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Properties of the STL-ionophone transducer

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III. MUSICAL ACOUSTICS

A. PROPERTIES OF THE STL-IONOPHONE TRANSDUCER

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Introduction

The STL-Ionophone was developed to fill the need of a sound source suitable for acoustical measurements on small resonators such as wood-wind instruments. In the sought for such a sound source three different gaseous discharges were tried in preliminary tests, viz. the electric arch, the glow discharge, and the corona discharge. In these tests the glow discharge proved advantageous; the arch was more unstable, and the corona discharge noisier. Therefore a sound source, the STL-Ionophone, was constructed with a glow discharge as the sound-emitting element. The STL-Ionophone has been briefly described earlier(1,2). It has been used to measure acoustical properties of wood-wind instruments(1,2,3,4,5) and organ pipes(6,7), and to determine sound velocity in gas mixtures(8). During these measurements the STL-Ionophone proved to be an excellent sound source in many respects. It also turned out to be able to register sound and motions in air. These facts motivated a continued and detailed study of the STL-Ionophone.

In this paper the findings of the continued study are reported and material is presented to give a more complete mapping and understanding of the physical properties of the transducing element, the glow discharge.

General description of the STL-Ionophone

The acoustically active part of the STL-Ionophone is a glow discharge in atmospheric air. The discharge is obtained by applying a high DC-voltage across two electrodes. If an AC-current of audio frequency is superimposed the DC-current through the discharge, the STL-Ionophone radiates sound. If the STL-Ionophone is placed in a sound field an AC-voltage appears superimposed on the DC-voltage across the electrodes. Furthermore changes of various parameters in the air can be recorded as changes in the DC-voltage across the electrodes. Thus the STL-Ionophone is a reversible transducer.

Main DC-conditions

In order to obtain a glow discharge two main conditions must be satisfied. First the voltage applied must exceed a certain potential, the breakdown potential. Sceondly the external circuit must be designed with respect to the chosen air gap and applied voltage.

In order to obtain a glow discharge, which is acoustically useful some further conditions must be fulfilled. The stability of the discharge must be satisfactory and the noise signal induced in the circuit sufficiently low. It is furthermore advantageous with low heat dissipation from the discharge and moderate voltages in the circuits.

The main parameters determining the behavior of the gaseous discharge are:

(1) the gas (atmospheric air),
(2) the electrodes (material and form),
(3) the geometry of the discharge (length and shape),
(4) the electrical current, and
(5) the supply circuit.

The gas, atmospheric air, represents a rather undefined parameter, which cannot be chosen by will. It can, however, be estimated, how normally occurring changes in density, moisture etc. will influence the working conditions and function of the discharge. The next four parameters, however, can be varied and should be chosen to optimize the properties of the STL-Ionophone and if possible to minimize the influence of variations in the first parameter.

(a) Initial condition(9)

The discharge is initiated by a spark breakdown. It is well known that the breakdown voltage varies from time to time. Normally, however, the following applies. Air is a gas, which has high breakdown strength. Paschen's law states that the breakdown voltage of a gas is a function of the product gas-pressure and gap length. For large values, as in the STL-Ionophone case, the breakdown potential increases with this product. Measurements of the breakdown potential V_{js} as a function of gap length d (Fig. III-A-1) show the same trend as for plane parallel electrodes (Cobine, Fig. 7.8) but at considerably lower voltage. It is furthermore known, that the breakdown potential increases with the humidity and the amount of electronegative gases (O_2 for instance).

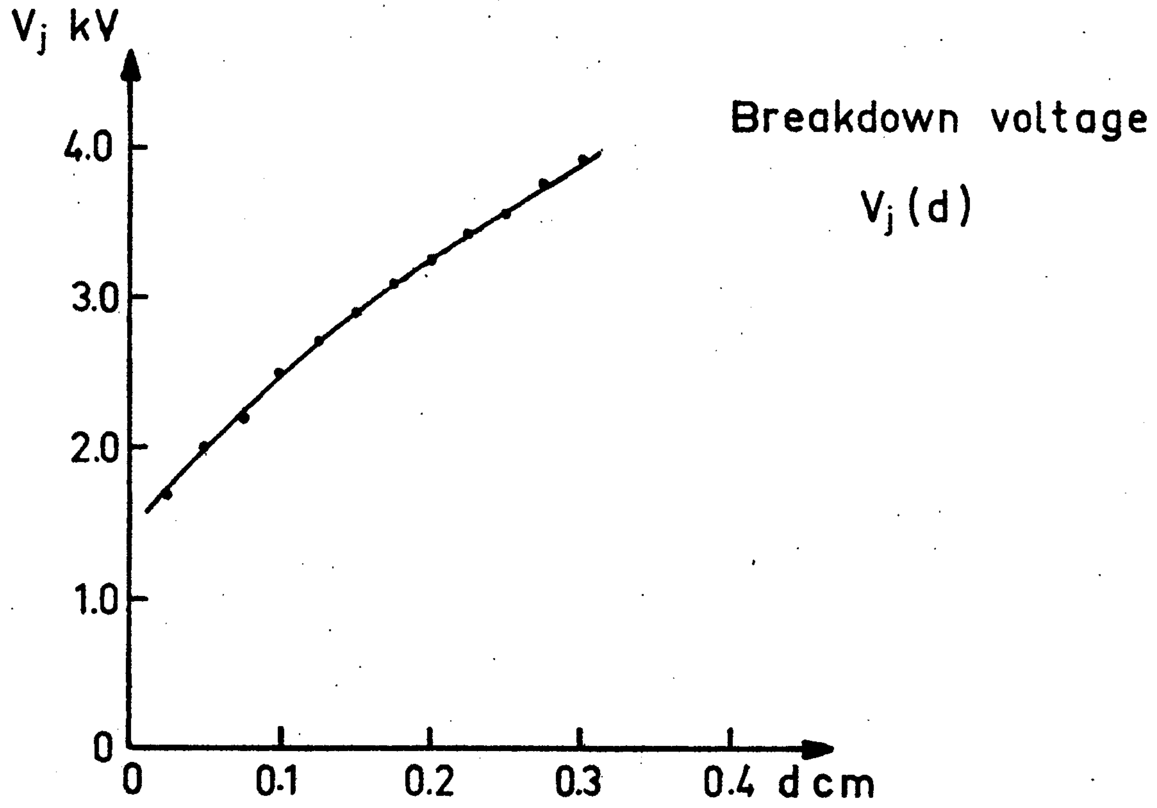

Fig. III-A-1. Breakdown voltage V_j as function of distance d.

The shape of the electrodes is important. Earlier studies show that the lowest breakdown voltage is obtained by a plane cathode and an anode with a sharp tip(10). This also agrees with our measurements. Impurities, especially on the cathode (affects the secondary emission) and sharp points in the fine structure may change the breakdown voltage considerably. Prolonged sparking, "conditioning", of the electrodes will remove these points and give a higher and more constant breakdown potential.

(b) Stationary conditions(11)

The voltage over a glow discharge at high pressure increases with decreasing current, i.e. the volt-ampere characteristic has a negative slope (Cobine, Fig. 8.19). Such a discharge is stable only if the sum of resistance in the supply circuit and the differential resistance of the discharge is greater than zero.

