High Voltage Engineering

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ELRCTRIC BREAK DOWN IN GASES

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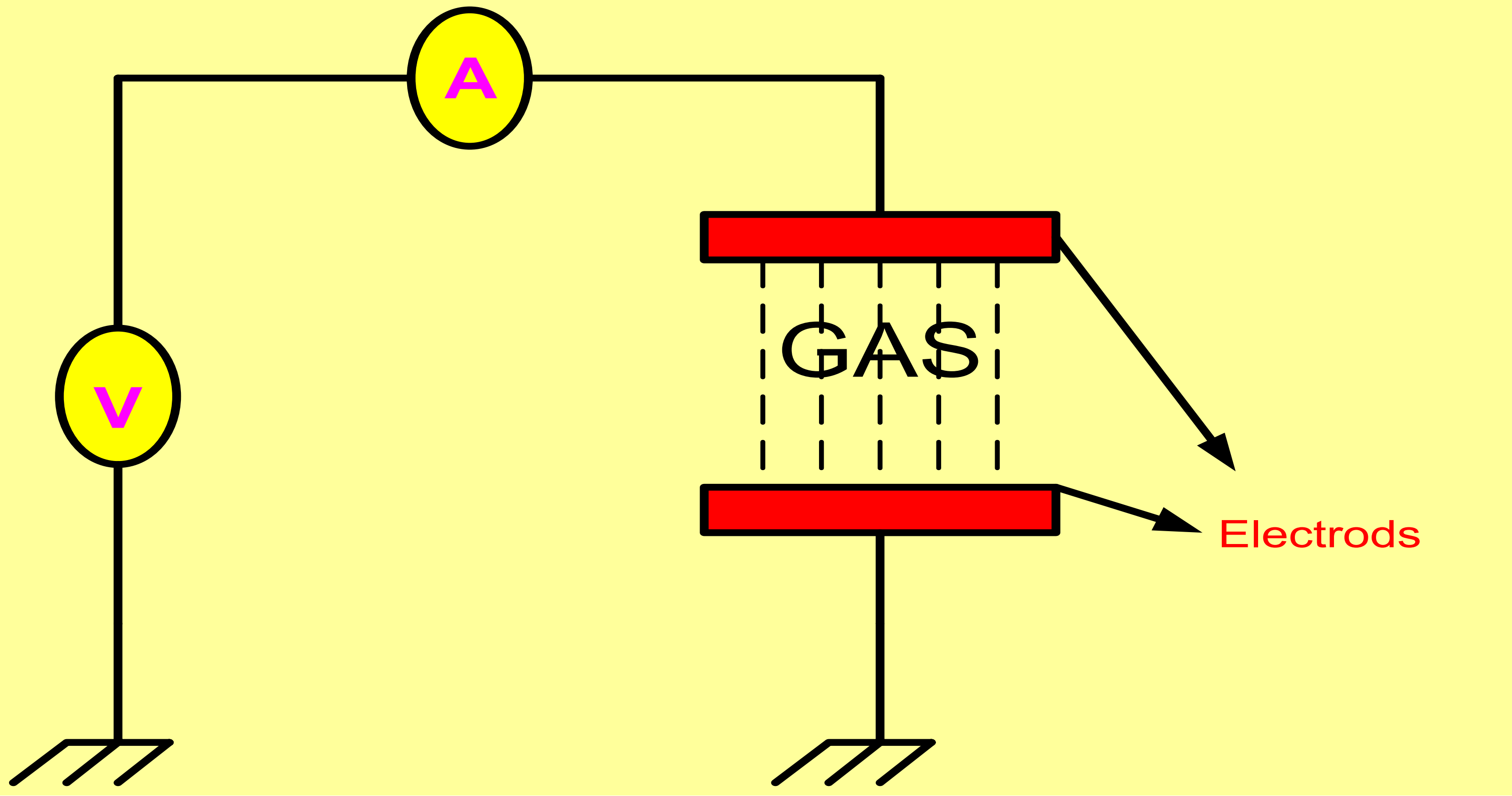
ELECTRIC BREAK DOWN IN GASES

The Townsend criteria for a spark.



ELECTRIC BREAK DOWN IN GASES

$$i = i_0 \frac{\exp(\alpha d)}{1 - \gamma\left(e^{\alpha d} - 1\right)}$$

i_o= initial current / sustain current
α=Townsend's First Ionization constant/coefficient
γ=Townsend's Second Ionization constant/coefficient

As the applied voltage across a spark gap increases the current increases in accordance with the above equation. If voltage increase continues a point comes when there is a sudden transition from the Townsend's dark current to a self sustaining discharge.

ELECTRIC BREAK DOWN IN GASES

This transition or spark, is accompanied by a sudden change in the current in the gap.

At this stage “i” becomes indeterminate and the denominator in the above equation vanishes, i.e. three different conditions

$$1-\gamma\ (\exp\ (\alpha d)-1) = 0$$

$$\gamma(\exp\ (\alpha d)-1) = 1$$

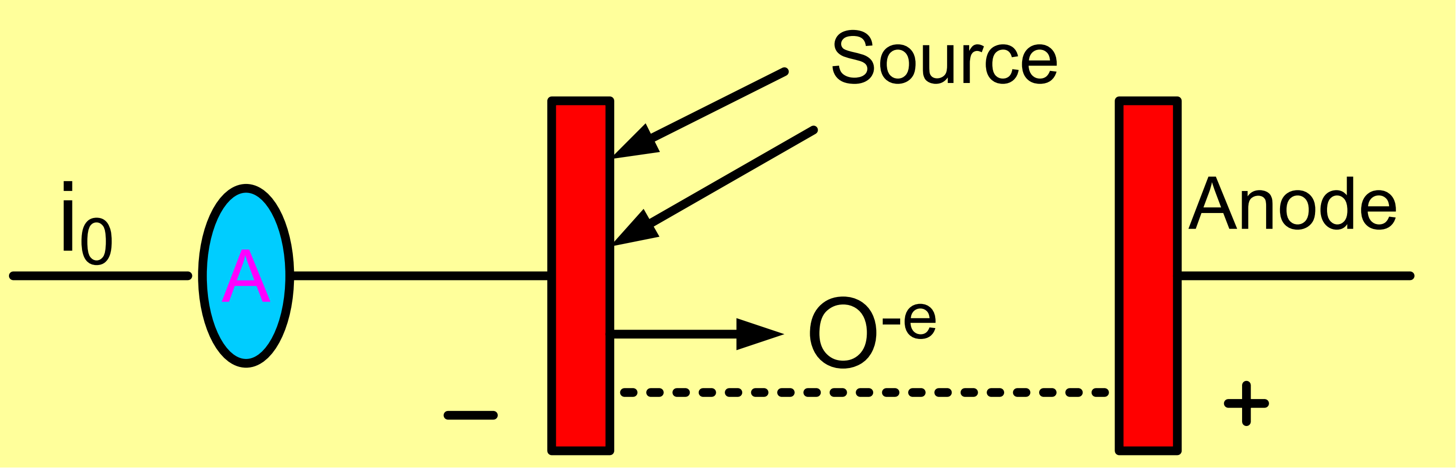
$$\gamma \exp\ (\alpha d) = 1 \quad \text{(approximately as } \exp(\alpha d) >> 1)$$

Theoretically i=∞ for first condition, but in practice it is controlled/Limited by the external circuit resistance Townsend’s defined this condition the onset of spark.

ELECTRIC BREAK DOWN IN GASES

Townsend's criterion for spark is as follows:

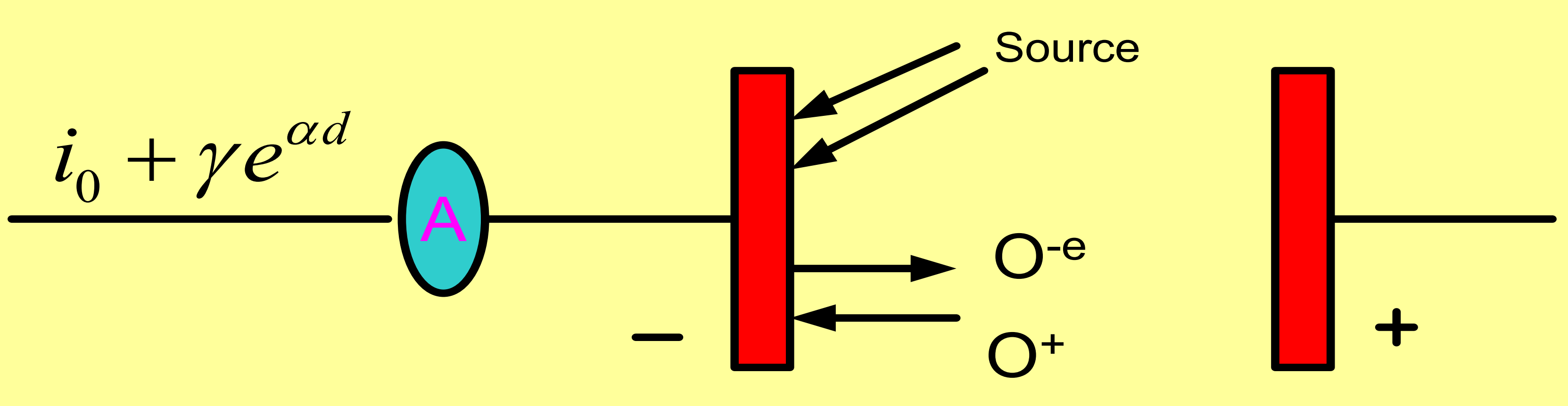
Stage1: **(Non-self –maintained discharge current)**



ELECTRIC BREAK DOWN IN GASES

The discharge current “i” is not self maintained that is on removal of the source producing the primary current i_o, ceases to flow.

