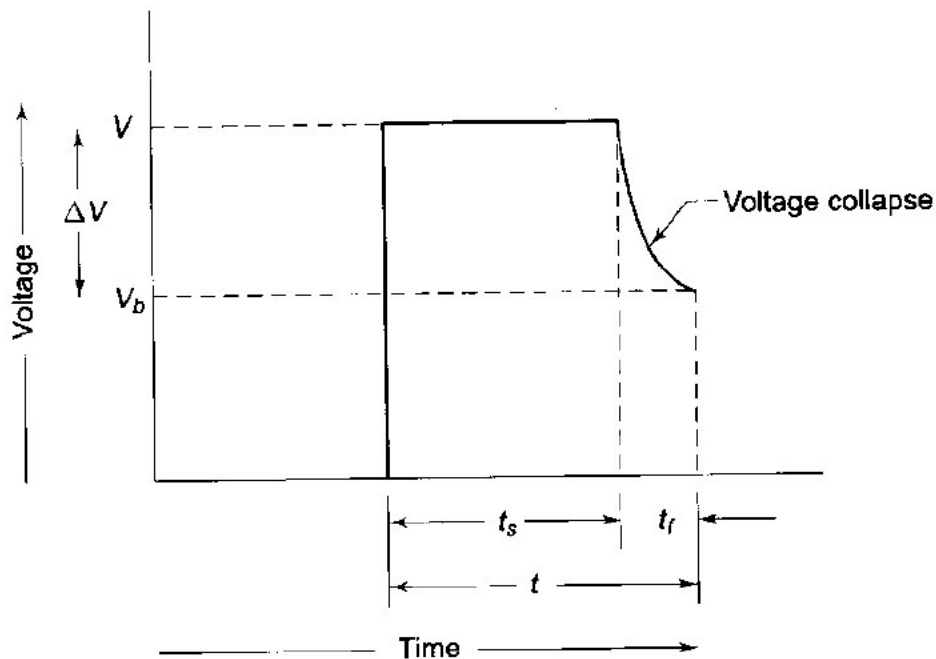


2.3 STATISTICAL TIME LAG



Breakdown with a step function voltage pulse. t_s = statistical time; t_f = formative time; t = total time

The time between application of voltage in excess of the static onset voltage and collapse of the gap resistance is the sum of the statistical and formative delay times, i.e.,

$$t_{\text{tot}} = t_f + t_s \quad (1)$$

The statistical delay time t_s is the time between application of the voltage and the initiation of an uninterrupted sequence of electron avalanches (or the onset of a streamer). The formative delay time t_f is the time taken from the end of the statistical time lag to the onset of discharge, characterized by the collapse of the applied voltage as a self-maintained glow or arc discharge forms.

If the electron is liberated by natural causes the statistical delay time may be as long as several seconds but on average is about 10^{-2} s. Free electrons are produced naturally in the atmosphere as a result of the arrival of cosmic rays and the presence of local radioactive materials or the penetration of ultraviolet radiation from the sun. The rate of production of free electrons created by these means is of the order of $10 \text{ cm}^{-3}\text{s}^{-1}$.

The most effective place to liberate initiatory electrons is at the cathode since they then undergo maximum ionizing collisions as they traverse the greatest distance to the anode. It is thus instructive to consider **the relationship between the rate of electron emission from a cathode and the mean statistical time lag.**

Suppose that the probability that an electron is emitted from the cathode in any interval t to $t+dt$ is constant and given by $J \cdot dt$. The probability of breakdown in

this interval is then $J.P.dt$, where P is probability that an electron initiates an uninterrupted avalanche sequence. Thus if the interval $(0,t)$ is divided into ν small intervals dt the probability that **no electron initiates** an uninterrupted avalanches sequence in t is

$$(1-J.P.dt)^\nu = (1-J.P.t/\nu)^\nu \quad (2)$$

and this is the probability that a time lag exceeds t . In the limit as ν is made very large this becomes equal to $\exp(-J.P.t)$. Consequently, statistical delay times follow the distribution

$$N_t/N_0 = \exp(-J.P.t) \quad (3)$$

where N_t/N_0 is the fraction of delay times greater than t . The average statistical delay time τ then equals $1/(J.P)$.

