1.2 BREAKDOWN IN COMPOSITE DIELECTRICS

A vacuum system is one in which the pressure maintained is at a value below the atmospheric pressure and is measured in terms of mm of mercury. One standard atmospheric pressure at 0°C is equal to 760 mm of mercury. One mm of Hg pressure is also known as one torr after the name of Torricelli who was the first to obtain pressures below atmosphere.

In a Townsend type of discharge, in a gas, the mean free path of the particles is small and electrons get multiplied due to various ionization processes and an electron avalanche is formed. In a vacuum of the order of 10–5 torr, the mean free path is of the order of few meters and thus when the electrodes are separated by a few mm an electron crosses the gap without any collision. Therefore, in a vacuum, the current growth prior to breakdown cannot take place due to formation of electron avalanches.

However, if it could be possible to liberate gas in the vacuum by some means, the discharge could take place according to Townsend process. Thus, a vacuum arc is different from the general class of low and high pressure arcs. In the vacuum arc, the neutral atoms, ions and electrons do not come from the medium in which the arc is drawn but they are obtained from the electrodes themselves by evaporating its surface material. Because of the large mean free path for the electrons, the dielectric strength of the vacuum is a thousand times more than when the gas is used as the interrupting medium.

In this range of vacuum, the breakdown strength is independent of the gas density and depends only on the gap length and upon the condition of electrode surface. Highly polished and thoroughly degassed electrodes show higher breakdown strength.

Electrodes get roughened after use and thus the dielectric strength or breakdown strength decreases which can be improved by applying successive high voltage impulses which of course does not change the roughened surface but removes the loosely It has been observed that for a vacuum of 10^{-6} torr, some of the metals like silver, bismuth-copper etc. attain their maximum breakdown strength when the gap is slightly less than 3 mm. This property of vacuum switches permits the use of short gaps for fast operation.

