General

DESIGN STANDARD

INSULATION

May 10, 2012 Revision A

Japan Aerospace Exploration Agency

This is an English translation of JERG-2-213A. Whenever there is anything ambiguous in this document, the original document (the Japanese version) shall be used to clarify the intent of the requirement.

Published by
Japan Aerospace Exploration Agency
Safety and Mission Assurance Department
2-1-1 Sengen Tsukuba-shi,Ibaraki 305-8505, Japan

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1 Scope of application

1.1 Purpose

The insulation design standard (referred to as “this standard” in this document) specifies fundamental requirements about power supply system insulation design of spacecraft developed by the Japan Aerospace Exploration Agency (referred to as “JAXA” in this document).

The appendices summarize the explanation of causes for breakdown and information required to utilize this standard.

1.2 Scope of application

This standard is applicable as a design standard insulation design for the power supply system up to a nominal voltage of 100V for spacecraft developed by JAXA.

The insulation design of printed circuit boards shall be compliant with other JAXA's printed circuit board design standard and shall not applicable to this design standard.

This standard assumes that project-specific specifications should be defined if there are parts which have difficulty in conforming to this standard, provided that the reasons for the difficulties are clearly presented.

2 References

This standard was created with reference to the following documents:

(1) IEC document

IEC-J60950 Safety standard of information technology devices

(2) Japanese Industrial Standards

JIS C 0704 Insulation distance, insulation resistance and withstand voltage of control device

JIS C 2110 Dielectric strength test method of solid electric insulation material

3 Terms

(1) Primary power supply

A power source which is generated/controlled by the power system (solar panel system and power supply system) of an aerospace vehicle, and commonly distributed to devices loaded in the aerospace vehicle.

(2) Primary power supply bus line

A bus line which distributes and supplies the primary power supply. Applicable bounds are those which have the same potential as the primary power supply input of loaded devices.

(3) Creeping surface discharge

Discharge that occurs on the boundary surface between different dielectrics.

(4) Conditioning

A process in manufacturing electrode structure, which removes projections on an electrode, adherences and micro particles on an electrode. There are methods such as current conditioning, glow discharge conditioning, and spark conditioning.

(5) Paschen's law

Under a constant temperature of a gas, in a uniform electric field, a voltage that generates sparking (Vs: Spark Voltage) is a function of product pd (gas pressure (p) and gap length (d)). This is called Paschen's law, because Paschen discovered this relationship based on this experiment.

4 General requirements

Various types of insulation materials are used in electronic devices and components on an aircraft, contributing to maintaining reliability of the aircraft under severe space environments. On the other hand, if a breakdown of insulation material occurs, it may cause serious damage to an aircraft. Therefore, it is required to conduct an insulation design with an understanding of insulation characteristics and breakdown phenomenon of the insulation materials.

(1) A distance between conductors shall be a level that does not cause a breakdown in the ground, lift-off and orbit operating environments. In particular, under lift-off conditions, exposure to significant change of atmospheric pressure causes a drop of neutral gas particle density between conductors. Insulation design requires paying attention to a breakdown under the Paschen's law.

(2) The distance between conductors shall be specified to be a level that does not cause a breakdown at the maximum operating voltage that can occur between conductors.

(3) The insulation design shall also include a specified interconductor distance by providing clearance in processing and assembling. This shall prevent

fluctuation and deformation for operating conditions on the ground, during lift-off, and in orbit, or shall account for the required distance after fluctuation or deformation.

(4) In many cases, insulation materials are mounted by applying significant pressure. They shall be mounted so as to avoid damage and cracks.

(5) Discharge voltages (breakdown voltages) depend on the shape of a conductor. A radius of curvature at the tip of a conductor shall be as large as possible, and avoid making sharp edges on a conductor surface where possible.

(6) Solid dielectrics may cause a drop of breakdown voltage under some conditions of use. Therefore, a thickness of solid dielectrics shall be specified in full consideration of derating in accordance with material characteristics and conditions of use.

(7) To prevent a drop in breakdown voltage caused by gas generated in the space, the insulation design shall avoid closed spaces between conductors where possible by taking actions such as providing a vent hole. When using insulation material made of hardened resin, bubbles and gases in the material must be completely removed in order to prevent the creation of a void.

(8) To prevent a breakdown caused by creeping discharge, barriers of pits and projections shall be provided on solid dielectrics surface where possible.

5 Design requirements and design methods

5.1 Insulation design

This section describes the fundamental requirements of insulation design with respect to power supply lines of a spacecraft with a bus voltage at 100 V (nominal) or lower.

The insulation design of printed circuit boards shall be compliant with JERG-0-042 “Design standard of printed circuit board and assembled parts,” and shall not applicable to this design standard.

5.1.1 Insulation design using dielectric gas

Table 5.1.1.-1 summarizes the requirements for interconductor distances in insulation design using dielectric gas.

If values shown in Table 5.1.1-1 cannot be satisfied, a different insulation method shall be used. The validity of each design shall be decided by analysis or evaluation, for each aircraft project.

Table 5.1.1.-1 Interconductor distance with dielectric gas (Note 1)

Maximum operating voltage (V) (Note 2) (Peak or direct current)	Interconductor distance (mm)	Remarks
210 V	1.0 or more	• Devices used in an environment where dust and humidity is controlled. • If double insulation is required, a different insulation method shall be added.

Note 1. Conditions in the air or in the vacuum are assumed.

Note 2. A maximum value of direct current voltage or pulse-like voltage applied between electrodes when a device is operating.

Table 5.1.1.-1 Explanation:

Values presented in Table 5.1.1.-1 have been specified with reference to the following concepts and documents, and in consideration of the designs made in the past and their track records in orbit.

(1) The breakdown of a gas is critical in a low pressure environment during the launch phase. Since a breakdown voltage of nitrogen gas, which is the main component of air, is 250 V or higher, it will not be a limiting factor in deciding an interconductor distance at 210 V or lower.

(2) The following official standards were referenced:
- IEC J60950 "Safety standard of information technology devices: Article 2.10.3, Table 2H"]
- JIS C 0704 "Insulation distance, insulation resistance and withstand voltage of control device: Article 4.2, Table 6"

(3) An interconductor distance shall be secured to reduce the risk of a critical breakdown caused by conductive chippings entering and remaining in between conductors.
(The size of conductor chipping is assumed to be 1mm or less.)

5.1.2 Insulation design using solid dielectrics

In electric design today, conventional "withstanding voltage" is comprehensive and can operate in any space environment. On one hand, this section describes the concept of finding a final withstanding voltage on the basis of the product of individually set derating ratios, by breaking down the space environment into elements such as temperature, frequency, material thickness, electron beam, ultraviolet ray, and voltage degradation. Using this method, a breakdown of material characteristics normally used is clearly shown, presenting indices to evaluate sensitivity for special applications of loosening or tightening under specific conditions. In the future, excessive designing margins may be eliminated.

$$V_{EMP} < V_{EFF}: = V_0 \times R_{temp} \times R_{frq} \times R_{thick} \times R_e \times R_{UV} \times R_{time}$$

V_{EMP}: Empirical withstand voltage
V_{EFF}: Effective withstand voltage
V_0: Mean value of nominal breakdown voltages
R_{temp}: Derating ratio about temperature
R_{frq}: Derating ratio about frequency
R_{thick}: Derating ratio about thickness

R_e: Derating ratio about electron beam
R_{UV}: Derating ratio about ultraviolet ray
R_{time}: Derating ratio about voltage degradation

Note: Note that this method of estimation does not take complex effects into consideration, assuming that each effect contributes linearly. This method is developed with an engineering approach, and has not been proved by materials science. In materials science, some of individual effects are understood from a unified view, which include material characteristics and theories. However, a comprehensive theory covering complex effects has not been established yet.

Note: Nominal breakdown voltage V_0 refers to a breakdown voltage for a short period (20 seconds or less) on a material with no history, at a room temperature and under a 50 Hz AC current.

The factors which cause a drop in a withstanding voltage are temperature, frequency, material thickness, electron beam, ultraviolet ray, and voltage degradation. Table 5.1.2.-1 summarizes the results on 17 materials, which are popularly used for an artificial satellite.

The electric design compatible with the current satellite 100 V bus employs insulation materials that withstand a peak voltage of approximately 300 V. For almost all materials tested on this test method, effective withstand voltage V_{EFF} was obtained to prove the assumed fact.

Table 5.1.2.-1 Breakdown strength of solid dielectrics

Material	Thickness	V_{EFF}	V_O	Remarks
PTFE tape	50 μm	2.5 kV	6.3 kV	
KAPTON® tape	25 μm	1.2 kV	5.5 kV	
CHO THERM®	0.38 mm	7.7 kV	12.0 kV	200 Hz
SOLITHANE	0.20 mm	2.9 kV	12.8 kV	
PARYLENE	20 μm	170 V	3.2 kV	100 kHz
Mica	75 μm	1.4 kV	8.0 kV	
URALANE®	1.0 mm	8.2 kV	27.0 kV	200 Hz
LUMIRROR®	50 μm	2.1 kV	6.5 kV	
Heat-shrinkable tube	0.18 mm	340 V	9.5 kV	100 kHz
Glass epoxy	0.2 mm	2.7 kV	11.7 kV	
RTV(S-691)	1.0 mm	9.9 kV	29 kV	200 Hz
ETFE wire	0.15 mm	2.4 kV	9.2 kV	200 Hz
di X C	20 μm	250 V	2.8 kV	
BT resin	0.1 mm	1.1 kV	5.0 kV	

Arathane	0.2 mm	2.1 kV	10.8 kV
RTV566	0.2 mm	440 V	4.2 kV
RTV142	0.2 mm	2.7 kV	7.7 kV

Note: Calculating conditions of V_{EFF}:

Temperature: 100°C, Frequency: 200 kHz (For a material with no dielectric strength data obtained for 200 kHz, calculation was made on the basis of a frequency described in Remarks.)

Thickness: Nominal thickness of specimens (See above. A tape thickness does not include thickness of adhesive.)

Electron beam fluence: $1 \times 10^{15}/cm^2$: (Equivalent to exposure for approximately 1 year on a stationary satellite surface. However, since a mechanical strength significantly drops on PTFE tape of $1 \times 10^{15}/cm^2$, calculation was made for $1 \times 10^{14}/cm^2$)

Ultraviolet irradiation: 800 ESD in wavelength band 200 to 400 nm (Applicable only to Kapton and ETFE wire)

Application time: 100 thousand hours (Equivalent to approximately 11 years)

Concept

The conventional concept of insulation design is as follows. (See Figure 5.1-1.) It is required to perform the withstanding voltage test, the dielectric strength test and the high-potential test for “maximum allowable voltages” as defined on the insulation materials, components, and devices in question. Every test must be passed.

“A withstanding voltage test” is specified to be sufficiently lower than a “breakdown voltage” and sufficiently higher than a “maximum allowable voltage.” For example, on a transformer, it is specified such as “300V for a maximum operating voltage at 100V or lower.” This is based on a general rule of thumb, which is sufficiently effective in spite of poor quantitative evidence.

The following presents the concept described in this section. A breakdown voltage of material depends on the effects of shapes and thickness, the effects of using conditions such as temperature and frequency, the effects of the space environment such as ultraviolet rays or electron beams, the effects of the application of electricity and reduction ratio due to statistical variations, which cause different effects both independently and synergistically. Thus, an “effective withstanding voltage” is given. This value must be higher than a “maximum allowable current.”

On the basis of this concept, quantitative grounds are given to an empirical rule. In addition, for a specific usage, an “effective withstanding voltage” can be used for a design value by loosening a certain reduction ratio with some grounds.

However, for the time being, a satisfactory database has not been established yet and an adequate track record is not available. It would be premature to address this field at this time.

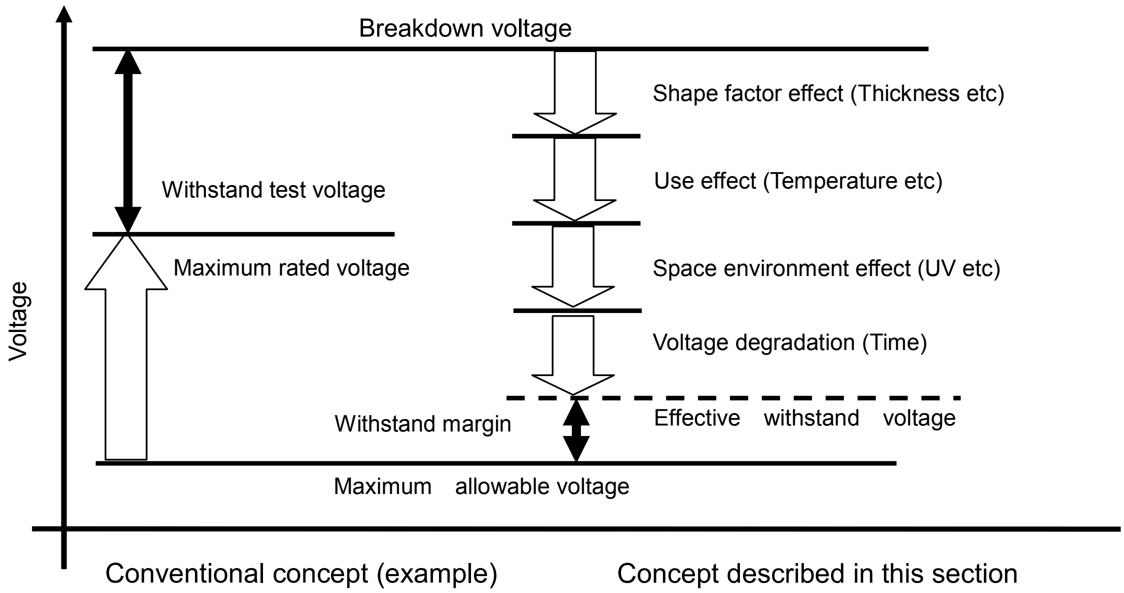


Figure 5.1-1 Concept of insulation design

5.1.3 Creeping insulation design

Table 5.1.3.-1 summarizes the requirements for creeping surface distance of solid dielectrics.