When experimental conditions are such that the formative time delay t_f cannot be assumed to be insignificant fraction of the total time lag the measured distribution may be written as

$$N_t/N_0 = \exp[-J.P.(t-t_s)] \quad (4)$$

These relations were first derived by Laue(1925) and verified experimentally by Zuber (1925). They form the basis of a **method by which the rate of electron emission from a given cathode may be obtained from observation of the distribution of time lags**. Thus, if a rectangular voltage impulse of sufficient amplitude to make **P approach unity** (see Fig.1) and to make the formative delay time t negligibly small is applied to a discharge gap at time $t=0$, then

$$J = (1/t).\ln(N_t/N_0) \quad (5)$$

and **estimates of J may be obtained from the slope of a linear graph of $\ln(N_t/N_0)$** . This will be the case in carefully controlled conditions. It is essential that N_0 should be large to obtain a adequate accuracy in the evaluation of J since the accuracy increases as $N_0^{1/2}$. Thus in order to achieve an accuracy of 3%, N should not be less than 1100. It can be used to study the role of electrode surface state in determining its ability to initiate discharges, or the efficiency of gap irradiation in producing breakdown.

When experimental conditions are such that the P cannot be assumed to be equal to 1, J and P can be found as follows.

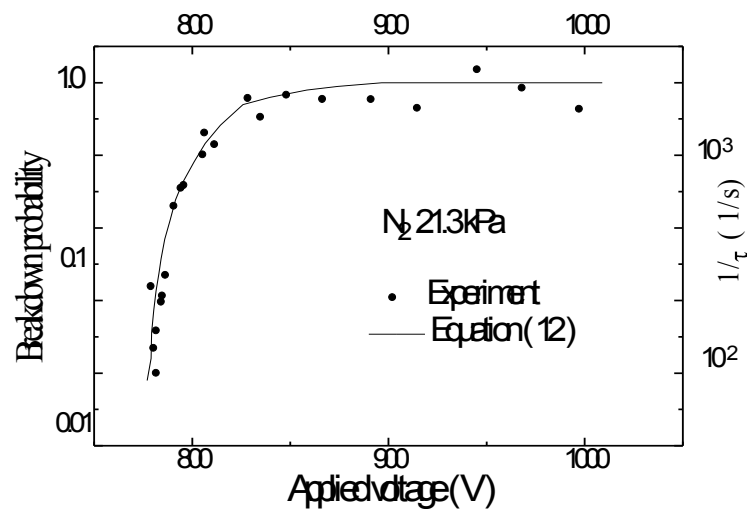
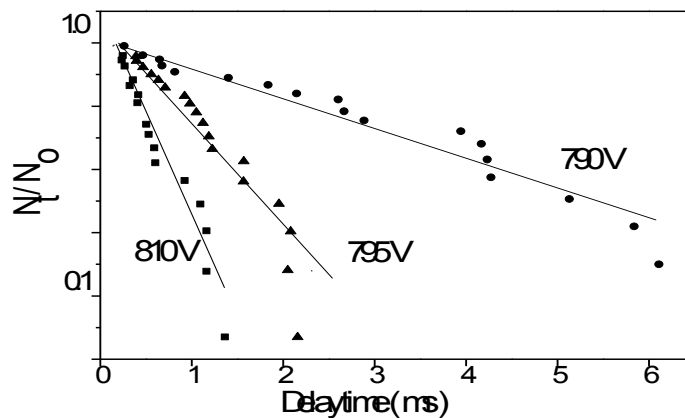


FIG.2. Laue plots of spark delay times in N_2 at 21.3 kPa Exp. conditions: 1.25-cm-diam steel cathode, electrode spacing $S=0.5$ mm. (Taken from: Hodges et al., Phys.Rev.A 31(1985)2610.