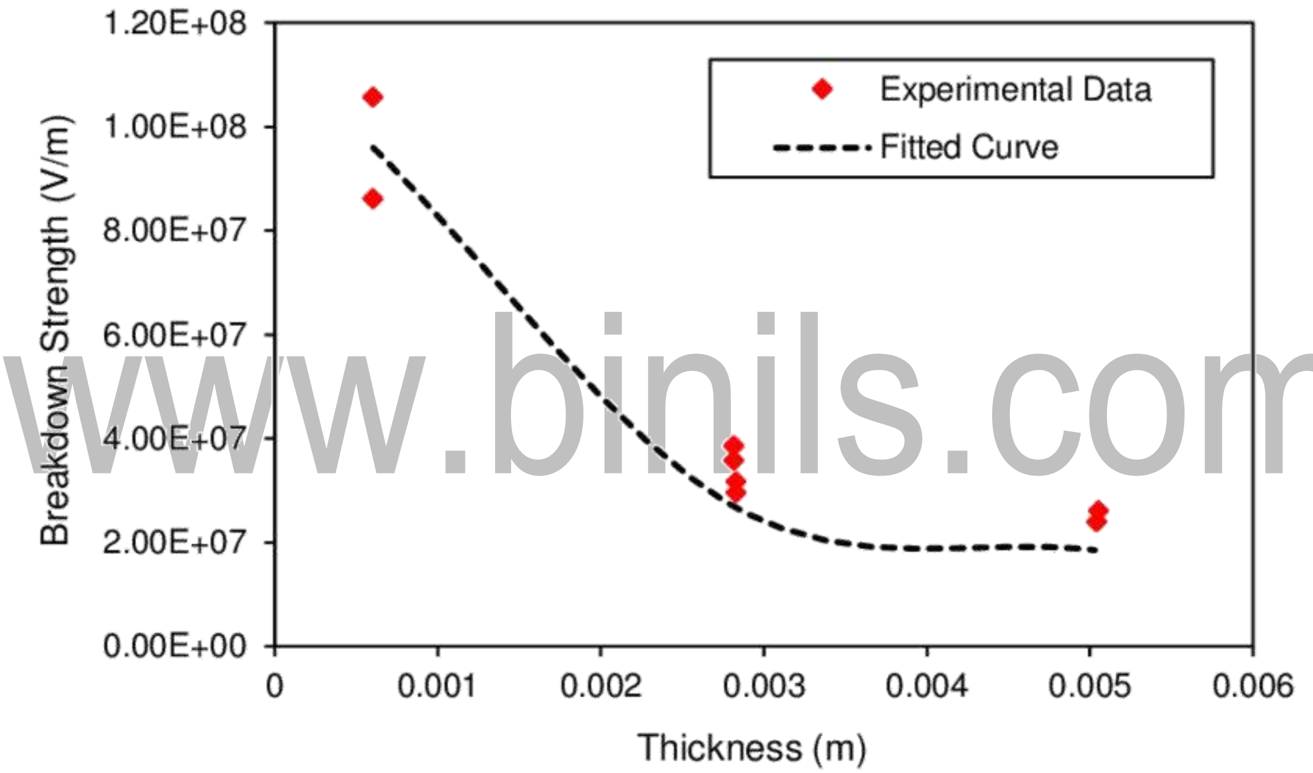


Figure 1.2.1 Glass fiber Composite Dielectric

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 138]

1.5 BREAKDOWN IN NON-UNIFORM FIELDS

In non-uniform fields, e.g. in point-plane, sphere-plane gaps or coaxial cylinders, the field strength and hence the effective ionization coefficient $\bar{\alpha}$ vary across the gap. The electron multiplication is governed by the integral of $\bar{\alpha}$ over the path ($\int \bar{\alpha}$ dx). At low pressures the Townsend criterion for spark takes the form

$$\gamma \left[exp\left(\int_0^d \bar{\alpha} dx\right) - 1\right] = 1$$

where d is the gap length. The integration must be taken along the line of the highest field strength.

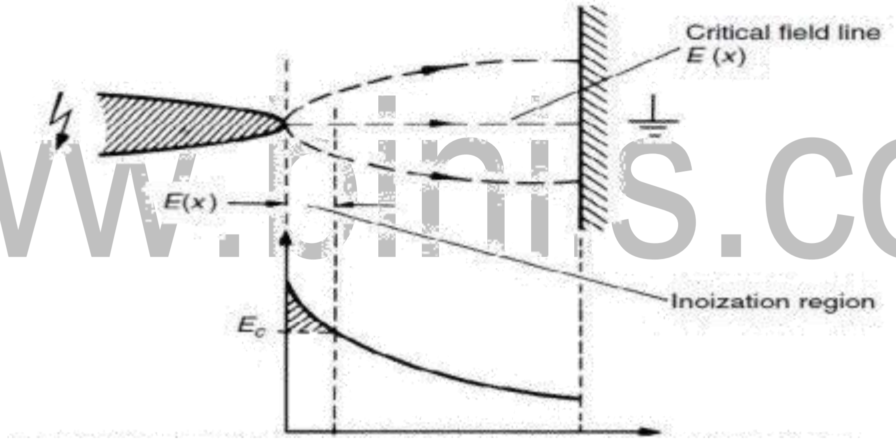


Figure 1.5.1 Electric field distribution in a non-uniform field gap

The expression is valid also for higher pressures if the field is only slightly non-uniform.In strongly divergent fields there will be at first a region of high values of E/p over which α/p >0. When the field falls below a given strength E_C the integral $\int \bar{\alpha}$ dx ceases to exist.

Townsend mechanism then loses its validity when the criterion relies solely on the γ effect, especially when the field strength at the cathode is low.

In reality breakdown (or inception of discharge) is still possible if one takes into

$$exp \int_0^{x_{c<d}} \bar{\alpha} dx = N_{cr}$$

account photo ionization processes. The criterion condition for breakdown (or inception of discharge) for the general case may be represented to take into account the non-uniform distribution of $\overline{\alpha}$ or where N_{cr} is the critical electron concentration in an avalanche giving,

$$\int_0^{x_c<d} \overline{\alpha} dx = ln\, N_{cr} \approx 18 - 20$$

Figure 1.5.1 illustrates the case of a strongly divergent field in a positive point plane gap. Equation is applicable to the calculation of breakdown or discharge inception voltage, depending on whether direct breakdown occurs or only corona.

