Chapter 3 High Voltage Outdoor Insulation and Surface Discharge

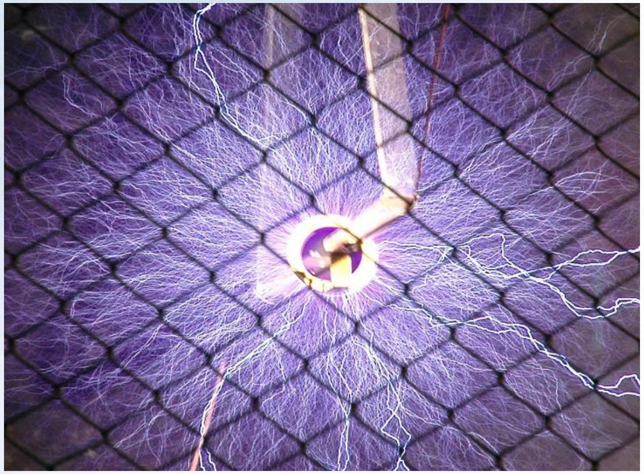
Core concepts of this chapter:

Atmospheric correction, high-voltage insulators,
outdoor insulation, surface flashover, sliding spark discharge,
pollution flashover, hydrophobicity transfer,
(silicone rubber) polymeric outdoor insulation

;

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

- Gas discharge is a unique phenomenon of gas under high voltage and high electrical stress



- For the study of high-voltage discharge, *starting* from the observation, and confirmation of physical phenomena, *then* analyze the reasons, speculate on the results, verify the conclusions, and *finally* determine the causal relationship between the test conditions and the discharge phenomenon
- For a given high-voltage insulation structure and its insulation materials, analyze and predict the possible discharge positions and characteristics under different high voltages, and point out possible improvement measures
- Surface discharge is a discharge that occurs at the gas-solid interface and is related to the characteristics of the gas, the surface and volume characteristics of the solid dielectrics, and the gas-solid field structure

Three types of factors…

- The discussion on discharge at the gas-solid interface is also a good reference for surface discharge at the liquid-solid interface

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

According to the position of the solid medium between electrodes, three types of electric field configurations (structures) are formed:

- Uniform electric field
- Extremely non-uniform electric field with weak vertical components
  (such as post insulators)
- Extremely non-uniform electric field with strong vertical components
  (such as bushing, motor output line, cable terminals)

The flashover voltage along the solid surface is much lower than the breakdown voltage of pure air gaps or pure solid structure.

Uniform electric field

Extremely non-uniform electric field with weak vertical components

Extremely non-uniform electric field with strong vertical components

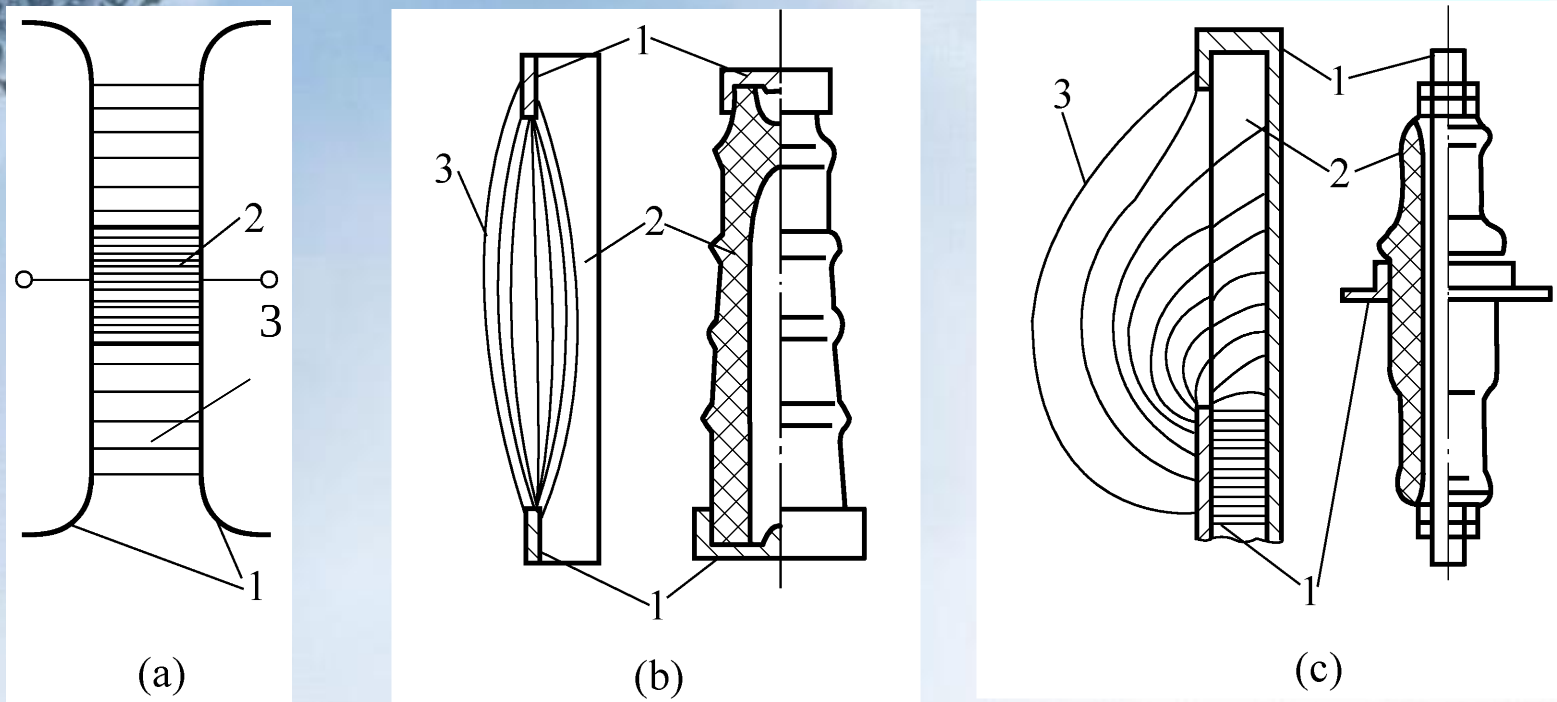


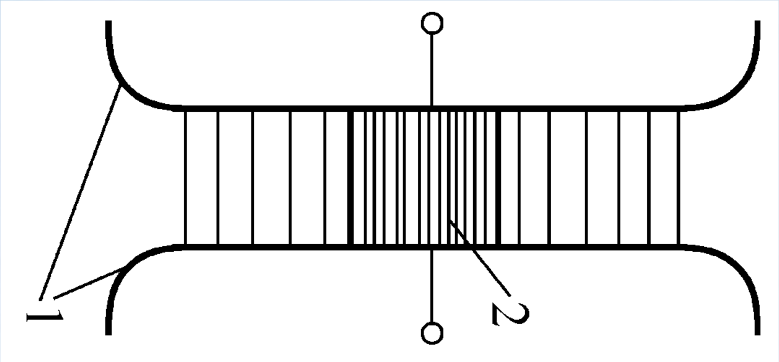
Figure 3-5: Several typical electrode configurations of solid dielectrics in electric field

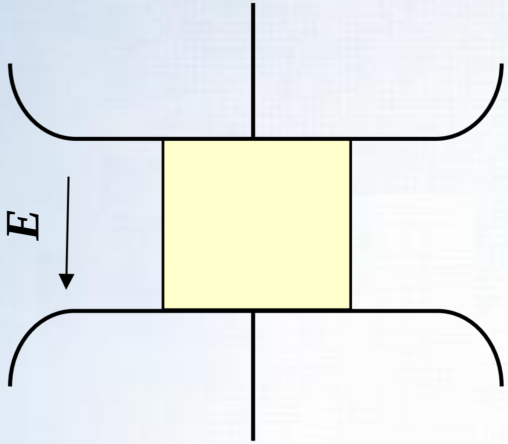
(a) Uniform field, with the direction of field strength parallel to the solid surface;
(b) Extremely non-uniform field, field direction is generally parallel to solid surface;
(c) Extremely non-uniform field, field direction is with a large angle to solid surface;
1- Electrode; 2- Solid dielectric; 3- Electric displacement line

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

(1) Surface discharge in a uniform electric field

Where the discharge will occur?
What is the impact of the solid block on gap discharge voltage?



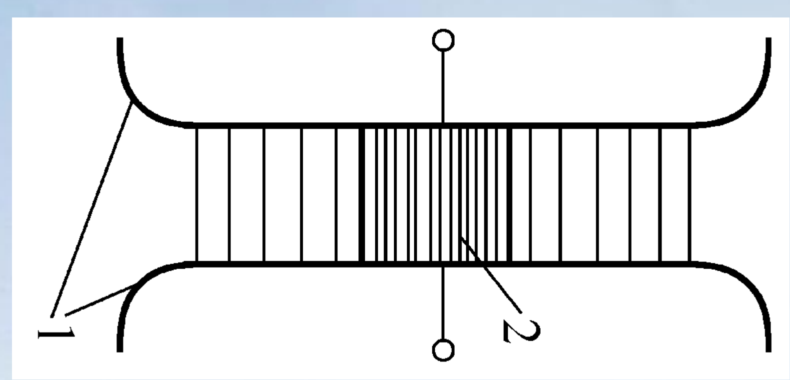


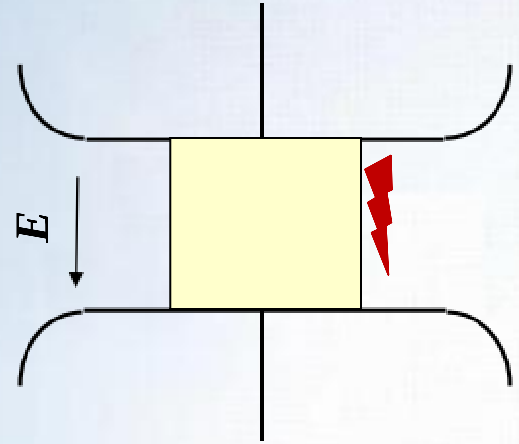
Are there any changes on the discharge when a solid dielectric block is placed into a uniform electric field?
(The breakdown strength of solid dielectrics is usually much higher than that of air)

