## 2.1. Gases as Insulating Media

- The simplest and the most commonly found dielectrics are gases.
- Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as Nitrogen ($N_2$), Carbon dioxide ($CO_2$), Freon ($CCl_2F_2$) and Sulphur hexafluoride ($SF_6$) are also used.
- Various phenomena occur in gaseous dielectrics when a voltage is applied.
- When the applied voltage is low, small current flow between the conducting electrodes and the insulation keep its electrical properties.
- Whereas if applied voltage is large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs.
- A strongly conducting spark formed during breakdown practically produces a short-circuit between the electrodes.
- The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage.
- Two types of electrical discharge in gases: (1) Non-sustaining discharges and (2) Self-sustaining types.

## 2.2. Ionization Processes

- At normal temperature and pressure, a gas acts as good insulating materials.
- When high voltage applied between the two electrodes immersed in gaseous medium, the gas becomes a conductor an electrical breakdown occurs.
- Ionization by collisions are two type:
  a. Elastic collisions: An elastic collision is a collision in which there is no net loss in kinetic energy in the system as a result of the collision.
  b. Inelastic collisions: A collision in which the total kinetic energy of the colliding bodies or particles is not the same after the collision as it was before (opposed to elastic collision).

### 2.2.1. Ionization by collision

- Ionization is defined as a process of leaving free electron from a gas molecule with the continuous generation of positive ion.
- In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.
- If we consider a low-pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. 2.1.
- If the energy (E) gained during this travel between collision exceeds the ionization potential, $V_i$, which is the energy required to remove an electron from its atomic shell, then ionization take place. This process can be represented as

$$e^- + A \xrightarrow{(E>Vi)} e^- + A^+ + e^-$$

Where, A is the atom, $A^+$ is the positive ion and $e^-$ is the electron

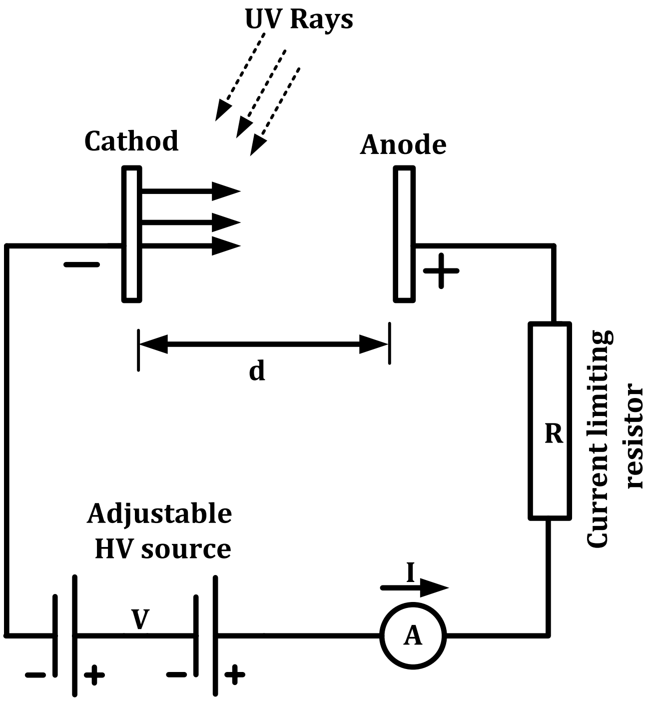


*Figure 2. 1 Parallel plate arrangement to study ionization*

- A few electron produce at the cathode by some external means, say by ultra-violet light falling on the cathode, ionize neutral gas particles producing positive ions and additional electrons.
- The additional electrons, then, themselves make 'ionizing collisions' and thus the process repeats itself.

### 2.2.2. Photo Ionization

- The ionization caused by cosmic radiation or photons is called photo-ionization.
- Photo-ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization potential.
- There are several processes by which radiation can be absorbed by atoms or molecules.
- They are (a) excitation of the atom to a higher energy state, and (b) continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionization, etc.
- This reversible process can be expressed as,

$$hv + A \rightleftarrows A^{+} + e^{-}$$

- Ionization occurs when

$$\lambda \leq c \cdot \frac{h}{V_1}$$

- Where,

  h = Plank constant

  c = velocity of light

  λ = wavelength of the incident radiation

$V_i$ = ionization energy of atom

- Substituting for h and c, we get, $\lambda \le \left(\frac{1.27}{V_I}\right) * 10^{-6} cm$
- Where $V_I$ is in electron volts (eV)
- The higher the ionization energy, the shorter will be the wavelength of the radiation capable of causing ionization.
- It was observed experimentally that a radiation having a wavelength of 1250 Å is capable of causing photo-ionization of almost all gases.

### 2.2.3. Ionization by interaction of metastable with neutral atoms

- In the atmosphere, there are some elements or atoms whose life time extends to few seconds, in certain electronic states. Such atoms are called metastable atoms.
- They have high potential energy.
- Therefore, metastable atoms are able to ionize neutral particle.
- It can be represented by following reaction of intersection.

$$A + B^m = A^+ + e^- + B$$

- Where,

  A = the atom to be ionized

  $B^m$ = metastable particle

  $A^+$ = positive ion of atom

  $e^-$ = negatively charged electron

### 2.2.4. Thermal Ionization

- At high electrical stress, the gas filling the gap between the electrodes is heated up.
- The gases at high temperature some of the gas molecules acquire high kinetic energy.
- The collision between molecules creates ions due to release of electron from the neutral particles.
- The electrons and other high speed molecules in- turn collide with each other and release more electrons. Thus the gas gets ionized.

### 2.2.5. Deionization by Recombination

- When positively and negatively charged particles present recombination take place.
- This Recombination process is the reverse process of photoionization and symbolically represented as,

$$A^+ + e^- \rightarrow A + hv$$

- Where,

  $A^+$= positive ion

  $e^-$ = an electron or negative ion.