If values shown in Table 5.1.3.-1 cannot be satisfied, a different insulation method shall be used or validity of a design shall be decided by analysis or evaluation, for each aircraft project.

For components with values of interconductor creeping distances lower than those presented in Table 5.1.3.-1, their use shall be permitted by guaranteeing the performances based on certified tests of individual components and in consideration of the track records of their uses in orbit.

Table 5.1.3.-1 Creeping distance of solid dielectrics

Maximum operating voltage (V) (Peak or direct current)	Creeping distance (mm)	Remarks
210 V or lower	1.0 or more	

<u>Table 5.1.3.-1 Explanation:</u>

Values presented in Table 5.1.3.-1 have been specified with reference to the following concepts and documents, and in consideration of the designs made in the past and track records in the orbits.

(1) In general, breakdown characteristics make no significant differences up to approximately 210V, even if an interconductor distance (gap) and creeping distance are thought to be the same.

(2) The following official standards were referenced:

- IEC J60950 “Safety standard of information technology devices: Article 2.10.4, Table 2L”
- JIS C 0704 “Insulation distance, insulation resistance and withstand voltage of control device: Article 4.3, Table 8”

5.2 Measures with double insulation

5.2.1 Definition of double insulation

To prevent the critical loss of functionality caused by a failure of only one part, measures such as constructing a redundant configuration on the spacecraft must be taken . From this a point of view, power supply lines such as the primary power supply bus line, the battery line (including charge array line and pyrotechnic goods igniting power supply lines, etc.) are thought to be the parts requiring insulation design measure. Shorting of those primary power supply bus lines and battery lines is thought to be the most critical failure and actions against such failures are impossible. Therefore, as a minimum requirement, a measure to include double insulation is specified in this design standard by limiting its application to primary power supply bus line and battery line only.

Therefore, double insulation shall be applied to the primary power supply bus line including a shorting failure separation circuit and its upstream lines, which are, in other words, the part that may cause a short of the primary power supply line and battery lines. However, exceptions may be made for cases where a redundant system can be built (a redundant system is provided and a faulty system can be separated by an overcurrent protective circuit and a current limiter). On the other hand, double insulation is not applied to semiconductor components such as IC, transistor and diode, and internal parts of connector, relay, and capacitor (including hermetic sealing part).

Double insulation is the method of insulation that uses two different methods chosen from 5.2.1.1 and 5.2.1.2 below. If shorting occurs on one part, the method prevents shorting on the other part depending on a cause of the shorting.

If using the same material is inevitable due to technical limitations of electrical, mechanical, thermal, or other conditions, the same material can be used in construction provided that the material has track records of flight or track records of evaluation and has data about insulation performances, mechanical strength, and thermal resistance, and satisfactory safety margin is secured. In that case, also, materials shall be chosen from 5.2.1.2 (2) below.

Materials in 5.2.1.2 (3) below are not regarded as insulating materials in double insulation.

5.2.1.1 Space insulation (interconductor insulation)

In an area to be insulated, a distance shall be included to prevent shorting between conductors caused by foreign matters and displacement expected in the area.

If a distance of 1mm or more is provided, it is regarded as an insulating material. If a distance of 1mm or more is provided between two bare conductors and no insulating material exists between them, it is regarded as single insulation. If the gap between two conductors is filled with an insulating material, it is regarded as double insulation.

5.2.1.2 Solid body insulation

Insulation is provided using the following solid body insulation material:

(1) Solid body insulation material

(a) Resin board
(b) Resin sheet
(c) Resin mold
(d) Coating
(e) Mica board
(f) Glass fiber
(g) Glass hermetic sealing
(h) Ceramic board
(i) Ceramic hermetic sealing

(2) Items allowed for using for double insulation with the same material.

(a) Resin sheet: BT resin, Lumirror sheet
(b) Resin board: GFRP, Rexolite
(c) Tape: Polyester tape, Kapton ® tape
(d) Wire material sheathing: Wire material shall be certified for installing on aircraft

(3) Items not regarded as insulation material

(a) Solder resist on printed board
(b) Surface treatment on alloy

Except for the cases where insulation is secured by types of treatment or application to insulation design.

(c) Ferrite

5.2.2 Parts to apply double insulation

Double insulation shall be applied to the following parts:

(1) Primary power supply bus line

On the panel side of the solar battery transmitting generated power to the primary power supply bus line, double insulation shall be applied from a point where the shorting of primary power supply bus line occurs due to a short at only one part to the end of the input of the shorting failure separation circuit that receives the power distribution and supply of the primary power supply bus line. Figure 5.2.2-1shows an example of the primary power supply bus line

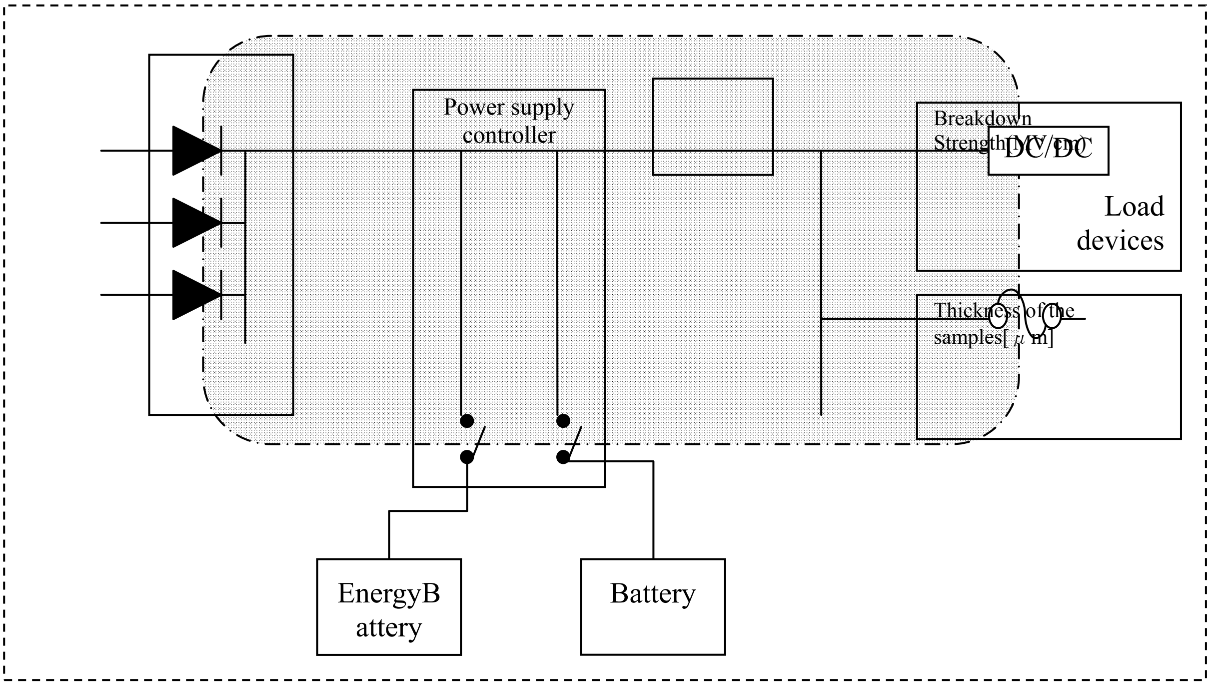


Figure 5.2.2-1 Primary power supply bus line example

(2) Battery line

The battery line shall include the charge array line (in a charge-array system) , the power line inside the battery, cell case, battery cabinet, and the pyrotechnic goods igniting the power supply line, in addition to the battery output line.

5.2.3 Implementation example of double insulation

N/A

6. Appendix

Appendix I Mechanism of breakdown

Various types of materials are used on a spacecraft. Among them, various types of insulation materials are used in electric and electronic devices and components of a spacecraft, which greatly contribute to maintaining reliability of a spacecraft in the severe space environment. However, the breakdown of insulation material may lead the spacecraft to a severe accident. It is necessary to apply materials with a thorough understanding of the breakdown phenomenon and breakdown characteristics of insulation materials. This section describes the breakdown phenomena and breakdown mechanism, and various factors that influence a breakdown. The insulation materials used in a spacecraft are solid body. This section focuses on the breakdown of the solid body itself, and creeping surface discharge related to the surface of a solid body and vacuum (or gas).

I.1 Mechanism of breakdown [1-3]

I.1.1 Conduction of solid body

A breakdown determines the ultimate useful life of electric insulation structure.
A deep understanding of electric conduction, which is a warning sign for a breakdown, leads to providing important information about the theory of electric physical properties, in addition to information about its engineering applications.

A current is defined as a quantity of electricity that passes through a cross section per unit of time. Therefore, a current density j [A/m^2] is expressed as follows, with the density of moving electric charge n [/m^3]and its moving speed v_d [m/s],

$$\left.\begin{aligned} j &= qnv_d = qn\mu E \\ v_d &= \mu E \end{aligned}\right\} \quad \cdots \text{(I.1)}$$

Where, E: applying limit [V/m], q: Charge amount of electric charge [C], μ: mobility [m^2/V•s]. If there are m types of moving electric charge, j is given by:

$$j = E\sum_{i=1}^{m} q_i n_i \mu_i \quad \cdots \text{(I.2)}$$

Meanwhile, conductance σ [S/m], which is one of physical values that describe electric conduction, is defined as follows:

$$\sigma = \frac{j}{E} = qn\mu \quad (= \frac{1}{\rho}) \qquad \cdots \text{(I.3)}$$

A reciprocal of σ is volume resistance ρ [Ωm]

The voltage-current characteristics, when increasing voltage is applied under constant conditions such as dielectric temperature and specimen thickness, are very important in evaluating electric insulation performance of a dielectric and in defining electric the conduction mechanism. In general, current-voltage characteristics changes as shown in the model of FigureI.1. The characteristics are divided into the following three fields. In solid dielectrics, almost no current saturation in the area emerges, unlike that of gases and pure liquids.

Area I is a part where electric field is relatively low. Current I increases linearly together with voltage V, adhering to the Ohm's law, I $\propto$ V.

In area II, a current increases on a non-linear basis deviating from Ohm's law, shifting to a breakdown eventually. This phenomenon is known as a dielectric breakdown. At this point, as shown in area III, a current that directly leads to a breakdown may be observed, which is clearly distinguished in some cases. The area where Ohm's law is true is referred to as "low-electric field area," and the non-linear area is referred to as "high-electric field area."

Since a breakdown exceeds the limit of maintaining an insulation performance for a dielectric, it becomes an important factor that ultimately determines the useful life of electric and electronic devices.

I.1.2 Breakdown mechanism of solid body

The mechanisms shown in TableI.1 are shown as breakdown mechanisms of a solid body. They are roughly divided into short-term breakdown and long-term breakdown. The following chart describes those breakdown mechanisms respectively.

First, short-term breakdown is described below:

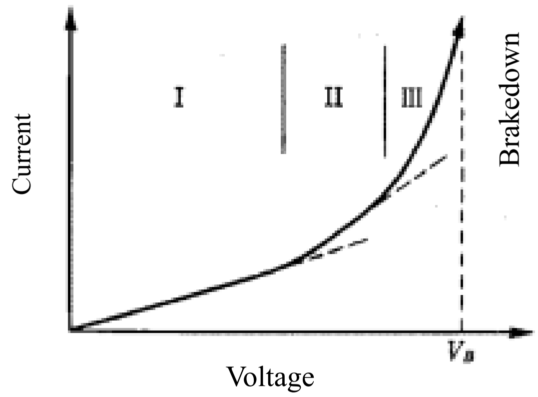


Figure I.1　Voltage (electric field) – Current characteristics of solid body dielectric

Table Ⅰ.1 Breakdown mechanism of solid body

Short time breakdown	Electronic breakdown process	Intrinsic breakdown Electronic avalanche breakdown Zener breakdown
	Thermal breakdown process	
Long time breakdown	Partial discharge Treeing Tracking	

I.1.2.1 Electronic breakdown process

(a) Intrinsic breakdown

Conducting electrons exist in solid dielectrics, although there are very few.　The conducting electron obtains energy A from electric filed E and gives energy B to the grid electron.　An electric field that breaks the balance between energy A and energy B is a breakdown of strength, or an intrinsic breakdown.