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

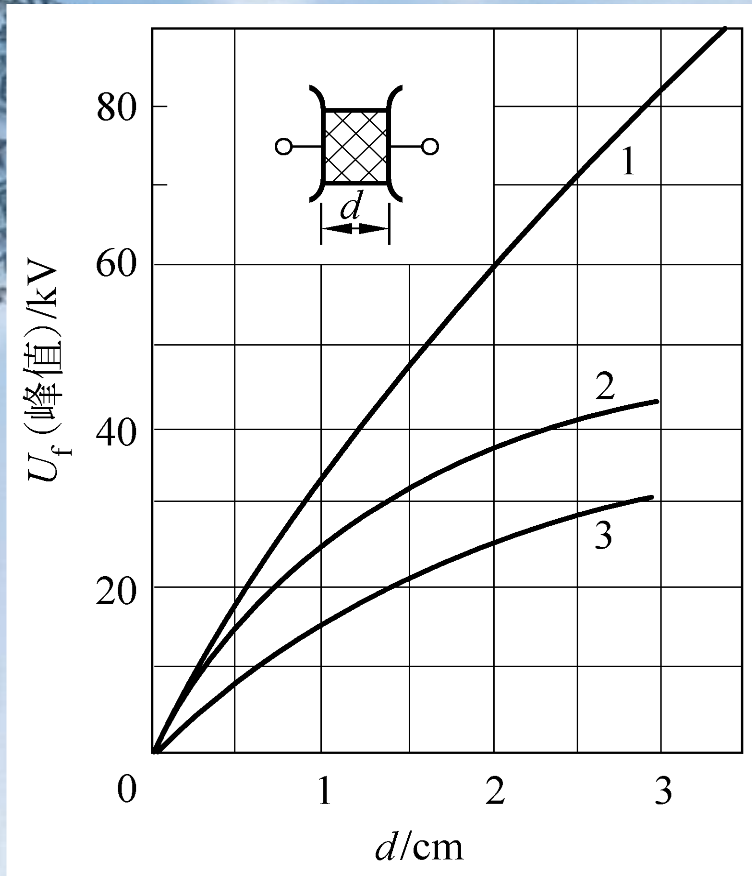
(1) Surface discharge in a uniform electric field

Where the discharge will occur? What is the impact of the solid block on gap discharge voltage?





The flashover voltage along the surface is much lower than the breakdown voltage of pure air gaps or pure solid structure



1- Air gap breakdown
2- Surface flashover under lightning impulse voltage
3- Surface flashover under AC voltage

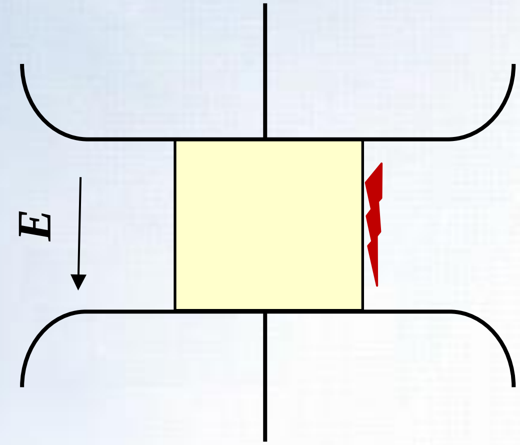


Figure 3-6: Flashover voltage vs flashover distance in air along the glass surface in the uniform field

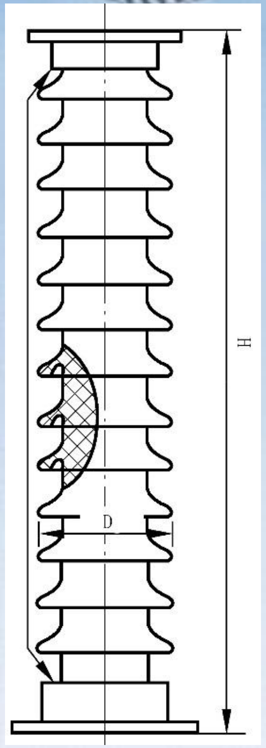
Why?
What factors affect it?

The flashover voltage along the surface is much lower than the breakdown voltage of pure air gaps or pure solid structure

Improving the contacting of electrode and insulation material, improving surface water resistance (hydrophobicity) are helpful to increase the surface flashover voltage

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

(2) Surface discharge in extremely non-uniform electric fields with weak vertical components



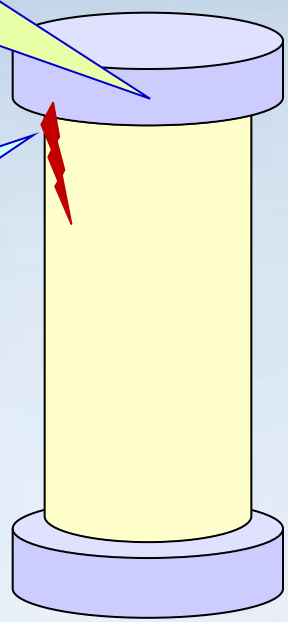
Post insulators: supporting equipment, high-voltage busbar

Electric field characteristics: In most areas, stress lines are generally parallel to insultaor surface

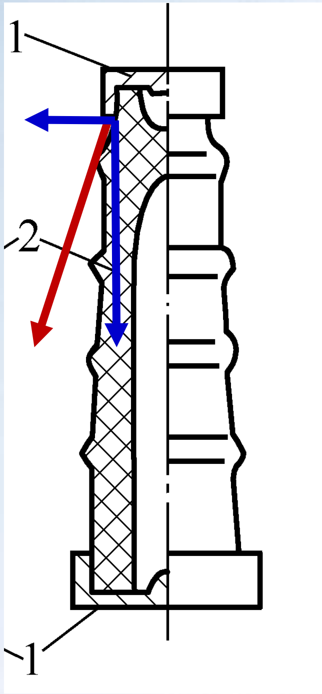
3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

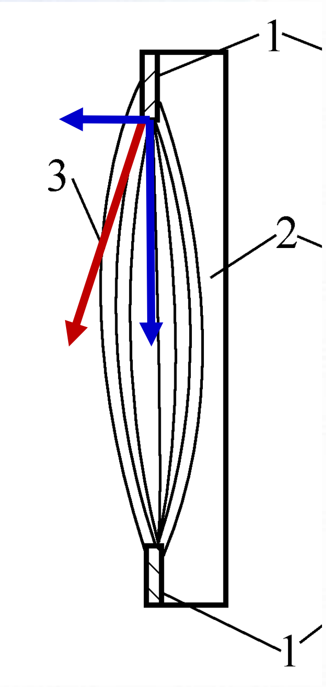
(2) Surface discharge in extremely non-uniform electric fields with weak vertical components

Where the discharge will occur? What is the impact of the solid block on gap discharge voltage?

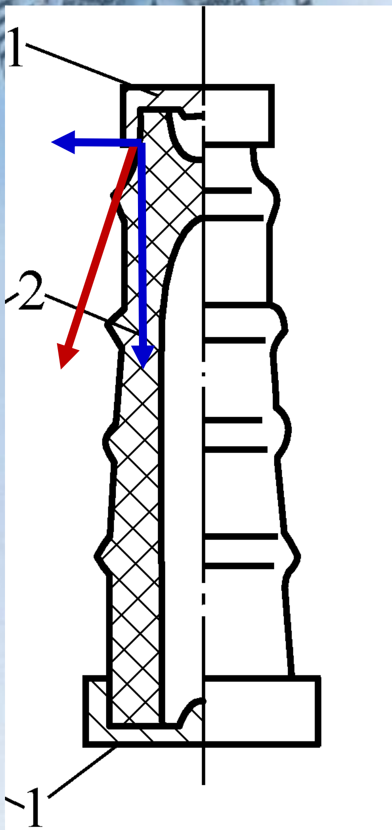


Field stress at the connection area between the high field stress electrode and the dielectric is mainly the tangential component
The vertical component perpendicular to the solid surface is relatively small

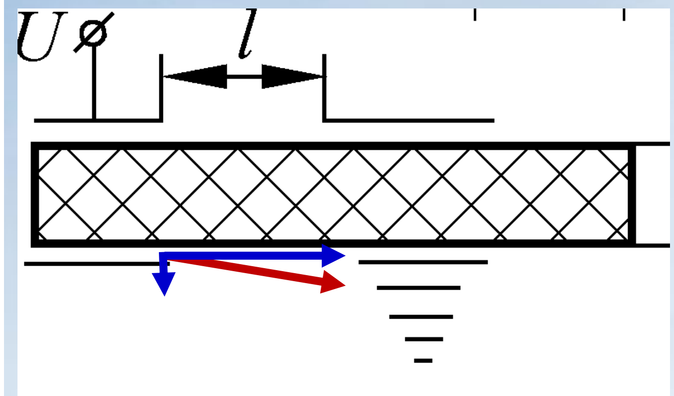




The flashover voltage along the surface is much lower than the breakdown voltage of pure air gaps or pure solid structure



Extremely non-uniform field, field direction is generally parallel to solid surface



Why?
What factors affect it?

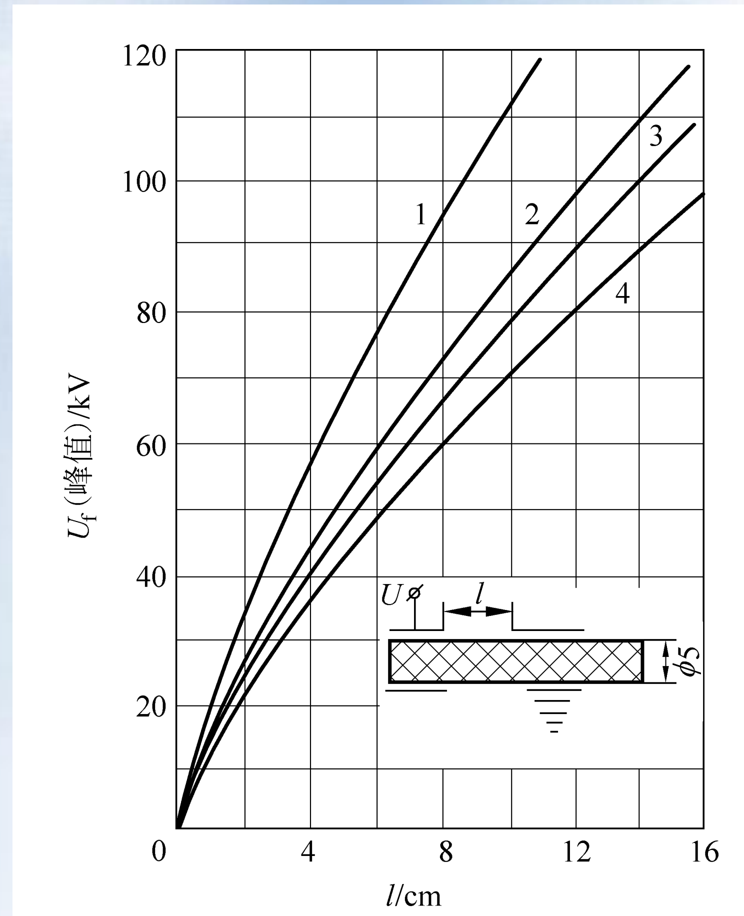


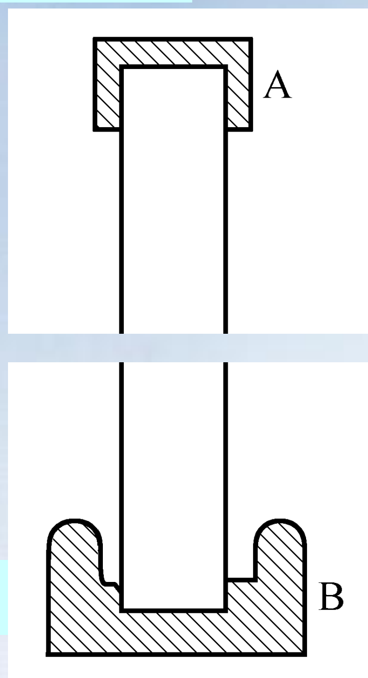
Figure 3-7: Power frequency flashover voltage vs flashover distance along the surface in extremely non-uniform field

