direct correlations between environmentally induced cone variations and perforance shifts have not been investigated. The determination of these correlations is the subject of this research.

II. POLYMER VISCOELASTICITY

Polymer viscoelasticity is characterized by several time-dependent phenomena. Polymers will continue elongating under a fixed load, or creep, with time. Under constant strain, the resultant internal stresses relax out at least partially with time. The dynamic behavior of polymers is more complex. Because of its time-dependent behavior, a polymer sample subjected to a sinusoidally oscillating strain absorbs some of the imparted energy by viscous heating. The stress in the sample lags the strain by some constant angle δ (for a fixed strain amplitude, frequency, humidity, and temperature), whose magnitude corresponds to the amount of viscoelastic damping the material provides. Under most conditions, polymers exhibit varying proportions of elastic and viscous behavior.

Paper is a polymer constructed of hydrogen-bonded cellulose fibers. Unlike other polymers, paper changes its level of crosslinking greatly with varying moisture content. As the moisture content is increased and fiber-to-fiber bonds are weakened, the paper's stiffness decreases and its viscous damping increases. Under high moisture conditions the paper can sustain less and less load until it finally dissociates. Paper shows little change in damping from radical temperature changes. McElroy (3) found a 30% change in modulus through a temperature range of -120°C. to +50°C., which is also not a sharp transition.

Other polymers such as polypropylene absorb very little water, but show similar mechanical changes with increased temperature. The glass transition temperature, T , marks

the transition from glassy, brittle, low-temperature behavior to the more fluid viscous high-temperature behavior. Most polymers exhibit a narrower transition region than paper and several orders of magnitude of modulus shift with temperature. In the transition region, the viscous damping reaches a maximum. Because of this relationship, in order to obtain the highest damping from a material it must be used in its region of highest modulus sensitivity to temperature.

Several simple spring an dashpot models are used to idealize the viscoelastic behavior of polymers. The Maxwell model, a series combination of a spring and dashpot, is shown in Figure 2a. This model is most useful in describing stress relaxation. The Voigt model of Figure 2b is a parallel combination of these elements A three-parameter model, as in Figure 2c, approximates a "standard linear solid" (4). Under dynamic loading, ie. time varying, there is a phase lag between any applied stress and its resulting strain. In this case the mechanical behavior of the polymer can be described by a complex modulus which consists of a real component (E') and an imaginary component (E''). This vector relationship is usually expressed as:

$$\tan \delta = \frac{E''}{E'}$$

where δ is the loss angle or internal loss factor, E' is the storage modulus, and E'' is the imaginary modulus.

The three-parameter model predicts a correlation between the loss angle and storage modulus, and the characteristic

relaxation time (5):

$$\tan \delta = A \frac{\omega\tau}{1 + \omega^2\tau^2} \qquad \text{and} \qquad E' = E_o - (E_o - E_r)\frac{1}{1 + \omega^2\tau^2}$$

where A is a modulus-dependent constant, τ is the characteristic relaxation time, and E_o and E_r are the unrelaxed and relaxed moduli, respectively.

Thermally activated processes usually follow an exponential rate law such as :

$$\tau = \tau_o \exp\left(\frac{H}{kT}\right) \quad ,$$

from which we see that the loss angle and storage modulus should show an exponential dependence on temperature. In the case of papers, moisture added lowers the chain mobility activation energy, providing a similar effect as that of temperature on other polymers.

Predictions of generalized polymer behavior can be made from these models. The loss angle goes through a maximum at $\omega\tau=1$. The storage modulus will start at its relaxed (glassy) value and as the temperature or humidity is raised it will undergo a transition to its high temperature or humidity value. This transition's inflection point will also be at $\omega\tau=1$. Similar behavior will result as the loading rate or dynamic frequency are decreased.

These results show that equivalences between the effects of environmental and use factors may be made. These correlations are illustrated graphically in Figure 3. Probably the most famous correlation of this sort was produced by Williams, Landel, and Ferry, and is known as the WLF shifting equation (6):

$$\log_{10}\left(\frac{\eta}{\eta_g}\right) = \frac{-17.44\ (T-T_g)}{51.6 + (T-T_g)} = \frac{-17.44\ \Delta T}{51.6 + \Delta T}$$

where η_g is the viscosity at T_g.

This equation shows a clear time-temperature dependence for polymers. From this a correlation factor, log a_t, can be found to relate each pair of factors, including humidity, temperature, and loading rate or frequency.

III. EXPERIMENTAL PROCEDURES

The samples used in this project were cut from paper and polypropylene loudspeaker cones. The samples used in static modulus and complex modulus measurements were cut as radial sections from the preformed speaker cones.

A standard humidification environment of 95% relative humidity and 90°F. was established for the acoustical tests. The room environment throughout these experiments was monitored and found to be 36 $\pm$ 1 % relative humidity and 70 $\pm$ 2°F.

Dehumidification curves were established for complete cones after a 24 hour equilibration in the humidity chamber. Upon removal they were weighed, and again repeatedly after intervals of drying in the room environment. Reference masses were taken 24 hours after removal. The same procedure was followed for the cones' surrounds. The cones used in this experiment initially had a damping bead of PVA at the inner edge of the surround. This bead was removed, since it absorbed considerable amounts of water and turned milky on humidification. To isolate the effects of cone absorption, all of the experimentation was done with cones and assembled drivers whose surround beads and dust caps were removed.

The speakers used in this project were of nominal eight inch diameter (low-mid frequency units typically used for two-driver bookshelf speakers) with foam surrounds. Some ten inch cones were obtained at first, but were not used because of their much slower water absorption and descrption rates.

An attempt was made to use one paper sample to determine the static modulus' humidity dependence. A comparison of the initial modulus (before humidification) and that of the cycled and dried out sample showed an error of several orders of magnitude. Although small strains were used, cyclic loading rendered this type of experiment invalid.

Next radial sections were cut from the treated and untreated paper cone stocks, and weighed. They were then humidified by holding in front of the vent of a cool-vapor humidifier for ten seconds on each side. After partial dehumidification, the samples were weighed and subjected to a tensile test on an Instron tensile tester. Two samples were placed in a dessicator to dehumidify them below room moisture level.

Several polypropylene samples were cut.A ring stand supported a thermometer and cone sample above a hot plate. After temperature equilibration each sample was removed and tested as quickly as possible. This crude method gave at least subjectively useful results.

More sectioned paper cone samples were humidified as before and tested in a Rheovibron direct reading viscoelastometer. This apparatus reads directly the loss tangent of a dynamically loaded sample under low tension. Paper samples were measured at room temperature and varying moisture levels. Paper and polypropylene samples were measured at room humidity and several temperatures using the attached oven assembly. Oven temperature was monitored with a digital thermometer.

Speakers were assembled identically except for the cone material. Reference swept sine wave frequency response curves were taken as references in a half-space anechoic chamber. After the drivers were put into the humidity chamber, they were allowed to equilibrate for a day. Each was measured "as removed", and this time noted as T_o. The units were measured occaisionally as they dehumidified in the room environment. An Acoustic Research AR-18 speaker box was used for a standard mounting for testing. One clear polypropylene unit had to be mounted on a baffle board since it was only available in a different frame configuration.

Humidification curves showed no water absorption by the polypropylene. Mechanical measurements showed the papers to be insensitive to temperature shifts in this experiment. By establishing these independences, any shifts in the response of the polypropylene cone can be attributed to the $20^{o}F$. temperature change, and any shifts in the response of the paper cone to the 59% relative humidity change.

IV. EXPERIMENTAL RESULTS

Dehumidification curves were obtained for an untreated paper cone and one which had been treated with a dip-applied plasticizer. These curves are shown in Figure 4. Further work was done with the treated cone, since it represents a commercially used material. Two polypropylene samples were investigated. One was black, probably from a slight carbon-black filler, and dimpled on both surfaces. The other was clear and minimally filled.

A plot of the static modulus versus moisture content is shown in Figure 5. The earlier dehumidification curves showed a 6% water absorbed from an ambient humidity shift of 36% to 95%. Figure 5 shows that in this range the modulus of the paper changes by 30%.

Figure 6 shows the dependence of the polypropylene samples' modulus on temperature. The slope of this curve is of the expected sign, but I expect that its value to be low due to poor sample heat control.

The frequencies at which peaks and dips in the measured acoustical response occurred were recorded for the first several resonances and antiresonances. Reading the location of the first peak was difficult because of its width and asymmetry. The first dip and the secon peak were clearly identifiable, and their positions after removal from the chamber are plotted in Figures 7 and 8.

These plots show a distinct transition at t=10 minutes for both the untreated and treated cones. This time corresponds to a 3% higher moisture content than at room equilibrium. By assuming a linear relation between mass percent water absorbed and ambient humidity, these transition times can be converted to equivalent ambient humidities. The initial moisture content of the cones on removal from the chamber was 6% for the untreated cone and 5% for the treated cone. By direct calculation, the transition humidity, or $R.H._g$, is 65% relative humidity for the untreated cone and 71% relative humidity for the treated cone.

Frankort (7) presented the equation below relating the first theoretical resonant frequency with the modulus and density of the cone material:

$$f_{ra} = \frac{c \cos\alpha}{2\pi R_b} \quad \text{where } c = (E/\rho)^{1/2}$$

and α is the cone apex angle, R_b is the resonant radius and f_{ra} is the resonant frequency.

These relations predict that shifting the modulus and/or density of a material will change the peak frequency by an amount directly proportional to $(E/\rho)^{1/2}$. Interpolating from Figure 4 yields the shift in these parameters directly. This proportionality predicts a peak frequency decrease of 32% with a moisture change equivalent to a humidity change from 36% to 95% relative humidity. The actual shift for the papers of Figure 8 was 38%, in good agreement with this prediction. Similar agreement is shown with the paper cones' first dip frequency.

The polypropylene shift is vastly underestimated, probably

due to the differences between the apparent and real tensile testing temperatures allowed by the heating method used.

Figure 9 shows the variation of the paper's loss tangent with humidity. The samples exhibited the expected increase in loss tangent, indicating increased internal damping with increased moisture.

Figure 10 is a plot of loss tangent versus temperature for paper and polypropylene samples between 40°C. and 80°C. The papers showed very little variation over this range. The polypropylene data indicates a double inflection in the plot similar to that reported for several polymeric materials by McCrum (8), Saito(9), and Reddish (10). Extrapolation of these points to a similar curve is indicated in this figure.

V. DISCUSSION AND SUGGESTIONS FOR FUTURE WORK

A characteristic shape was noticed for the first response peak of the paper cones at room temperature and humidity. The peak has three "steps" leading up the lower frequency end of the resonance, whereas the high side seems to be unaffected. Locally stiffer cone segments, or even fiber bundle segments under higher tension would resonate at higher frequencies than the bulk, and low stiffness abnormalities would produce the reverse effect. More likely this asymmetric behavior is indicative of local regions of high density contaminants or higher density pulp. This lack of homogeneity and sample-to-sample consistency has been a major impetus for designs using other polymers. The polypropylene cones studied do nott show this behavior.

The results of this study show that paper-coned loudspeakers shift their frequency response significantly with changes in ambient humidity with fast equilibration rates. The response of paper to moisture content suggests the adoption of a new characteristic parameter for fibrous polymers, the glass transition relative humidity or $R.H._g$. Similar to the glass transition temperature, the $R.H._g$ indicates the humidity level at which the polymer shifts from stiff, glasslike behavior to more fluid, viscous behavior.

The plasticizing treatment used on the paper cones increases the $R.H._g$ from 65% to 71% for the samples tested. A reduction in the area of exposed fibers after treatment may cause this

effect. As support for this theory, the treated cones absorbed 5% water as opposed to 6% water for the untreated cones after similar length chan er equilibration.

Over the range of temperatures and humidities tested, which includes most of the normal operating environments for home speakers in this country, polypropylene is a much more mechanically stable material than paper. Extrapolation of the polypropylene curves indicate a transition temperature of about 110°F.

The variability of paper's properties with humidity allow it to be used as a powerful design tool. This characteristic provides the ability to adjust the cone's modulus and loss tangent in a single assembled speaker in order to get the desired combination of frequency bandwidth and freedo from cone resonance induced response anomalies. Once the desired response is obtained, the material may be tested under a similar environment. The knowledge of the modulus, loss tangent, and density of the cone would allow the design of a polymer or polymer alloy material which would provide the same response without humidity sensitivity. Once designed, such a cone could give tighter conformation to design specifications on a unit-to-unit basis.

The peak frequency shift curves could also be used to determine the drying time for conventional paper cones which are subjected to a dip treatment. As Frankort(11) suggested, the dependence of the peak frequencies on $(E/\rho)^{1/2}$ is verified for the papers used in this study.

The considerable peak shift of paper cones with humidity

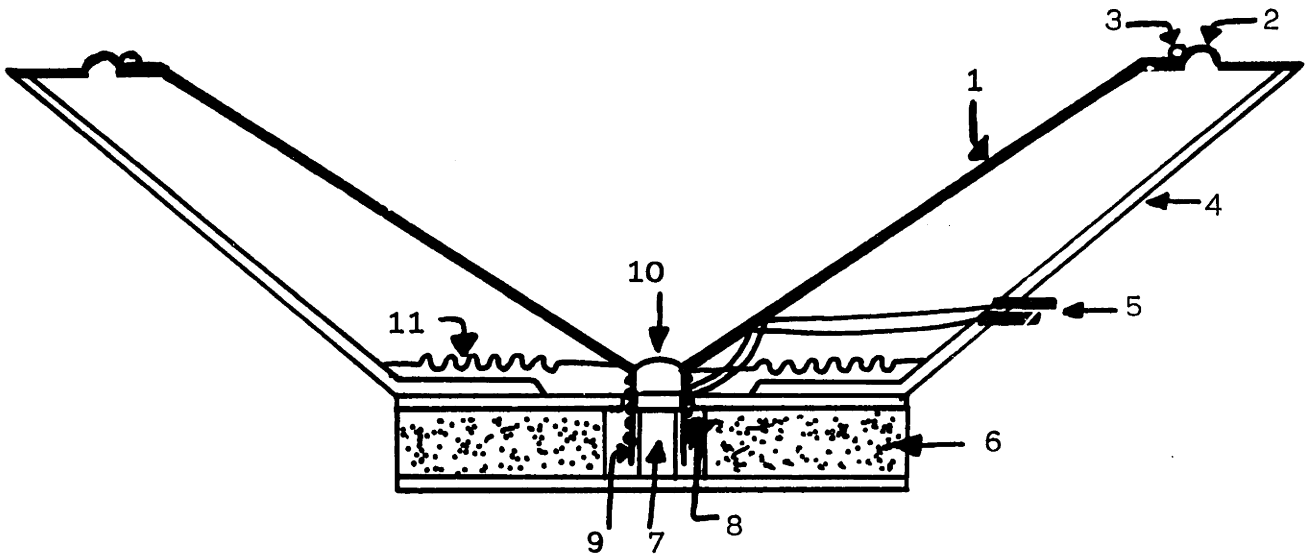
suggests that it is not a wise choice to use heavily equalized speaker designs with paper coned drivers, since the equalization would probably accentuate such a peak shift.

The drivers used in this study were "stripped" of several elements which could also alter driver performance in varying environments. The PVA surround bead used on many drivers is highly absorptive and the effects of humidity on it and the driver's response should be investigated. Humidification of paper dust caps may also affect loudspeaker performance, although this effect may be small compared to that of cone absorption.

Further work on the effects of humidity on papers could result in uantification of a time-humidity correlation factor as the WLF equation provides for time-temperature dependence. Investigation of the voice coil former temperature at the cone junction could provide information on which polymers would be acceptable for extended high output applications such as cone materials for public address and concert sound reinforcement systems. Hopefully, these correlations of loudspeaker cone resonances with readily measurable properties will allow more controlled selection and design of cone materials.

FIGURE 1

CUT-AWAY SIDE VIEW

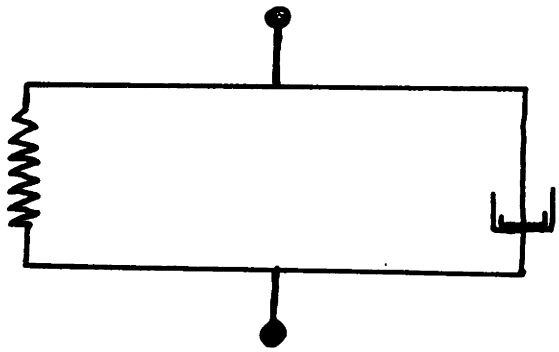


1 - LOUDSPEAKER CONE
2 - SURROUND OR SKIVER
3 - PVA DAMPING BEAD (SOME DESIGNS)
4 - FRAME OR BASKET - Assembly mainframe.
5 - VOICE COIL LEAD CONTACTS
6 - MAGNET
7 - POLE PIECE AND SUPPORT
8 - VOICE COIL WINDINGS
9 - VOICE COIL FORMER
10- DUST CAP
11- SPIDER - Holds voice coil aligned in gap.

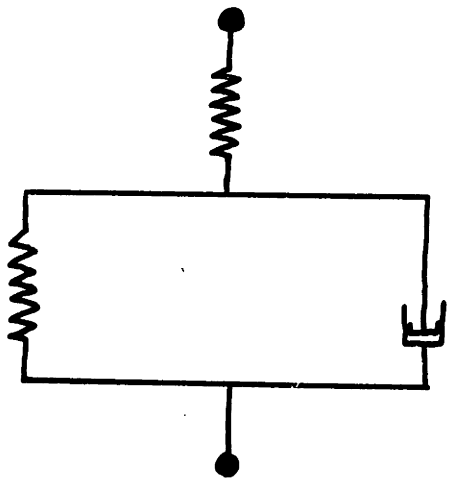
GENERAL MOVING COIL LOUDSPEAKER DESIGN
(NOT TO SCALE)