Assuming that all electrons in a solid body have identical energy W, A is found as follows: If an electron is moving in direction z by the force of electric field E while colliding with grid, a kinetic momentum of electron p_z is:

$$\left(\frac{dp_z}{dt}\right)_{\substack{\text{Electric}\\\text{field}}} = -eE \qquad \cdots \text{(I.4)}$$

Where, e is charge quantity of electron (= 1.6 × 10^{-19}C). Collision with grid is:

$$\left(\frac{dp_z}{dt}\right)_{\text{grid}} = -\frac{p_z}{\tau(W,T_0)} \qquad \cdots \text{(I.5)}$$

Where, □□(W,T_0) is momentum relaxation time, which depends on W and grid temperature T_0. Since p_z is constant under stationary state,

$$\left(\frac{dp_z}{dt}\right)_{\substack{\text{Electric}\\\text{field}}} + \left(\frac{dp_z}{dt}\right)_{\text{grid}} = 0 \qquad \cdots \text{(I.6)}$$

Therefore, moving speed of electron v_{ez} in direction z is:

$$v_{ez} = \frac{p_z}{m} = -\frac{e}{m}\tau(W,T_0)E \qquad \cdots \text{(I.7)}$$

Where, m is a mass of electron (= 9.1 × 10^{-31}kg) . Setting a current density as j, A = jE and a current by one electron is expressed as, according to equation (I.1) , since j = -ev_{ez}:

$$A(E,W,T_0) = jE = -ev_{ez}E = \left(\frac{e^2}{m}\right)\tau(W,T_0)E^2 \qquad \cdots \text{(I.8)}$$

Since a ratio of losing energy B by collision in a unit time depends on W and T_0, it is set as B (W, T_0) .

Figure 1.2 shows a conceptual chart of A and B dependency on W.

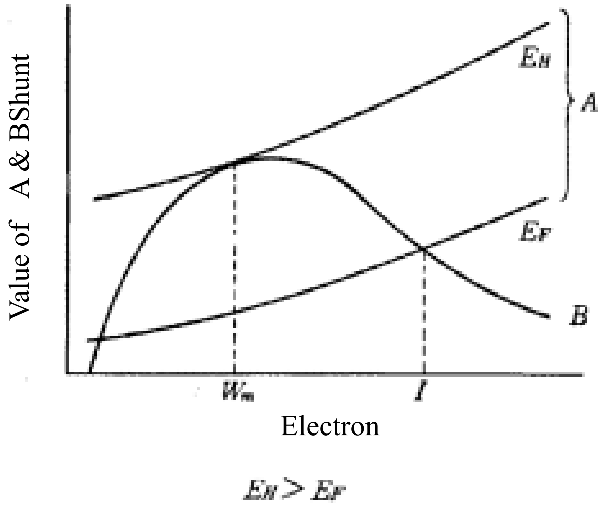


Figure I.2 Relation between A, B and electron energy W

In Figure I.2, Von Hippel said that EH is a breakdown in strength because A > B is true for any W when E > EH, and energy of electron increases infinitely without a balancing point. EH is referred to as Hippel's low energy criterion.

On the other hand, if E < EH, electrons can increase under some conditions, when electron energy becomes to be an energy level I that is required to excite electron from valence band to conduction band of dielectric. Fröhlich set an electric field E_F for I as breakdown strength. This is referred to as Fröhlich's high energy criterion.

(b) Electron "avalanche" breakdown

This is an analogy to a breakdown of a gas. Electrons accelerated by an electric field repeats collision and ionization and the number of electrons grow to become an avalanche, which causes a breakdown. Breakdown conditions are expressed by the following equation:

$$\alpha d = h_c \qquad \cdots \text{(I.9)}$$

α is collision ionization factor, which is the number of collisions in a unit distance, [/m], d is the thickness of a dielectric [m], and h_c is a constant, for which approximately 40 is often used by empirical means. (Seitz's 40-generation theory) The collision ionization factor α in a solid body is, setting the number of times an electron ionizes in a unit time as w [/s], given as follows:

$$\alpha = \frac{w}{v_e} = \frac{w}{\mu_e E} \qquad \cdots \text{(I.10)}$$

Where, v_e is moving speed of an electron [m/s]. Meanwhile, w is found as follows. When an electron with average energy W_{av} moves in an electric filed, the time t_I required to reach ionizing energy I and distance l_I of moving in the direction of the electric filed are respectively:

$$t_I = \frac{\sqrt{2m}(\sqrt{I} - \sqrt{W_{av}})}{eE} \quad \cdots (I.11)$$

and

$$l_I = \frac{I - W_{av}}{eE} \quad \cdots (I.12)$$

Meanwhile, an electron may collide before obtaining energy I. Setting $p(t_I)$ as the probability that an electron does not collide with an atom within time t_I, which is a probability of obtaining energy I or higher, and setting $\tau(W_{av})$ as collision relaxation time (time from a collision to a next collision) , the relation is:

$$w = \frac{p(t_I)}{\tau(W_{av})} \quad \cdots (I.13)$$

If equation (I.10) and equation (I.13) are substituted into equation (I.9), and solving the equation for E, a breakdown strength E_B on the avalanche breakdown is as follows:

$$E_B = \frac{p(t_I)d}{\tau(W_{av})\mu_e(W_{av})h_c} \quad \cdots (I.14)$$

$p(t_I)$ is expressed as follows:

$$p(t_I) = \exp(-\int_0^{t_I} \frac{dt}{\tau(W_{av})}) \quad \cdots (I.15)$$

An equation of motion for an electron moving freely in an electric field is:

$$\frac{dW}{dt} = mv_e \frac{dv_e}{dt} = (2mW)^{1/2} \frac{eE}{m} \quad \cdots (I.16)$$

Therefore, equation (I.15) is put as follows:

$$p(t_I) = \exp(-E/H) \quad \cdots (I.17)$$

Where,

$$H = \frac{1}{e}(\frac{m}{2})^{1/2} \int_{Wav}^{I} \frac{dW}{W^{1/2}\tau(W)} \quad \cdots (I.18)$$

Therefore, E_B is:

$$E_B = \frac{H}{\ln\{\dfrac{d}{E_e \mu_e (W_{av}) \tau (W_{av}) h_c}\}} \quad \cdots \text{(I.19)}$$

E_B is a function of gap length d. A specimen with a low thickness is vulnerable to avalanche breakdown. Figure I.3 shows comparison between an experiment of the breakdown strength conducted on sodium chloride (NaCl) and the electron avalanche breakdown theory.

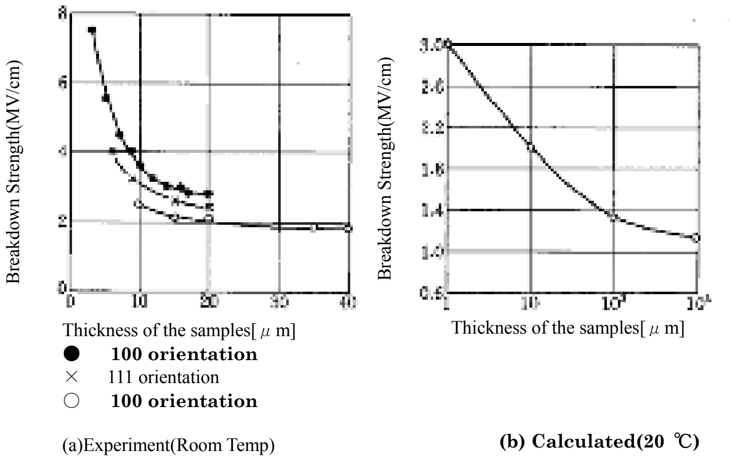


Figure I.3 Comparison between experimental values and calculated values based on the avalanche breakdown theory pertaining to the breakdown strength of NaCl

(c) Zener breakdown

The Zener breakdown considers that electrons in a conduction band suddenly increase due to a tunnel effect under a high electric field, and that the breakdown occurs when the generation of heat caused by the current of electrons leads to an exceedingly critical temperature. This model was proposed as one for a thin specimen with a narrow band gap between a conduction band and a valence band. For example, this is applicable to a breakdown caused by a reverse bias to a p-n junction of Ge. The breakdown of electric field strength is in the order of 10 MV/cm.

I1.2.2 Thermal breakdown process

Applying an electric field to a solid body of insulation material generates Joule heat, and the heat is lost by the rise of temperature of the solid body and diffusion to the surrounding area. Figure I.4 shows the concept in relation to the heat radiated and heat generated. If an electric field E_1 is applied in an ambient temperature T_0, at first the temperature rises gradually since the heat generated exceeds heat radiation, until they balance at T1 in the figure. If an electric field becomes E_{Tc}, the balancing point becomes T_{0c}. With a higher electric field, the heat generated always exceeds the heat radiated and the temperature continues rising without any balancing point.

In general, the temperature at which a solid body of insulation material reaches heat breakdown T_{0c}' is higher than T_{0c} in Figure I.4. However, if an electric field of E_{Tc} or higher is applied in asteady state, the temperature of T_{0c}' is always maintained. Therefore, E_{Tc} is a thermal breakdown of the strength of the solid body insulation. However, when a pulse voltage is applied and the time required for temperature rise to T_{0c}' is longer than a pulse voltage width, an electric field of E_{Tc} or higher does not cause a breakdown. Therefore, the breakdown strength is a function of the time between applying a voltage to a breakdown.

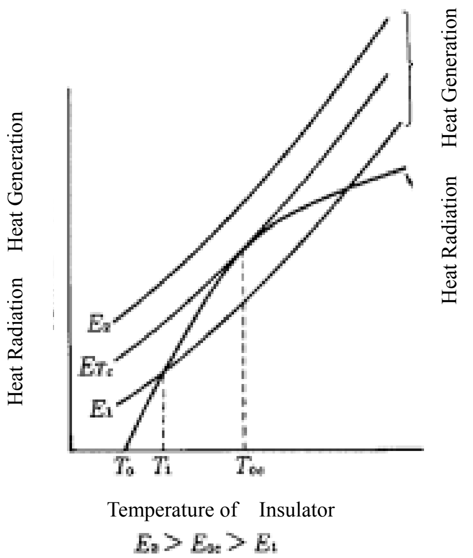


Figure I.4 Conceptual chart of heat generation and heat radiation on solid body

The fundamental equation of thermal conduction in a solid body, according to the thermal balancing conditions in unit volume of solid body,Heat value = (Heat of rising temperature of solid body) + (Heat radiation to surroundings by thermal conduction), is, as follows:

$$\sigma E^2 = C_v \frac{\partial T}{\partial t} - \mathrm{div}(K \mathrm{grad} T) \qquad \text{••• (I.20)}$$

Where, T: Temperature of solid body [K], C_v: Specific heat of solid body [J/kg・K], K: Thermal conductivity of solid body [W/m・K], and Conductivity [S/m].

In general, analytically solving equation (I.20) is difficult even under simple boundary conditions. Here, a case where the optimum condition, which is applying a direct current, is considered.

If a direct current is applied, the first term on the right side of equation (I.20) can be ignored:

$$-\operatorname{div}(K \operatorname{grad} T) = \sigma E^2 \qquad \cdots \text{(I.21)}$$

If it is assumed that an infinitely flat, uniform, isotropy solid body of insulation material with a thickness d is placed in the parallel flat electrodes as shown in Figure I.5, and heat flows only in z direction, then, equation (I.21) is:

$$\frac{\partial}{\partial z}(K\frac{\partial T}{\partial z}) + \sigma(\frac{\partial V}{\partial z})^2 = 0 \qquad \cdots \text{(I.22)}$$

Where, V is a potential in the solid body [V]. And the following is true:

$$\sigma E = -\sigma\frac{\partial V}{\partial z} = j \qquad \cdots \text{(I.23)}$$

If equation (I.23) is substituted into equation (I.22) and integrated:

$$jV = \int_0^z \frac{\partial}{\partial z}(K\frac{\partial T}{\partial z})dz = K\frac{\partial T}{\partial z} \qquad \cdots \text{(I.24)}$$

If the above is substituted into equation (.23) and integrated:

$$V_0{}^2 = 2\int_T^{Tm} \frac{K}{\sigma} dT \qquad \cdots \text{(I.25)}$$

However, if V_0: Applying voltage [V], T_0: Ambient temperature [K], T_m: Temperature of center of body [K], breakdown occurs when $T_m = T_{0c}$. Therefore, a breakdown voltage V_B is as follows. In other words, substitute the equation above by $T_m = T_{0c}$, $T = T_0$, $V_B = V_0/2$ (Only a half is considered since temperature distribution is symmetrical for ∵z = 0):

$$V_B = 8\int_{T_0}^{T0c} \frac{K}{\sigma} dT \qquad \cdots \text{(I.26)}$$

If substitution can be made as $\sigma(T) = \sigma_0 \exp(-\varphi/kT)$, $K(T) = K_0$:

$$V_B \cong (\frac{8kT_0{}^2K_0}{\sigma_0\phi})^{1/2}\exp(\phi/2kT_0) \qquad \cdots \text{(I.27)}$$

Where, k: Boltzmann constant (= 1.38×10^{-23} J/K) , φ: Work function.