1- Pure air gap; 2- Paraffin wax
3- Resin immersed paper;
4- Porcelain or glass

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

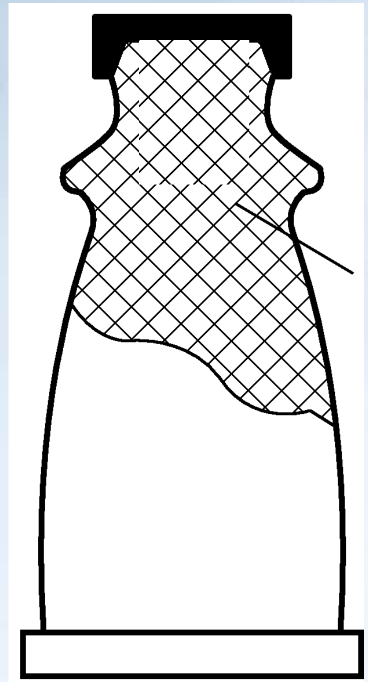
(2) Surface discharge in extremely non-uniform electric fields with weak vertical components

A:Unshielded

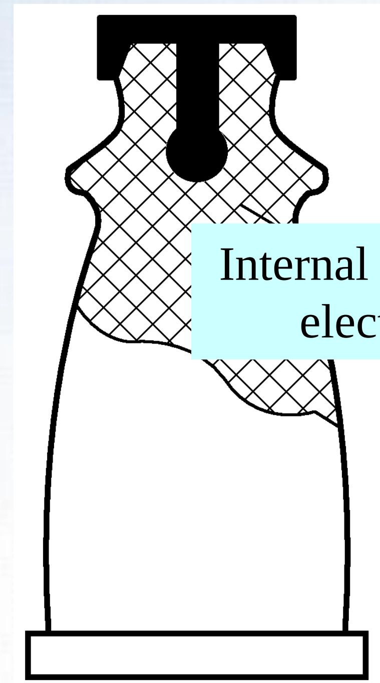


B:Shielded

Without internal shielding



With internal shielding



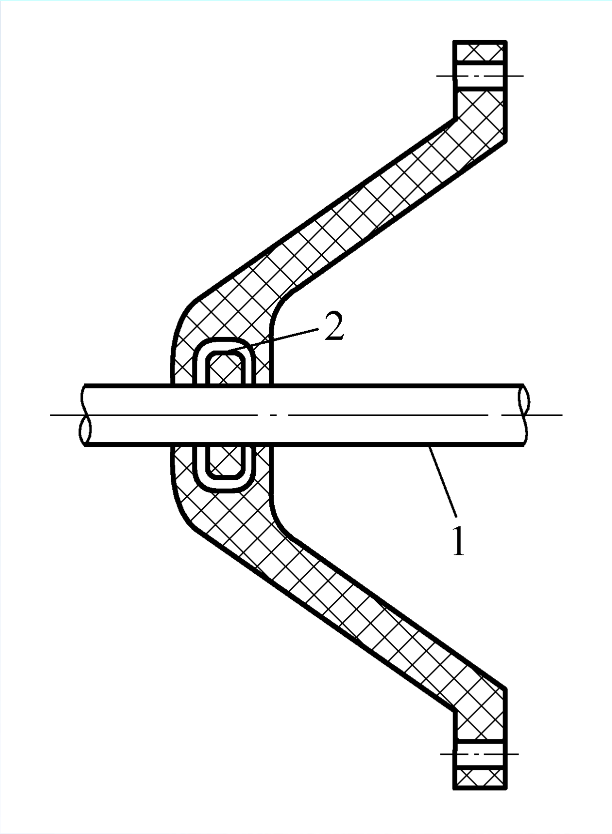
Internal shielding electrode

The use of shielded electrodes to increase the surface flashover voltage
(How does the above electrodes shield the original high stress area?)

3.3 Surface flashover of insulators (discharge on clean and dry surfaces)

(2) Surface discharge in extremely non-uniform electric fields with weak vertical components

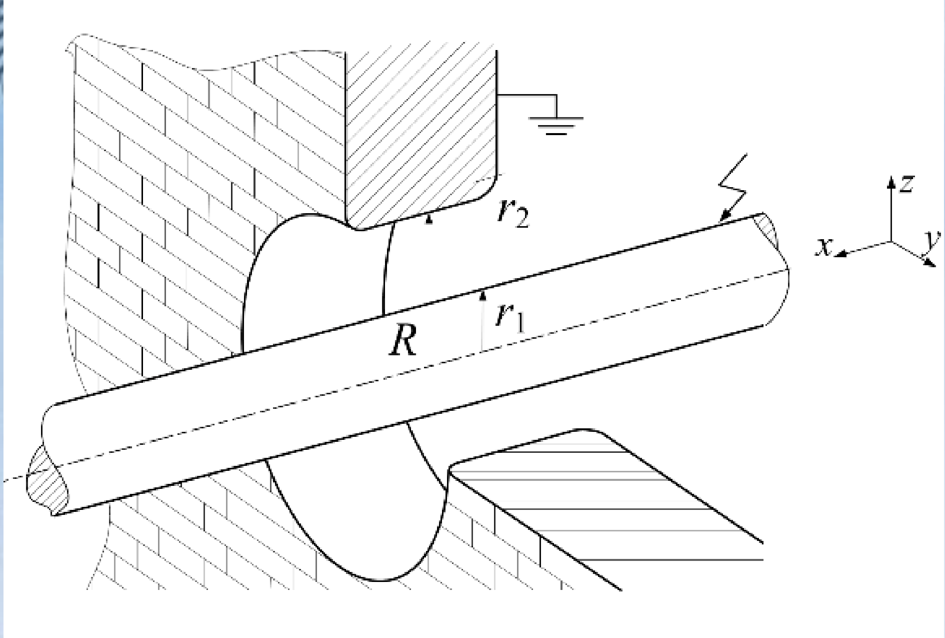
Internal shielding electrode of basin insulator

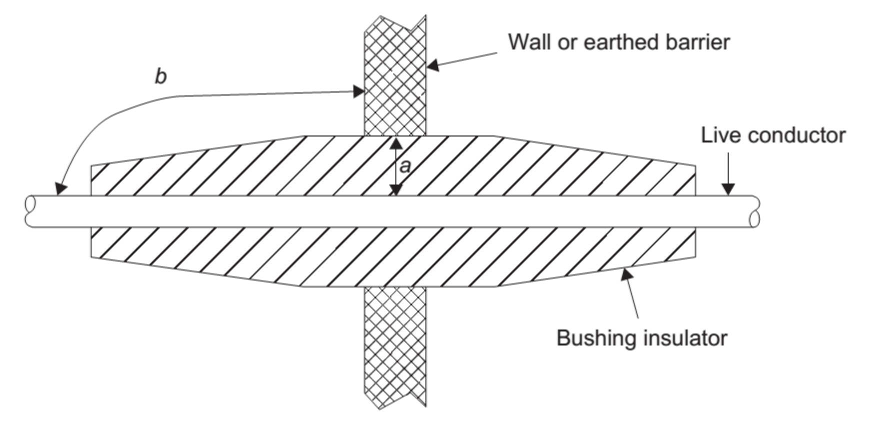


The use of shielded electrodes to increase the surface flashover voltage

(How does the above electrode shield the original high stress area?

(3) Surface discharge in extremely non-uniform electric fields with strong vertical components





Cross-section of high-voltage conductor cylinder passing through a grounded wall

When high-voltage conductor pass through a grounded wall or a grounded equipment enclosure, a specific "high-voltage bushing" is required

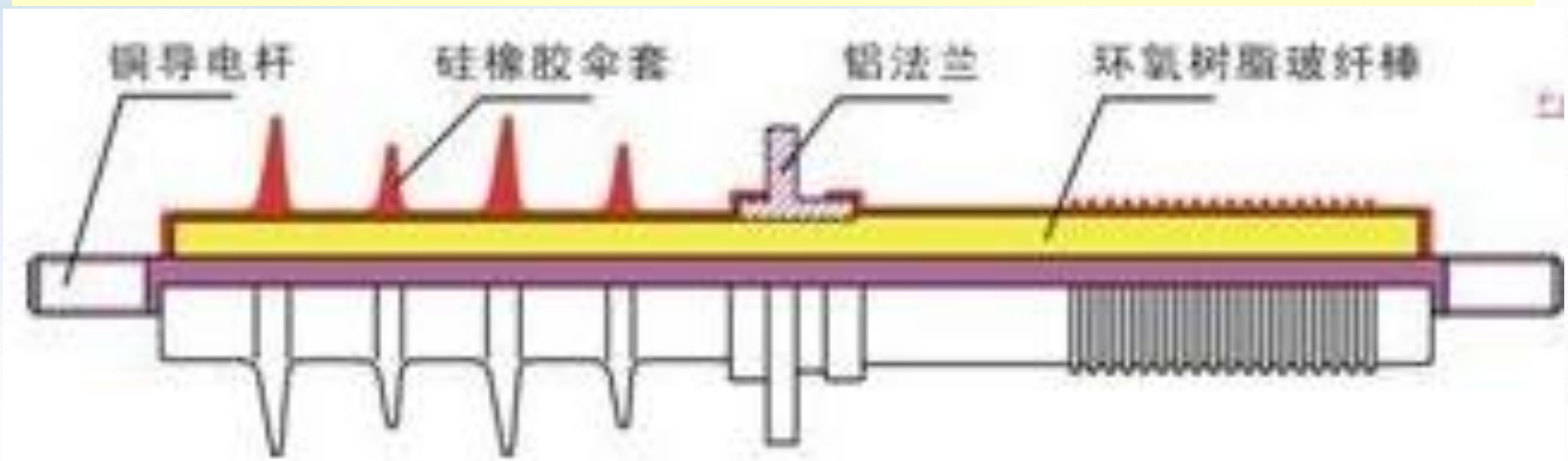
Classified by function:
Wall bushing
Transformer bushing
GIS bushing