Stage2: **(Self-sustaining discharge current) or (sparking threshold)**



$$\gamma e^{\alpha d} = 1$$

ELECTRIC BREAK DOWN IN GASES

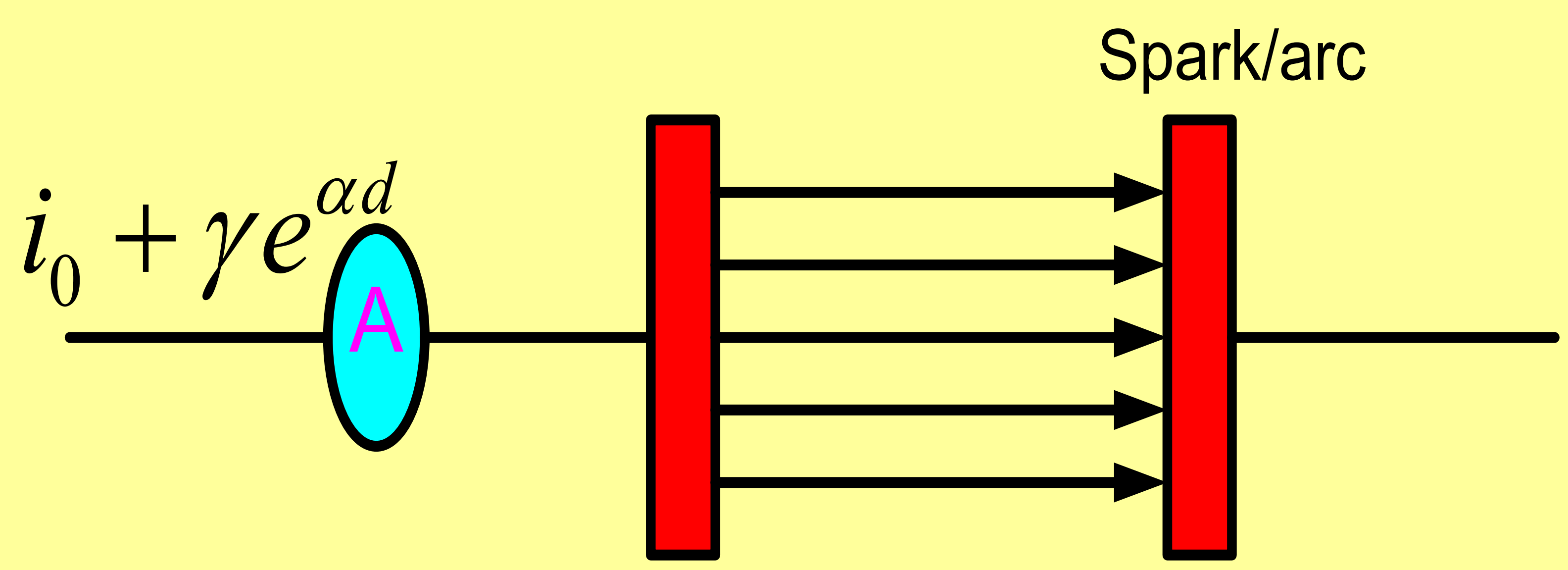
The number of ions pairs (exp (αd)) produced in the gap by the passage of one electron

Avalanche is sufficiently large that resulting positive ion, on bombarding the cathode, are able to release one secondary electron and so cause a repetition of avalanche process

The discharge is then self sustaining and can continue in the absence of the source producing i_o, so that the criterion $\gamma \mathrm{e}^{\alpha \mathrm{d}} = 1$ can be set to define the "sparking threshold"

ELECTRIC BREAK DOWN IN GASES

Stage 3: (Heavy current due to successive avalanches)



$$\gamma e^{\alpha d} > 1$$

ELECTRIC BREAK DOWN IN GASES

Stage 3: (Heavy current due to successive avalanches)

The ionization produced by successive avalanches is cumulative

The spark discharge grows more rapidly the more does $\gamma \exp(\alpha d)$ exceeds unity

THE SPARKING POTETIAL (Pashen's Law)

$\gamma e^{(\alpha d)}=1$ (Threshold equation)

From calculation and experimental studies on breakdown voltages for short gaps and at relatively low pressure

$$\alpha/P= F_1(E/P)$$
$$\gamma= F_2\ (E/P)$$

Ionization coefficients α and γ are expressed as function of field strength (E) and pressure (P).

THE SPARKING POTETIAL (Pashen's Law)

Threshold equation comes out

$$F_2\left(\frac{V}{pd}\right)\exp\left[pdF_1\frac{V}{pd}\right]=1$$

$$V_s=F\left(pd\right) \qquad \rightarrow\left(Pashen's\ Law\right)$$

THE SPARKING POTETIAL (Pashen's Law)

Ed= V for uniform field
V_s=sparking potential
p=pressure
d=gap length

Thus the sparking potential V_s is a function of the product of gas pressure and gap length (Pd) alone. This relation is known as Paschen's Law. (1889)

- The Equation (V_s =F(Pd)) does not imply simply that the relation is linear although it is found in practice to be linear over certain regions.

THE SPARKING POTENTIAL (Pashen's Law)

- The breakdown voltages for uniform field gaps in gases at different pressures may therefore be plotted in the form of curves relating the sparking voltage with the product of gap length and gas pressure.

- A comparison between the experimentally determined and the calculated break down values for nickel cathode in hydrogen at reduced pressure is made in **fig 2.1.**

THE SPARKING POTETIAL (Pashen’s Law)

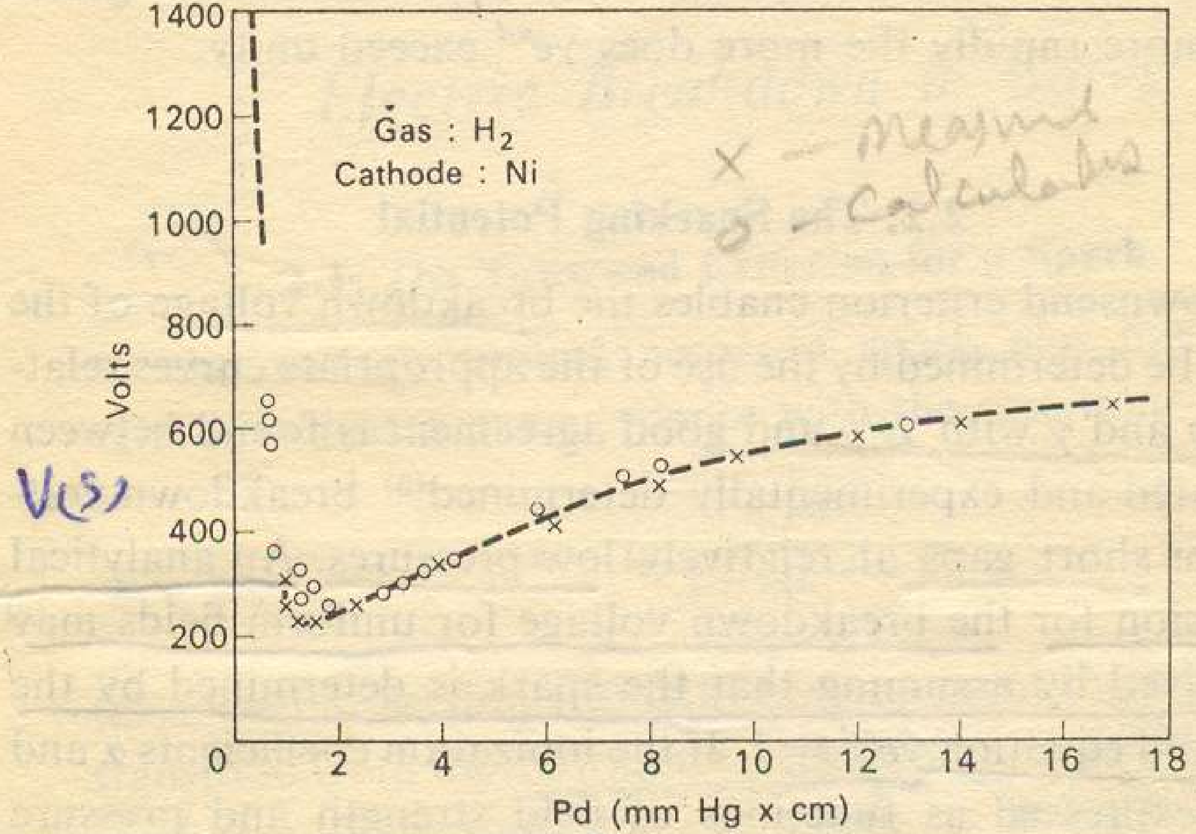


FIG. 2.1. Comparison between the measured and calculated breakdown values for a Ni cathode in H_2. The crosses denote the measured values; the circles the calculated values.

THE SPARKING POTENTIAL (Paschen's Law)

The sparking potential decreases with increasing the values of Pd, reaches a minimum value at a critical value of Pd and then increases again

No break down can be obtained below the critical sparking potential by decreasing either of the parameters

Explanation: The existence of the minimum value in a sparking potential may be explained qualitatively by considering the, "Efficiency of ionization of electrons traversing the gap at different electrons energies".

THE SPARKING POTETIAL (Paschen's Law)

Case-1: $Pd > (Pd)_{min}$

Neglecting the effect of the secondary coefficient for values $Pd>(Pd)_{min}$ values of "Electron crossing the gap make more frequent collisions with the gas molecules than that at minimum Pd , but the energy gain between collisions is lower than that at minimum Pd".

Hence the probability of ionization and collision is lower unless the voltage is increased.

THE SPARKING POTETIAL (Paschen's Law)

$$\text{Case-2: } Pd < (Pd)_{\min}$$

The electrons may cross the gap without making collisions.

The point of $(Pd)_{min}$ corresponds to highest ionizing efficiency.

Table in next slide gives minimum sparking potentials for the more common gases.

THE SPARKING POTENTIAL for Different Gases

GAS	Vs Minimum	Pd, mm Hg X cm
Air	327	0.567
H_2	273	1.15
He	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	0.6

THE SPARKING POTETIAL (Paschen's Law)

The measured minimum sparking voltage in a given gas also depends upon the "Work function" of cathode material.

EFFECT OF SPACE CHARGE ON BREAK DOWN VOLTAGE

$$\alpha = F\left(\frac{E}{d}\right)$$

The ionization coefficient (α) is a function of the field gradient existing in the gap and its value is therefore affected by the pressure of space charges.

“With-in an avalanche α may increase or decrease with distance depending upon the initial value of α and initial number of electrons”.

EFFECT OF SPACE CHARGE ON BREAK DOWN VOLTAGE

“Positive ion space charge field reduces the applied field acting on the electrons and thus reduces their ionization capability”.

These above effects take place when ion concentration is more than 10^6 but less than 10^8.