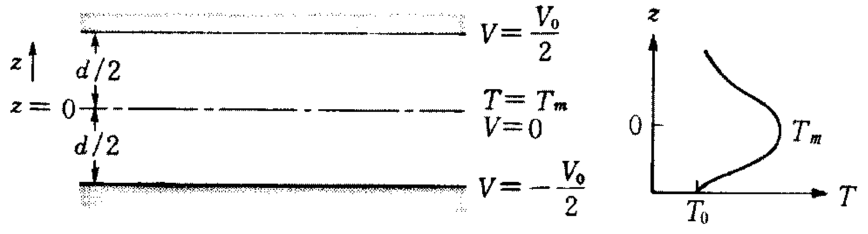


Figure I.5 Uniform and isogonic infinite flat plate specimen

I1.2.3 Electromechanical breakdown

If a Maxwell stress by applying electric filed becomes greater than the mechanical stress of a specimen, the specimen is mechanically pressed down and electrical breakdown then occurs. The breakdown strength in that case is found as follows:

If an electric field E is applied to a solid body insulation material, the following Maxwell stress occurs:

$$F_e = \frac{\varepsilon}{2} E^2 \qquad \text{... (I.28)}$$

Where, ε: dielectric constant of specimen.

On the other hand, when a thickness of specimen with Young ratio Y shrinks from d_0 to d, an internal stress is, according to definition of Young ratio:

$$F_m = \int_d^{d_0} Y \frac{dl}{l} = Y \ln \frac{d_0}{d} \qquad \text{... (I.29)}$$

If Fe and Fm balance with each other when voltage V is applied to a board specimen of thickness d, the following is obtained by substituting Fe = Fm and V = Ed:

$$V^2 = \frac{2d^2 Y}{\varepsilon} \ln \frac{d_0}{d} \qquad \text{... (I.30)}$$

Value V becomes highest by changing d when d/d_0 = exp(-1/2) 0.6, rather than dV/dd = 0. In other words, a maximum voltage VB allowed to apply without pressing down a specimen mechanically is that at d = $0.6d_0$, and a breakdown electric field E_B is:

$$E_B = \frac{V_B}{d} = 0.6\left(\frac{Y}{\varepsilon}\right)^{1/2} \qquad \text{... (I.3v)}$$

Figure I.6 shows comparison between actual measurement values of breakdown strength and calculated values of electrical mechanical strength for polyethylene and polyisobutylene. It illustrates sharp drops of E_B around 80°C and -40°C well.

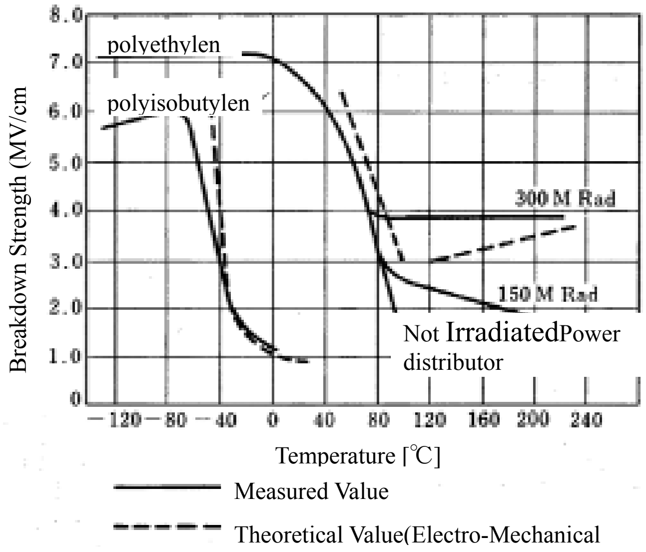


Figure I.6 Breakdown strength dependency of polyethylene and Polyisobutylene on temperature

I1.2.4 Partial discharge

This next section describes a breakdown over a long period of time. A solid body of insulation material may be destroyed by a voltage applied for a long period of time. The three factors, partial discharge, treeing, and tracking are considered as causes. From a practical viewpoint, it is important to understand the processes of this type of breakdown.

First, look at a breakdown over a long period of time caused by partial discharge. As shown in Figure I.7, if a board-like bubble (void) exists in a solid body insulation material (thickness: d) with a thickness t and a cross section A, its equivalent circuit is shown as in figure (b). In the figure, assuming that t << d and a dielectric constant of the solid body is ε_r, an electric field in the void is E_c, and an electric field in the solid body is E_a, the following is true:

$$E_c = \varepsilon_r E_a \qquad \cdots \text{(I.32)}$$

An electric filed in a void is ε_r time as high as that in the solid body. Meanwhile, the following are true in the figure:

$$C_b = \frac{\varepsilon_0 \varepsilon_r A}{d-t}, \qquad C_c = \frac{\varepsilon_0 A}{t} \qquad \cdots \text{(I.33)}$$

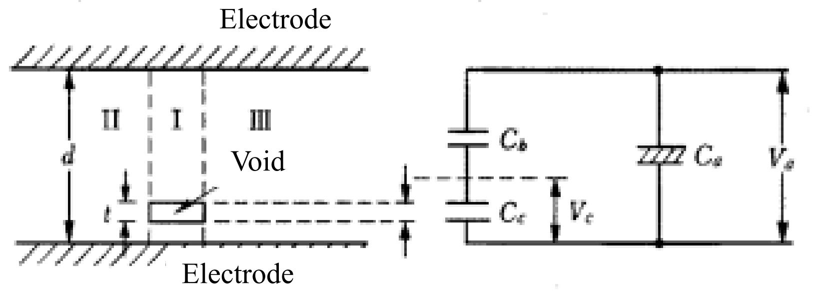
Therefore, a voltage V_c applied to the void when a potential difference V_a between electrodes is as follows:

$$V_c = \frac{C_b}{C_c + C_b} V_a = \frac{V_a}{1 + \frac{1}{\varepsilon_r}(\frac{d}{t} - 1)} \qquad \cdots \text{(I.34)}$$

Therefore, when Breakdown strength of the gas in the void is E_B, a voltage between electrodes to cause breakdown in the void is :

$$V_{ao} = E_B t\{1 + \frac{1}{\varepsilon_r}(\frac{d}{t} - 1)\} \qquad \cdots \text{(I.35)}$$

Discharge in a void is referred to as partial discharge or void discharge, and V_{ao} is referred to as partial discharge onset voltage.



(a) Void in Sample **(b) Equivalent Circuit of (a)**

Cc:Capacitance of void
Cb:Capacitance of Ⅰ
Ca: Capacitance of Ⅱ、Ⅲ

Figure I.7 Insulation material containing void and equivalent circuit

Figure I.8 shows voltage changes of parts when Va in Figure I.7 is a sine-wave alternating current. If a potential difference in void Vc reaches $V_c = E_B t = V^+$ and discharge starts once in C_c, V_c sharply drops to V_r by ΔV. Vr is referred to as residual voltage. This occurs because an electric charge of the opposite sign is accumulated on the insulation material surface in the void by partial discharge, as shown in Figure I.9(b), an electric field caused by the accumulated electric charge E_s cancels the external electric field Ea. The time required for Vc to drop by ΔV is decided by the continuing time of discharge. It is extremely short, such as approximately 10^{-8}s, no electric charge is supplied from the power supply. Therefore, a voltage applied to Ca drops by the following value:

$$\delta V = \Delta V \frac{C_b}{C_a + C_b} << \Delta V \qquad \text{••• (I.36)}$$

If Va continues to rise after discharge, Ec also rises as shown in Figure I.9(c) in proportion to the external electric field. Since the electric field caused by the accumulated electric charge Es exists, the practical electric fields in the void (E_c+E_s) rise, and V_c rises also. If it reaches V_+, partial discharge occurs again. This similarly occurs when Va drops also, and changes of V_c are shown in Figure I.8. A true electric charge Q that makes discharge in the void is

$$Q = \Delta V (C_c + \frac{C_a C_b}{C_a + C_b}) \cong \Delta V (C_b + C_c) \qquad \text{••• (I.37)}$$

An apparent discharge electric charge Q’ is given by the following equation:

$$Q' = \delta V C_a \cong \Delta V C_b \quad \cdots \text{(I.38)}$$

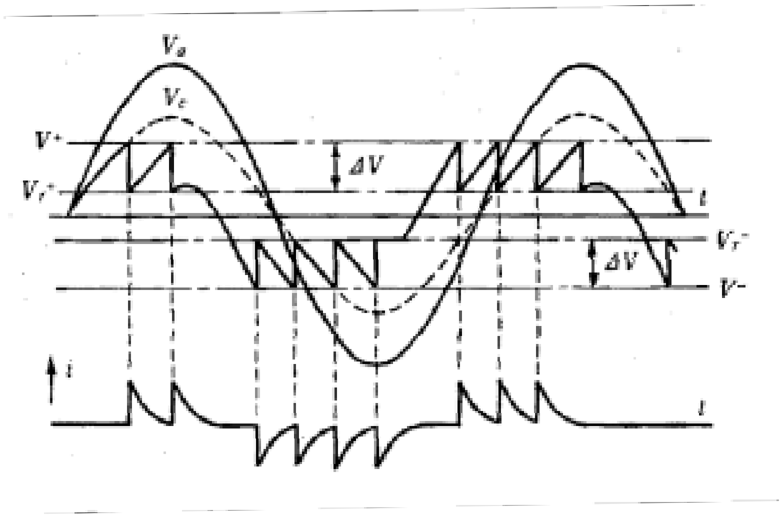


Figure I.8　Void discharge current with alternating current voltage applied

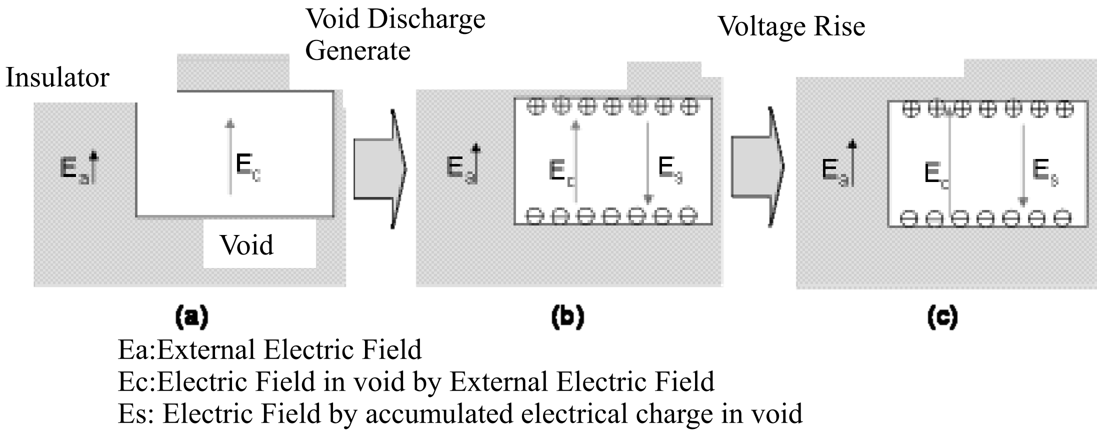


Figure I.9　Change of electric field in void

Next, a partial discharge occurs when a direct current voltage is applied.　As shown in Figure I.10, upon a rise of voltage, an electric field E_c rises in a void in response to the external electric field E_a, just as the case with applying an alternating current voltage.　Moreover, a partial discharge occurs when E_B is reached.　If the electric charge generated by the discharge adheres to the inner wall of the void, it lowers the internal electric field. If a rise of voltage stops after that, the electric field in the void remains low under the influence of the accumulated electric charge. However, if this condition continues for a long period of time, the electric charge accumulated inside leaks toward the facing electrode because of the external electric field E_a. Therefore, the electric charge accumulated on the inner wall decreases and the electric field E_s of the accumulated charge drops, gradually increasing the electric field inside the void. If this rise in the electric field continues and E_B is reached, a partial discharge occurs again. As described above, a rate of partial discharge caused by a direct current voltage is determined by the leak of electric charge. A time constant of such a leak is decided by the product $\varepsilon\rho$ of a permittivity ε and volume resistivity ρ of an insulation material. Since the volume resistivity of an insulation material is extremely high, the time constant is high. Therefore, the frequency of discharge is lower with respect to direct current, in comparison with that of alternating current.

