Chapter 2 Insulation Characteristics of Air under Different Voltage Waveforms

2.1 Analysis of electric field distribution and field adjustment

2.2 Insulation characteristics of air under continuous applied voltage

2.3 Insulation characteristics of air under lightning impulse voltage

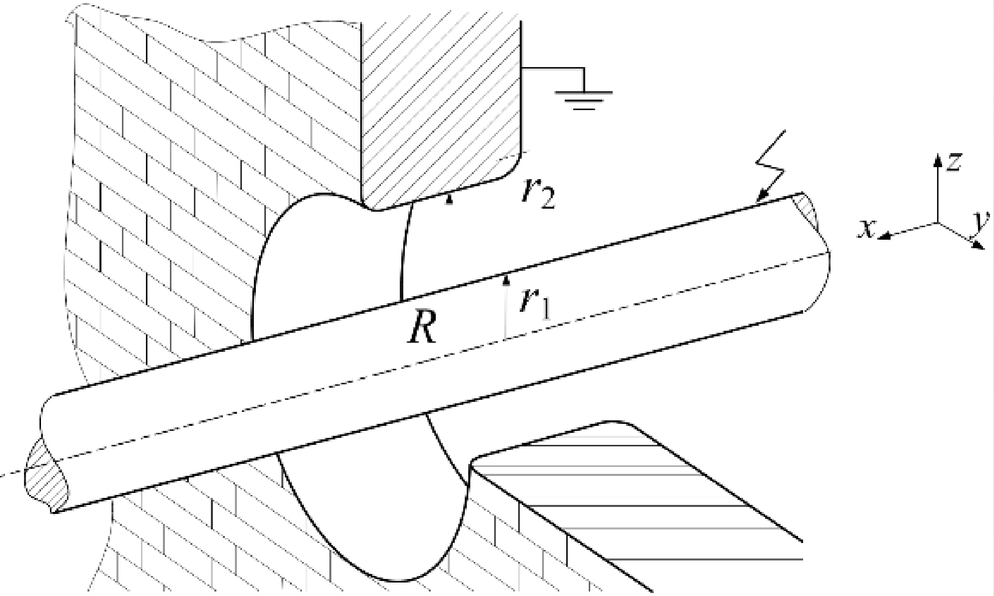
2.4 Insulation characteristics of air under switching impulse voltage

2.5 Measures to increase gas gap breakdown voltage

Core concepts of this chapter:

high voltage and high electric stress, non-uniform field, electric field control, lightning and switching impulse voltage, 50% breakdown voltage, v-t characteristics, breakdown strength of air, high vacuum insulation, SF_6 insulation

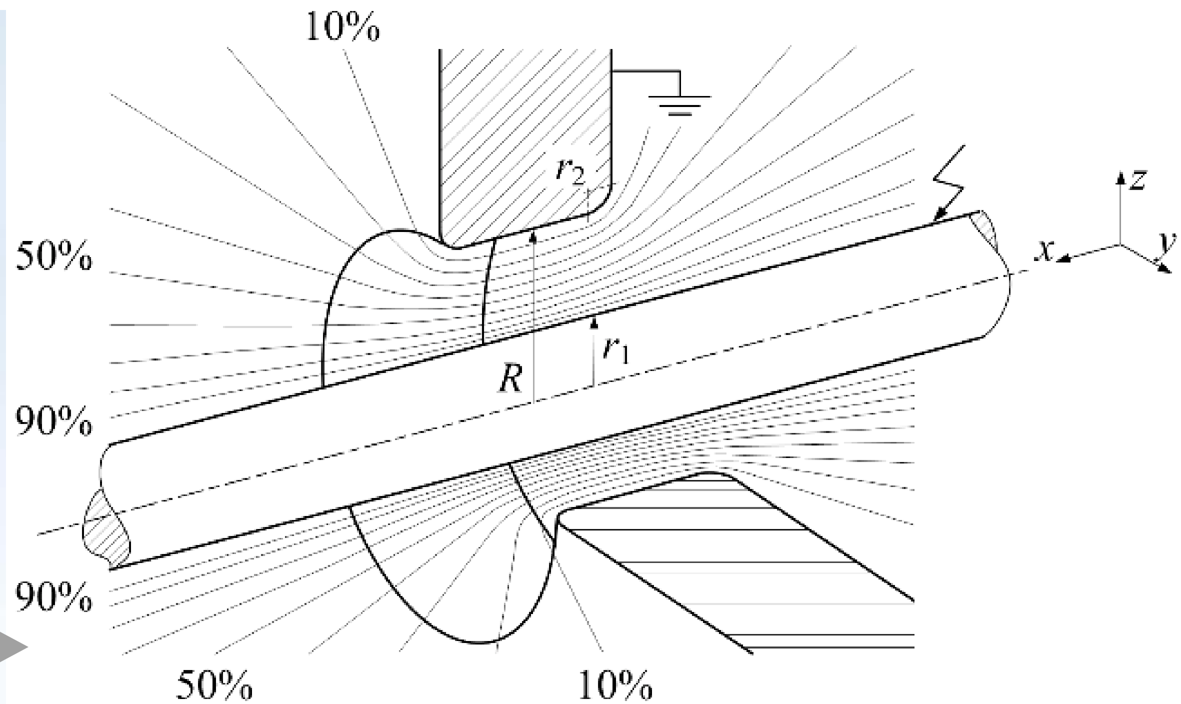
2.1 Analysis of electric field distribution and field adjustment



Cross-section of a HV conductor rod passing through a grounded wall

- Discharge occurs when the field stress exceeds the withstanding value,
- Field calculations is possible, but field measurement is very difficult.
- Firstly, a general analysis of the field distribution is required.

Where is the position with the highest electric field?
How to adjust the electric field distribution (field control) ?

