

HARWELL - HIGH VOLTAGE TECHNOLOGY COURSE No. 2

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High voltage electrostatic separators

- Abstract -

Introduction : Review of the most important problems involved in the design of electrostatic separators for high energy physics (bushings, insulators, electrodes, and vacuum tank).

Electrodes : Investigation of the most important parameters acting on the high voltage behaviour of plane electrodes (nature, surface state, shape, area, pressure and gap). A possible theoretical explanation of the pressure effect by taking into account the sputtering phenomena.

Bushings and insulators : Behaviour of different types of bushings and insulators for feeding and holding very high voltage in vacuum.

## 1. INTRODUCTION

During the last few years, fundamental research in high energy physics has required high energy separated beams of elementary particles. To achieve separation of these particles the most common and simple way is to analyse the velocity of the particles which have first been selected in momentum. The velocity selection requires a very high constant electric field in vacuum, over a large volume because of the very high energy of the beam. The apparatus which fulfils these conditions is called an "electrostatic separator". The typical size of this kind of apparatus is a few metres in length and a square metre in section. The most important problem to solve, is to create the highest electrical field possible in a vacuum lower than a few torr (for avoiding scattering phenomena) between plane electrodes of a few metres length, half a metre width and with a gap of several centimetres. The intensity of the electric field must be stable with time, for large periods (days), with the lowest sparking rate possible (a few sparks per hour are acceptable). This kind of application of vacuum breakdown research is far from the experimental conditions in which the different vacuum studies are normally performed (small area of a few  $\text{cm}^2$ , very small gap  $<$  a millimetre, and a low voltage  $<$  50 kV). It was then worthwhile to investigate vacuum breakdown across large gaps (1 - 10 cm) with large area plane electrodes. Different laboratories have consequently started these kinds of studies.

Three main problems have to be studied :

1. The electrodes.
2. The insulators for holding the electrodes.
3. The bushings for feeding the electrodes.

A few years ago the performance of the then existing separators was essentially limited by the electrodes (maximum field  $\sim$  60kV/cm for a 10 cm gap). Since the discovery of the favourable effect of an insulating coating on the cathodes (1964 at CERN), which increased the maximum field by about 70%, the limitation of the performance is now given at the largest gaps either by the bushings or the insulators. The problem to solve for these insulators and bushings is to hold 600 kV in vacuum, (which is the maximum d.c. voltage available

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from the CERN standard HT supplied) over the smallest possible length of insulating material.

Finally the last question to investigate in the design of an electrostatic separator is the size, the shape of the vacuum tank and the kind of pumping system. Other problems arise also, such as mechanical accuracy, stability of the different components and financial considerations, but we shall limit the discussion to the high voltage problems.

## 2. ELECTRODE STUDIES

### 2.1 Some definitions

In order to define some expressions which will often be used, it seems worthwhile to describe first the general behaviour of the tests performed in this kind of research. At CERN, the high voltage experiments are performed in polished stainless steel model tanks. A small one (Fig. 1) for small area electrode tests, which are quicker to achieve and a large one for full scale tests (Fig. 2). Both tanks are evacuated by an oil diffusion pumping system with a liquid nitrogen trap between the pump and the tank for stopping the oil vapour back-streaming. A controlled gas leak allows the regulation of the pressure in the tank between the ultimate pressure (a few  $10^{-7}$  Torr) and  $\sim 10^{-2}$  Torr. A pair of Sames  $\pm 600$  kV electrostatic generators supply each model with + and - voltages, stable to about 1 part in  $10^3$ . This kind of facility is similar to those used by other laboratories dealing with the same problems. It differs in some cases only by the pumping system (Hg instead of oil diffusion pumps) or the size, shape and nature of the tank. The gap between the electrodes is adjustable between zero and 15 cm ( $\pm 0.1$  mm) without breaking the vacuum.

When the pressure reaches about  $10^{-6}$  Torr in the vacuum tank, a symmetrical voltage is applied such that a weak current (10 to 20  $\mu\text{A}$ ) appears. An increase of the voltage is then observed, as a function of time, until an asymptotic value is reached. During this period, weak electrical breakdowns are superimposed on to the mean current; as a general rule, the appearance of these currents is accompanied by the degassing of the electrodes and tank walls; this degassing decreases progressively when approaching the voltage asymptotic value.

This process is called "Low pressure conditioning" and the voltage asymptotic value "the maximum conditioning voltage  $U_{fmax}$ "; the time required to reach  $U_{fmax}$  is called " $T_{fmax}$ " (Fig. 3a).

The pressure in the vacuum tank is then progressively increased by a controlled injection of the chosen gas (air, Ar,  $N_2$  or He). In all cases the breakdown voltage increases above  $U_{fmax}$  when the pressure is raised and this pressure effect is stronger, the larger the gap (Fig. 3b). This breakdown voltage  $U_d$  is defined as the voltage limited, either by an electrical breakdown (characterized by a high current during a very short time), or by a stable current of 10  $\mu A$  when a weak current without sparks is observed. Only a weak dispersion of  $U_d$  is noticed when sparks occur between the electrodes ( $< 3\%$ ). A large dispersion occurs only after damage to some part of the system of the electrodes, bushings or insulating supports. Damage can be caused either after a large number of sparks or by an external contamination (mainly organic vapours). When pressure reaches a critical value  $p_c$  in the range between a few  $10^{-4}$  and a few  $10^{-2}$  Torr, there is a sharp drop of the breakdown voltage. Accompanying this is a high current, corresponding to a general glow throughout the whole of the interior of the vacuum tank. It indicates that the region of gaseous Paschen discharges has been reached. The highest value of  $U_d$  is generally observed for a pressure quite near to  $p_c$  and is called  $U_{dmax}$ . This critical pressure is higher the smaller the size of the vacuum tank.

The curves  $U_f = f(t)$  and  $U_d = f(p)$  are then plotted for each test electrode at various gaps and for different kinds of gas. Several duration runs at pressure about 10 to 30% below  $p_c$  are achieved for recording the evolution of the "sparking rate  $\mathcal{T}$ " as a function of time. The chosen working point is called " $\mathcal{P}(U_o, p_o, d_o)$ " with  $U_o < U_d(p_o, d_o)$ . As a general observation a decreasing of the sparking rate is followed by a sudden sharp increase (Fig. 3c). " $T_x$ " is then defined as the time during which  $\mathcal{T}$  is smaller than  $x$ . Generally " $x$ " is taken as 0.1 spark/minute which is a convenient working condition for an electrostatic separator.

2.2 Most important parameters acting on the fundamental quantities

$U_{fmax}, T_{fmax}, U_d, p_c, T_x$  and  $\tau$

The different tests performed and the behaviour of the electrostatic separators observed for several years show that in a general way :

1.  $U_{fmax} = f(el, d, g, p, \mathcal{H})$

where  $el$  = electrodes material - surface state - shape and area.

$d$  = gap

$g$  = nature of residual gases.

$p$  = vacuum tank pressure.

$\mathcal{H}$  = history of the system and specially the time period of pumping (degassing) and the total number of discharges already sustained.

$T_{fmax} = f(\mathcal{H}, el, g)$

2.  $U_d = f(p, d, g, el, \mathcal{H})$

$p_c = f(g, \text{size of the vacuum tank}, d \text{ (weakly)})$

3.  $T_x = f(U_f, \mathcal{P}, g, \mathcal{H})$

where  $\mathcal{P} = \mathcal{P}(U_o, p_o, d_o)$  working point chosen for the long duration run

$\tau = f(\mathcal{P}, t, \mathcal{H})$

where  $t$  = time

The various parameters are given beginning by those showing the strongest influence.

The most important part of the results are coming from the small area electrodes ( $\sim 300 \text{ cm}^2$ ). The whole series of results obtained with metallic electrodes for cathode and anode, such as stainless steel, tungsten, copper, copper-Beryllium alloy, Chromium, and hard steel are situated always around  $U_{dmax} = 500 \text{ kV}$  for a 5 cm gap (Ref. 1). With aluminium (Ref. 2) and specially with Titanium (Ref. 3) the value of  $U_{dmax}$  is increased by more than 20%. An increase of about 70% is obtained by the use of cathodes covered with insulating coatings of special characteristics. Interesting but not reproducible results have been obtained also by the use of heated glass cathodes (Ref. 4,5,6).

Murray at Berkeley achieved a working field of 100 kV/cm across a 5 cm gap with a glass cathode heated at  $\sim 100^{\circ}\text{C}$  in a 3 m separator (Ref. 4). But, at Brookhaven, with a 2 m semi-conducting glass cathode, working at room temperature, with the same resistivity as the Berkeley heated glass ( $\sim 2.5 \cdot 10^9 \Omega\text{cm}$ ) only 40 kV/cm has been achieved for a 10 cm gap which corresponds to about 60 kV/cm for a 5 cm gap (Ref. 6).

### 2.3 Effect of the electrodes on $U_{fmax}$ , $T_{fmax}$ and $U_d = f(p)$

Four electrode parameters were investigated separately :

1. material
2. surface state
3. shape
4. area

#### 1. Material

It can be seen (Fig. 4) that the  $U_d = f(p)$  curves ( $U_{fmax} = U_d(10^{-6} \text{ Torr})$ ) are similar in their general shape, but the maximum breakdown voltage values  $U_{dmax}$  obtained, keeping the other parameters constant, are extremely different ( $310 \text{ kV} \leq U_{dmax} \leq 820 \text{ kV}$ ). These results show firstly that an insulating layer on the cathode gives, until now, the highest "insulation strength". Secondly an increase of the pressure always improves the breakdown voltage in the same general way for both metallic and coated electrodes. A more careful investigation of the properties of the oxidized aluminium electrodes shows that the alumina coating must be thin ( $\sim 5 \mu\text{m}$ ) (Fig. 6), sealed, not too hard (Fig. 5) and on the cathode (Fig. 4). An aluminium oxidization made in a sulfuric bath at low temperature ( $< 4^{\circ}\text{C}$ ) produces the hardest alumina layer. However, it crazes rapidly when electrical breakdown occurs; this effect is cumulative because more cracks initiate more sparks. A microscopic observation shows, on the contrary, the oxidization made at room temperature ( $\sim 20^{\circ}\text{C}$ ) produces a less hard coating than at low temperature. In that case the coating is not crazed by electrical breakdowns and gives consequently slightly better insulation strength. The good properties of aluminium compared with other metallic electrodes could be explained by the presence of a natural oxide layer on aluminium. It can also be noticed that the optimum thickness seems independent of the gap, but its

effect is larger, the smaller the gap. Recent results show that  $U_{dmax}(5 \mu m) / U_{dmax}(10 \mu m) = 2$  for a 0.25 millimetre gap. The conditioning time  $T_{fmax}$  seems to be about the same for all metallic electrodes ( $\sim 2$  hours) but is ten times longer for the oxidized cathodes. This fact could be correlated with the impossibility to draw stable currents from the insulating layers as it is for metallic surfaces and consequently a longer time is required to degas and clean the electrode-vacuum interface during the conditioning period.

In the case of the alumina coated cathode an important unexpected improvement of the value of  $U_{fmax}$  and  $U_d$  is obtained by using an uncoated polished aluminium anode instead of a polished stainless steel one (Fig. 11). Unfortunately, the anode is irreversibly damaged after only a few weeks of operation; the sparks are then confined to one region, the anode is destroyed by the formation of large craters and the value of  $U_{dmax}$  drops sharply but oddly not  $U_{fmax}$ .

Studies with three types of heated glass cathodes (area  $\sim 2500 \text{ cm}^2$ ) with a polished 304 stainless steel anode and a 5 cm spacing give interesting results and show that the optimum glass resistivity lies in the  $10^{11} \Omega \text{ cm}$  range. (Figs. 8, 9, 10).

## 2. Surface state

The surface state is one of the most difficult parameters to control. Even if it were possible to analyse with accuracy the surface finish and composition before applying the voltage, the various phenomena occurring when a field is applied (sputtering, degassing, particle exchanges, surface migration, temperature effects, vapour contamination) would completely modify the original state. However, the general behaviour in respect of surface conditions can be qualitatively described.

Electron microscopic studies have shown that very small protrusions grow on the electrode surfaces when an electric field of sufficient magnitude has been produced (Ref. 7,8,9,10). This growing is essentially temperature and field dependent. A recent theoretical analysis (Ref. 11) gives an explanation of the two experimental facts observed, namely the better the

polishing and the harder the electrode surface, the higher the voltage maintained (Ref. 3). This analysis gives moreover, the stability conditions of a plane surface exposed to a high electric field as a function of the microscopic surface geometry and a fundamental limit of the applied field based on mechanical limitations; it is derived that whatever is the polished state, protrusions will grow and give sparks induced by field emission phenomena occurring at the tip of the protrusions.

The stability condition is  $\lambda < \sqrt{3}$

The mechanical limit is  $E_0 = 1.46 \cdot 10^5 \sqrt{\frac{\gamma}{r}}$

where  $\lambda$  = ratio between major and minor axes of the protrusion.

$E_0$  = macroscopic gap field in V/m.

$\gamma$  = surface tension of the protrusion material in N/m.

$r$  = minor axis of the protrusion in m.

Experimental studies show that the surface finish is more critical for small gaps than for large ones. For the large gaps the effect is stronger on  $U_{fmax}$  than on  $U_{dmax}$ .