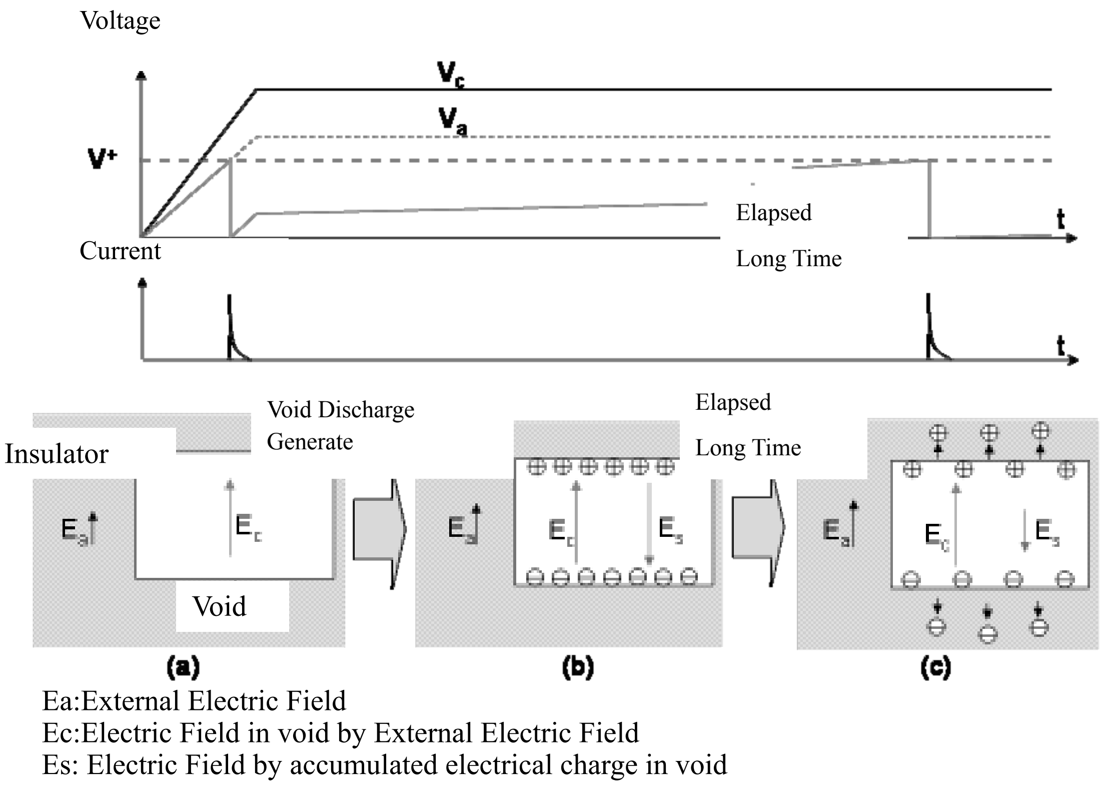


Figure I.10 Partial discharge with direct current voltage applied

As described above, if a void exists in a solid body of insulation material, an electric field in the void becomes high and generates a partial discharge. Since a partial discharge becomes the cause for energy loss in insulation material, it increases as apparent electrostatic tangent tanδ increases. If it continued for a long time, insulation deterioration occurs as the result of the following, and a breakdown of the complete circuit occurs under a low voltage that is several times as low as applying a voltage for a short time.

The following three reasons account for insulationdeterioration:

1) Cutting of molecular structure caused by collisions of charged particles to an insulation material, and chemical reactions such as cross-linking and oxidization.
2) Thermal deterioration caused by a local temperature rise caused by collision of charged particles.
3) Oxidization caused by products that are discharged, such as O_3, NO, and NO_2.

Figure I.11 shows the long-time breakdown voltage – Useful life characteristics (V-t characteristics) of epoxy resin, which is a representative insulation material, applying alternating current voltage. Under such V-t characteristics, it is known that a reversed n-power law is true for applying voltage (electric field) and determining a useful life on an empirical basis:

$$t = kV^{-n} \quad \text{… (I.39)}$$

A useful life is assessed by value of n. If a void exits, n value becomes low as shown in Figure I.12, indicating a short useful life.

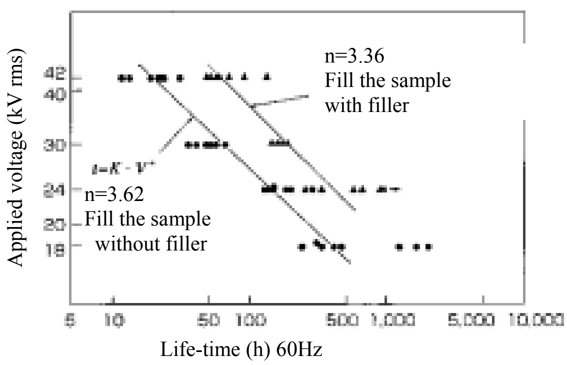


Figure I.11 AC voltage V-t characteristics of epoxy resin

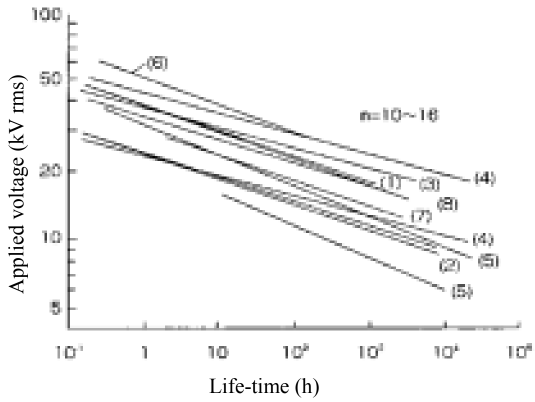


Figure I.12 AC voltage V-t characteristics of epoxy resin (with void)

I1.2.5 Treeing

If a partial high-electric field, such as a projection on an electrode, exists in the solid body of insulation material, a discharge path (tree) made of a thin pipe is generated. If it creates a short between electrodes, it causes a complete circuit breakdown. Such an arborescence discharge path is referred to as treeing. It is likely to occur if a needle-like projection, conductive fiber, or water exists on an electrode of a thick specimen. A tree emerges at a far lower voltage than at the intrinsic breakdown voltage of the insulation material, and leads to complete breakdown.

I1.2.6 Tracking

If salt, dust, or moisture adheres to a part of an insulation material surface where an electric filed exists in a creeping direction, it gradually forms a conductive path (track), which can cause a creeping flashover at a low voltage. The phenomenon of producing a track on an insulating material surface such as this is referred to as tracking. The phenomenon of forming a low-resistance conducting path on an organic insulation material surface because of carbonization due to arc discharge heat or conductive products caused by arc discharge (vapor deposition of electrode metal) is referred to as arc tracking. Carbonization due to heat of arc discharge is likely to occur on any insulation material with a high percentage of carbon content. On the other hand, materials with N or O are bonded in the middle of carbon backbone, such as amino-resin and polyamide resin, which are resistant to carbonization in general, and have good anti-arc performances. On the contrary, materials with an aromatic ring in its molecule such as phenol resin and PBT have poor anti-arc performances. Meanwhile, with respect to materials with tracking caused by conductive products due to an arc discharge, the time required to produce tracking depends on the electrode materials, the discharging energy, and the number of times of discharge.

I1.3 Creeping discharge mechanism

Creeping discharge occurs along the boundary surfaces of different dielectrics. Therefore, the phenomena are divided into discharge on a solid body surface in a gas, discharge on a solid body surface in a vacuum, discharge on a solid body surface in a liquid, and on the boundary between a gas and a liquid. Since this section is concerned with space devices, it describes discharge on a solid body surface in a gaseous phase, on a solid body in a vacuum, and between different solid bodies.

I1.3.1 Creeping discharge in the gaseous phase

Models of creeping surface discharge, as shown in Figure I.13(a), are roughly divided into two: An electric line of force is perpendicular to a solid dielectrics surface, and it is parallel to the surface as Figure I.13 (b). Creeping discharge does not necessarily start with an electrode on a high-voltage side. If an electric field near the electrodes on the ground side is intense, the discharge starts on that side. If creeping discharge creates a short between electrodes, it causes a creeping flashover with a flash.

(a) Creeping discharge on perpendicular electric line of force

Because an electric field on the tip of an electrode is high, creeping discharge occurs and develops at a low voltage and discharge expands very well. Bushing and cable terminals have this type of structure.

(b) Creeping discharge on parallel electric line of force

Since the strength of electric fields is approximately the same at any position, a discharge that starts at a point leads to flashover instantly. A discharge starts with a point with large electric field distortion, such as at junctions between dielectric and electrode (triple junction) and a metal piece adhering to a dielectric surface. This is the structure of an insulator and spacer holding a high-voltage conductor.

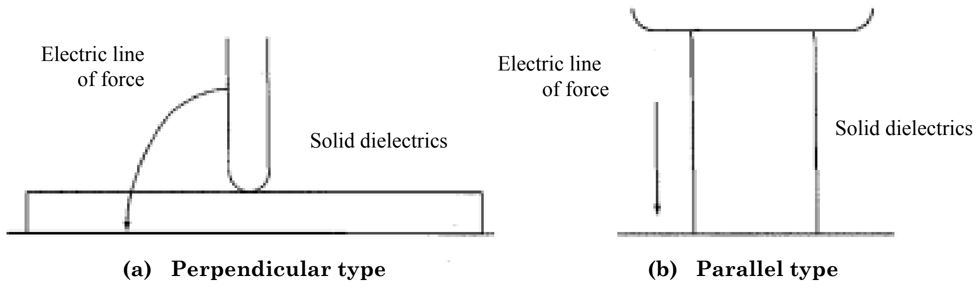


Figure I.13 Typical electrode structure of creeping discharge

Figure I.14 shows the mechanism for a creeping discharge. The area at the tip is ionizing intensely (electronic avalanche) while a plasma-state trunk exists at the back. Together, they are referred to as a creeping streamer. If discharging continues for a long period of time, a conductive leader is formed at the back of the streamer. The properties of a creeping discharge include expanding with contact to a solid dielectrics and flowing a large charging current. An electrode in which a charging current flows is referred to as back electrode.

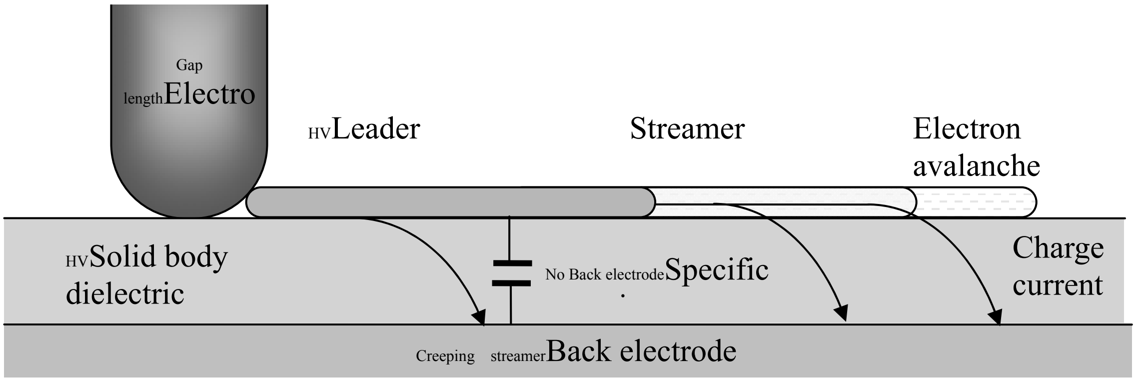


Figure I.14 Mechanism of developing creeping discharge

I1.3.2 Creeping discharge in a vacuum [4,5]

A solid body of insulation material is used to support a high-voltage part in a vacuum. Performance of holding high-voltage on a solid body of insulation material in a vacuum is lower than a vacuum gap of the same dimensions. A discharge is likely to occur on a creeping surface of insulation material. Until now, various creeping discharge mechanisms in a vacuum have been discussed in the following three phases:

(1) Initial phase (2) Growing phase (3) Final phase

(1) Creeping discharge initial phase

As shown in Figure I.15 of the conceptual diagram of creeping discharge in the initial phase, creeping discharge on insulation material in a vacuum is triggered by the discharging of an electron from a triple junction (junction of insulation material/cathode metal/vacuum). The concentration of electric fields occurs at the junction, and electrons are discharged to the electric field.

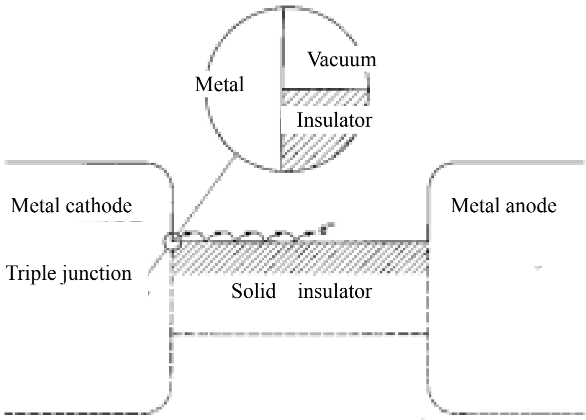


Figure I.15 Initial phase of vacuum creeping discharge

(2) Creeping discharge growing phase

Various mechanisms are considered regarding how the electrons discharged from the triple junction begin to discharge, which include secondary electron emission avalanche, electrons increasing in a solid body, and electron collisions. This section describes the Secondary Electron Emission Avalanche (SEEA) which is most accepted.

When electrons emitted from a triple junction collide with the surface of insulation material, and when the secondary electrons produced at that point collide with the surface of the insulation material again to increase the secondary electrons, it forms an avalanche. (Figure I.16) In general, a secondary electron emission factor on the surface of insulation material has an energy dependency on primary electron (incoming electron) as shown in Figure I.17. If the energy of colliding electrons is in the area of emission at a factor larger than 1 (usually 10eV to keV), it results in an emission of more electrons than electrons coming into the insulation material. Then, the part of causing secondary electron emission becomes positively charged.