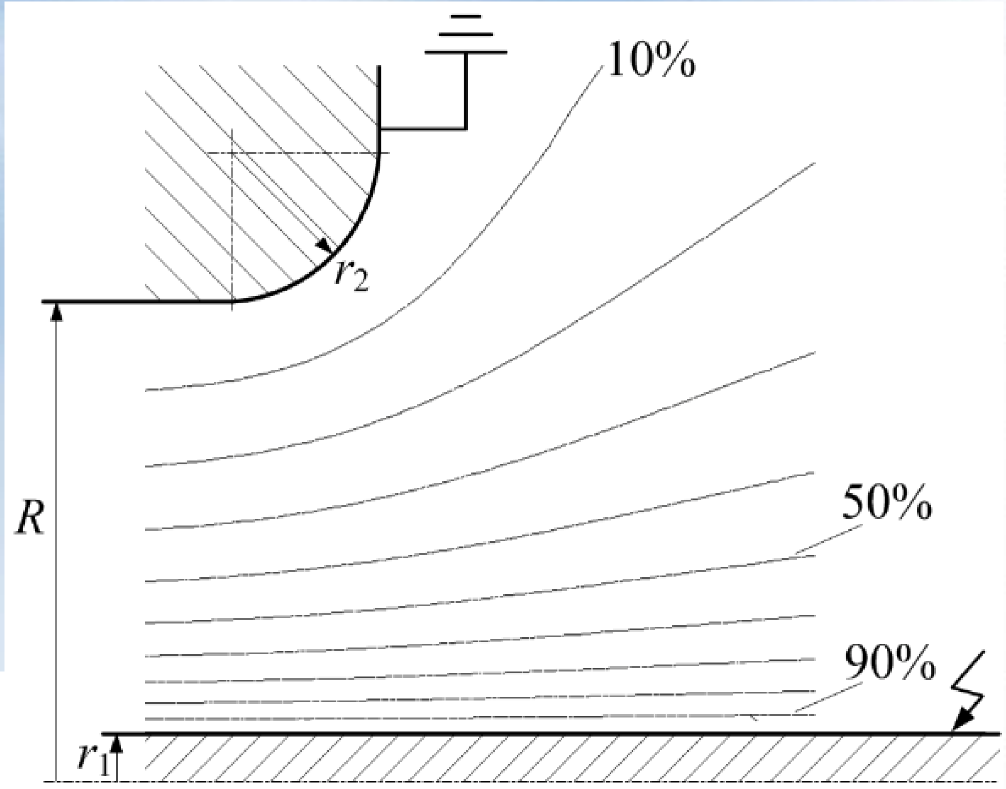


Electric field distribution on the *x*-*y* plane and *x*-*z* plane

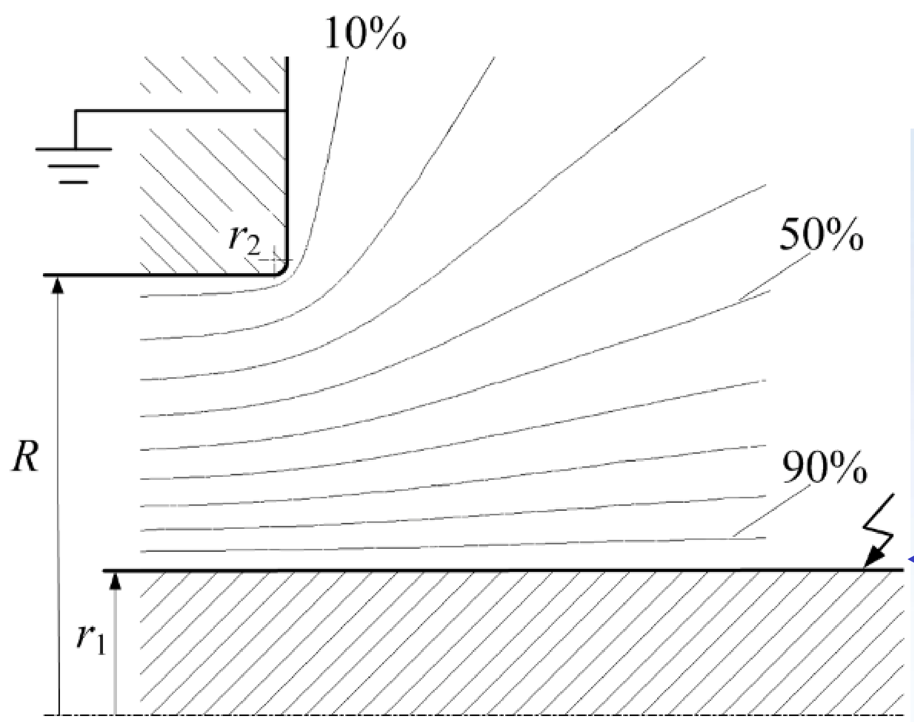
2.1 Analysis of electric field distribution and field adjustment

Electrode with high field stress could be high potential, low potential or ground potential electrodes

- What factors affect the distribution of electric fields?
- What is the influence of voltage on the electric field ?



Reducing r_1 and increasing r_2, then the highest field stress is on the surface of conductor rod



Increasing r_1, and reducing r_2, the highest field stress is at the corner of the wall hole

2.1 Analysis of electric field distribution and field adjustment

Expanding the curvature radius of high field electrodes to reduce the field stress on electrode surface

- Learn to estimate where is the position with the highest field stress
- Understand how to shield the high stress electrodes

China Electric Power Research Institute (China EPRI)
7200kV/480kJ
outdoor impulse voltage generator and voltage divider
(segmented electrodes)

Expanding the curvature radius of high stress electrodes **(segmented electrodes)**

± 1800kV/2A cascade HVDC generator and voltage divider of China EPRI

1500kV/2A power frequency test transformer and voltage divider of China EPRI

Expanding the curvature radius of high stress electrodes **(segmented electrodes)**

Expanding the curvature radius of high field electrodes to reduce the field stress on electrode surface

- Learn to estimate where is the position with the highest field stress
- Understand how to shield the high stress electrodes

Southern Power Grid UHV National Engineering Laboratory

- Learn to estimate where is the position with the highest field stress
- Understand how to shield the high stress electrodes