Measured volt-ampere characteristics of the STL-Ionophone discharge are shown in Fig. III-A-2. Empirically it was found that

$$V_j = \frac{4 \cdot d}{I_j + 0.13 \cdot 10^{-3}} + 350 \qquad \text{Eq. (1)}$$

where V_j is the voltage in volts, I_j the current in amp., and d the electrode distance in cm.

The slope gives a primary condition for minimum resistance of the supply circuit in order to obtain a stable discharge. The minimum supply voltage $V_{o\ min}$ giving a stable discharge thus equals the sum of voltages over the supply-circuit resistance and the discharge. If this voltage is less than the breakdown potential, the supply voltage should be increased above the breakdown potential and the circuit resistance increased to give the chosen current.

How V_o and R_1 should be chosen can be estimated from Fig. III-A-3 and Fig. III-A-4. Fig. III-A-3 gives a minimum value for $R_1 = f(I_j, d)$ for a given current and gap length d. Minimum V_o can be estimated from Fig. III-A-4 ($V_{o\ min}$). If the breakdown voltage V_{js} is greater than $V_{o\ min}$ the resistance R_1 should be increased at least $(V_{js}-V_j)/I_j$. It should, however, be pointed out that the measures presented are mean values, which means that V_o, R_1 etc. must be slightly adjusted in a given application.

Physics of the glow discharge (DC-properties)

In the preceding paragraph the necessary main conditions have been discussed for obtaining a stable discharge. These conditions are, however, not sufficient. Moreover a low noise level is important for technical applications. Little work has previously been done on high pressure glow discharges in inhomogenous electrical fields and therefore fundamental experimental studies were required for an understanding of the physics of the discharge. The results were the following.

A glow discharge in air shows a blueish negative glow and a violet positive column. The discharge of the STL-Ionophone shows furthermore, when studied through a magnifier, a negative glow just in front of the cathode followed by a weak violet glow. Thereafter follows a dark region and finally the positive column. The light intensity of the positive column is maximum along the axis of the column and increases towards the anode. The light from the negative glow and the positive column seems to decrease, but the length of the positive column to increase, with a decrease in current.

The voltage distribution was measured for two different currents (Fig. III-A-5) with a langmuir sond. The diagrams show that the electrical field is strong close to the cathode. The pronounced curvatures of the curves close to the anode and the cathode, mark two space charge regions, a positive charge at the cathode and a negative at the anode. The weak electrical field between these regions shows that the charge density is here about zero. The cathode drop is about the one expected for Copper-Air. It must be noted, though, that the sond was disturbing the field, when placed close to the anode and thus gives misleading information at these points.

Fig. III-A-2 shows how the DC-voltage V_j across the glow discharge depends on gap length d and current I_j. The gross features are that the voltage decreases with increasing current but increases with an increase in gap length. The voltage is highly dependent on the gas; it has been found slightly lower for N_2 and considerably lower for He and Ar. This is in good agreement with earlier experiments(11). Different electrodes, shapes, and materials, Fe, Cu, and Fe covered by M_gO, have been tried but show no definite influence on the V_j - I_j characteristic.

The stability of the discharge is critical and has therefore been studied in detail. By means of microscope it has been verified that the positive column starts from the tip of the anode, which means that a sharp and well-

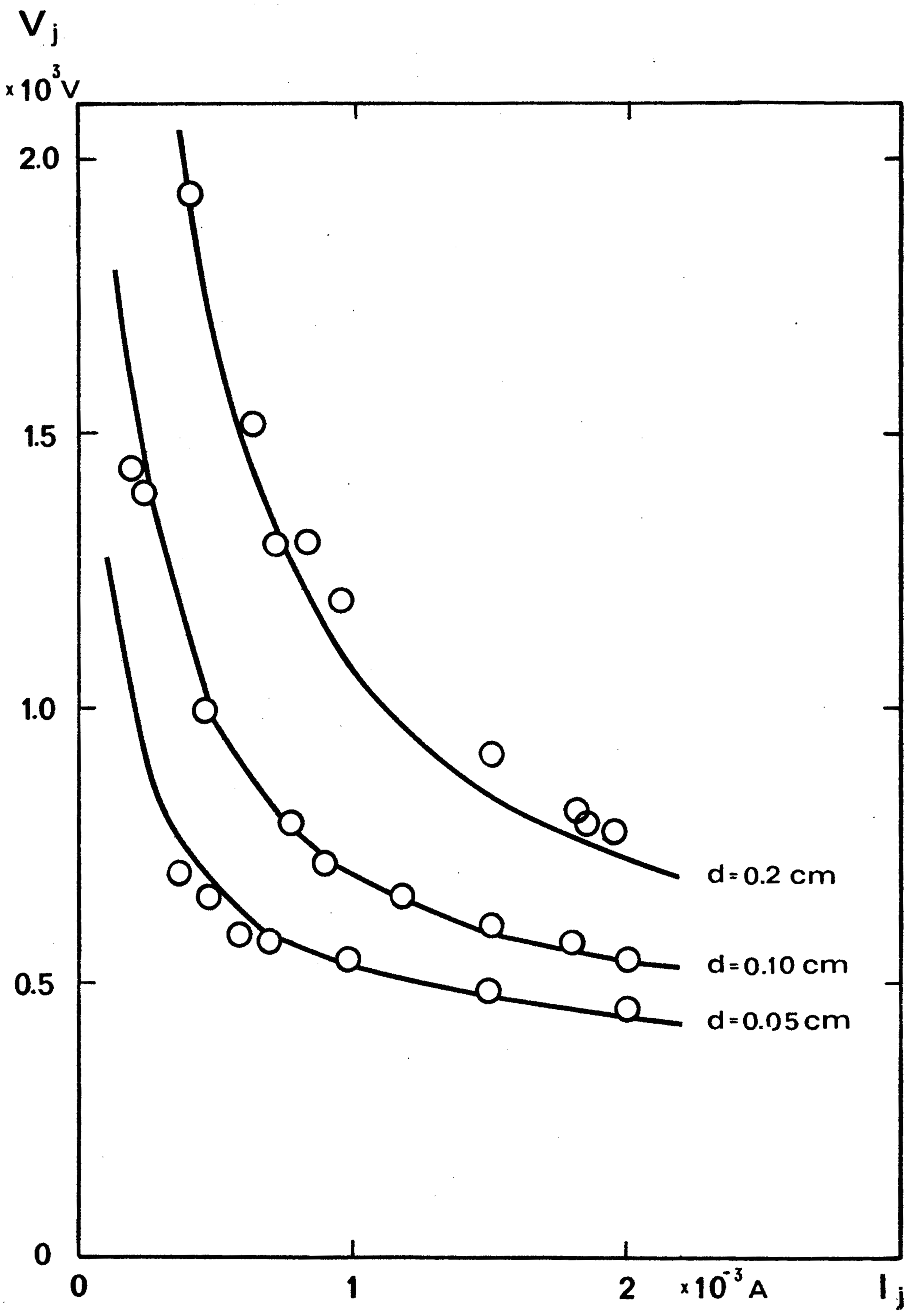

Fig. III-A-2. Discharge voltage V_j as function of current I_j and distance d. Circles mark measured values and the lines calculated from $V_j = (4d/(I_j + 0.13 \cdot 10^{-3})) + 350$ (C G S)