Relating to the effect of the composition of the electrode-vacuum interface, it seems that intermetallic compounds such as carbides or sulfides in the surface of electrodes of both polarities reduce the insulation strength. (Ref. 3). The influence of organic compounds on the electrode surface seems polarity dependent (Ref. 12). An organic film on the cathode improves the insulation strength but the same film on the anode reduces the breakdown voltage. In the behaviour of the electrostatic separators it has been observed many times that oil contamination gives rise to large gap currents and decreases the breakdown voltage threshold ( $U_{fmax}$ ,  $U_d = f(p)$  decrease and  $T_{fmax}$  increases).

### 3. Shape

Electrostatic separators require plane parallel electrodes or more precisely constant field integrals along the different particle trajectories in the velocity selector in order to minimize the spatial aberrations which decrease the actual separation. The only shape problem in the separators is the electrode edges. A systematical study with a 5 cm gap shows that the radius of



curvature of the anode edge can be smaller than a millimetre without any statistical increasing of the edge sparking rate compared to the plane one. The radius of curvature of the cathode edge is more critical, certainly because of field emission enhancement factors, but can be as small as a few millimetres. It seems that anode depressions of a few millimetres in front of a plane cathode increase appreciably the sparking rate probability and must be avoided especially in the case of coated cathode-stainless steel anode geometry (Fig. 11).

#### 4. Area

As a general rule it can be said that an increase of an electrode area results in a decrease of  $U_{fmax}$  and  $U_d$  and an increase of the conditioning time  $T_{fmax}$ . The experimental variation of insulation strength with the area (from about  $300 \text{ cm}^2$  to  $30000 \text{ cm}^2$ ) noticed at CERN for large gaps ( $> 1 \text{ cm}$ ) can be represented by the law :

$$\frac{U_d(S_1)}{U_d(S_2)} = \left( \frac{S_2}{S_1} \right)^\mu$$

where  $S_1, S_2$  are electrode areas

$$\mu \cong 0.082$$

This area effect seems independent of the pressure. Between small area test electrodes ( $315 \text{ cm}^2$ ) and large area separator electrodes ( $\sim 13500 \text{ cm}^2$ ) the conditioning time is multiplied by about ten ( $\sim 20$  hours to 200 hours for the alumina coated cathode-stainless steel anode first conditioning period). These results for the area effect do not agree on the value  $\mu = \frac{1}{3}$  given by McCoy for small gaps (1mm)(Ref. 13).

#### 2.4 Effect of the gap "d" on $U_{fmax}$ and $U_d = f(p)$

The effect of the gap on the breakdown voltage is an important parameter in the understanding of the physical phenomena occurring in vacuum electrical breakdown. The knowledge of this influence is also very important for optimising the optics of separated beams (particle flux and separation). Often the law for the voltage-gap relationship is given as  $V = Kd^\alpha$  where  $\alpha$  and  $K$  are

constants. For small gaps the value of  $\alpha$  is about one and this value agrees with field emission breakdown theories, but for large gaps  $\alpha$  is lower than one and seems to be in agreement with clump theories ( $0.4 < \alpha < 0.7$  in our tests (Fig. 7)(Ref. 1)). The transition between these two gap ranges is situated in the few millimetres region (Ref. 14). It will be shown later that, introducing the pressure effect, the breakdown-voltage-gap relationship cannot be represented as above, and in fact, it can be shown that  $\text{Log } U_d - \text{Log } d$  graph curves (Fig. 7) are not perfectly straight lines. Their mean slopes are nearly the same for both alumina coated and metallic uncoated cathodes. From this important fact it is likely that the breakdown process is of the same nature in both cases. For the highest gaps tested the breakdown values are biased, especially in the 10 m separator case, because of sparks occurring along the insulators of the bushings. For rather smaller gaps (below 3 cm) alumina coated cathodes give irregular results and large and stable gap currents after only a few breakdowns. It is also experimentally observed that the value of the gap has an influence on the intensity of the pressure effect; this influence is proportional to the  $\frac{3}{2}$  power of the gap ( $\left. \frac{dU_d}{dp} \right|_d \sim d^{\frac{3}{2}}$ ) and  $\left. \frac{dU_d}{dp} \right|_{d=1 \text{ cm}}$  is about zero (Figs. 14,15). A possible theoretical explanation of this effect will be given further on.

### 2.5 Effect of the nature of the gas "g" on $U_{fmax}$ , $T_{fmax}$ , $U_d$ , $p_c$ and $T_x$

Until now, no careful investigation of the nature of the residual gases has been made. However, various effects can be summarized. The maximum conditioning voltage  $U_{fmax}$  increases slowly with the pumping time, during which the organic vapour level decreases. An organic vapour contamination induces a sharp fall of  $U_{fmax}$ . After each long duration run at a point  $\mathcal{P}(U_o, p_o, d_o)$  allowing to measure the  $T_x$  value, it is possible to restore the original conditions by a low pressure conditioning which ends when the  $U_{fmax}$  voltage value is reached. The conditioning time  $T_{fmax}$  is always shorter than the preceding one, although  $U_{fmax}$  is slightly increased. This phenomena is probably due to the decreasing of the organic vapour level when increasing the pumping time. This cycle (high pressure-low pressure working) can be repeated as often as necessary as long as the system has not reached an irreversibly damaged state (influence of  $\mathcal{H}$  parameter). For the same injected gas, the time  $T_x$  is

increased after each cycle and can reach a practically infinite value ( $> 500$  hrs). These experimental observations show clearly the importance of the separator components cleaning during the first assembly and the disastrous consequences on the insulation strength performances of an appreciably oil vapour backstreaming pumping system. The influence of the nature of the injected gas on  $U_d = f(p)$  and  $p_c$  has been measured for air, nitrogen, argon and helium. From these experiments it is clear that the influence of the gas is only a function of its ionisation cross section. Unexpected influence has been observed on the value of  $T_x$  (Fig. 12) curves are given for a 3 metre separator with alumina coated cathode and stainless steel anode; however these results are not reproducible with accuracy, probably because of the pumping time influence noticed above.

#### 2.6 Effect of the conditioning voltage $U_f$ on $T_x$

Instead of waiting, during the conditioning period, until the maximum voltage  $U_{fmax}$  is reached, it is important for a separator operating on a beam to know what influence a lower conditioning voltage value  $U_f$  has on the working time  $T_x$ . It is observed that  $T_x$  decreases exponentially with  $U_f$  :

$$T_x = T_{xmax} \left( \frac{U_f}{U_{fmax}} \right)^\gamma$$

where  $\gamma \cong 8$

$$T_{xmax} = T_x \text{ for } U_{fmax}$$

#### 2.7 Effect of the chosen working point $\mathcal{P}(U_o, p_o, d_o)$ on $T_x$ and $\tau$

As the time passes when a chosen condition  $\mathcal{P}(U_o, p_o, d_o)$  has been fixed, one observes that the critical pressure  $p_c$  remains constant, but the whole curve  $U_d = f(p)$  moves down to lower and lower breakdown voltage values until a certain minimum. The decreasing rate is not constant with time and depends essentially on vacuum cleanness and consequently on the total pumping time as pointed out before. This means that keeping  $U_o$  and  $d_o$  constant, the width  $\Delta p$  between  $p_m$  and  $p_c$  (Fig. 3b) diminishes because of the increase of  $p_m$ . When  $p_m$  reaches  $p_o$  the sparking rate increases quickly. Therefore to obtain

the largest value of  $T_x$  it is clear that  $p_o$  must be chosen near  $p_c$  and that the higher the  $U_o$  value ( $U_o < U_d(p_o, d_o)$ ) the smaller the time  $T_x$ .

The measurement of the influence of  $U_o$  on the sparking rate  $\tau$  is difficult because  $T_x$  must be large enough for getting a good statistic ( $> 100$  hrs). An accurate measurement could have been achieved with a 3 m alumina coated cathode-stainless steel anode separator (Fig. 13) showing the sharp increase of the sparking rate when approaching the maximum breakdown field  $E_d$  ( $E_d = \frac{U_d}{d_o}$ ).

### 2.8 Effect of the pressure and possible explanation

The most striking new phenomena occurring in large gap high voltage vacuum breakdown experiments is the very strong influence of the pressure on the breakdown voltage  $U_d$ . This effect is not observed for gaps smaller than a centimetre and, as pointed out before, is stronger the larger the gap. Up to now, no theory proposes any explanation of this gap dependent pressure effect. Only qualitative interpretations have recently been reported (Ref. 7,8).

The next theoretical development is supported by the following experimental facts :

1. As noticed before, the general experimental behaviour of the large gap breakdown voltage experiments with the different parameters and especially with the pressure and the gap, is similar for both metallic and coated cathodes. It can then be assumed that the vacuum breakdown mechanism is of the same nature in both cases.

2. From the electron microscopic studies performed during the last few years it now seems proven that protrusions appear and grow even on smooth surfaces under the influence of the electric field. Such analyses also show definitely that electronic field emission currents exist at the tip of cathodic protrusions prior to breakdown.

3. Experimental results obtained at present show that the pressure effect is mainly due to ions and not to the pressure itself in the sense of molecular collisions.

4. The last experiment reported by Slattery (Ref. 15) proves that the impact of micron-sized particles can cause a vacuum arc to develop between parallel electrodes and shows that at a given field and gap there is a minimum particle energy necessary to cause a discharge.

A theoretical analysis can then be made assuming two fundamental mechanisms :

1. A sharp cathode protrusion emits a current which can be computed using the modified Fowler-Nordheim equation (Ref. 16). This field emission current leads to two main energy exchange phenomena : the volume joule heating, proportional to  $\rho I^2$  which increases rapidly with current (I) and also with the protrusion temperature T in the usual case where resistivity  $\rho$  increases with temperature. The Nottingham surface heating, proportional to the emitted current I, increases less rapidly with I and decreases with T, becoming negative (i.e. cooling) at sufficiently high temperature. At high emission current densities, the resistive heating is predominant and the Nottingham effect exerts only a stabilizing action on the protrusion tip temperature (Ref. 17). After a certain time  $\tau_1$ , the tensile strength of the protrusion material becomes less than the mechanical stress exerted by the electric field on the emitting point, because of this heating. Then the protrusion can be torn away and a charged "clump" is obtained, which will gain energy crossing the gap and be sublimated when striking the anode if its energy is high enough. It is assumed that a vacuum arc can be initiated within the vapour created following Slivkov's processes (Ref. 18).

2. The cathodic emitting area is, at the same time, bombarded by the positive ions created both in the residual gas and at the anode by the emitted electrons. This ionic bombardment leads to the sputtering of the protrusion. After a certain time  $\tau_2$ , the electronic emission can be stopped by reduction of the sharpness of the emitting point.

Then, if  $\tau_2$  is greater than  $\tau_1$ , a clump could be created, which, depending on its energy, may generate a vacuum arc.

Assuming that the protrusion can be assimilated to the shape of a semi-ellipsoid of revolution standing on a flat surface, a complete mathematical analysis can be made (Ref. 5). The final result of this development gives the following breakdown criterion :

$$E_d^4 \exp. \left( - \frac{A}{E_d} \right) = B \frac{p}{d} + \frac{C}{d^2}$$

A, B, C are constants in the first approximation. They are only a small function of  $E_d$ .

This criterion compared with experimental results gives good results (Figs. 14,15). In particular, from the above equation one can derive that :

$$\left. \frac{d U_d}{dp} \right|_d \sim d^{\frac{3}{2}}$$

as found in the experiments.

Keeping  $E_d$  constant in the above equation and choosing three different couples  $(p_i, d_i)$ , a homogeneous linear system with three unknowns is obtained ( $A' = E_d^4 \exp(-\frac{A}{E_d})$ , B, C), whose determinant has to be equal to zero. This condition gives a relation between the three couple values  $(p_i, d_i)$  taken at constant breakdown field :

$$\sum d_i p_i (d_k^2 - d_j^2) = 0$$

(i, j, k = 1, 2, 3)

This relation applied to many experimental results fits accurately within the experimental errors in  $p_i$  and  $d_i$ .

For gaps lower than 1 cm the pressure seems to have no effect on the breakdown voltage. This fact could be correlated with the other transition noticed for the slope of the  $\text{Log } U_d - \text{Log } d$  curves in this same gap region. It is likely that this transition corresponds to a change in the vacuum breakdown initiation mechanisms.

### 3. INSULATORS

Only very few studies have been done to investigate the conductivity and flashover along solid insulators in vacuum. The high electric field now produced, between electrodes with a few centimetres spacing, in the electrostatic separators requires a systematic research of the parameters acting on the behaviour of high voltage stand off insulators in vacuum. These studies are now in progress at different laboratories. This is the reason why only a general account of the problems involved will be given together with a few practical examples.

As a general fact, the insulation strength along a solid insulator surface in vacuum is always lower than either the proper dielectric strength of the insulator material or the interelectrode strength for the same vacuum gap. As in large electrode vacuum gaps, the flashover voltage of an insulator is not linear with the insulator length. The field strength seems to decrease more quickly with this length than for the vacuum electrode gaps. This accounts for the usual technique of dividing the potential with metallic rings in the very high voltage accelerating tubes ( $V > 1$  MV).

From experimental observations it seems that the initiating flashover mechanisms are to be found at the triple junction of solid dielectric, vacuum and cathode. The shape of the insulator-cathode junction must therefore always be designed to decrease to a minimum the value of the field in that region. For this purpose two important features must be realized.