500kV AC OHL, 4-split conductor, with a split diameter of 64cm

1000kV AC OHL, 8-split conductor, with a split diameter of 102cm

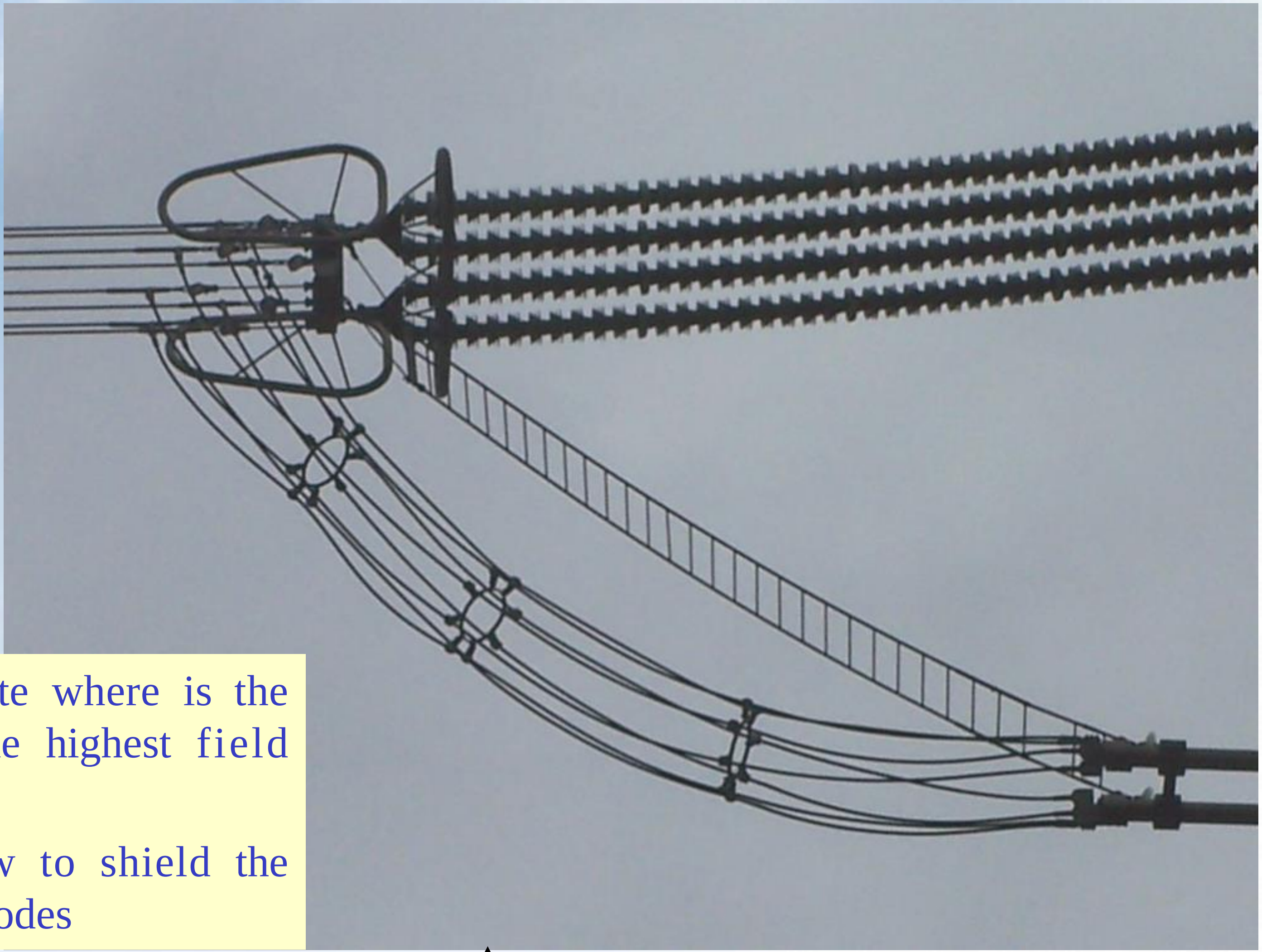
Split conductor, expanding the equivalent curvature radius of high stress electrodes to reduce the surface field stress of each conductor

Fig. 9• Installation of low-noise conductors in an actual 1,000-kV

1000kV overhead line
8-split conductors
in China

"Beaded" high-voltage lead

Expanding the equivalent curvature radius of high stress electrodes



- Learn to estimate where is the position with the highest field stress
- Understand how to shield the high stress electrodes

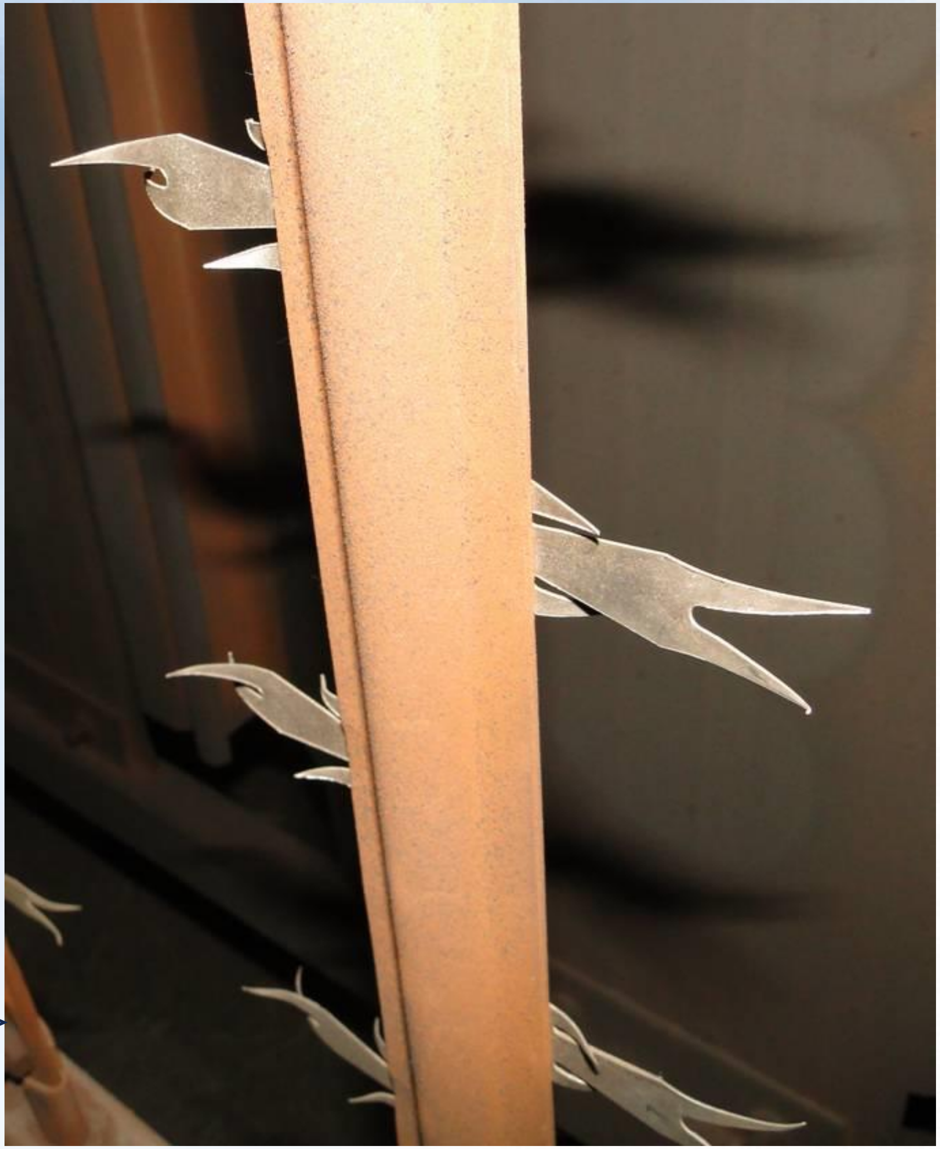
Shielding ring at the end of tensile insulator strings

Expanding the equivalent curvature radius of high stress electrodes

- Learn to estimate where is the position with the highest field stress
- Understand what is shielding

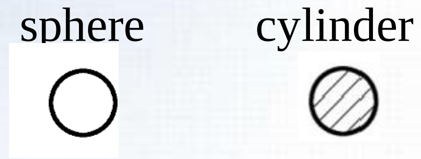
Reduce the curvature radius of high stress electrodes, to enhance the local field stress