Classified by outdoor insulation materials:
Porcelain bushing
SiR composite bushing

Classified by internal insulation materials:
SF_6 bushing
Oil filled bushing
Oil or Resin immersed paper bushing (OIP or RIP)
(Capacitive bushing)

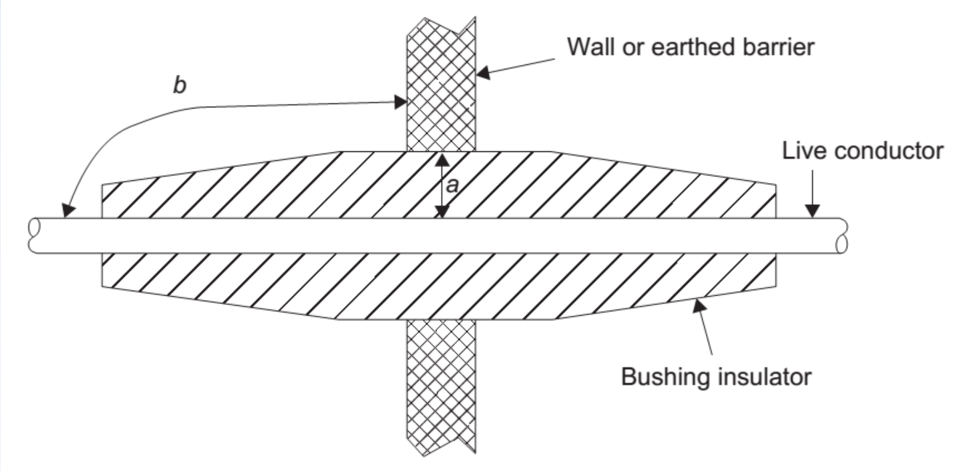
Wall Bushing

The electric field in the flange area is most concentrated, and the electric field line is generally perpendicular to the surface of the solid insulating material



When designing a bushing, what is the expected discharge voltage along path a or b?

- A $U_a >> U_b$
- B $U_b >> U_a$
- C $U_a > U_b$(a little bit)
- D $U_b > U_a$(a little bit)
- E $U_b \approx U_a$

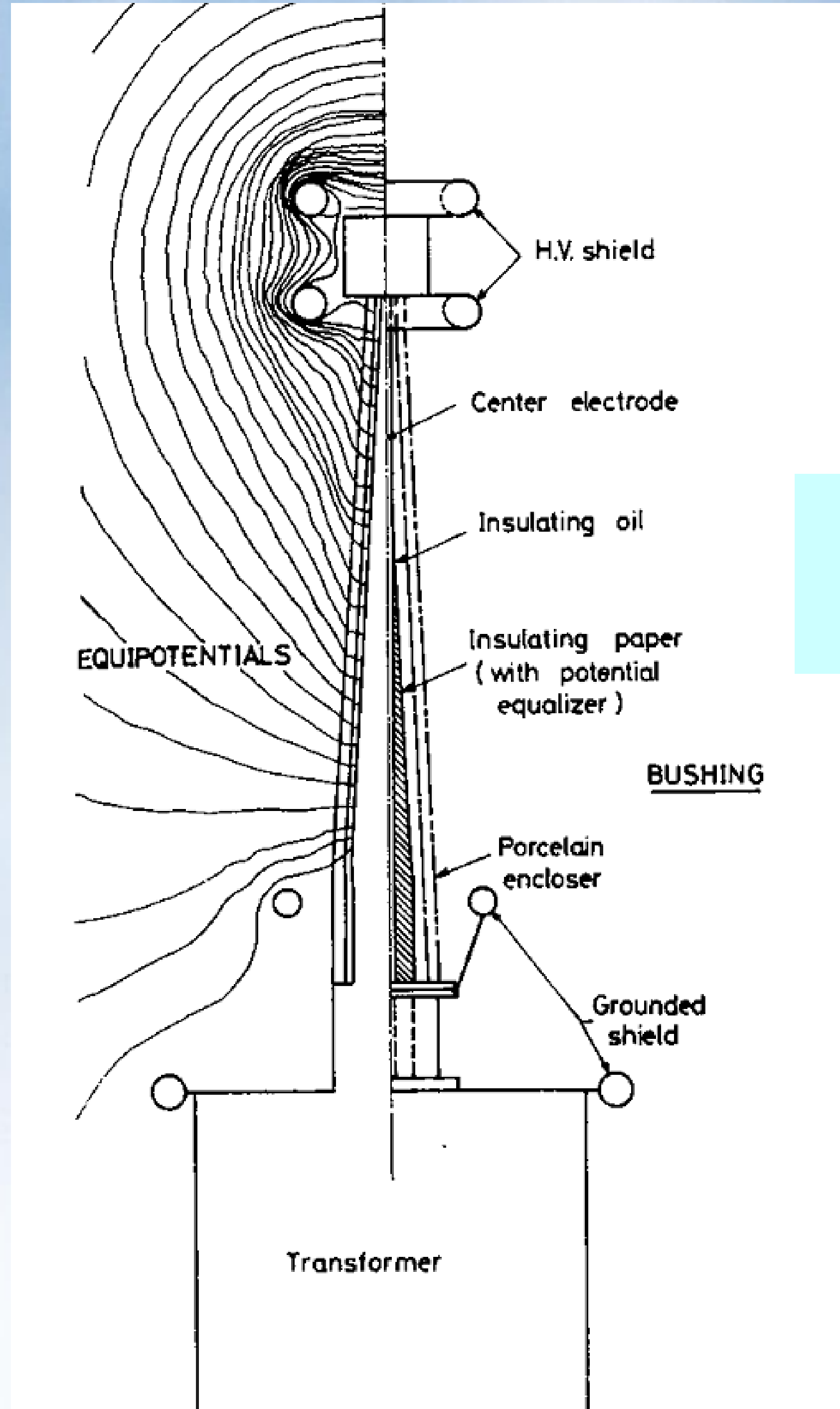


submit


±500kV
Wall Bushing

±800kV Wall Bushing

Hollow insulators for GIS bushing and surge arrester, post insulator



Transformer Bushing

500kV single-phase transformer

1000kV single-phase transformer

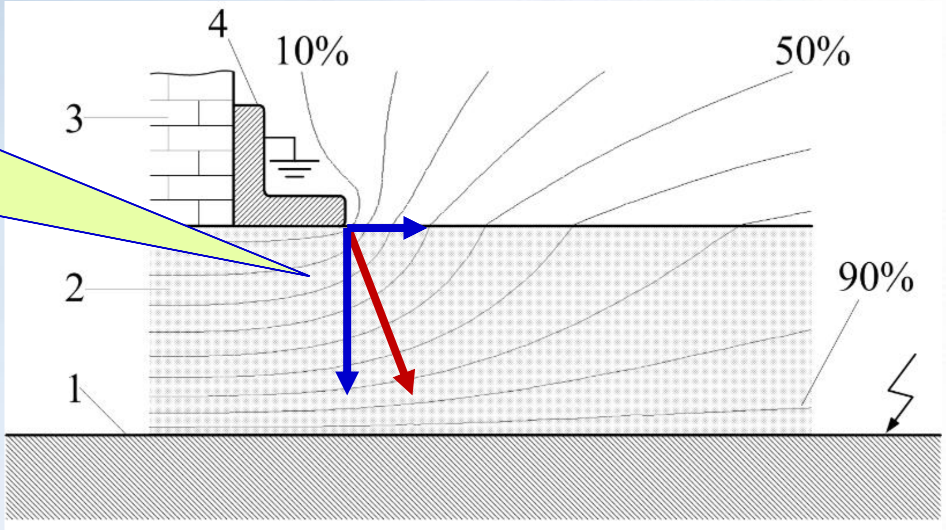
(3) Surface discharge in **extremely non-uniform** electric fields with **strong vertical components**

Electric field characteristics of bushing

(extremely non-uniform field with strong vertical components):

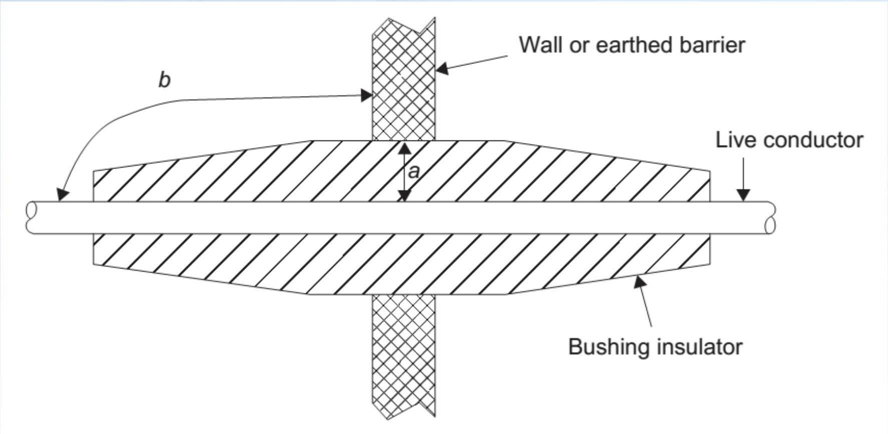
The electric field in the flange area is most concentrated, and the electric field line (stress line) is generally perpendicular to the surface of the solid insulating material

Field stress at the connection area (flange area) between the high field stress electrode and the dielectric is mainly the vertical component