1. A geometry which provides a recess of the cathode end of the insulator into the metallic negative electrode. (A metallic cone cap is generally used).

2. A contact between the dielectric and the metal, which avoids field intensification.

This second important condition is generally achieved either by a cement with a similar dielectric constant to the insulator or by a metalisation of the insulator contact region.

Another parameter which seems very important in pulsed high voltage problems, especially for certain types of materials such as lucite, perspex, polyethylene, hard epoxy resin, is the angle between the insulating and the metallic surfaces around the contact region. The optimal angle and shape is found to be an insulating cone between two parallel metallic planes, the cone half angle being  $\sim 50^\circ$  with shank at the cathodic contact side (Ref. 19).

From the different tests performed at CERN a few conclusions could be drawn. The insulating material tested is a high voltage porcelain made in Langenthal (Switzerland). If the porcelain to metal contact is made with a cement it seems important to avoid the cement overlapping the insulator section. A suitable contact is achieved by sealing with tin the porcelain into a metallic cap. Both, sealed and cemented contacts, give similar results. The field strength obtained lies between 45 and 50 kV/cm for 4 and 9 cm insulator lengths. As for the electrodes, a low pressure conditioning period and a pressure effect are observed. The surface state of the porcelain is an important factor; between bare and glazed porcelain a factor of two in the flashover field strength is noticed (4cm porcelain bar : glazed  $U_d = 100$  kV, bare  $U_d = 220$  kV)

#### 4. BUSHINGS

Tests have been made in a few laboratories to investigate the ability of a bushing alone to support high voltage. The polarity effects are important and the design for negative and positive bushings must be different. The general problems occurring in this design are similar to those involved with the insulators; the major difference is the presence of a charged metallic conductor inside the insulator. Various methods of introducing voltages of 600 kV in a vacuum have been proposed and tested : conventional methods with an axial high voltage cable inside an insulating tube for air-to-vacuum bushings, special designs for pressurised gas-to-vacuum bushings with potential dividing rings distributed along the insulator (Ref. 20), and an original method with an electron accelerated beam feeding the electrode (Ref. 21).



Different bushing investigations are now in progress at CERN and two kinds of improvement have been achieved on the previous CERN bushing performances. For the negative bushing, the introduction of an alumina coated shield at the vacuum high voltage side of the insulator leads to a similar improvement of the insulation strength as for the electrodes (Figs. 19,20). The introduction of a grid biased by a negative voltage with respect to the tank wall (Fig. 17) in the positive bushing is now under test. Better results than with the grid grounded (Fig. 18) seem to be obtained when the grid is biased. This idea was first proposed and tested by Britton, Arnold and Denholm (private communication); they got an increase from 500 to 750 kV when a grid was biased by  $\sim 750$  V negative. This grid effect is likely correlated with the suppression of the secondary particles leaving the tank wall, hitting the bushing and causing breakdown. For the negative bushing (Fig. 19) no influence of the  $\alpha$  angle has been observed ( $30^\circ \leq \alpha \leq 60^\circ$ ).

#### 5. CONCLUSION

The construction of an apparatus using very high voltage in vacuum is only based on experimental test and cannot be designed mathematically. As we have seen, the difficulties are coming from the large number of parameters involved and the numerous effects they have on the breakdown voltage results. A possible way of improving again the present electrostatic separator results (Fig. 16) would be to take more advantage of the pressure effect by decreasing to a minimum the size of the vacuum tank. More fundamental investigations must be made to explain the part of the various parameters and particularly the good effect of thin insulating cathode coatings in the insulation of high voltages in vacuum.

F. Rohrbach.

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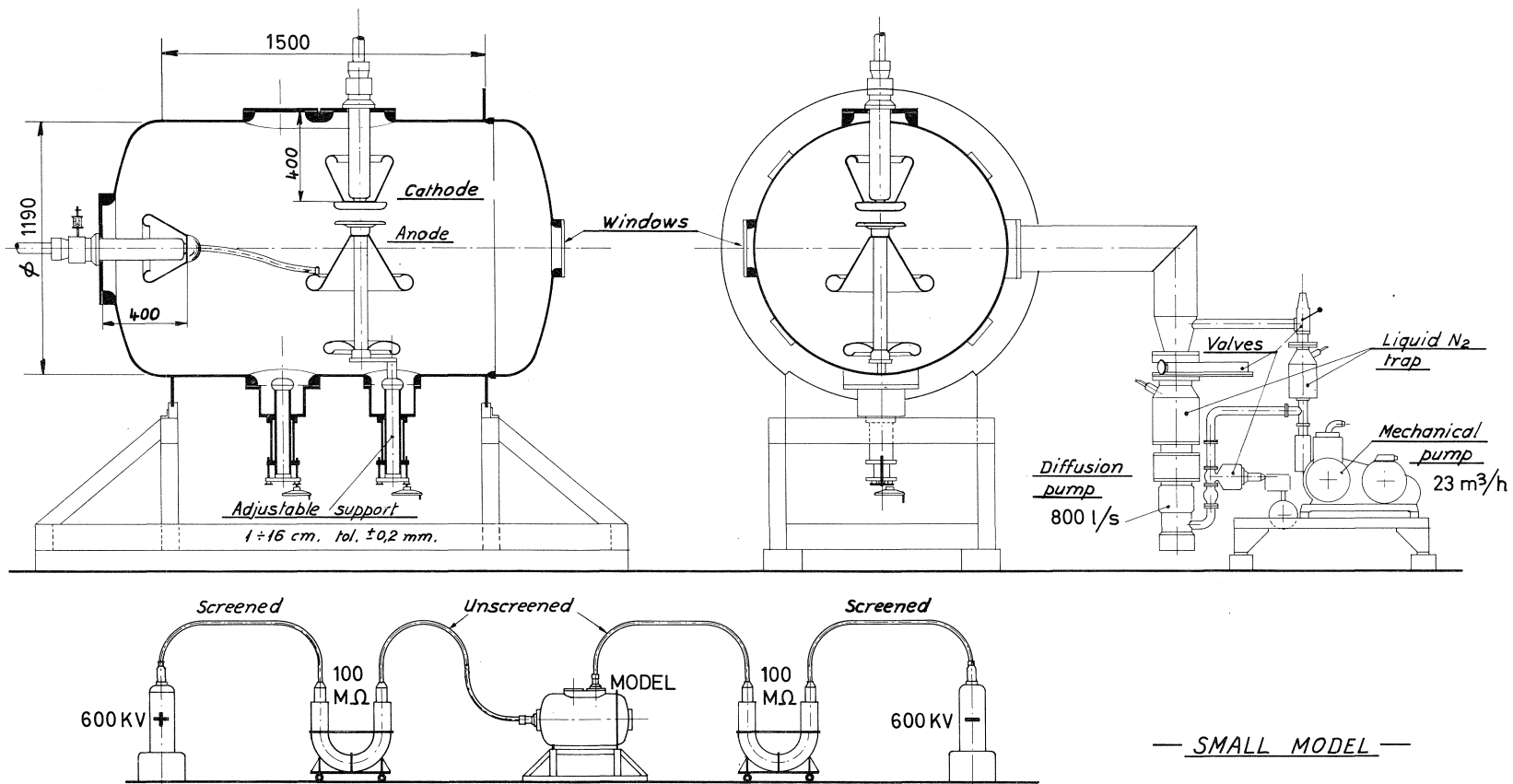
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**Table I.** Influence of electrodes on voltage breakdown with 5cm. gap

Test N <sup>o</sup>	Cathode					Anode		Max. voltage breakdown KV
	Metal	diameter thickness mm.	bath temp. °C	layer thickness µm.	Sealing	Metal	diameter Thickness mm.	
1	Al. 99,69%	200/20	—	—	—	Inox.304	220/10	690
2	"	"	~ 20	1,5 - 3	H <sub>2</sub> O = 100° + acetic acid PH = 5,4	"	"	780
3	"	"	"	4 - 7	"	"	"	810
4	Peraluman	"	"	9 - 10	"	"	"	790
<sup>2)</sup> 5	Al. 99,69%	"	"	4 - 7	"	Al. 99,69%	"	780
6	"	"	"	25 - 30	"	Inox. 304	"	740
7	"	"	~ 4	92 - 102	—	"	"	480
<sup>1)</sup> 8	Inox. 304	220/10	—	—	—	Al. 99,69%	170/20	310
9	Al. 99,69%	200/20	—	—	—	"	200/20	670
11	Inox. 304	220/10	—	—	—	Inox. 304	220/10	485
12	Peraluman	200/20	~ 20	5 - 6	"	"	"	820
13	Al. 99,99%	140/10	~ 20	5 - 7,5	—	"	"	720
14	Al. 99,69%	170/20	~ 4	25 - 30	—	"	"	710
15	"	200/20	~ 4	7 - 10	—	"	"	540
16	Peraluman	200/20	~ 20	1,5 - 2,5	"	"	"	770

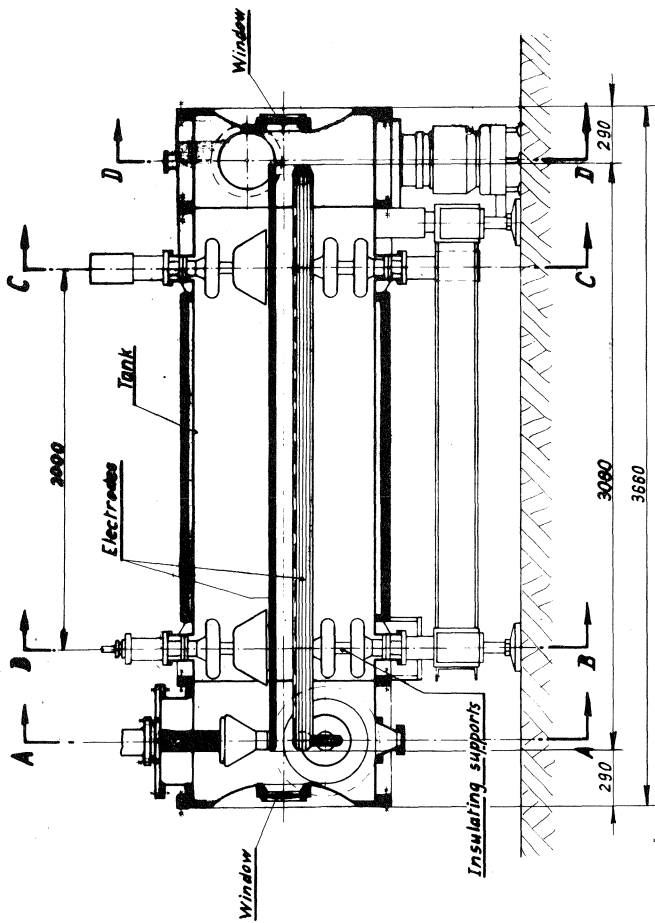
1) Aluminium anode of test N<sup>o</sup> 8 was anodized like the cathode of test number 14

2) For test number 5 the gap was 4 cm.



— SMALL MODEL —

Fig. 1

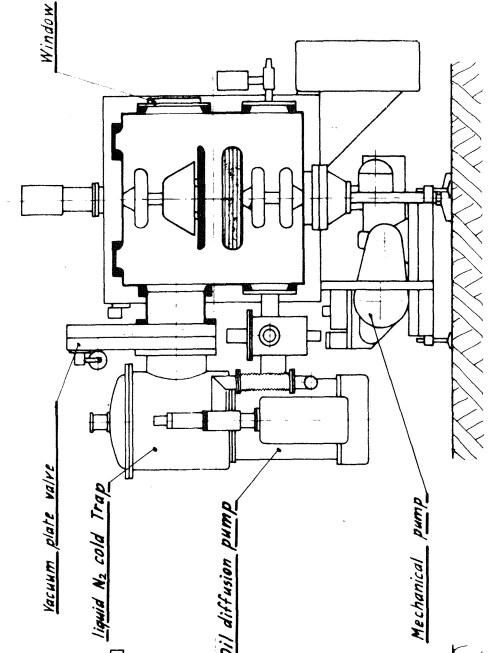
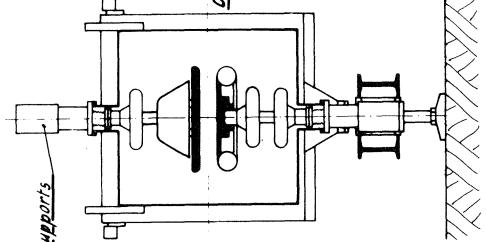
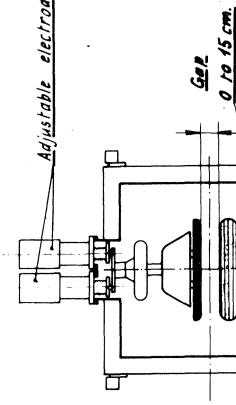
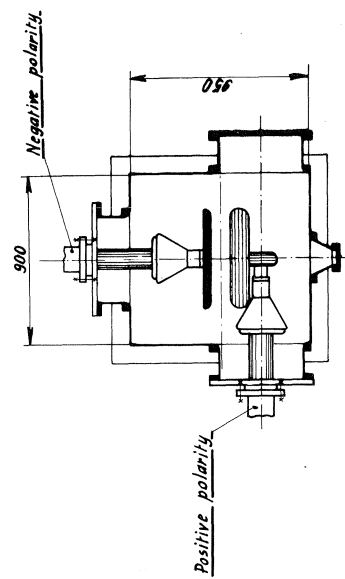