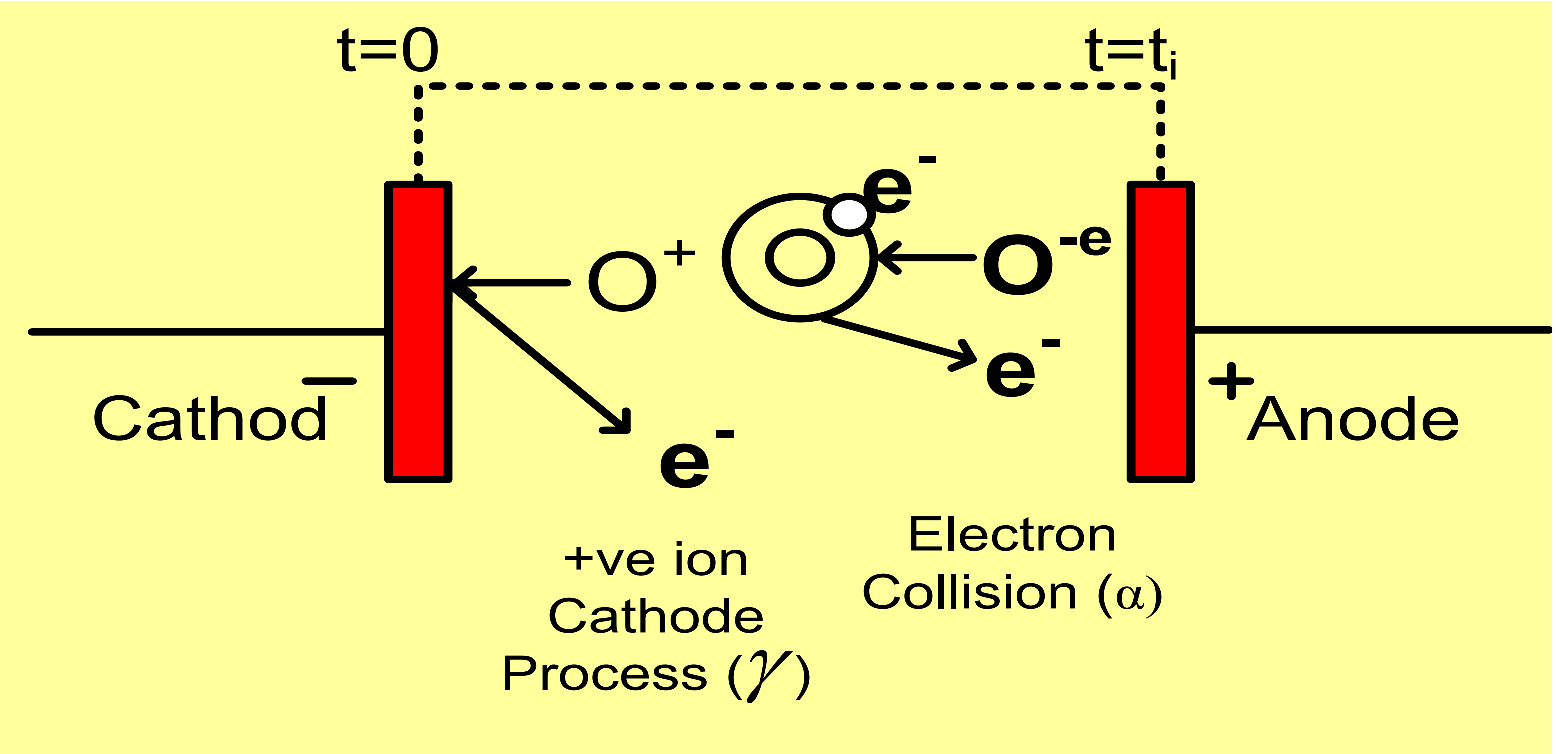
When ion concentration exceeds from 10^8, the avalanche current followed by a steep rise in current and break down of the gap followed

“Raether” suggested that at this stage the positive ion space charge field attains sufficiently high value to initiate a Streamer

EFFECT OF SPACE CHARGE ON BREAK DOWN VOLTAGE

The space charge fields play an important role in a mechanism of Corona and spark discharges is non-uniform field gaps.

THE STREAMER MECHANISM OF SPARK



THE STREAMER MECHANISM OF SPARK

In the spark mechanism originally suggested by Townsend the gap current grows as a result of ionization by electron impact in the gas and electron emission at the cathode by positive ion impact.

According to the theory then, the formative time lag should be equal to the ion transit time t_i

Pressures around atmospheric and above the experimentally determined time lags have been found to be much shorter than ti

Townsend’s theory could still apply if a faster mechanism of electron generation at the cathode operated, e.g. photoemission due to excitation in gas

THE STREAMER MECHANISM OF SPARK

Photoemission due to excitation in the gas, but in many cases the experimentally determined plots of “log i” against “d” show no departure from linearity before breakdown and therefore do not indicate the existence of new secondary mechanism or effects.

Further more cloud chamber photographs (Experimental results) have shown that under certain conditions the space charge develops in an avalanche is capable of transferring the avalanche in to a “Plasma Streamer”. The conductivity then grows very rapidly and the break down occurs in the channel of this avalanche. Meek, Loeb, Meek and Raether postulated the streamer theory of spark based on the following considerations.

THE STREAMER MECHANISM OF SPARK

Auxiliary Avalanche
due to
Photoionization

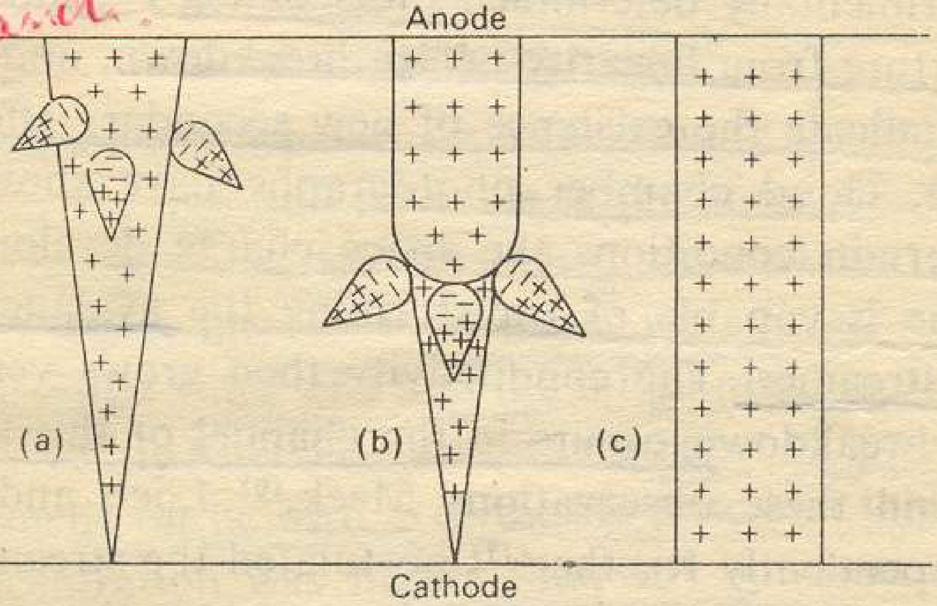


FIG. 2.2. Diagrammatic representation of the development of the conducting channel in the streamer mechanism.

THE STREAMER MECHANISM OF SPARK

Stage - 1

When an avalanche which is initiated by an electron leaving the cathode reaches the anode, the electrons owing to their high mobility are swept away and the positive ion remain in a nearly conical channel with the head at the anode

See **fig2.2(a)**

Due to the exponential character of the ionization in the avalanche the density of ions will be highest near the anode

THE STREAMER MECHANISM OF SPARK

Stage - 2

The positive ion charge will produce field distortion in both radial and axial directions and it will be the greatest at the head of the avalanche

In the surrounding gas photoelectrons are produced which initiate auxiliary avalanches directed towards the stem of the main avalanche

The greatest multiplication in these auxiliary avalanches occurs along the axis of the main avalanche where the space charge field increases the external field.

THE STREAMER MECHANISM OF SPARK

Stage - 2

Positive ions left behind these avalanches lengthen and intensity the space charge of the main avalanche in direction of the cathode and the process develops as a self propagating streamer

See fig 2.2(b).

THE STREAMER MECHANISM OF SPARK

Stage - 3

The process continues until the streamer crosses the gap and a conducting channel providing the bridge through which the external circuit discharges. See **fig 2.2(c).**

Three successive stages in the development of the conducting channel are shown diagrammatically in **figure 2.2**

THE STREAMER MECHANISM OF SPARK

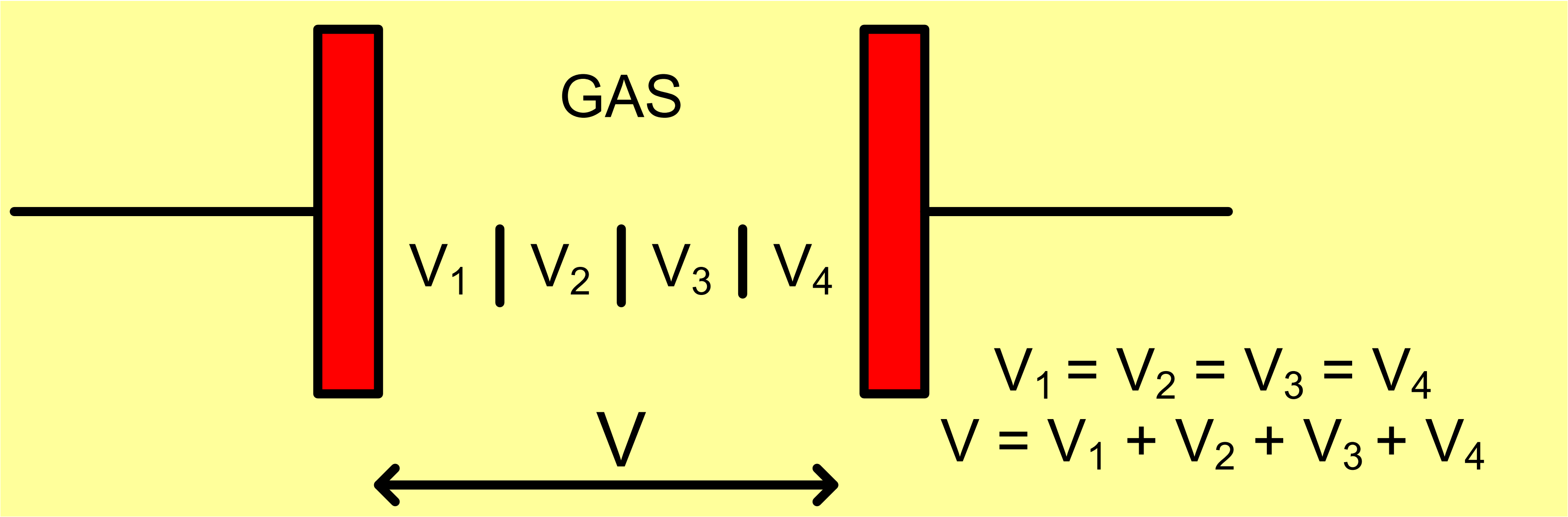
Stage - 3

(b) The Streamer has crossed half the gap length and in **(c)** The gap has been bridged by a conducting channel through which external circuit discharges.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

Uniform field are produced in gaps where applied voltage is uniformly divided across the gaps. Usually parallel plates are referred to be uniform field gap provided the gap distance is small compared to the size of the electrodes/plates.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS



$$V_1 = V_2 = V_3 = V_4$$

$$V = V_1 + V_2 + V_3 + V_4$$

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

Electrodes may be parallel plate or sphere gaps of bigger size.