Anderson's group [6] invented a model that SEEA leads to a complete breakdown. Insulation materials in a vacuum, particularly on a ceramic surface, are covered with multiple layers of adsorption gas. When SEEA electrons collide with the surface of the insulation material, the adsorption gas is emitted and it forms a partially-ionized gas cloud from the electrons in the SEEA. Residing positive ions increases the electric field of the triple junction. As a result, electrons emitted from the triple junction increase and a current flowing along the surface of the insulation material also increases. This process produces a creeping discharge on the surface of the insulation material.

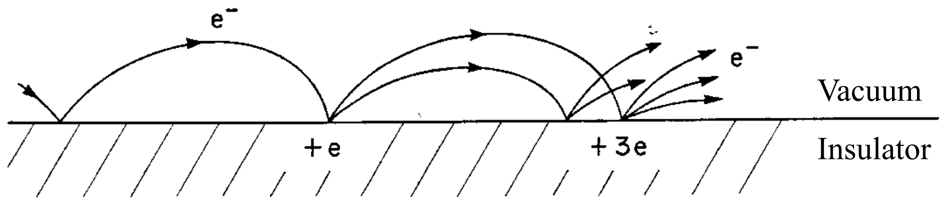


Figure I.16　Increase of electrons by SEEA electrons

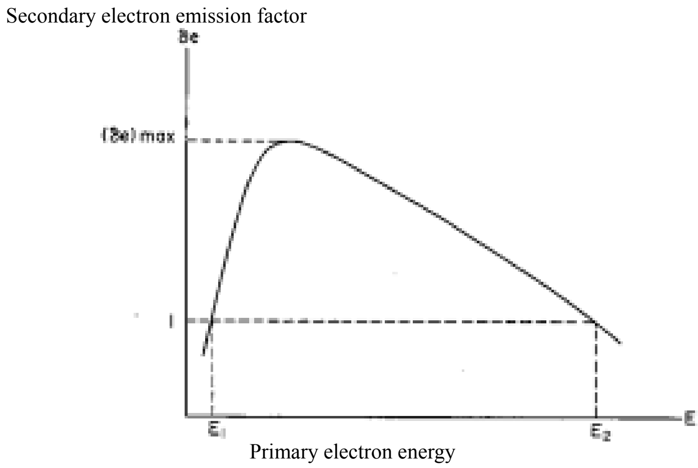


Figure I.17　Secondary electron emission characteristics of insulation material

(3) Creeping discharge final phase

It is generally accepted that the final phase of a creeping discharge is electric discharge in the gas emitted from the surface of the insulation material.

Figure I.18 shows the inter-electrode dependency of creeping discharge voltage on representative materials, Teflon® and Macor.　Discharge voltage increases in response to the increase of inter-electrode distance.　However, it shows a tendency of gradual saturation.　It also indicates that the discharge voltage depends on the types of materials.

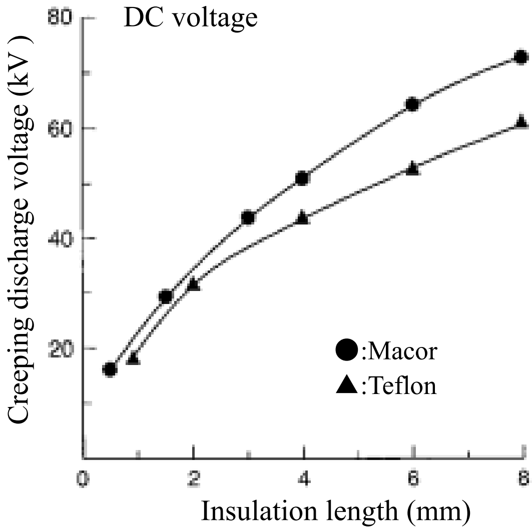


Figure I.18　Dependency of creeping discharge voltage
on inter-electrode distance in vacuum

I1.3.3 Discharge on surface

In an insulation structure, as shown in Figure I.19, there may be a bonding surface between different materials.　On such a surface, there may be a layer of air on the bonding. Peeling is likely to occur due to thermal history after bonding.　A discharge may occur on such a surface.　Figure I.20 shows the breakdown characteristics on a bonding surface between Noryl resin, which is used for a small coil and silica-filled epoxy resin.　As shown, a breakdown voltage is low on the bonding surfaces between the different materials.　In addition, after a history of thermal shocks, peeling occurs on the surface, approaching a breakdown electric field of air (3kV/mm).　Moreover, if a back electrode has been formed, a breakdown voltage is likely to become even lower.

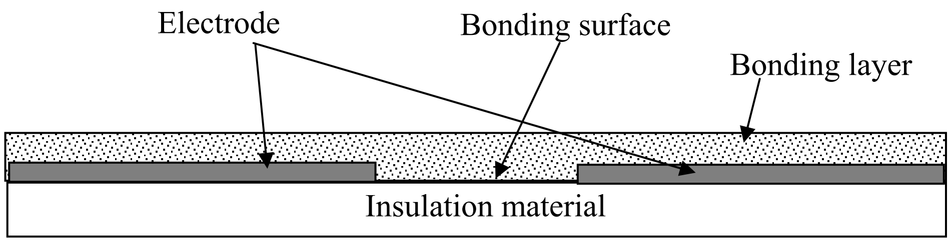


Figure I.19　Complex insulation structure with insulation material surface

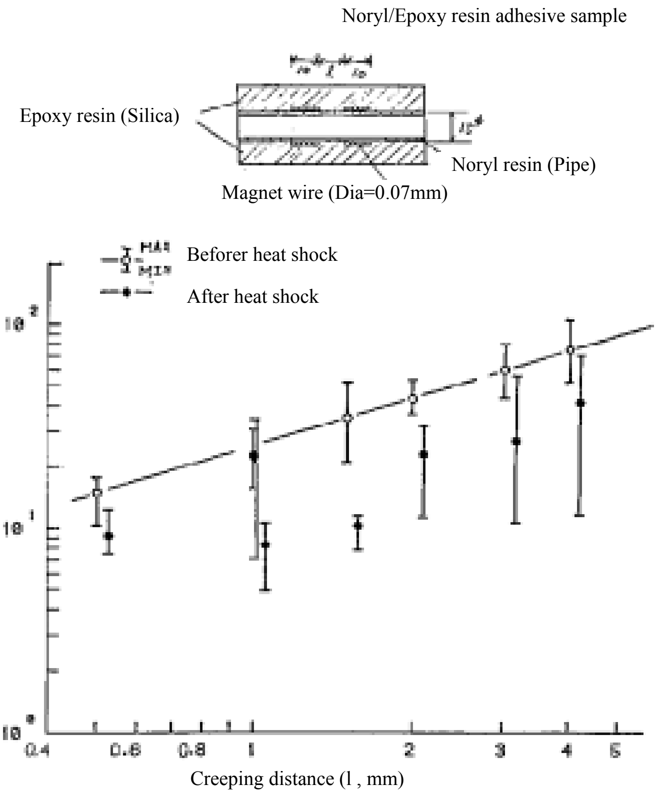


Figure I.20 Breakdown characteristics on bonding surface

I1.3.4 Influence of charging on breakdown

On a spacecraft, high-energy charged particles existing in space may get into a device and may charge the solid body of insulation material in an installed device. It may have an influence on the breakdown of a solid body of insulation material. However, there have been few studies on insulation conducted from this point of view because high voltages are not applied to spacecraft. There are only discussions concerning the influences of electron beam radiation on the voltage characteristics of creeping discharge in a vacuum. Figure I.21 shows this study. [7] This suggests that a glass creeping discharge voltage drops because of the radiation of the electron beam. This is considered because the electron beam radiated on a glass creeping surface distorts the creeping electric field, making a discharge more likely.

However, various studies have been conducted concerning the space charge effect in a solid body, as a secondary factor that influences the breakdown of a solid body. When a high electric field is applied to an insulation material and a space charge is formed inside, the internal electric field is distorted and the breakdown aspect is greatly changed. The formation of a space charge is based on the uneven distribution of a positive and negative charge. A charge is supplied from electrodes (injection) and inside a solid body. In most cases, a space charge effects cause problems with an uneven electric field. They particularly emerge in a direct current electric field.

If a formed space charge has the same sign as the electrode voltage polarity, it is called a homo-charge, which is primarily injected from the electrode. If it has a different sign, it is called hetero-charge, which is caused by the movement of a charge in a solid body. A homo-charge relaxes an electric field in front of an electrode, and functions to prevent a breakdown. However, as it is seen in a direct-current power transmission, reversing polarity of voltage induces a high electric field in front, which increases the probability of a breakdown. In addition, a short circuit with a negative electric field applied to a needle electrode with a space charge formed may lead to local breakdown.

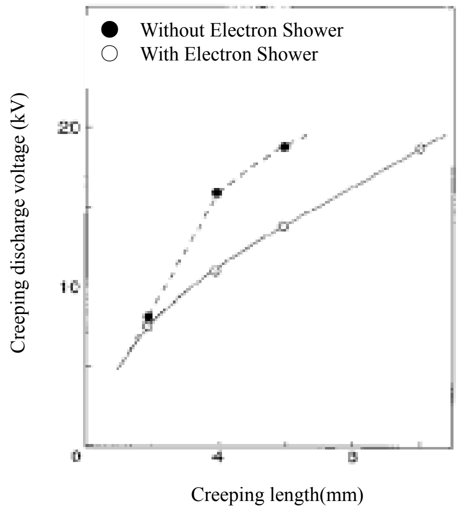


Figure I.21 Influence of electron beam radiation on creeping discharge voltage characteristics of glass in vacuum

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Appendix II Influence of concentrating an electric field and an electron emission from electrode material

II1 Relation between electrode shape and electric field [1]

Take a look at a system in Figure II.1, which is composed of electrodes and a space between them. Setting $\varphi = \varphi$ (x, y, z) as optional at an arbitrary point p (x, y, z) in this space, φ satisfies the following Poisson equation if a space charge density is ρ:

$$\mathrm{div}(\mathrm{grad}\phi) = -\frac{\rho}{\varepsilon} \quad \cdots \text{(II.1)}$$

Where, ε is a dielectric constant of the space. If there is not a space charge, setting ρ = 0 makes the following Laplace equation:

$$\mathrm{div}(\mathrm{grad}\phi) = 0 \quad \cdots \text{(II.1)}$$

Therefore, solving the equation (II.1) or (II.2) gives an electric field distribution in space under the following boundary conditions on electrode surface:

$$\phi = V_i \text{ (i: Electrode number)} \quad \cdots \text{(II.1)}$$

Table II.1 provides solutions of analysis on electric fields in an electrode alignment that is frequently used in handling high-voltage phenomena.

Electric fields with complex electrode shapes and complex boundary shapes of space media are solely found using numerical calculations. The numerical calculations include the calculus of finite differences, the finite element method, the charge simulation technique, and the surface charge method.

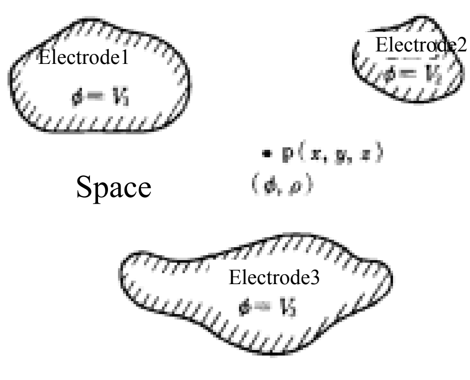
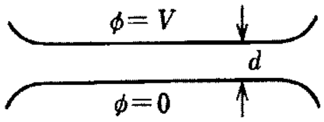
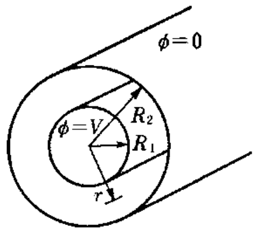
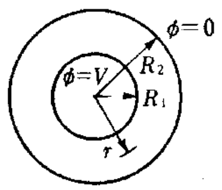
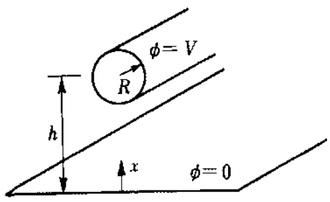
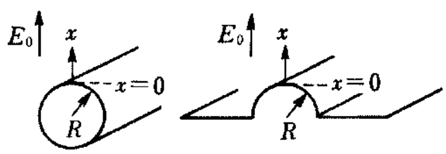


Figure II.1 Potential in space between electrodes

TableII.1 Electric field with fundamental electrode alignment

(The field amplification factor f = E_{max}/E_{av}, where
E_{max}: Maximum electric field, E_{av}: Average electric field)