Section A-A

Section B+B

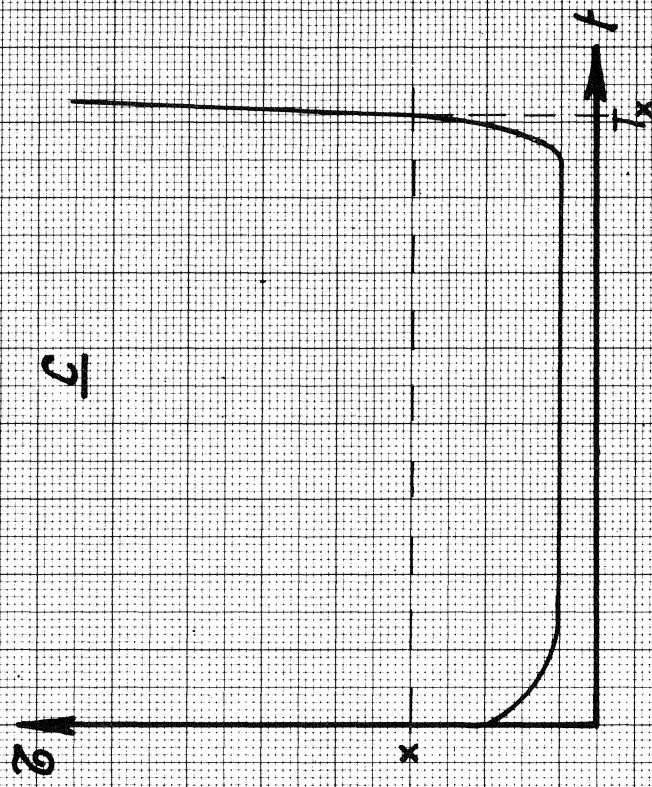
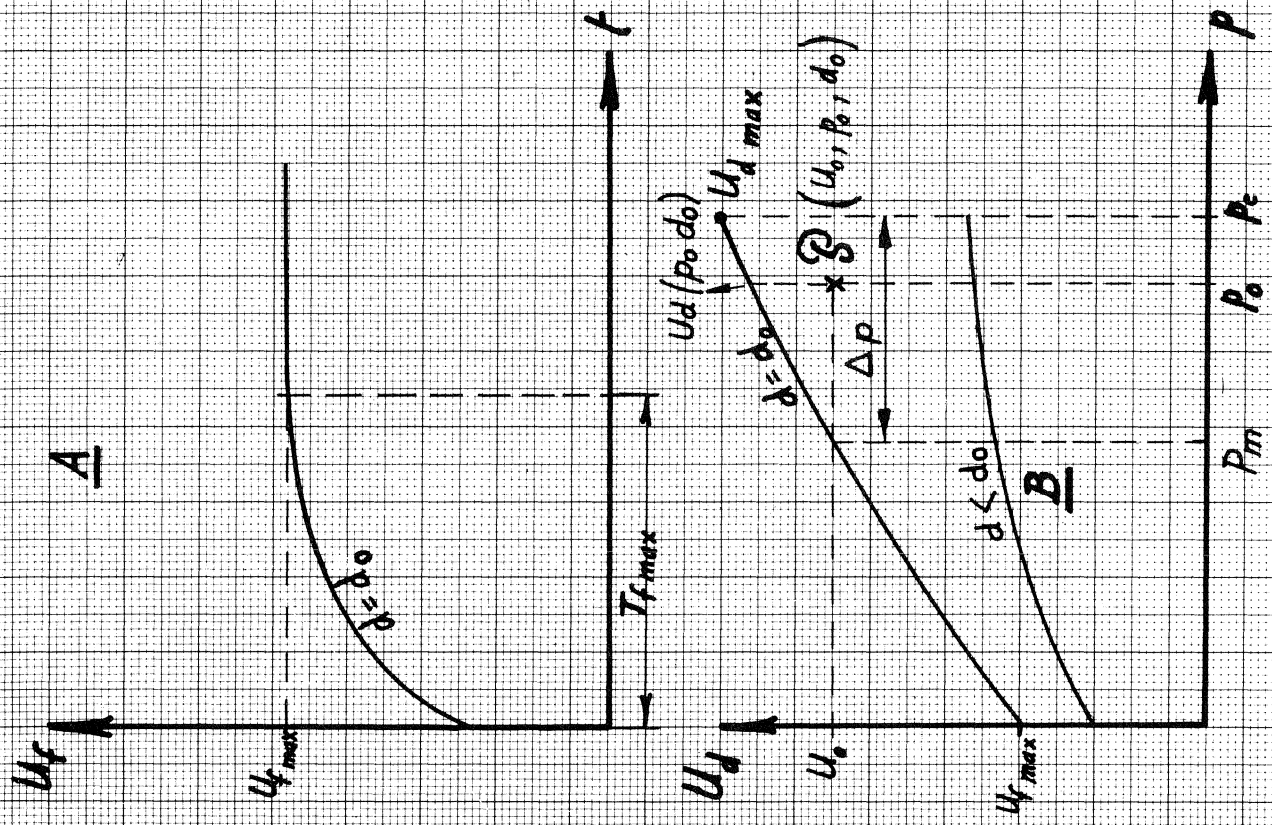
Section C+C