The breakdown voltage gap length characteristics in different gases between uniform field electrodes have been studied by numerous investigators and the various results have been summarized by Meek and Craggs.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

Typical experimental curves obtained for CO_2, Air and H_2 are reproduced in **fig2.3**

A large proportion of these experiments were carried out at pressures below atmospheric primarily with a view to study the mechanism of break down and the factors which affect it

At these pressures (below atmospheric) the break down follow strictly the Townend mechanism based on the idea of primary (α) and secondary (γ) ionization.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

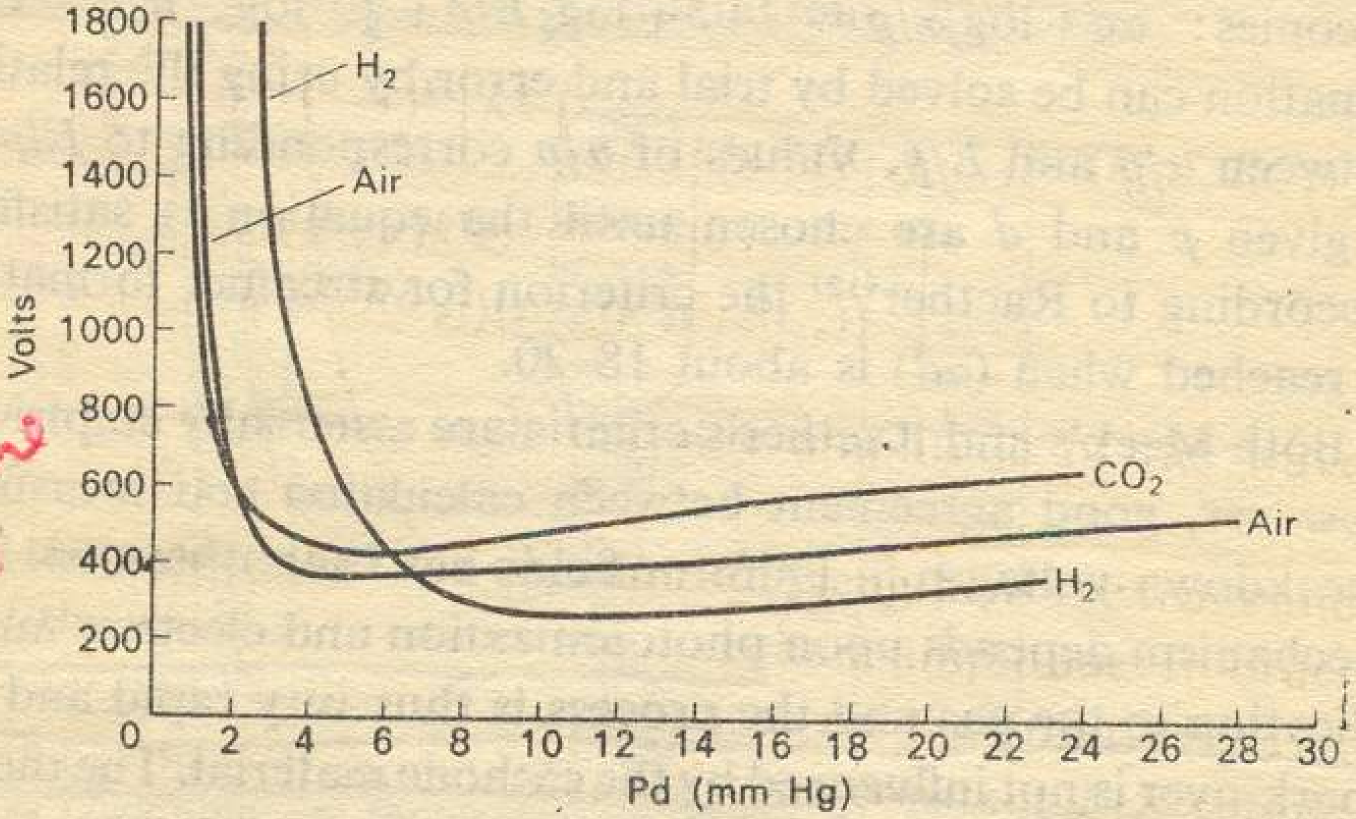


FIG. 2.3. The sparking voltage in uniform field (temp. = 20°C).

Below Atmosphere pressure!

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

At pressures near atmospheric and above streamer mechanism which invokes field distortion by space charges has been suggested to operate.

There is however some experimental evidence which indicates that in non-over volted gaps, the break down may still be explained in terms of Townsend spark criteria.

At Low pressures the break down is affected by the material of the cathode, the effect becoming particularly noticeable at low values of Pd near the minimum break down voltage.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

Typical curves are obtained which shows the effect in argon gas for barium (Ba), magnesium (Mg) and Aluminum (Al) cathodes are included in **fig 2.4.**

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

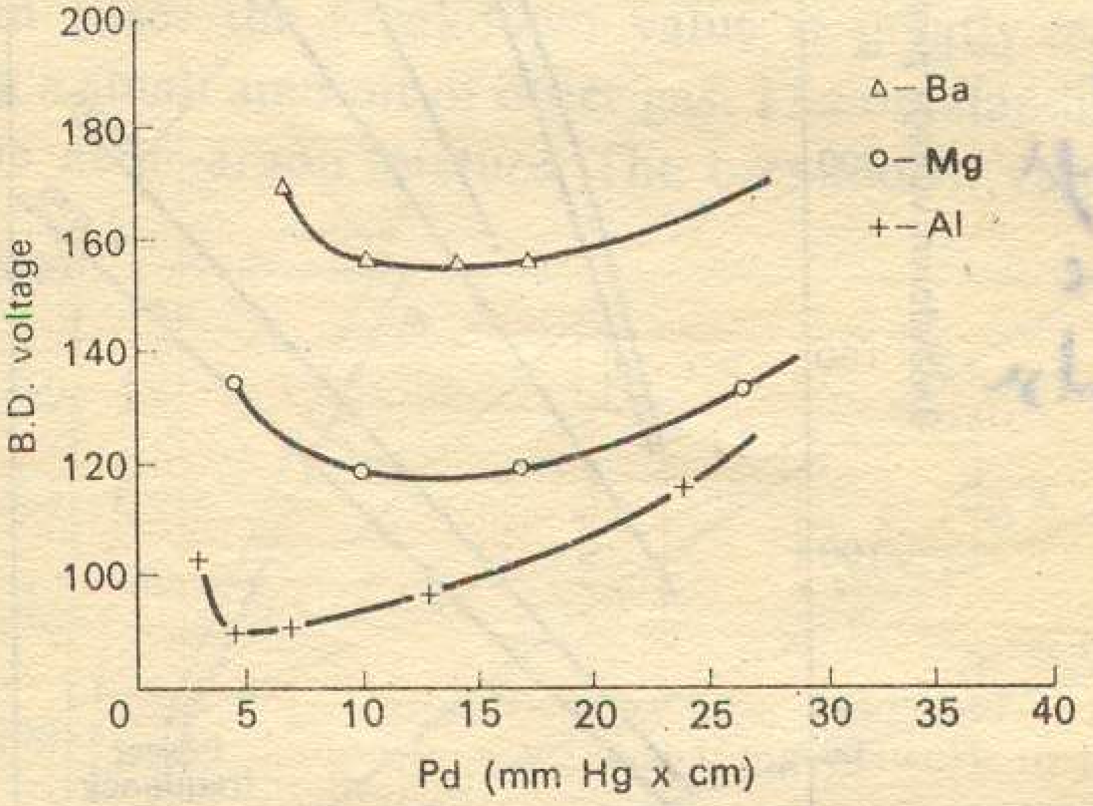


FIG. 2.4. Breakdown voltage curves in argon for Ba, Mg and Al cathodes.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

High/Compressed Gas Pressure

A group of gases which in recent years has been widely studied in connection with their application as an insulating medium in high voltage apparatus, notably in their compressed states are highly electronegative gases.

These gases (compounds) are usually of high molecular weight and complexity and thus offer an increased opportunity for inelastic collisions. Amongst the more important members of this type are Sulphurhexa Floride (SF_6) and the various Freon gases.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

High/Compressed Gas Pressure

These gases, apart from their high molecular weight, possess strong ability of attracting and holding free electrons through the attachment processes.

Consequently, they manifest a high dielectric strength. **Fig2.5** shows the dielectric strength obtained for SF_6.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

High/Compressed Gas Pressure

uniform field B.D.V
Depends on.
① Pressure.
② gap distance.
③ type (O_2, CO_2, SF_6)
④ cathode material
⑤ irradiation
⑥ type of voltage applied, i.e. A.C
D.C or impulse

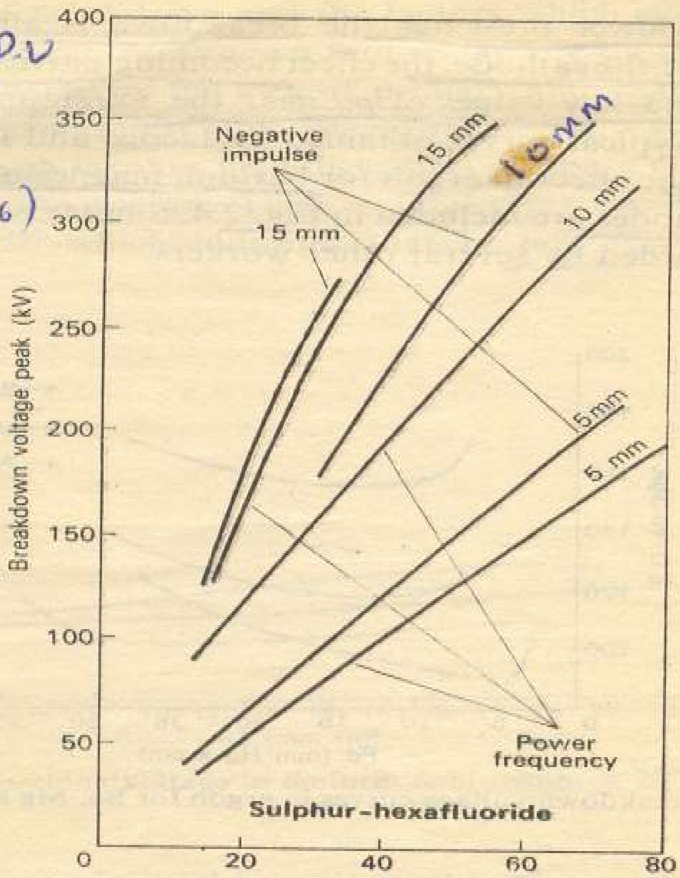


FIG. 2.5. 50 c/s breakdown voltage characteristics between 5 cm dia. spheres for SF_6.

BREAK DOWN VOLTAGE CHARACTERISTICS IN UNIFORM FIELDS

High/Compressed Gas Pressure

The values quoted in the literature for dielectric strength of SF_6 relative to air measured at atmospheric pressure in uniform field gaps vary between 1.6 and 2.62.

Large difference in this value may be due to different levels of irradiation uses. Irradiation affects greatly the direct breakdown voltage in SF_6.

BREAK DOWN IN GAS MIXTURES (PENNING EFFECT)

In certain gases the break down value is greatly reduced by admixing a small amount of other gas

The outstanding example is Neon-Argon mixture

The break down value of the mixture is less than in pure neon or pure Argon

Fig:2.6 shows the lowering in the break down of neon by adding to it a small percentage of Argon gas.