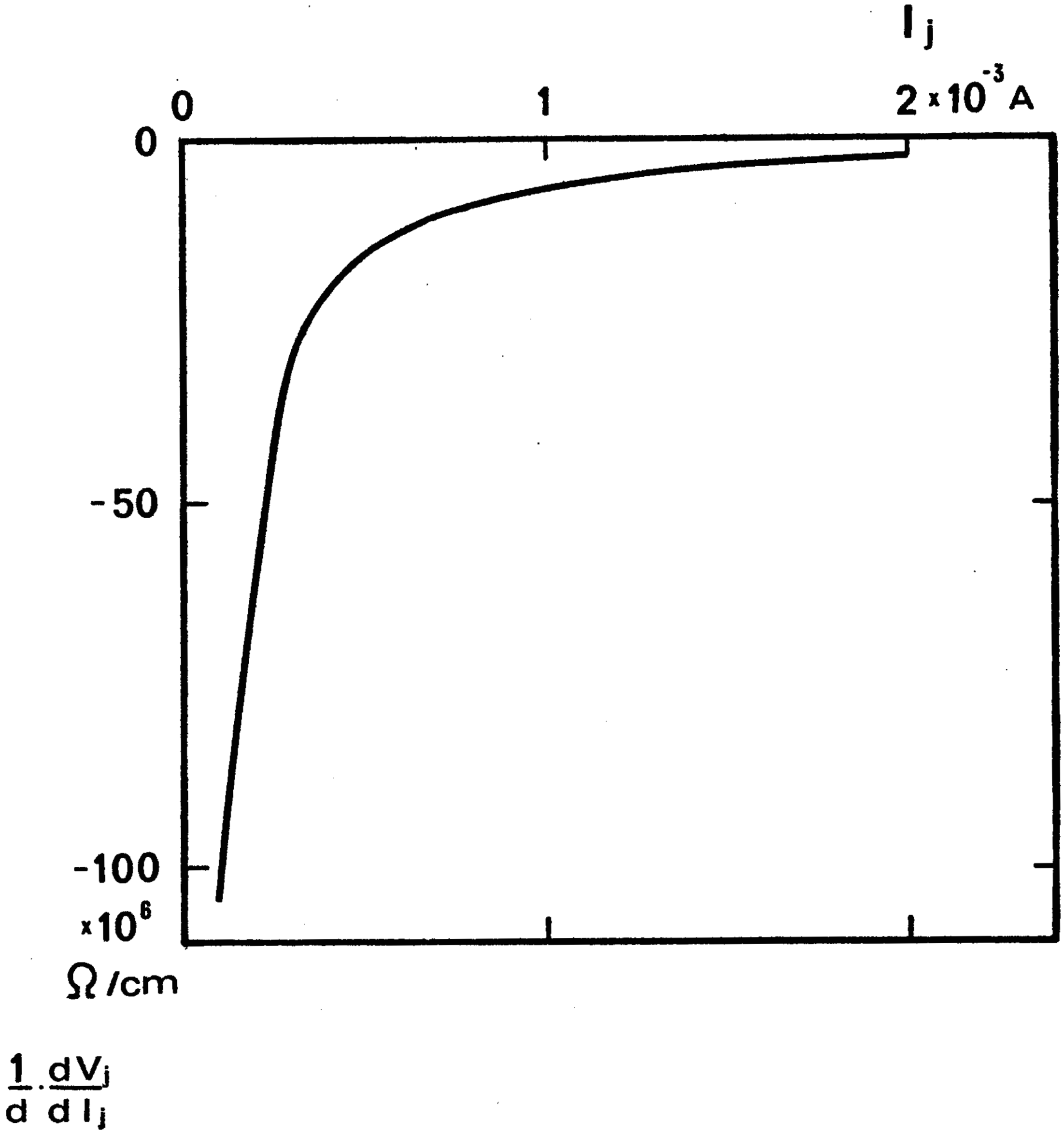

Fig. III-A-3. Graph for estimation of minimum resistance R_1 for a stable discharge.

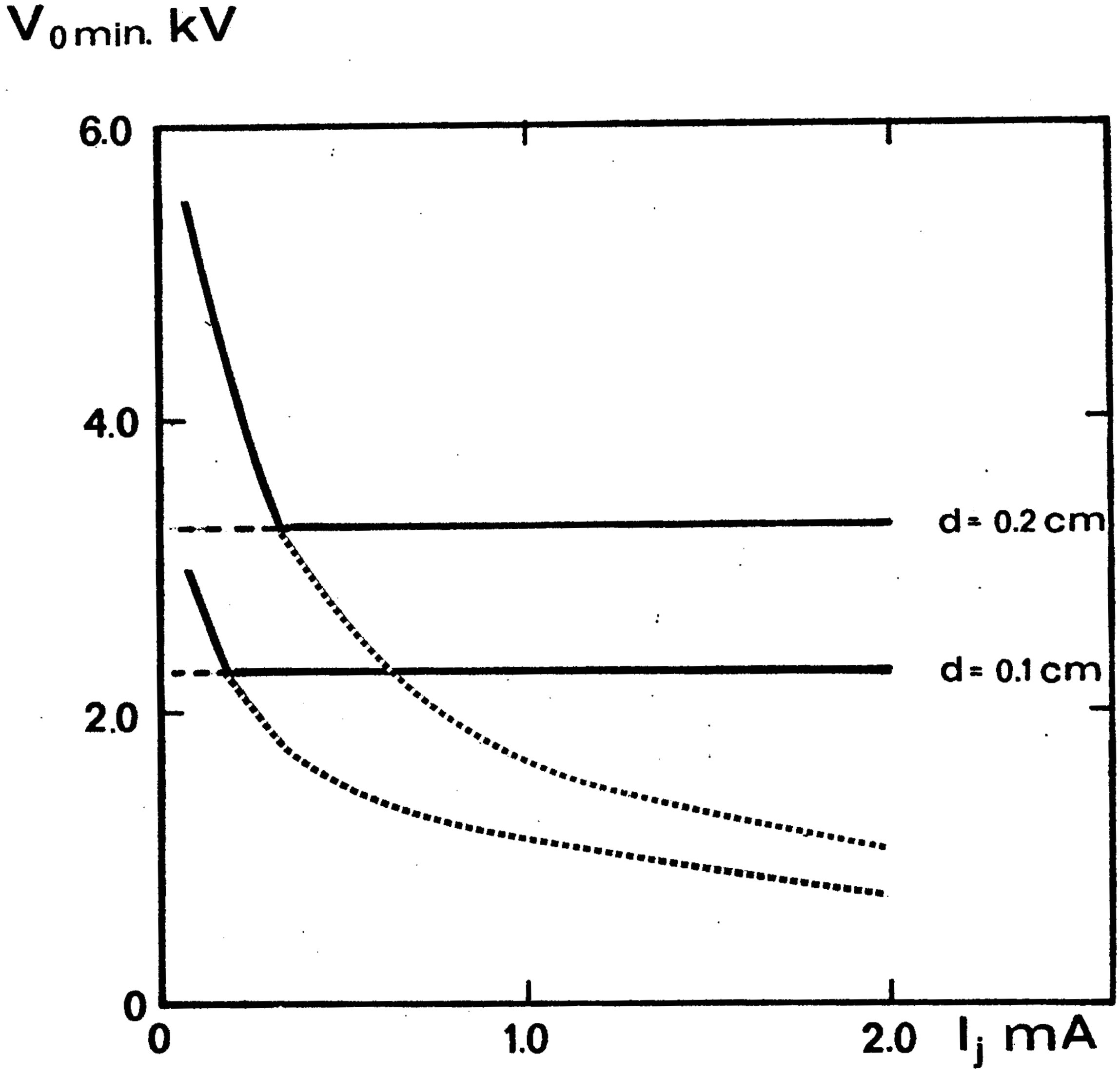

Fig. III-A-4. Minimum supply voltage V_o as function of current I_j and distance d. The curved lines derive from the stability criterium and the straight lines from the breakdown voltage criterium.