Section D+D



3 metres electrostatic separator

Fig. 2

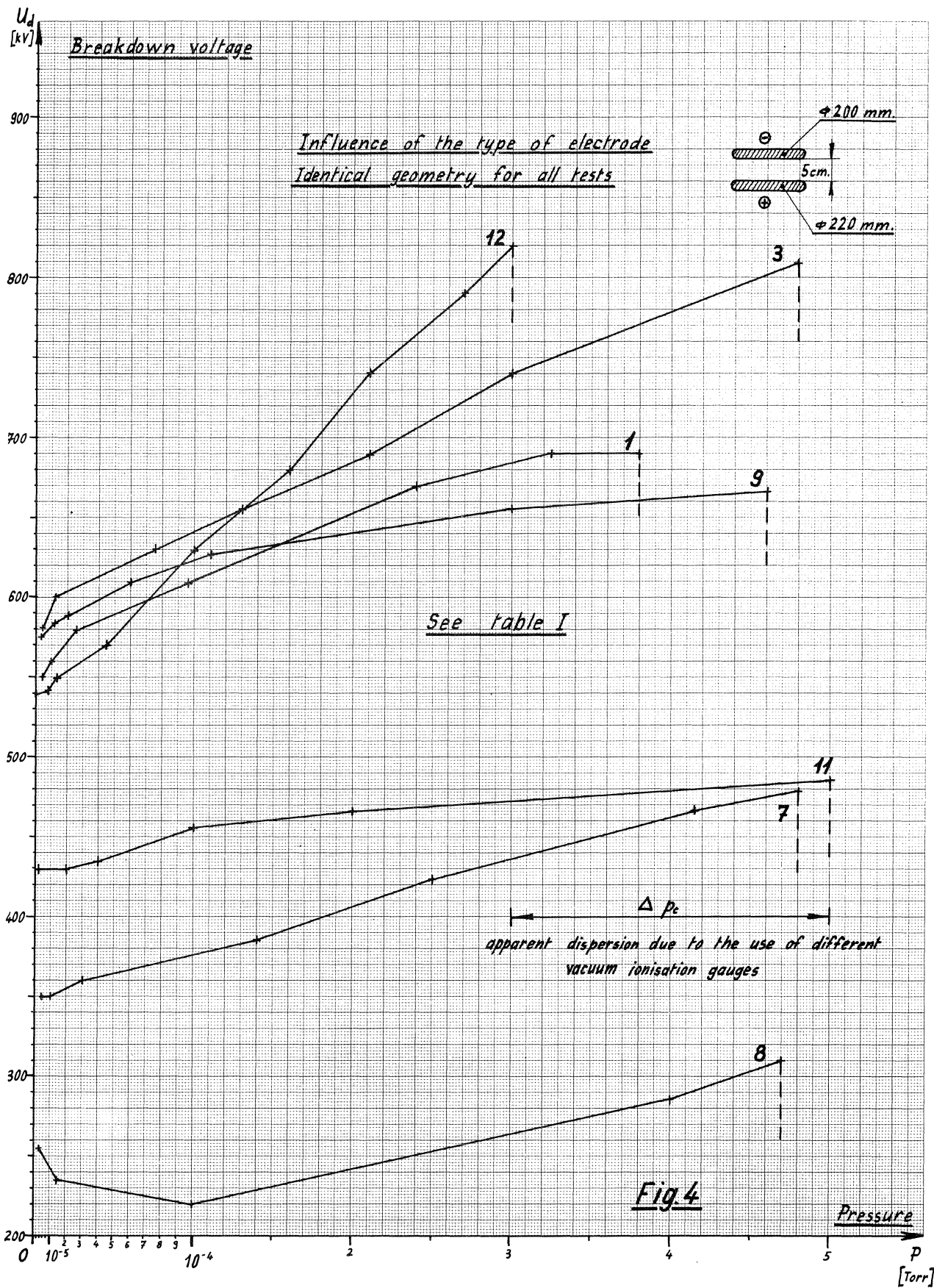


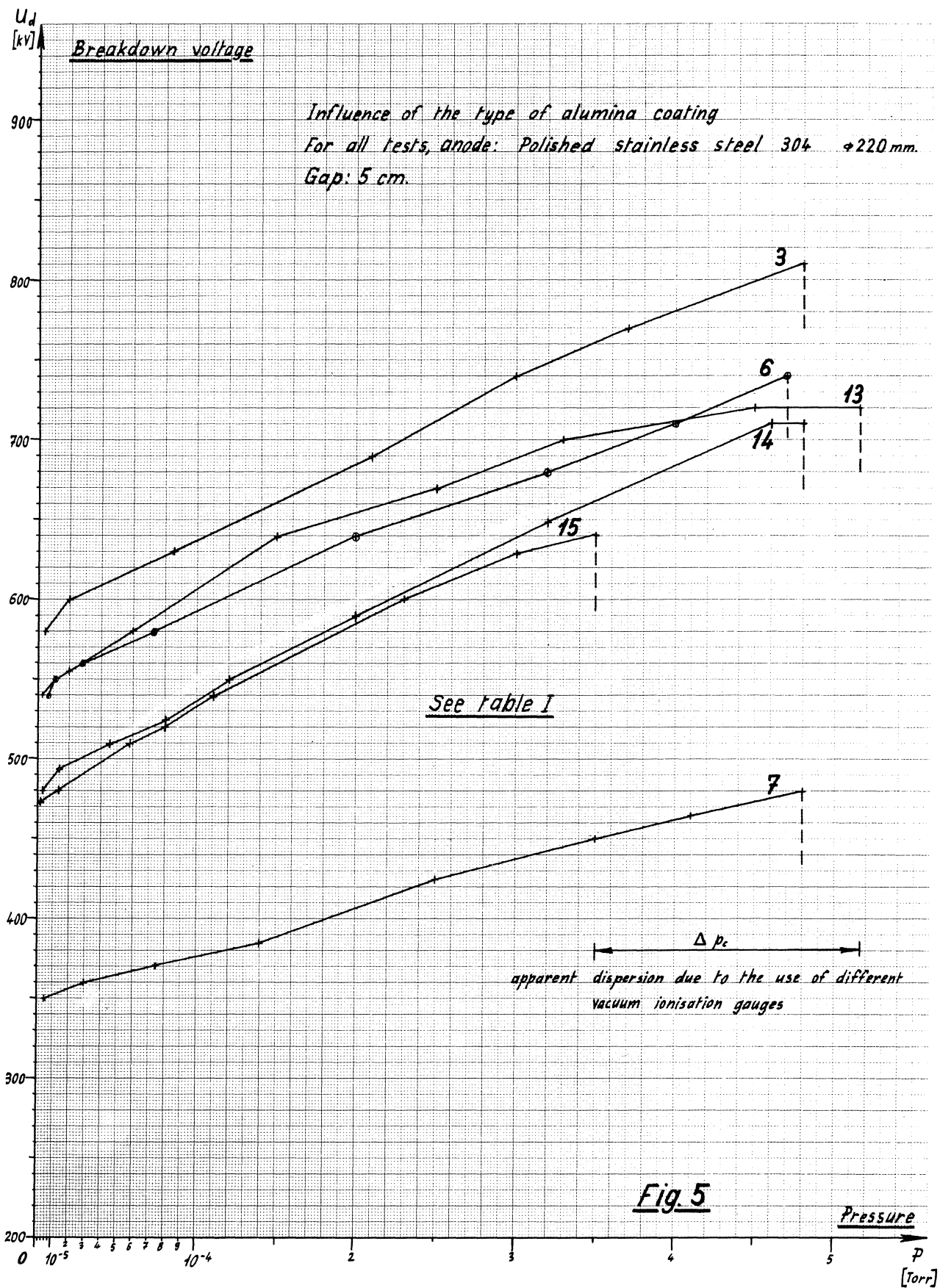
General behaviour and definitions

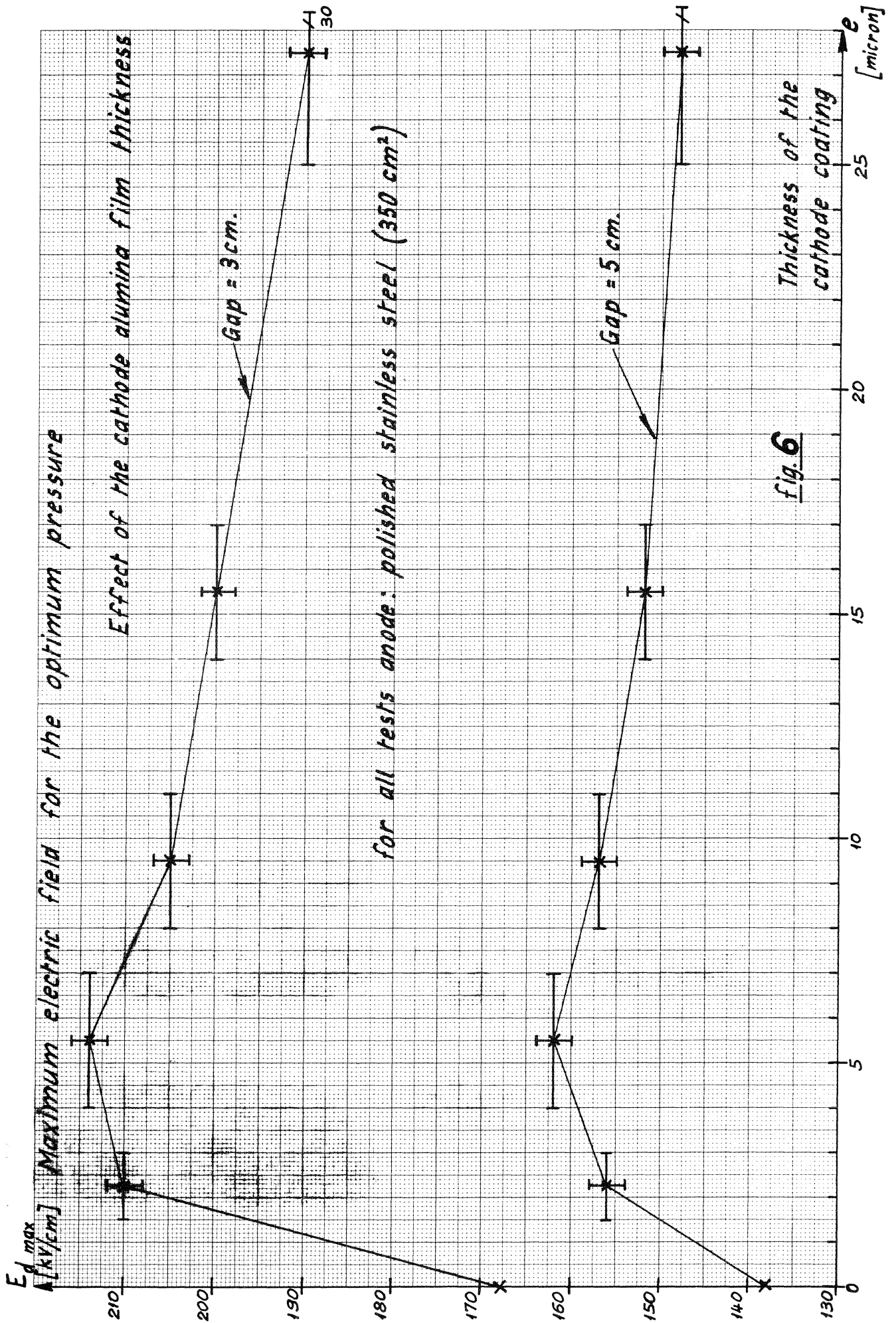
- A - Low pressure conditioning curve
- B - Breakdown voltage pressure curve
- C - Sparking rate as a function of time for  $\mathcal{B}(U_0, p_0, d_0)$