BREAK DOWN IN GAS MIXTURES (PENNING EFFECT)

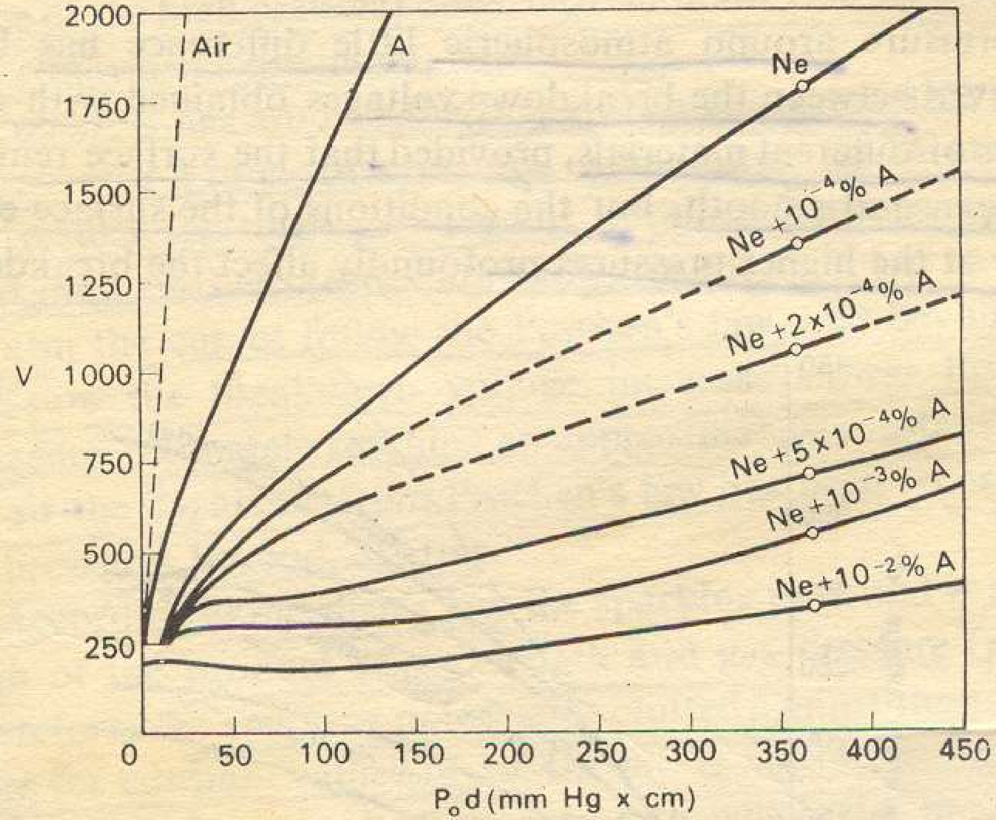


FIG. 2.6. Breakdown voltage curves in neon–argon mixtures between parallel plates at 2 cm spacing at 0°C.

BREAK DOWN IN GAS MIXTURES (PENNING EFFECT)

- The reason for this lowering in the break down potential is that lowest excited state is neon
- ($3S^3P_2$) is metastable and its excitation potential (16eV) is about 0.9 eV greater than the ionization potential of Argon.

- The metastable atoms have a long life in Neon gas, and on hitting Argon atoms there is very high probability of ionization of them.

BREAK DOWN IN GAS MIXTURES (PENNING EFFECT)

- A low concentration of Argon is thus adequate to ensure large increase in ionization.

- If the concentration of Argon atoms is too high, the electrons will lose energy in exciting them and hence there is an Argon concentration giving a minimum breakdown potential.

BREAK DOWN IN COMPRESSED GASES

At or around atmospheric pressure

1) Little difference has been observed between the break down voltages obtained with electrodes of different materials, provided that the surface remained clean and smooth.
2) Nitrogen gas (N_2) follows Paschen's law up to 10atm pressure.
3) Air follows Paschen's law up to 20atm.
4) That is at low pressures gases follow Paschen's law.(Vs =f(Pd))

BREAK DOWN IN COMPRESSED GASES

At Higher pressure

Conditions of the surface especially at the higher pressures profoundly affect a break down characteristics.

Fig 2.7 shows some results recorded by Howell for air between plane electrodes of various degree of “Roughness”.

At high pressures gases does not follow Paschen’s law.

BREAK DOWN IN COMPRESSED GASES

At Higher pressure

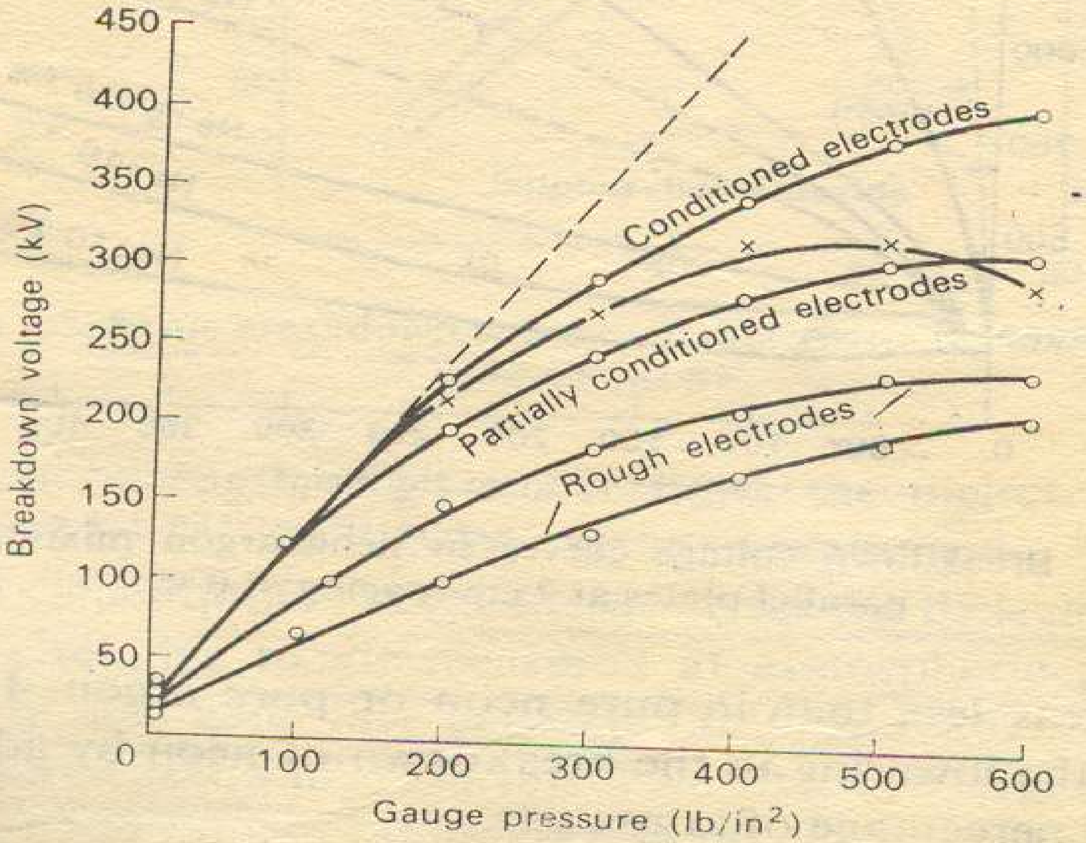


FIG. 2.7. Effect of electrode conditions on the breakdown voltage of a 0·25 in. gap between plane electrodes.

BREAK DOWN IN COMPRESSED GASES

Rough Electrode

“When the surface had been sand-papered but not polished”.

Partially conditioned

In this case electrodes are polished and then subjected to a number of sparks.

Conditioned Electrodes

In this case electrodes were obtained after sparking for long time (i.e.) prolonged sparking.

BREAK DOWN IN COMPRESSED GASES

- Howell explained the differences between the various curves **(Fig: 2.7)** in terms of small point discharges existing at the irregularities on the electrodes surfaces.

- Then discharges cause a consideration pre-break down current and the resultant space charges may cause field distortion which gives rise to a lower break down voltage.

- Cohen has studied the break down characteristics of N_2 over a range of pressures up to 75atm and the result for three gap lengths obtained between uniform field mild steel electrodes are shown in **fig 2.8.**

BREAK DOWN IN COMPRESSED GASES

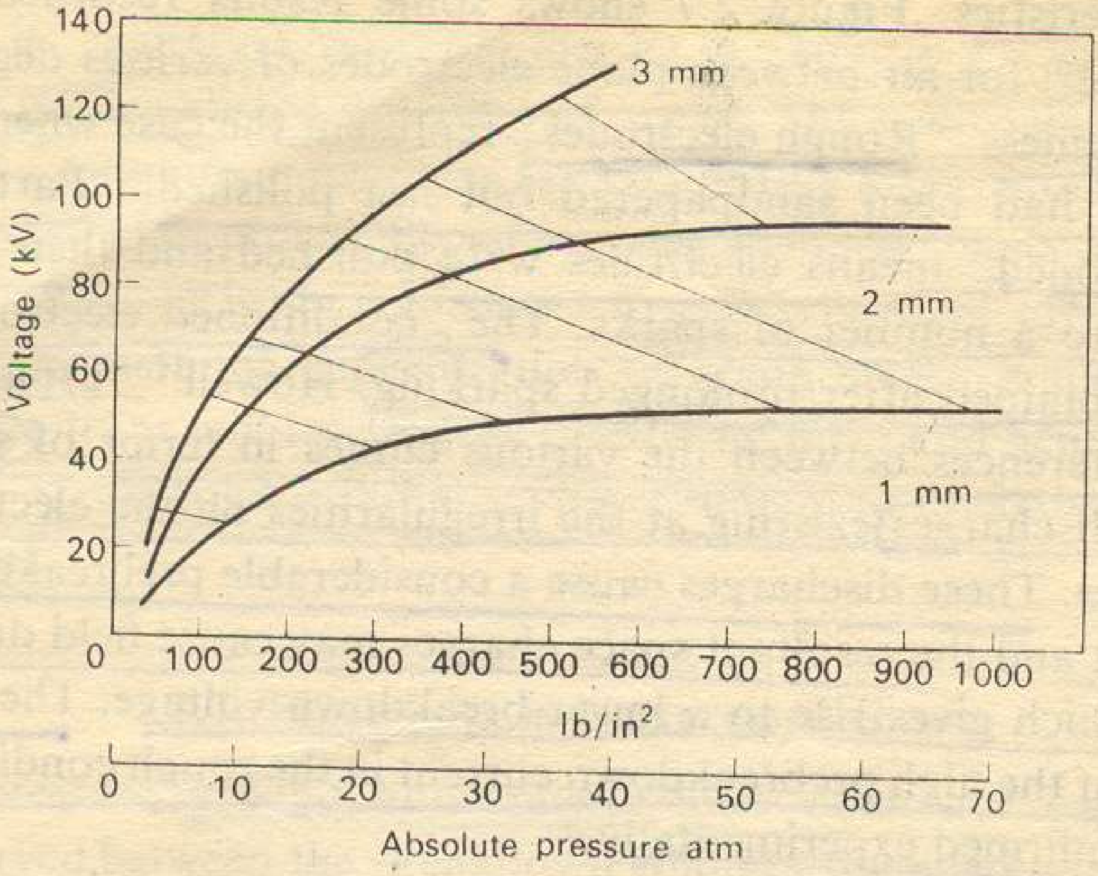


FIG. 2.8. The spark breakdown strength in compressed N_2. Electrod material: mild steel; gap lengths 1, 2 and 3 mm.