- The photon energy released (hv) would be absorbed by a third body C present.
- The third body C may be another heavy particle or electron and represented as

$A^+ + C + e^- \rightarrow A^* + C \rightarrow A + C + hv \frac{d\eta}{dt} = K\eta^2$

- At high pressure, recombination rate is directly proportional to the positive and negative ions.
- Let positive ions $\eta_+$ and negative ions $\eta_-$ with equal concentration and the rate of recombination.

$$\frac{d\eta_+}{dt} = \frac{d\eta_-}{dt} = K\eta_+\eta_-$$

- Where, K = recombination coefficient
- Since $\eta_+ \approx \eta_- = \eta$
- From above comparison, we get

$$\frac{d\eta}{dt} = K\eta^2$$

- The variation of the recombination coefficient K with Pressure in air as shown in below,

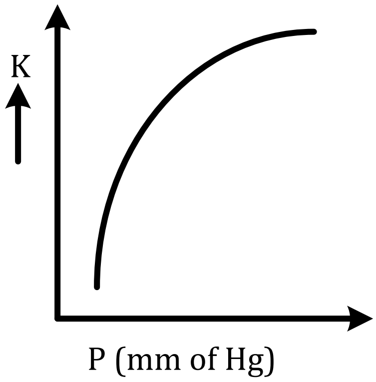


*Figure 2. 2 Recombination coefficient K with pressure in air*

### 2.2.6. Deionization by Attachment

- Electrons can combine with neutral atoms or molecules to form negative ions, in certain gases.
- Some of the Gases have a characteristics that are lacking one or two electrons in their outer surface known as electronegative gases.
- Electronegative gases have very high dielectric strength due to formation of negative ion during deionization process.
- The reaction represented symbolically as

$$AB + e \rightarrow (AB^-) + hv$$

- It may also be happen that the atom AB will be dissociate into $A^+$ and $B^-$ ion which will be represented by as below

$$AB + e \rightarrow (AB)* + e \rightarrow A^+ + B^- + e$$

- The above to reaction will be depended on the energy level of electron which will be attached with the atom AB.

## 2.3. Townsend First Ionization Coefficient

- Let us consider a parallel plate capacitor having gas as in insulating medium and separated by a distance as shown in Fig.2.1
- Let us assume that $n_0$ electrons are emitted from the cathode.
- When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision.
- Let α be the average number of ionizing collisions made by an electron per centimeter distance travel in the direction of the filed (α depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient).
- Fig. 2.3 illustrates the breakdown phenomenon of a gas and the growth of current in the gas which is responsible for breakdown.
- The curve has three regions:
  a. Ohmic region
  b. Saturation region
  c. Townsend's discharge region

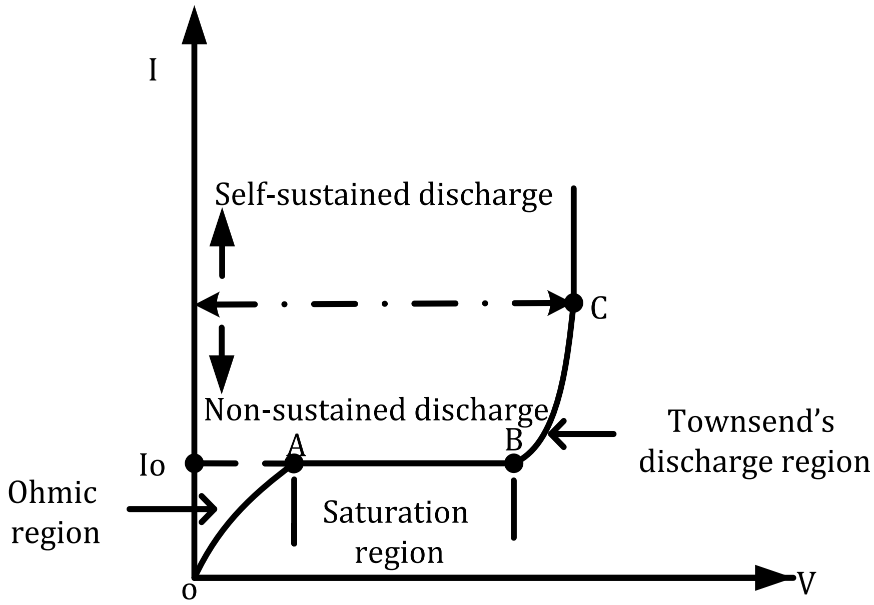


*Figure 2. 3Typical current growth curve In Townsend discharge*

- It is observed from the figure that the current at first increases proportionally with the increases in field or voltage. This region is called ohmic region.
- After this state, a situation comes when current become constant $I_0$ even if voltage is increased. The constant current $I_0$ is called the saturation current.
- At still higher voltage, the current increases exponentially.

- The exponential increase in current is due to ionization of gas by electron collision with gas molecules.
- As the voltage increase, electric field intensity V/d increases and hence the electrons are accelerated more and more and the electron get higher kinetic energy and therefore, knock out more and more electrons.
- At any distance x from the cathode, let the number of electrons be $n_x$.
- When these $n_x$ electrons travel a further distance of dx they give rise to ($\alpha n_x dx$) electrons.

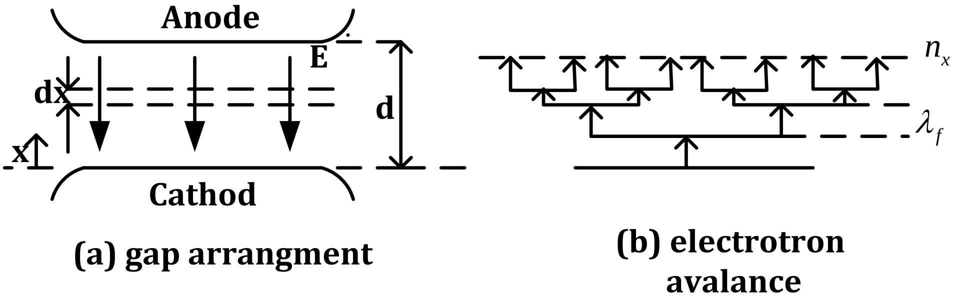


*Figure 2. 4Electron avalanche*

$$dn_x = \alpha n_x dx$$

$$\frac{dn_x}{n} = \alpha dx$$

$$\ln n = \alpha x + A \text{..............................(i)}$$

$$(at(x=0), n_x = n_0)$$

$$\therefore A = \ln n_0 \; put \text{ in equation (i)}$$

$$\therefore \ln n = \alpha x + \ln n_0$$

$$\therefore \ln n - \ln n_0 = \alpha x$$

$$\therefore \ln\left(\frac{n}{n_0}\right) = \alpha x$$

$$\therefore \left(\frac{n}{n_0}\right) = e^{\alpha d}\text{, at x=d distance,}$$

$$\therefore \text{n} = n_0 e^{\alpha d}$$

- The average current in the gap, which is equal to the number of electrons travelling from the above equation per second will be

$$\text{I=I}_0 e^{\alpha d}$$

Where $e^{\alpha d}$ =electron avalanche, $I_o$ =initial current Ampere

## 2.4. Townsend Second Ionization Co-efficient

- The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode.
- The probability amplification of the electrons being release in the gap by other mechanisms increases, and these new electrons create further avalanches.
- The other mechanisms are
  (i) The positive ions released may have sufficient energy to cause liberation of electrons from the cathode when they impose on it.
  (ii) The excited atoms or molecules in avalanches may emit photon, and this will lead to the emission of electrons due to photo-emission.
  (iii) The metastable particles may diffuse back causing electron emission.
- The electrons produced by these processes are called secondary electrons.
- The secondary ionization coefficient $\gamma$ is defined in the same way as $\alpha$ , as the net number of secondary electrons produced per incident positive ion, photon, exited particle, or metastable particle, and the total value of $\gamma$ is the sum of the individual coefficients due to the three different processes, i.e. $\gamma = \gamma_1 + \gamma_2 + \gamma_3$.
- $\gamma$ is called Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.
- Following Townsend's procedure for current growth, let us assume
  $n_+$ = number of secondary electrons produced due to secondary ( $\gamma$ ) processes.
  ($n_0 + n_+$)= total number of electron leaving the cathode.
- The total number of electron n reaching the anode becomes,