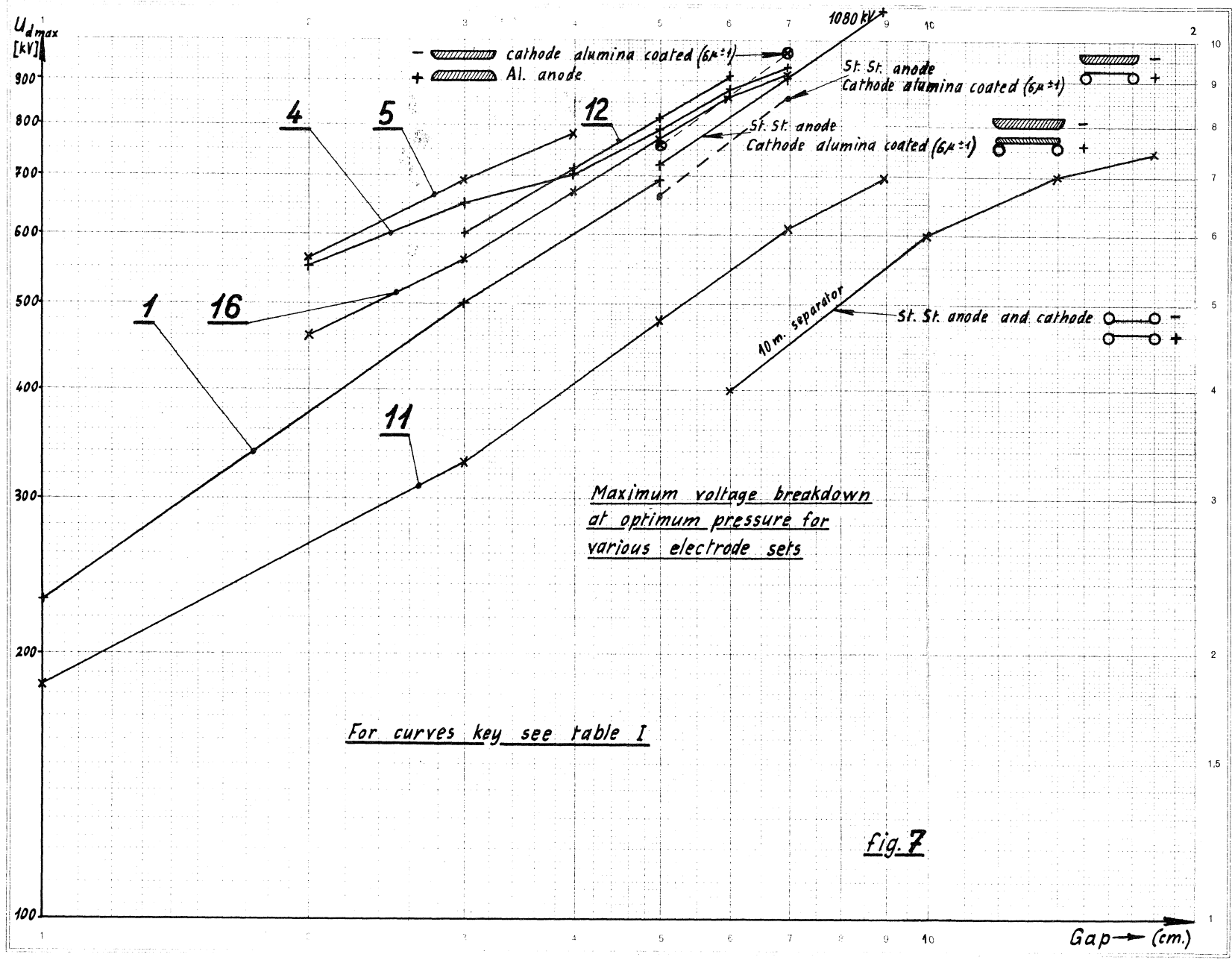
fig. 3

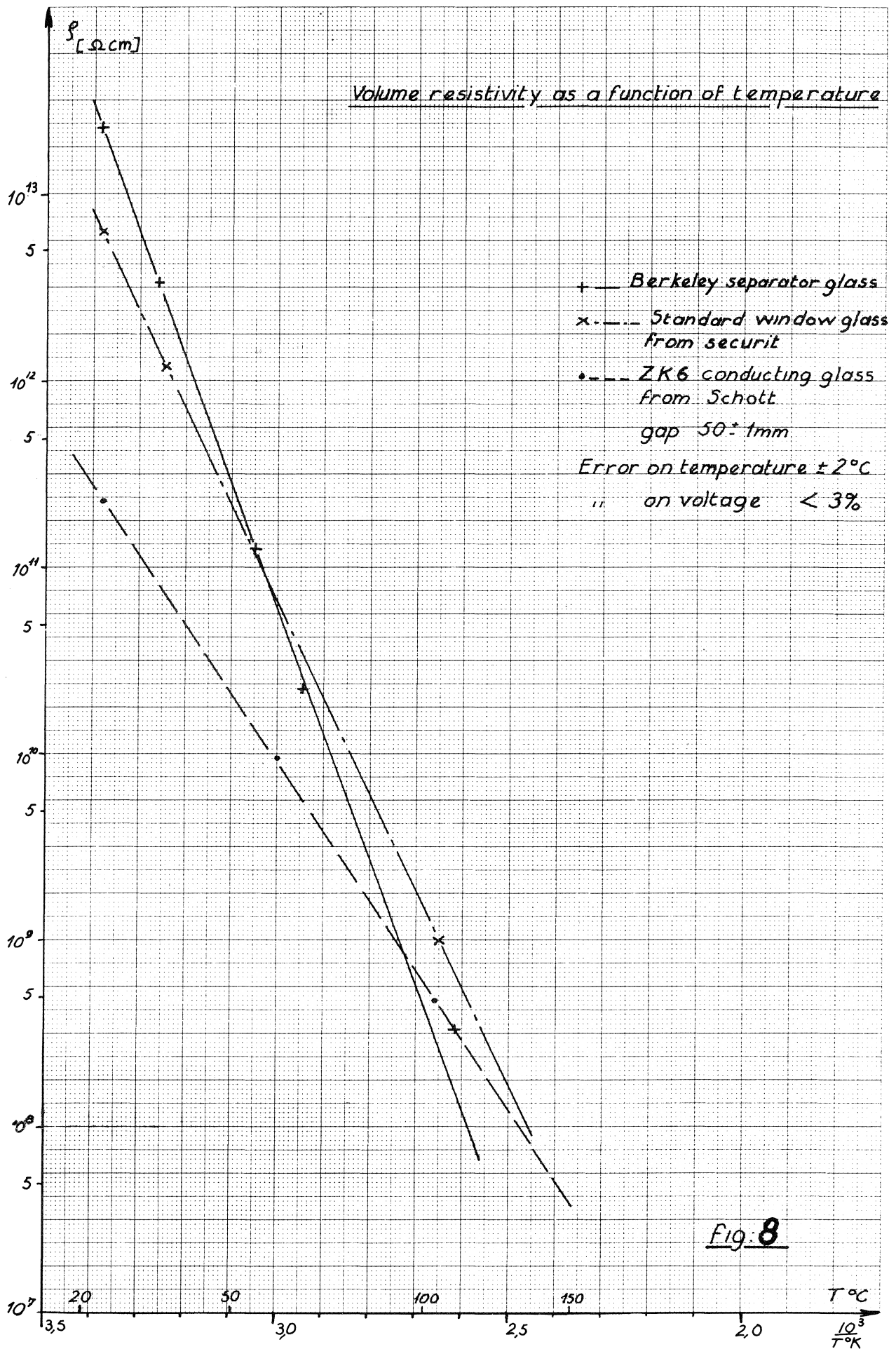




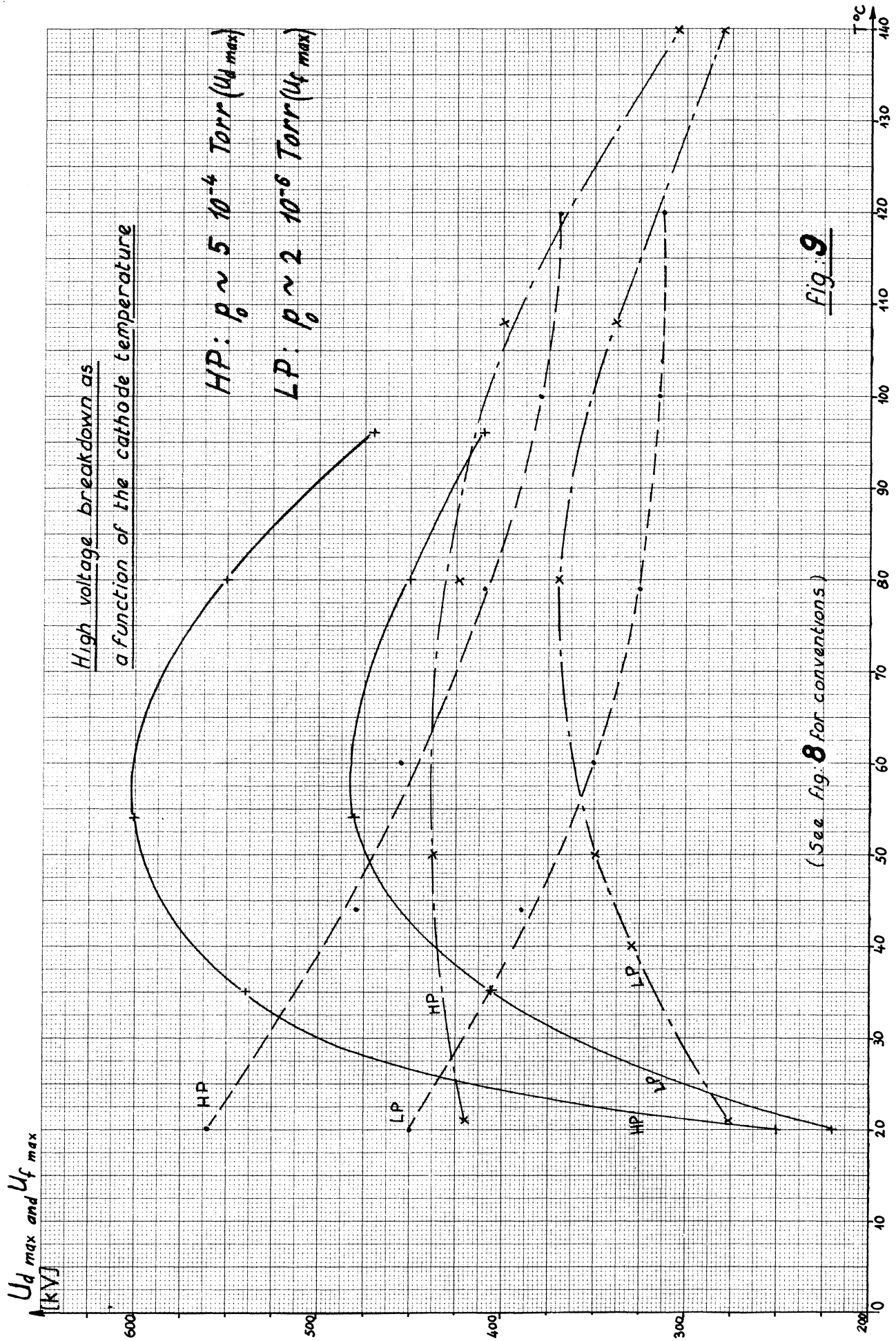


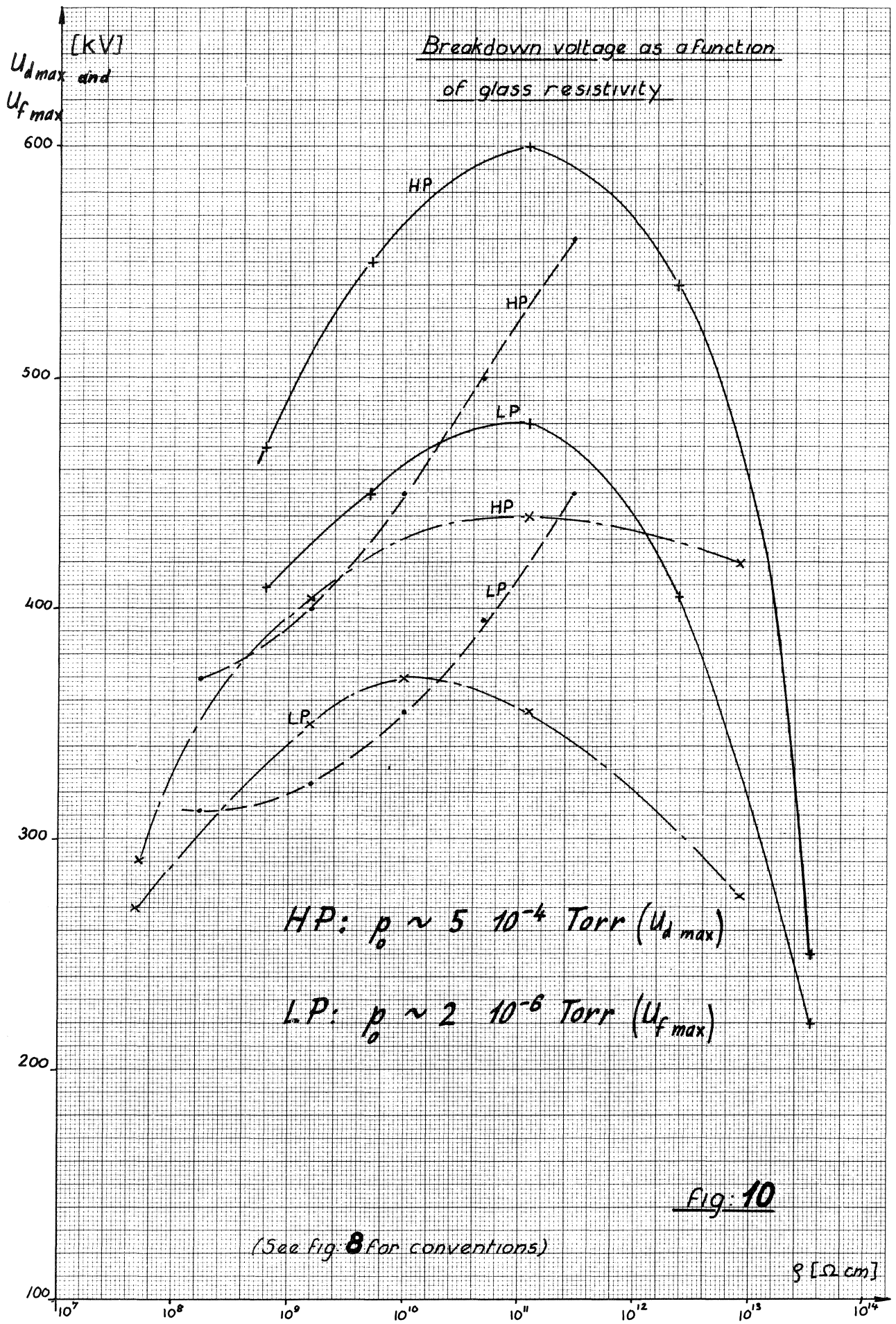


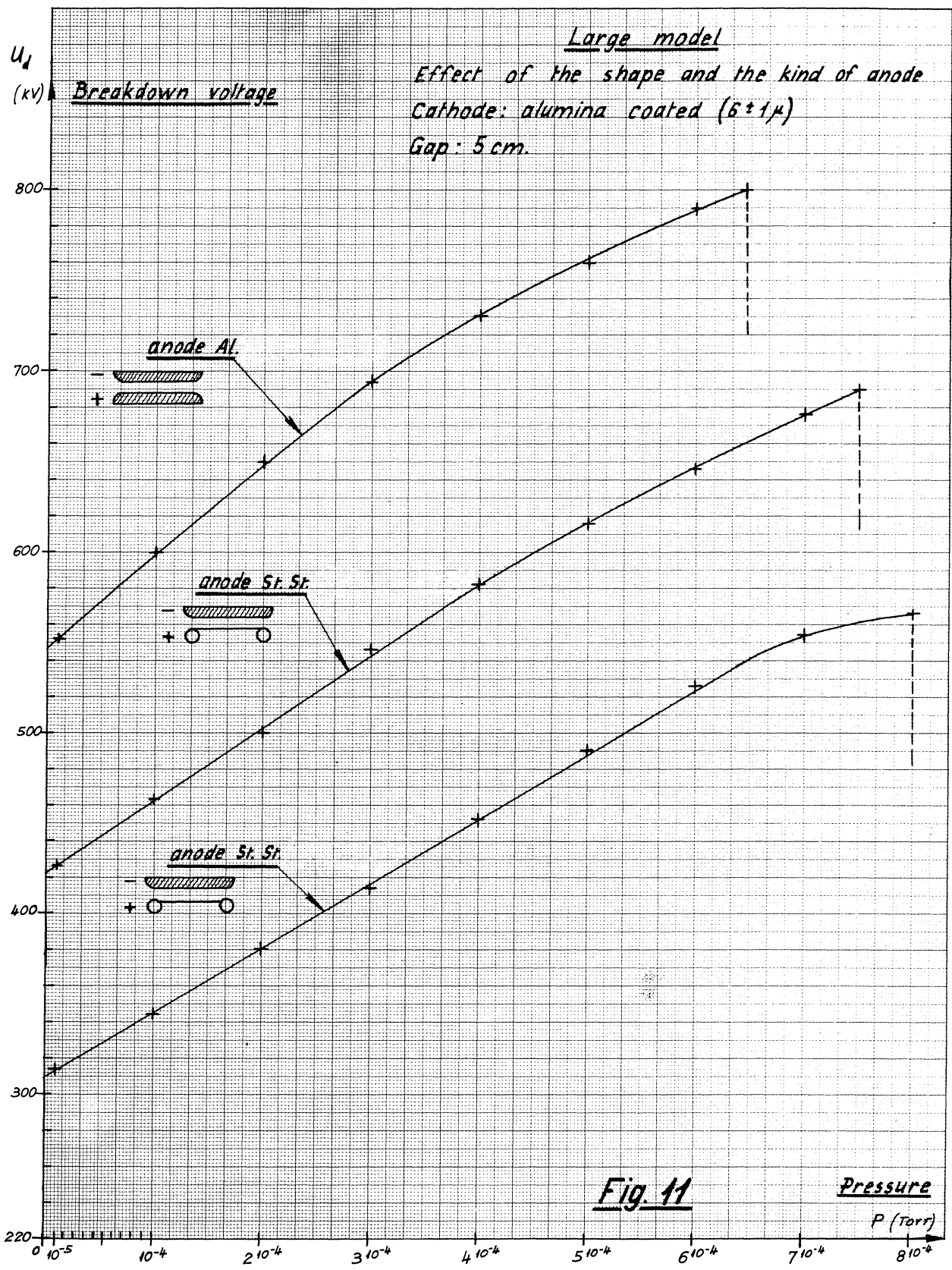