FIGURE 2

(a) Maxwell Model



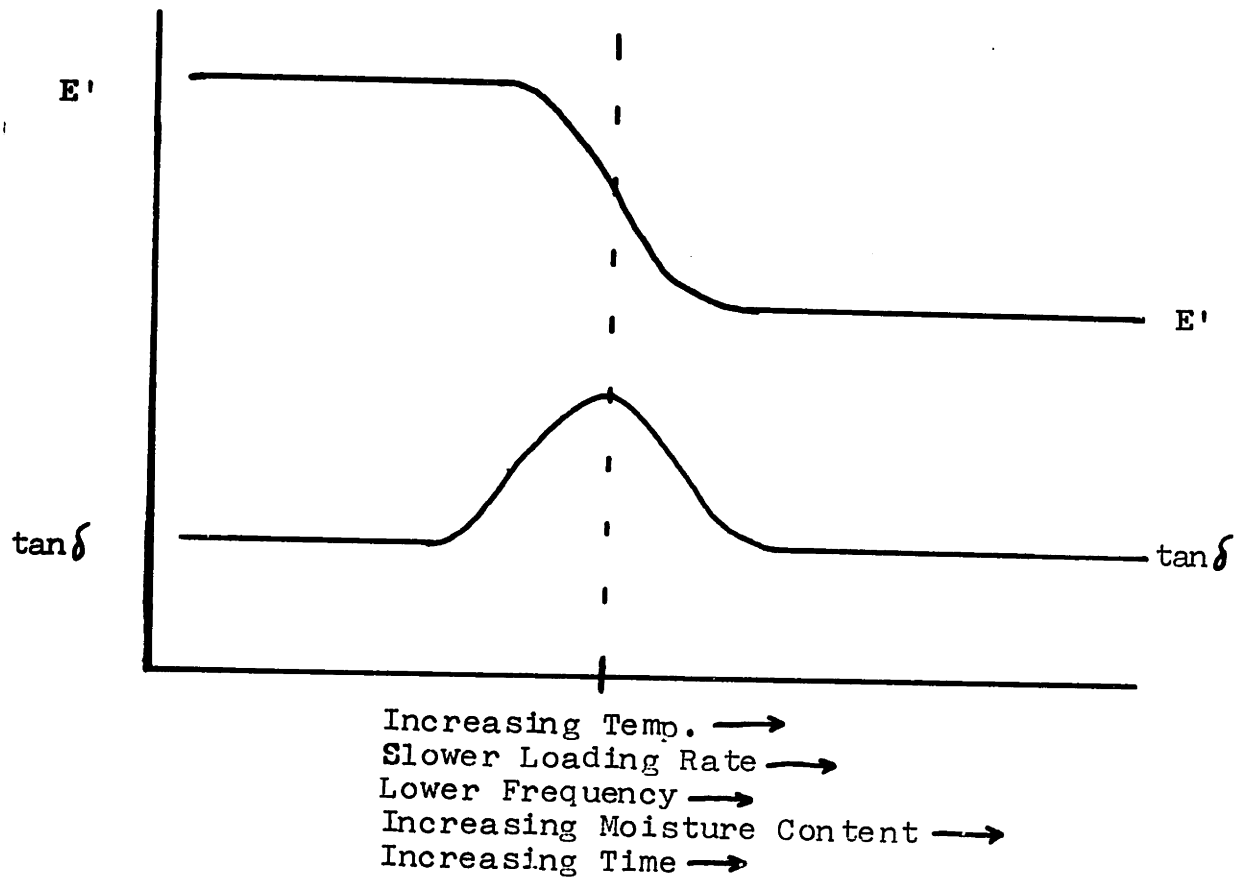
(b) Voigt Model



(c) Standard Linear Solid Model

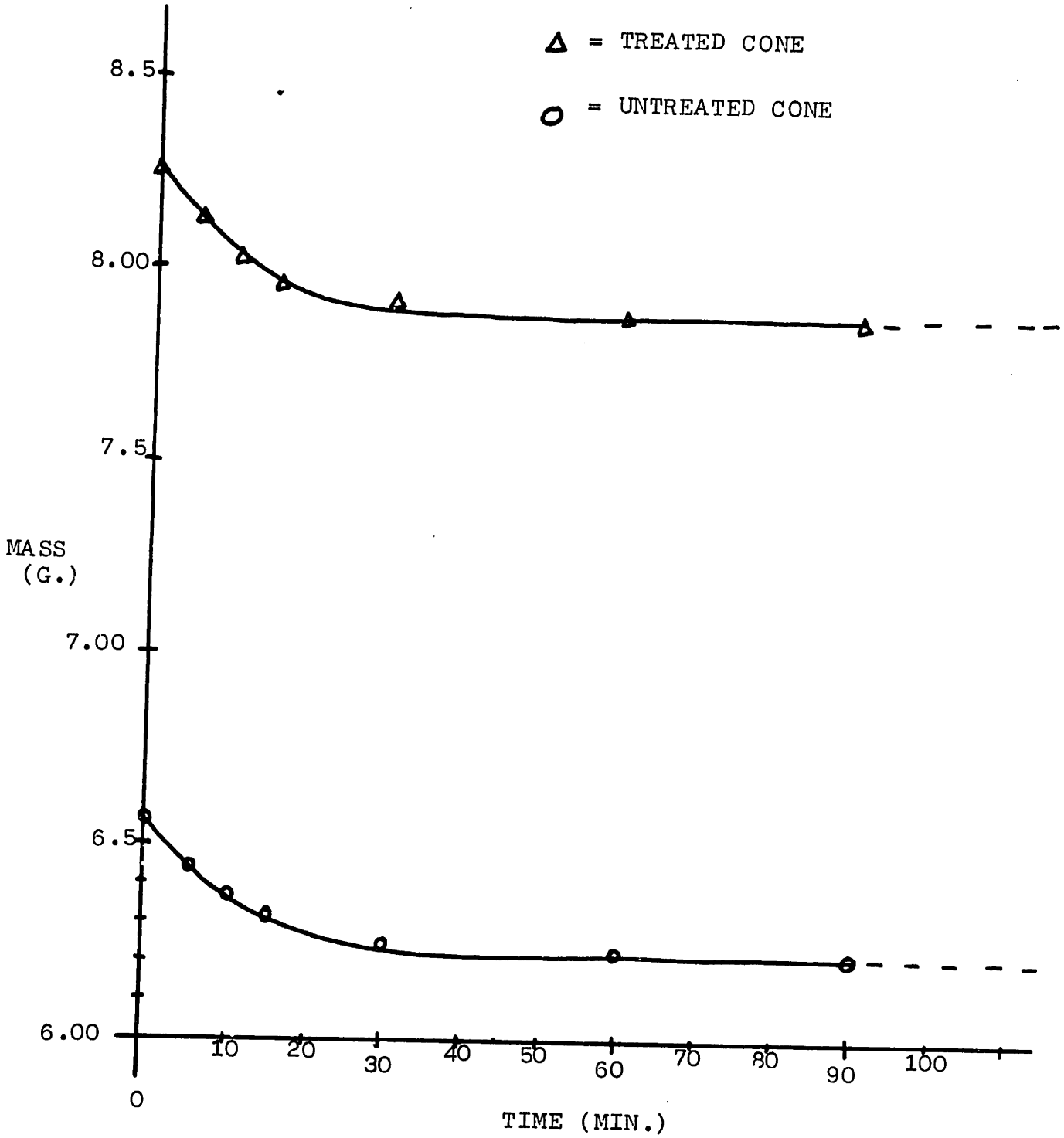
SPRING AND DASHPOT VISCOELASTIC MODELS

FIGURE 3



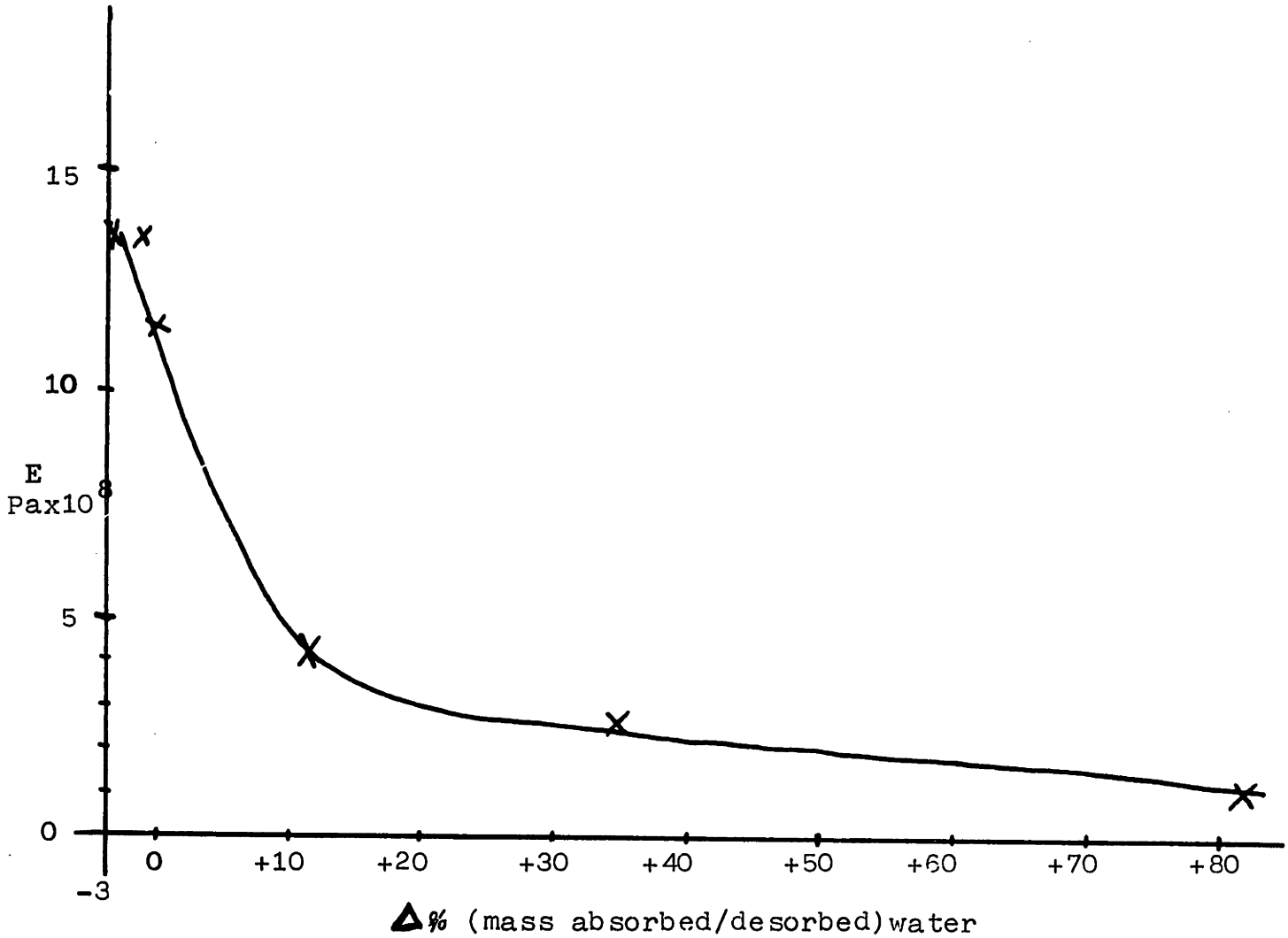
SHIFT FACTOR CORRELATIONS

FIGURE 4



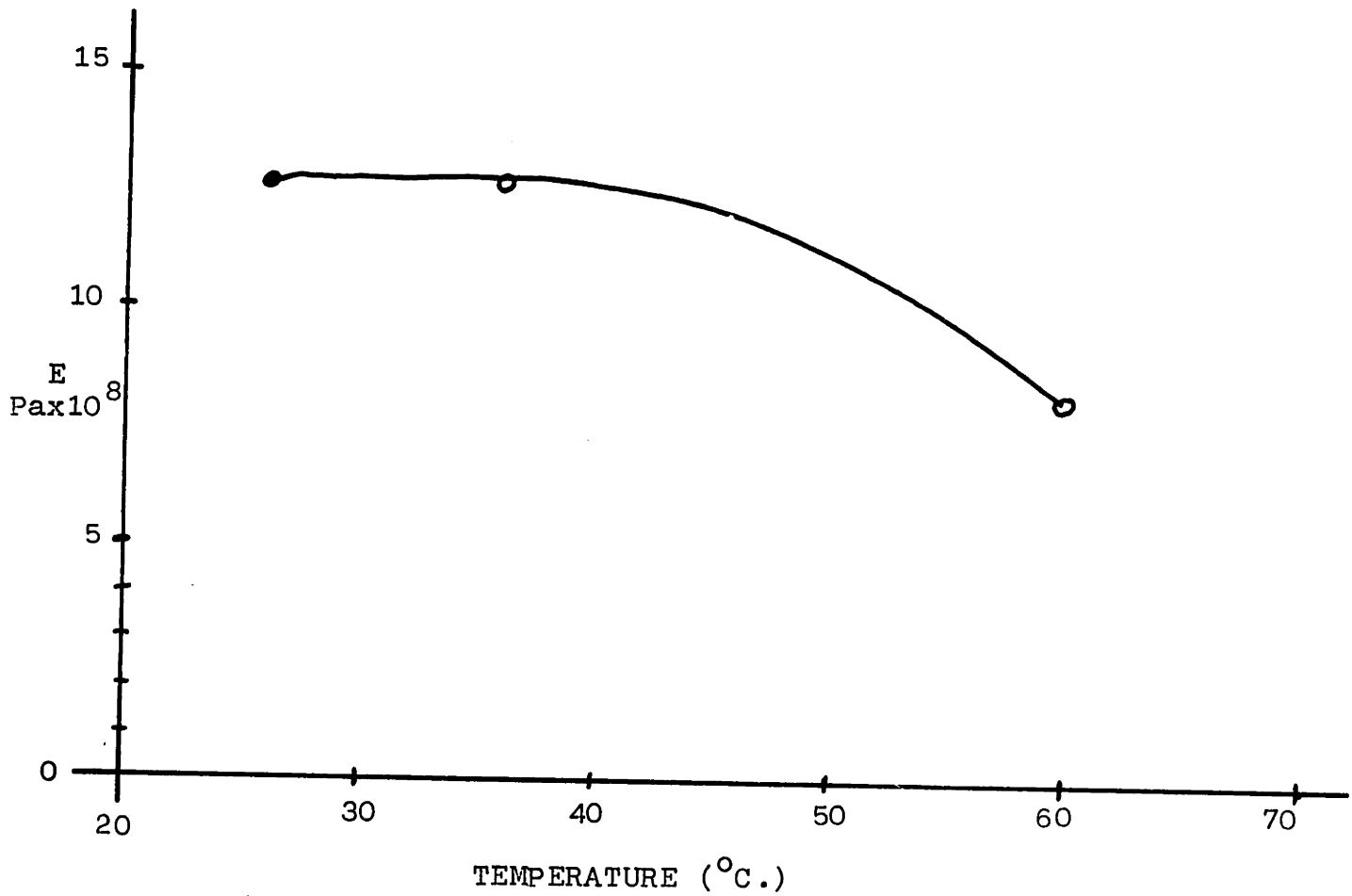
DEHUMIDIFICATION MASS LOSS VS. TIME FOR UNTREATED AND TREATED PAPER CONES

FIGURE 5



STATIC MODULUS VS. MOISTURE CONTENT

FIGURE 6



STATIC MODULUS VS. TEMPERATURE FOR

POLYPROPYLENE CONE

FIGURE 7

FREQUENCY VS. TIME AFTER REMOVAL FROM CHAMBER
-FIRST ANTIRESONANCE DIP

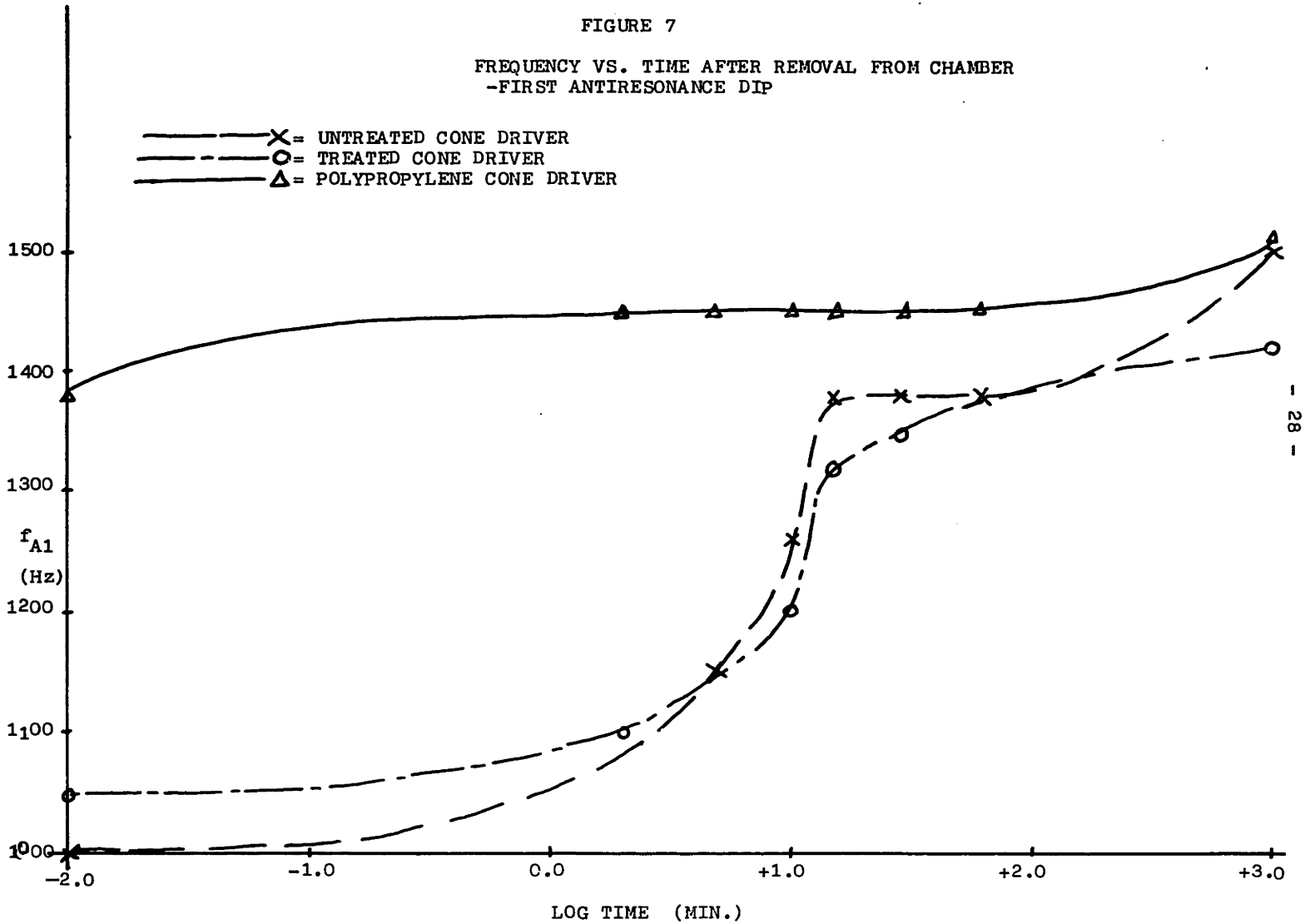


FIGURE 8

FREQUENCY VS. TIME AFTER REMOVAL FROM CHAMBER
-SECOND RESONANCE PEAK

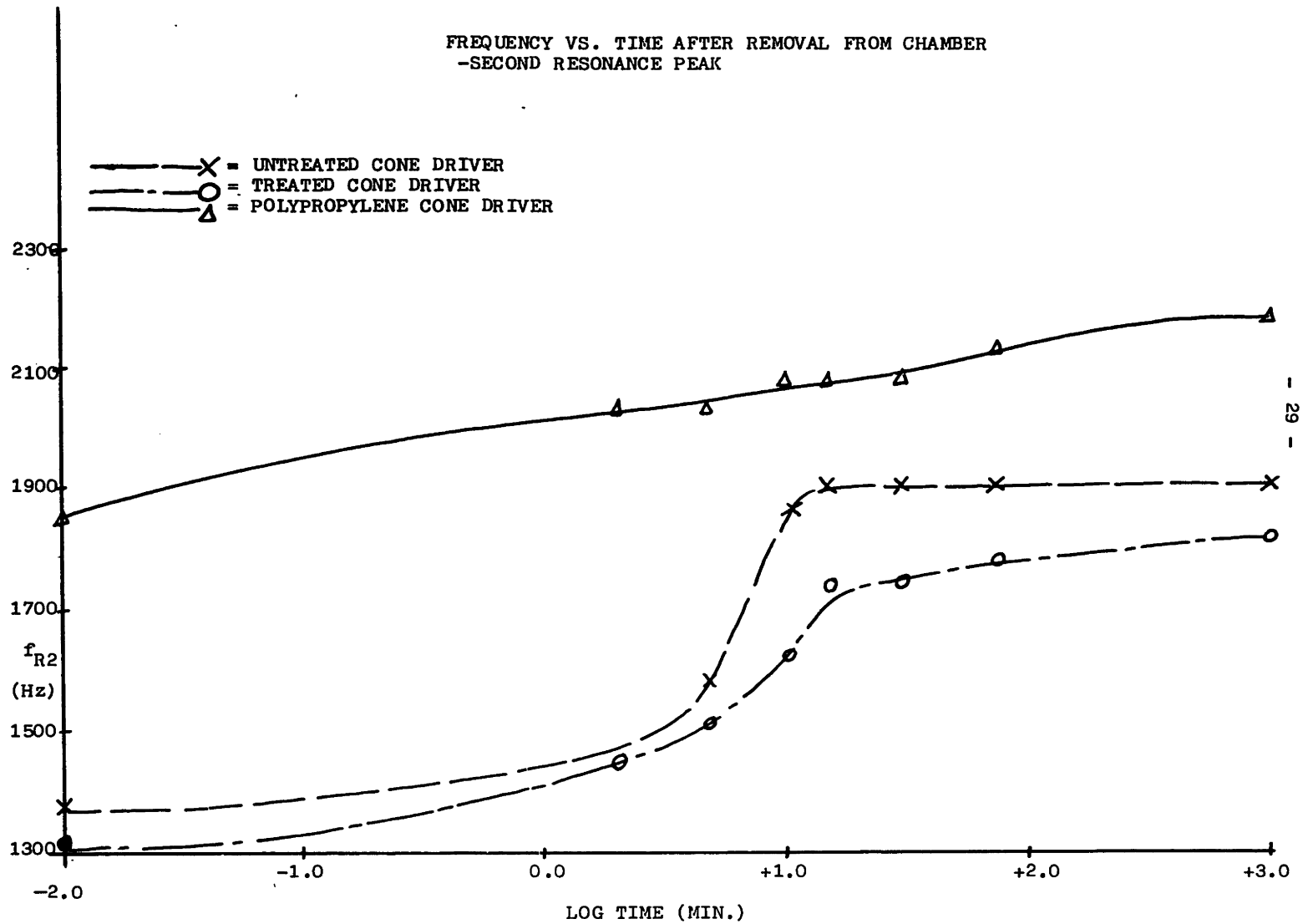
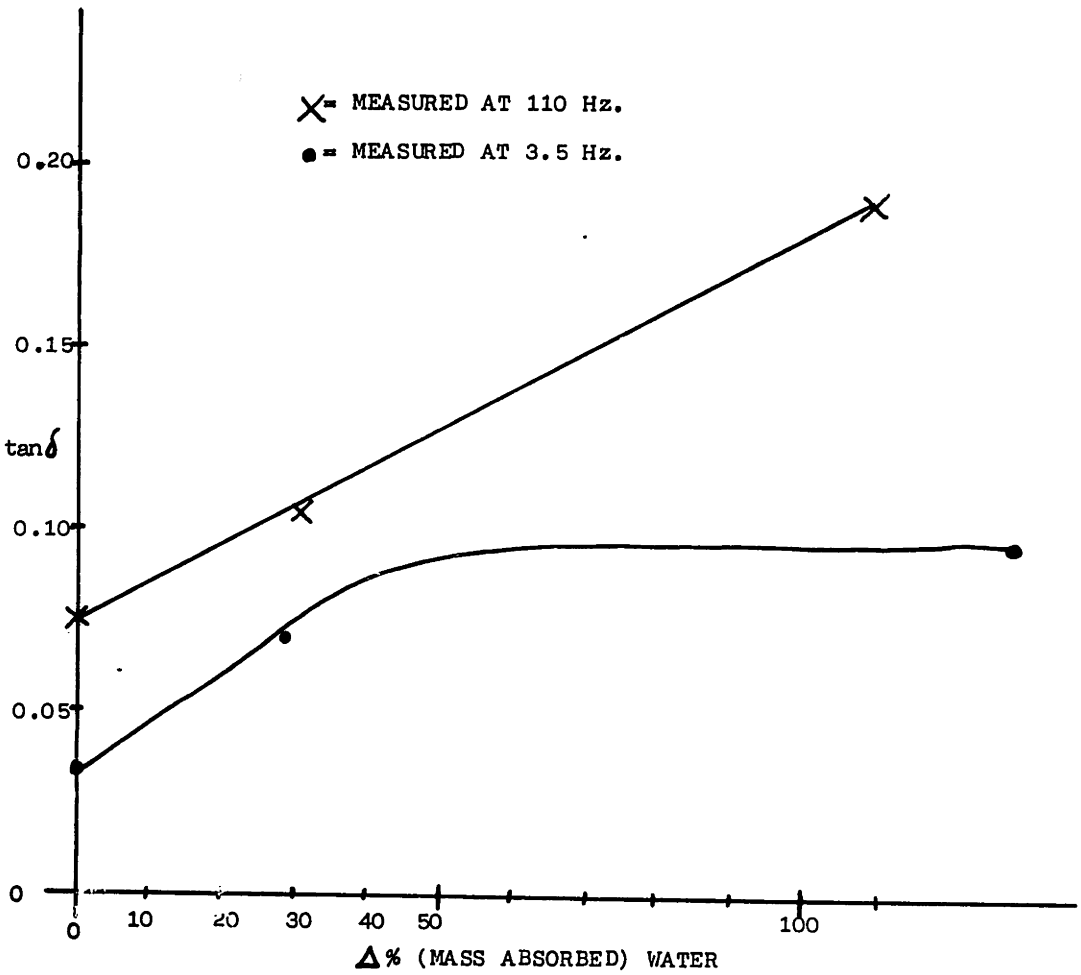
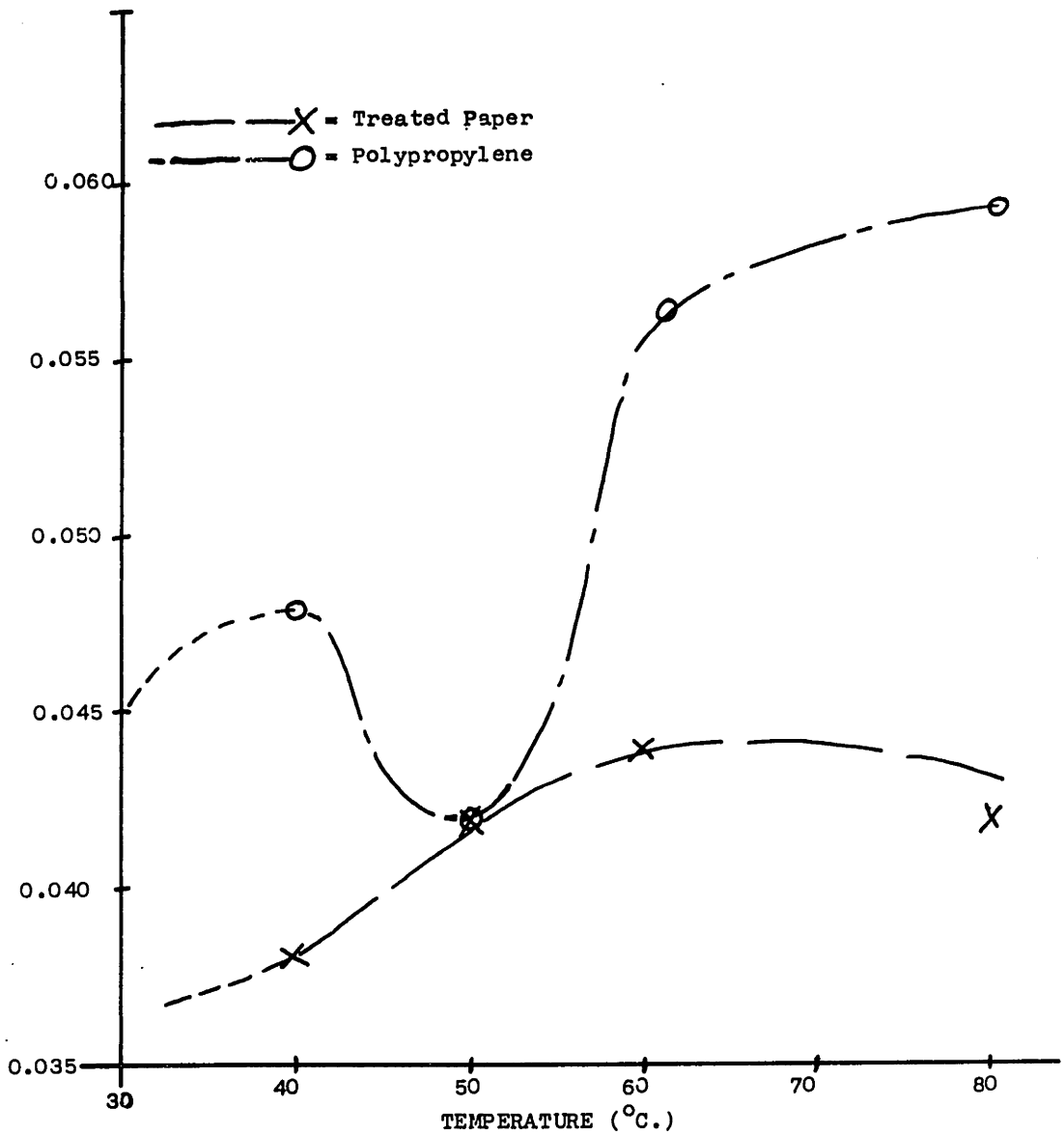