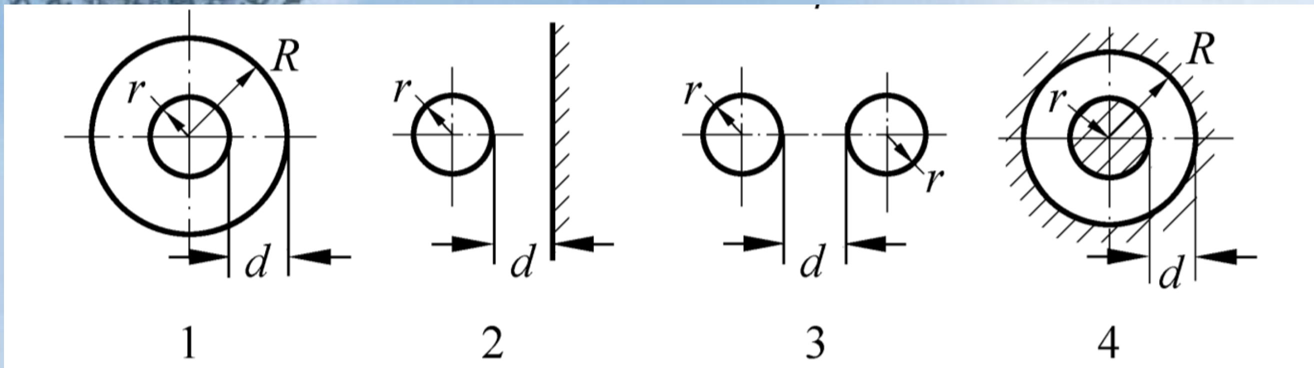
HV electrode of electrostatic precipitator



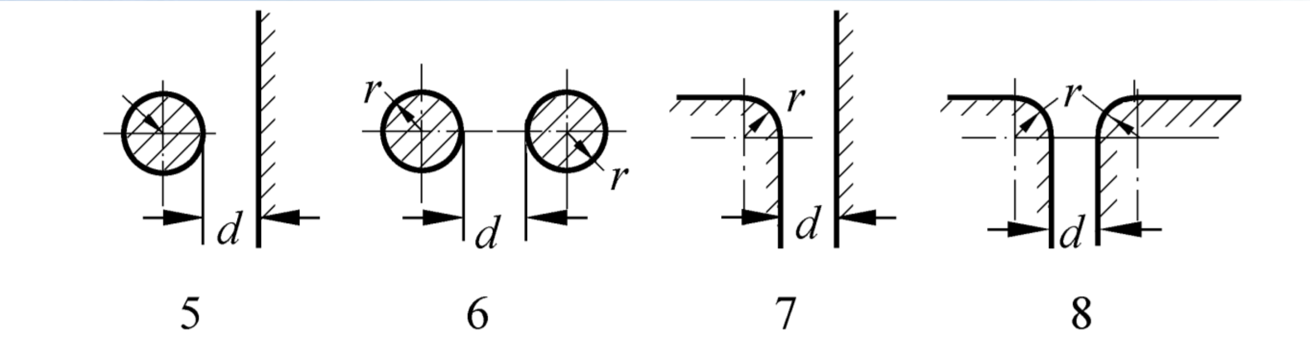
2.1 Analysis of electric field distribution and field adjustment

Several typical electrode structures



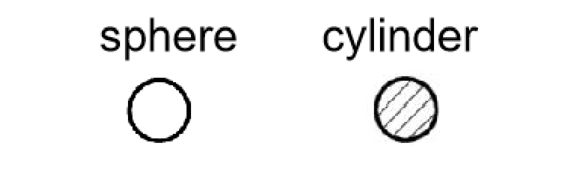


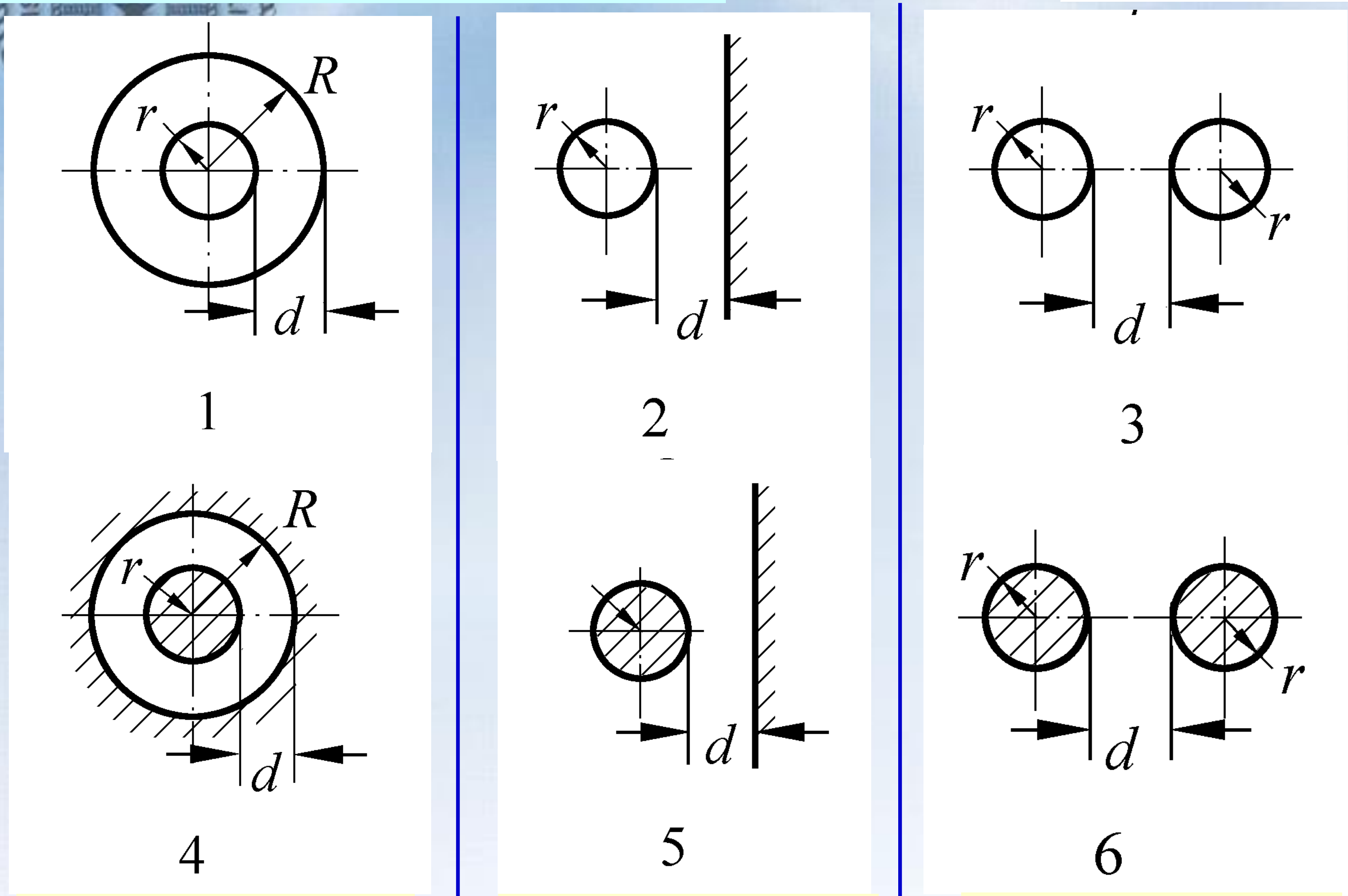
1--concentric sphere 2--sphere-plate 3--sphere-sphere 4--coaxial cylinder



5--cylinder-plate 6--parallel cylinder 7--curved surface-plane 8--curved surface-curved surface

2.1 Analysis of electric field distribution and field adjustment





Compare
1 and 4,
2 and 5,
3 and 6,

Which field is more uniform under the same size (same r and d) ?