Effect of the type of gas

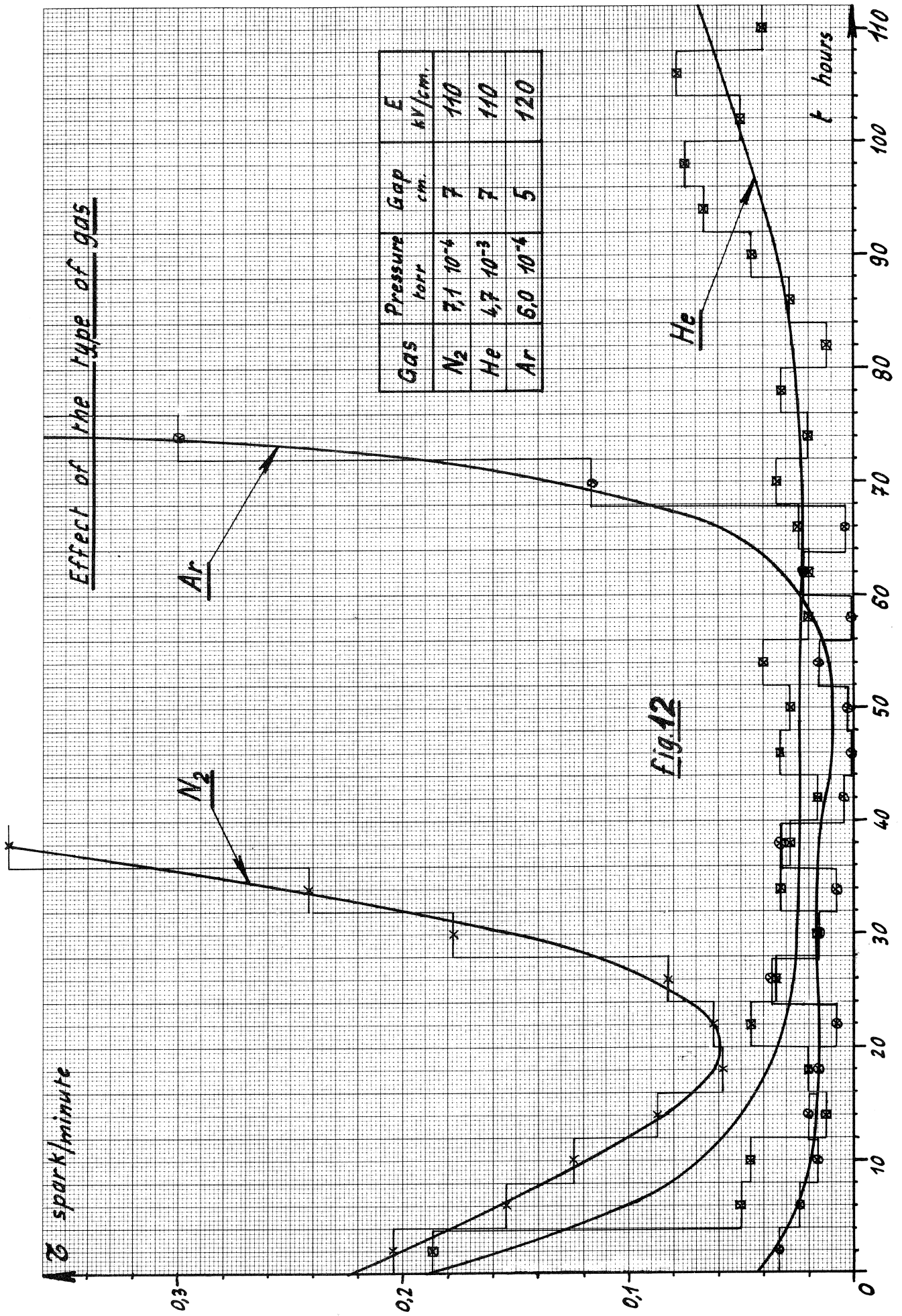
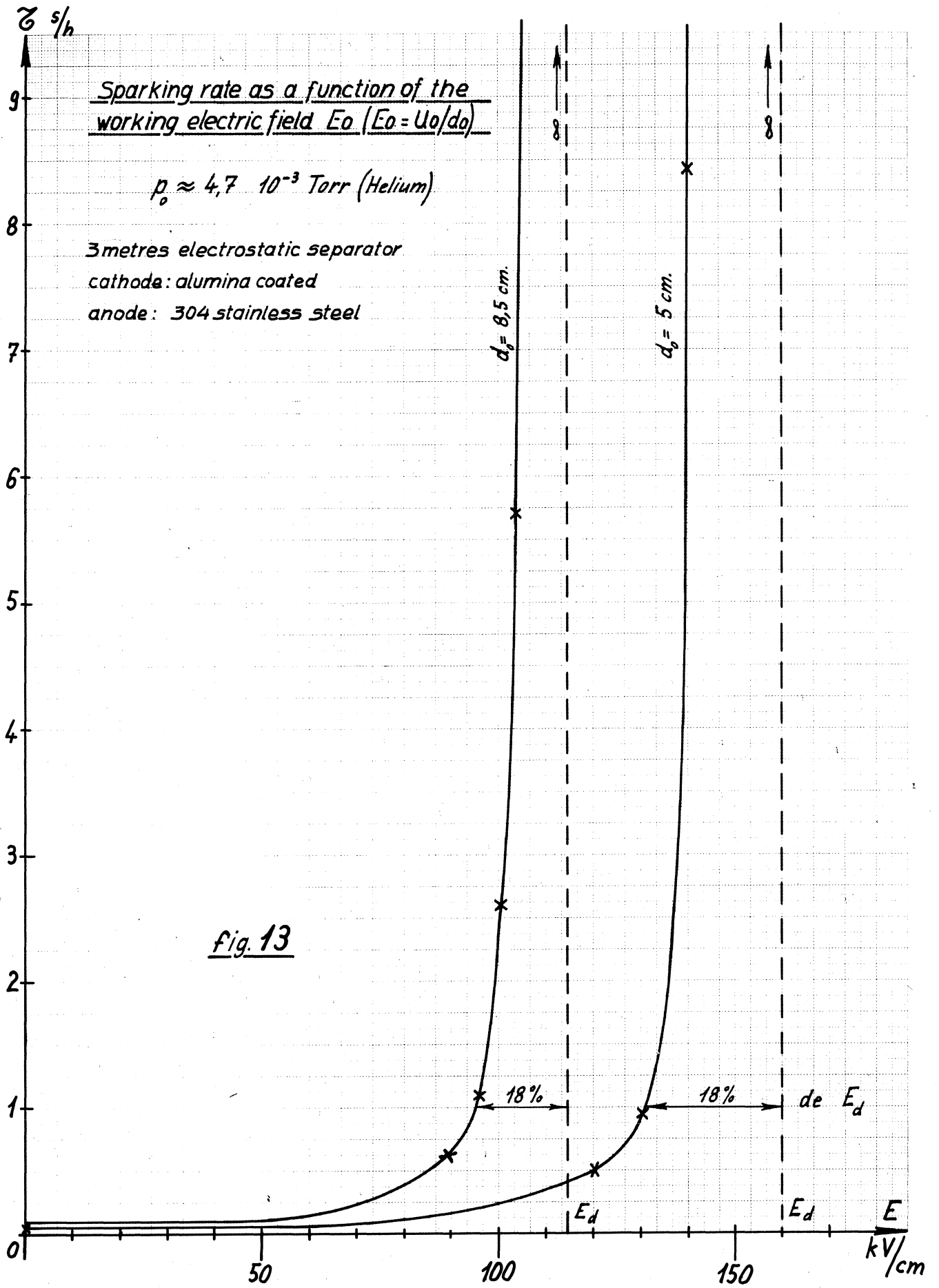
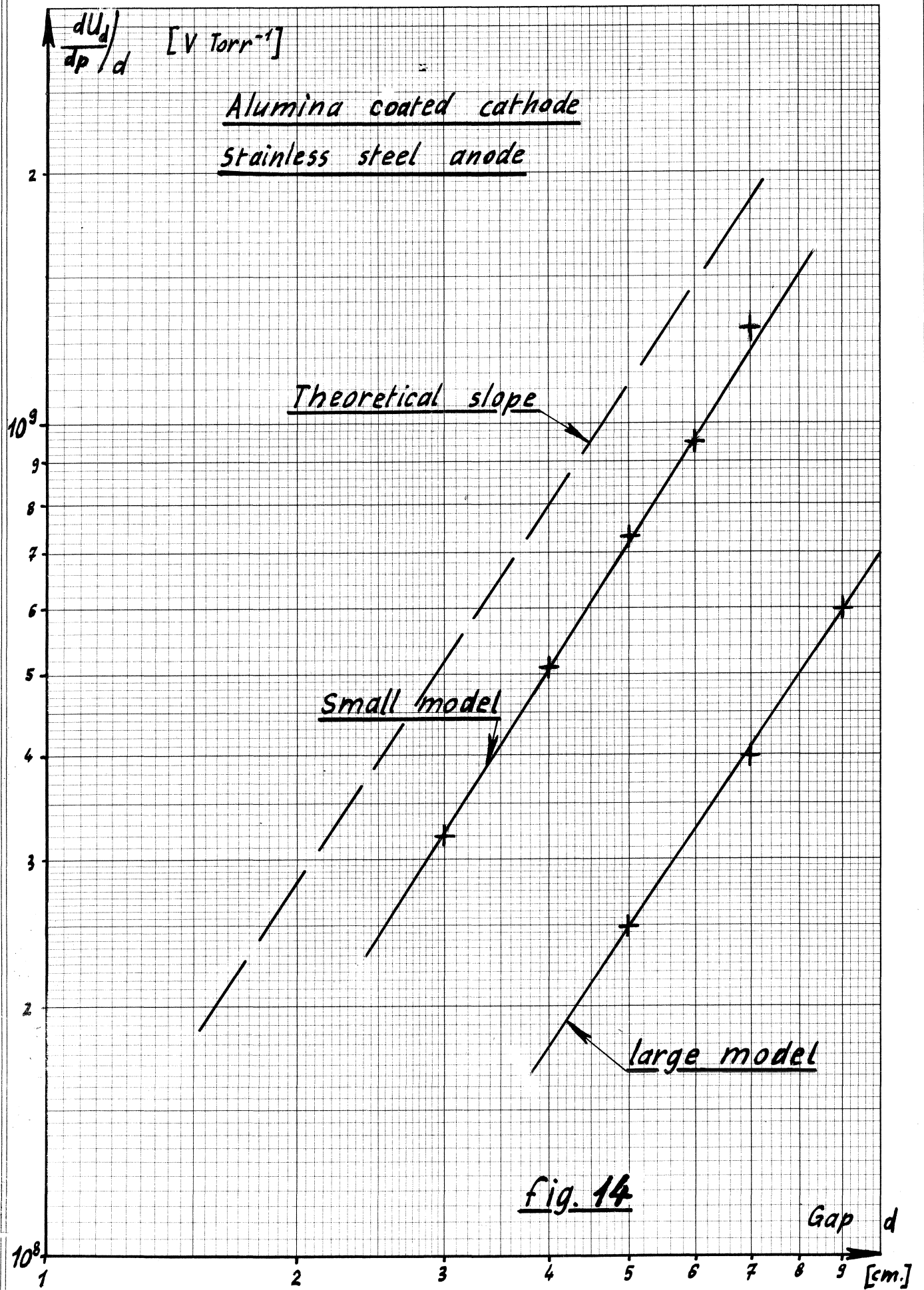
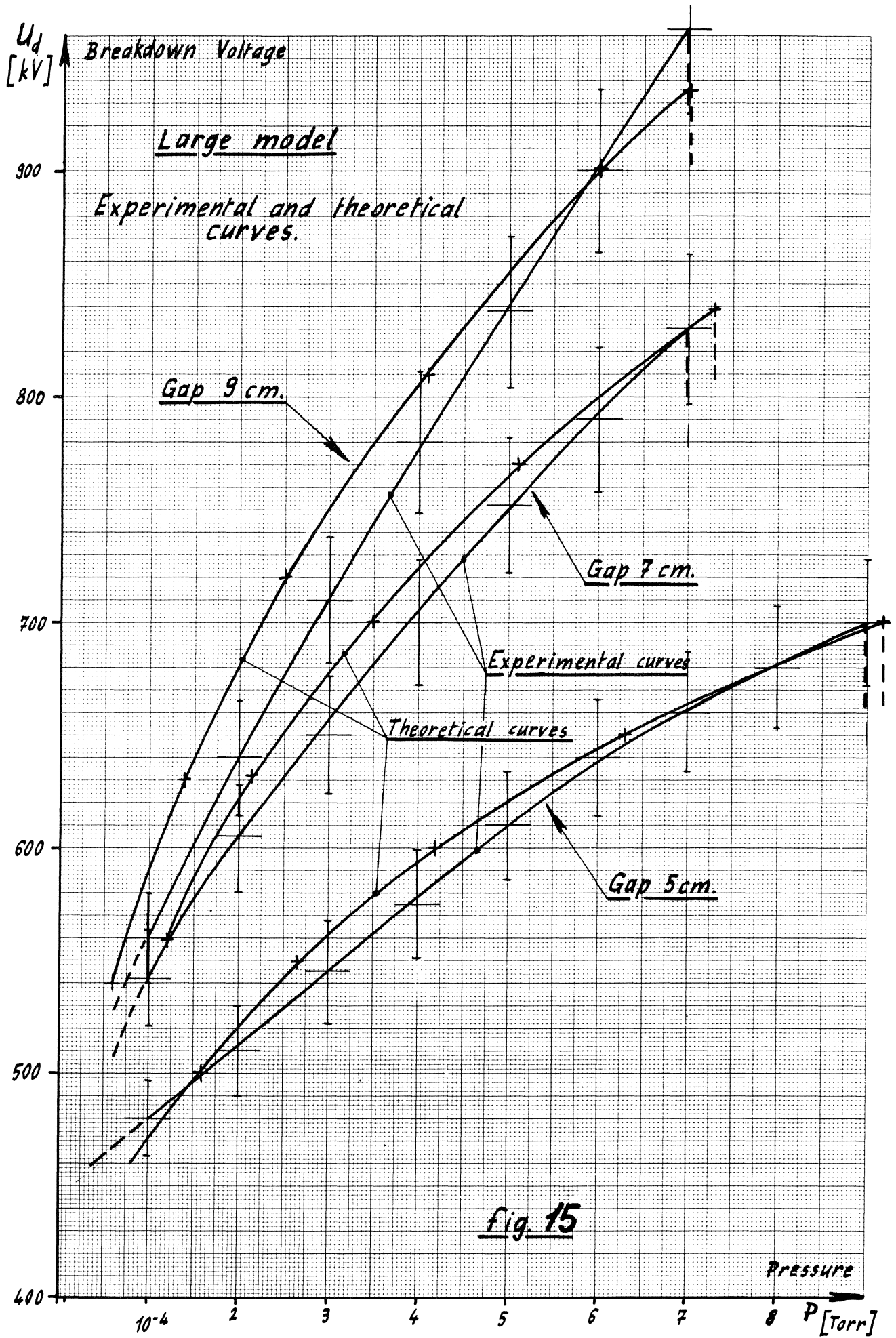
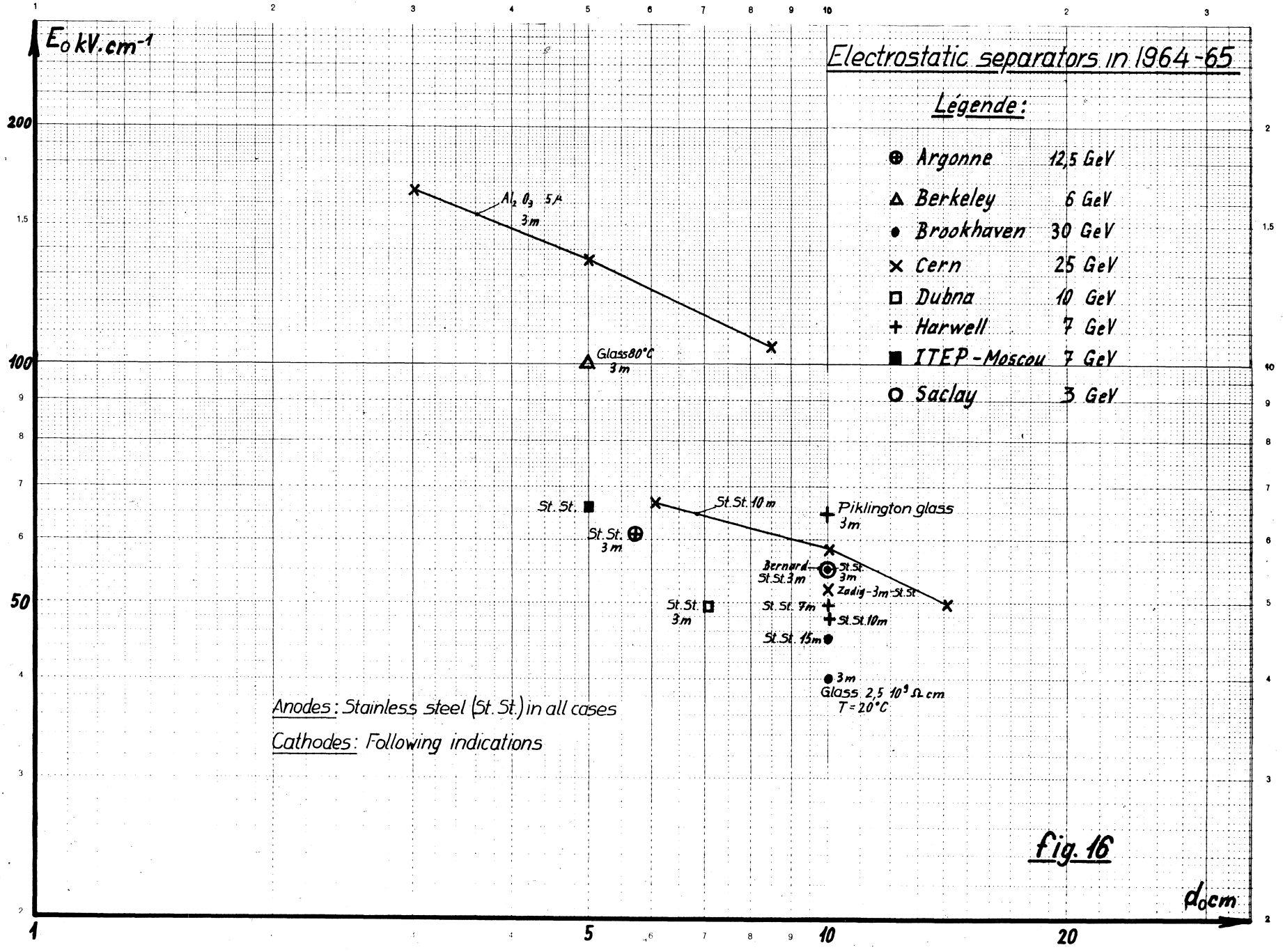


