Breakdown of Gaseous Dielectrics

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Introduction

- Gases (incl. air) are normally good electrical insulating material.
- Air is most commonly used insulating material.
- Other Gaseous insulating materials include:
  - ➢ Nitrogen (N_2) ,
  - ➢ Carbon dioxide (CO_2) ,
  - ➢ Freon ($CCl_2 F_2$) and
  - ➢ Sulferhexafluoride (SF6)

Introduction

Dielectric parameters

Dielectric materials are characterized by the following parameters:

- Dielectric strength (Breakdown strength)
- Relative permittivity (Dielectric constant)
- Insulation Resistance
- Dielectric loss (Loss factor)

A good dielectric material should have higher dielectric strength, higher dielectric constant and lower dielectric loss.

Introduction

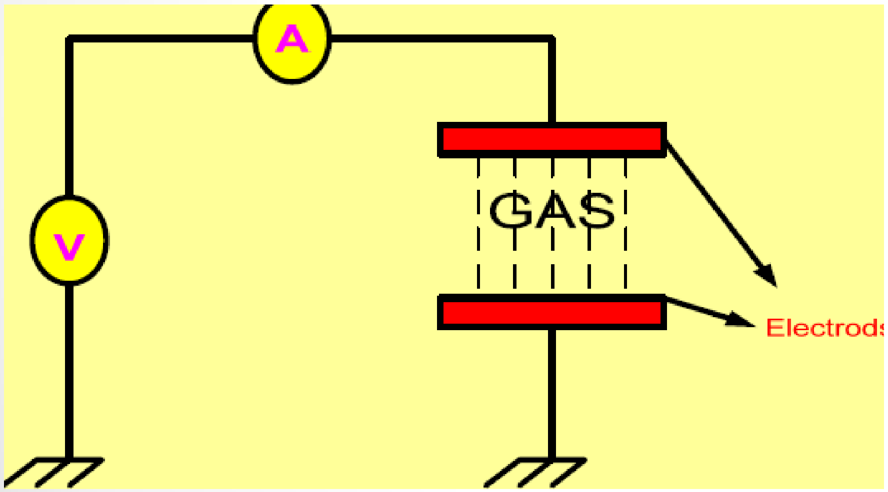
- Under high E-field conditions, gases become ionized, leading to sparks or flashover.
- Why??

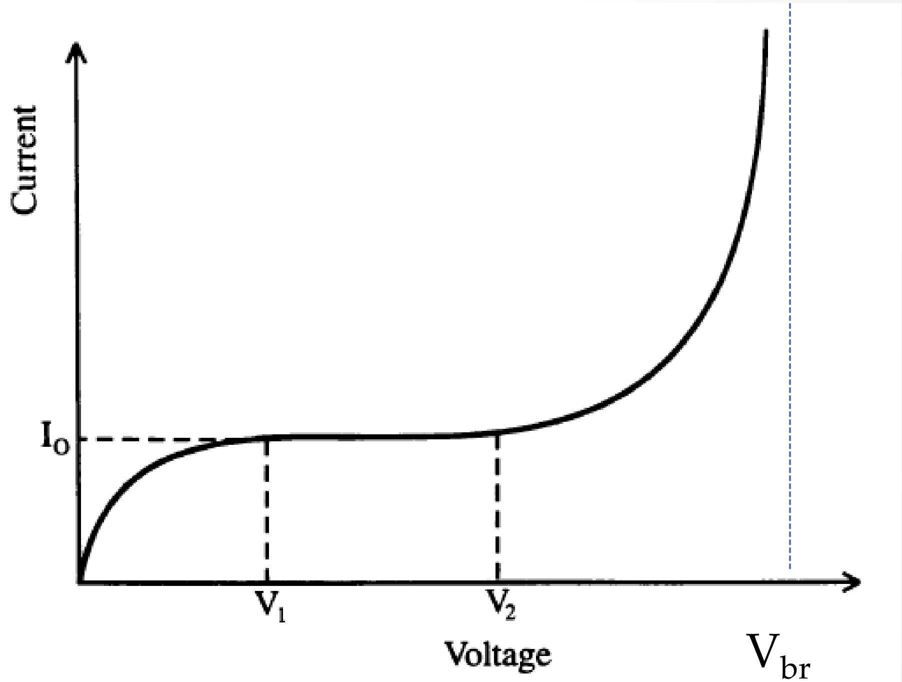
Townsend's Theory

Streamer 's Theory

Breakdown Mechanism

- The V-I characteristic for an ordinary gas between parallel plate electrodes is shown





Breakdown Mechanisms

Ionization by Collision

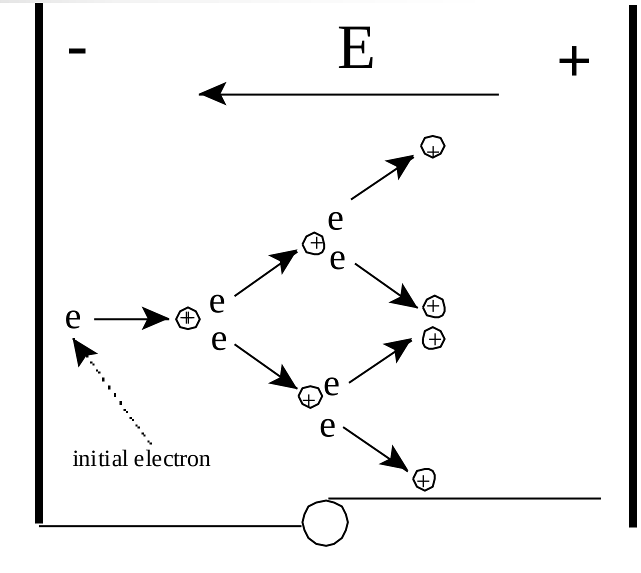
- Free initiating electrons always present (cosmic rays)
- Initiating electrons accelerated by Lorentz force due to the E-field
- Electron gains kinetic energy and collide against gas atoms
- Ionization occurs if this energy exceeds the ionization energy of the atom, sets free more electrons and leaves positive charge behind.