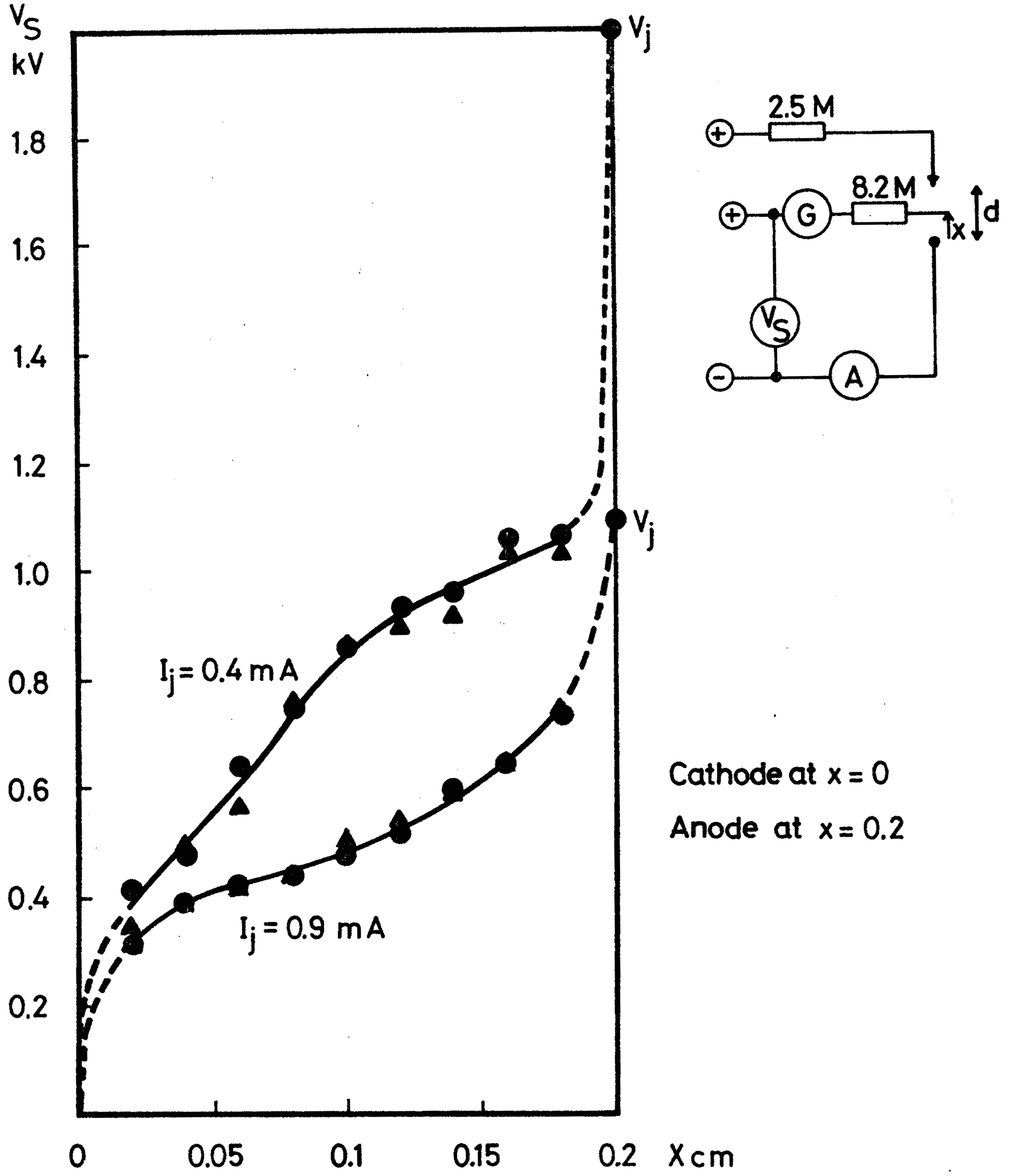

Fig. III-A-5. Voltage distribution V_s in the discharge. Triangles mark first series of measurements and circles the second.

defined anode is preferable. Besides this, tip angle and tip radius and material seem to be of little importance regarding the stability. The conditions are different at the negative side. The negative glow is not situated just outside the tip of a sharp cathode, but close to the tip at a small hollowness. A highly polished cathode makes the negative glow move around outside its surface, thus giving a not stable discharge.

The noise level is furthermore a very important factor. The noise signal having a total amplitude of 0.1-1.0 V rms for a stable discharge, is of the flicker type, i.e. strong components at low frequencies and decreasing for higher frequencies. It is hypothesized that this depends on the temperature in the discharge. Therefore the noise level was measured for different gases, Air, N_2, Ar, and He, thus obtaining different discharge temperatures. It was found that for the two first mentioned gases the noise level was about the same, but lower for Ar and He. This supports the hypothesis.

Once a stable discharge is obtained, the noise level seems to be little influenced by the electrodes. In certain cases a higher stability and lower noise level is obtained after a doping procedure with $HgNO_3$ of the cathode.

The heat dissipation of the discharge may in some applications be critical. It can be calculated from Fig. III-A-2 and the result is shown in Fig. III-A-6. It was found from Fig. III-A-6 that the heat dissipation increases with the square-root of current. A glow discharge produces various products, mainly small amounts of nitrous gases. It has been found that the production of these increases with the square of the current, Fig. III-A-7.

Physics of the glow discharge (AC-properties)(12)

Assuming that the glow discharge is a simple resistance, the AC-resistance would be given by the slope of the V_j - I_j characteristic. However, the magnitude of the AC-impedance was found to be smaller than the magnitude of the V_j - I_j slope. The reason for this was shown to be that the AC-impedance consists not only of a resistive but also of a reactive part. The resistive part is negative for low frequencies but increases with frequency and becomes positive for high frequencies (Fig. III-A-8). The reactive part is inductive, because of the mass of the charged particles, and decreases slightly for increasing frequencies, i.e. is not a simple inductance. It has not been possible to measure the influence of the acoustical radiation on the electrical properties, only a little part of the inserted energy is radiated as sound.