FIGURE 9



LOSS TANGENT VS. HUMIDITY FOR PAPER CONES

FIGURE 10



LOSS TANGENT VS. TEMPERATURE FOR
PAPER AND POLYPROPYLENE CONES

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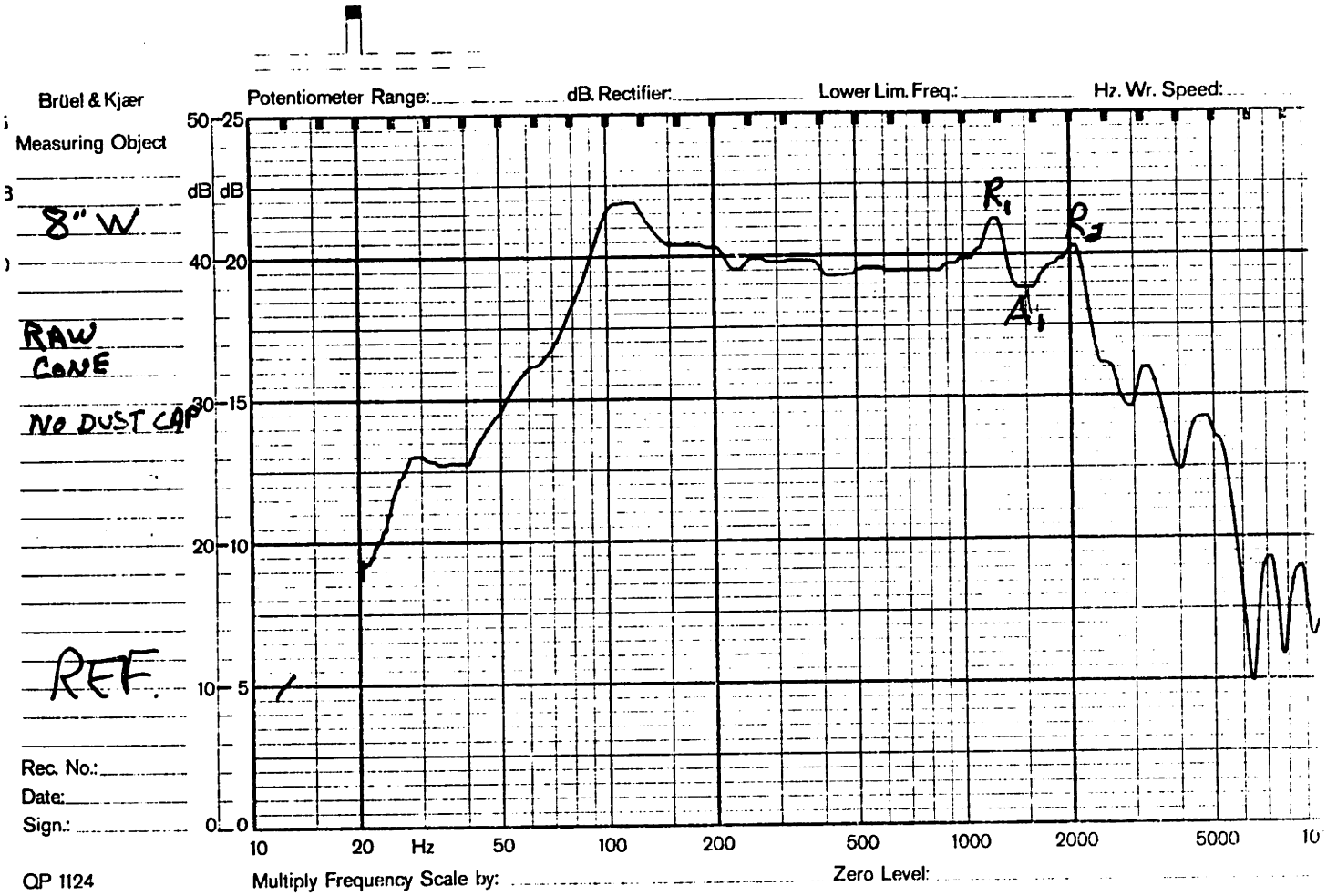
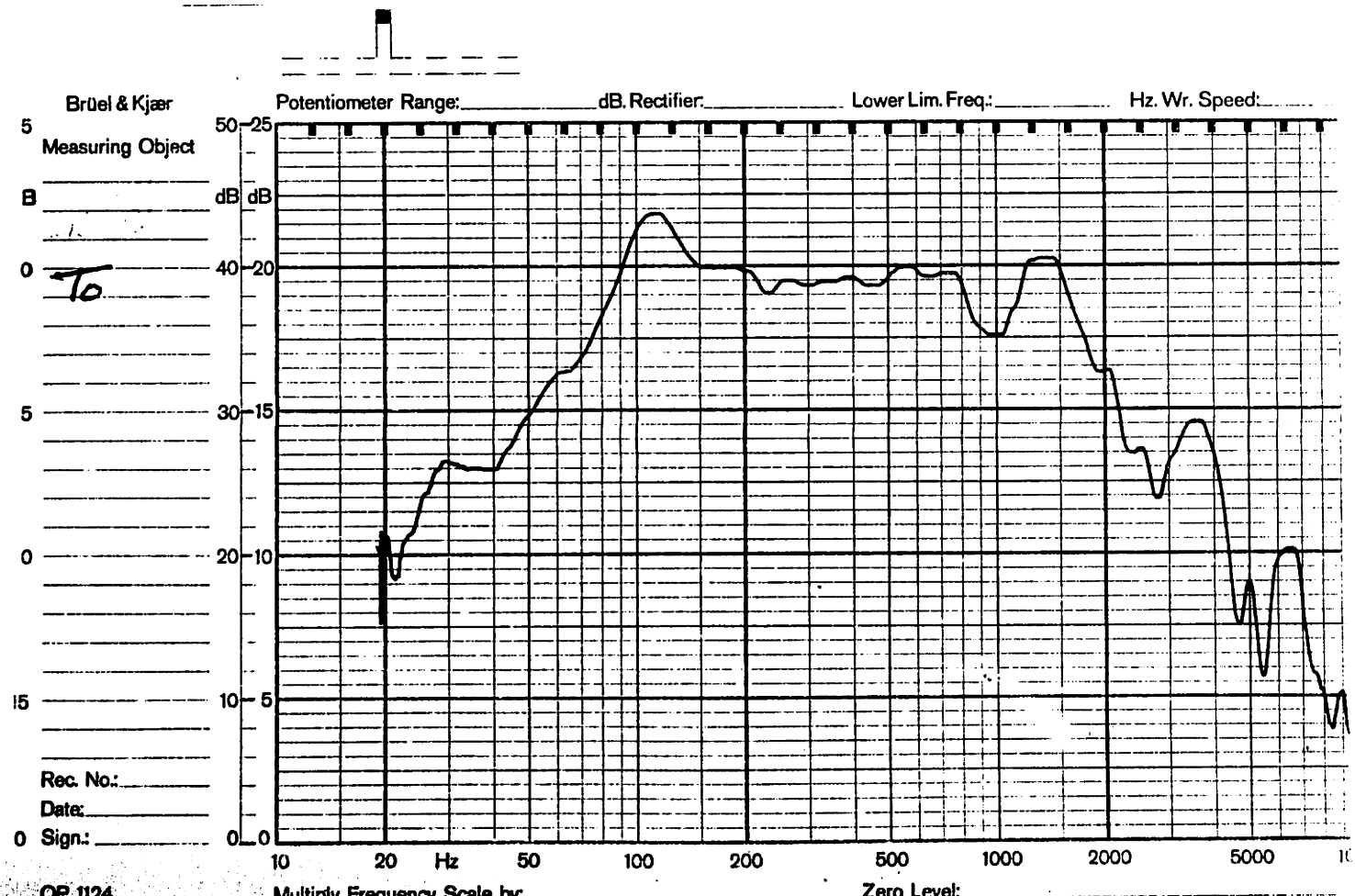
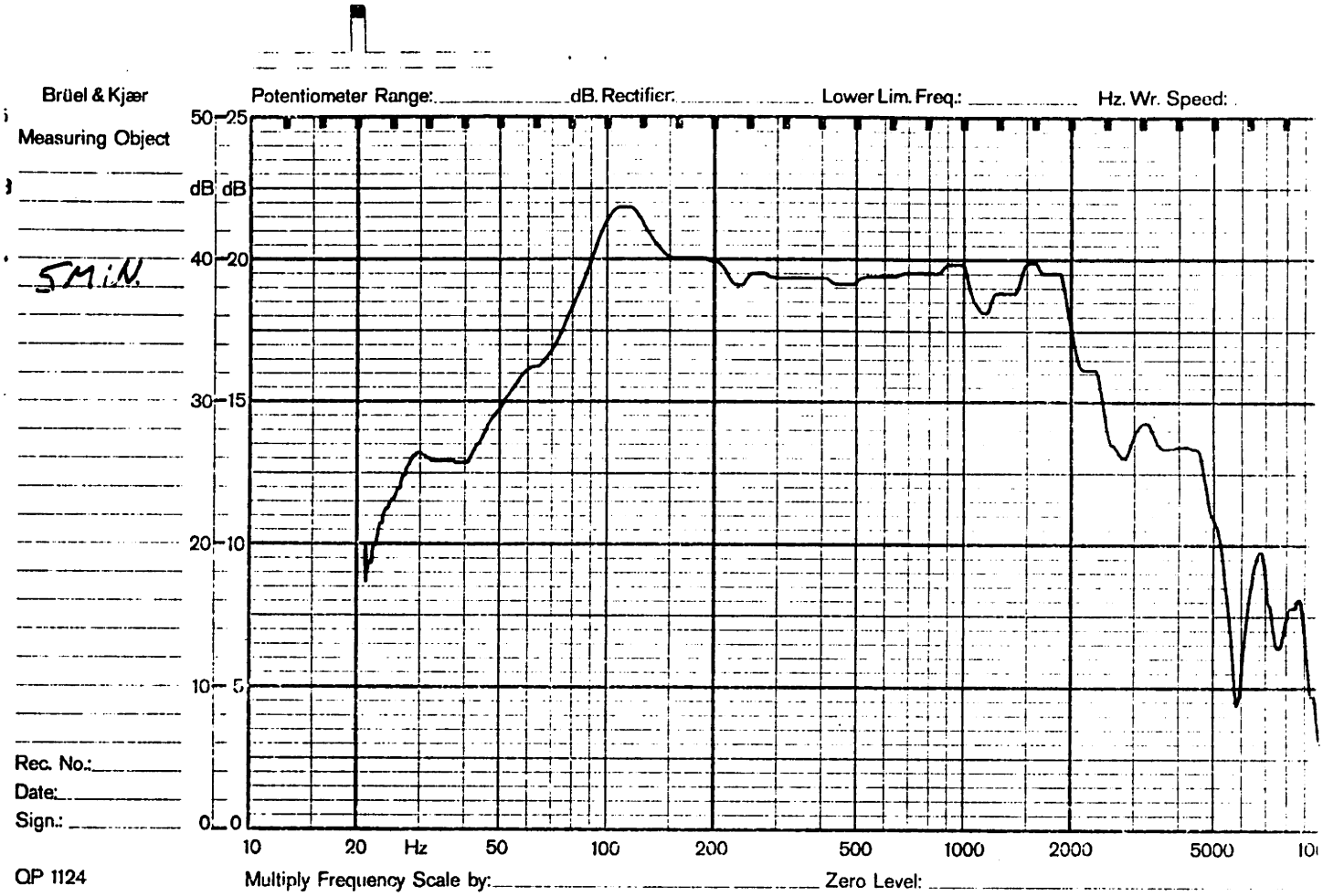
APPENDIX 1 - FREQUENCY RESPONSE DATA






Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
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dB dB
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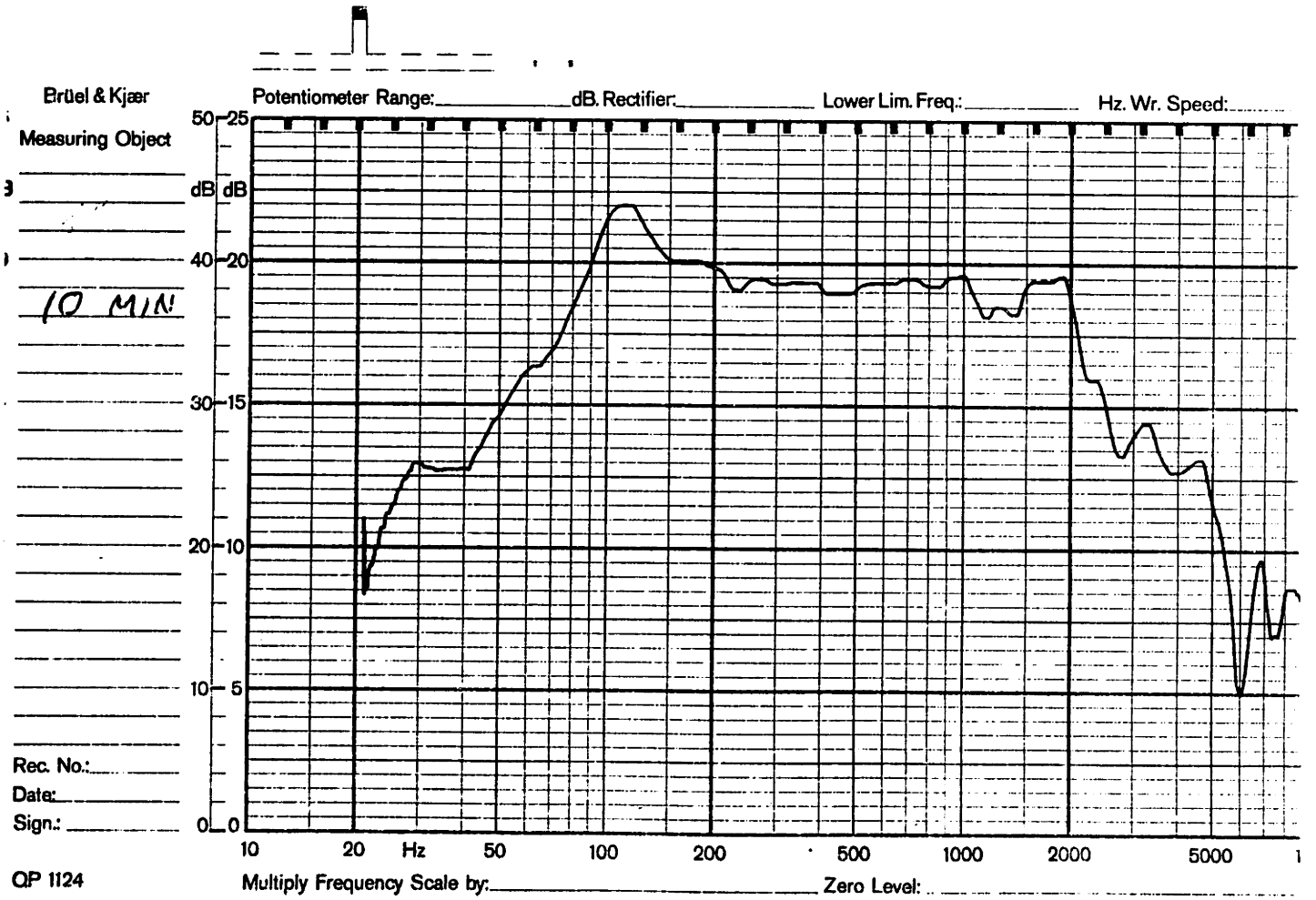
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Hz. Wr. Speed:
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dB dB
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QP 1124
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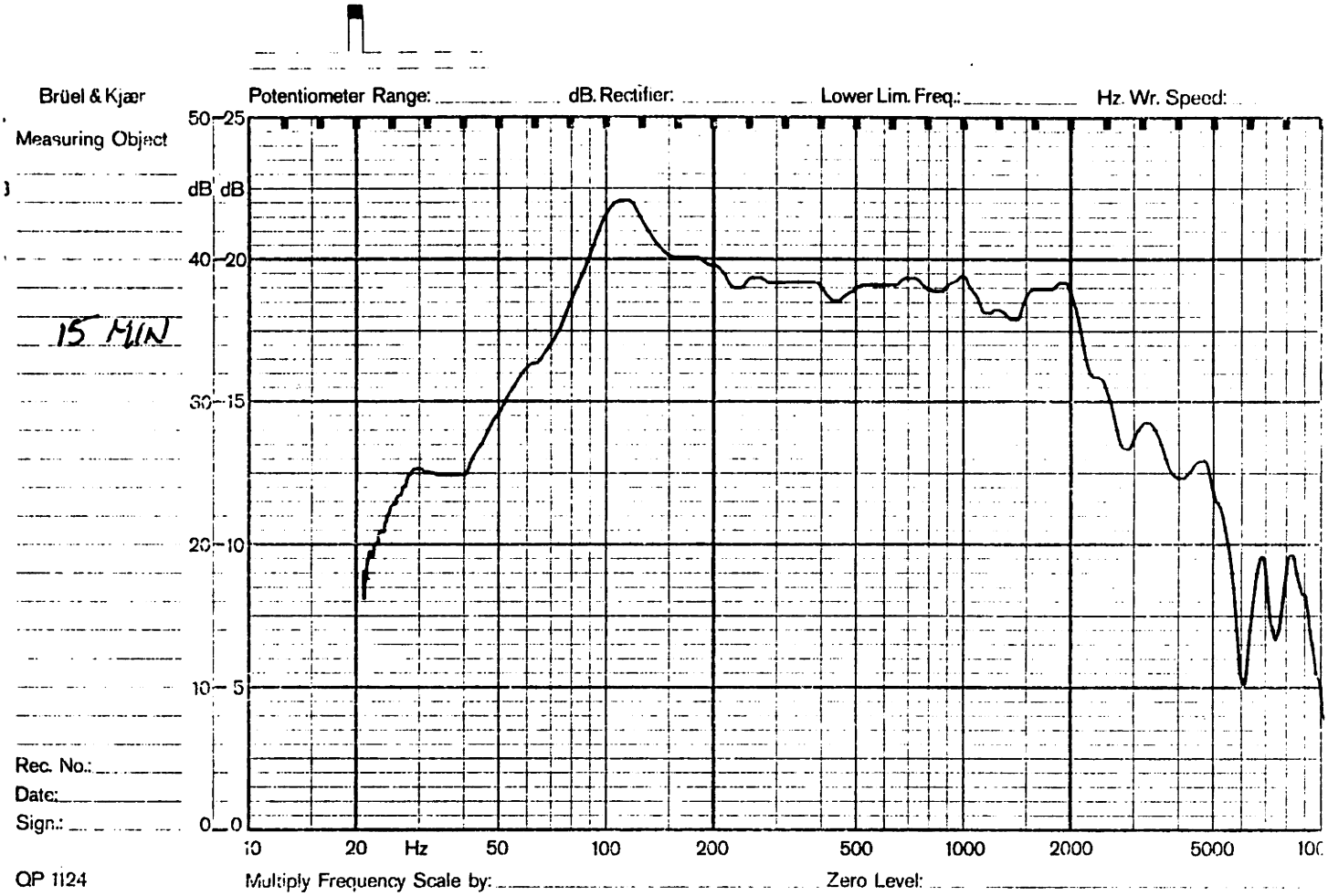
Zero Level:


Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
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dB dB
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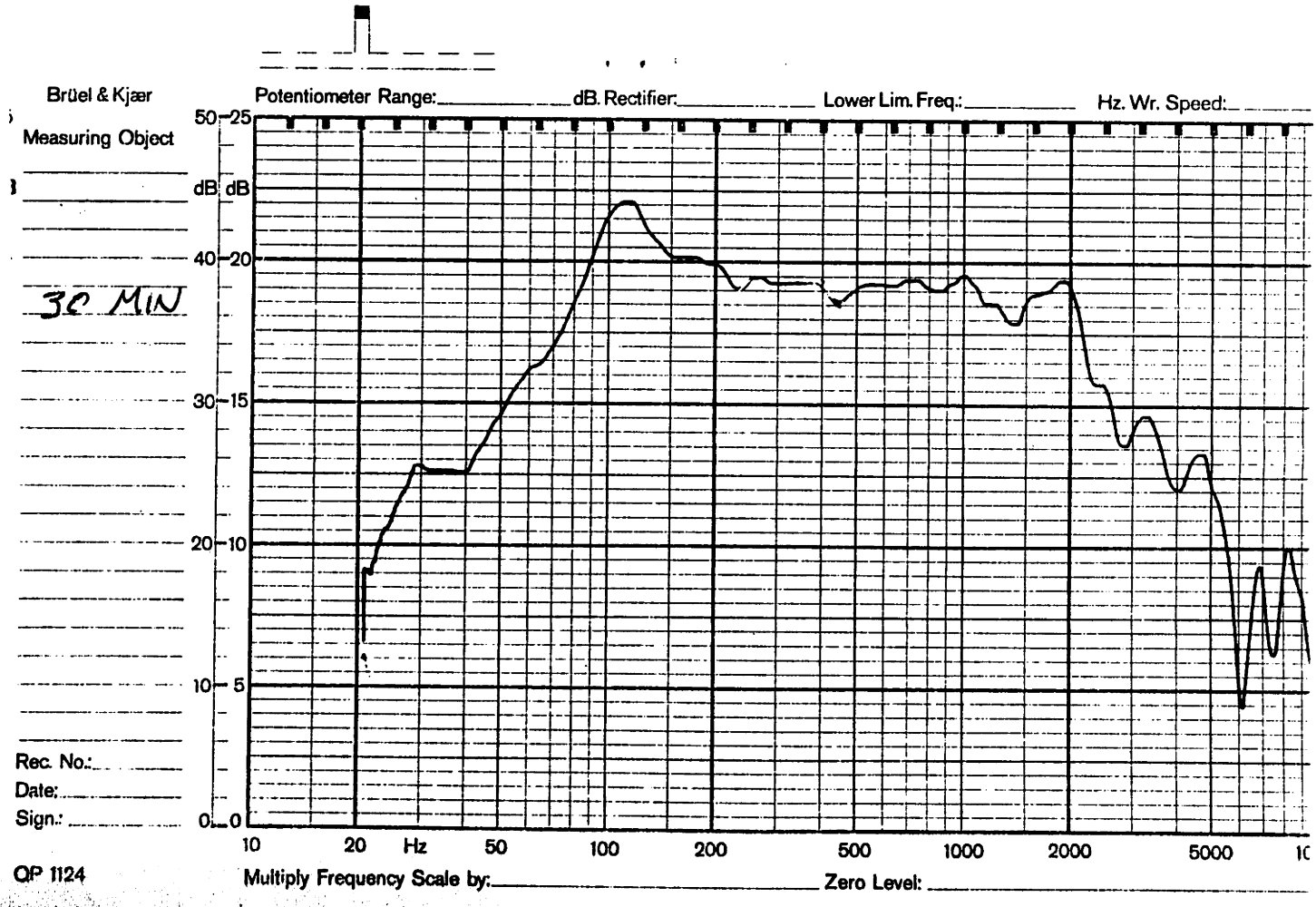
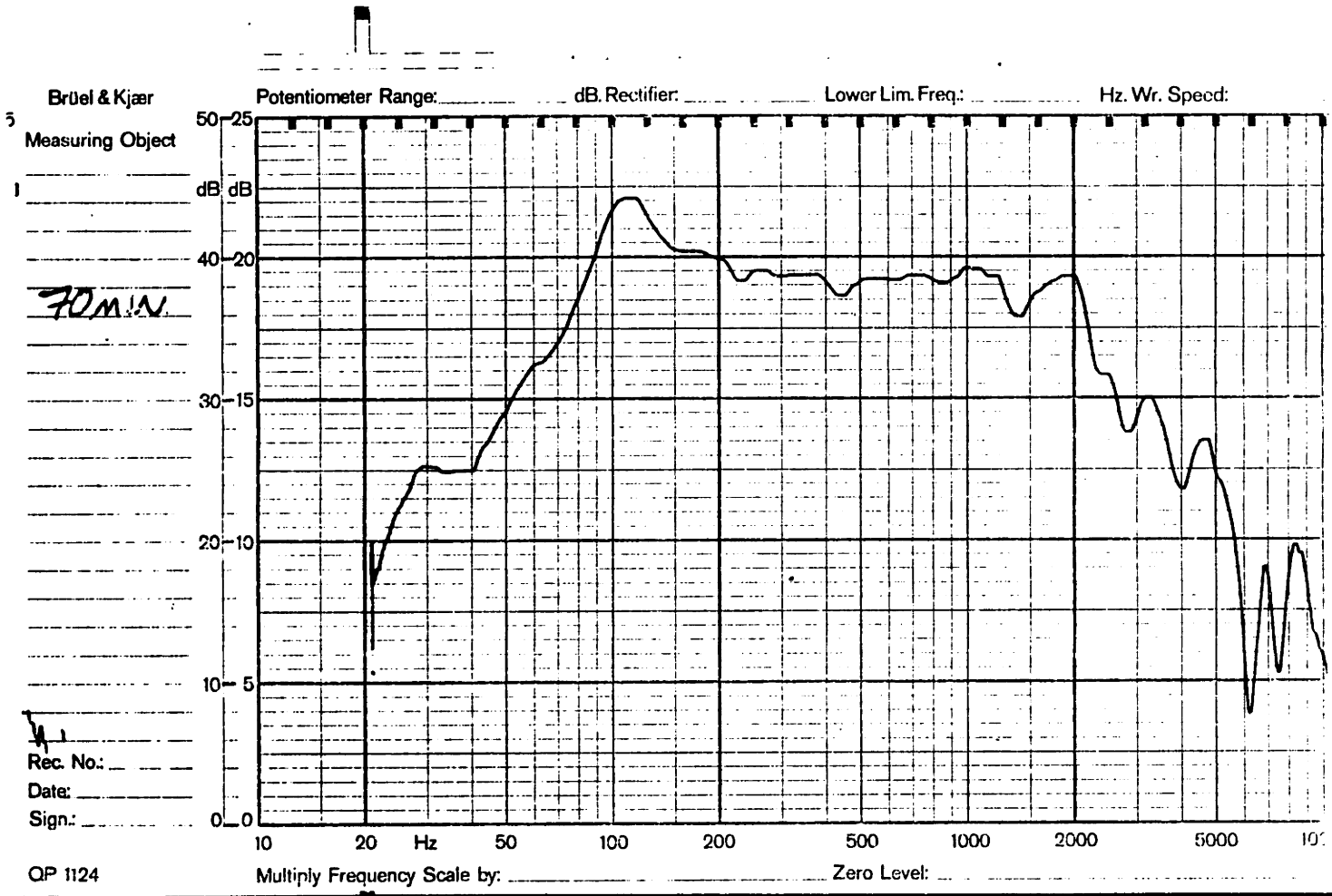

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
30 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
10 20 Hz 50 100 200 500 1000 2000 5000
Rec. No.:
Date:
Sign.:
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
70MIN
Rec. No.:
Date:
Sign.:
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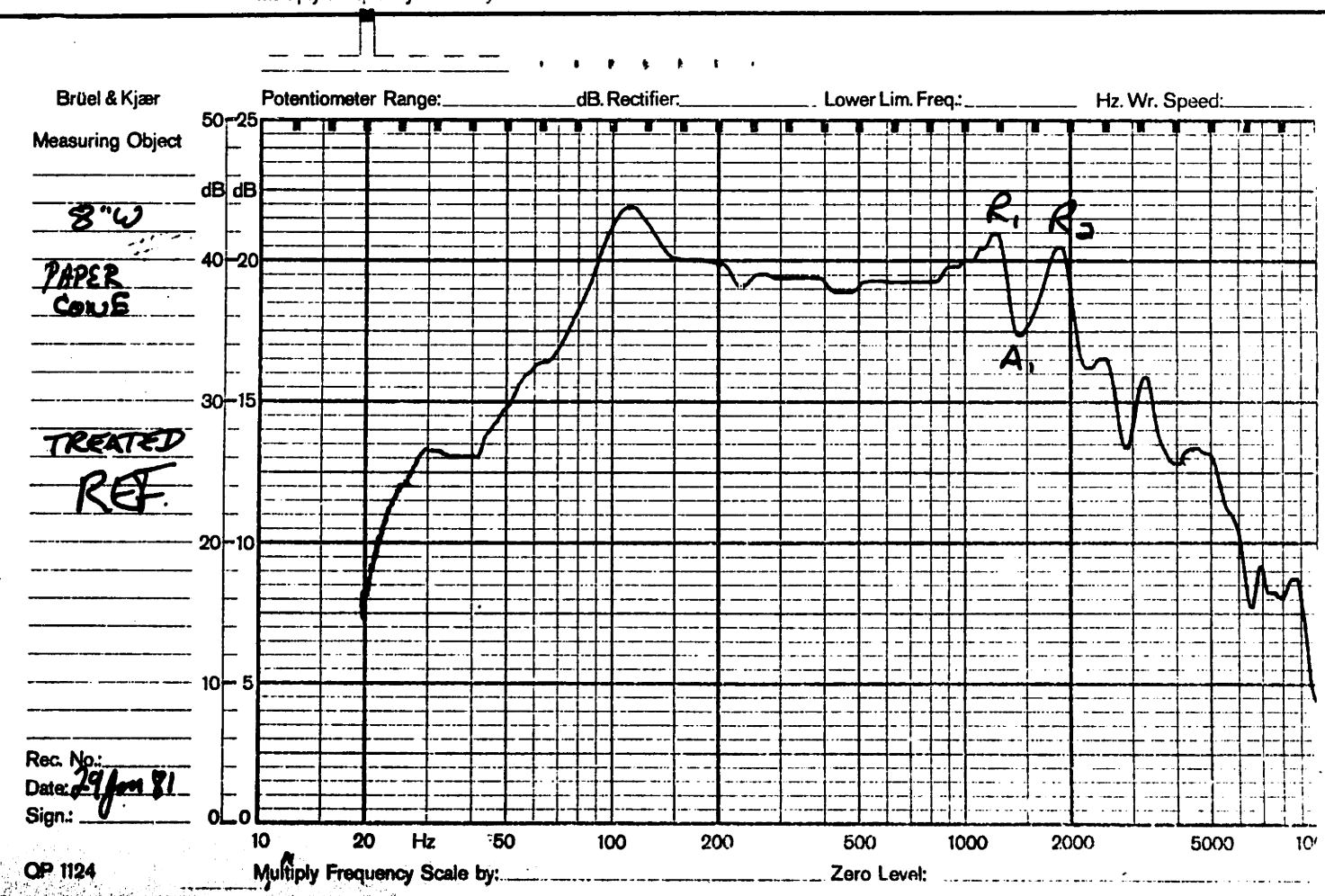
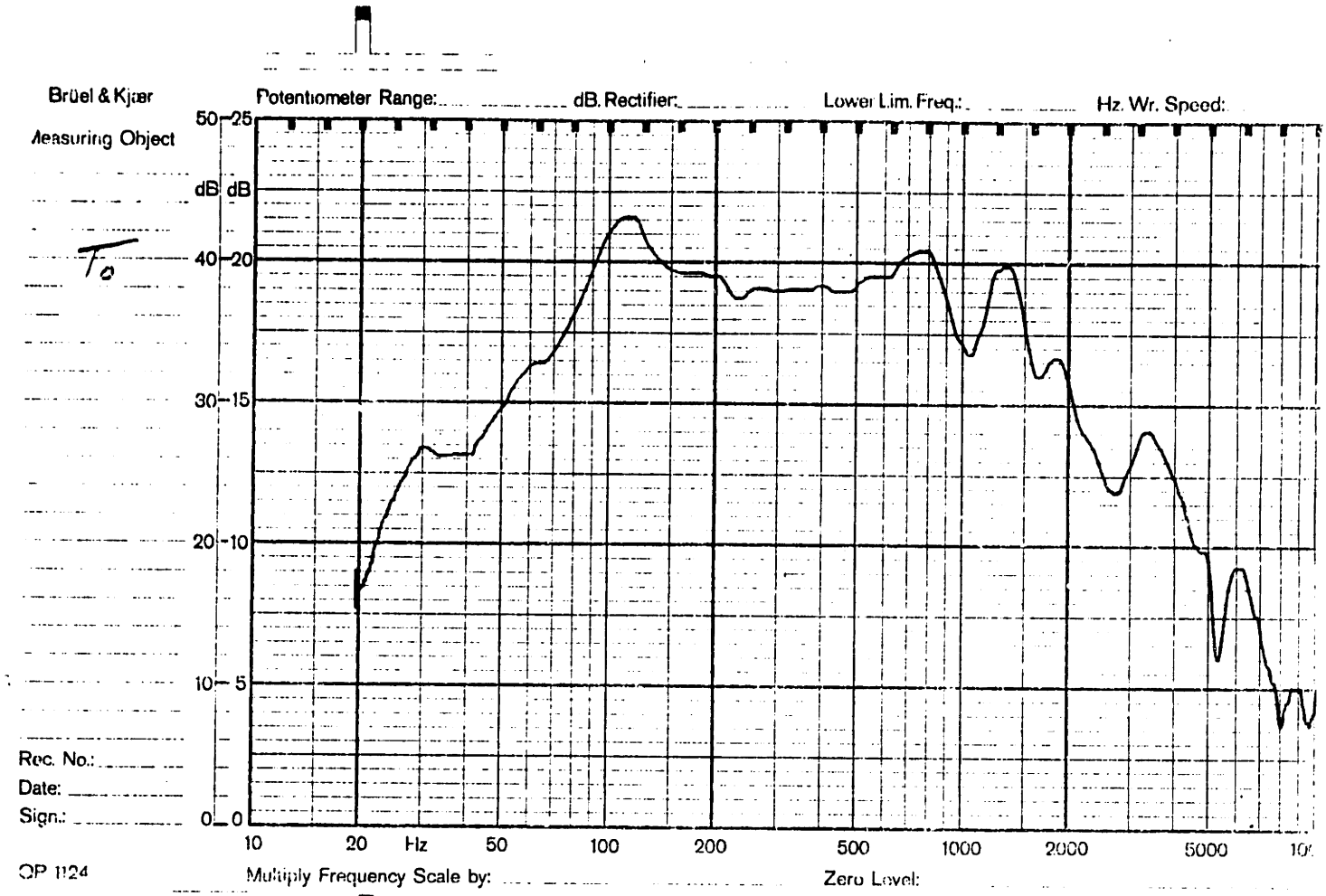
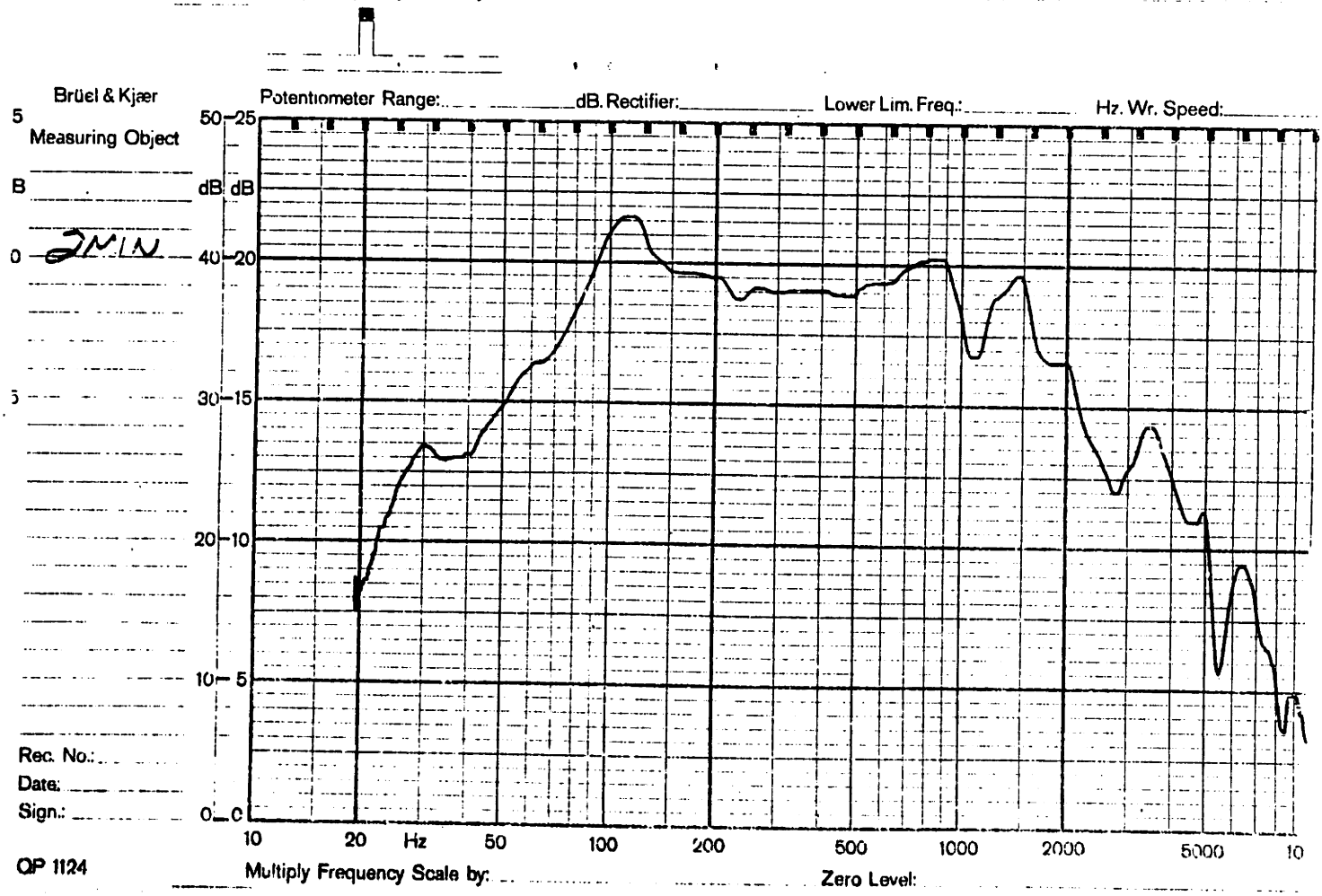
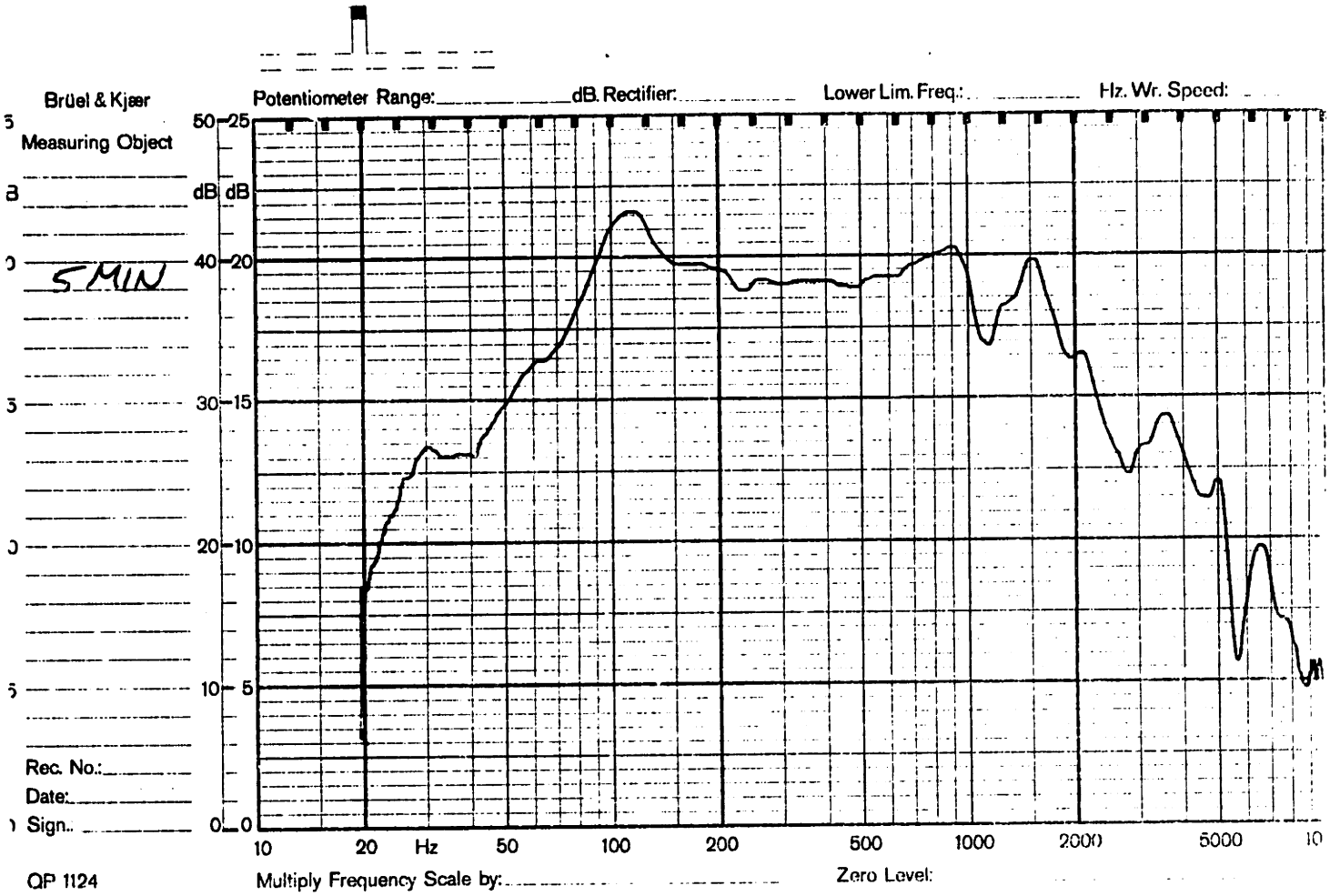
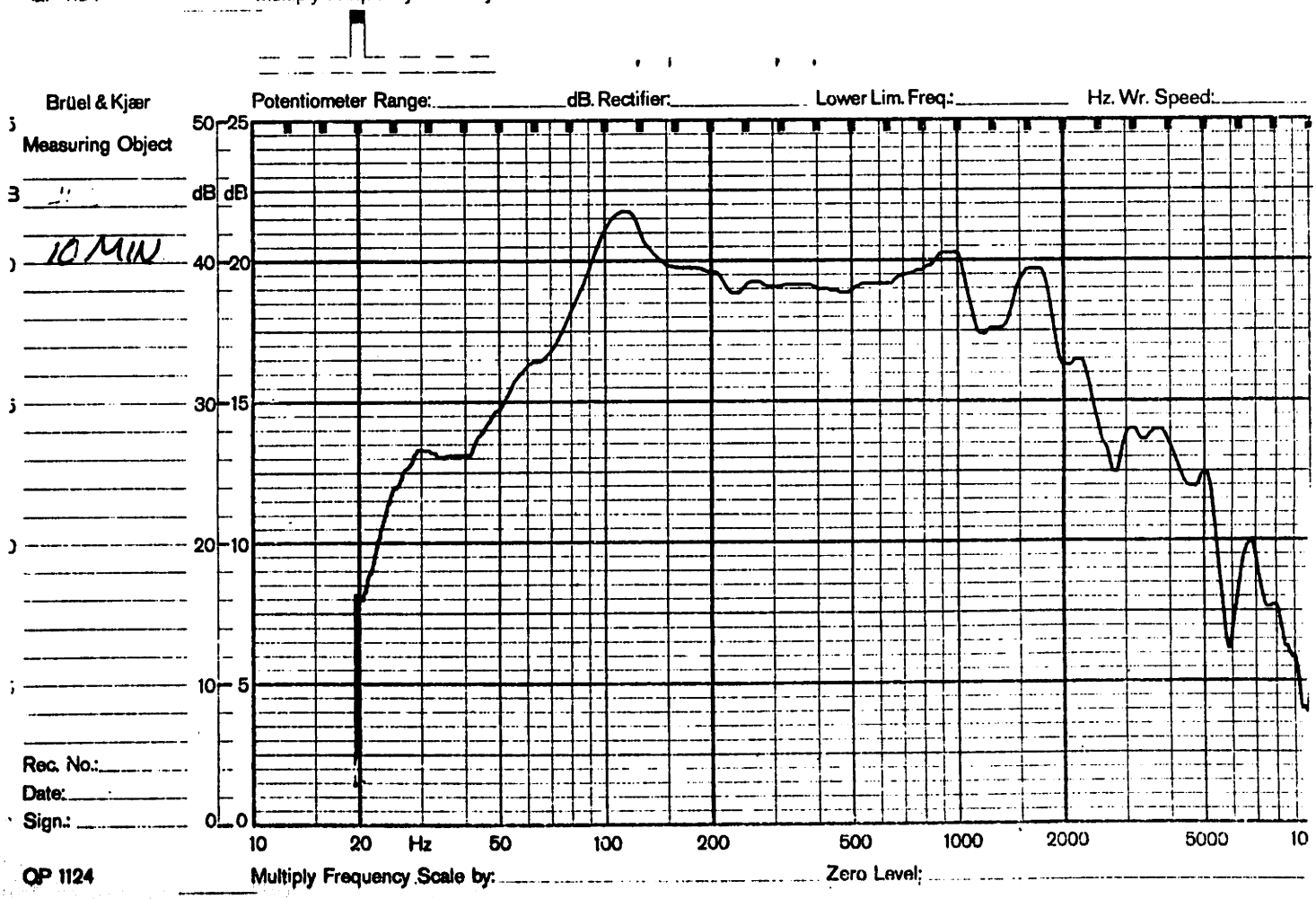
dB dB
40 20
30 15
20 10
10 5
0 0
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