$$n = (n_0 + n_+) e^{\alpha d} \quad \text{..............................(i)}$$

$$n_+ = \gamma\left[n - (n_0 + n_+)\right]$$

$$n_+ = \gamma n - \gamma n_0 - \gamma n_+$$

$$(1+\gamma) n_+ = \gamma (n - n_0)$$

$$n_+ = \frac{\gamma(n - n_0)}{1+\gamma}$$

Substituting $n_+$ value in equation (i)

$$n = \left[n_0 + \frac{\gamma(n - n_0)}{1+\gamma}\right] e^{\alpha d}$$

$$n = \left[\frac{n_0 + \gamma n_0 + \gamma n - \gamma n_0}{1+\gamma}\right] e^{\alpha d}$$

$$n = \left[\frac{n_0 + \gamma n}{1+\gamma}\right] e^{\alpha d}$$

$$n(1+\gamma) = (n_0 + \gamma n) e^{\alpha d}$$

$$n + \gamma n = n_0 e^{\alpha d} + \gamma n e^{\alpha d}$$

$$n + \gamma n - \gamma n e^{\alpha d} = n_0 e^{\alpha d}$$

$$n\left[1 + \gamma\left(1 - e^{\alpha d}\right)\right] = n_0 e^{\alpha d}$$

$$n\left[1 - \gamma(e^{\alpha d} - 1)\right] = n_0 e^{\alpha d}$$

$$n = \frac{n_0 e^{\alpha d}}{\left[1 - \gamma(e^{\alpha d} - 1)\right]}$$

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

- This is Townsend's current growth equation due to primary and secondary ionization.

## 2.5. Transition from Non-Self Sustained Discharges to Breakdown (Townsend Breakdown Mechanism)

- We know that

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

- Where, I=current at anode

  $\alpha$ =Townsend's first ionization coefficient

  $\gamma$ =Townsend's second ionization coefficient

  d = gap-length of electrodes

- The current becomes $\infty$ if

$$1 - \gamma\left(e^{\alpha d} - 1\right) = 0$$

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

$$e^{\alpha d} \gg 1$$

- $\gamma e^{\alpha d} = 1$ defines condition for begining of spark formation.
- Three possible condition:

  (1) if $\gamma e^{\alpha d} = 1$: In this condition, the discharge is said to be Self-sustained because, discharge will sustain itself even if source producing $\mathrm{I}_0$ (as shown in fig.) is removed.

  (2) if $\gamma e^{\alpha d} > 1$: In this case, the ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly.

  (3) if $\gamma e^{\alpha d} < 1$: In this condition, the current is not self-sustained. because, removal of source, the current $\mathrm{I}_0$ is only remain constant.

- Fig.2.3 shown the various regions of breakdown criteria. For region BC the criterion is $\gamma e^{\alpha d} < 1$

- The region near the point C indicates the Threshold region $\gamma e^{\alpha d} = 1$
- The region beyond C illustrates the criterion, if $\gamma e^{\alpha d} > 1$

## 2.6. Breakdown in Electronegative Gases

- Electronegative gases are the gases that have similarity towards electrons. When electron comes into contact with these gas molecules, the gas molecule attracts the electrons and becomes negative ion.
- The gases, which are lacking in one or two electrons in their outer shell are known as electronegative gases.
- The most common attachment processes encountered in gases are
  a. Direct Attachment: In which an electron directly attaches to form a negative ion.
  $$AB + e^- \rightarrow AB^- + hv$$
  b. Dissociative Attachment: In which gas molecules split into their constituent atoms and
  Electronegative atoms from negative ions.
  $$AB + e \rightarrow A + B^- + e$$
- A simple gas of this types is oxygen. Other gases are Sulphur hexafluoride, Freon, carbon dioxide, and fluorocarbons.
- In this gases, 'A' is usually Sulphur or carbon atom, and 'B' is oxygen atom or one of the halogen atoms or molecules.
- With such gases, the Townsend current growth equation is modified to include ionization and attachment.
- An attachment coefficient ($\eta$) is defined, similar to $\alpha$ as the number of attaching collisions made by one electron drifting one centimeter in the direction of the filed.
- Under these conditions, the current reaching the anode, can be written as

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

- Townsend breakdown criterion for attaching gases can also be find out by equating the denominator in equation (i)

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

- This shown that for $\alpha > \eta$, breakdown is always possible irrespective of the values of $\alpha, \eta,$ and $\gamma$.
- If on the other hand, $\eta > \alpha$ equation approaches an asymptotic from with increasing value of d,

$$\gamma \frac{\alpha}{(\alpha-\eta)} = 1$$

$$\therefore \gamma\alpha = \alpha - \eta$$

$$\therefore \quad \eta = \alpha - \gamma\alpha$$

$$\therefore \quad \alpha = \frac{\eta}{(1-\gamma)}$$

$$\alpha = \eta \;\; (\gamma \text{ is very small } \leq \; 10^{-4})$$

- If the pressure is constant then this condition put the limit of value of E below which no breakdown is possible irrespective of the value of 'd' and the limit value is critical E for that pressure. eg. For $SF_6$ 117V $cm^{-1}$ $torr^{-1}$ at $20^{\circ}C$

## 2.7. Time Lags for Breakdown

- Theoretically the mechanism of spark breakdown is considered as a function of ionization processes under uniform field conditions.
- In practical engineering designs, the breakdown due to rapidly changing voltage or impulse voltage is of great importance.
- Actually there is a time difference in the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called as the time lag.
- The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c. or slowly varying (50Hz a.c.) voltages. This is no difficulty in satisfying this condition.
- With rapidly varying voltage of short duration ($\approx 10^{-6}$s), the initiatory electron may not be present in the gap then the breakdown cannot occur due to not available free electron.
  - **i. Statistical time-lag($t_s$):** is defined as the time lapsed between the application of voltage sufficient to cause breakdown and the appearance of initiating electron is called as statistical time lag.
- The Statistical time lag depends upon the amount of pre-ionization present in the gap.
- This in turn depends on the size of the gap and the quantity of radiation that produces the primary electrons.
- The techniques generally used for irradiating the gaps include ultraviolet radiation, radioactive materials and light sources.
  - **ii. Formative time-lag($t_f$):** After the appearance of electron, the time $t_f$ required for the ionization process to develop fully to cause to the breakdown of gap is called as formative time-lag.
- The formative time lags depend mostly on the mechanism of the avalanche growth in the gap.
  - **iii. Total time-lag (t):** is define as the sum total of Statistical time-lag and formative time-lag $T = t_s + t_f$