$$e^- + A \text{---------} \quad e^- + A^+ + e^-$$

- No of electrons reaching the anode is greater than that liberated from cathode

Breakdown Mechanisms

Ionization by Collision



When an electron e is placed in E, it will be accelerated with a force eE towards the anode, and it gains an energy

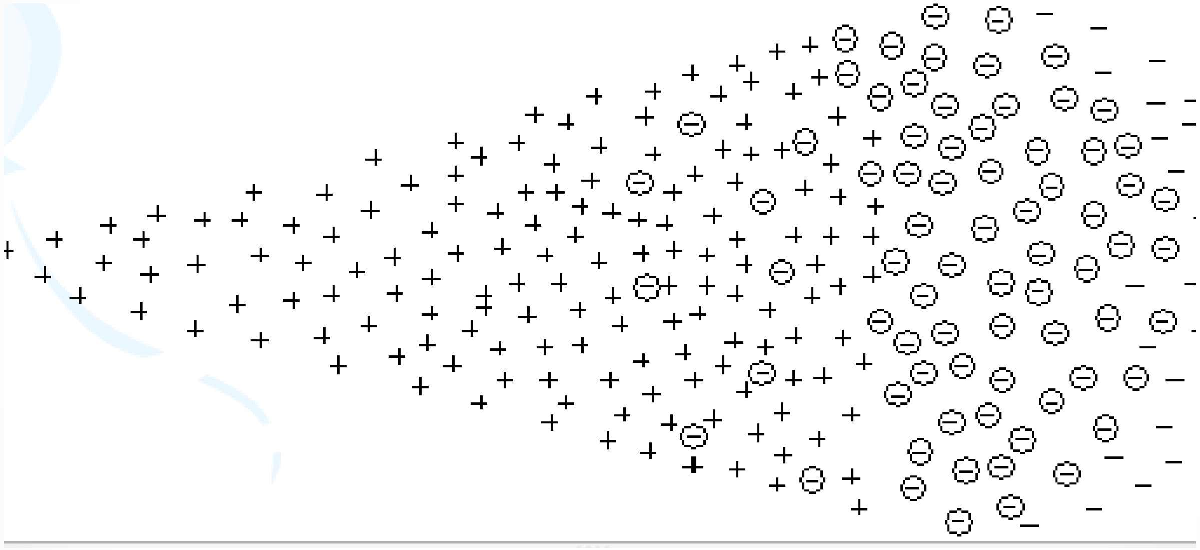
$$W_i = eEx = \frac{1}{2}mv^2$$

$$M + e^- \left(\tfrac{1}{2} mv^2\right) \rightarrow M^+ + 2e^-$$

Where x is the distance traveled by the electron from the cathode, m is the mass and v is the velocity of the electron. $x=\lambda$ mean free path.

Breakdown Mechanisms

Avalanche



Breakdown Mechanisms

- Mean Free Path λ: is defined as the average distance traveled between each collision.

$$\boldsymbol{\lambda} = \frac{K\,T}{\pi\, r^2\; P}$$

- Where K is Boltzmann's constant, r is the radius of the particle, T is absolute temperature and P is the pressure of gas.
- The mean free path depends upon the concentration of particles or the density of the gas.

Breakdown Mechanisms

Excitation

If the collision energy is not sufficient, then the atom will come to an excited state only

$$M + e^- \left(\tfrac{1}{2} mv^2\right) \rightarrow M^* + e^-$$

The excited molecule can subsequently give out a photon of frequency ν with energy emitted $h\nu$.
The energy is given out when the electron jumps from one orbit to the next.

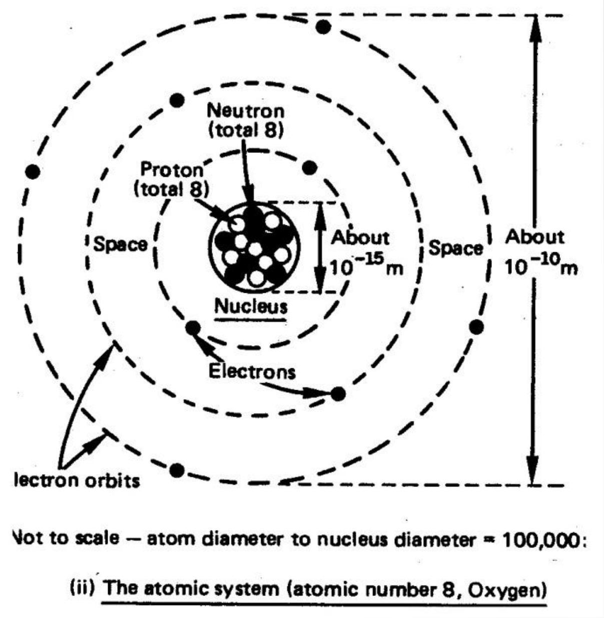
$$M^* \rightarrow M + h\nu$$

h is Planck's constant= 6.624×10^{-34} Js

Ionization Mechanisms

Photo Ionization

- Energy gained from light raises electrons to higher energy level (orbit)
- Energy is absorbed when moving to higher orbit
- Energy is emitted when falling back
- If energy gained exceeds the ionisation energy of the gas the electron leaves the atom



$h\nu + A \leftarrow A^*$

$h\nu + M \rightarrow M^+ + e^-$ $h\nu > W_i$

$c/\lambda = \nu$

Short wave light is more stronger

h - Plank's Constant, $=6.624 \times 10^{-34}$ J s
λ - Wavelength of Incident radiation
c - Velocity of Light
Vi-Electron Volts

Ionization Mechanisms

Thermal Ionization

- When a gas is heated to high temperature, some of the gas molecules acquire high kinetic energy and release electrons.
- These electrons and other high-velocity molecules in turn collide with other particles and release more electrons.
- Saha derived an expression for the degree of ionization β in terms of the gas pressure and absolute temperature as follows:

$$\frac{\beta^2}{1-\beta^2} = \frac{2.4 \times 10^{-4}}{p} T^{5/2} e^{-W_i/KT}$$

Where p is the pressure in Torr, W_i the ionization energy of the gas, K the Boltzmann's constant

β the ratio n_i/n and n_i the number of ionized particles of total n particles. Since β depends upon the temperature it is clear that the degree of ionization is negligible at room temperature.