1.4 BREAKDOWN IN SOLID DIELECTRICS

Solid insulating materials are used almost in all electrical equipments, be it an electric heater or a 500 MW generator or a circuit breaker, solid insulation forms an integral part of all electrical equipments especially when the operating voltages are high. The solid insulation not only provides insulation to the live parts of the equipment from the grounded structures, it sometimes provides mechanical support to the equipment. In general, of course, a suitable combination of solid, liquid and gaseous insulations is used.

The processes responsible for the breakdown of gaseous dielectrics are governed by the rapid growth of current due to emission of electrons from the cathode, ionization of the gas particles and fast development of avalanche process. When breakdown occurs the gases regain their dielectric strength very fast, the liquids regain partially and solid dielectrics lose their strength completely.

The breakdown of solid dielectrics not only depends upon the magnitude of voltage applied but also it is a function of time for which the voltage is applied. Roughly speaking, the product of the breakdown voltage and the log of the time required for breakdown is almost a constant i.e,

$V_b = 1n\ t_b =$ constant

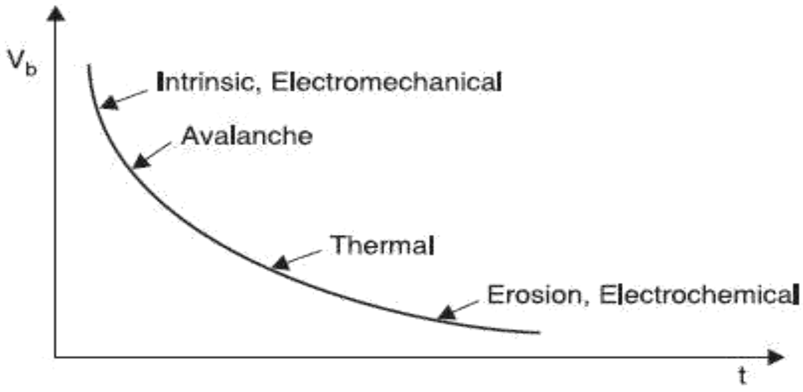


Figure 1.4.1 Variation of V_b with time of application

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 147]

The dielectric strength of solid materials is affected by many factors viz. ambient temperature, humidity, duration of test, impurities or structural defects whether a.c., d.c. or impulse voltages are being used, pressure applied to these electrodes etc. The mechanism of breakdown in solids is again less understood. However, as is said earlier the time of application plays an important role in breakdown process, for discussion purposes, it is convenient to divide the time scale of voltage application into regions in which different mechanisms operate. The various mechanisms are:

- Intrinisic Breakdown
- Electromechanical Breakdown
- Electrochemical Breakdown

Intrinsic breakdown in solids

If the dielectric material is pure and homogeneous, the temperature and environmental conditions suitably controlled and if the voltage is applied for a very short time of the order of 10–8 second, the dielectric strength of the specimen increases rapidly to an upper limit known as intrinsic dielectric strength. The intrinsic strength, therefore, depends mainly upon the structural design of the material i.e., the material itself and is affected by the ambient temperature as the structure itself might change slightly by temperature condition.

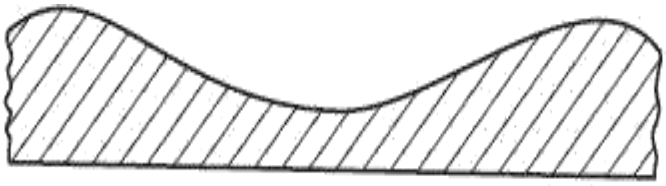


Figure 1.4.2 Specimen designed for intrinsic breakdown

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 152]

In order to obtain the intrinsic dielectric strength of a material, the samples are so prepared that there is high stress in the centre of the specimen. The stresses required are of the order of one million volt/cm. The intrinsic strength is generally assumed to have been reached when electrons in the valance band gain sufficient energy from the electric field to cross the forbidden energy band to the conduction band. In pure and homogenous materials, the valence and the conduction bands are separated by a large energy gap at room temperature, no electron can jump from valance band to the conduction band.