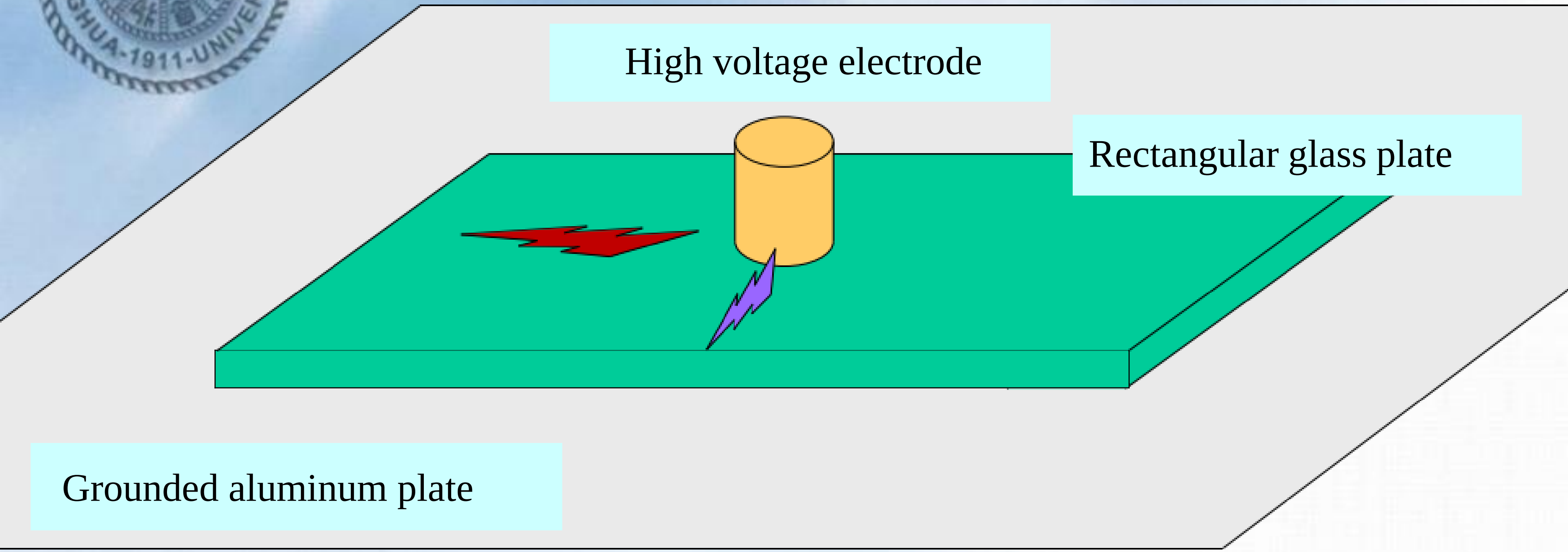
Simplified electric field structure for wall bushing near the flange area

1-High-voltage conductor rod; 2-Dielectric
3-Wall; 4- Grounded flange



HV conductor passing through a grounded wall

(3) Surface discharge in **extremely non-uniform** electric fields with **strong vertical components**



Electrode configuration for demonstration of sliding spark discharge

How different are the discharges in different directions in the demonstration experiment?

Watch the sliding spark discharge video

(3) Surface discharge in extremely non-uniform electric fields with strong vertical components

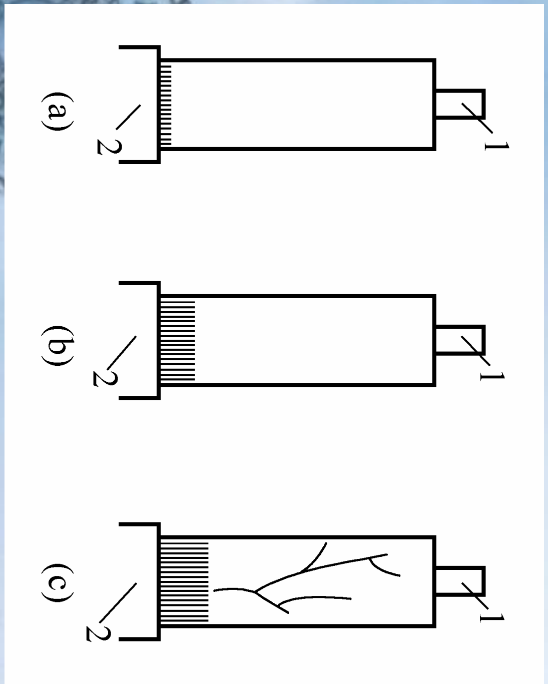
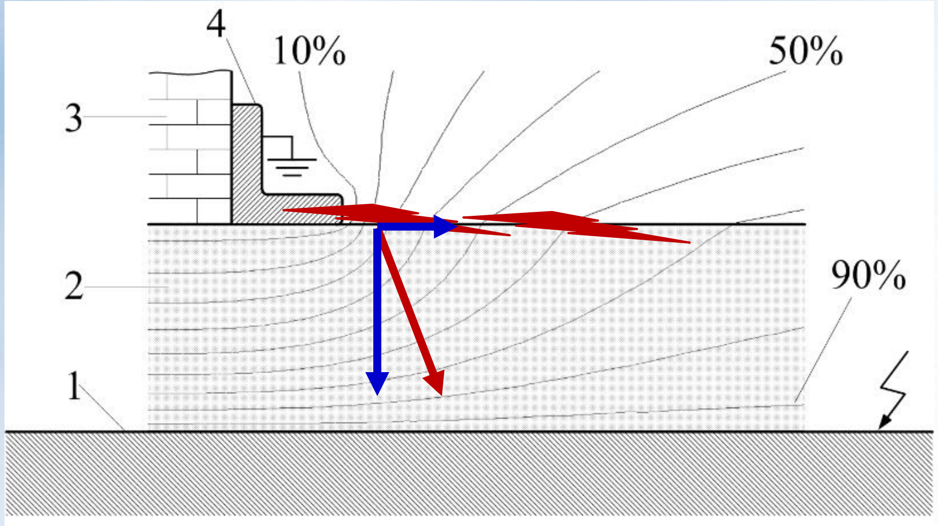


Figure 3-8 Development process of surface discharge under power frequency voltage

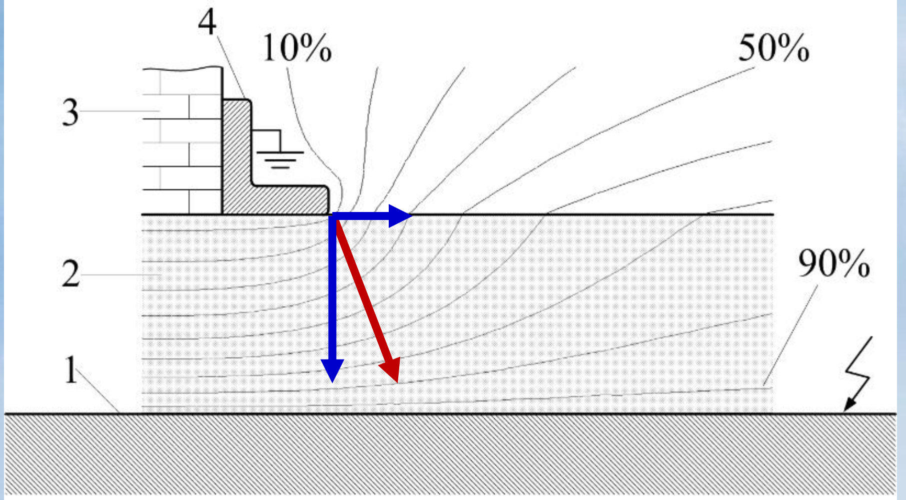
(a) Corona discharge
(b) Fine line glow discharge
(c) Sliding spark discharge



Simplified electric field structure for wall bushing near the flange area

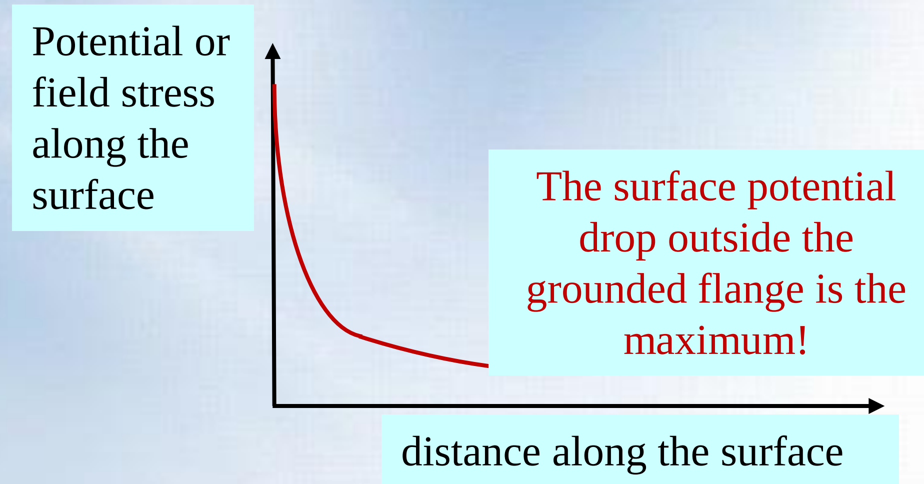
1- High-voltage conductor cylinder;
2- Dielectric;
3- Wall; 4- Grounded flange

See video of sliding spark discharge



Simplified electric field structure for wall bushing near the flange area

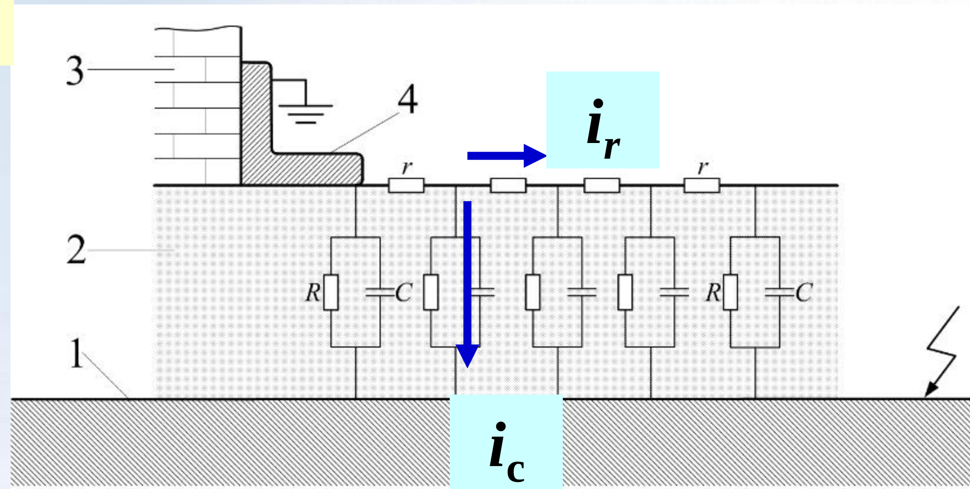
The surface field stress outside the grounded flange is the highest!