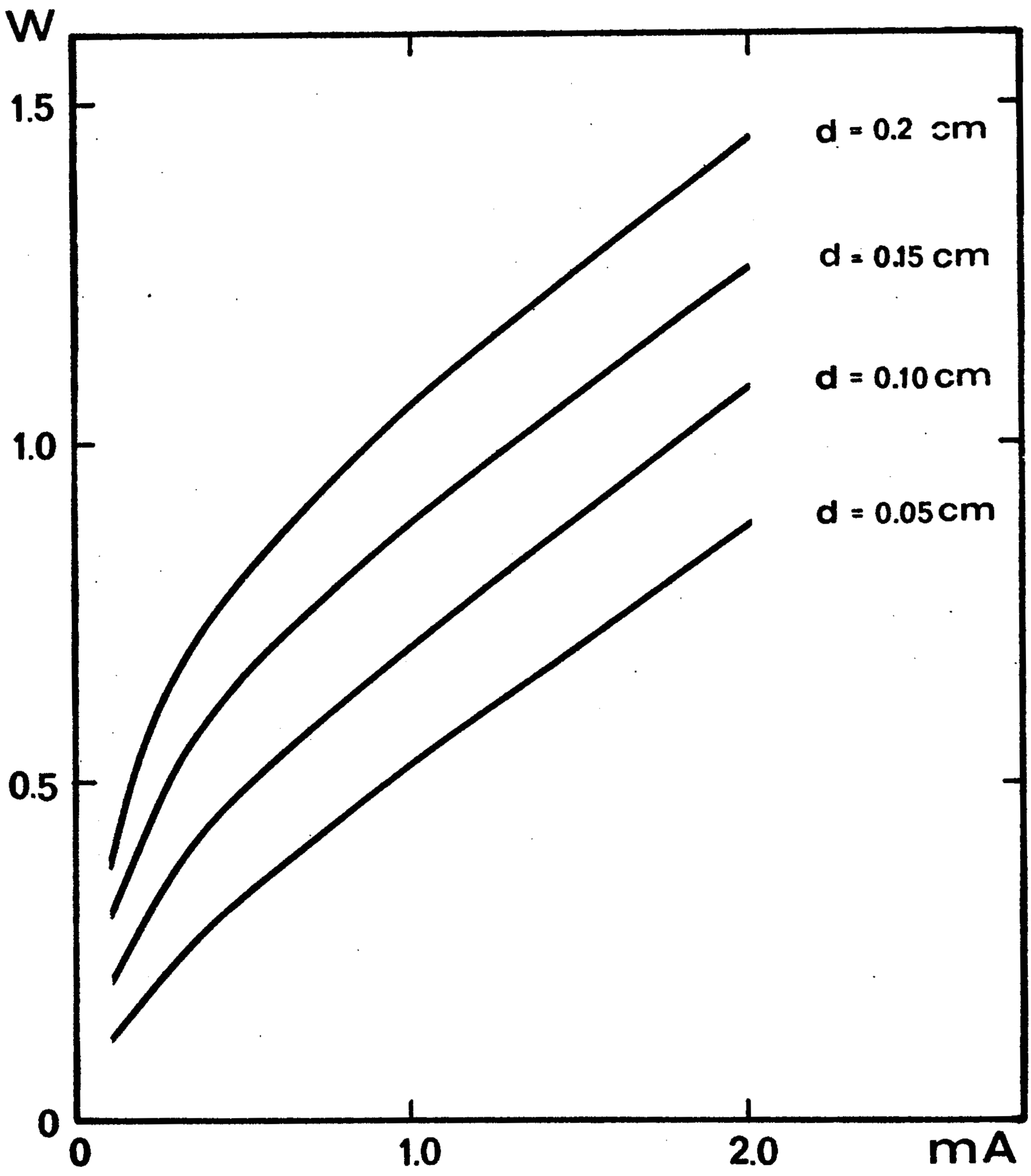

Fig. III-A-6. Heat dissipation as function of current I_j and distance d.

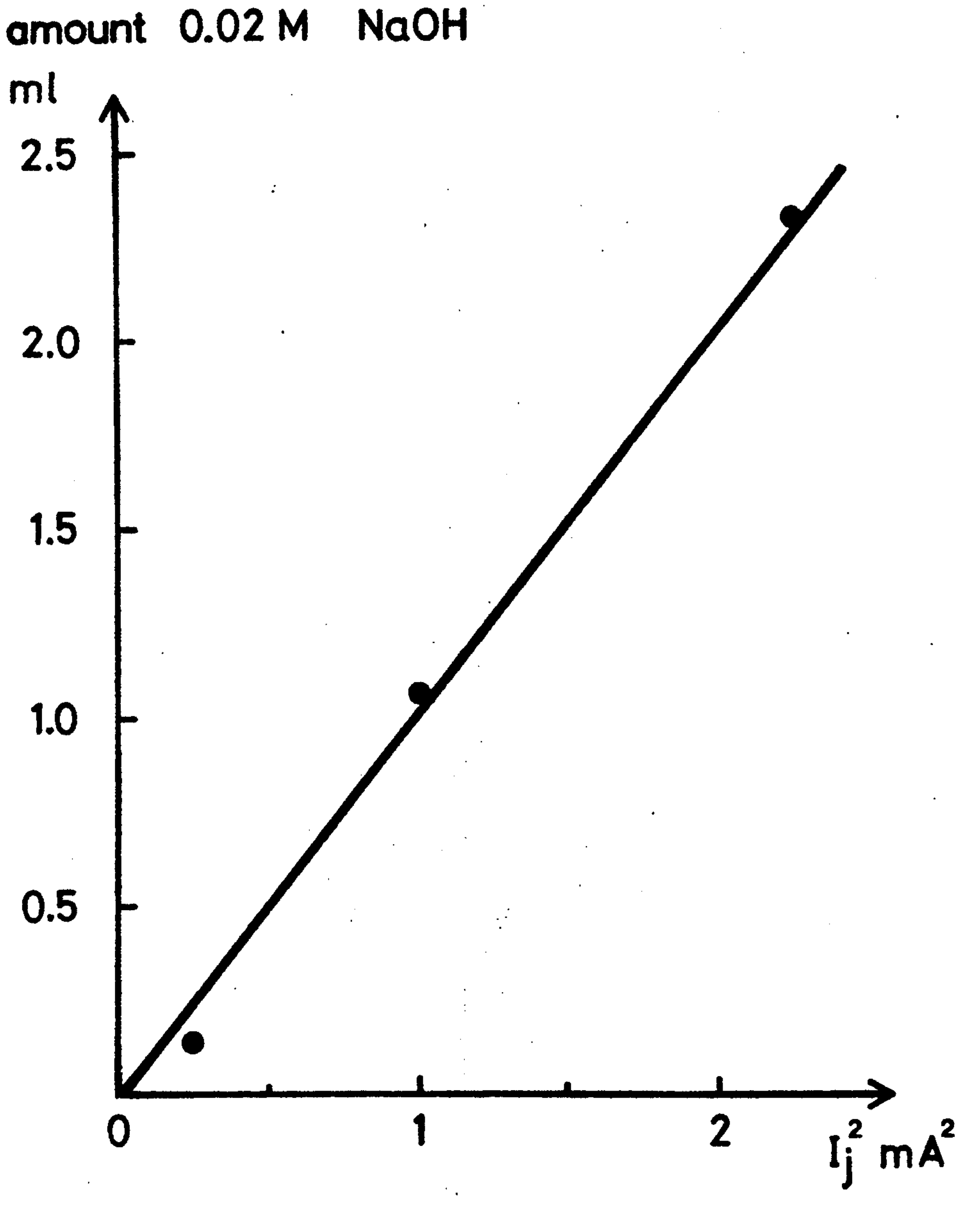

Fig. III-A-7. Amount of nitrous gases produced as function of current.