Ionization Mechanisms

Secondary Ionization

- Electron emission due to Positive Ion Impact
- Electron emission due to Photons
  - ➢ Positive ion can cause emission of electrons from the cathode by giving up its K.E on impact.
  - ➢ Energy (in the form of photons) by UV light cause electron to escape from a metal. It occurs if $h\nu > W_i$, where Wi is the work function and ν is the threshold frequency.

Ionization Mechanisms

CATHODE PROCESSES—SECONDARY EFFECTS

- Cathode plays an important role in gas discharges by supplying electrons for the ionization.
- The energy required to knock out an electron from a Fermi level is known as the work function and is a characteristic of a given material.

Metal	Work function (EV)
Copper	3.9
Aluminum	1.8
Iron	3.9

Ionization Mechanisms

CATHODE PROCESSES—SECONDARY EFFECTS

- At room temperature, the conduction electrons of the metal do not have sufficient thermal energy to leave the surface.
- However, if the metals are heated to temperature 1000°K and above, the electrons will receive energy from the violent thermal lattice in vibration sufficient to cross the surface barrier and leave the metal.
- Richardson developed an expression for the saturation current density Js as $J_s = AT^2 e^{-W/KT}$

$A=120\times10^4$ A/m^2 K^2 ; K is Boltzmann constant, T Absolute temp and W is the work function of the metal

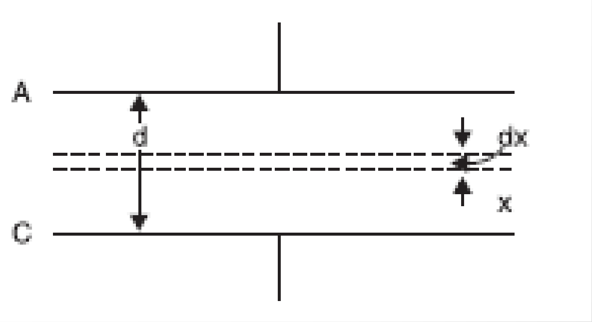
Ionization Mechanisms

CATHODE PROCESSES—Other factors include

- Bombardment of the surface of the electrode by some particles (For. Example, by positive ions with sufficient energy)
- Irradiating the surface of the metal by short wave radiation
- By applying strong external field (Cold emission)

Townsend's Theory

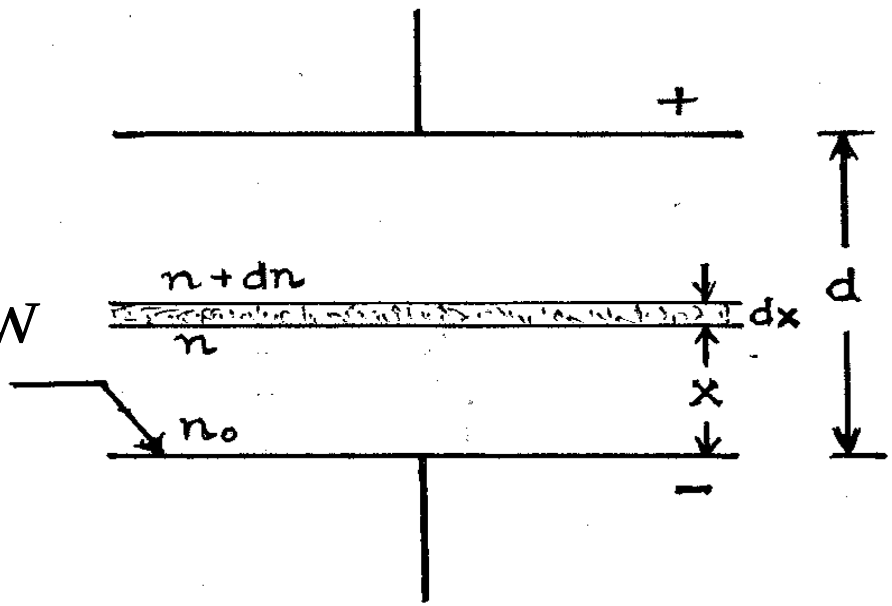
- Townsend suggested that the gap current grows as a result of ionization by electron collision in the gas and electron emission at the cathode by positive ion impact.
- Townsend defined the number of electrons produced per electron per unit length as the quantity α. Using Townsend's first ionization coefficient the incremental increase of electrons is given as:
- $$dn_x = \alpha\, n_x dx$$



Townsend's Theory

- n_0 the initial number of electrons near the cathode.

- Assuming 'n_x ' as the number of electrons at distance 'x' from the cathode, the number of new electrons created 'dn_x' in a slab of thickness 'dx' ,