The conductivity of pure dielectrics at room temperature is, therefore, zero. However, in practice, no insulating material is pure and, therefore, has some impurities and/or imperfections in their structural designs. The impurity atoms may act as traps for free electrons in energy levels that lie just below the conduction band is small. An amorphous crystal will, therefore, always have some free electrons in the conduction band. At room temperature some of the trapped electrons will be excited thermally into the conduction band as the energy gap between the trapping band and the conduction band is small.

An amorphous crystal will, therefore, always have some free electrons in the conduction band. As an electric field is applied, the electrons gain energy and due to collisions between them the energy is shared by all electrons. In an amorphous dielectric the energy gained by electrons from the electric field is much more than they can transfer it to the lattice. Therefore, the temperature of electrons will exceed the lattice temperature and this will result into increase in the number of trapped electrons reaching the conduction band and finally leading to complete breakdown. When an electrode embedded in a solid specimen is subjected to a uniform electric field, breakdown may occur.

An electron entering the conduction band of the dielectric at the cathode will move towards the anode under the effect of the electric field. During its movement, it gains energy and on collision it loses a part of the energy. If the mean free path is long, the energy gained due to motion is more than lost during collision. The process continues and finally may lead to formation of an electron avalanche similar to gases and will lead finally to breakdown if the avalanche exceeds a certain critical size.

1.1 CORONA AND ITS EFFECT

Corona is a phenomenon that has the capability for degrading insulators, and causing systems to fail. In this discussion, formulas are provided to calculate the voltage at which corona occurs, and a mention is made of a useful application for corona. Corona, also known as partial discharge, is a type of localized emission resulting from transient gaseous ionization in an insulation system when the voltage stress, i.e., voltage gradient, exceeds a critical value.

The ionization is usually localized over only a portion of the distance between the electrodes of the system. Corona can occur within voids in insulators as well as at the conductor/insulator interface.

Corona Inception

Corona inception voltage is the lowest voltage at which continuous corona of specified pulse amplitude occurs as the applied voltage is gradually increased. Corona inception voltage decreases as the frequency of the applied voltage increases.Corona can occur in applications as low as 300V.

Corona Extinction

Corona extinction voltage is the highest voltage at which continuous corona of specified pulse amplitude no longer occurs as the applied voltage is gradually decreased from above the corona inception value. Thus, once corona starts, the voltage must be decreased to get it to stop.

Corona Detection

Corona can be visible in the form of light, typically a purple glow, as corona generally consists of micro arcs. Darkening the environment can help to visualize the corona. We once attached a camera (set to a long exposure time) to a viewing window in a vacuum chamber to confirm that corona was indeed occurring, and thereby confirming our suspicions. You can often hear corona hissing or cracking. Thus, stethoscopes or ultrasonic detectors (assuming you can place them in a safe location) can be used to find corona. In addition, you can sometimes smell the presence of ozone that was produced by the corona. (Who said you don't use all your senses when troubleshooting?). It is important that the voltage source and the coupling capacitor exhibit low noise so as not to obscure the corona. In its simplest form the pulse detection network is a resistor monitored by an oscilloscope. Don't dismiss this simple technique as crude, as we once used this method to observe the presence of corona in an improperly terminated high voltage connector, even after a dedicated corona tester failed to find any.

Corona Effects

The presence of corona can reduce the reliability of a system by degrading insulation. While corona is a low energy process, over long periods of time, it can substantially degrade insulators, causing a system to fail due to dielectric breakdown. The effects of corona are cumulative and permanent, and failure can occur without warning.

Corona causes:

- Light
- Ultraviolet radiation
- Sound (hissing, or cracking as caused by explosive gas expansions)
- Ozone
- Nitric and various other acids
- Salts, sometimes seen as white powder deposits
- Other chemicals, depending on the insulator material
- Mechanical erosion of surfaces by ion bombardment
- Heat (although generally very little, and primarily in the insulator)
- Carbon deposits, thereby creating a path for severe arcing.

Beneficial Corona

The sound generation effects of corona can be utilized to build high accuracy audio speakers! The major advantage is that there is zero mass that needs to be moved to create the sound, so that transient response is improved.

Corona Prevention

Corona can be avoided by minimizing the voltage stress and electric field gradient. This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors.