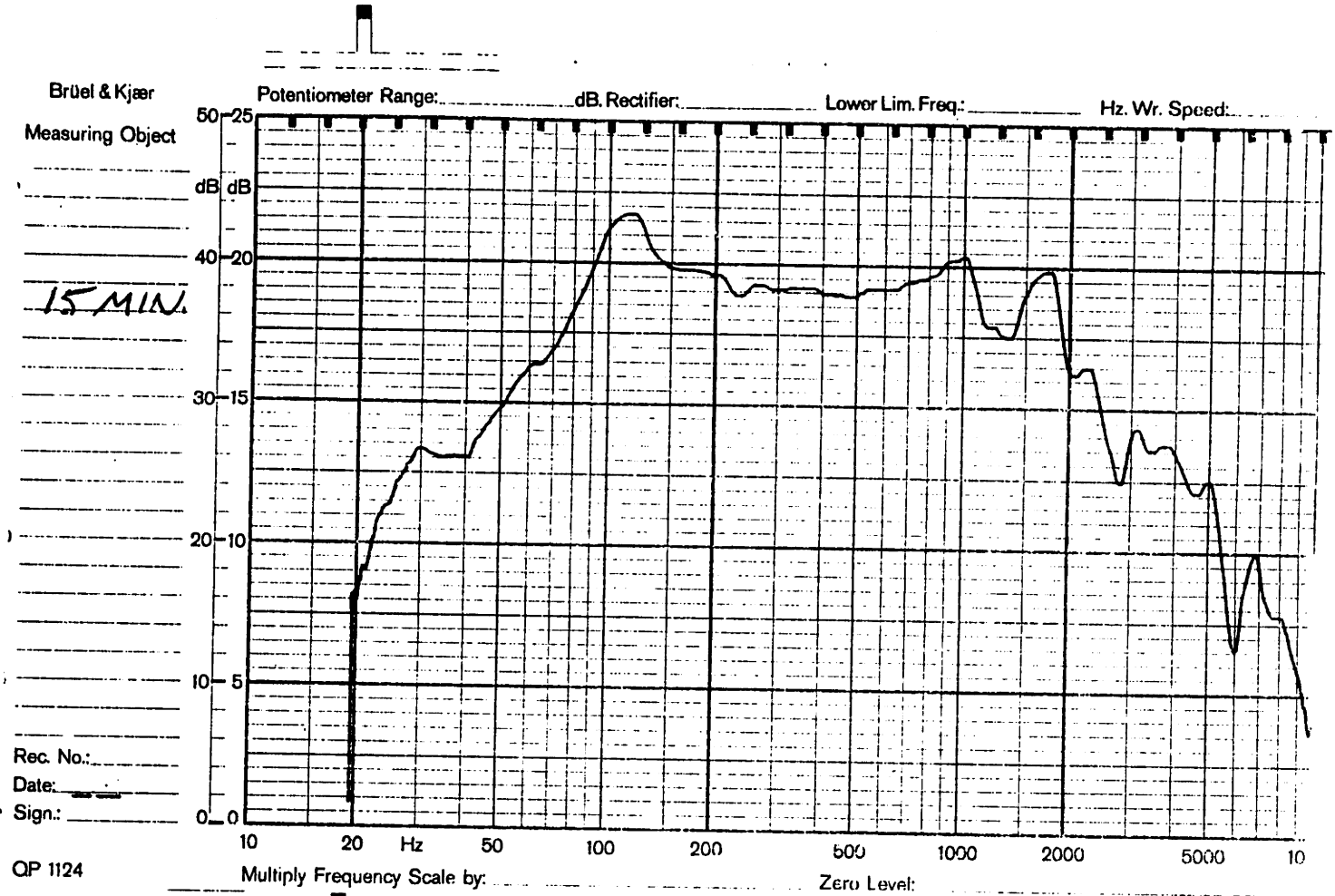

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
8"W
PAPER
CONE
TREATED
REF.
R1
R2
A1
Rec. No.:
Date: 29 Jan 81
Sign.:
50 25
dB dB
40 20
30 15
20 10
10 5
0 0
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

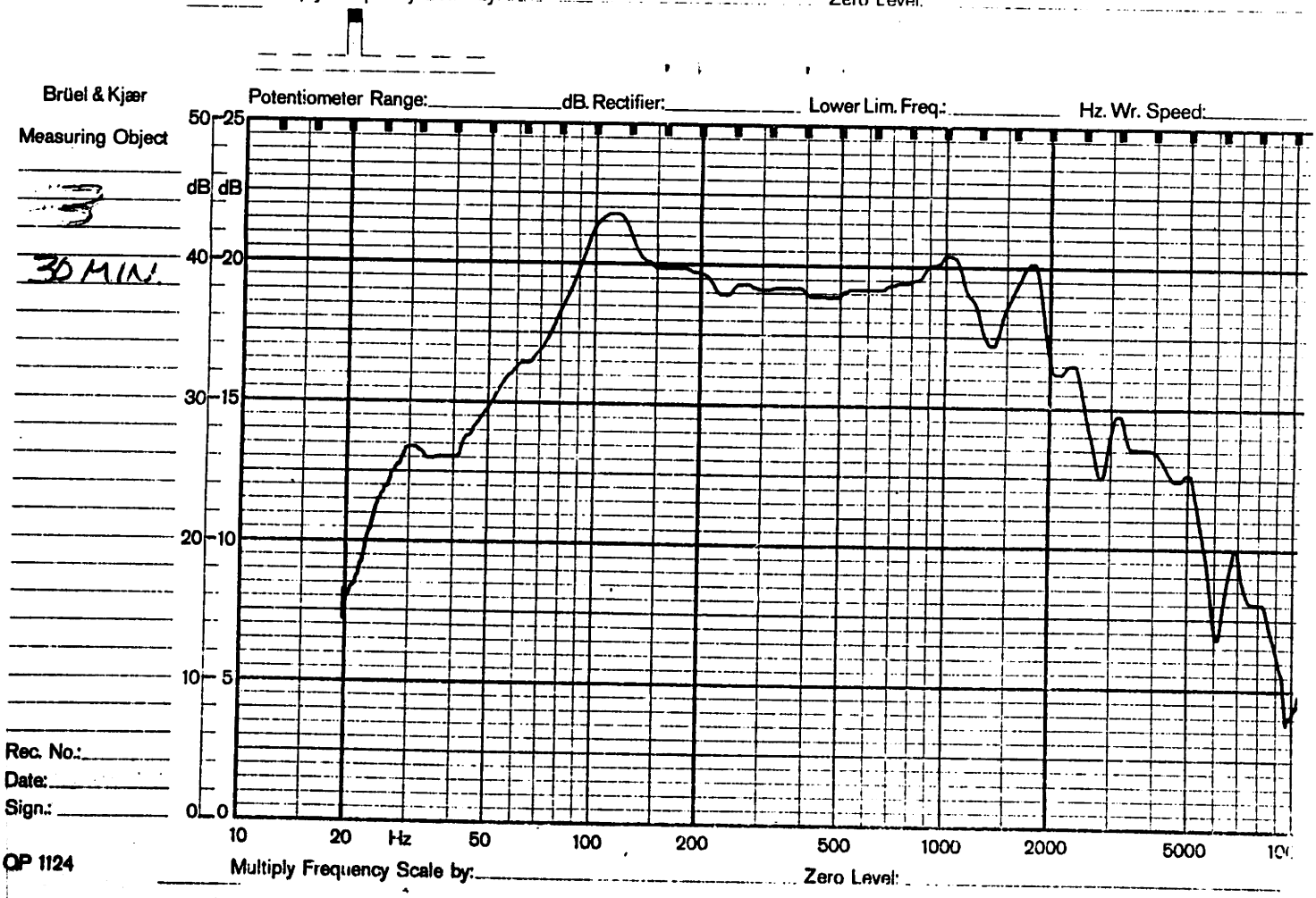

Brüel & Kjær
Measuring Object
To
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
50 25
dB dB
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10
20
Hz
50
100
200
500
1000
2000
5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

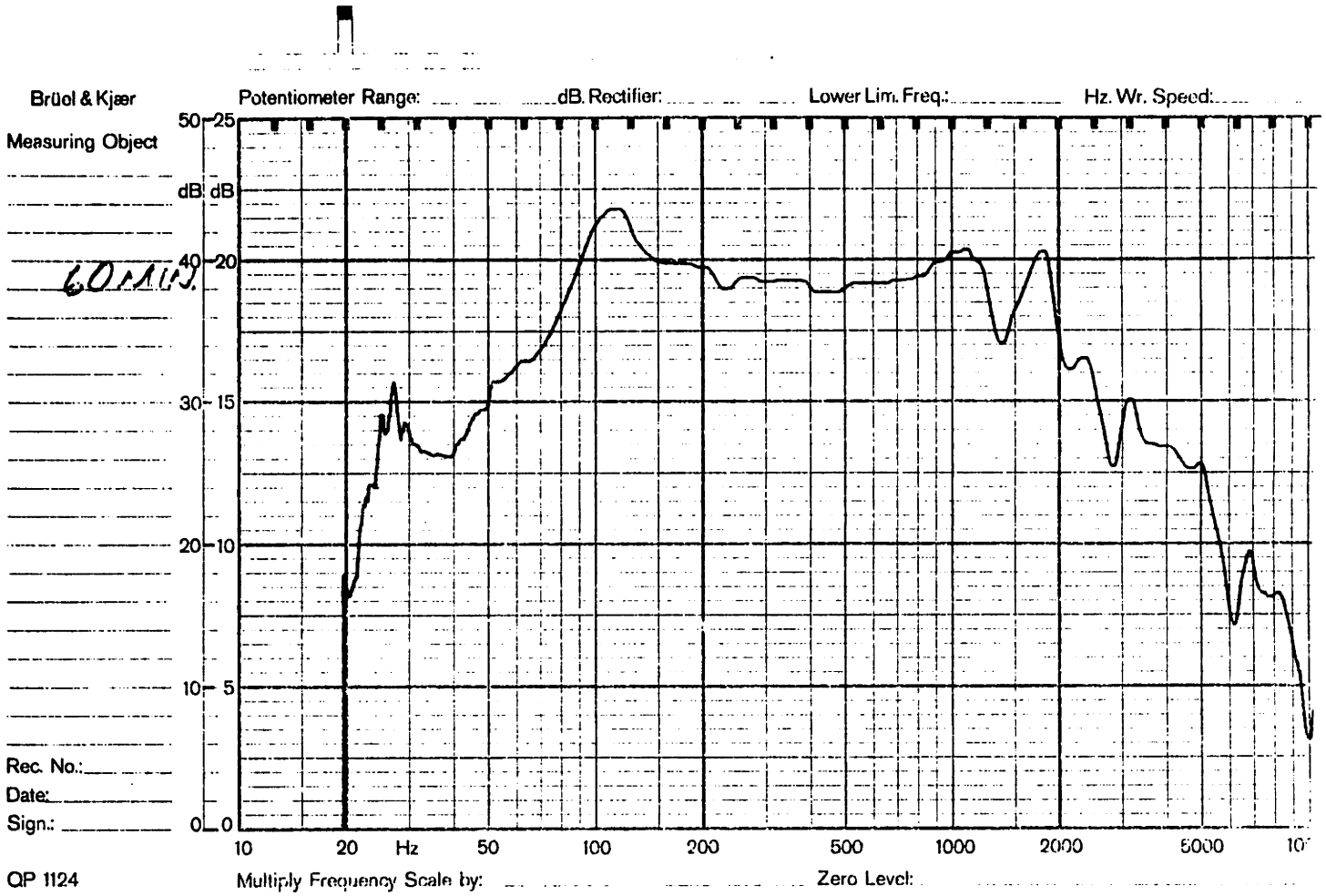

Brüel & Kjær
Measuring Object
2MIN
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
50 25
dB dB
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10
20
Hz
50
100
200
500
1000
2000
5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

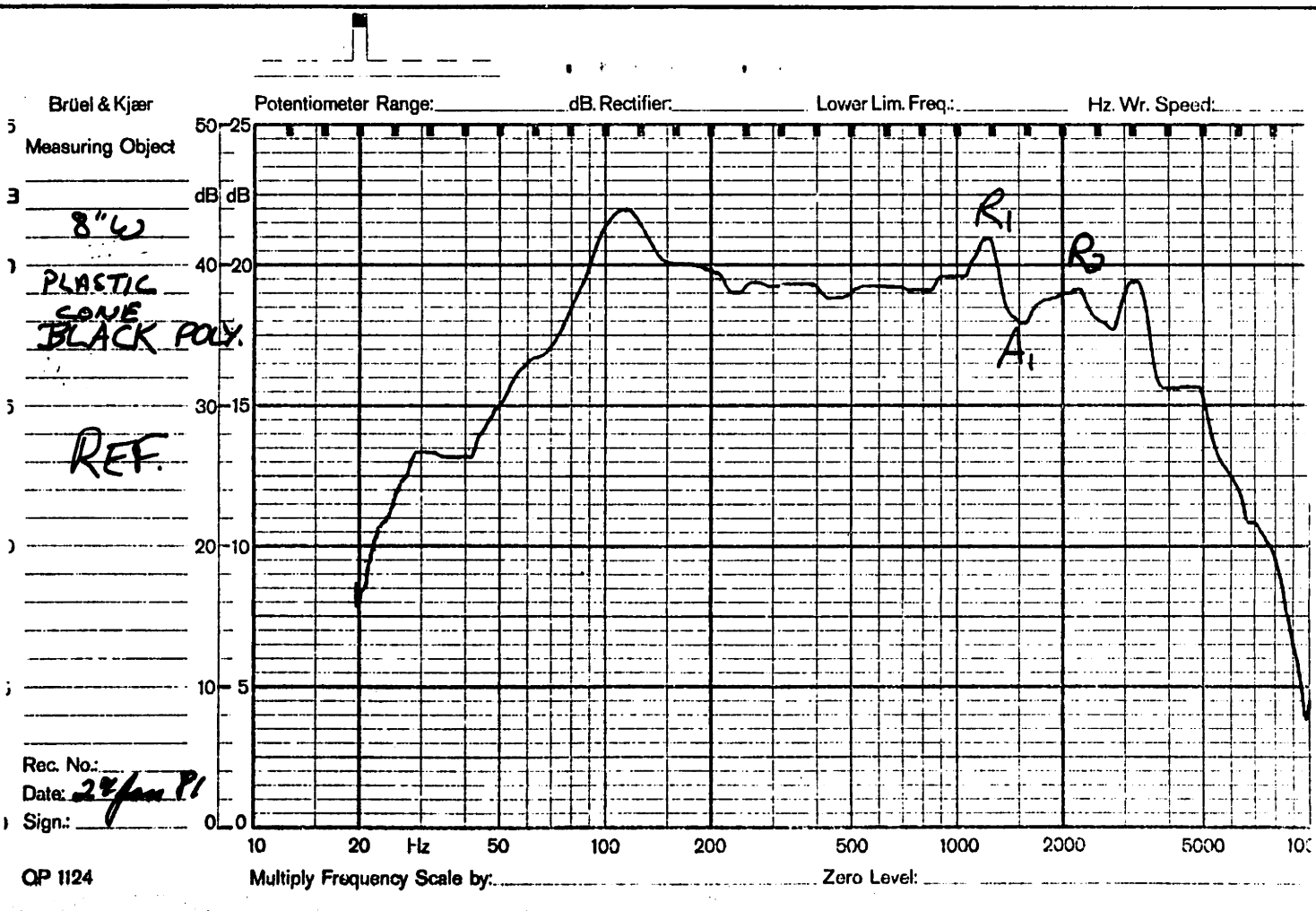

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
5 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
10 20 Hz 50 100 200 500 1000 2000 5000 10
Rec. No.:
Date:
Sign.:
QP 1124
Multiply Frequency Scale by:
Zero Level:

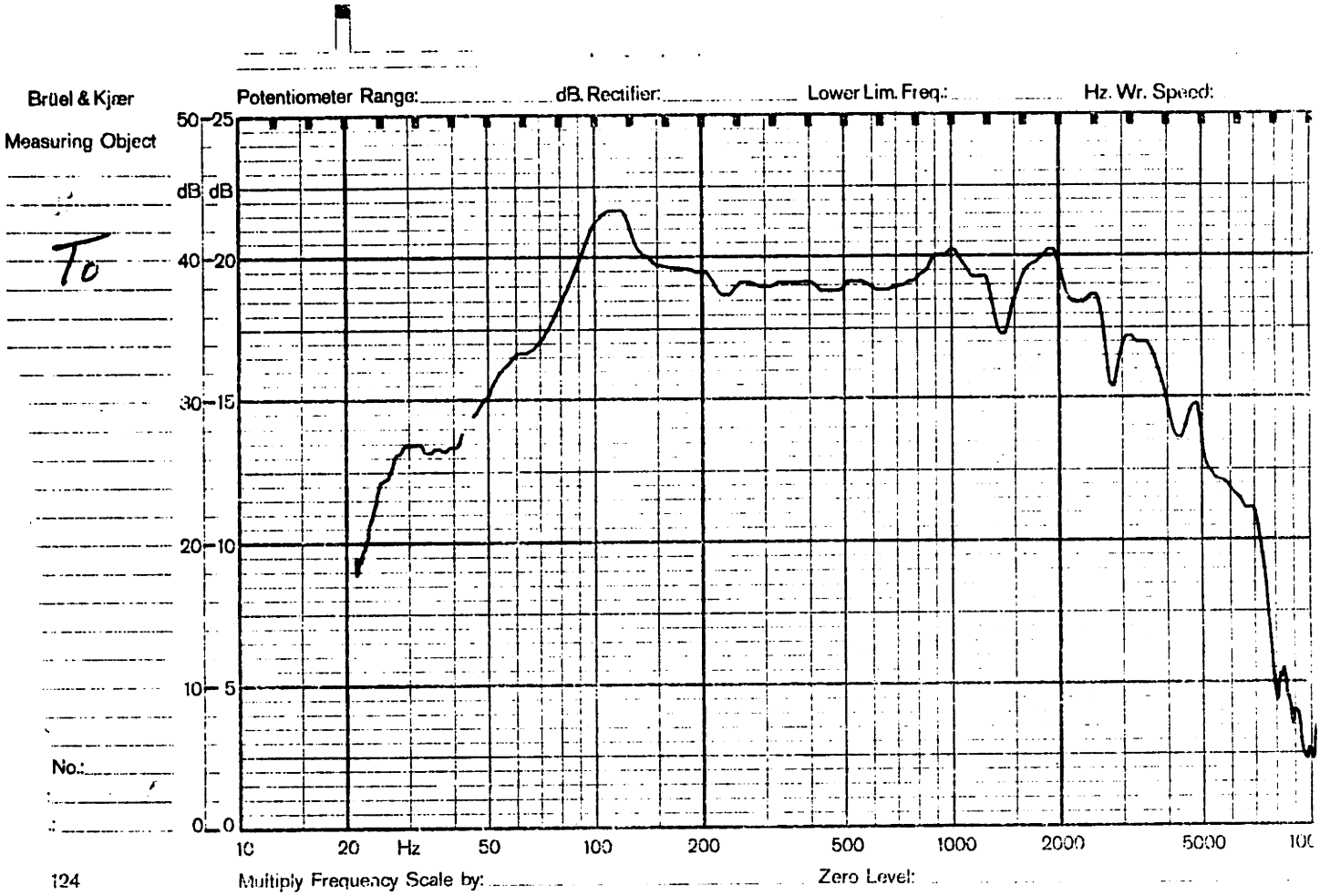

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
10 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
10 20 Hz 50 100 200 500 1000 2000 5000 10
Rec. No.:
Date:
Sign.:
QP 1124
Multiply Frequency Scale by:
Zero Level:

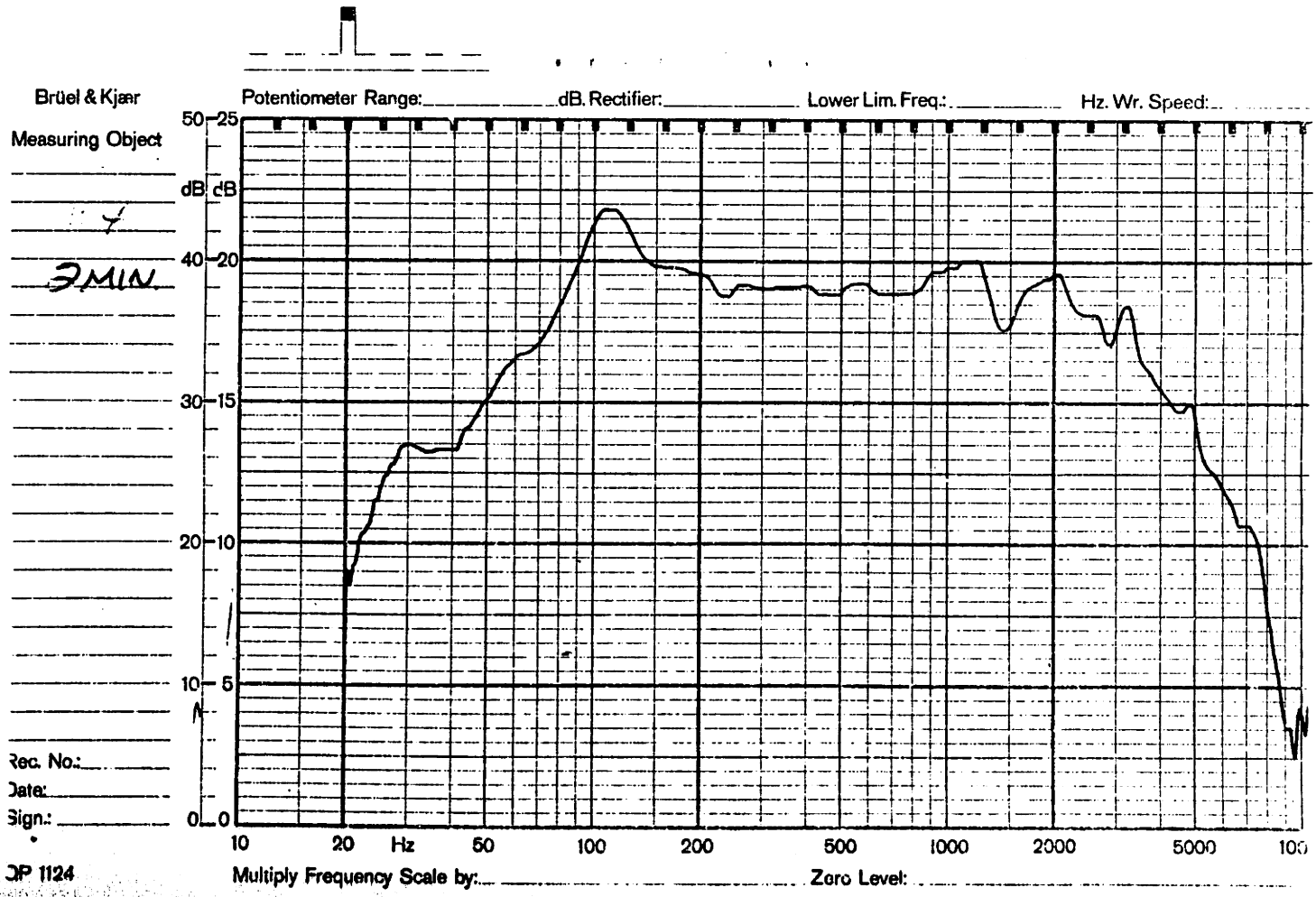

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
15 MIN.
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000 10
QP 1124
Multiply Frequency Scale by:
Zero Level:

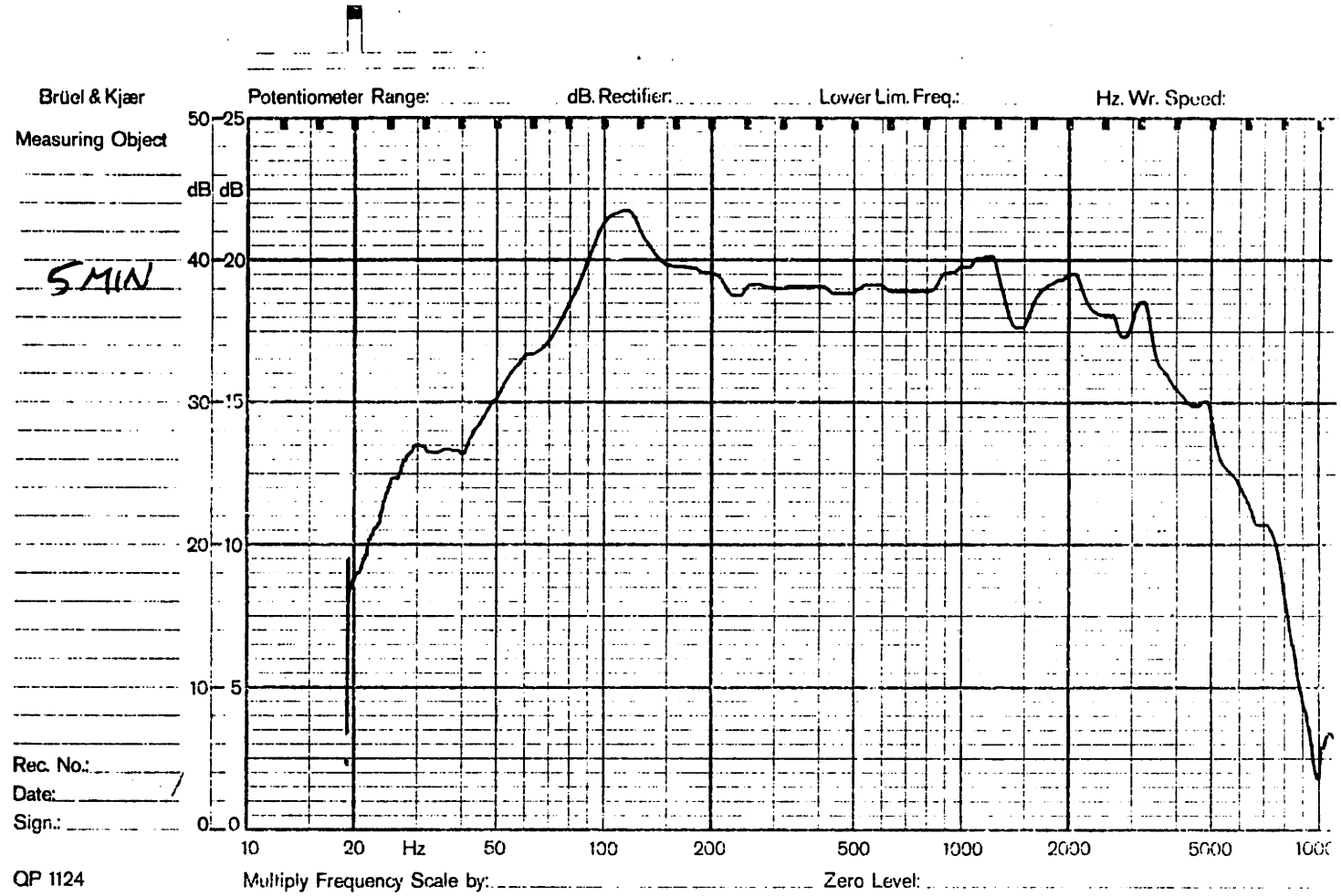

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
30 MIN.
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

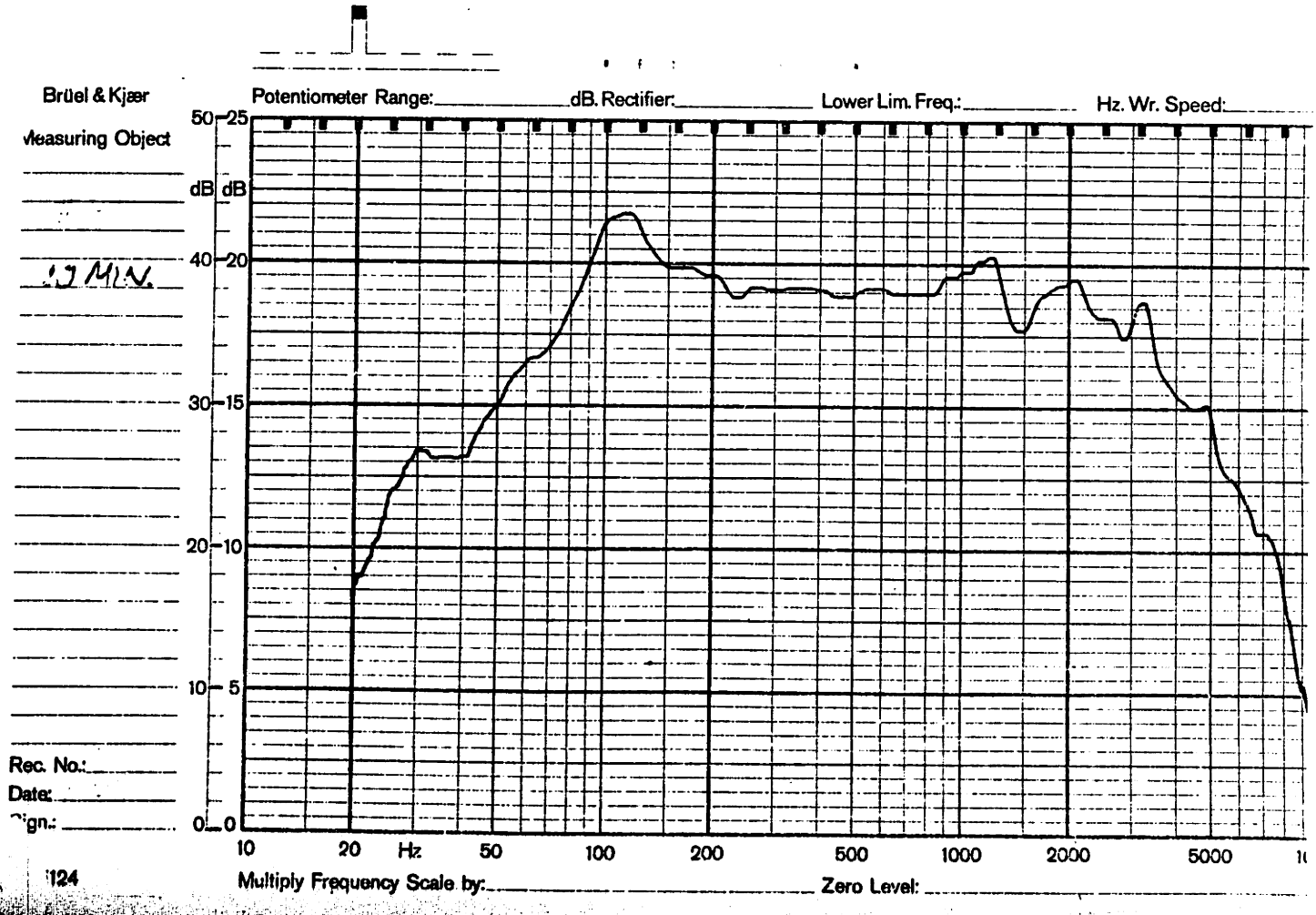

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
60 mm
dB
Rec. No.:
Date:
Sign.:
Hz
Multiply Frequency Scale by:
Zero Level:
QP 1124

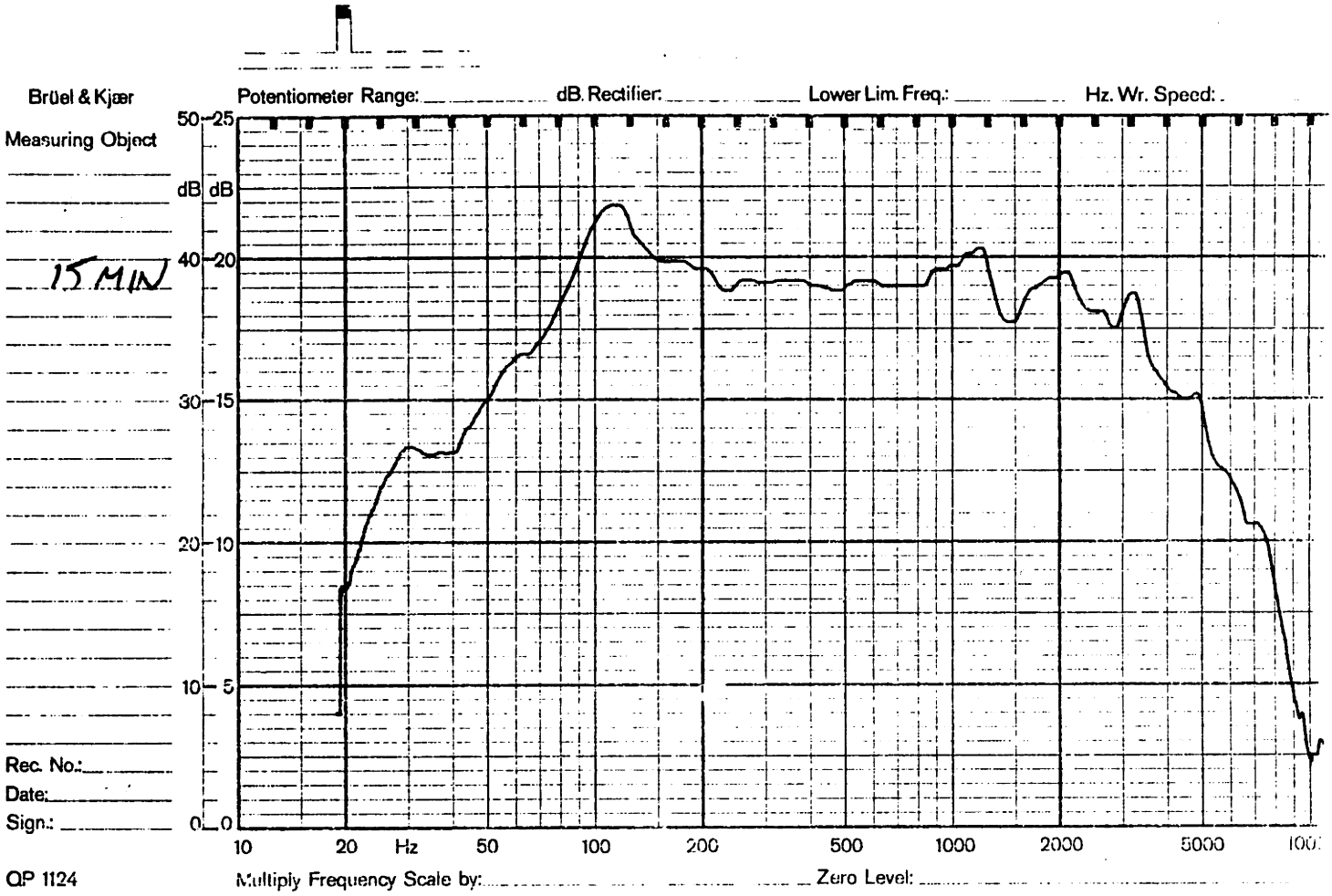

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
8" ω
PLASTIC CONE
BLACK POLY.
REF.
R1
R2
A1
dB
Rec. No.:
Date:
Sign.:
Hz
Multiply Frequency Scale by:
Zero Level:
QP 1124