- $dn_x = n_x \, dx \, \alpha$: i.e., $dn_x/n_x = \alpha \, dx$

Townsend's Theory

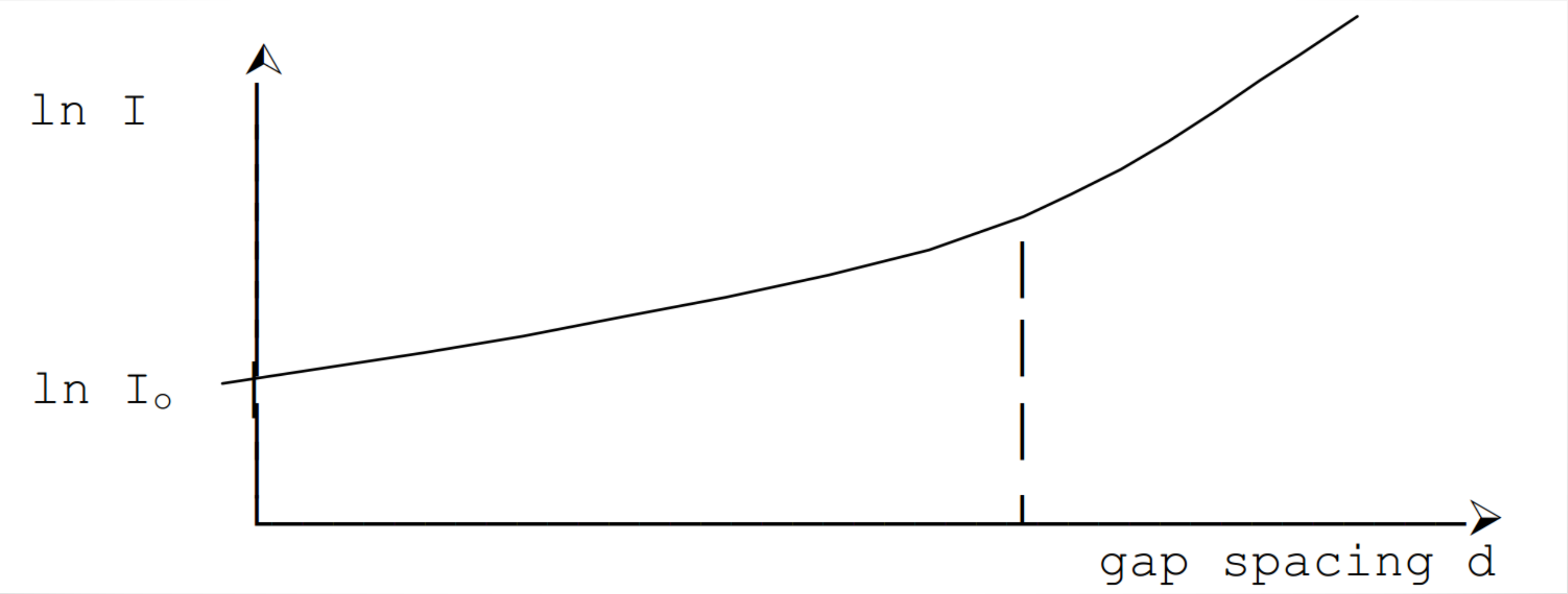
- Integrating the above , we get $\ln (n/n_0) = \alpha d$
- $n = n_0 \exp (\alpha d)$
- As'I'is proportional to the no. of electrons , 'n', we can write , $I = I_0 \exp (\alpha d)$: i.e., $\ln I = \ln I_0 + \alpha d$
- which is the equation of a straight line with slope 'ά'.

Townsend's Theory

The growth of current is shown in the curve below,

$$\ln I = \alpha d + \ln I_0$$

$$y = m x + c$$



Current Growth through Secondary Process

- Let n_0'=no of secondary electrons
- n_0''=total no of electrons leaving the cathode.
- $n_0'' = n_0' + n_0$
- No of electrons reaching the anode

$$n = n_0'' \exp(\alpha d) = (n_0' + n_0) \exp(\alpha d)$$

$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]} \quad I = \frac{I0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

- Breakdown Criteria $\gamma[\exp(\alpha d) - 1] = 1$

Ionization Mechanisms

Electron Attachment : Electronegative Gases

- Collisions in which electrons attached to atoms to form negative ions.
- Electron attachment represents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low voltages. The gases in which attachment plays an active role are called electronegative gases.

$$M + e^- (mv^2) \longrightarrow M^-$$

- Electrically insulating gases, CO2 and SF6 exhibit this property.

Ionization Mechanisms

Electron Attachment: Electronegative Gases

$$I = I_0 \frac{\left[\frac{\alpha}{\alpha-\eta} e^{(\alpha-\eta)d}\right] - \left[\frac{\eta}{\alpha-\eta}\right]}{1 - \left[\gamma \frac{\alpha}{\alpha-\eta} e^{(\alpha-\eta)d} - 1\right]}$$

η=attachment coefficient

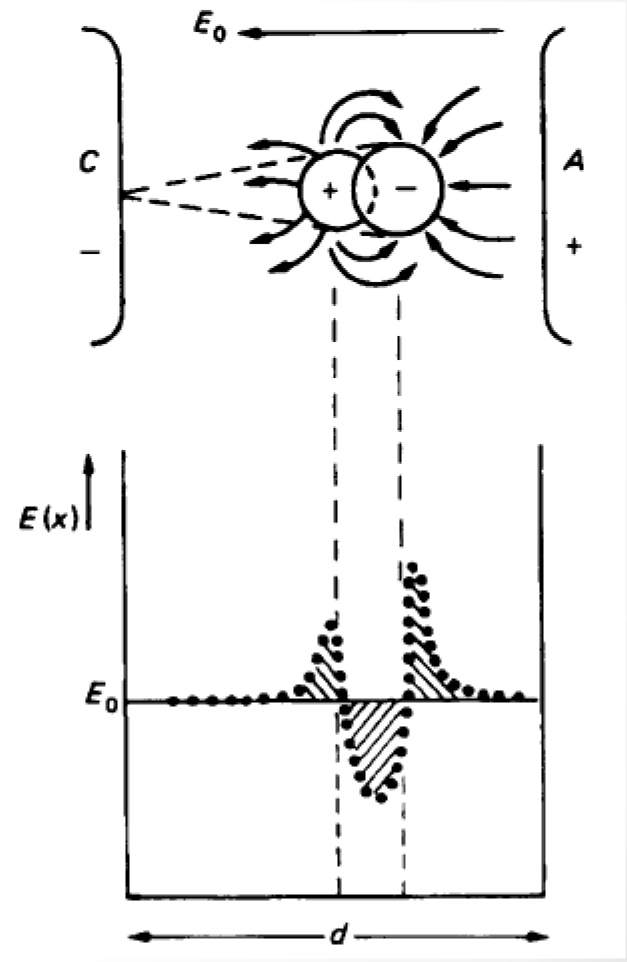
The corresponding criteria for spark breakdown is:

$$\gamma \frac{\alpha}{\alpha - \eta}\left[e^{(\alpha - \eta)d} - 1\right] = 1$$

Ionization Mechanisms

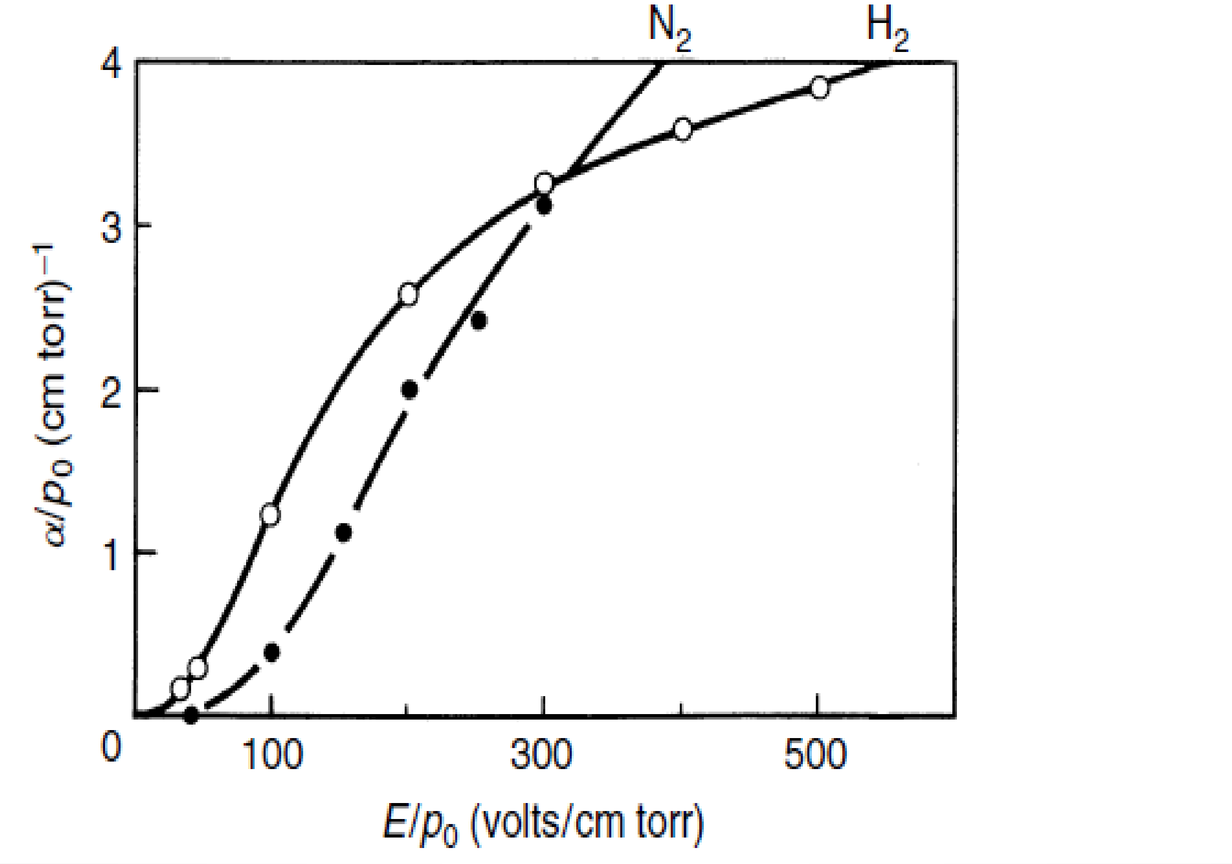
Streamer Theory

- The field at the anode side and cathode side of the avalanche is enhanced.
- A streamer is started due to field enhancement at the head and tail side of initial avalanches due to charge separation.



Townsend's Theory

Alpha'α' is a function of ' E/p' and the dependence of (α/p) on 'E/p' is shown below.



Paschen's Law

It has been shown earlier that the breakdown criterion in gases is given as

$$\gamma\,[\exp(\alpha d) - 1] = 1$$

where the coefficients α and γ are functions of E/p, i.e

$$\left.\begin{aligned}\frac{\alpha}{p} &= f_1\left(\frac{E}{p}\right)\\ \gamma &= f_2\left(\frac{E}{p}\right)\end{aligned}\right\}$$