Electrode alignment	Electric field
Parallel flat plates 	$E = \frac{V}{d}$ $f = 1$
Coaxial cylinders 	$E = \frac{V}{r \ln(R_2 / R_1)}$ $f = \frac{R_2 / R_1 - 1}{\ln(R_2 / R_1)}$
Concentric sphere 	$E = \frac{R_1 R_2}{r^2 (R_2 - R_1)} V$ $f = \frac{R_2}{R_1}$
Cylinder and flat plate 	$E = \frac{2\sqrt{h^2 - R^2}}{(h^2 - R^2 - x^2) \ln(\frac{h + \sqrt{h^2 - R^2}}{R}} V$ $f = \frac{\sqrt{h^2 - R^2}}{R \ln \frac{h + \sqrt{h^2 - R^2}}{R}}$
Cylinder and half-cylinder projection in uniform electric field 	$E = \{1 + \frac{R^2}{(R + x)^2}\} E_0$

<table>
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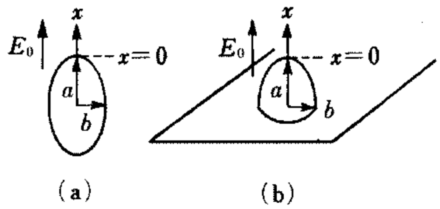
<td>
Oval and oval projection in uniform electric field


</td>
<td>
Case a>b
$$E = E_0\left[1-\frac{\tanh^{-1}\sqrt{\frac{a^2-b^2}{x^2}}-\sqrt{\frac{a^2-b^2}{x^2}}\left(\frac{x^2}{x^2-a^2+b^2}\right)}{\tanh^{-1}\sqrt{\frac{a^2-b^2}{a^2}}-\sqrt{\frac{a^2-b^2}{a^2}}}\right]$$
Case a=b
$$E = E_0\left(1+\left(\frac{a}{a+x}\right)^2\right)$$
Case E0=0, Electrical Charge=Q on oval
$$E = \frac{Q}{4\pi\varepsilon(x^2-a^2+b^2)}$$
</td>
</tr>
</table>

II2 Electrode material and electron emission

If a voltage is applied between electrodes placed in a vacuum, the current- voltage characteristics shown in Figure II.2 are obtained. If a voltage of high electric field that can cause breakdown is applied, a field emission of electron from the cathode occurs due to the tunnel effect. The electric field emission current I_e is a stable current decided by a work function φ of an electrode material and an electric field E, which is expressed by the equation of Fowler-Nordheim (F-N). However, if I_e is measured between electrodes with an area larger than a certain size, the value is significantly larger than the theoretical value in general. An I_e value of the actual measurement is explained by the fact that the electric field on a local cathode surface is thought to be 100 times as high as the macro electric field E. Here, the concept of field enhancement factor β is introduced, expressing Ie by the following equation:

$$I_e = \frac{1.54\times10^{-6}(\beta E)^2 A_e}{\phi}\cdot\exp\left|\frac{-6.83\times10^7\phi^{3/2}}{\beta E}\right| \quad [\mathrm{A}] \cdots (\mathrm{II.4})$$

Where, A_e is an electric field emission area.

The cause why β occurs is, in general, thought to be a micro projection (protrusion, whisker, projection, irregularity) of approximately several μm. The existence of such projections is observed under various conditions. Those projections are thought to have formed from the melting of electrodes due to an arc discharge, melting due to the collision of micro particles, ion etching, the growth caused by electrostatic field or an electric field emission, or the elimination of impure particles.

An actually-measured leader current before a breakdown is verified to be an electric field emission current by the fact that the F-N plot becomes linear. (Figure II.3 shows an example of F-N plot.) According to the gradient of this line, a value for β is determined.

In general, a cathode having an area of a certain size has two or more sources of emitting an electric field, which are projections. In this case, also, it is verified that I_e plot is roughly linear based on experiment and theory. On the basis of the F-N plot, the effective field enhancement factor and effective electric field emission area are determined as effective and average factors. Even if a shape of projection is constant, β fluctuates depending on inter-electrode distance d. If d becomes smaller, it approaches the uniform electric field, and β decreases. Ultimately, when d = 0, the value becomes β = 1 regardless of the shapes of the projections. Figure II.4 shows an example of d-β characteristics.

It is reported that if the micro electric field βE at the tip of projection reaches approximately 5×10^7 V/cm, the electric field emission is restricted due to the space electric charge effect of electric field emission electrons. In this case, the F-N plot deviates from a line at high-electric field area as shown in Figure II.3.

Even under an extremely high vacuum on the order of 10^{-9} Torr, gas adsorption molecules cannot be removed completely while the electric field emission is influenced by gas adsorption of the emission source. The following effects of gas adsorption are considered:

1) Fluctuation of I_e due to changes of work function φ and effective electric field emission areas.
2) Occurrence of superimposed noise on I_e

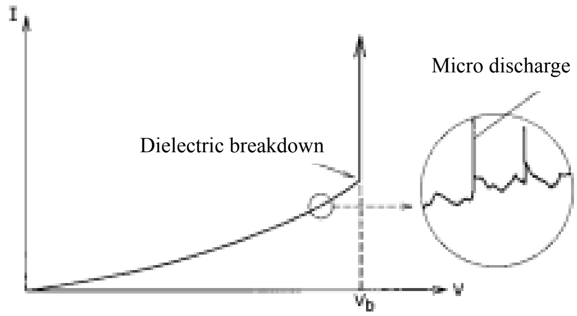


Figure II.2 Voltage-current characteristics between electrodes in vacuum

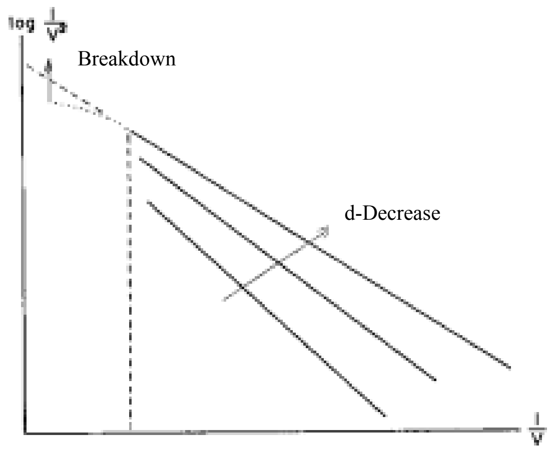


Figure II.3 F-N plot in vacuum gap

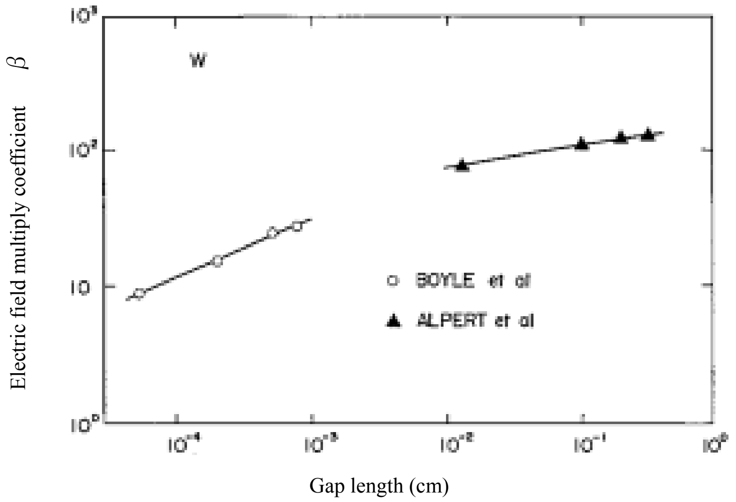


Figure II.4 Gap length in vacuum and electric field multiplication factor

II3 Influence of work function in metals

The electric field emission current I_e, is influenced by work function φ as it is clearly found by (II.4). If work function φ becomes greater, I_e becomes smaller. Table II.2 shows work functions of metals in general.

Table II.2 Work functions of metals

Metal	Work function φ (eV)	Melting point (K)
C	4.34	3800
Co	4.41	1490
Cs	1.38	302
Fe	4.21	1540
Mo	4.20	2630
Ni	4.01	1725
Pt	5.32	2047
Ta	4.10	3123
W	4.52	3655

II4 Surface treatment of electrode

Since discharge voltages (breakdown voltages) change depending on conditions of the electrode surface, the following treatments are effective on electrodes, particularly for those used under high electric fields and under vacuum conditions:

(1) Providing surface treatments:
- Cleaning with solvent
- Chemical etching
- Cleaning by discharge
- Inorganic coating

(2) Performing conditioning
- Current conditioning
- Glow discharge conditioning
- Spark conditioning

Figure II.5 shows an example of current conditioning. Between electrodes placed in a vacuum, a voltage that is lower than an expected breakdown voltage is applied. Then, after the current flow between the electrodes becomes stable, the voltage is increased on a step-by-step basis. A leading current gradually drops while a voltage is applied, and the frequency of current spikes and current pulses caused by micro discharge gradually decreases. According to this method, projections on electrodes, adhesives on electrodes, and micro particles are removed.

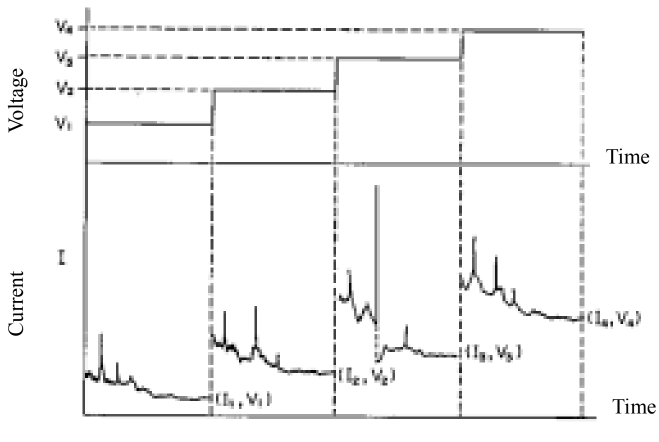


Figure II.5 Current conditioning

References

[1] Hara and Akiyama, "High-voltage Pulse Power Engineering", (Morikita Publishing) (1991)

Appendix III Influence of neutral molecular on discharging

III1 Paschen's law in gas [1,3]

A voltage that produces a spark discharge in a uniform electric field is referred to as a spark voltage. A spark voltage V_s is the function of product pd, of gas pressure p, and gap length d, under a constant temperature of gas. Since Paschen discovered this through experimentation, this is referred to as Paschen's law.

$$V_s = B\frac{pd}{\ln\{\frac{Apd}{\ln(1+\frac{1}{\gamma})}\}} = B\frac{pd}{\mathrm{const.}+\ln(pd)} \quad \cdots \text{(III.1)}$$

Where, A and B are constants.

Figure III.1 shows the spark voltages of representative gasses as functions of pd. With a constant gap length, lowering the pressure results in gradual drop of spark voltages. This is because average free paths (the average value of the distance in which electrons in gas flies freely between successive two collisions) are prolonged, and then acceleration by an electric field increases, encouraging collision and ionization. The spark voltages show a minimum value at a certain pd value, and become sharply high at pressures lower than at that point. This is because average free paths become too long, decreasing the number of collisions of electrons between electrodes, making collisions and ionization inactive again.

By differentiation of equation (III.1) with pd, a minimum spark voltage $(V_s)_{min}$ (Paschen minimum) is found to be:

$$(V_s)_{\min} = 2.718\frac{B}{A}\ln(1+\frac{1}{\gamma}) \quad \cdots \text{(III.2)}$$

Setting $(pd)_c$ as a pd that gives a minimum spark voltage, $((V_s)_{min})$:

$$(pd)_c = \frac{2.718\ln(1+\frac{1}{\gamma})}{A} \quad \cdots \text{(III.3)}$$

Table III.1 shows an example of $(V_s)_{min}$ and $(pd)_c$ of an actual measurement.

If the pressure drops below the Paschen minimum value, the discharge voltage suddenly rises. Figure III.2 shows the dependency of discharge voltages on pressure in a parallel flat-plate electrode system under a high vacuum environment.