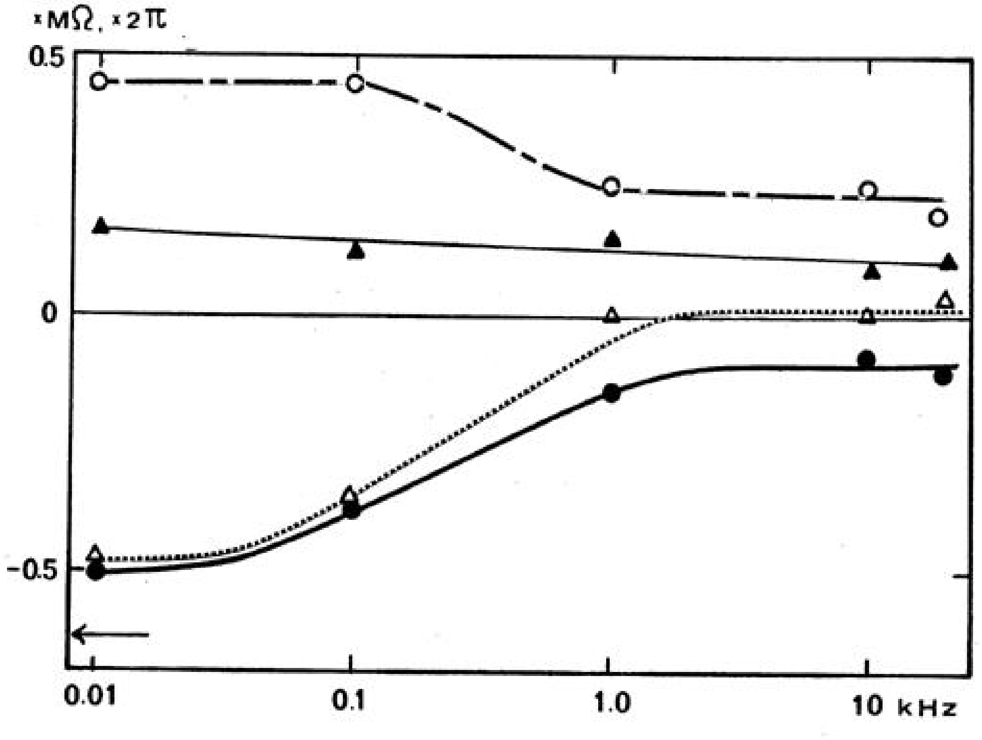

Fig. III-A-8. AC-impedance of the discharge as function of frequency.
Circles mark the argument of the impedance,
Filled circles the magnitude,
Triangles the resistive part, and
Filled triangles the imaginary part.

It should also be noted that the discharge is sensitive to external electrostatical fields; it is possible to modulate or demodulate the discharge with a third electrode. It is, however, very unsensitive to magnetic fields. This effect is as expected from the plasma physics.

Acoustical parameters of the discharge

General

Two factors of great general importance for an electroacoustical transducer is fulfilled by the glow discharge used.

Firstly the glow discharge is a very small transducer, the product of propagation constant of sound and largest radial distance is smaller than 0.5 for audio frequencies (< 20 kHz). This means that the transducer can be regarded as a point source or point receiver in most practical applications and that it will normally cause negligible distrubance when placed in an acoustical field.

Secondly there exists no resonances in the glow discharge in the audio frequency range and therefore no peaks or dips will be introduced in the frequency response.

(a) The glow discharge as a sound emitter

The main characteristics of the glow discharge as sound emitter are presented in the following. Detailed measurements verified that the discharge worked as a simple sound source, i.e. a small pulsating sphere with constant source strength, volume velocity. In the measurements the DC- and AC-currents I_j and i_j through the discharge were constant, i.e. the discharge was supplied energy from constant current generators. Measurements from 110 Hz to 4 kHz on cylindrical tubes proved the source strength to be constant within $\pm$ 10 %. Free-field measurements from 2 to 20 kHz gave constant source strength within $\pm$ 6 % independent of frequency and direction.

Empirically the source strength q_j was found to obey the equation

$$q_j = k \cdot V_j \cdot i_j \qquad \text{Eq. (2)}$$

where V_j is the DC-voltage over the discharge, i_j the current through the discharge, and k a constant $\approx$ 0.3 cm^3/Sec. V.A.). Eqs. (1) and (2) say that with a d = 0.2 cm, I_i = 1 mA, and i_j/I_j = 30 % a source strength q_j = 0.06 cm^3/sec is obtained, i.e. ≈ 25 dB SPL at 1 kHz and 10 cm distance. Eq. (1) indicates together with Eq. (2) that q_j is roughly proportional to the electrode distance d and modulation degree i_j/I_j. This was found to be in good agreement with direct measurements.

The acoustic noise signal is smaller than the noise in an anechoic chamber and is therefore difficult to measure. It can, however, be estimated from Eq. (2) and the electric noise, which gives a q_j corresponding to an i_j of about 1 μA.

The harmonic distortion of the system (modulator and discharge) was found largely to depend on modulation degree. With a modulation degree of 10 % the second harmonic was about 30 dB below the fundamental and the third harmonic about 45 dB. When the modulation was increased to 50 % the second harmonic increased to about -20 dB and the third to -35 dB. Some distortion originates from the modulator, but the main part from the discharge.

The acoustical impedance of the sound source, the discharge, is very high and was not possible to measure. Therefore measurements of resonance frequencies and bandwidth of tubes were made by: 1) a sound emitter with a capillary, diameter 0.06 dm and length 5 cm, and 2) a discharge transducer. A comparison revealed no or small significant differences.

The frequency range of the discharge transducer extends well above 20 kHz, considerable energy output has been registrated up to 150 kHz. These properties indicate that the discharge should be a good emitter of pulses. An example of the discharge as pulse emitter is shown in Fig. III-A-9. The pulse duration is about 1 msec and the pulse is propagating in a cylindric tube. The distortion may depend on the damping properties of the transmitting medium.