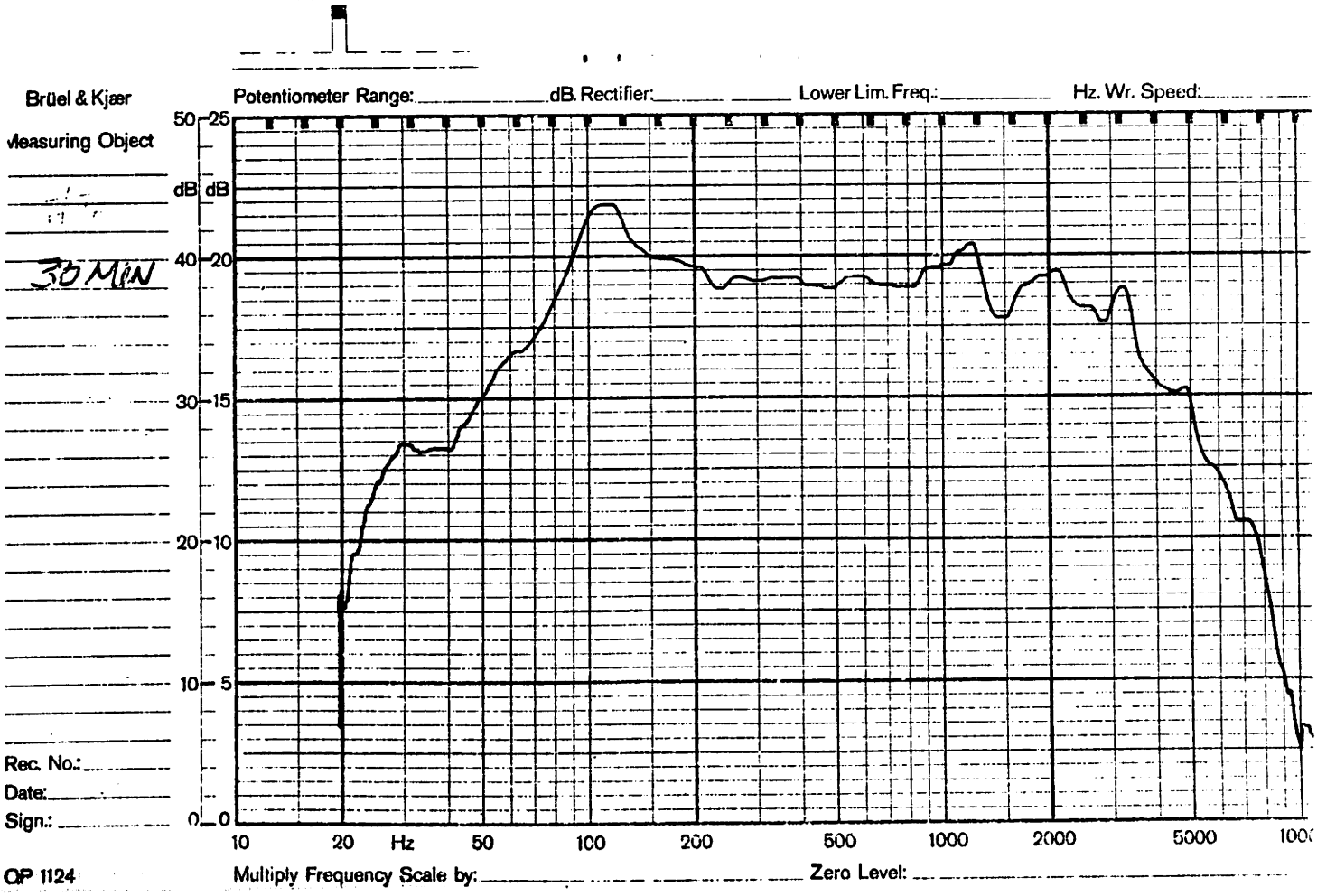

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
To
No.:
50 25
dB dB
40 20
30 15
20 10
10 5
0 0
10
20
Hz
50
100
200
500
1000
2000
5000
124
Multiply Frequency Scale by:
Zero Level:

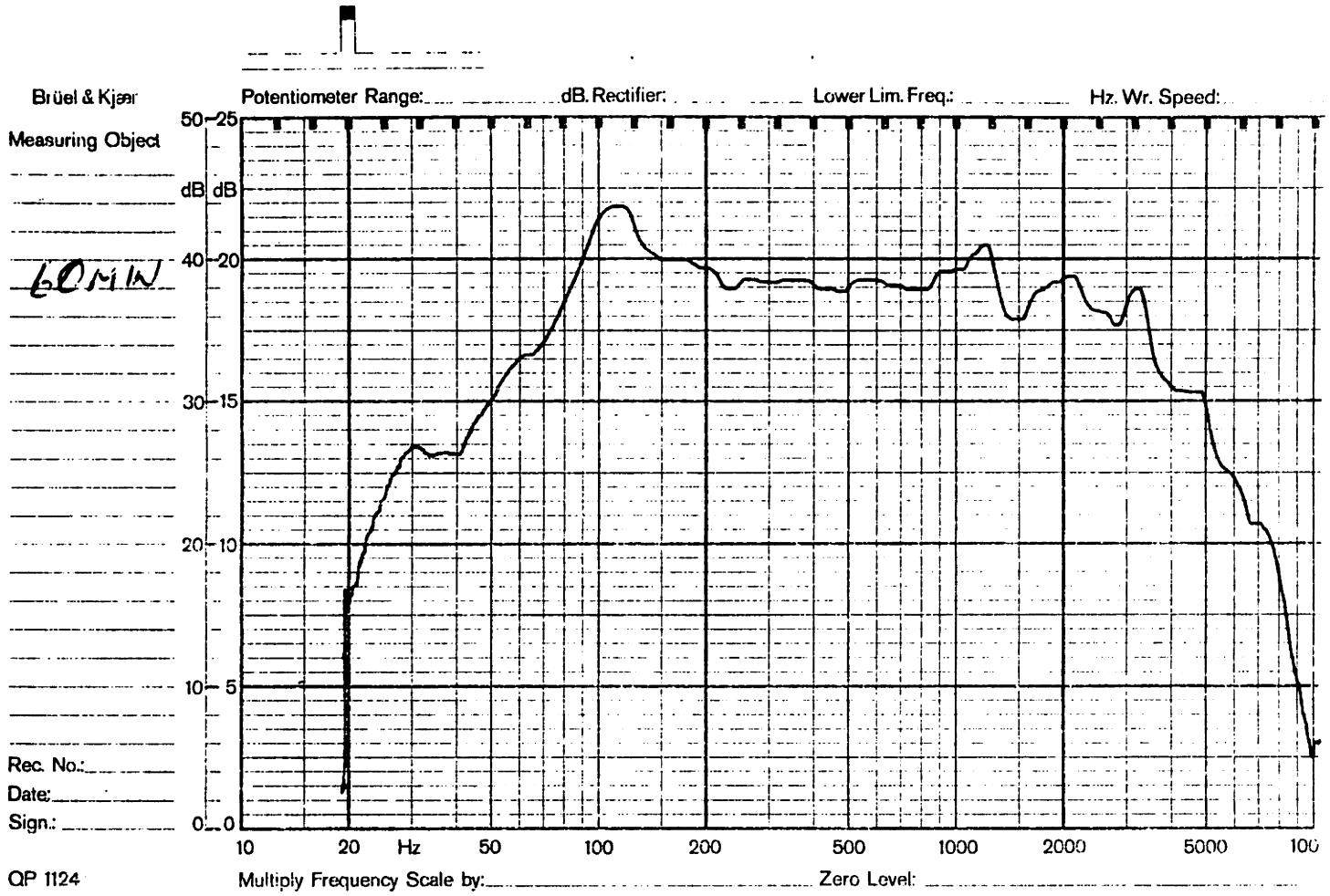

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
3MIN.
50 25
dB dB
40 20
30 15
20 10
10 5
0 0
10
20
Hz
50
100
200
500
1000
2000
5000
Rec. No.:
Date:
Sign.:
JP 1124
Multiply Frequency Scale by:
Zero Level:

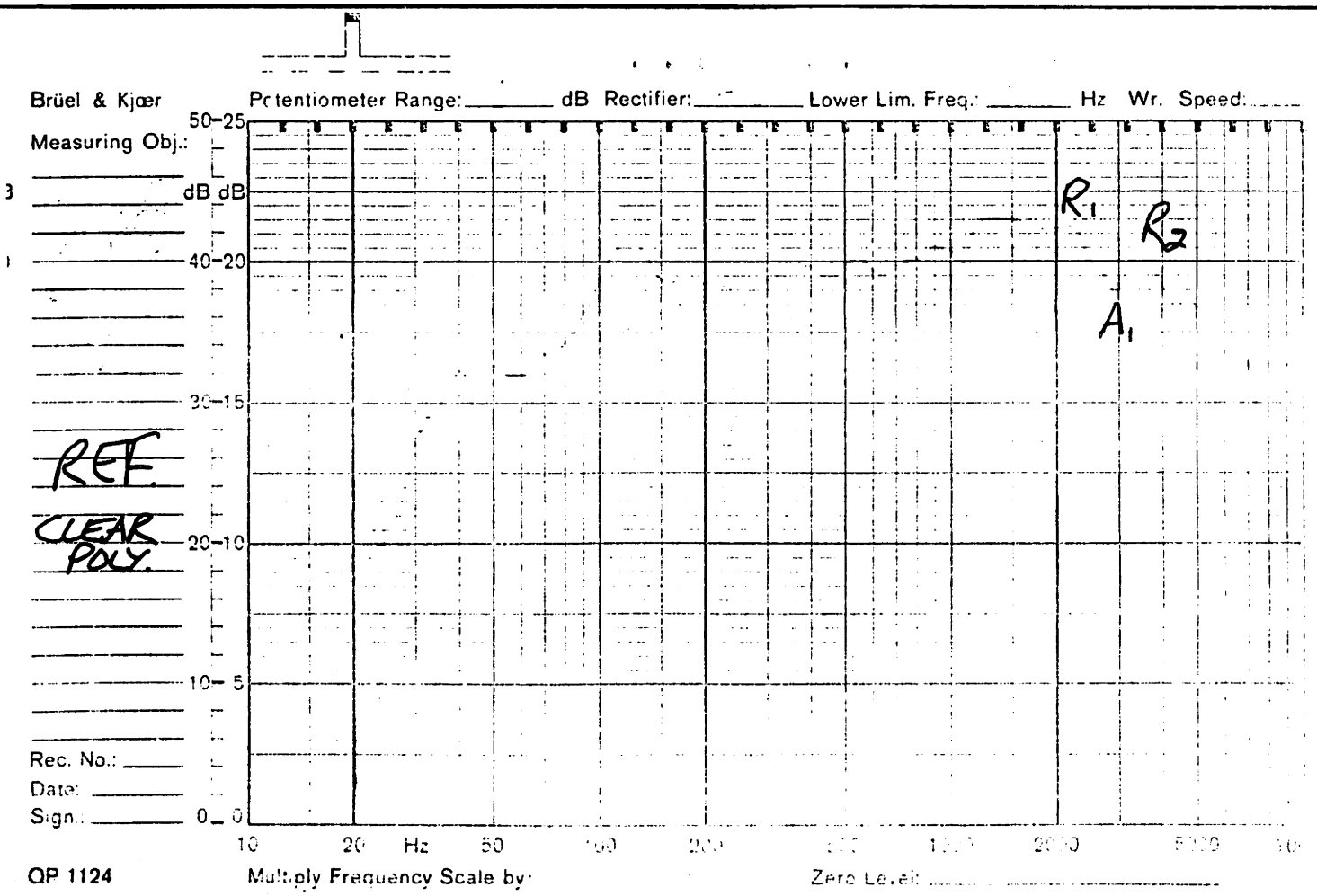

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
5 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

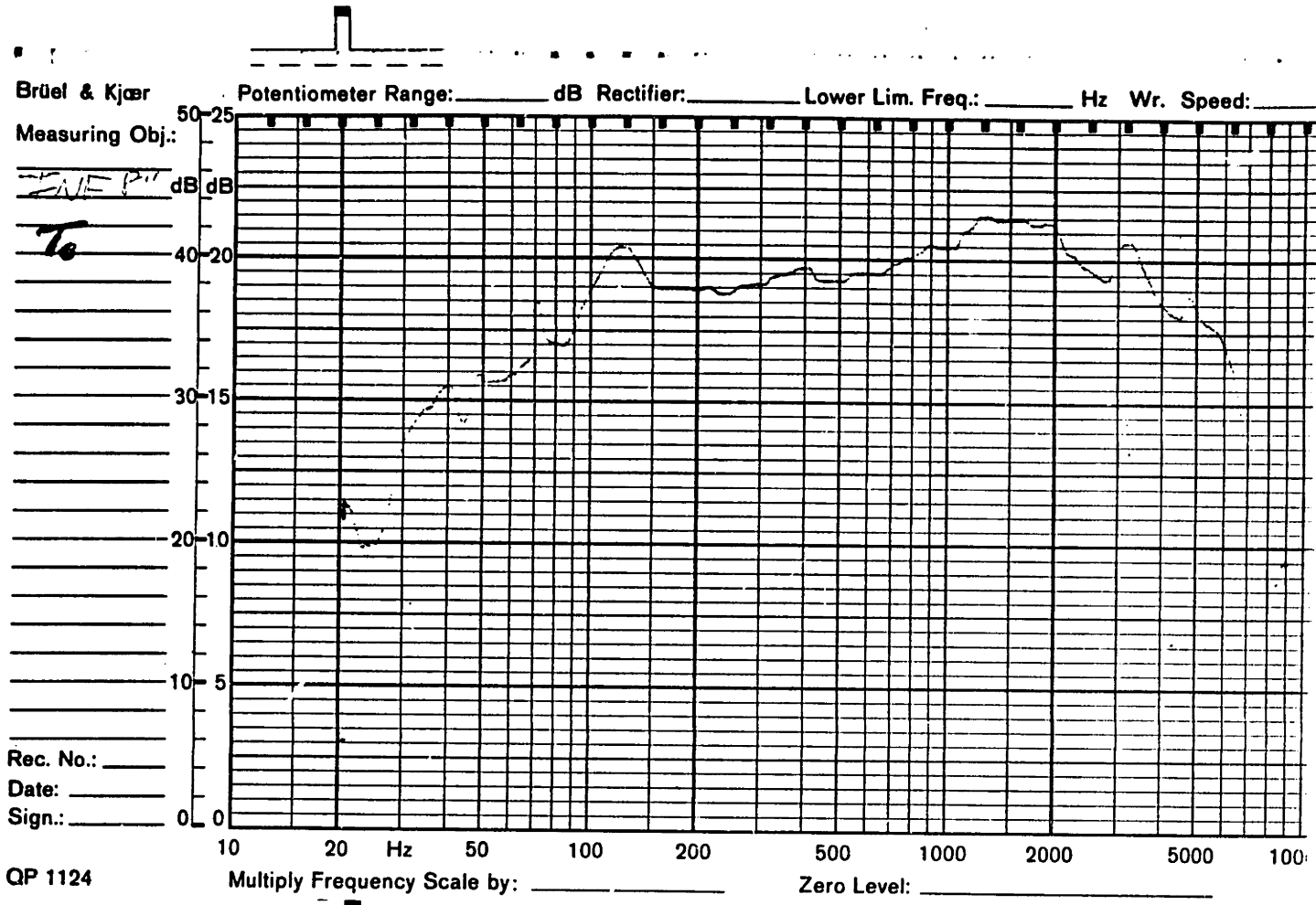

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
10 MIN.
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
Multiply Frequency Scale by:
Zero Level:

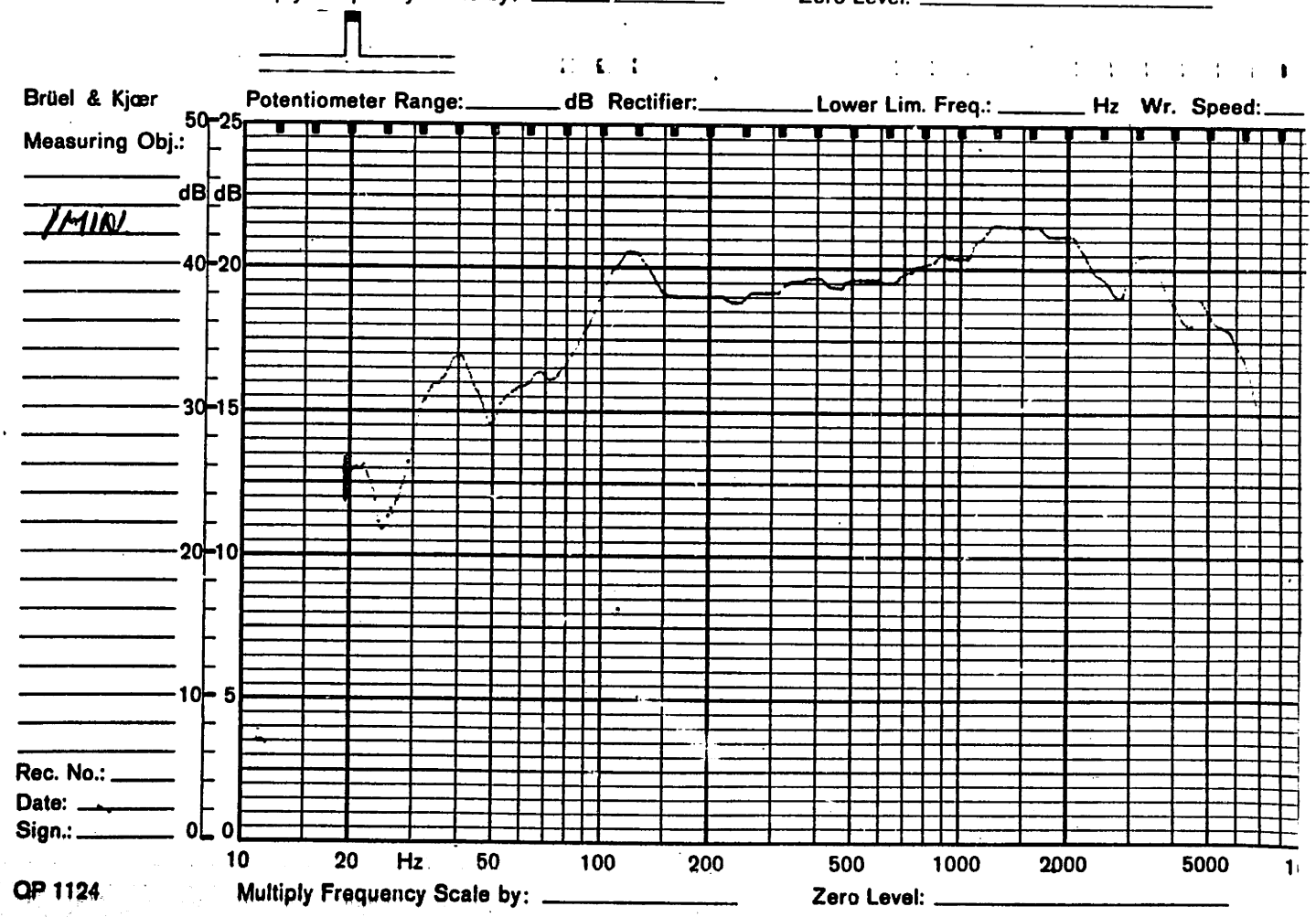

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
15 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

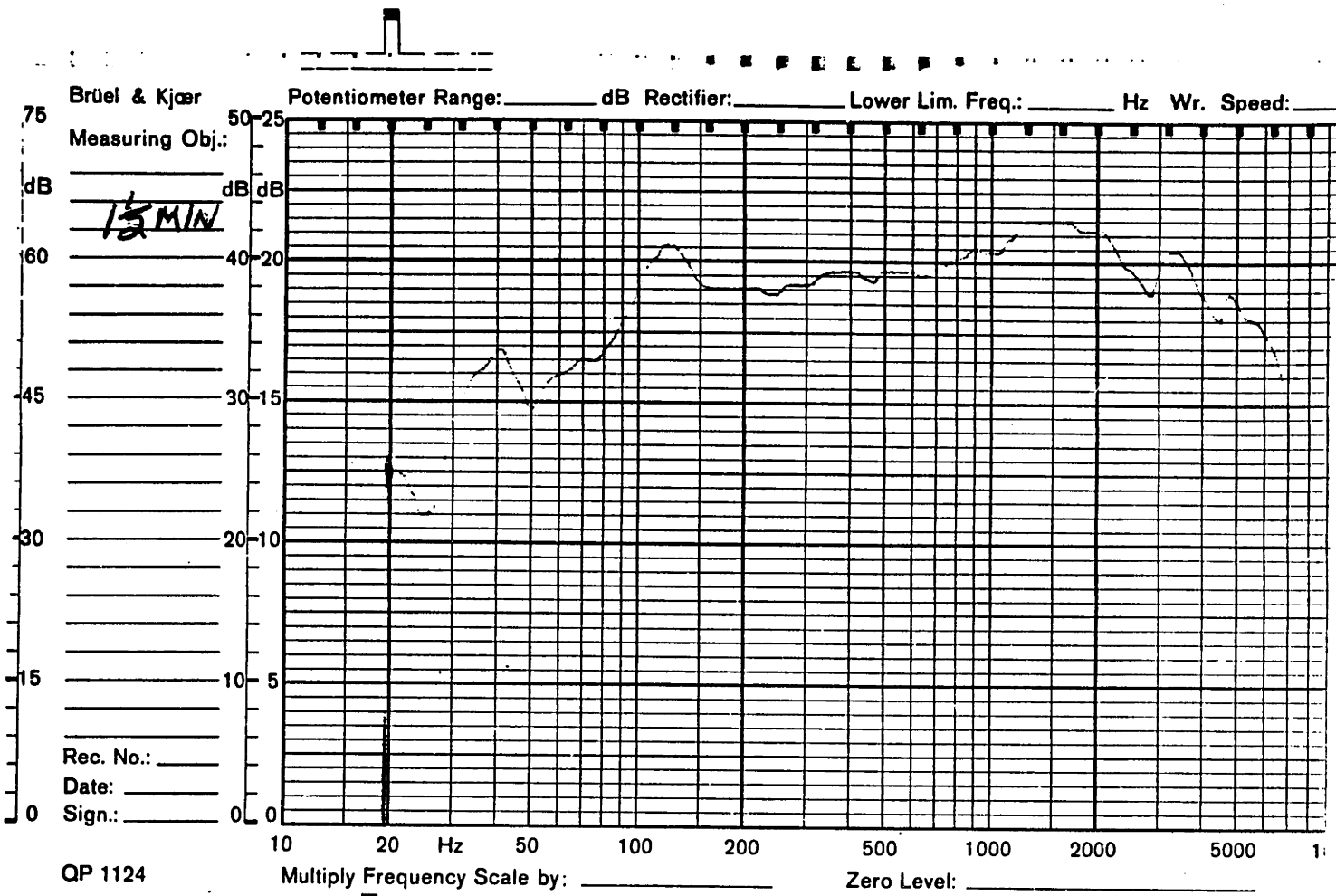

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
30 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