Field distribution along the bushing surface

Conditions for sliding spark discharge:

- The electric field with sufficient vertical and horizontal components
- The voltage is alternating



Equivalent circuit of wall bushing

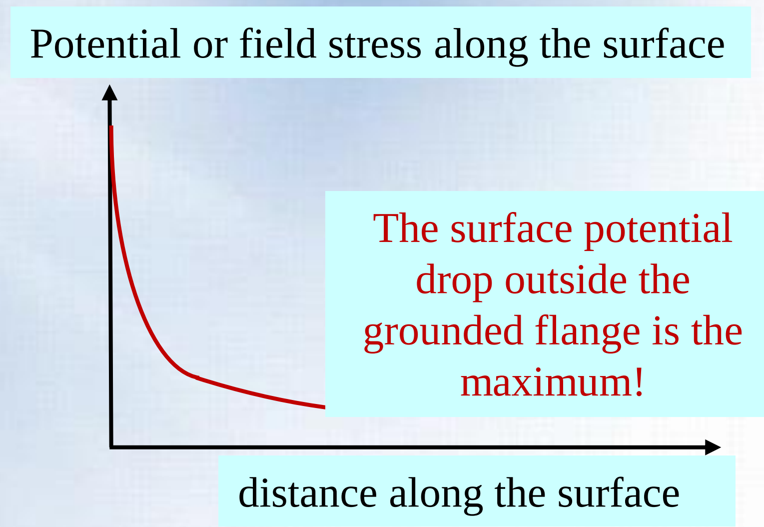
1-HV conductor; 2-Dielectric
3-Wall; 4- Grounded flange

The key to understanding sliding spark discharge:
The ratio of the radial capacitance current i_c outside the flange to the surface resistance current i_r

Relation between the initial voltage U_0 of sliding discharge and various parameters

$$U_0 = \frac{E_0}{\sqrt{\omega C_0 \rho_s}}$$

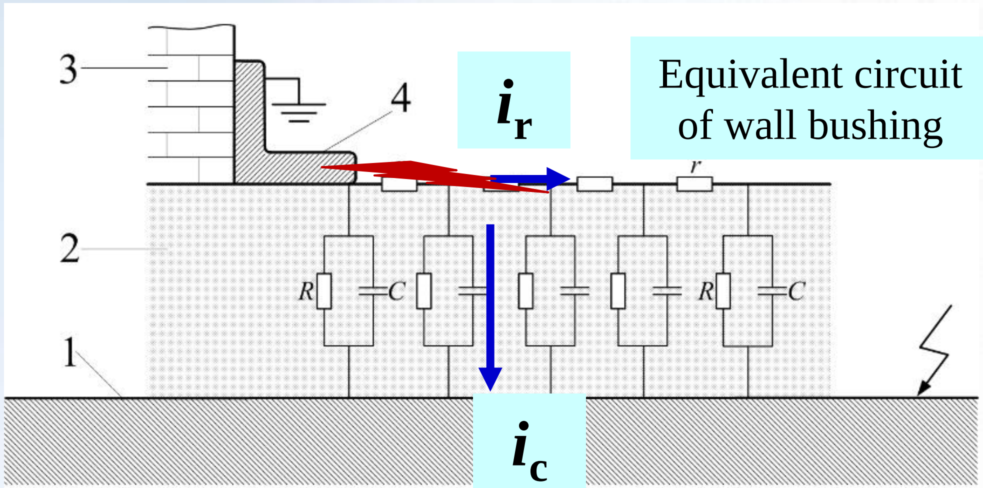
E_0: The initial field stress of sliding discharge
ω: angular frequency of applied voltage
C_0: specific surface capacitance
ρ_s: surface resistivity



Field distribution along the bushing surface

Specific surface capacitance refers to the capacitance value per unit area between the dielectric surface and another electrode

$$C_0 = \frac{\varepsilon_r}{4\pi \times 9 \times 10^{11} \times r_2 \ln \frac{r_2}{r_1}}$$



The criteria for sliding discharge: the electric field with sufficient vertical and horizontal components, and the voltage is alternating.

Factors affecting the voltage of sliding flashover discharge: voltage frequency, surface resistivity, insulation thickness, dielectric constant, distance along the surface？ …

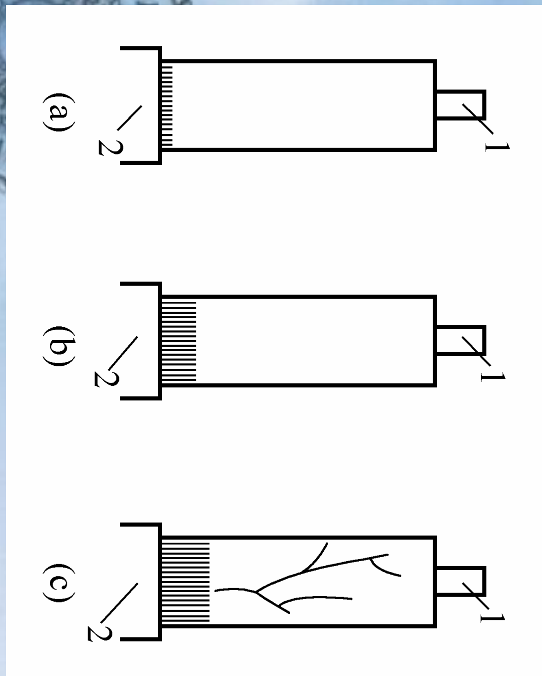
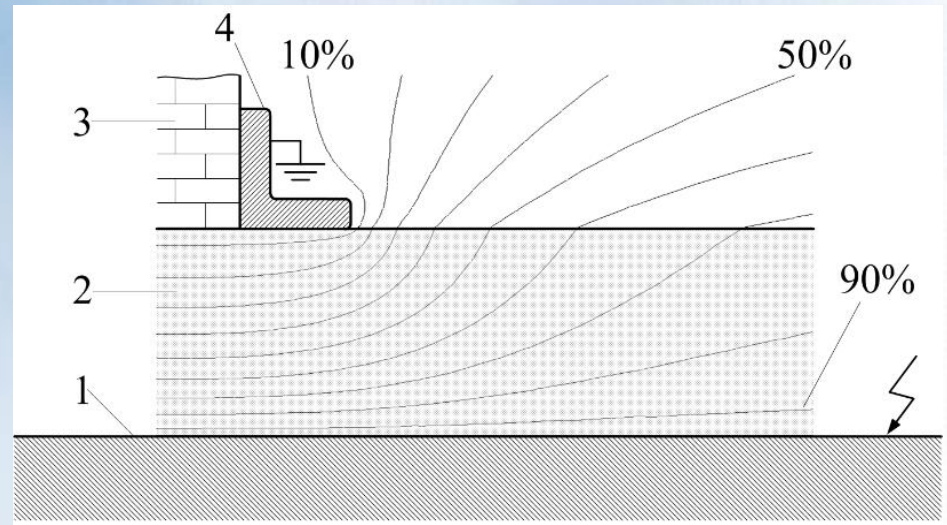


Figure 3-8 Development process of surface discharge under power frequency voltage

(a) Corona discharge
(b) Fine line glow discharge
(c) Sliding spark discharge



Simplified electric field structure for wall bushing near the flange area

1- High-voltage conductor cylinder;
2- Dielectric;
3- Wall; 4- Grounded flange

Think about sliding discharge videos again

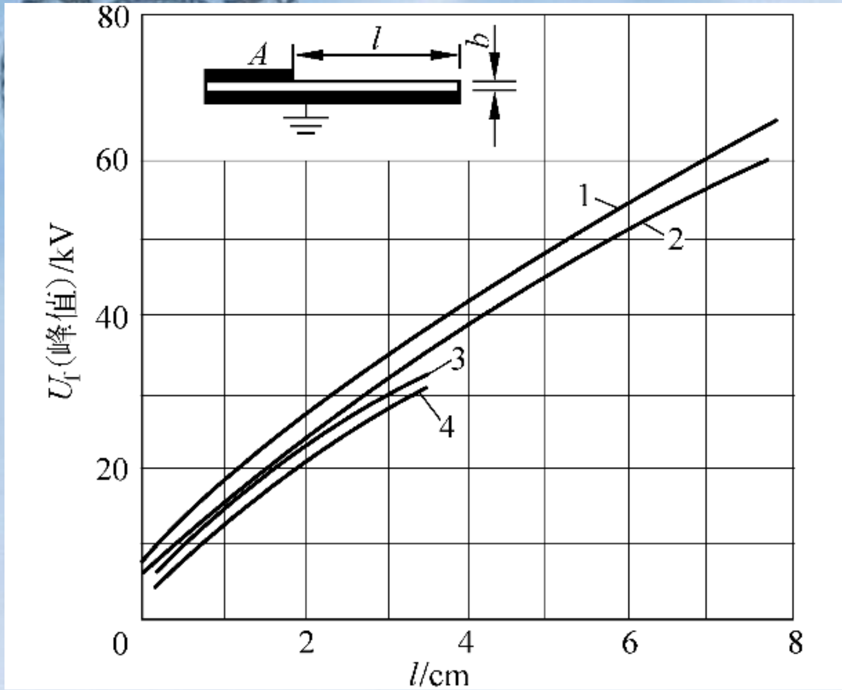


Figure 3-11 Relationship between DC surface flashover voltage and flashover distance of adhesive paperboard

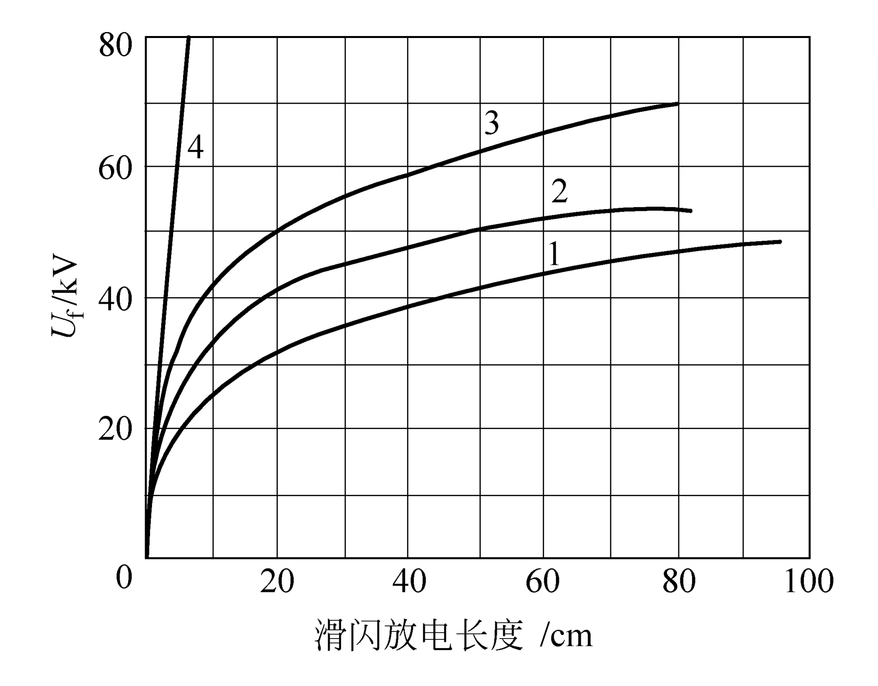


Figure 3-12 The length of sliding spark discharge along the surface of glass tubes vs the applied lightning impulse voltage

1,3-electrode A is positive; 1,2-b=4mm
2,4-electrode A is negative; 3,4-b=1mm

Glass tube, inner and outer diameters φ_1/φ_2 (cm):
1—0.85/0.97； 2—0.63/0.90； 3—0.60/1.01；
4—Air gap breakdown voltage

How the C_0 change?