1.6 THERMAL BREAKDOWN

When an insulating material is subjected to an electric field, the material gets heated up due to conduction current and dielectric losses due to polarization. The conductivity of the material increases with increase in temperature and a condition of instability is reached when the heat generated exceeds the heat dissipated by the material and the material breaks down.

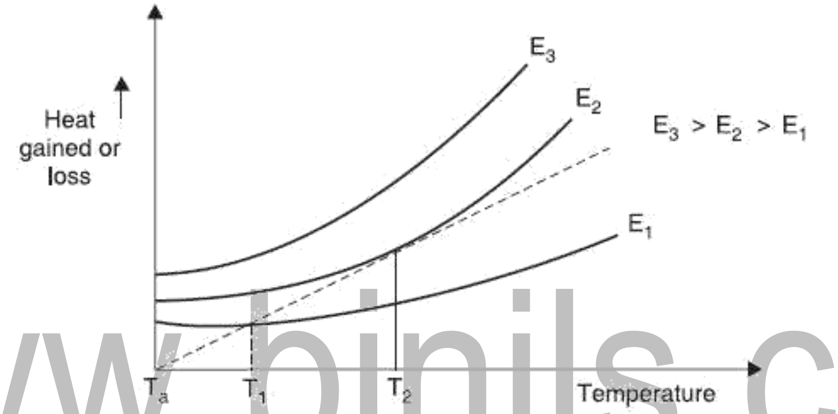


Figure 1.6.1 Thermal stability or instability of different fields

Source: "High Voltage Engineering" by C.L. Wadhwa , Page –271]

Fig. shows various heating curves corresponding to different electric stresses as a function of specimen temperature. Assuming that the temperature difference between the ambient and the specimen temperature is small, Newton's law of cooling is represented by a straight line.

The test specimen is at thermal equilibrium corresponding to field E_1 at temperature T_1 as beyond that heat generated is less than heat lost. Unstable equilibrium exists for field E_2 at T_2,and for field E_3 the state of equilibrium is never reached and hence the specimen breaks down thermally.

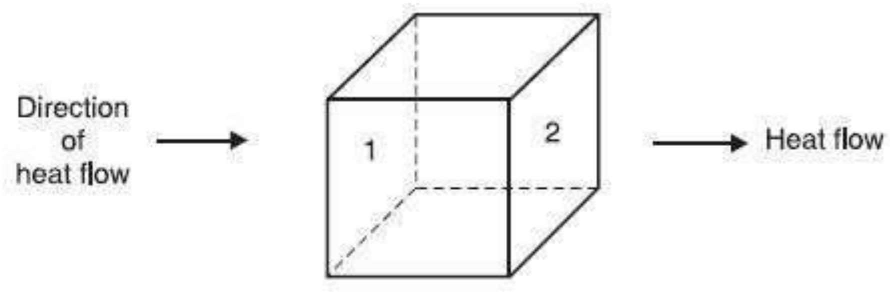


Figure1.6.2 Cubical specimen—Heat flow

Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 275]

In order to obtain basic equation for studying thermal breakdown, let us consider a small cube (Fig. 2.14) within the dielectric specimen with side Δx and temperature difference across its faces in the direction of heat flow (assume here flow is along x-direction) is ΔT. Therefore, the temperature gradient is