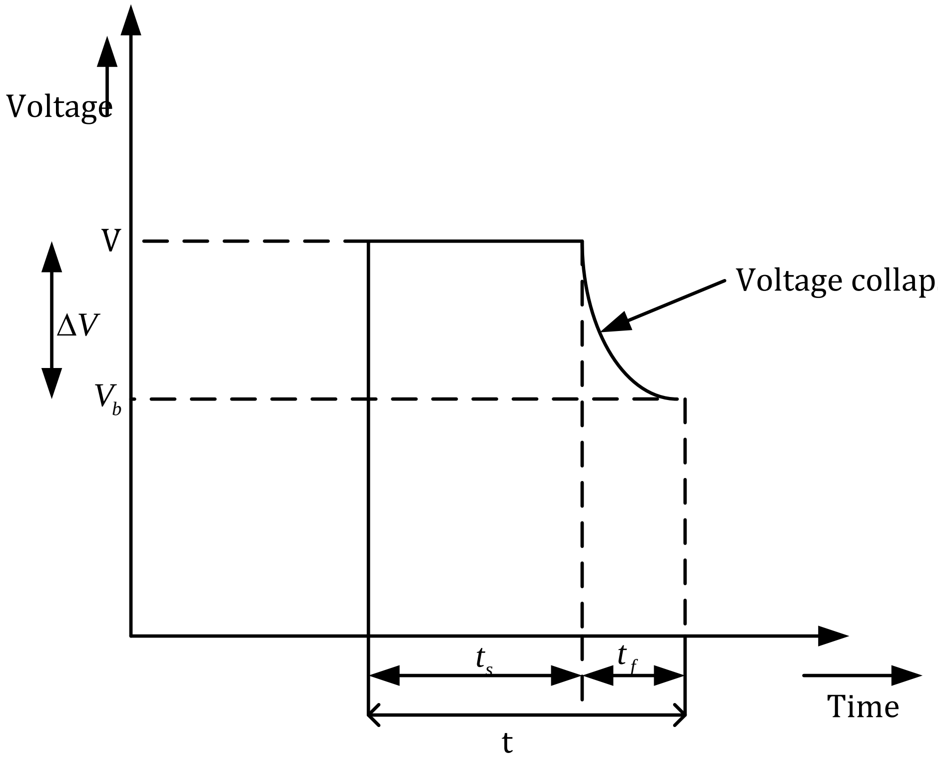


*Figure 2. 5Breakdown with a step function voltage pulse*

## 2.8. Limitations of Townsend's Theory:

- Townsend theory or Townsend's mechanism applied to gas-discharge phenomenon, was found to have some drawback or limitations.
  - (i) First drawback is that according to Townsend's theory, the current growth occurs as a result of ionization process only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.
  - (ii) Secondary, the Townsend's mechanism predicts the time-lag of the order of $10^{-5}$ seconds. While in practice, the breakdown was observed to occur at very short time of the order of $10^{-8}$ sec.
  - (iii) Townsend's mechanism predicts the very diffused from of discharge but in practice, it was found to be filament and irregular.

## 2.9. Streamer or Kanal Mechanism of Breakdown Of Spark:

- The streamer Mechanism of Breakdown is also known as "Kanal" mechanism of breakdown.
- The Streamer theory removes the limitation and drawbacks of Townsend's theory.
- We know that the charges in between the electrodes separated by a distance d increase by a factor $e^{\alpha d}$ when field between electrodes is uniform.
- This is valid only if we assume that the field $E_0$ = V/d is not affected by the space charges of electrons and positive ions.

- Raether has observed that if the charge concentration is higher than $10^6$ but lower than $10^8$ the growth of an avalanche is weakened i.e., dn/dx < $e^{\alpha d}$ .
- Whenever the concentration exceeds $10^8$, the avalanche current is followed by steep rise in current and breakdown of the gap takes place.
- The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration have been attributed to the modification of the electric field $E_0$ Due to the space charge field.
- Fig. 2.6 shows the electric field around an avalanche as it progresses along the gap and the resultant field i.e., the superposition of the space charge field and the original field $E_0$.
- Since the electrons have higher mobility, the space charge at the head of the avalanche is considered to be negative and is assumed to be concentrated within a spherical volume.
- It can be seen from Fig. 2.6 that the filed at the head of the avalanche is strengthened.
- The field between the two assumed charge Centre's i.e., the electrons and positive ions is decreased as the field due to the charge centres opposes the main field $E_0$ and again the field between the positive space charge Centre and the cathode is strengthened as the space charge field aids the main field $E_0$ in this region.
- It has been observed that if the charge carrier number exceeds $10^6$, the field distortion becomes noticeable.
- If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortion is only near the head of the avalanche, it does not have a significance on the discharge phenomenon.
- However, if the charge carrier exceeds $10^8$, the space charge field becomes almost of the same magnitude as the main field $E_0$ and hence it may lead to initiation of a streamer.

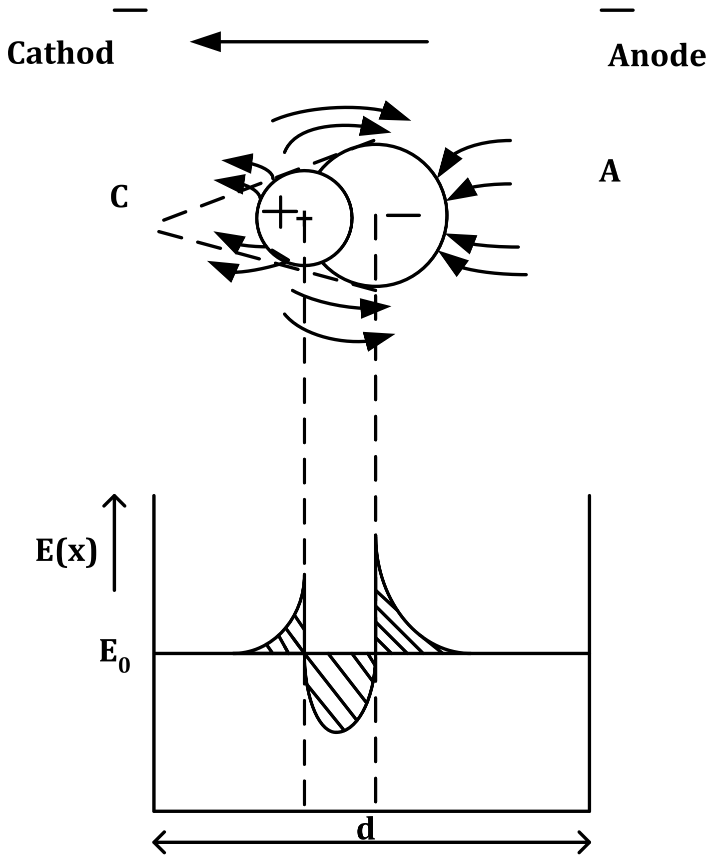


*Figure 2. 6 Breakdown with a step function voltage pulse*

- The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.
- This photon falls on the molecules and again electrons are release which is called photoionization.
- Photoionization of gas molecules is the secondary mechanism of ionization responsible for breakdown.
- On the whole, it is observed that due to (i)Enhancement of field (ii)Primary ionization (iii) Photoionization