BREAK DOWN IN COMPRESSED GASES

Up to about 10 atm the curves follow Paschen’s law and beyond this pressure the break down voltage increases slower than the pressure ultimately reaching an approximate value.

In air the departure from Paschen’s law has been recorded at pressure beyond 20 atm. **Fig:2.8.** According to Paschen’s law the sparking potential (V_s) is a function of (Pd).

If therefore the sparking potential is plotted against gas pressure (P) for constant values of (Pd) the law is obeyed if a series of horizontal lines result.

BREAK DOWN IN COMPRESSED GASES

The extent to which the break down characteristics in compressed N_2 depart from the Paschen’s law is indicated by the inclination of the lines to the horizontal shown in **fig 2.8**

Cohen has demonstrated that the failure of Paschen’s law in N_2 above 10atm and air 20atm is accompanied by corresponding failure of the linear relation which exits at lower pressures between the Townsend’s first ionization coefficient at break down (α_s) and the gas pressure (P).The relation in N_2 and the air is plotted in fig2.9.Upto 10atm the variation of “α_s” with “P” is approximately linear. In N_2 (curve-b) an abrupt decrease in α_s Continued in Slide.

BREAK DOWN IN COMPRESSED GASES

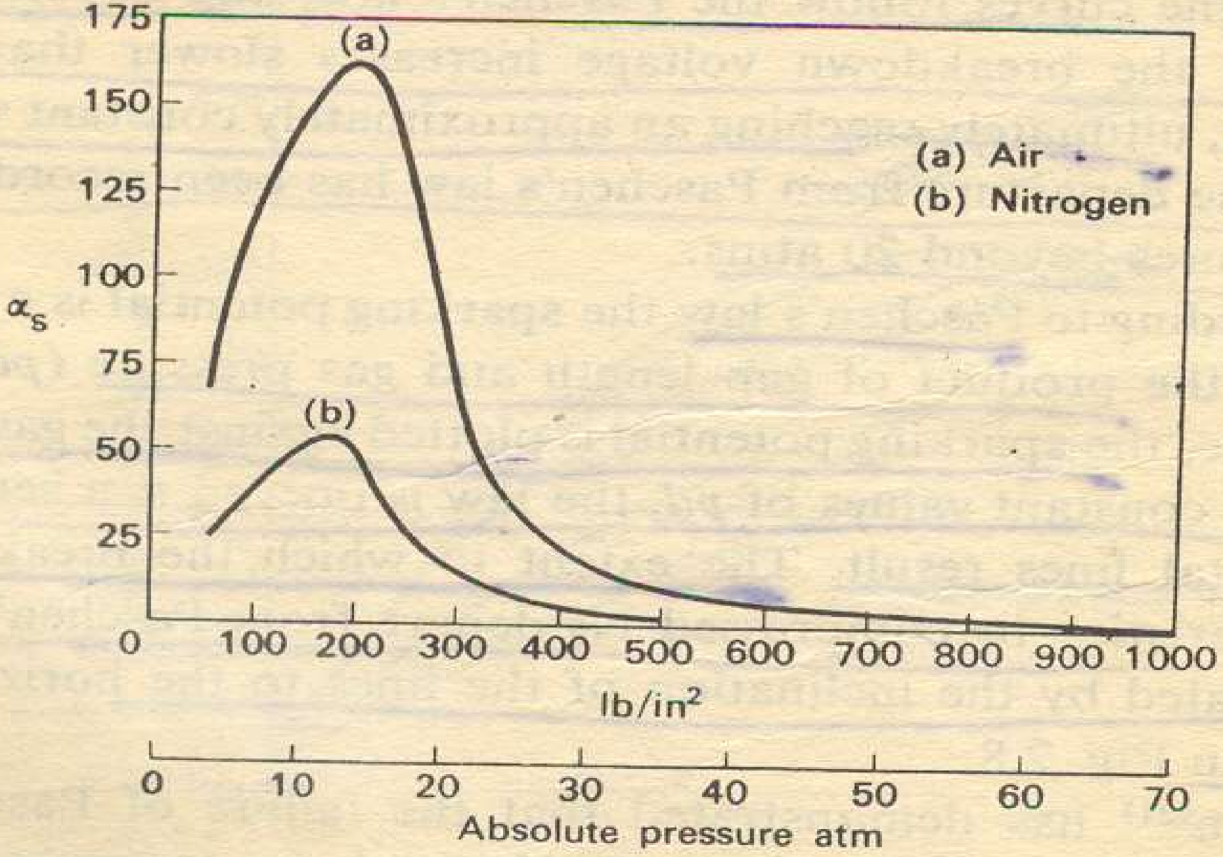


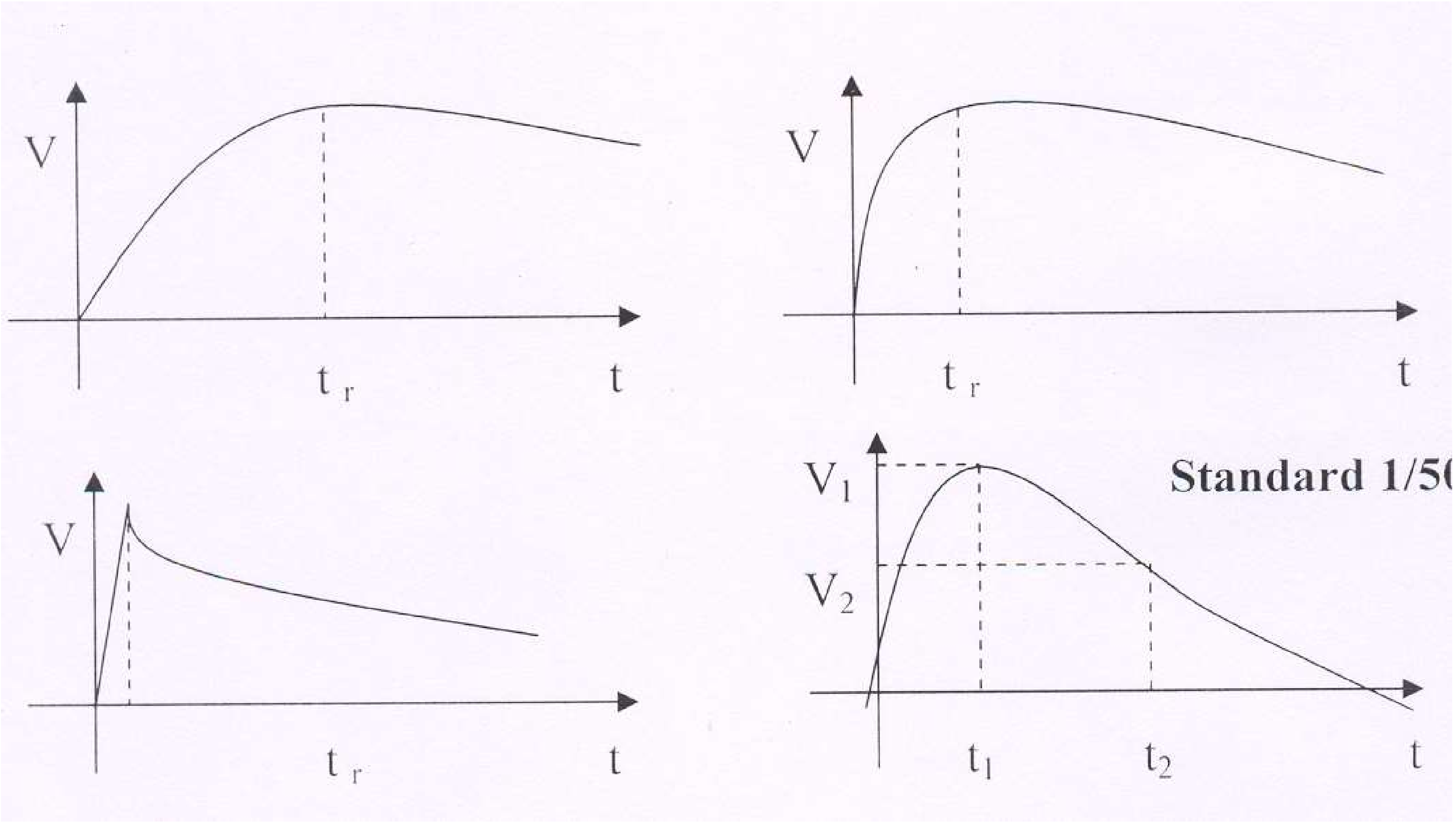
FIG. 2.9. The variation of α_s with pressure. Electrode material: mild steel; gap length 1 mm, (a) air, (b) N_2.

BREAK DOWN IN COMPRESSED GASES

follows above 10atm, while in air $\boldsymbol{\alpha_s}$ starts falling above 15atm (α_s falls more at higher pressure).

The electron avalanches which dominant the theories of break down of small gaps at lower pressures become progressively less significant as the energy gained by electrons between their frequent collisions with atoms or molecules becomes insufficient to cause ionization.

SURGE BREAK DOWN VOLTAGE-TIME LAG



SURGE BREAK DOWN VOLTAGE-TIME LAG

For a break down to occur, initiatory electrons must be available to start the avalanche.

With slowly rising voltages there are usually sufficient initiatory electrons created by cosmic rays and the naturally occurring radioactive sources.

Under surge- voltages and pulses of short duration, however the gap may not break down as the peak voltage reaches the lowest break down potential (Vs) unless the presence of initiatory electrons is ensured by using artificial irradiation.

SURGE BREAK DOWN VOLTAGE-TIME LAG

With weak irradiation the peak value may have to be greatly increased so that the voltage remains above the DC value for longer intervals of time

Fig 2.10 illustrates the break down on a step-function voltage pulse.