The physical process behind the sound generating process is not fully understood. Eq. (2) indicates that the source strength is proportional to the supplied AC-power to the discharge. This suggests that the energy conversion is a thermodynamical process. A theoretical study assuming an adiabatic process in an ideal gas, however, does not give a constant source strength but a source strength decreasing with the frequency squared thus giving a theoretical result contradictory to the measured. A close study of

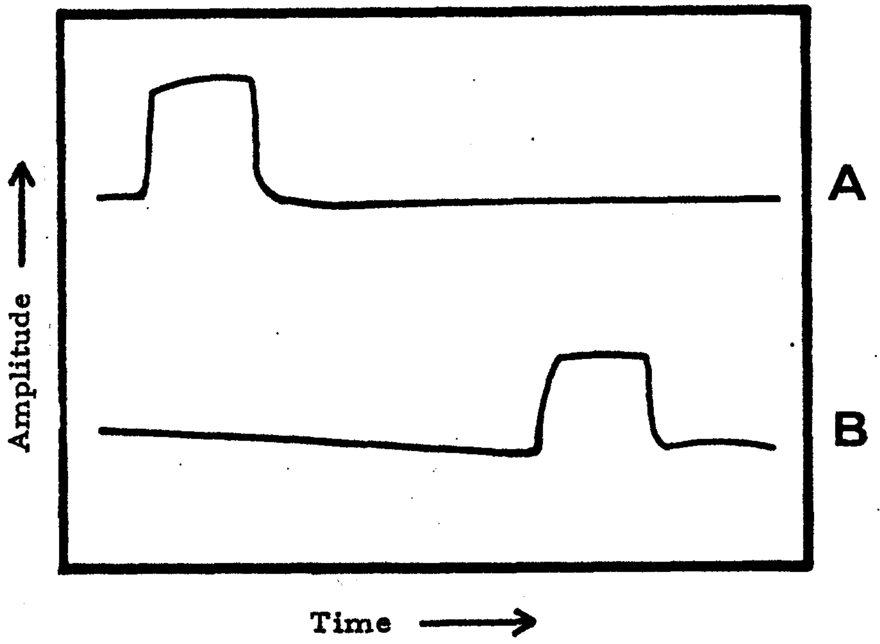

Fig. III-A-9. The discharge as pulse transmitter in a cylindric tube.
A, current through the discharge.
B, pressure response.
Pulse duration 1 msec.

the discharge when modulated by a low frequency signal, showed that: 1) the light intensity increased with the current, 2) the positive column of the discharge rocks, and 3) the width of the anode column increases. The rocking motion should give a dipole radiation characteristic which is contradictory to direction characteristics of the discharge. It is therefore believed that the width changes observed is the main process for the sound generation.

The properties of the discharge sound-emitter can briefly be summarized as follows. The discharge can be regarded as a simple source with constant source strength and high impedance. The output can be considerably increased only by increasing the electrode separation. This will, however, also increase the heat dissipation, which may be disadvantageous.

(b) The microphone properties of the glow discharge

Preliminary experiments with the glow discharge as microphone indicated that it was sensitive to motion of air, a velocity microphone. In the following detailed experiments, however, it was shown that it registered displacement rather than velocity.

A simple two-electrode arrangement was used in order to study the properties of the discharge exclusively. This arrangement gave not a highly stable and reproducible discharge. Thus only qualitative results were obtainable. These results are presented in this section.

Two main directions of maximum sensitivity were found, the first with the discharge perpendicular to and the second with the discharge in parallel with the sound propagation. Extensive studies gave the following interpretation of the phenomenon, Fig. III-A-10. When the discharge is placed perpendicular to the propagation of sound, its sensitivity depends on how the discharge is curved. Maximum sensitivity is obtained when the discharge is bent in a plane parallel with the sound propagation. The phase of the output signal is changed 180° when the discharge (Fig. III-A-10.a) is bent away from instead of (Fig. III-A-10.c) towards the sound source. A position (Fig. III-A-10.b) in-between, a presumably straight discharge, can give voltage variations corresponding to double the frequency of the acoustical signal.

When the presumably straight discharge is set in parallel with the sound propagation, it gives voltage variations with the fundamental frequency of

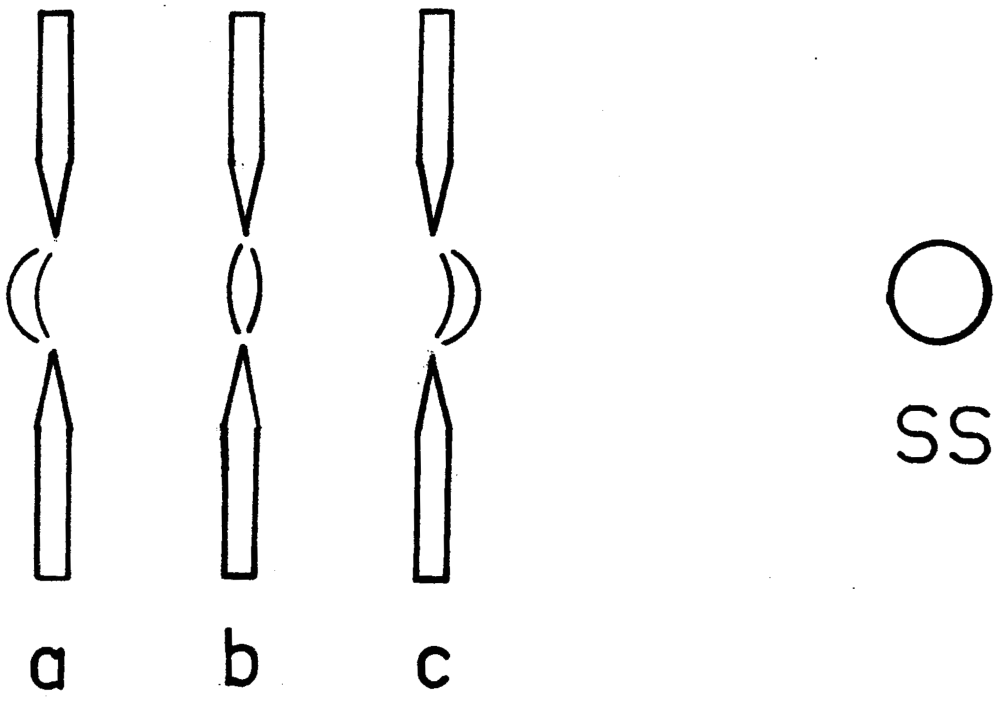

Fig. III-A-10. Different discharge shapes a, b, and c; SS sound source.

the acoustical signal. If the polarity is changed the phase of the output is changed 180°. The results suggest that, in the first case (the discharge perpendicular to the sound propagation direction), the voltage variations in the output signals are due to length variations of the discharge effected by the sound wave. If so, a curved discharge will be varied in length by variations in curvature around equilibrium. A straight discharge, however, will be lengthened on both sides of its equilibrium because of curving which accounts for a frequency doubling in the output signal.

The mentioned directions of maximum sensitivity were also found when the discharge was tried as a velocity meter in an air flow. The amplitude was, however, so large that side effects, as a totally changed curvature of the discharge, were encountered. It was also possible to measure both DC-velocity and sound simultaneously. The sound sensitivity was, however, dependent on the velocity of the air stream.

Typical constant-velocity frequency-responses of the discharge microphone are shown in Fig. III-A-11*. The figure clearly shows that for higher frequencies the discharge registers displacement rather than velocity, a slope of more than 6 dB/octave. The horizontal part of the curve, at lower frequencies, indicates a velocity dependency. Typical relations between air flow velocity and DC-voltage changes are shown in Fig. III-A-12. Up to a certain velocity the air velocity is proportional to the voltage change but for higher velocities the sensitivity decreases.

The microphone properties of glow discharge can be shortly summarized as follows. The discharge is sensitive to the motion of air. It has two orthogonal directions of maximum sensitivity, with the sound propagating in parallel and perpendicular to the discharge.