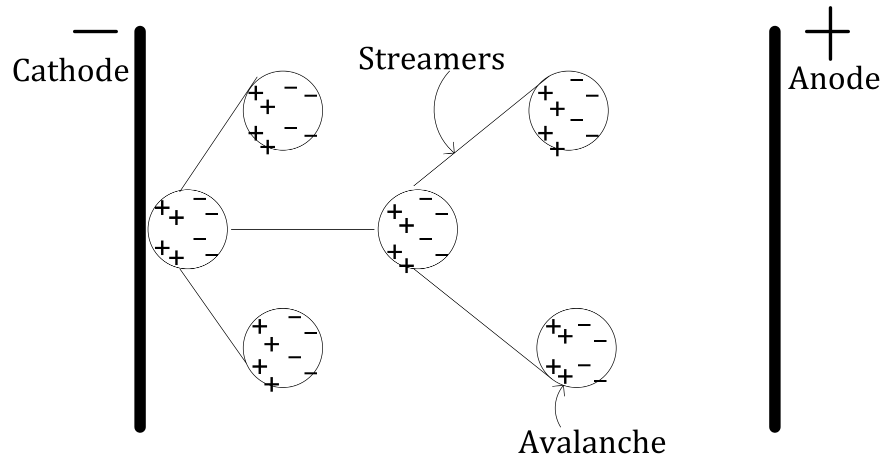


*Figure 2. 7 Formation of secondary avalanches due to photo-ionization*

- Size of the electron avalanche is gradually increased and the avalanches are transformed into channels of ionization which proceeds towards the anode.
- Such channels are called the steamer (anode streamer).
- Finally the gas breakdown, at the moment of breakdown the avalanche has got specific size which is called critical size of avalanche.
- The streams are shown in fig. 2.7.
- **Mathematical Aspect of Streamer's Theory:**
- After the theory proposed by Townsend, Rather and Meek developed an empirical formula for Streamer spark criterion which is given by

$$\alpha X_c = 17.7 + \ln X_c + \ln \frac{E_r}{E_0} \text{..........................(i)}$$

Where, $\alpha$ =Townsend's first ionization constant

$X_c$ = elongated and critical size of electron avalanche at the time of breakdown

$E_r$ = Radial field due to space charge

$E_0$ = externally applied field

- When the avalanche is converted into a Streamer,

$$E_r = E_0 \qquad \therefore \frac{E_r}{E_0} = 1 \qquad \therefore \ln \frac{E_r}{E_0} = \ln 1 = 0$$

$$\therefore \alpha X_c = 17.7 + \ln X_c \text{.....................................(ii)}$$

- During breakdown the size of avalanche becomes equal to gap-length or spacing between electrodes, so $X_c$ = d (gap length)
- Therefore Eq.(ii) will be

$$\alpha_d = 17.7 + \ln d$$

- Meek also suggested the expression for $E_r$ by

$$E_r = 5.3\times10^{-7} \frac{\alpha e^{\alpha X}}{(X/P)^{1/2}} \text{.....................................(iii)}$$

Where, P=pressure of gas in the gap.

- The minimum breakdown voltage is assumed to correspond to the condition when
  a. Avalanche has crossed the gap equal to "d"
  b. Size of avalanche X=d
  c. Space charge field $E_r$ approaches to applied field E.

  $\therefore$ X=d, $E_r = E$

- The expression (iii) becomes

$$E = 5.3\times10^{-7} \frac{\alpha e^{\alpha d}}{(d/P)^{1/2}}$$

- Taking ln on both sides, we get

$$\ln E = (5.3\times10^{-7}) + \ln\left[\alpha \cdot e^{\alpha d}\right] - \frac{1}{2}\ln\left(\frac{d}{p}\right)$$

$$= -14.5 + \ln\alpha + \alpha\cdot d \ln_e e - \frac{1}{2}\ln\left(\frac{d}{p}\right)$$

- Adding(-ln P) to both sides, we get,

$$\ln E - \ln P = -14.5 + \ln\alpha + \alpha\cdot d - \ln P - \frac{1}{2}\ln\left(\frac{d}{p}\right) \quad (\because \ln e = 1)$$

$$\ln\left(\frac{E}{P}\right) = -14.5 + \ln\left(\frac{\alpha}{P}\right) + \alpha\cdot d - \frac{1}{2}\ln\left(\frac{d}{p}\right) \quad \left(\because \ln\alpha - \ln p = \ln\left(\frac{\alpha}{p}\right)\right)$$

- The experimental determined value of $\frac{\alpha}{P}$ and corresponding values of $\frac{E}{P}$ at given pressure P are used to solve the above equation by trial and error method to solve this equation.
- Values of $\frac{\alpha}{P}$ corresponding to $\frac{E}{P}$ at a given pressure are chosen until the equation is satisfied.

## 2.10. Paschen's Law:

- Paschen's theory is one of the most important theories related to breakdown of gaseous insulating material.
- It is widely used in the design of extra high voltage equipments.
- The gas to be used in the apparatus is matched and studied with operating voltage of the system.
- The breakdown voltage must be greater than the operating voltage of the system.

- **Paschen's Law:** The law essentially sates that, at higher pressures (above a few torr) the breakdown characteristics of a gap are function (generally not linear ) of the product of the gas pressure(p) and gap length(d),

  usually written as $V_b = f\,(\mathrm{p{\cdot}d})$
- The above relation does not imply that breakdown voltage $V_b$ is directly proportional to product the product of p and d.