The dependence of the average delay times on voltage is shown in Fig.3. The right ordinate applies to the experimental points. Each point is the reciprocal of an average delay time and represents the slope of a line like those in Fig.2. As the applied voltage increases, the delay time approaches an asymptotic value which is determined by J (the rate of appearance of electrons) since the value of P is approaching one. The asymptotic value establishes the position of the scale on the left ordinate, which gives the breakdown (i.e., the discharge onset) probability P . If the value of P for given gap voltage is found using the scale on the left ordinate, then corresponding value of J can be found using the Laue equation (4).
 FIG.3. Experimental breakdown delay times and calculated discharge initiation probabilities for N_2



at 21.3 kPa ($S = 0.45$ mm, $\gamma = 1.2 \times 10^{-2}$)

2.4 IMPORTANCE OF CATHODE SURFACE CONDITIONS: CATHODE CONDITIONING.

In the absence of illumination and heating of the cathode the source of initiatory electrons is almost always field dependent emission. From very pure clean metal surfaces in ultra-high vacuum significantly large field emission currents, i.e. current densities $>10^6$ electrons $\text{cm}^{-2} \cdot \text{sec}^{-1}$ require strong electric fields on the order of 10^7 V/cm. However, it is well established that large rates of electron emission can be obtained from cold unilluminated cathodes in gases at electric fields as low as 10^4 to 10^5 V/cm. In these cases surface contaminating films and microprojections play a vital role in the electron production process. There is evidence which suggests that the emission mechanisms may involve detachment of electrons from electronegative molecules attached to the surface or intense local electric fields set up by ions, created in an earlier discharge, across thin insulating films. Thus, positive ions are produced in the gas drift to the cathode, where they can reside for even several minutes. If there is an oxide or tarnish layer on the cathode, or a dust particle, the positive ions can create an intense field across the layer or particle and cause field emission of electrons. List (1961) considered that, when positive ions were being formed on a cathode layer at a faster rate than the ions were leaking away, the field emission of electrons from the layer continually increased to cause breakdown. The breakdown criterion was of the form

$$A.R.(E/\varepsilon - B)^C \cdot [\exp(\alpha \cdot x) - 1] = 1 \quad (1)$$

where R and ϵ were the resistivity and permittivity of the cathode layer, A, B and C were constants and E was the applied field. This criterion is of similar form to the Townsend criterion

$$\gamma[\exp(\alpha x) - 1] = 1 \quad (2)$$

but is dependent on E/p and E . Since the "classical" criterion(2), from which Paschen's law can be derived, is dependent only on E/p and not E . In agreement with this, deviations from Paschen's law occurring obviously when the electric field strength at the discharge onset reaches values of the order of 10^5 V.cm^{-1} (see Fig.4) are usually described to the onset of field emission.

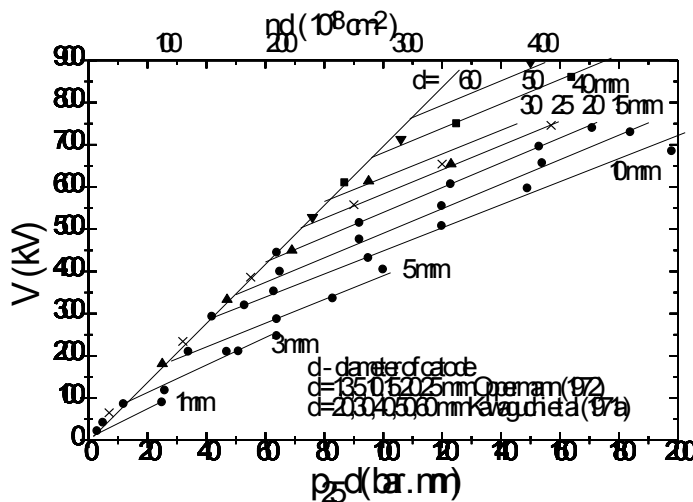


FIG.4. Breakdown voltages in SF_6 at high pd.