SURGE BREAK DOWN VOLTAGE-TIME LAG

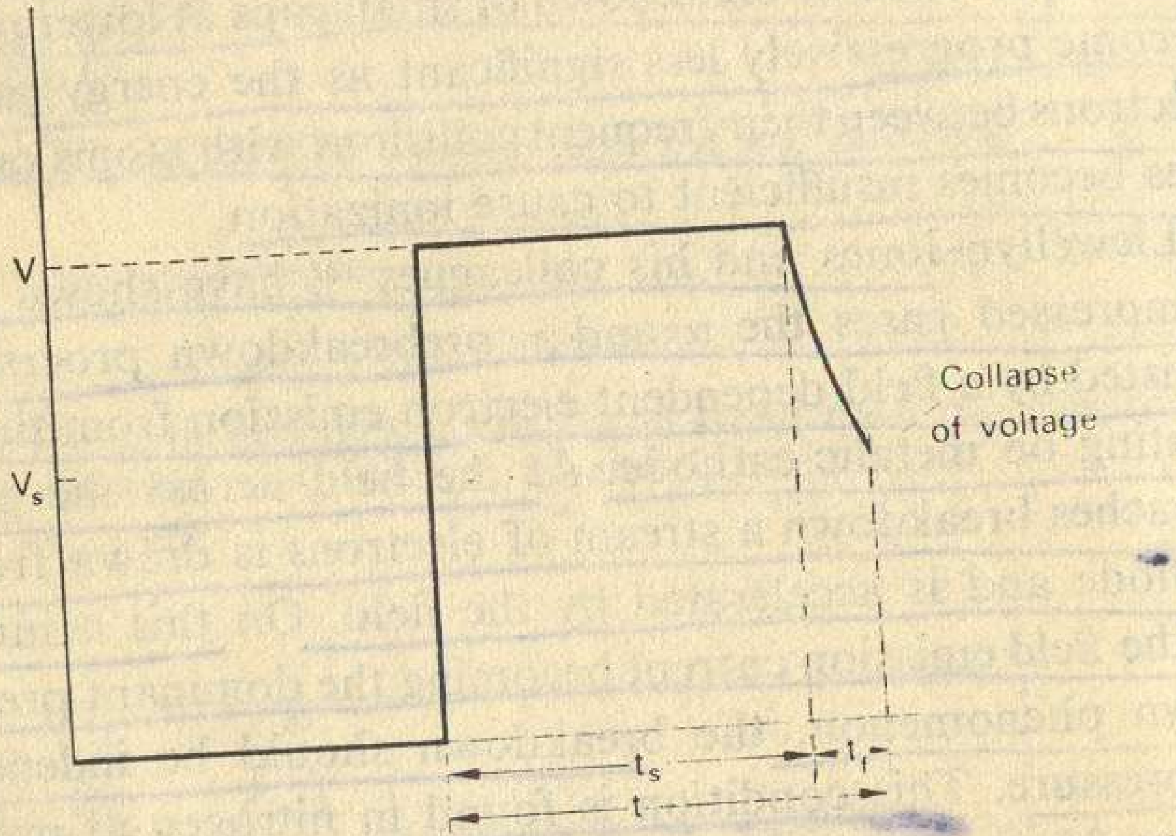


FIG. 2.10. Breakdown on a step-function voltage pulse. t_s—statistical time; t_f—formative time; t—total time.

SURGE BREAK DOWN VOLTAGE-TIME LAG

TIME LAG (t)

The time which elapses between the application of a sufficient voltage to cause break down of a gap is called time Lag (t).

$$t = t_s + t_f$$

t = Time lag
t_s = Statistical Time lag
t_f = Formative time lag

SURGE BREAK DOWN VOLTAGE-TIME LAG

Statistical Time Lag (t_s)

It is the time elapses during the voltage application and a primary electrons appears to initiate the discharge.

Formative Time Lag (t_f)

It is the time requires for the break down developing once initiated (i.e. after one electron is produced in the gap until break down takes place).

The statistical time lag depends upon the amount of pre-ionization present in the gap. This in turn depends upon the size of gap and the radiation producing the primary electrons.

SURGE BREAK DOWN VOLTAGE-TIME LAG

Formative Time Lag (t_f)

The techniques generally used for irradiation of gaps artificially includes:

Ultraviolet light
Radioactive materials
Illumination by auxiliary sparks

The formative time lags (t_f) depend essentially upon the mechanism of spark growth in question.
In cases when the secondary electrons arise entirely from electron emission at the cathode by positive ion impact, the transient time of the positive ion from anode to cathode will be the dominant factor determining the formative time lag.

SURGE BREAK DOWN VOLTAGE-TIME LAG

Formative Time Lag (t_f)

Note:

Formative time lag is usually much shorter than the statistical time lag and consequently the t_s can be determined by measuring the total time lag.

$$t = t_s + t_f$$

But $t_s >> t_f$

Hence t = ts

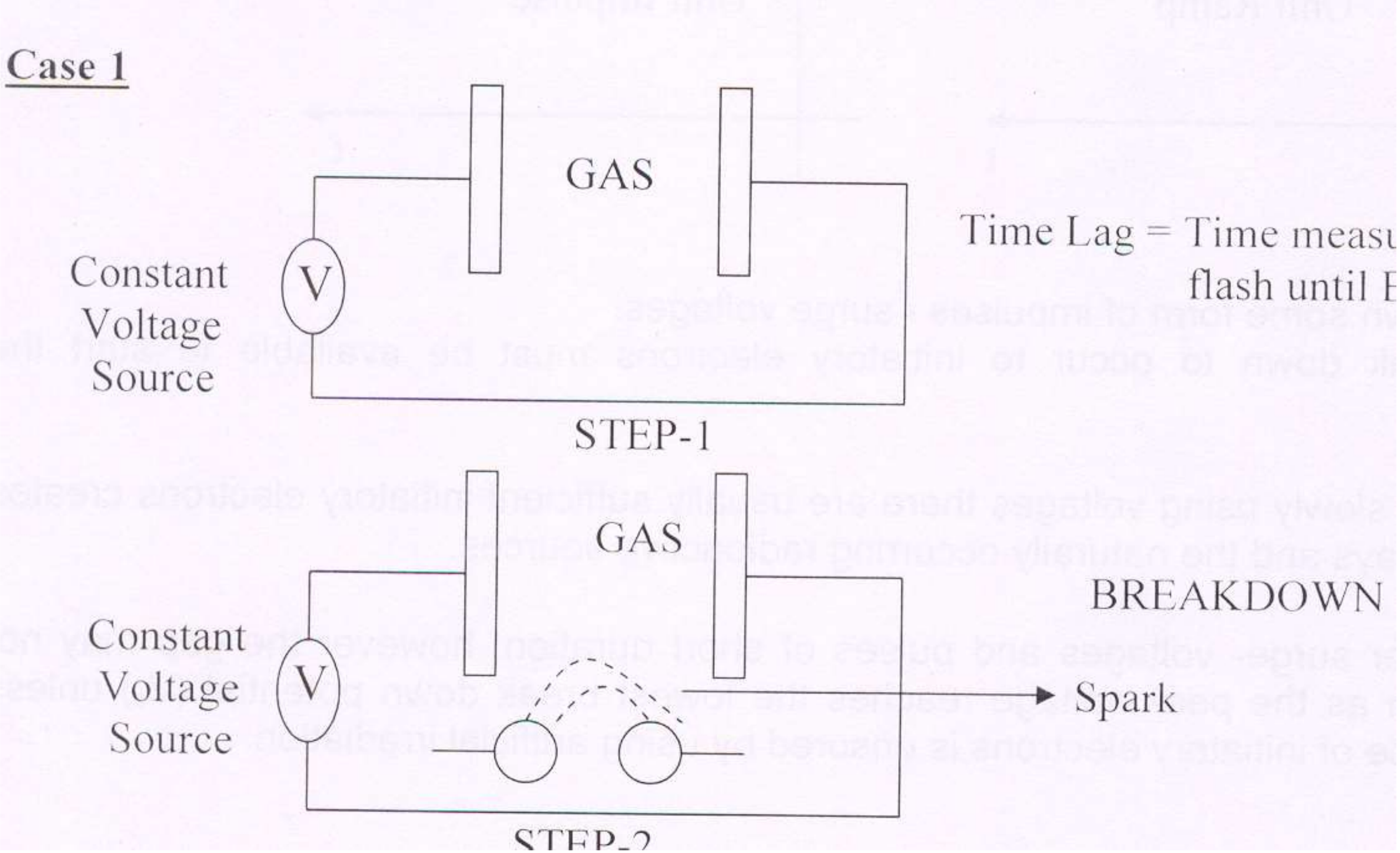
SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

In the techniques generally used either a constant voltage is applied to an irradiated gap and a spark is initiated by a sudden illumination of the gap from a nearly spark, or an over voltage is suddenly applied to a gap already illuminated.

SURGE BREAK DOWN VOLTAGE-TIME LAG

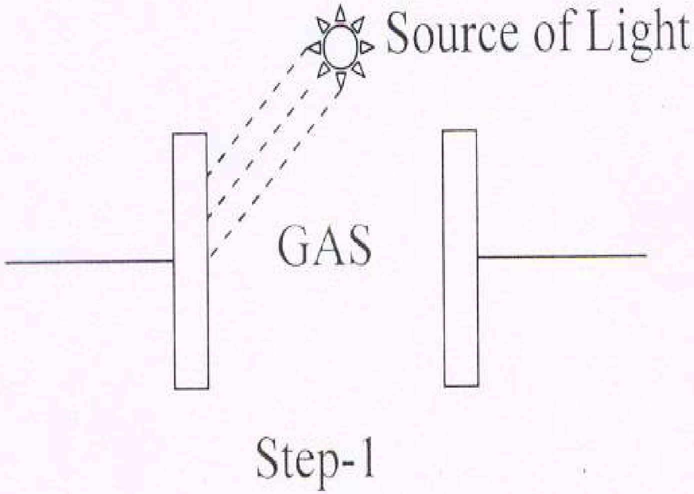
EXPERIMNTAL STUDY OF TIME LAGS



SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

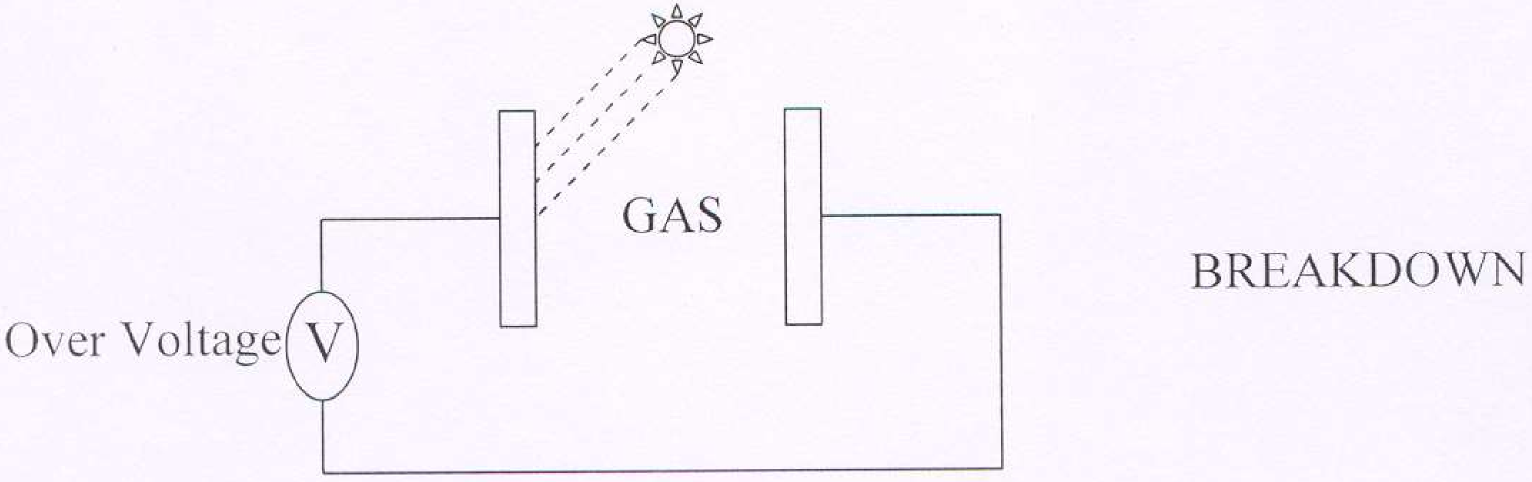
Case 2



Time Lag-Time b/w Voltage application until Breakdown.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS



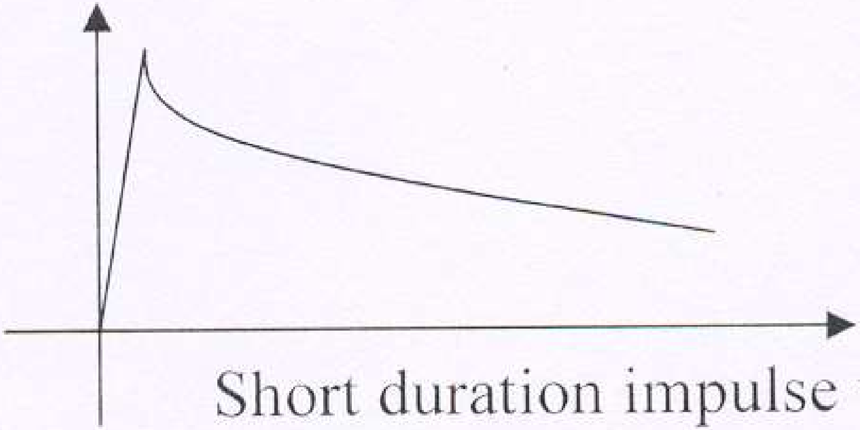
STEP-1

Over voltage condition may be obtained either by superimposing a step voltag upon a DC voltage already applied to a gap.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

Or an impulse voltage of a suitably short front duration.



Short duration impulse voltage wave

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

The measured time lags for a given experimental conditions are usually presented graphically by plotting the average time lags against the over voltages.

The latter is defined as the percentage ratio of voltage in question to the minimum direct voltage which will cause break down in case when an impulse voltage is used on its own, the time lags are plotted against the impulse ratio, defined as the ratio of the applied impulse voltage to the minimum direct break down voltage.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

The measured time lags value are affected by factors such as

- **Intensity of the back ground irradiation**
- **Nature and the condition of the electrode surface**
- **Gap length**
- **Electron affinity of the gas**

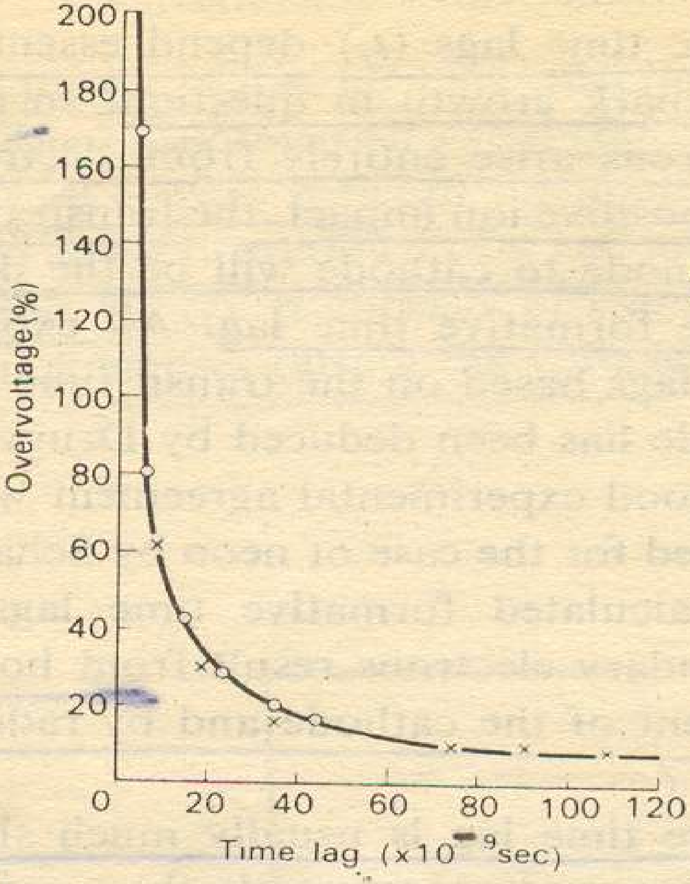
SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

- With a gap illuminated from an intense ultraviolet source, time lags down to 10^{-8} seconds and shorter have been recorded in highly over volted gaps.
- **fig 2.11** shows time lag of spark break down for short gaps with the cathode irradiated by a quartz mercury lamp, between spheres in air.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS



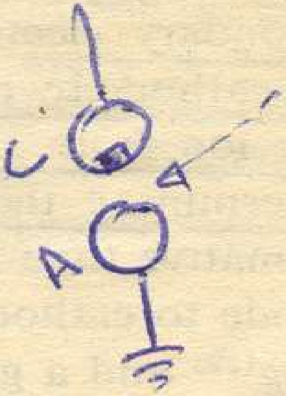


FIG. 2.11. Time lag of spark gap as function of overvoltage for short gap between spheres with intense ultraviolet illumination of the cathode in air.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

- Results obtained by Messner for a 2cm uniform field gap in air or shown in **fig 2.12.**

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

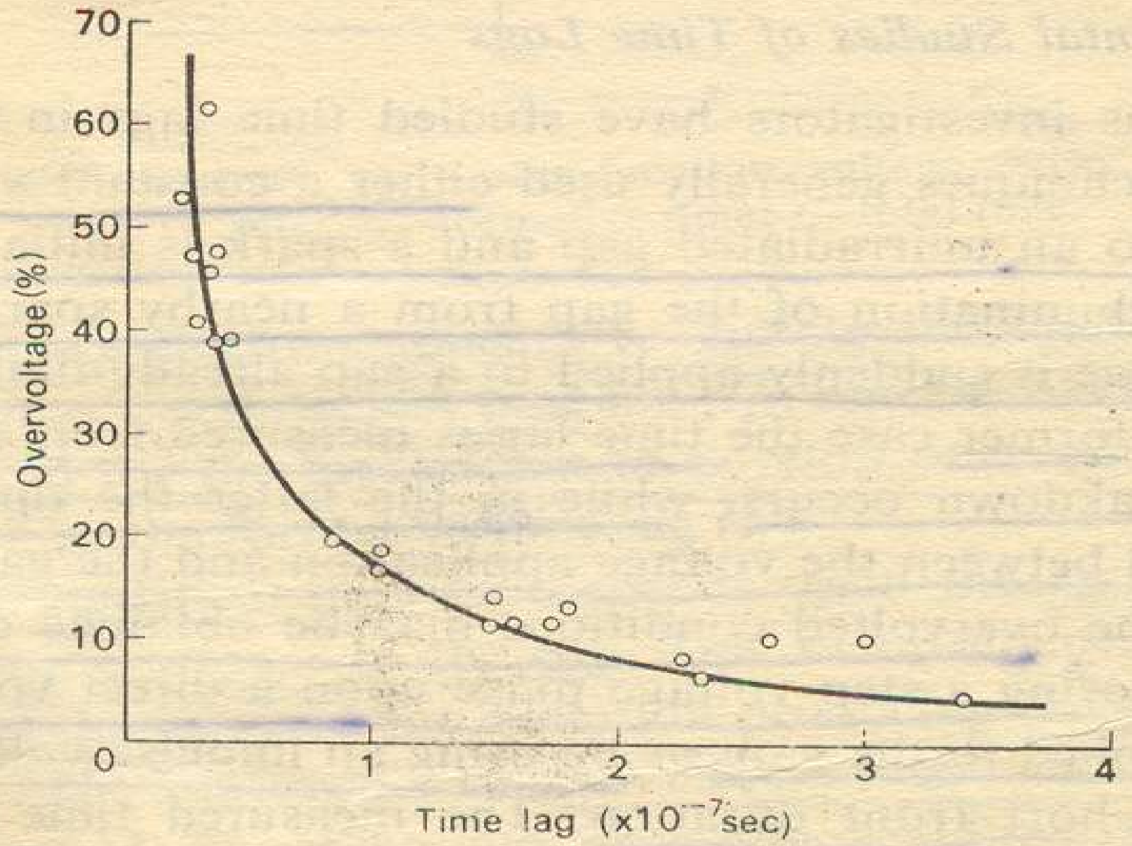


FIG. 2.12. Formative time lag as a function of overvoltage for a 2-cm gap between spheres in air.

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

Fisher and Benderson studied time lags in air between uniform field electrodes in slightly over volted conditions and the results obtained for four gap length are shown in **fig 2.13**

SURGE BREAK DOWN VOLTAGE-TIME LAG

EXPERIMNTAL STUDY OF TIME LAGS

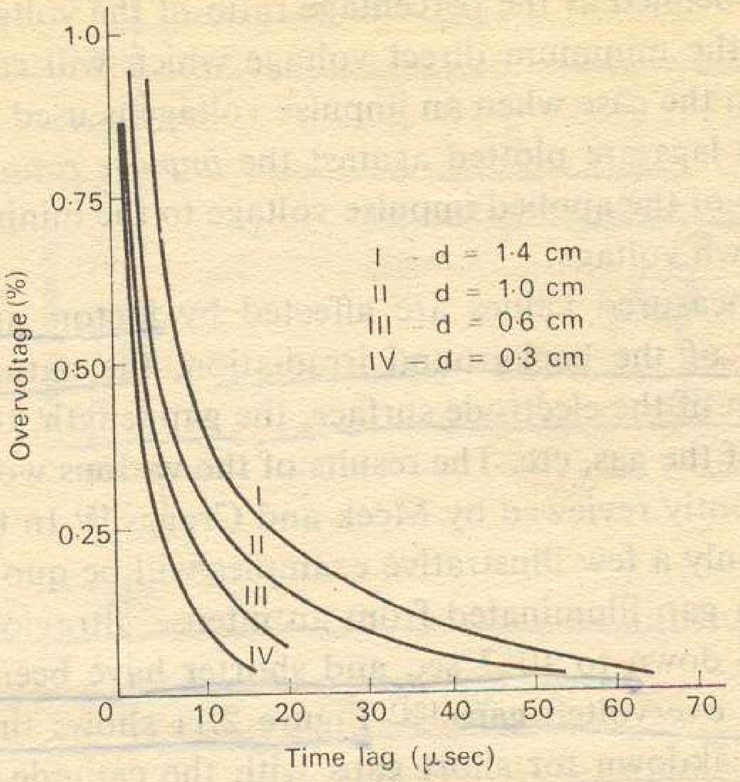


FIG. 2.13. Time lag as a function of overvoltage for four gap lengths. The curves represent the average data for all pressures between atmospheric and 200 mm Hg.

Next Lecture

- Breakdown phenonmenon will be continued