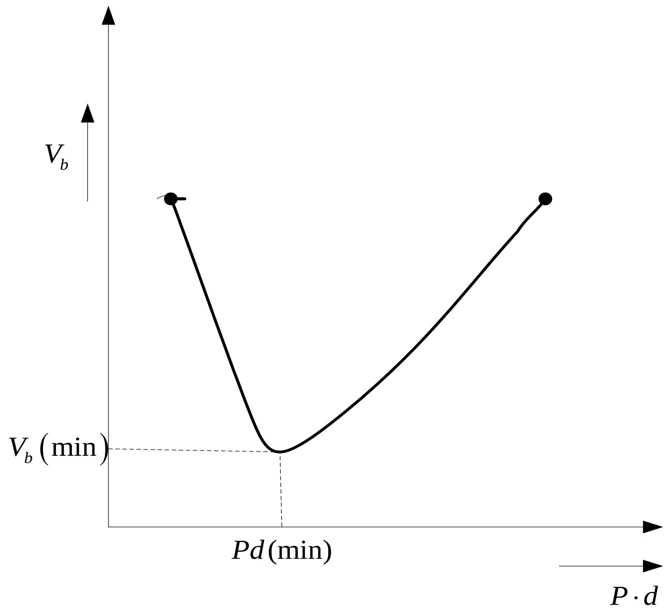


*Figure 2. 8 $V_b$ varies non-linearly with the product Pd*

- The breakdown voltage $V_b$ varies non-linearly with the product $p \cdot d$. The non-linear variation can be seen from the graph of a particular gas.
- From the definitions of Townsend's first ionization constant, $\frac{\alpha}{p}$ is the function of $\frac{E}{p}$.
- That is $$\frac{\alpha}{p} = f\left[E/\mathrm{p}\right]$$ $$\therefore \alpha = f\left[E/\mathrm{p}\right] \times p$$

  And Townsend's criterion for Breakdown is

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

$$f\left[\frac{E}{p}\right]\cdot p\cdot d=\ln\left(1+\frac{1}{\gamma}\right)=K$$

$$f\left(\frac{V_b}{p\cdot d}\right)\cdot p\cdot d=K\quad\left(\because E=\frac{V_b}{d}\right)$$

$$f\left(\frac{V_b}{p\cdot d}\right)=\frac{K}{p\cdot d}$$

$$V_b=f\left(p\cdot d\right)$$

- This is called Paschen's law
- **pd$_{(min)}$ And V$_{b(min)}$:**
- The Paschen's curve, the relationship between V and pd is shown in above graph for three gases $CO_2$, air and $H_2$. It is seen that the relationship between V and pd is not linear and has a minimum value for any gas.
- This means that a breakdown voltage of a uniform field gap is a unique function of the product of p, the gas pressure and d, the electrode gap, for a particular gas and for a given electrode material.
- We know that

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

$$d=\frac{1}{\alpha}\left[\ln\left(1+\frac{1}{\gamma}\right)\right]\text{.......................................................................}(i)$$

$$=\frac{1}{pf_1\left(\frac{V_b}{pd}\right)}\ln\left[1+\frac{1}{f_2\left(\frac{V_b}{pd}\right)}\right]\text{.........................................................}(ii)$$

- Where $\frac{\alpha}{p}=f_1\left(\frac{E}{p}\right)$ and $\frac{\gamma}{p}=f_2\left(\frac{E}{p}\right),\ E=\frac{V_b}{d}$
- '$\alpha$' may be assumed to follows an exponential function and may be written as

$$\alpha=Ape^{\frac{-Bp}{E}}=Ape^{\frac{-Bpd}{V_b}}$$

- Substituting for '$\alpha$' in equation $(i)$

$$d=\frac{1}{Ap}e^{\frac{-Bpd}{V_b}}\ln\left[1+\frac{1}{r}\right]$$

Or

$$V_b=\frac{Bpd}{\ln\frac{Apd}{\ln\left(1+\frac{1}{r}\right)}}$$

- The minimum value for V can be obtained by making $\frac{dV_b}{d(\text{pd})}=0$ which gives rise to

$$pd_{(\min)}=\frac{e}{A}\ln\left[1+\frac{1}{r}\right] \text{ where, } \quad e=2.178$$

$$V_{b(\min)}\frac{eB}{A}\ln\left[1+\frac{1}{r}\right]$$

## 2.11. Penning effect:

- Paschen's law does not hold good for many gaseous mixtures. A typical example is that of mixture of Argon in neon.
- A small percentage of Argon in Neon reduces substantially the dielectric strength of pure Neon.
- In fact, the dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon.
- The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is metastable and its excitation potential (16eV) is about 0.9eV greater than the ionization potential of Argon.
- The metastable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionization them.
- This phenomenon is known as Penning Effect.

## 2.12. Corona Discharges:

- If the electric field is uniform and if the field is increased gradually, just when measurable ionization begins, the ionization leads to complete breakdown of the gap.
- However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many sign in the form of visual and audible discharges. These discharges are known as **Corona discharges**.
- This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone.
- Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges.
- Corona also gives rise to radio interference.
- The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_w=30md\left[1+\frac{0.301}{\sqrt{dr}}\right] \text{.........................................(i)}$$

- For the case of coaxial cylinders, whose inner cylinder has a radius r the equation becomes $E_c = 31md\left[1+\frac{0.308}{\sqrt{dr}}\right]$..........................................................................................$(ii)$

  Where m is the surface irregularity factor which becomes equal to unity for highly polished smooth wires; d is the relative air density correction factor given by,

  $$\mathrm{d} = \frac{0.392b}{(273+T)}$$

  Where b is the atmospheric pressure in torr, and t is the temperature in $^{\circ}C$ ,d = 1 at 760 torr and 250C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.
- On the high voltage conductors at high pressures there is a distinct difference in the visual appearance of the corona under positive and negative polarities of the applied voltage.
- When the voltage is positive, corona appears as a **uniform bluish white sheath** over the entire surface of the conductor.
- On the other hand, when the voltage is negative, the corona will appear like **reddish glowing spots** distributed along the length of the wire.
- Investigations with point-plane gaps in air showed that when point is negative, corona appears as current pulses called **Trichel pulses**, and the repetition frequency of these pulses increases as the applied voltage is increased and decreases with decrease in pressure.
- On the other hand, observations when the point is positive in air showed that the corona current increases steadily with voltage. At sufficiently high voltage, current amplification increases rapidly with voltage, up to a current of about $10^{-7}$A, after which the current becomes pulsed with repetition frequency of about 1 kHz composed of small bursts.
- This form of corona is called **burst corona**. The average current then increases steadily with applied voltage leading to breakdown.
- Fig. 2.9 shows the corona inception and breakdown voltages of the sphere-plane arrangement. From the figure, it is clear that—

  (i) For small spacing (Zone–I), the field is uniform and the breakdown voltage depends mainly on the gap spacing.

  (ii) In zone–II, where the spacing is relatively larger, the electric field is non-uniform and the breakdown voltage depends on both the sphere diameter and the spacing. (iii) For still larger spacing.