$$E = \frac{V}{d}$$

Paschen's Law

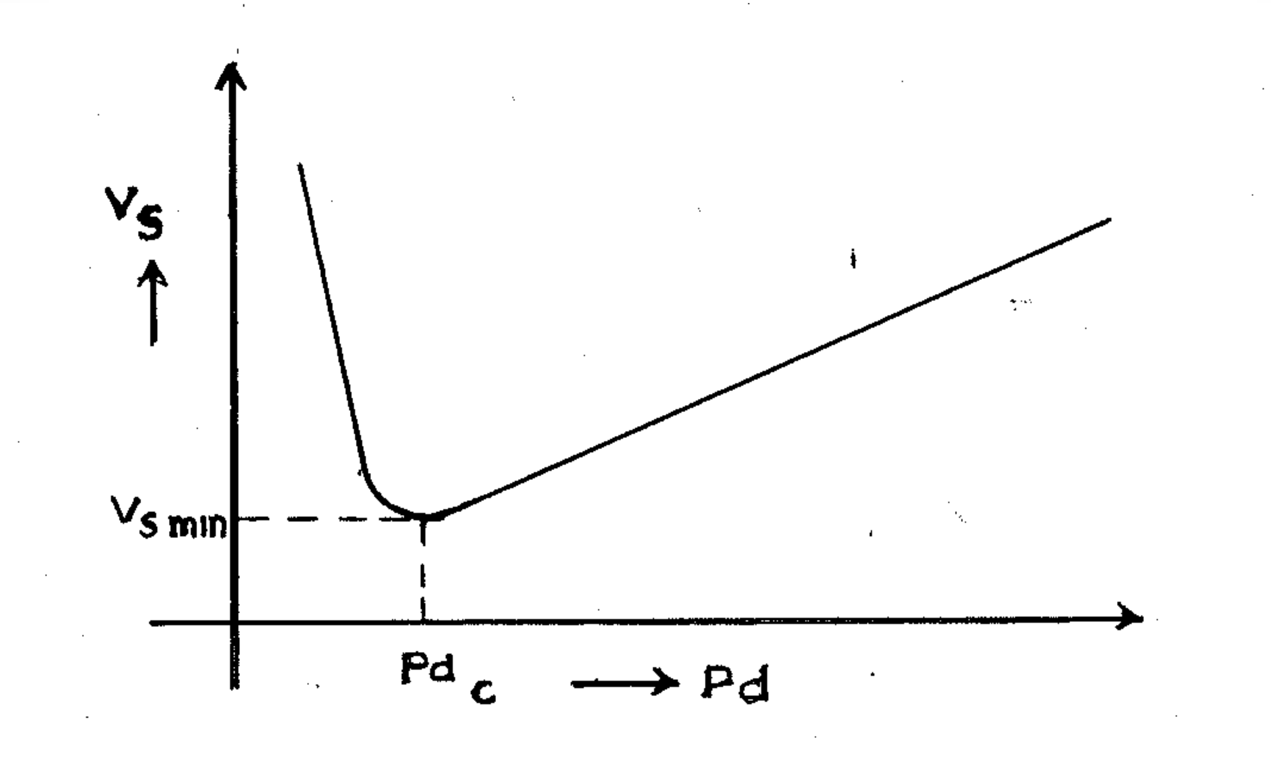
Substituting for E in the expressions for α and γ and rewriting Eq. we have

$$f_2\left(\frac{V}{pd}\right)\left[\exp\left\{pd f_1\left(\frac{V}{pd}\right)\right\} - 1\right] = 1$$

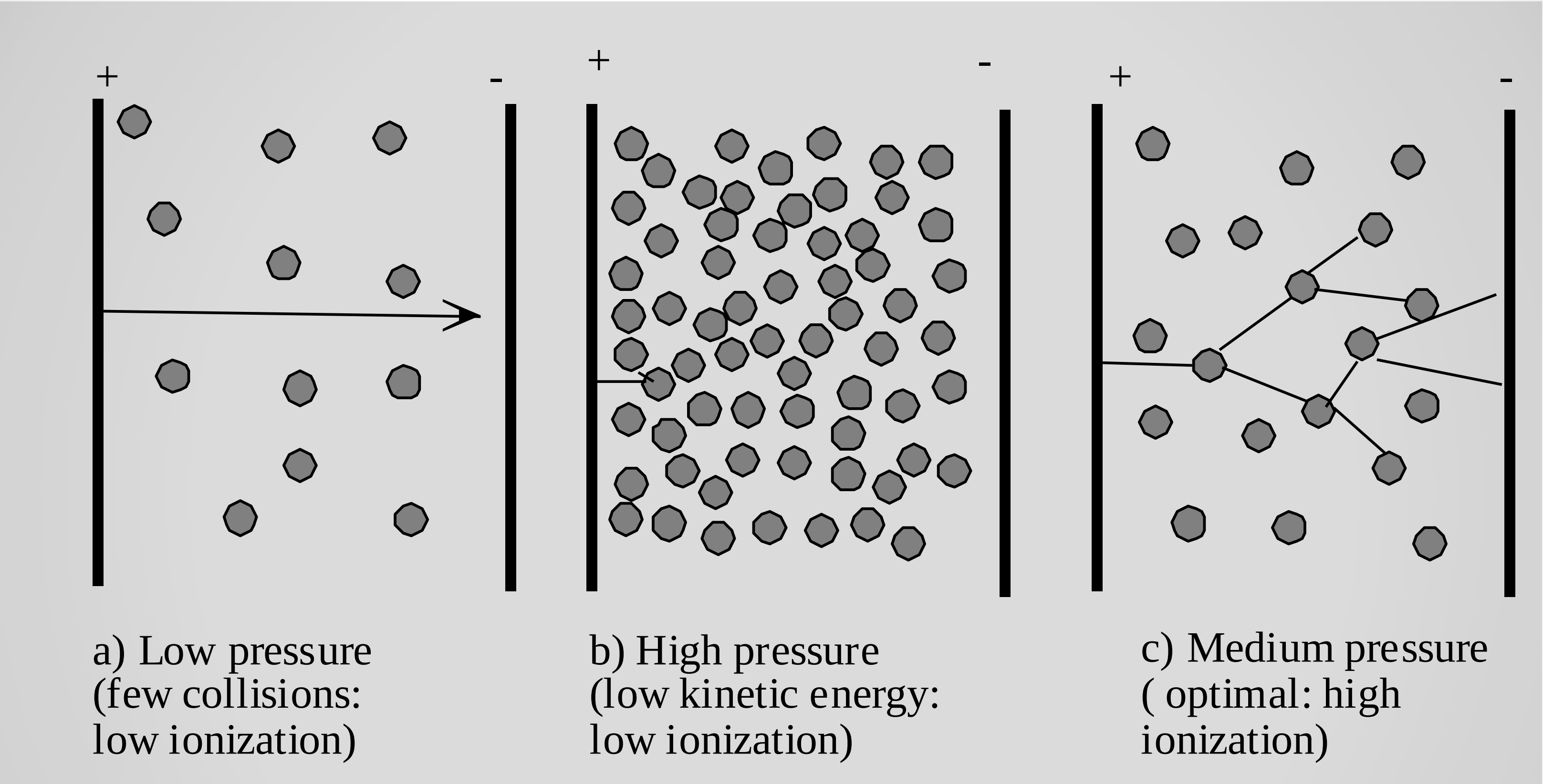
This equation shows a relationship between V and pd, and implies that the breakdown voltage varies as the product (pd) varies.