$$\frac{\Delta T}{\Delta x} \approx \frac{dT}{dx}$$

Let $\Delta x_2 = A$. The heat flow across face 1

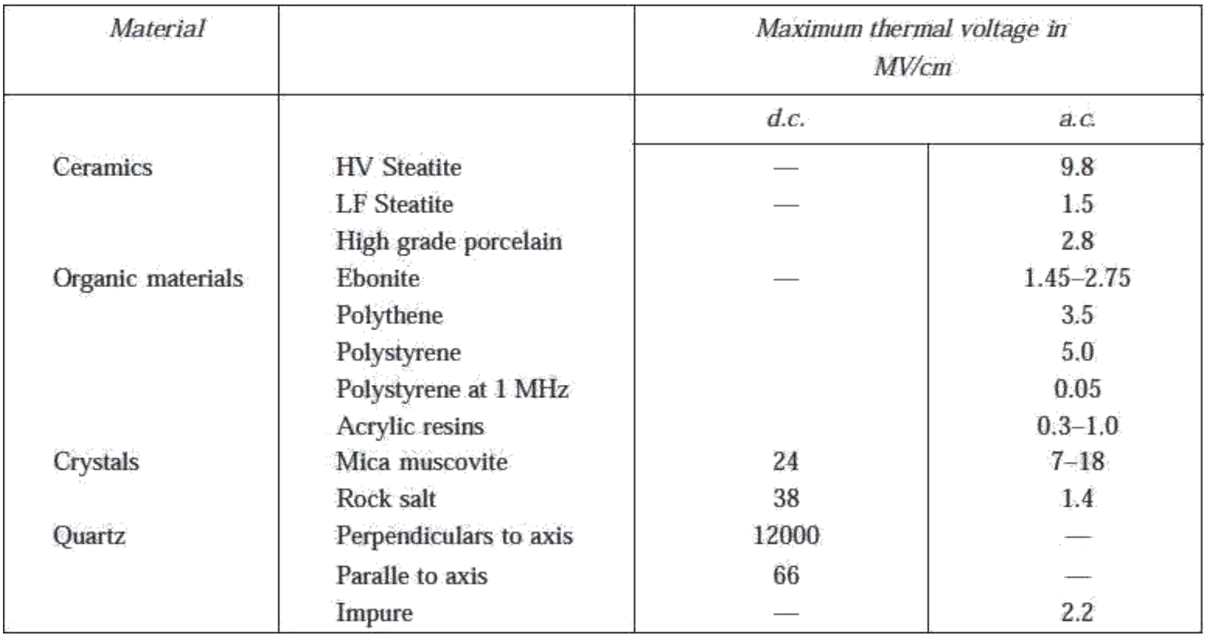
$$KA \frac{dT}{dx} \text{ Joules}$$

Heat flow across face 2

$$KA \frac{dT}{dx} - KA \frac{d}{dx}\left(\frac{dT}{dx}\right) \Delta x$$

Here the second term indicates the heat input to the differential specimen. Therefore, the heat absorbed by the differential cube volume.

$$= \frac{KA \frac{d}{dx}\left(\frac{dT}{dx}\right) \Delta x}{\Delta V} = K \frac{d}{dx}\left(\frac{dT}{dx}\right)$$



Material		*Maximum thermal voltage in MV/cm*	
		d.c.	*a.c.*
Ceramics	HV Steatite	—	9.8
	LF Steatite	—	1.5
	High grade porcelain		2.8
Organic materials	Ebonite	—	1.45–2.75
	Polythene		3.5
	Polystyrene		5.0
	Polystyrene at 1 MHz		0.05
	Acrylic resins		0.3–1.0
Crystals	Mica muscovite	24	7–18
	Rock salt	38	1.4
Quartz	Perpendiculars to axis	12000	—
	Paralle to axis	66	—
	Impure	—	2.2

Table 1.6.1 gives for thick specimen, thermal breakdown values for some dielectric under

Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 286]

Let C_V be the thermal capacity of the dielectric, σ the electrical conductivity, E the electric field intensity. The heat generated by the electric field = σE_2 watts, and suppose the rise in temperature of the block is ΔT, in time dt, the power required to

$$C_v \frac{dT}{dt} \text{ watts}$$

raise the temperature of the block by ΔT is

Therefore, $C_v \frac{dT}{dt} + K \frac{d}{dt}\left(\frac{dT}{dx}\right) = \sigma E^2$

The solution of the above equation will give us the time required to reach the critical temperature T_C for which thermal instability will reach and the dielectric will lose its insulating properties. However, unfortunately the equation can be solved in its present from C_V, K and σ is all functions of temperature and in fact σ may also depend on the intensity of electrical field. Therefore, to obtain solution of the equation, we make certain practical assumptions and we consider two extreme situations for its solution

1.7 VACUUM BREAKDOWN

Breakdown in a vacuum is mostly influenced by the material's condition at and/or adjacent to the surface. The contamination of such as hydrocarbon compounds and water molecules would be easily dissociated by an electron- stimulated desorption process. The electric discharge in vacuum results from the neutral atoms, ions and electrons emitted from the electrodes themselves. Cathode spots are formed depending upon the current flowing. For low currents a highly mobile cathode spot is formed and for large currents a multiple number of cathode spots are formed. These spots constitute the main source of vapour in the arc. The processes involved in drawing the discharge will be due to high electric field between the contacts or resistive heating produced at the point of operation or a combination of the two. The cathode surfaces, normally, are not perfectly smooth but have many micro projections.