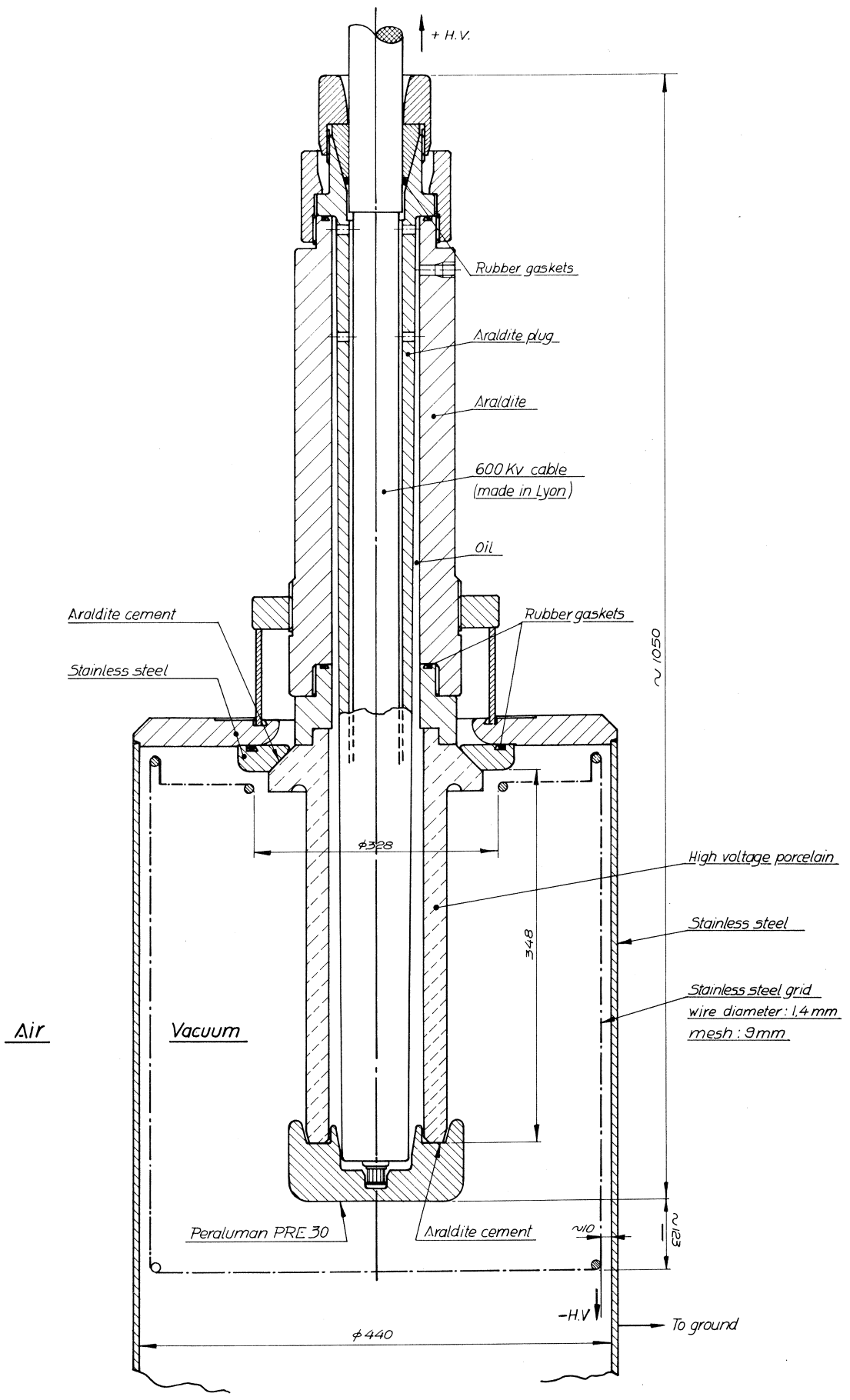
FIG. 12







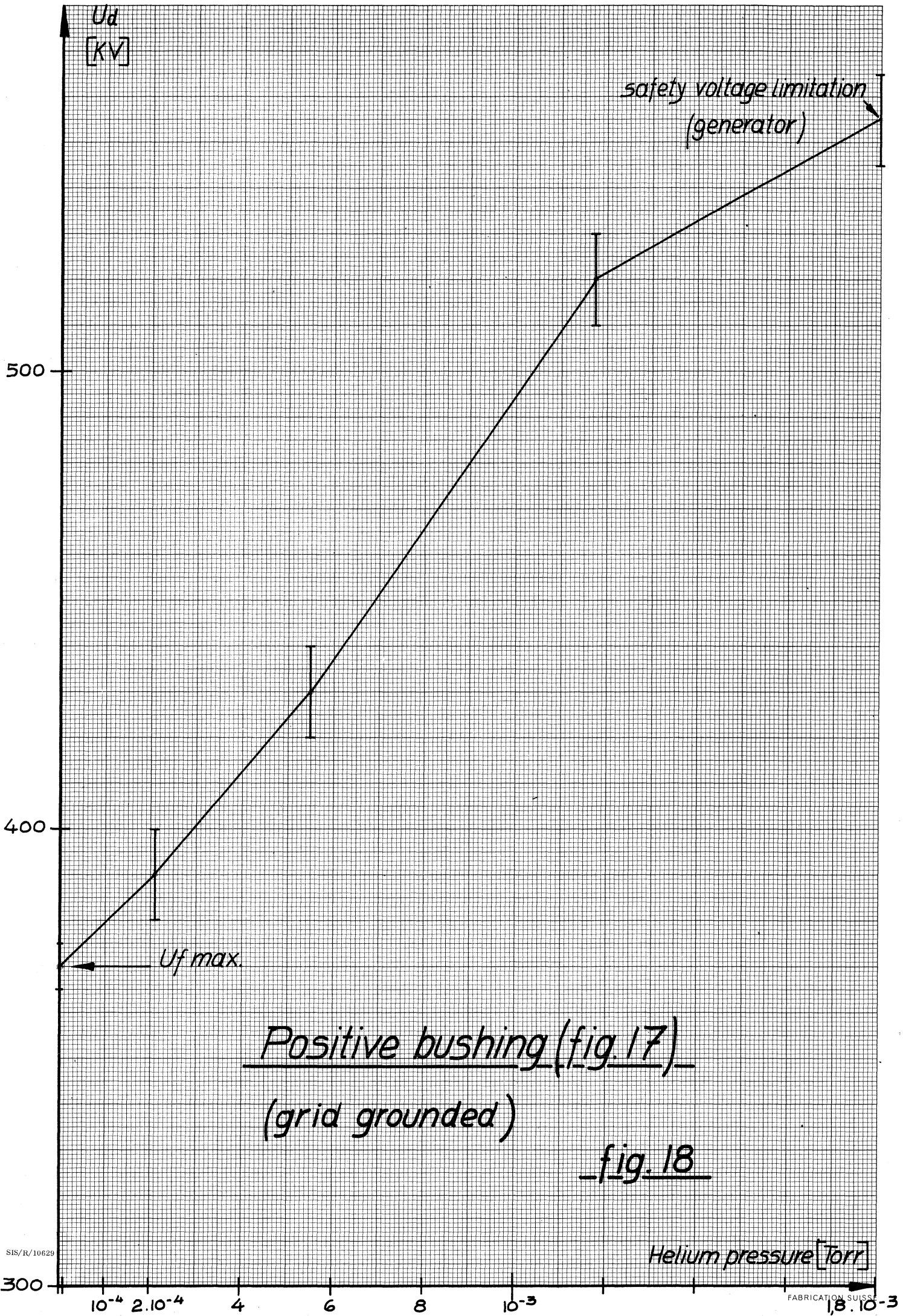


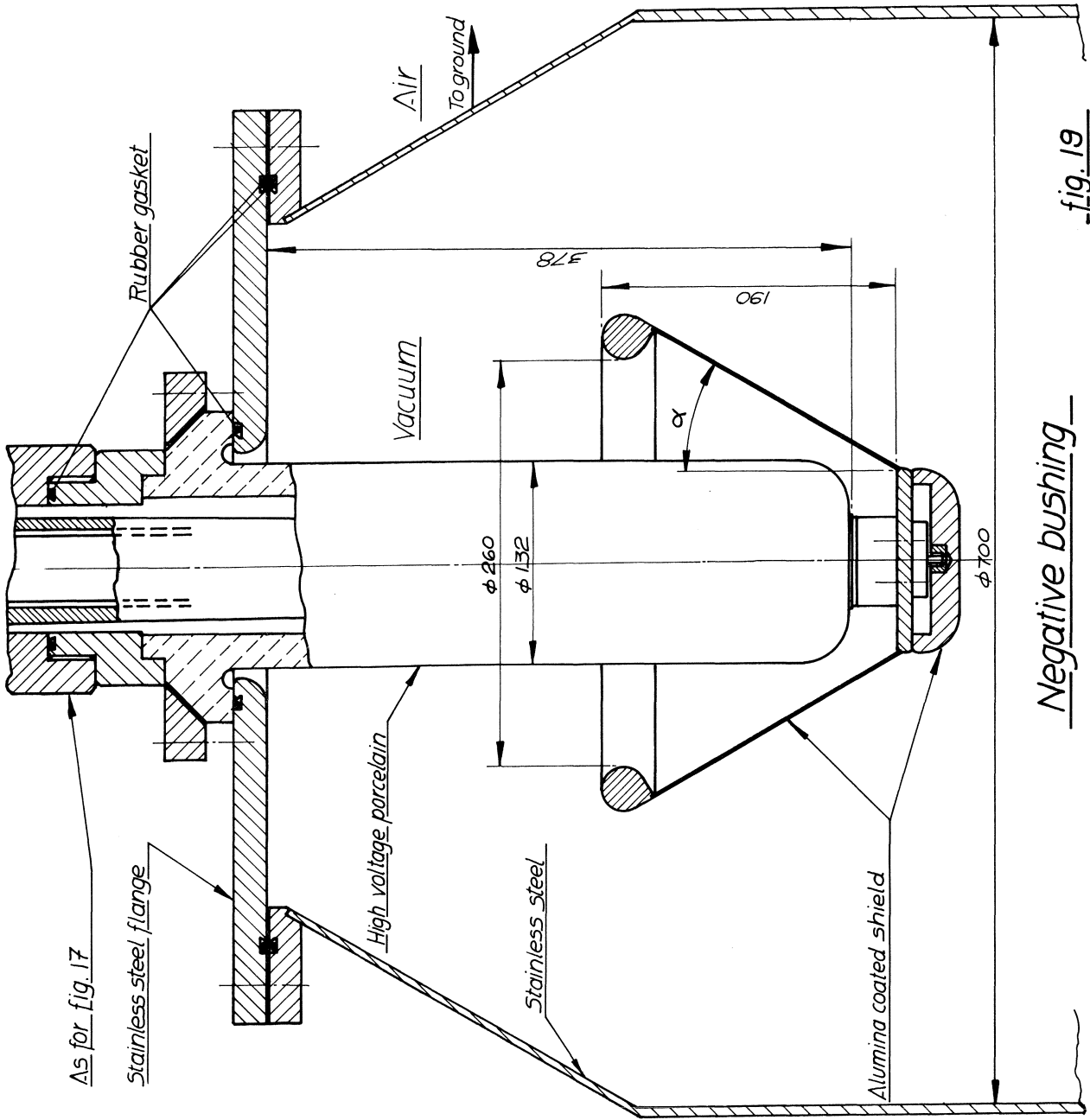


Positive high voltage bushing

fig. 17







Negative bushing

fig. 19