1--concentric sphere

4--coaxial cylinder

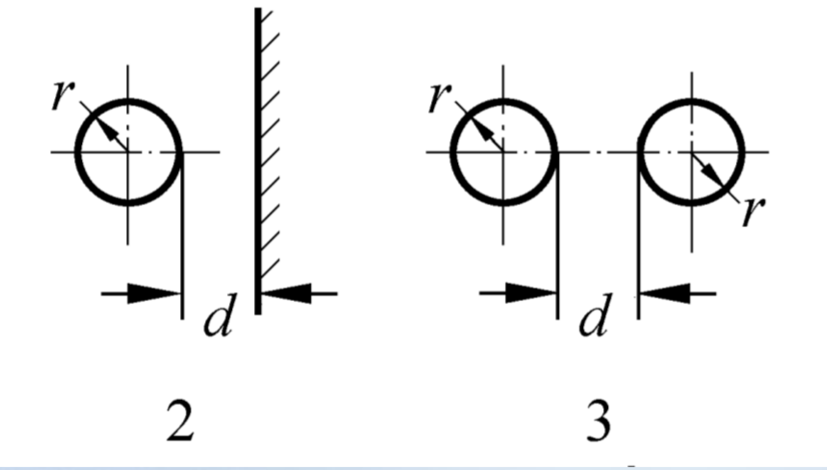
2--sphere-plate

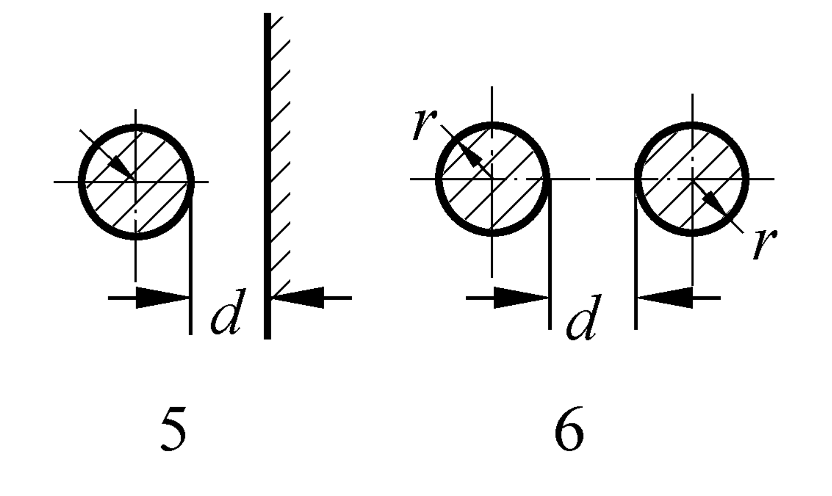
5--cylinder-plate

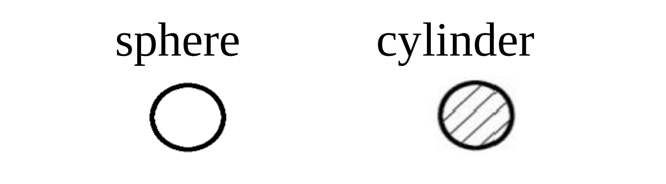
3--sphere-sphere

6--parallel cylinder

2.1 Analysis of electric field distribution and field adjustment





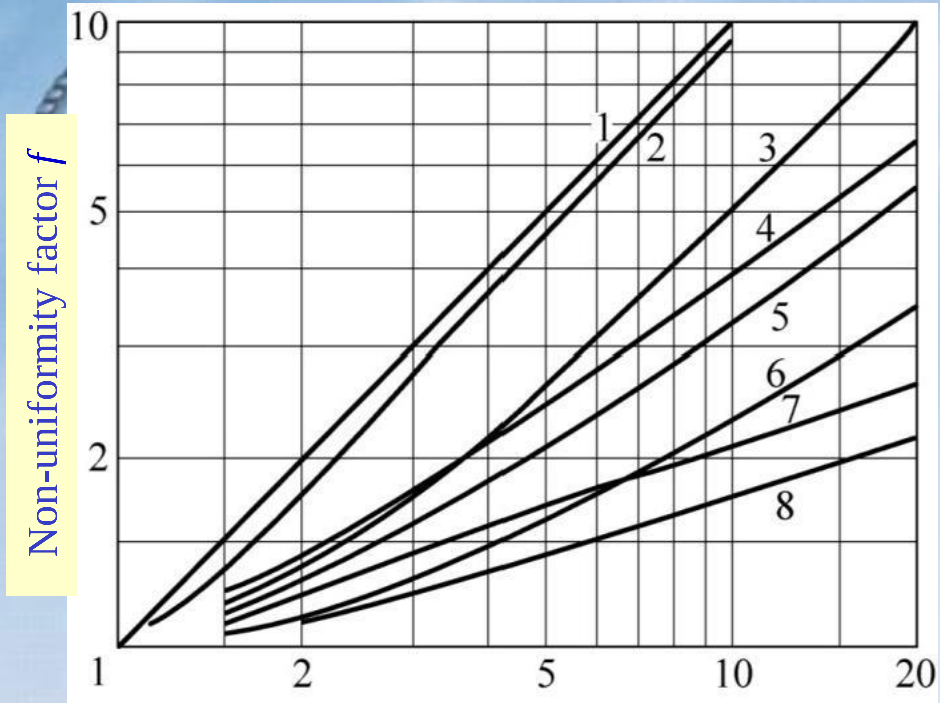


2--sphere-plate 3--sphere-sphere

Which is more uniform, 2 or 3 of the same size (same *r* and *d*) ?

Which is more uniform, 5 or 6 of the same size (same *r* and *d*) ?