Paschen's Law

Paschen's law describes the dependence of the breakdown voltage on the product of both pressure and distance (pd).



Paschen's Law



Low gas density - more kinetic energy gained but less collisions

High gas density – more collisions but less energy gained

Paschen's Law

It is seen that the relationship between V and pd is not linear and has a minimum value for any gas. The minimum breakdown voltages for various gases are given in Table.

Table 2.1 Minimum Sparking Potential For Various Gases

Gas	V_s min (V)	pd at V_s min (torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7

Paschen's Law

Based on the experimental results, the breakdown potential of air is expressed as a function of pd as

$$V = 24.22\left[\frac{293\,pd}{760T}\right] + 6.08\left[\frac{293\,pd}{760T}\right]^{1/2}$$

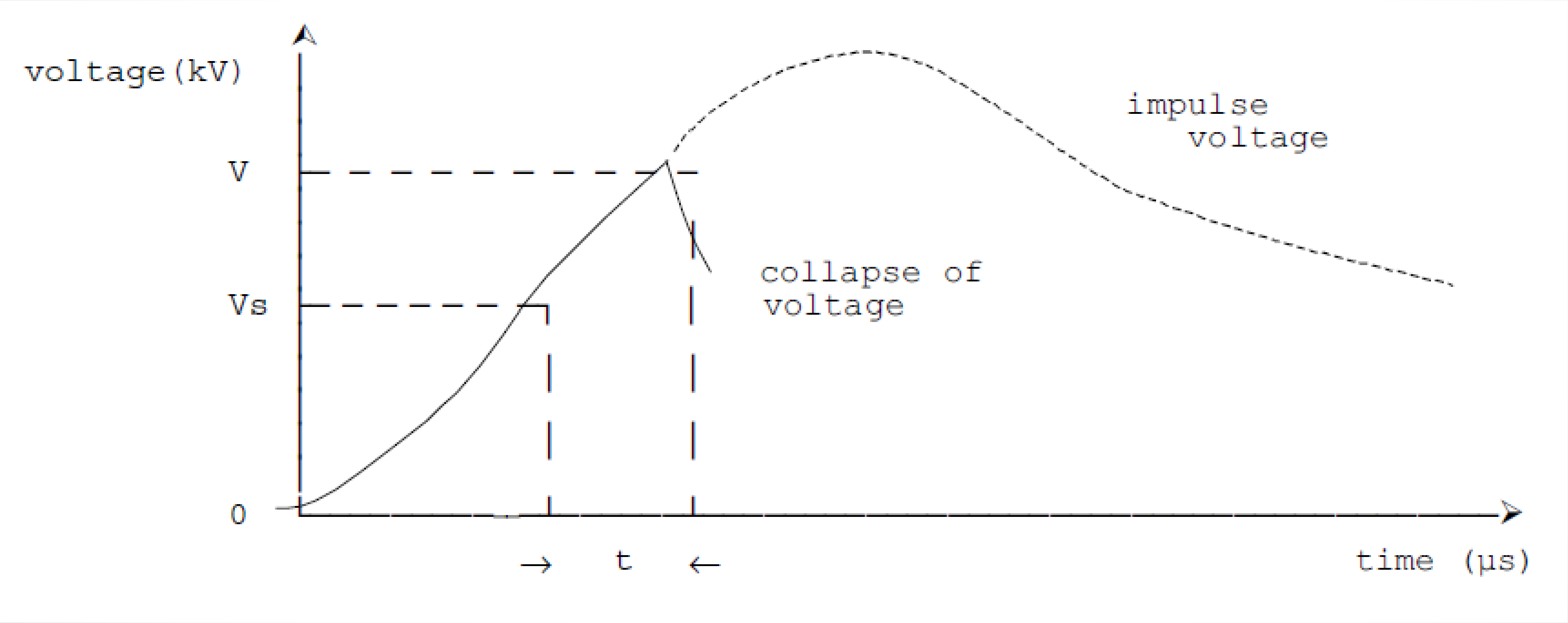
At 760 torr and 293 °K.

$$E = V/d = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \text{kV/cm}$$

This equation yields a limiting value for *E* of 24 kV/cm for long gaps and a value of 30kV/cm for 1cm gap. This is the usually quoted breakdown strength of air at room temperature and at atmospheric pressure.

Time Lag of Breakdown Due To Impulse Voltage

- The time it takes for a gap to break down, once a pulsed voltage is applied at the gap, is comprised of a statistical lag time and a formative time.