  (iii) at large spacing(zone-III) the field is non-uniform and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

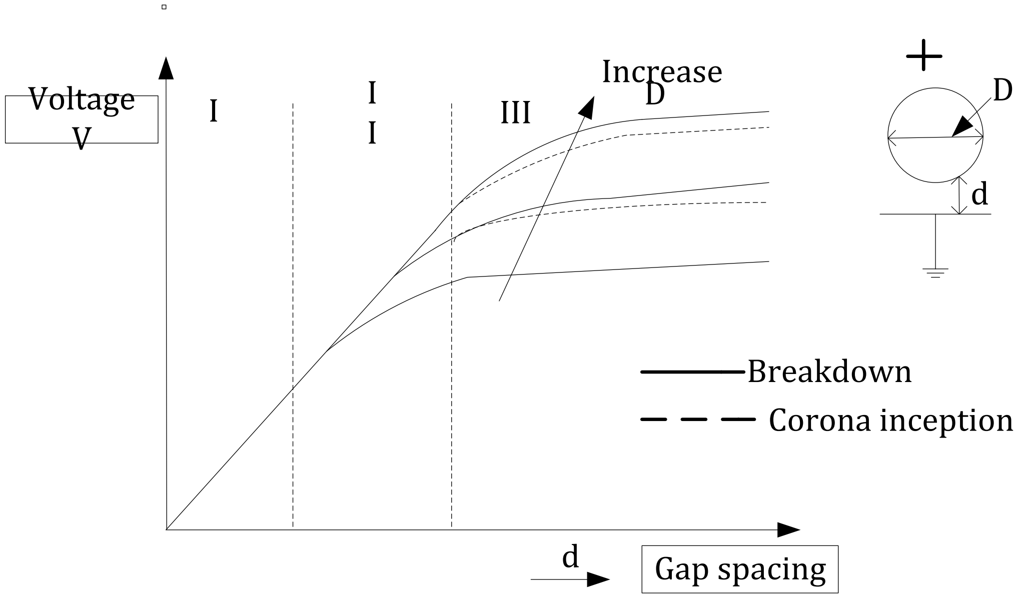


*Figure 2. 9Breakdown and corona inception characteristics for spheres of different diameter in Sphere - plane gap geometry*

## 2.13. What is Vacuum?

- Vacuum is a system in which the pressure is maintained at a value much below the atmospheric pressure.
- Vacuum may be classified as: (1mmHg = 1 Torr)
  - (i) High Vacuum: $1\times10^{-3}$ to $1\times10^{-6}$ *Torr*
  - (ii) Very High Vacuum: $1\times10^{-6}$ to $1\times10^{-8}$ *Torr*
  - (iii) Ultra-High Vacuum: $1\times10^{-9}$ *Torr* and below.
- For electrical insulation purposes the range of vacuum generally used is the 'high vacuum' in the pressure range of $10^{-3}$ Torr to $10^{-6}$ Torr.

## 2.14. Vacuum Breakdown:

- In Townsend discharge electrons get multiplied due to various ionization processes and an electron avalanche is formed.
- In a high vacuum, even if the electrodes are separated by a few centimeters, an electron crosses the gap without encountering any collisions.
- Therefore, the current growth prior to breakdown cannot be due to the formation of electron avalanches.
- If gas is liberated in the vacuum gap, then breakdown can occur in the manner by Townsend process.
- During the last 70 years or so, many different mechanisms for breakdown in vacuum have been proposed. These can be broadly divided into three categories

  (i) Particle Exchange Mechanism

(ii) Field emission mechanism

(iii)Clump theory

**(i) Particle Exchange Mechanism:**

- In this mechanism, it is assumed that a charged particle would be emitted from one electrode under the action of the electric field and when it impose on the other electrode, it liberates oppositely charged particles due to ionization of absorbed gases.
- An electron present in the vacuum gap is accelerated towards the anode and on impact releases a positive ions and C photons.
- These positive ions are accelerates towards the cathode, and impact each positive ion liberates B electrons and each photon Liberates D electrons, as shown in fig 2.10.
- Breakdown will occur if the coefficients of production of secondary electrons exceeds unity.

  (AB + CD) > 1
- This theory was modified to allow for the presence of negative ions and the criterion for breakdown then becomes (AB +EF) > 1
- Where A and B same as before and E and F represent the co-efficient for (–Ve) and (+Ve) ion liberation.

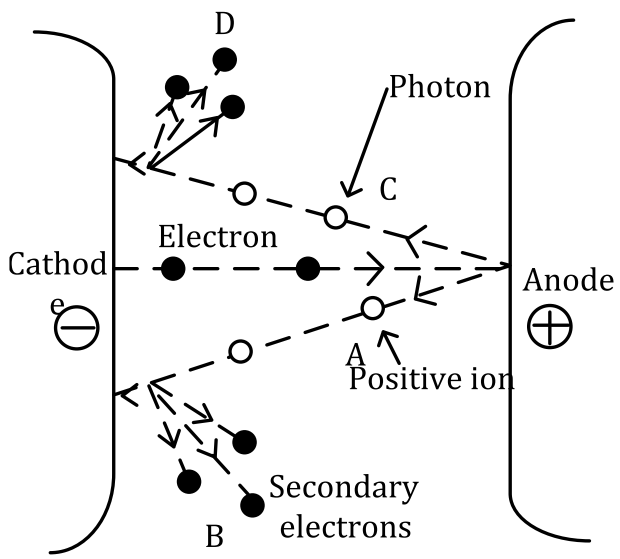


*Figure 2. 10 Partial exchange mechanism of vacuum breakdown*

**(ii)Field Emission Theory:**

**(1)Anode Heating Mechanism:**

- In this theory, Due to field emission bombard the electrons which is produced at small micro projection on the cathode.
- This causes a load rise in temperature & release gases and vapours into vacuum gap.
- These electrons ionize the atoms of the gas & produce positive ions.

- These positive ions react of the cathode & increase the primary electron emission and produce secondary electrons by bombarding the surface.
- These process continues until a number of sufficient electrons are produced to give rise to breakdown.

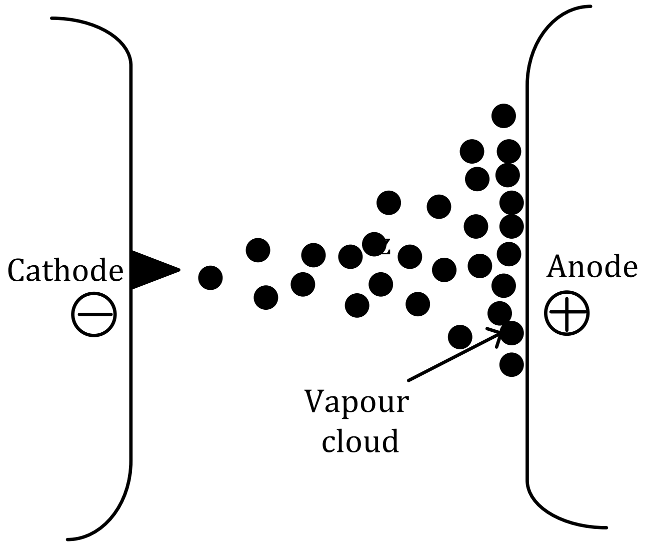


*Figure 2. 11Electron beam anode heating mechanism of vacuum breakdown*

**(2) Cathode Heating Mechanism:**

- This mechanism explain that near the breakdown voltage of the gap, shape points on the cathode surface are responsible for the existence of the pre breakdown current, which generated according to the field emission process.
- This current cause's resistive heating at the tip of a point and when a critical current density is reached the gap melts and explodes, thus initiating vacuum discharge.
- Practical evidence shows that breakdown take place by this process when the effective cathode electric field is of the order of $10^6$ to $10^7$ V/cm.