5--cylinder- plate 6--parallel cylinder



Geometric characteristic factor $p=\frac{r+d}{r}$

2.1 Analysis of electric field distribution and field adjustment

1--concentric sphere 2--sphere-plate

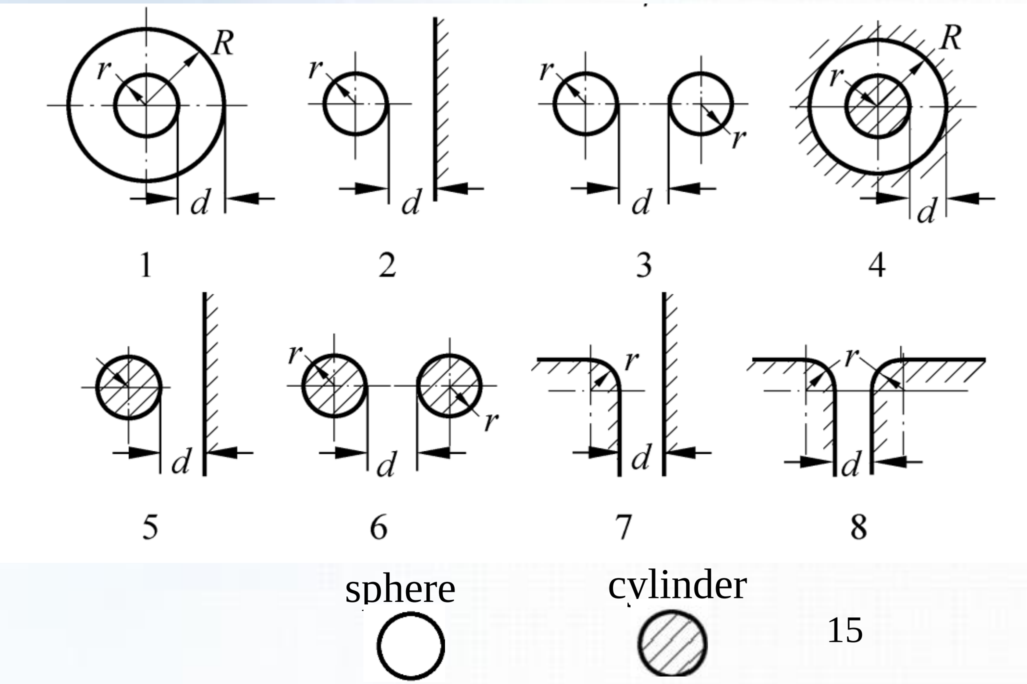
3--sphere-sphere 4--coaxial cylinder

5--cylinder-plate 6--parallel cylinder

7--curved surface-plane

8--curved surface-curved surface

Several typical electrode structures and their non-uniformity factor



- Under the same size, **field on cylindrical surfaces are more uniform than spherical surfaces**

- Under the same size, **field on symmetry is more uniform than asymmetry**

Chapter 2 Insulation Characteristics of Air under Different Voltage Waveforms

2.1 Analysis of electric field distribution and field adjustment

2.2 Insulation characteristics of air under continuous applied voltage

2.3 Insulation characteristics of air under lightning impulse voltage

2.4 Insulation characteristics of air under switching impulse voltage

2.5 Measures to increase gas gap breakdown voltage

Core concepts of this chapter:

high voltage and high electric stress, non-uniform field, electric field control, lightning and switching impulse voltage, 50% breakdown voltage, v-t characteristics, breakdown strength of air, high vacuum insulation, SF_6 insulation

2.2 Insulation characteristics of air under continuous applied voltage (AC &DC)

2.2.1 Insulation characteristics of air gaps in a uniform electric field

$$U_b = 24.22\delta d + 6.08\sqrt{\delta d} \quad \text{(peak)}$$

The breakdown strength of air under various voltages in a uniform electric field is almost the same, roughly equal to 30kV/cm (peak)

It is difficult to realize large scale uniform electric field in engineering practice

In electrical equipment, the distance of a uniform electric field is not long

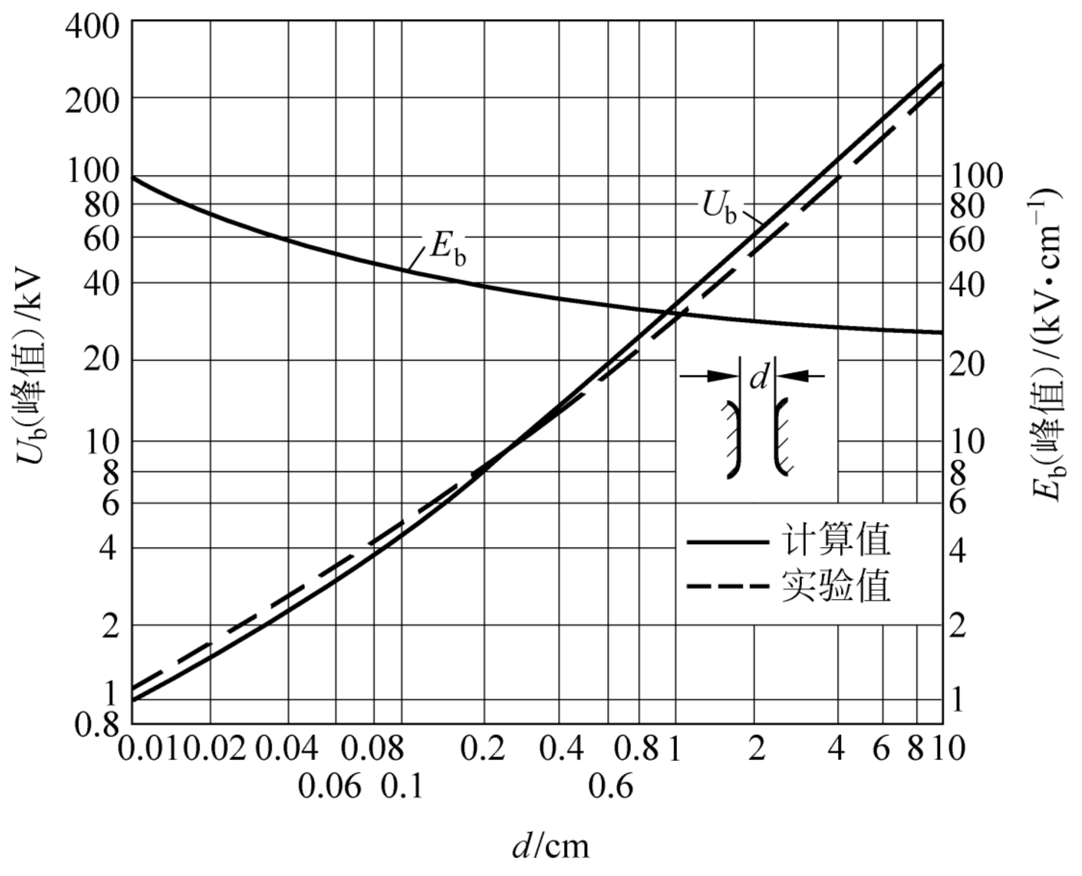


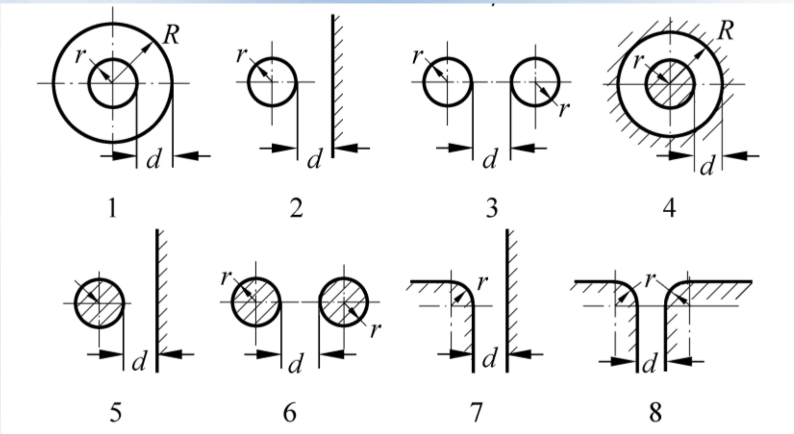
Figure 2-11

Relation between the breakdown voltage U_b, breakdown field strength E_b, and gap distance d of air gaps in a uniform electric field