Due to their small area of cross-section, the projections will suffer explosive evaporation by resistive heating and supply sufficient quantity of vapour for the arc formation. Since in case of vacuum, the emission occurs only at the cathode spots and not from the entire surface of the cathode, the vacuum discharge is also known as cold cathode discharge. In cold cathode the emission of electrons could be due to any of the combinations of the following mechanisms:

Field emission; (ii) Thermionic emission; (iii) Field and Thermionic emission; (iv) Secondary emission by positive ion bombardment; (v) Secondary emission by photons; and (vi) Pinch effect. The stability of discharge in vacuum depends upon: (i) the contact material and its vapour pressure, and (ii) circuit parameters such as voltage, current, inductance and capacitance.

It has been observed that higher the vapour pressure at low temperature the better is the stability of the discharge. There are certain metals like Zn, Bi which show these characteristics and are better electrode materials for vacuum breakers. Besides the vapour pressure, the thermal conductivity of the metal also affects the current chopping level. A good heat conducting metal will cool its surface faster and hence its electrode surface temperature will fall which will result into reduction in evaporation rate and arc will be chopped because of insufficient vapour.

On the other hand, a bad heat conductor will maintain its temperature and vaporization for a longer time and the arc will be more stable. The process of multiplication of charged particles by the process of collision is very small in the space between the electrodes in vacuum, electron avalanche is not possible. If somehow a gas cloud could be formed in vacuum, the usual kind of breakdown process can take place. This is the line of action adopted by the researchers to study mechanism of breakdown in vacuum. By finding the way, gas cloud could be created in a vacuum.

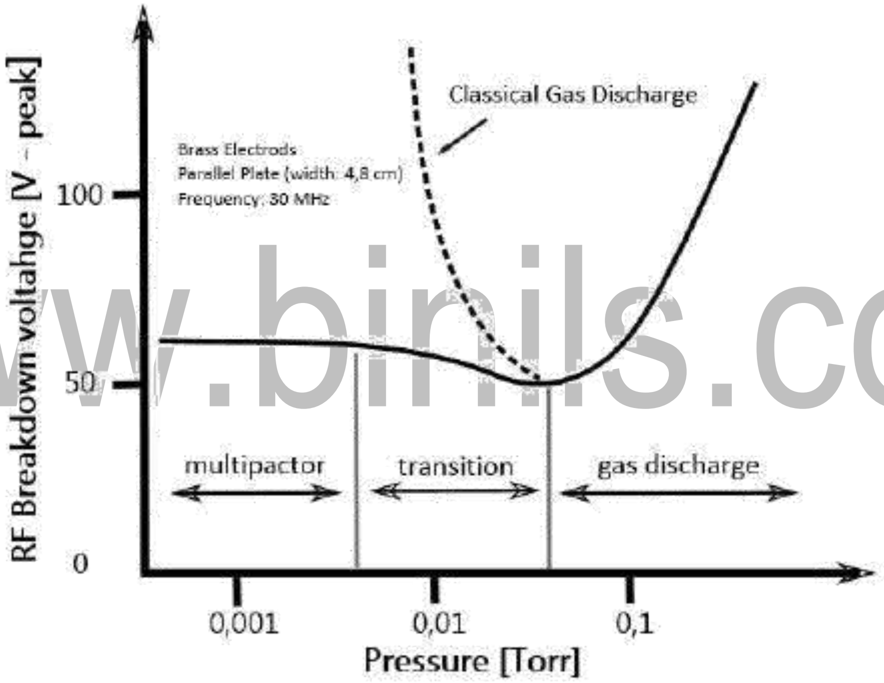


Figure 1.7.1 Breakdown discharge in Vacuum

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 296]