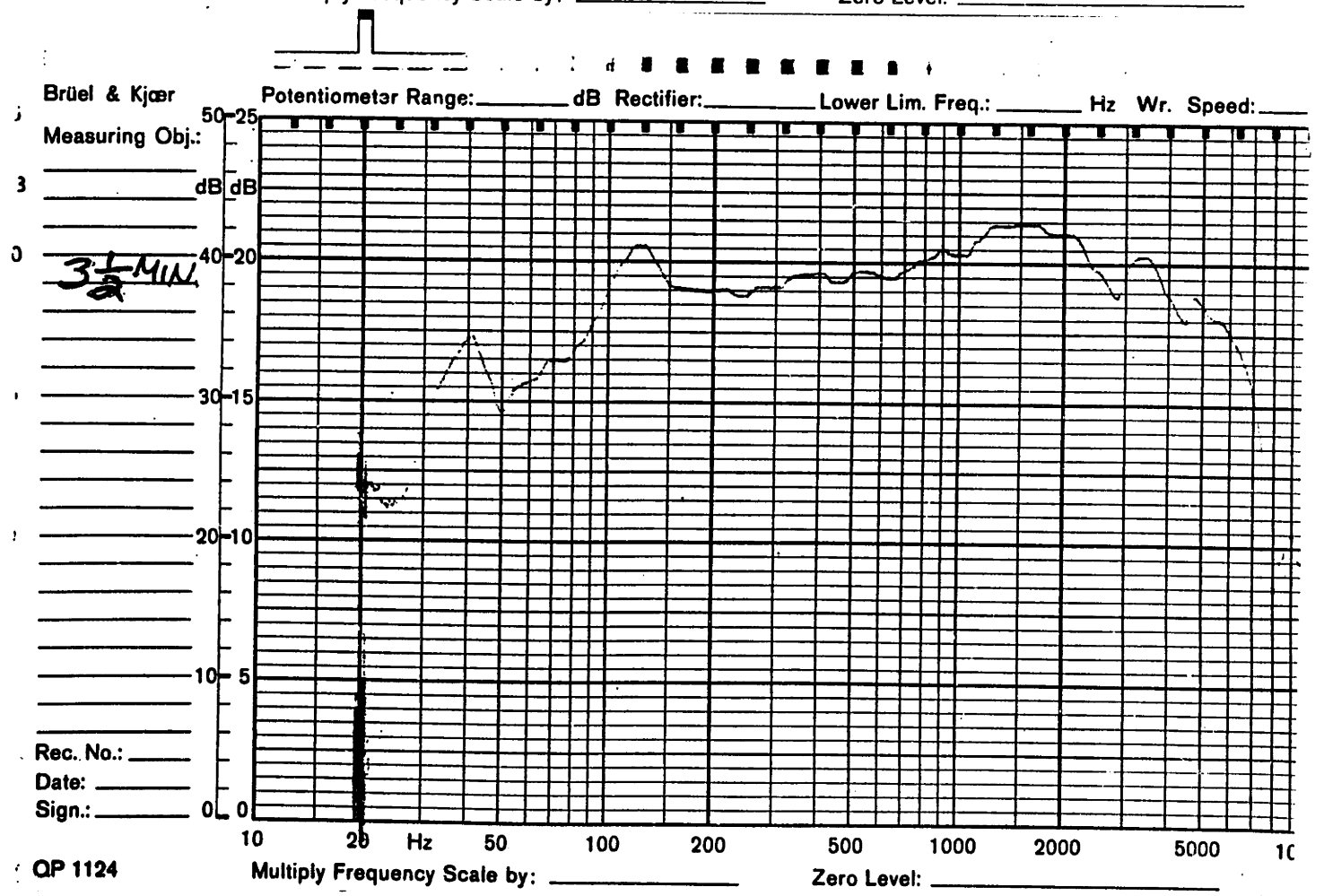

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
Measuring Object
60 MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000 100
QP 1124
Multiply Frequency Scale by:
Zero Level:

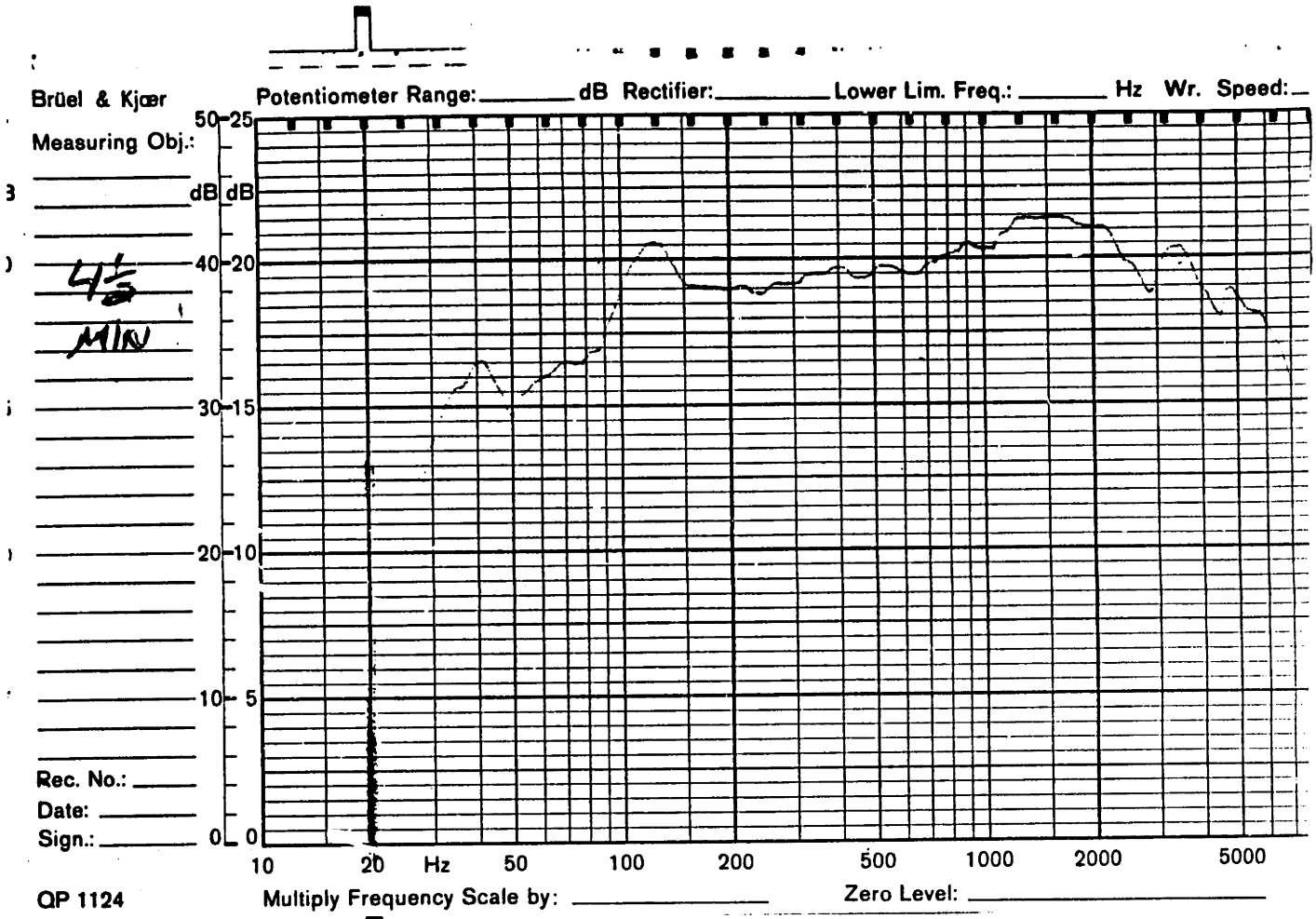

Brüel & Kjær
Potentiometer Range:
dB Rectifier:
Lower Lim. Freq.:
Hz Wr. Speed:
Measuring Obj.:
REF.
CLEAR POLY.
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
R1
R2
A1
Rec. No.:
Date:
Sign.:
10 20 Hz 50
QP 1124
Multiply Frequency Scale by:
Zero Level:

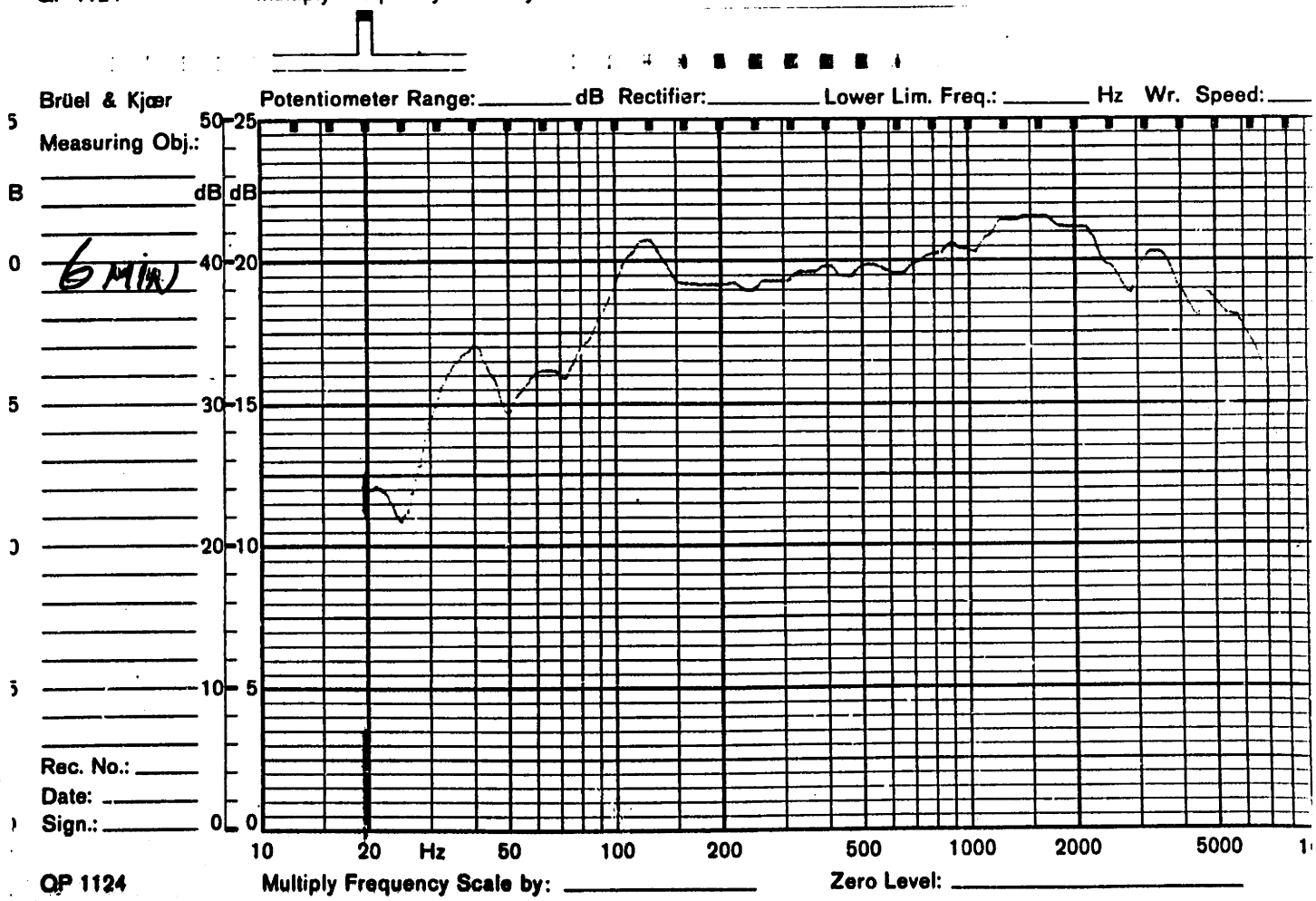

Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

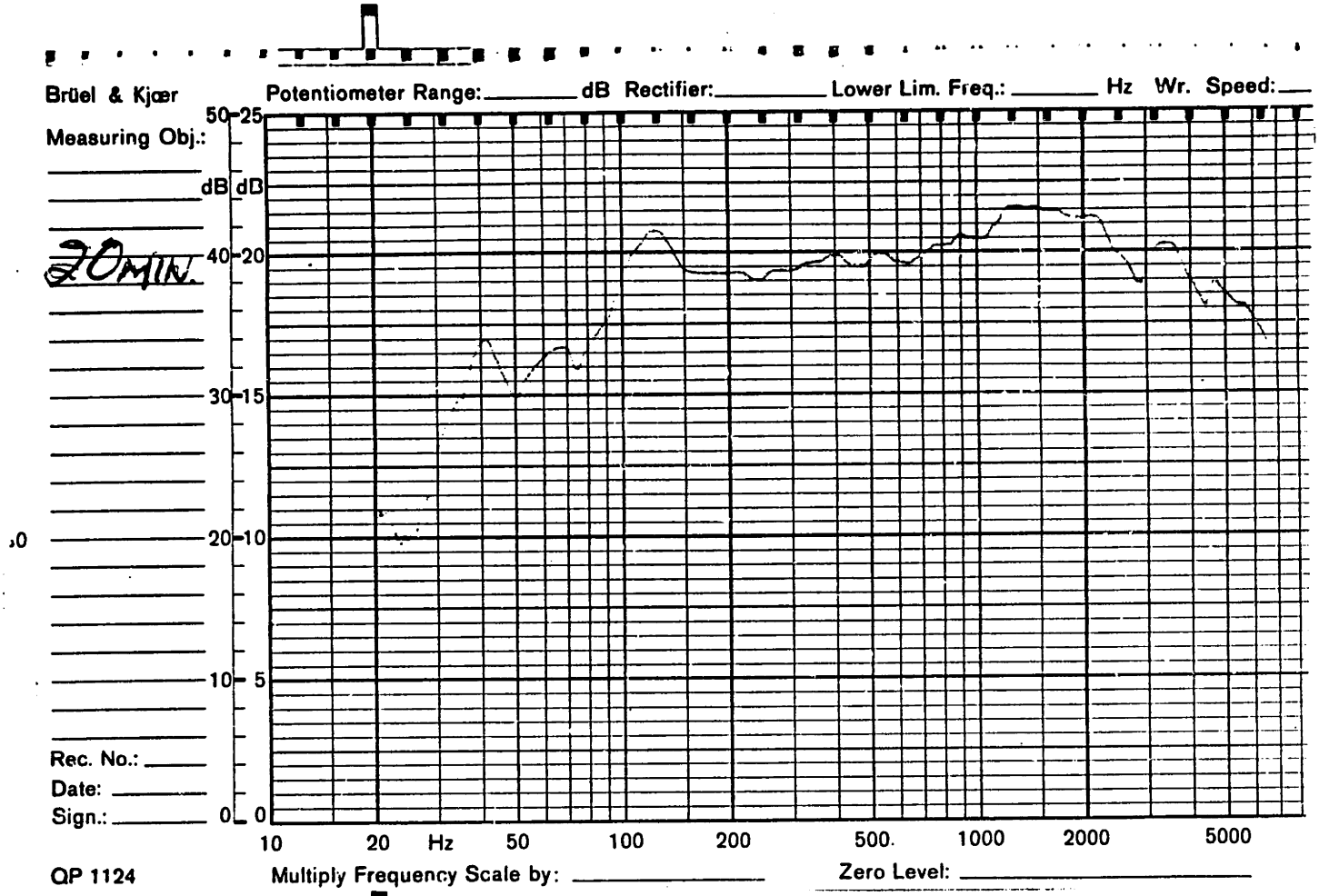

Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
1/MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

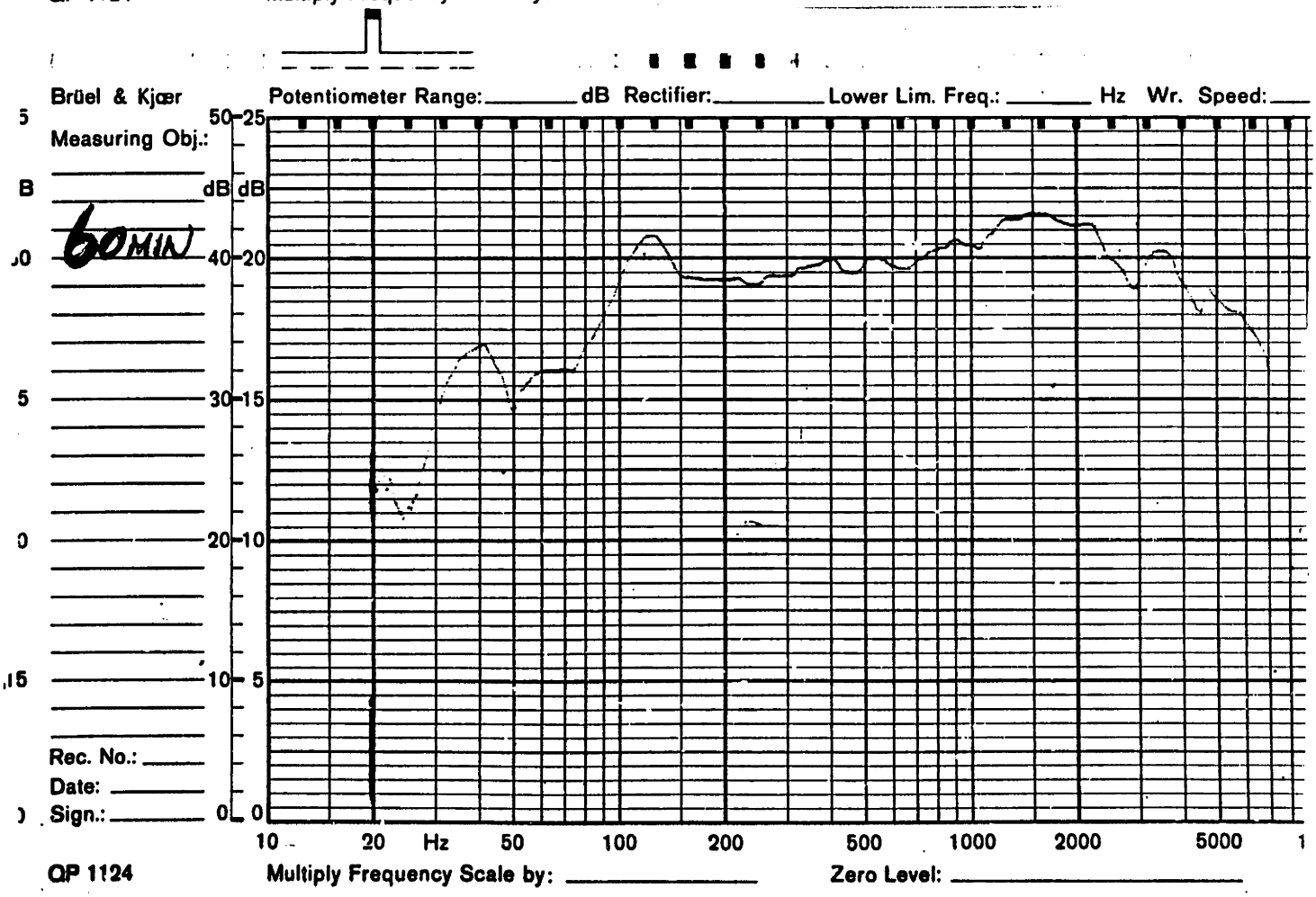

Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
1½ MIN
Rec. No.:
Date:
Sign.:
dB
Hz
10 20 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
3½ MIN
Rec. No.:
Date:
Sign.:
dB
Hz
10 20 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
4½ MIN
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
6 MIN
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
20MIN.
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:


Brüel & Kjær
Potentiometer Range: dB Rectifier: Lower Lim. Freq.: Hz Wr. Speed:
Measuring Obj.:
60MIN
dB dB
50 25
40 20
30 15
20 10
10 5
0 0
Rec. No.:
Date:
Sign.:
10 20 Hz 50 100 200 500 1000 2000 5000
QP 1124
Multiply Frequency Scale by:
Zero Level:

APPENDIX 2 - TABULATED DATA

TABLE 1 - STATIC MODULUS OF HUMIDIFIED PAPER

*All samples were cut to a cross-sectional area of $7 \times 10^{-6} m^2$.

Sample	Δ%(mass)	Y/X	X-Head(mm/min)	Chart(mm/sec)
1	0	.4/1.0	0.5	100
2	+35	.4/4.3	0.5	100
3	+12	.4/2.8	0.5	100
4	+83	.4/8.1	0.5	100
5	-1.0	.4/.85	0.5	100
6	-3.0	.4/.85	0.5	100

TABLE 2 - STATIC MODULUS OF HEATED POLYPROPYLENE

*All sampleu were cut to a cross-sectional area of $7 \times 10^{-6} m^2$.

Sample	Temp. (°C.)	Y/X	X-Head(mm/min)	Chart(mm/sec)
1	26	.4/1.00	0.5	100
2	36	.4/.90	0.5	100
3	60	.4/2.8	0.5	200

TABLE 3 - LOSS TANGENT FOR HUMIDIFIED PAPER

Sample	Δ%(mass)	f(Hz)	tan δ	A.F.	D.F.	tan δ Range
1	0	110	.074	30	52	50
2	0	35	.070	30	41	50
3	0	11	.040	30	70	50
4	0	3.5	.033	30	52	50
5	31	110	.138	30	85	50
6	30	35	.075	30	90	50
7	34	11	.090	30	97	50
8	29	3.5	.070	30	87	50
9	110	110	.190	30	130	50
10	111	35	.120	30	190	50
11	114	11	.108	30	157	50
12	124	3.5	.095	30	195	50

TABLE 4 - LOSS TANGENT FOR HEATED PAPER AND POLYPROPYLENE

Sample	Temp (°C.)	tan δ	f(Hz)	A.F.	D.F.	tan δ Range
Paper 1	40	.038	110	30	71	60
2	50	.042	110	30	50	60
3	60	.044	110	30	50	60
4	80	.042	110	30	50	60

APPENDIX 2 - (Cont'd)

Table 4 Continued

Sample	Temp (°C.)	tanδ	f(Hz)	A.F.	D.F.	tanδ Range
Poly. 1	40	.048	110	30	79	60
2	50	.042	110	30	80	60
3	60	.057	110	30	100	60
4	80	.059	110	30	140	60