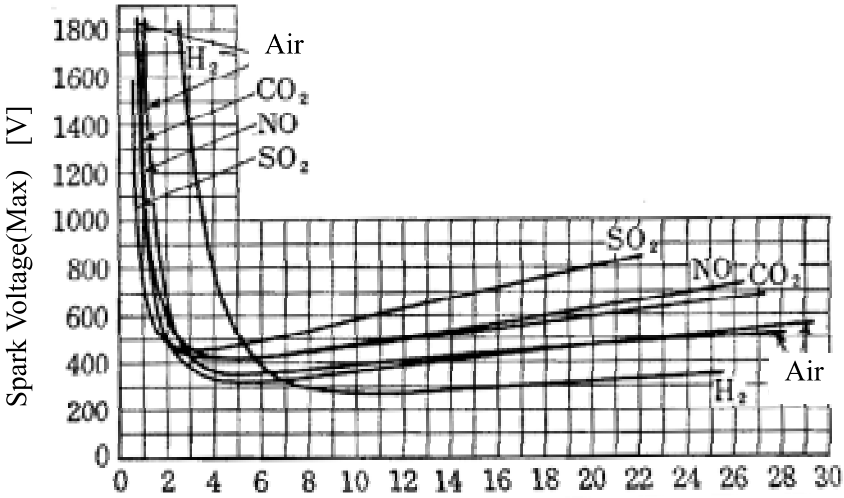


Figure III.1 Example of Paschen curve

Table III.1 Minimum spark voltages ($(V_s)_{min}$) and pd that gives the value ($(pd)_c$)

Gas	$(V_s)_{min}$ (V)	$(pd)_c$ (mm・Torr)
Air	330	5.67
H_2	270	11.5
O_2	450	7.0
N_2	250	6.7
He	Approximately 156	Approximately 40
Ar	233	7.6
Ne	186	3.0
Na vapor	335	0.4
CO_2	420	5.4

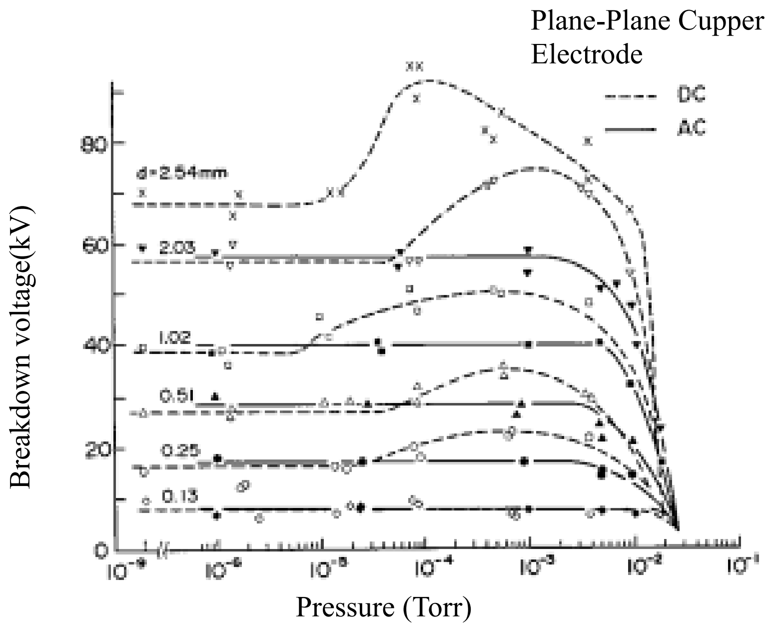


Figure III.2 Dependency of inter-electrode discharge voltage on pressure in vacuum [2]

III2 Issues and measures on hot launch

During the lift-off of a spacecraft, pressure in the unit sharply drops from the atmospheric pressure (approximately 760 Torr). Turning on the power supply mounted in the unit under those conditions, may cause a discharge according to Paschen's law, depending on a level of voltage. Usually, the gas in the unit is thought to be air. According to Table III.1, conditions to produce a voltage at 330 V or higher should be avoided.

References

[1] The Institute of Electrical Engineers of Japan, Discharge Handbook Publishing Committee, “Discharge Handbook” (Ohmsha) (2003)

[2] R.V.Latham, “High Voltage Vacuum Insulation: The physical Basis”, (Academic Press, Inc.) (1981)

[3] Otori, Sekiguchi, Kono, “Ionization Gas Study”, (The Institute of Electrical Engineers of Japan) (1969)

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Appendix IV Creeping distance and discharge voltage

IV1 Creeping distance and discharge voltage [1]

Creeping discharge is significantly influenced by the alignment of electrodes. The cases are roughly divided into those on a dielectric with back electrode and those without a back electrode.

(1) Cases without a back electrode

In the atmosphere, generally, flashover characteristics are similar in most cases to those of metal electrodes in the air. Therefore, a creeping flashover voltage can be expected on the basis of the data, or creeping distance can be found in the reverse. However, it may be more complex if the distortion of electric field is significant due to the existence of a dielectric, or if surface conditions are difficult. In general, in many cases, a creeping flashover voltage drops sharply due to dirt, damage or moisture on the dielectric surface, under conditions of utility frequency voltage and direct current. Sufficient margins must be given.

(2) Cases with a back electrode

Since these conditions are extremely complex, a flashover may occur at an unexpected distance. Extra attention must be paid in the design phase. Flashover voltages when applying a sharp rising impulse voltage span a significant range, and are well approximated by either of the following two equations. In other words, setting a creeping flashover voltage as V [V], a specific capacitance as C_0 [F/m] ($C_0 = \varepsilon/d$, ε: Dielectric constant of dielectric, d: Thickness of dielectric), a creeping distance as l [m], and a wave front steepness of a voltage as dV/dt [V/s]:

$$V = \frac{K_b}{\sqrt[8]{{C_0}^3}} \cdot \sqrt[5]{l} \qquad \text{(IV.1)}$$

Where, K_b is 73.6 against a positive impulse voltage and is 74.25 against a negative impulse voltage.

$$V = \frac{K_d}{\sqrt[5]{C_0}\sqrt[20]{\dfrac{dV}{dt}}} \cdot \sqrt[5]{l} \qquad \text{(IV.2)}$$

Where, K_d is 135.5 against a positive impulse voltage and is 139.5 against a negative impulse voltage.

(a) Influence of creeping distance

As shown in Figure IV.1, and Figure IV.2, a longer creeping distance does not necessarily lead to a rise of creeping flashover voltage. In the figure, the solid line indicates the calculation by equation (IV.1), and the dotted line indicates the calculation by an equation (IV.1). The circles indicate experimental values.

(b) Influence of dielectric constant

As shown in Figure IV.1, a greater dielectric constant leads to a drop of the creeping flashover voltage.

(c) Influence of dielectric thickness

As shown in Figure IV.2, increasing thickness is effective in increasing a creeping flashover voltage.

(d) Influence of specific capacitance

Figure IV.3 shows the relation between impulse creeping flashover voltages and specific capacitances. On the basis of the gradient of the line, an index of specific capacitance C_0 in the equation above is found to be -0.4. The glass in Figure IV.3 is fiberglass.

(e) Comparison of creeping discharge characteristics between air and a vacuum environment

Table IV.1 indicates creeping flashover voltages using various spaces. Figure IV.4 shows the dependency of streamer length on pressure, found on the basis of a creeping discharge figure. It indicates that a streamer length changes in proportion to the reciprocal of atmospheric pressure. In addition, at the same voltage, a drop of atmospheric pressure leads to a higher rate of developing a creeping streamer.

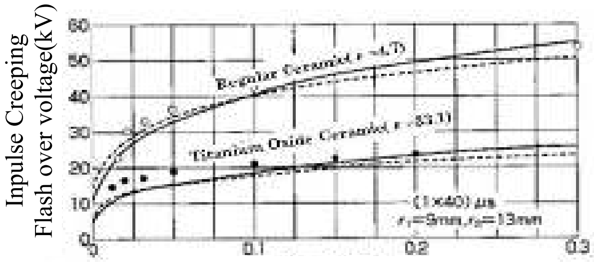

Figure IV.1 Influence of dielectric constant of dielectric (r1: Inner diameter, r2: Outer diameter)

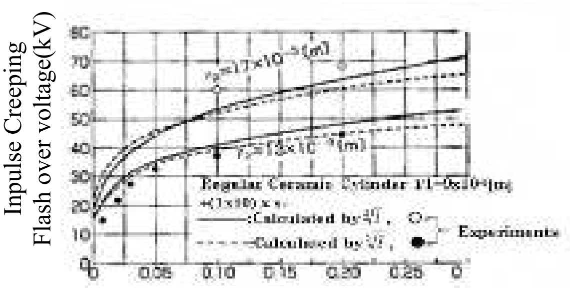

Figure IV.2 Influence of thickness of dielectric (r1: Inner diameter, r2: Outer diameter)

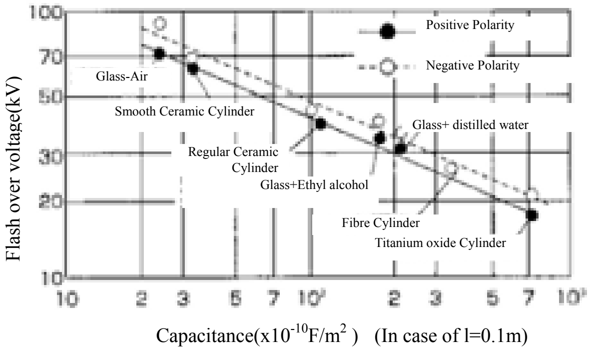

Figure IV.3 Relation between creeping flashover voltage and specific capacitance

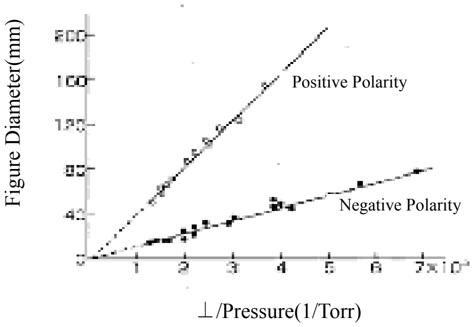

Figure IV.4 Relation between pressure and streamer length (diameter/2)

Table IV.1 Creeping discharge characteristics in vacuum and in air (Electrode: Stainless-steel SUS)

Material	Relative permittivity εr	Lengthof Spacer (mm)	Spacer Diameter (mm)	Vacuum (10^{-6}Pa) BreakdownElectricField (kV/mm)			Air (10^{-5}Pa) BreakdownElectricField (kV/mm)		
				DC	Inpulse 1.2/50μs	AC (peak)	DC	Inpulse 1.2/50μs	AC (peak)
Teflon	2.1	2.0 4.0	7.0 7.0	16.0 10.9	15.1 10.3	12.8 8.5	2.75 2..45	2.80 2.50	2.80 2.45
Plastic Glass	3.2	4.0	7.0	12.0	12.3	9.9	2.25	2.37	2.55
Quartz	3.8	5.0 6.5	9.5 9.5	8.6 8.2	8.6 8.3	7.8 7.1	2.9 2.7	2.9 2.7	2.7 2.7
Pyrex Glass	4.6	2.0 4.0	6.35 6.35	16.5 11.5	15.5 11.1	14.0 9.9	3.75 2.36	3.75 2.45	3.75 2.63
Ceramic	5.8	2.0 4.0	7.0 7.0	16.6 12.6	16.2 12.5	14.25 10.25	2.50 2.50	2.50 2.45	2.75 2.63
Sapphire	12.0	3.1	12.55	9.0	8.4	7.3	1.81	1.87	1.94

IV2 Concept of preventing creeping surface discharge

In general, a creeping barrier is used to prevent a creeping discharge. A creeping barrier, as shown in Figure IV.5, is composed of the insulation base with a surface on which the originally creeping discharge develops, and a creeping barrier installed approximately perpendicular to the base, which is called a “shade” or a “pleat.” The insulation base, in practical application, corresponds to the “core” of a support insulator or the “shell” of bushing. An electrode covering the insulation base mounted on one side is called a back electrode. A support insulator has no back electrode, although it corresponds to the core electrode of a bushing. In general, a creeping discharge is likely to be longer in a structure with a back electrode. From viewpoint of practical insulation, increasing the distance in creeping direction still leads to a drop in the discharge voltage.

Also, it is effective to cover the whole creeping electrodes with coating. However, enough consideration must be taken to prevent the enclosure of a layer of air or the occurrence of cracks due to its thermal history.

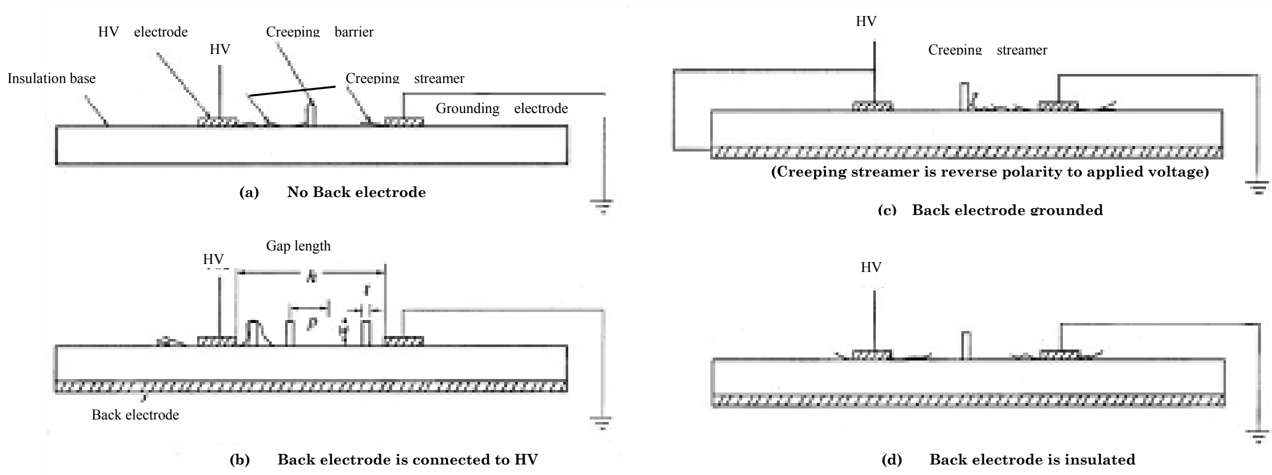

Figure IV.5 Example of barrier insulation structure

References

[1] The Institute of Electrical Engineers of Japan, Discharge Handbook Publishing Committee, “Discharge Handbook” (Ohmsha) (2003)