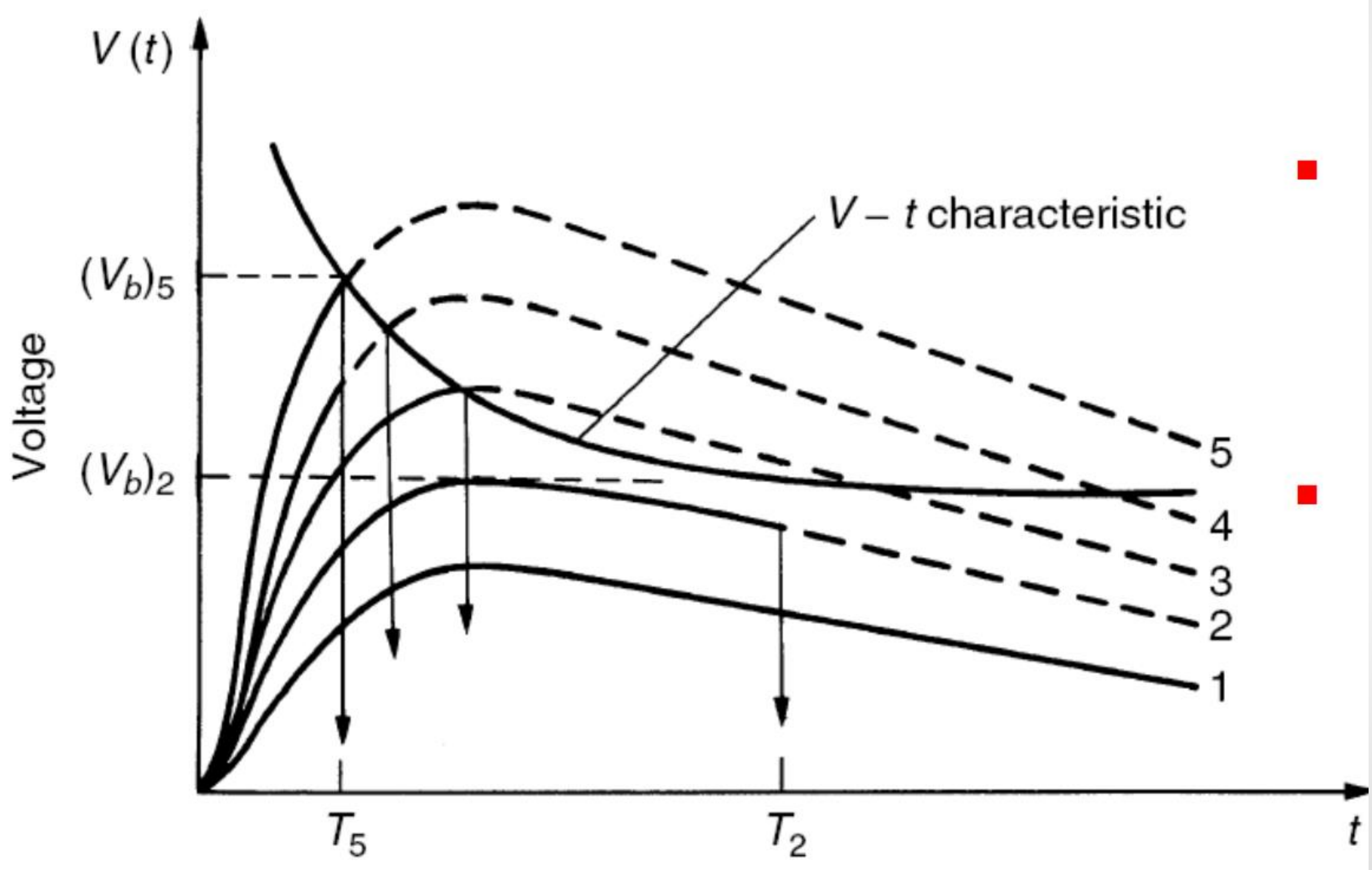


Time Lag of Breakdown Due To Impulse Voltage

- Statistical time lag 't_s': is the time taken to find electrons near the cathode surface to start the ionization process.

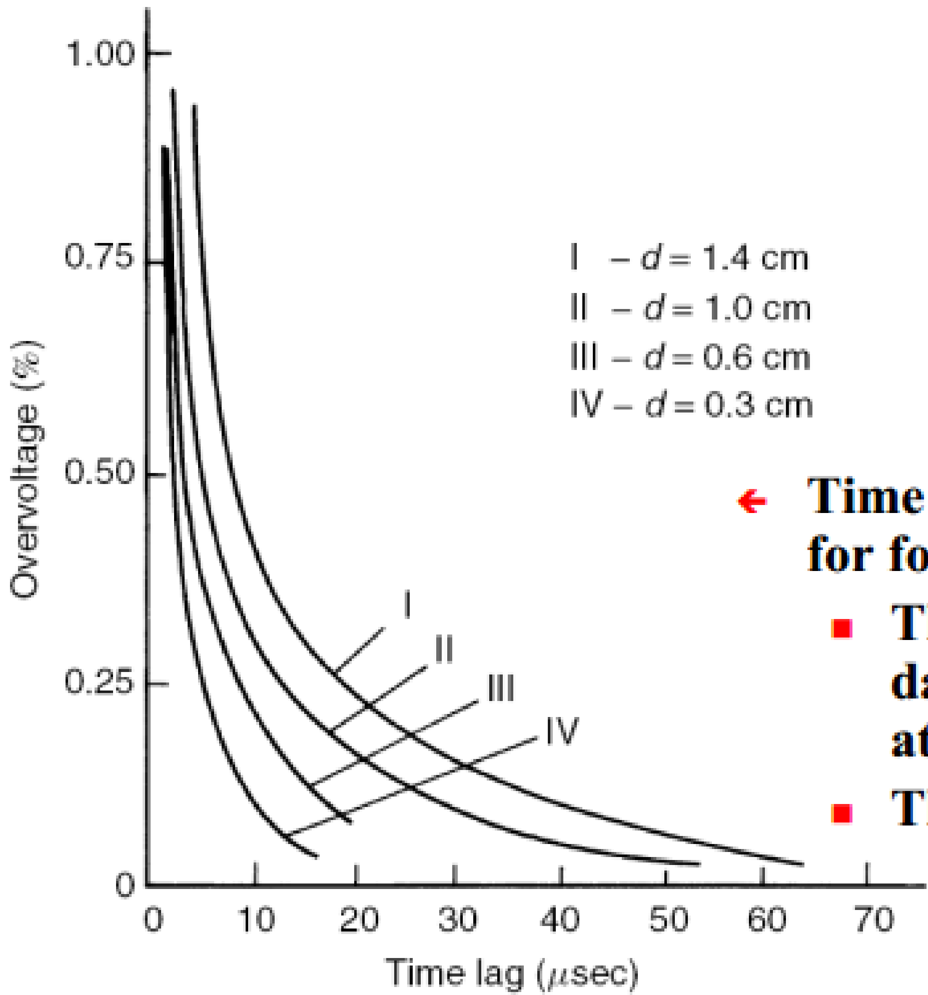
- The formative time lag t_f : is the time taken to complete the ionization process.

Time Lag of Breakdown Due To Impulse Voltage



Time Lag of Breakdown Due To Impulse Voltage

- **Experimental results of time lags (example)**



← **Time lag as a function of overvoltage for four gap lengths in air.**

- **The curves represent the average data for all pressures between atmospheric and 200 mm Hg**
- **The overvoltage represents V_p-V_s**