The stability and the reproducibility of the discharge were not sufficient for a more general use. Recently a more elaborate electrode arrangement,

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* The microphone properties were studied by means of the following arrangement. A sound transducer was placed at one end of a closed tube of metal and square cross section. At the other end, also closed, a pressure microphone was placed. The transmitter excited the air-column and by means of the microphone it was controlled that a standing wave was excited, and its amplitude and phase were measured. At half-way from the ends and in the center of the tube, the discharge was formed between the electrodes mounted on an insulator. The insulator could be turned 360° either way and was level with the inside surface of the tube. By working at resonance necessary high amplitudes were obtained. The arrangement furthermore supplied shileding against air motions and electrical disturbances.

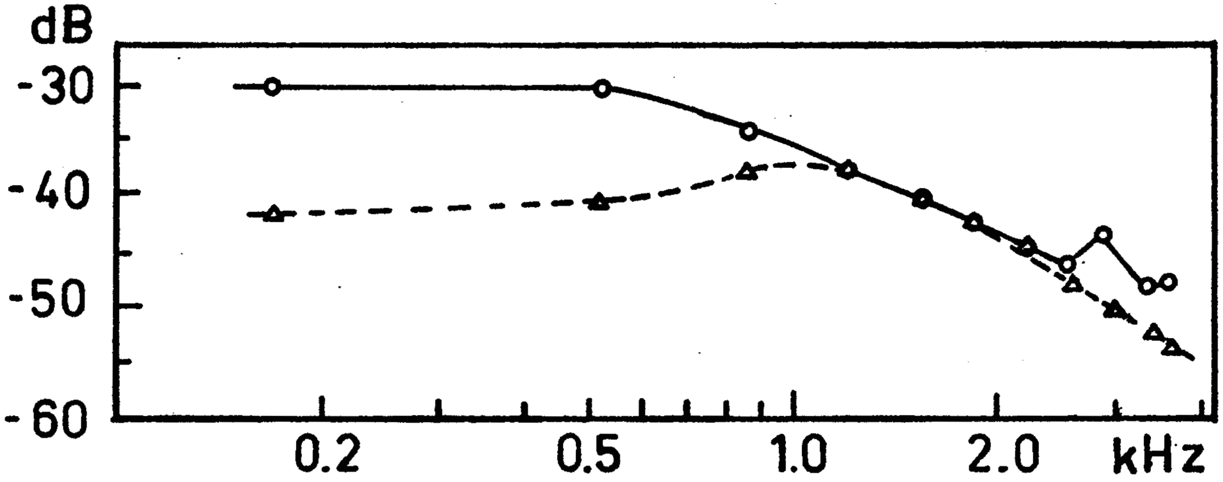

Fig. III-A-11. Constant-velocity frequency-responses of a discharge. Circles for the case with the discharge perpendicular to and triangles for the case with the discharge in parallel with the sound propagation.

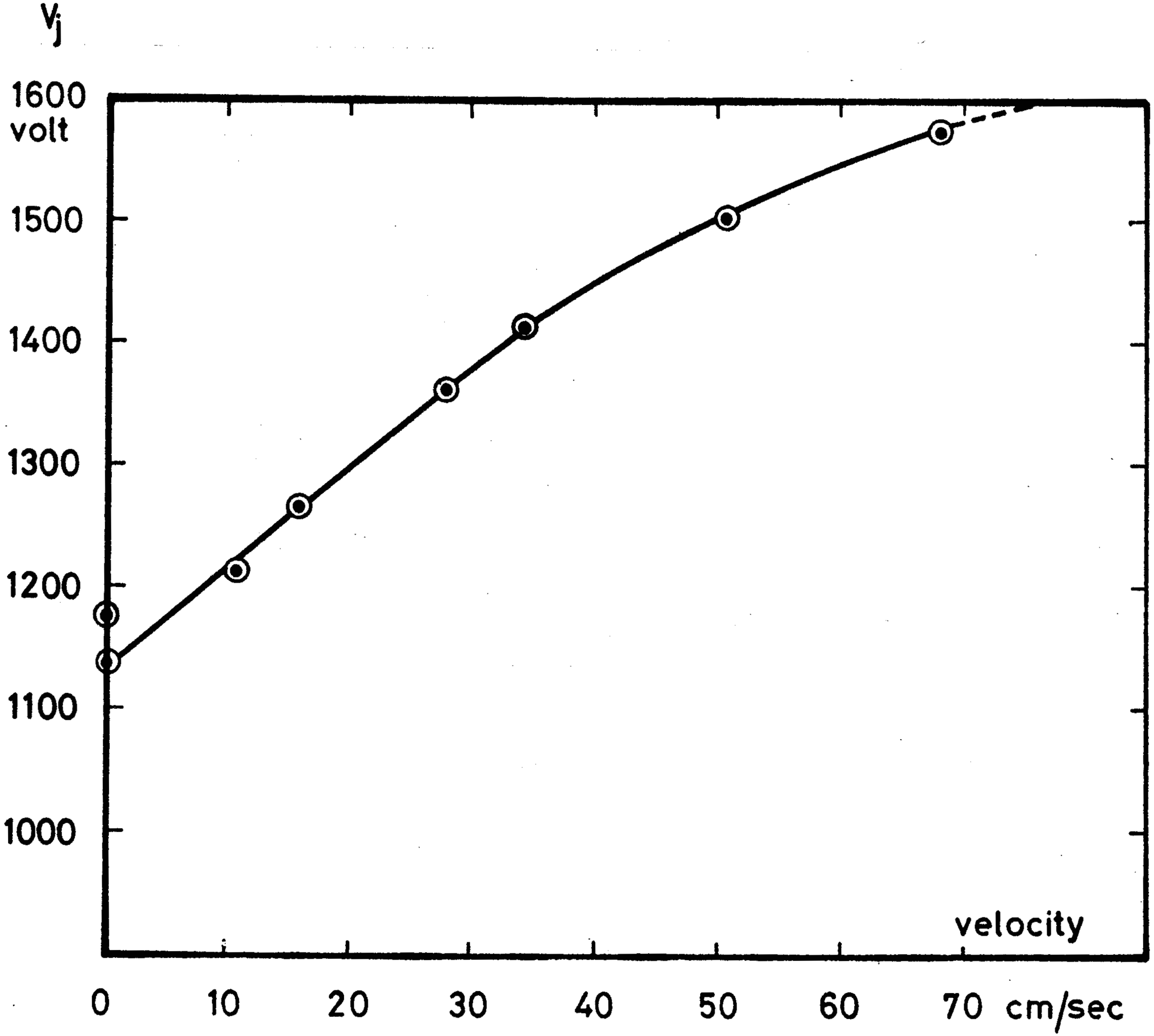

Fig. III-A-12. Discharge voltage V_j as function of the DC air velocity. Discharge at 90° to the air flow. I_j = 0.6 mA.

giving a highly stable discharge has been invented for the technical product the STL-Ionophone. Measurements with this electrode arrangement indicate that an amplitude limiting effect was the cause of the flattening of the constant-velocity frequency-response at lower frequencies. The later electrode arrangement thus gives a fall of 6 dB/octave over the whole frequency range of the constant-velocity frequency-response.

The work with the STL-Ionophone continues with a detailed study of the transducer properties of the technical product with improved electrode arrangement.

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