2.2 Insulation characteristics of air under continuous applied voltage (AC&DC)

2.2.2 Insulation characteristics of air gaps in slightly non-uniform electric fields

$$U = E_{max}\frac{d}{f} \qquad U_b = U_c = E_0\frac{d}{f}$$



- According to the corona occurs or not before gas gap breakdown, the non-uniform field can be classified into **slightly non-uniform** field and **extremely non-uniform** field.
- Slightly non-uniform field: no obvious corona phenomenon before breakdown. When the highest field stress E_{max} reaches the corona inception stress E_0, the applied voltage U is the corona inception voltage U_c, and is also the breakdown voltage U_b

- For slightly non-uniform fields, field non-uniformity has a significant impact on the discharge/breakdown voltage
- Slightly non-uniform fields are often estimated using simplified typical electrodes using the empirical formula in Table 2-1

- Table 2-1 presents the corona inception stress formula for several typical electrode configurations, in peak value
- The estimation formulas for E_0 and U_c in Table 2-1 are also applicable to extremely non-uniform fields. But the estimation of gap breakdown voltage U_b is only applicable to slightly non-uniform electric fields

表 2-1 几种典型电极的简化估算公式

电极形状	电极表面最大场强 E_{max}	电场不均匀系数 f	电晕起始场强 E_0	电晕起始电压 U_c
同心球	$E_{max}=\dfrac{RU}{r(R-r)}$ 式（2-1）	$f=R/r$ 式（2-2）	$E_0=24\delta\,(1+1/\sqrt{r\delta})$ 式（2-3）	$U_c=E_0\dfrac{(R-r)r}{R}$ 式（2-4）
球-平板	$E_{max}=0.9\dfrac{U}{d}(1+\dfrac{d}{r})$ 式（2-5）	$f=0.9(1+\dfrac{d}{r})$ 式（2-6）	$E_0=27.7\delta\,(1+0.337/\sqrt{r\delta})$ 式（2-7）	$U_c=E_0\dfrac{dr}{0.9(d+r)}$ 式（2-8）
球-球	$E_{max}=0.9\dfrac{U}{d}(1+\dfrac{d}{2r})$ 式（2-9）	$f=0.9(1+\dfrac{d}{2r})$ 式（2-10）	$E_0=27.7\delta\,(1+0.337/\sqrt{r\delta})$ 式（2-11）	$U_c=E_0\dfrac{d}{0.9(1+d/2r)}$ 式（2-12）
同轴圆柱	$E_{max}=\dfrac{U}{r\ln(R/r)}$ 式（2-13）	$f=\dfrac{R-r}{r\ln(R/r)}$ 式（2-14）	$E_0=31.5\delta\,(1+0.305/\sqrt{r\delta})$ 式（2-15）	$U_c=E_0 r\ln(\dfrac{R}{r})$ 式（2-16）
圆柱-平板	$E_{max}=\dfrac{0.9U}{r\ln(\frac{d+r}{r})}$ 式（2-17）	$f=\dfrac{0.9d}{r\ln(\frac{d+r}{r})}$ 式（2-18）	$E_0=30.3\delta(1+0.298/\sqrt{r\delta})$ 式（2-19）	$U_c=E_0\dfrac{r\ln(\frac{d+r}{r})}{0.9}$ 式（2-20）
平行圆柱	$E_{max}=\dfrac{0.9U}{2r\ln(\frac{d+2r}{2r})}$ 式（2-21）	$f=\dfrac{0.9d}{2r\ln(\frac{d+2r}{2r})}$ 式（2-22）	$E_0=30.3\delta\,(1+0.298/\sqrt{r\delta})$ 式（2-23）	$U_c=E_0\dfrac{2r\ln(\frac{d+2r}{2r})}{0.9}$ 式（2-24）

注：表中 E_0、E_{max} 的单位为 kV/cm (峰值)，U_c 的单位为 kV (峰值)，r、R、d 的含义见图 2-2，其单位均为 cm。

Can be used to estimate (calculate) the corona onset stress and corona onset voltage of both slightly non-uniform and extremely non-uniform fields,

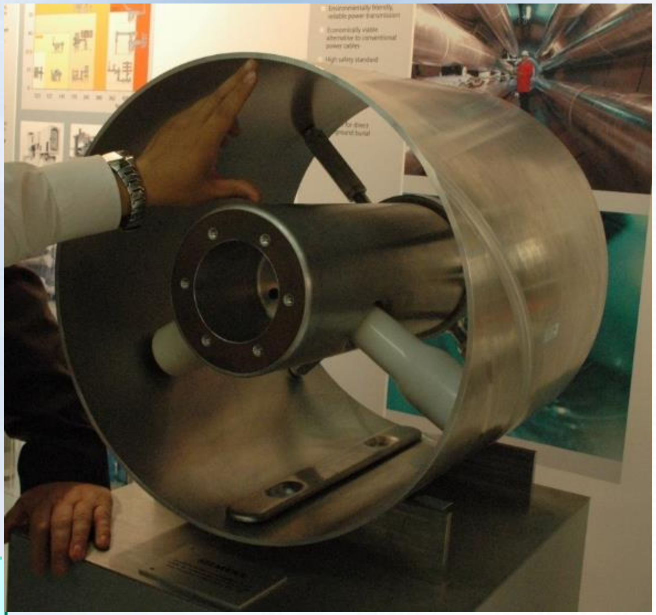
Can be used to predict the gap breakdown voltage of slightly non-uniform fields

Can not be used to calculate the gap breakdown voltage of extremely non-uniform fields

2.2 Insulation characteristics of air under continuous applied voltage

2.2.2 Insulation characteristics of air gaps in slightly non-uniform electric fields

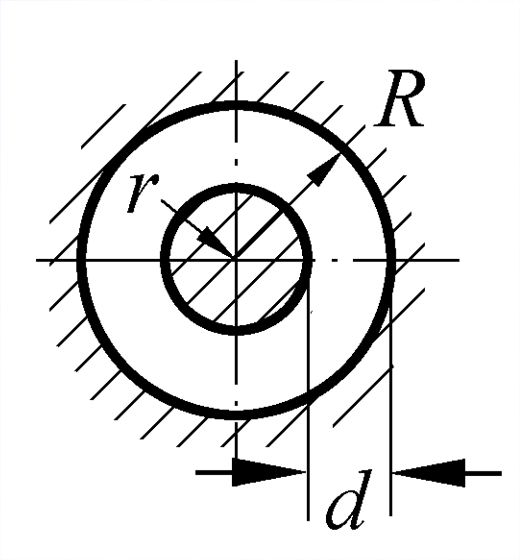
$$U = E_{\max}\frac{d}{f} \qquad U_b = U_c = E_0\frac{d}{f}$$