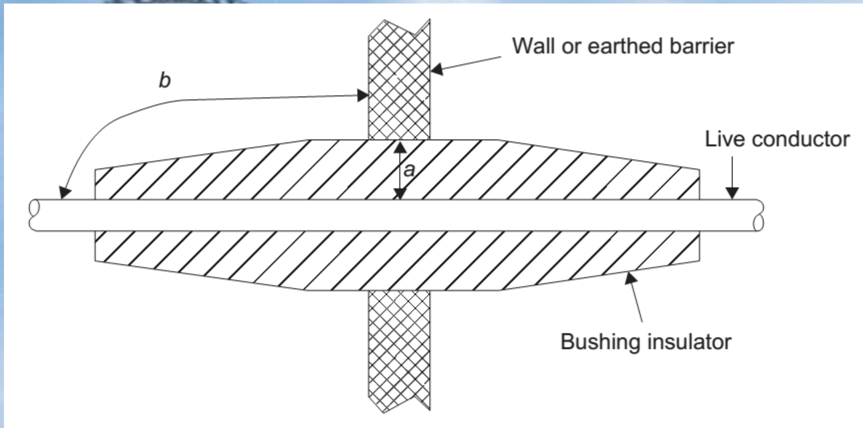


Figure 12.1 Non-condenser bushing

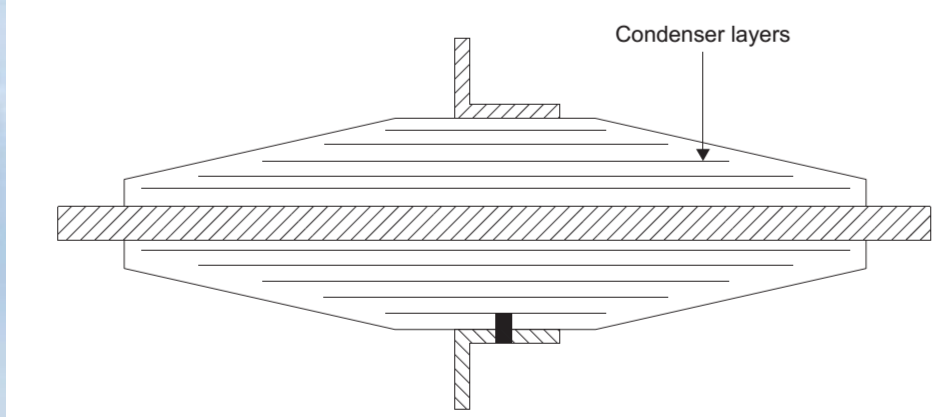


Figure 12.4 Condenser bushing

Using floating capacitance screen with different spacing and length across multiple layers to adjust radial and surface field stress

Without capacitance screen

With several capacitance screen

This type of bushing also known as capacitive bushing

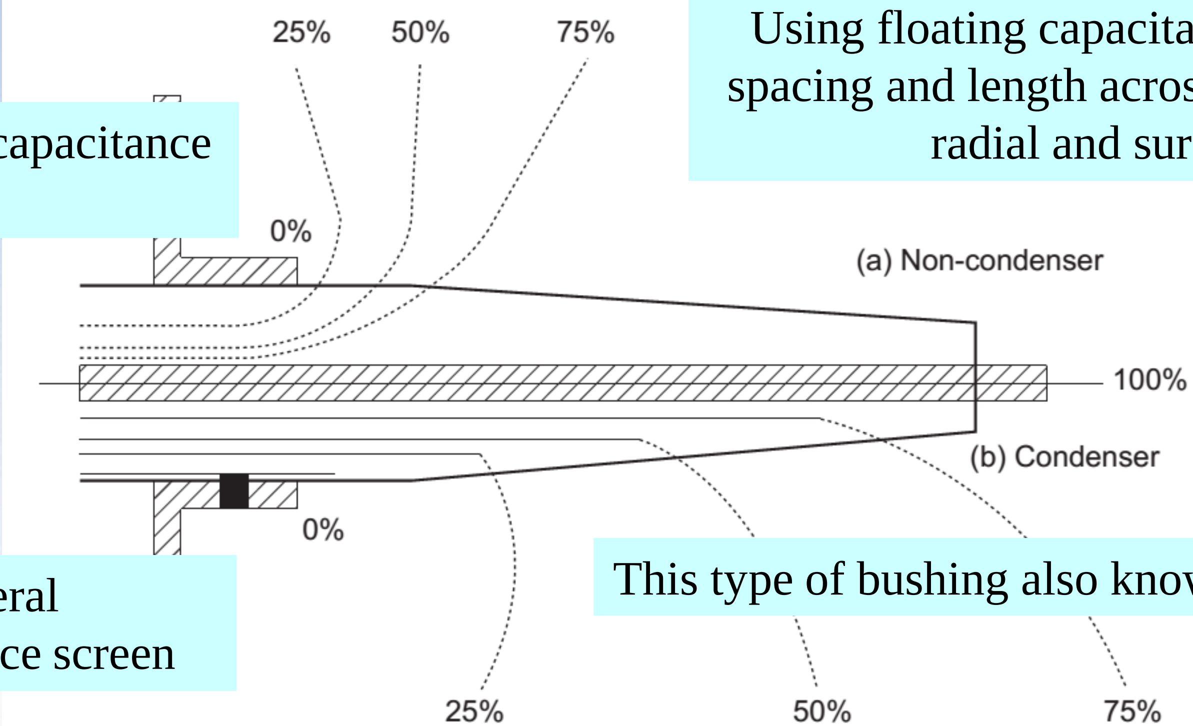
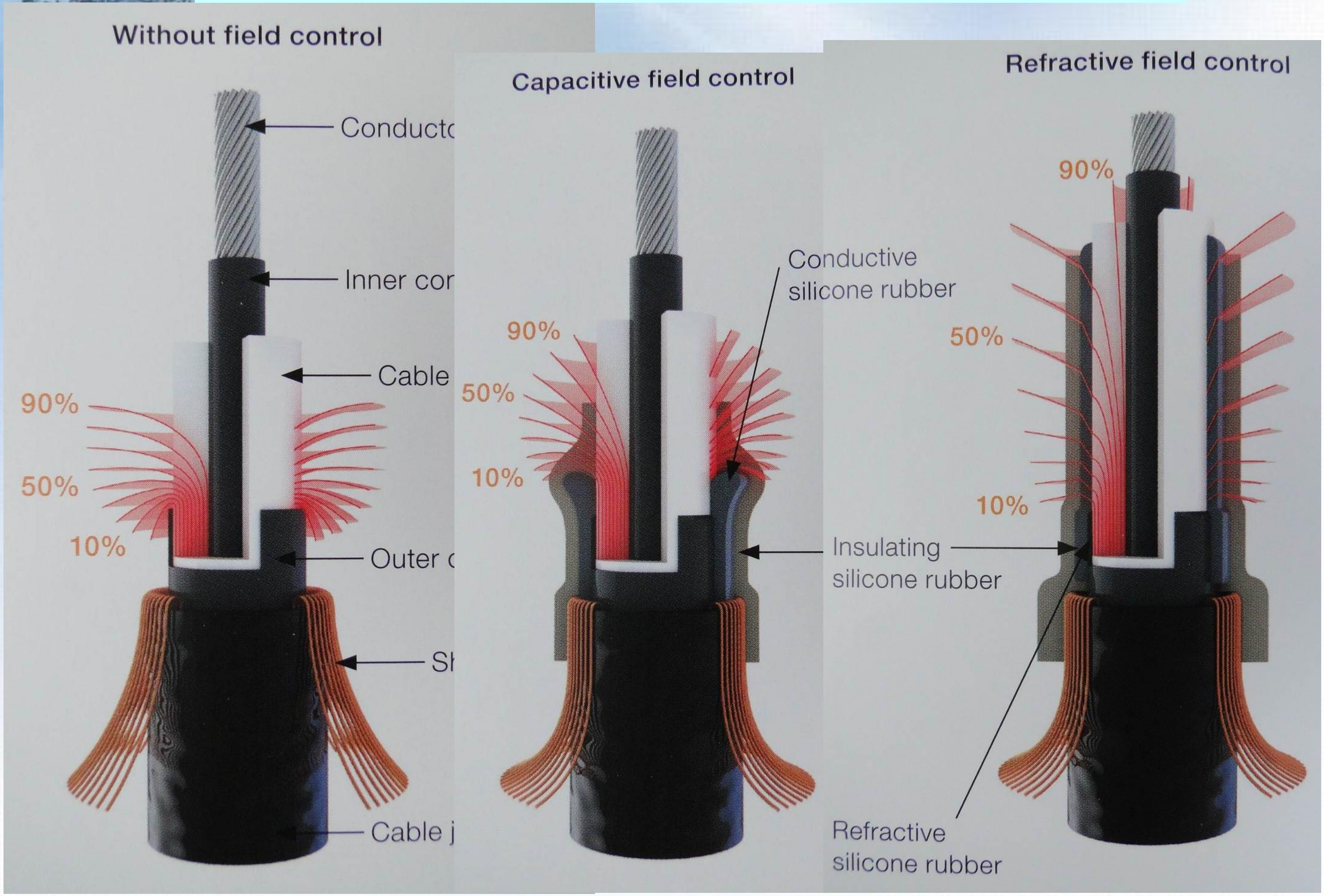