The failure of Paschen's law due to field emission processes is important from point of view of high-pressure gas insulation in HV apparatus. For example, although SF_6 is widely used as a HV

insulating medium, at electrical stresses in excess of about $2 \times 10^5 \text{ V/cm}$, the breakdown strength obviously falls short of that predicted theoretically on the base of Paschen's law (see Fig.4). However, this shortfall appears not to be a failing of the SF_6 itself since some experimenters have found that, by taking great care over preparation and choice of electrode material and size, the theoretical strength can be attained at stresses up to about $2 \times 10^6 \text{ V/cm}$. Consequently, the poor performance of HV gas insulation is often attributed to electronic field emission from emission sites, which generally switch on at threshold fields of roughly $2 \times 10^5 \text{ V/cm}$ to give noisy and unstable pre-breakdown currents of some $10 \mu\text{A}$.

The performance of HV gas insulation can be improve by so-called cathode conditioning. The breakdown voltage V_S of a uniform-field discharge gap at pressures up to a critical pressure value is independent of the number of breakdowns if the discharge energy is restricted to prevent damage to electrodes. At higher pressures, when the applied field strength is of the order 10^5 V/cm , V_S increases with the number of breakdowns and eventually reaches a fairly constant value. This "spark-conditioning effect" is shown in Fig.5, where it is seen that V_S can be more than doubled after 100 sparks. The number of conditioning sparks and the relative increase in V_S become larger as the electrode area and field are increased, so that sometimes hundreds or several thousands of conditioning sparks are required. Spark conditioning is primarily an electrode effect, and electrodes conditioned at one pressure need further conditioning when the pressure, and therefore the field, is increased. It is usually interpreted as the successive destruction of the more

intense field emission sites such as dust particles, contaminating films, and microprojections, until eventually there are a large number of similar sites remaining. This is illustrated in Fig.6 for highly polished steel electrodes in nitrogen, where a decrease in electron emission rates due to conditioning corresponds apparently to a reduction in number of cathode field emission sites.

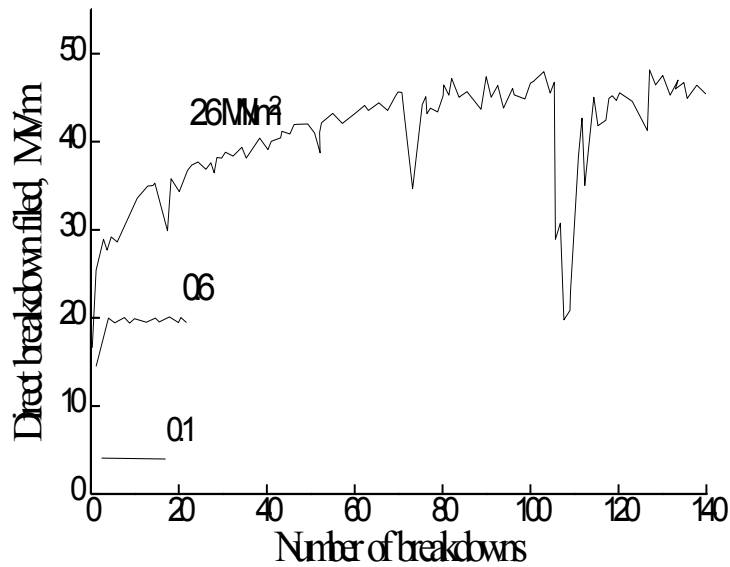


FIG.5. Effect of spark conditioning on the breakdown field of compressed nitrogen, using parallel plane oxidised-copper of 25 mm diameter at a spacing of 1 mm.