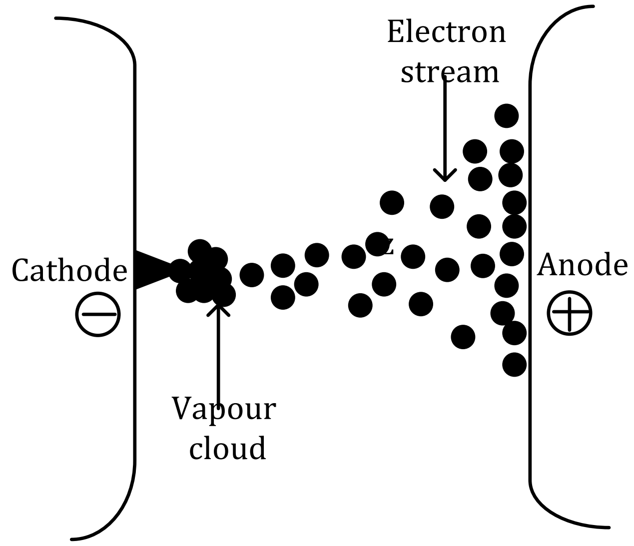


*Figure 2. 12 Cathode Heating Mechanism*

**(3)Clump Theory:**

- Basically this theory has been developed on the following assumptions (Fig. 2.13)

  (1)A loosely bound particle (clump) exists on one of the electrode surfaces.

  (2) On the application of a high voltage, this particle gets charged, subsequently gets detached from the mother electrode, and is accelerated across the gap.

  (3) The breakdown occurs due to a discharge in the vapour or gas released by the impact of the particle at the target electrode.

- Cranberg was the first to propose this theory. He initially assumed that breakdown will occur when the energy per unit area, W, delivered to the target electrode by a clump exceeds a value C', a constant, characteristic of a given pair of electrodes.

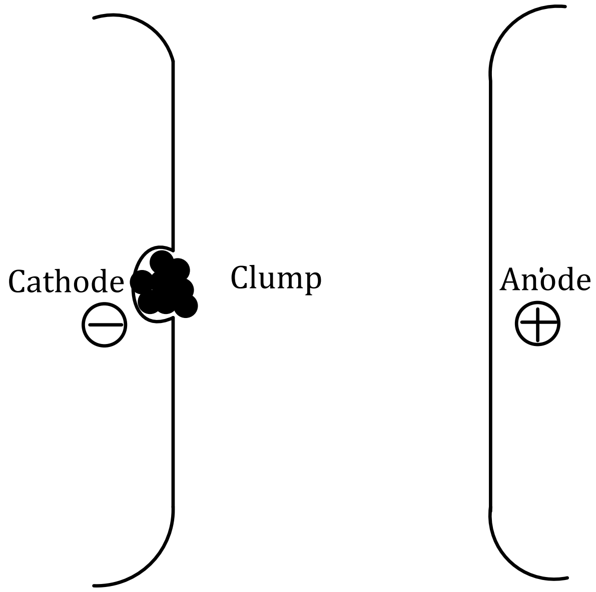


*Figure 2. 13(i) Clump is loosely attached to the surface*

- VE = C'

- The quantity W is the product of gap voltage (V) and the charge density on the clump. The latter is proportional to the electric field E at the electrode of origin. The criterion for breakdown, therefore, is

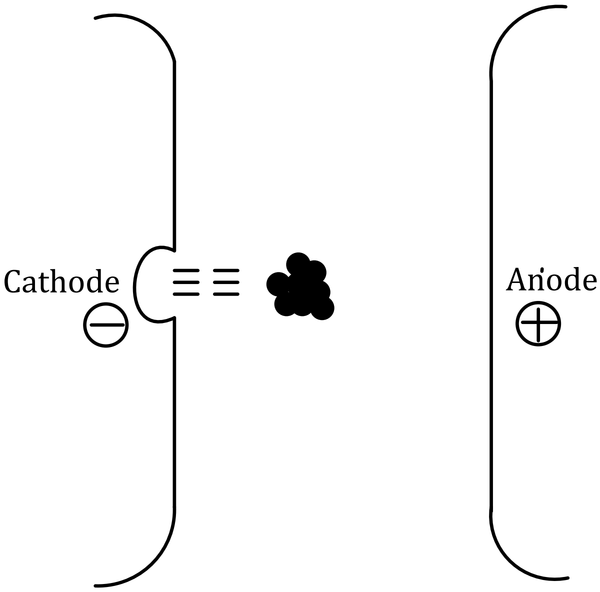


*Figure 2. 14 Clump detached from the cathode surface and is accelerated across the gap*

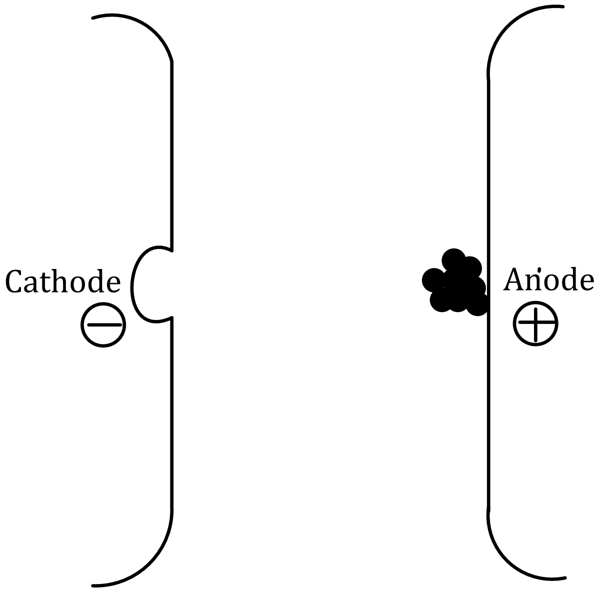


*Figure 2. 15 Impact of the clump on the anode gives out a cloud of the metal vapour*

- In case of parallel plane electrodes the field E = V/d where d is the distance between the electrodes. So the generalized criterion for breakdown becomes,

$$V= (Cd)^{1/2}$$

Where C is another constant involving C and the electrode surface conditions.