Figure 12.5 Field distribution in non-condenser and condenser bushings

Cable terminals can also use semiconductor "stress control layer" with specific shapes to control electric field



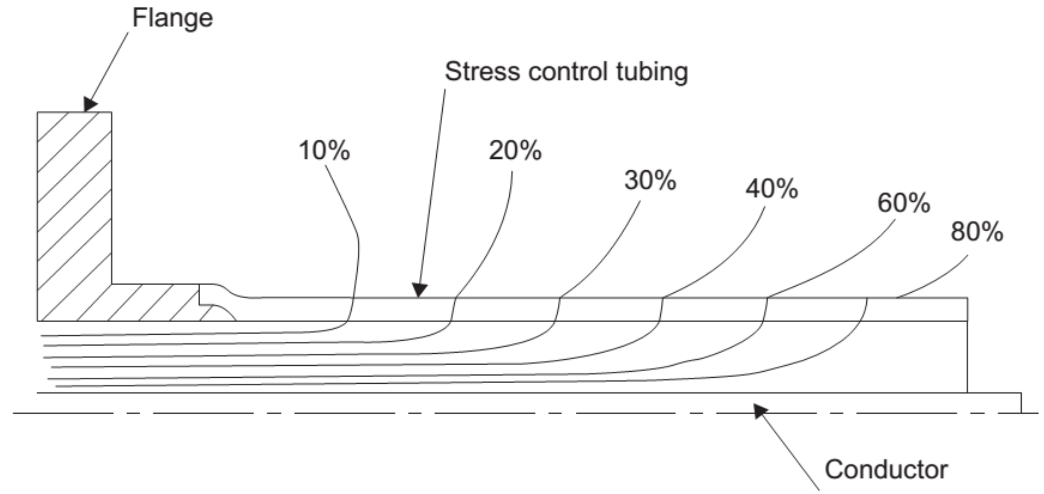


Figure 12.3 Stress control using heat-shrinkable stress control layer

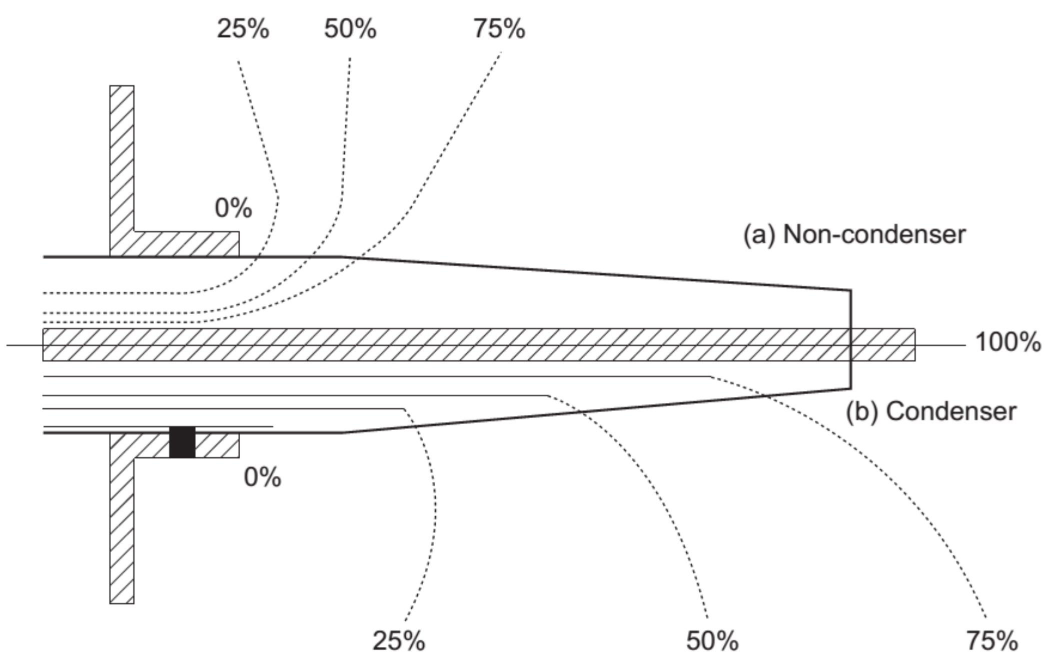


Figure 12.5 Field distribution in non-condenser and condenser bushings

Figure 4.26 *Photographs of bushing (courtesy Micafil, Switzerland). (a) Wall bushing, outdoor–indoor, rated 123 kV/1250 A. (b) Transformer bushing with 'dry' insulation, rated 170 kV a.c./630 A, BIL 750 kV*

Chapter 3 High Voltage Outdoor Insulation and Surface Discharge

3.1 The influence of atmospheric conditions on air gap discharge

3.2 High voltage outdoor insulation and high voltage insulators

3.3 Surface flashover of insulator

3.4 Rain flashover of insulator

3.5 Pollution flashover of insulator

Difficulties of students:
From a simplified theoretical model
to complex engineering practices

Core concepts of this chapter:
Atmospheric correction, high-voltage insulators,
outdoor insulation, surface flashover, sliding spark discharge,
pollution flashover, hydrophobicity transfer,
(silicone rubber) polymeric outdoor insulation

;

3.4 Rain flashover of insulators

Wet test : insulators subjected to high voltage together with a standard rain shower
water resistivity (100 Ωm at 20℃)
and rainfall (1-2mm/min)

the ratio of rain flashover to dry flashover voltage of cap-and-pin insulator:

Lightning impulse voltage:

$U_{rain}= (0.9\sim0.95)\ U_{dry}$

One minute power frequency voltage:

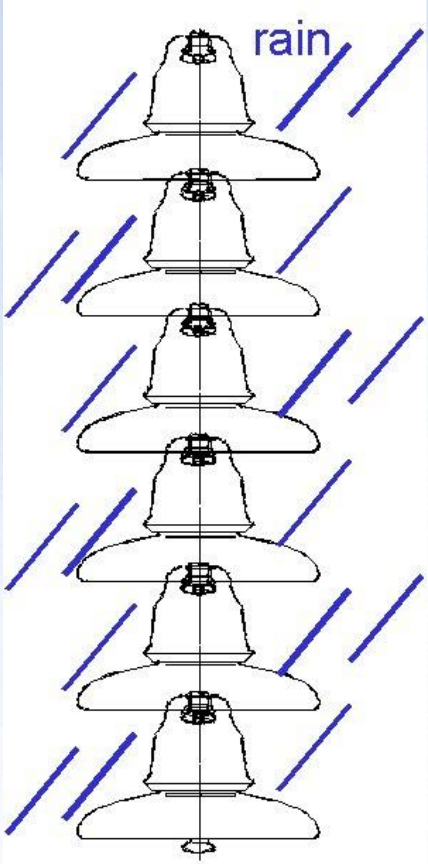
$U_{rain} = (0.50\sim0.72)\ U_{dry}$

One minute DC voltage:

$U_{rain} =(0.36\sim0.50)\ U_{dry}$

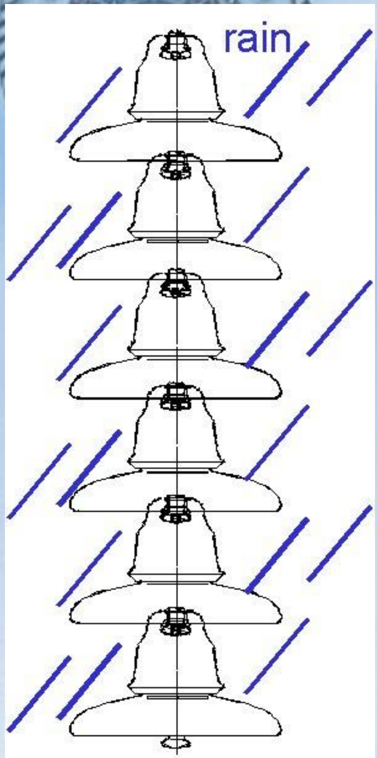
The AC and DC rain flashover voltage of insulators decreased dramatically!

What factors affect the rain flashover performance of insulators?



Rain exposure is a common occurrence for outdoor insulators
The wet withstand voltage of insulators must be higher than the operating voltage and have sufficient margin.
One of the important roles of insulator sheds!

Artificial Rain Test (wet test) Method for Insulators



Standard rain

Water resistivity (100 Ωm at 20℃)
Rainfall (1-2mm/min)
rainfall direction: ≈45°
rainfall: horizontal 1.0-2.0mm/min
vertical 1.0-2.0mm/min

Pre raining time: 15 minutes
Wet withstand time: 1 minute

Atmosphere correction:
only air density correction applied

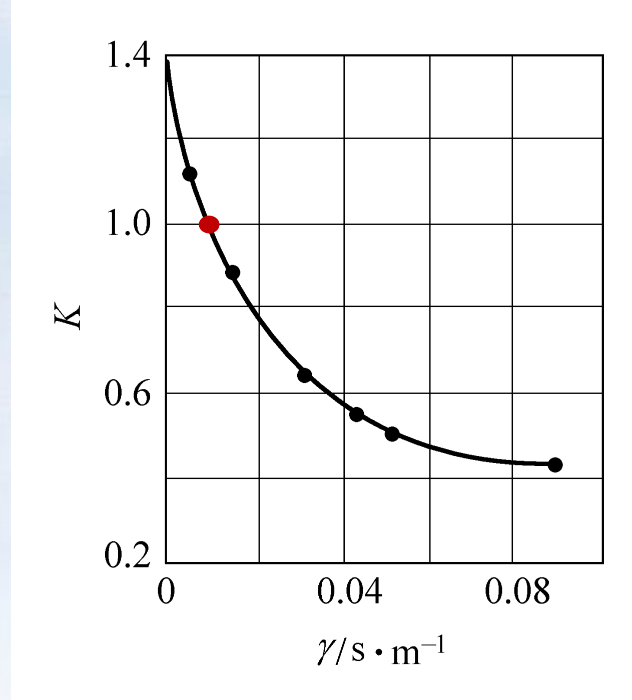


Figure 3-19 Effect of water conductivity on wet flashover voltage

It is not easy to achieve a large scale of uniform rainfall to meet above requirements.
The difficulty of wet flashover test for UHV insulators is high.

Approach to increase wet flashover voltage:
shed parameters, hydrophobic surfaces, large-sized cutting-rain sheds

The flashover voltage for water with a conductivity of 10^{-4} (Ω.cm)$^{-1}$ is 1.0