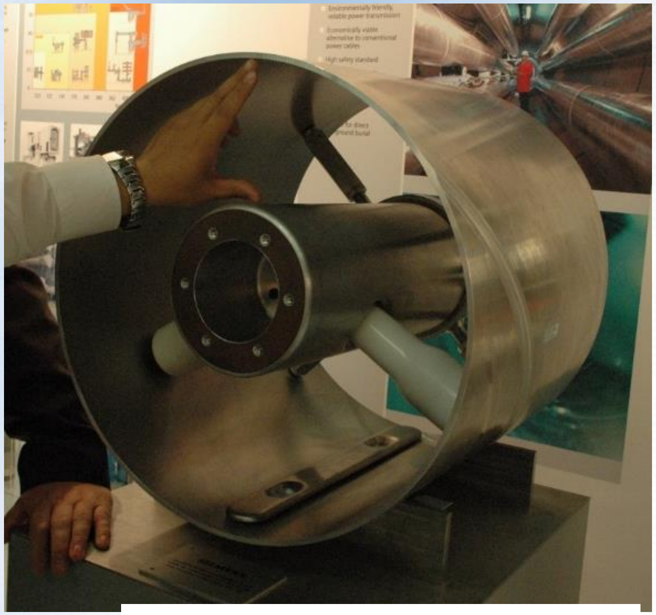
Example: A coaxial cylindrical air gap with an inner electrode connected to negative DC voltage, and an outer cylinder grounded. Inner and outer electrode radius are r and R respectively

When R=20cm is fixed, while r increases from r_1=6cm to r_2=10cm, that is, the distance between electrodes d decreases from d_1=14cm to d_2=10cm

Please calculate the variation of breakdown voltage in the gap between the coaxial cylindrical electrodes.



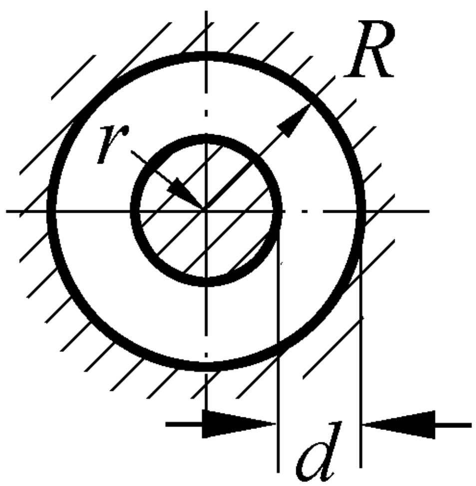
2.2 Insulation characteristics of air under continuous applied voltage



2.2.2 Insulation characteristics of air gaps in slightly non-uniform electric fields

$$U = E_{max}\frac{d}{f} \qquad U_b = U_c = E_0\frac{d}{f}$$

Solution: For coaxial cylindrical electrodes



$$E_{max} = \frac{U}{r\ln\frac{R}{r}}$$

式(2-13)

$$f = \frac{R-r}{r\ln\frac{R}{r}}$$

式(2-14)

$$E_0 = 31.5\delta\left(1 + 0.305/\sqrt{r\delta}\right)$$

式(2-15)

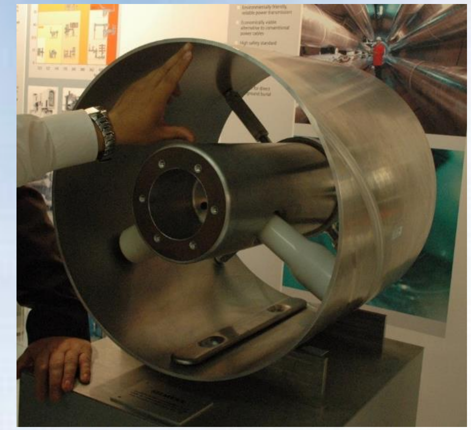
$$U_c = E_0\, r\ln\frac{R}{r}$$

式(2-16)

2.2 Insulation characteristics of air under continuous applied voltage

2.2.2 Insulation characteristics of air gaps in slightly non-uniform electric fields

$$U = E_{max} \frac{d}{f} \qquad U_b = U_c = E_0 \frac{d}{f}$$



Example: A coaxial cylindrical air gap with an inner electrode connected to negative DC voltage, and an outer cylinder grounded. Inner and outer electrode radius are r and R respectively. When R=20cm is fixed, while r increases from r_1=6cm to r_2=10cm, that is, the distance between electrodes d decreases from d_1=14cm to d_2=10cm. **Please calculate the variation of breakdown voltage in the gap between the coaxial cylindrical electrodes.**

Solution: The calculation formula for the non-uniformity factor f and gap breakdown voltage U_c of the coaxial cylindrical air gap is shown in Table 2-1.

When R=20cm, r_1=6cm, and d_1=14cm, f_1=1.94 and U_{c1}=256kV can be obtained;

When R=20cm, r_2=10cm, and d_2=10cm, f_2=1.44 and U_{c2}=239kV can be obtained.

Discussion: The gap distance decreased by nearly 30%, but the breakdown voltage is only decreased by less than 7%. The increase in the uniformity of the electric field leads to a significant increase in the breakdown voltage.

U_{c1}/d_1=18.3kV/cm, while U_{c2}/d_2=23.9kV/cm.

- In a slightly non-uniform field, the uniformity of the electric field has a significant impact on the gap breakdown voltage!

2.2 Insulation characteristics of air under continuous applied voltage (AC&DC)

2.2.3 Insulation characteristics of air gaps in extremely non-uniform electric fields

- For extremely non-uniform fields, the field non-uniformity has limited or little effect on the breakdown voltage. The distortion of the electric field caused by the space charge formed by corona will significantly affect the development of discharge.

- There is an obvious corona phenomenon before breakdown, and there is a big difference between corona inception voltage and gap breakdown voltage.

- The empirical formula in Table 2-1 can also be used to estimate the corona inception stress and corona inception voltage of extremely non-uniform fields, but cannot be used to estimate the gap breakdown voltage!

The gap breakdown voltage of extremely non-uniform fields is mainly obtained through experiments (and it is a 1:1 experiment), or by referring to curves obtained under similar experiment conditions. The breakdown voltage cannot be calculated!

Analysis of extremely non-uniform fields mainly focus on the field is symmetrical or not: classified into rod-rod (symmetrical) and rod-plane (non-symmetrical)

And then check the voltage polarity: positive or negative polarity

Symmetrical and voltage polarity are the two most important factors influence breakdown

2.2 Insulation characteristics of air under continuous applied voltage

2.2.3 Insulation characteristics of air gaps in extremely non-uniform electric fields

Positive rod-plane: $E_b \approx 4.5$ kV/cm
Negative rod-plane: $E_b \approx 10$ kV/cm

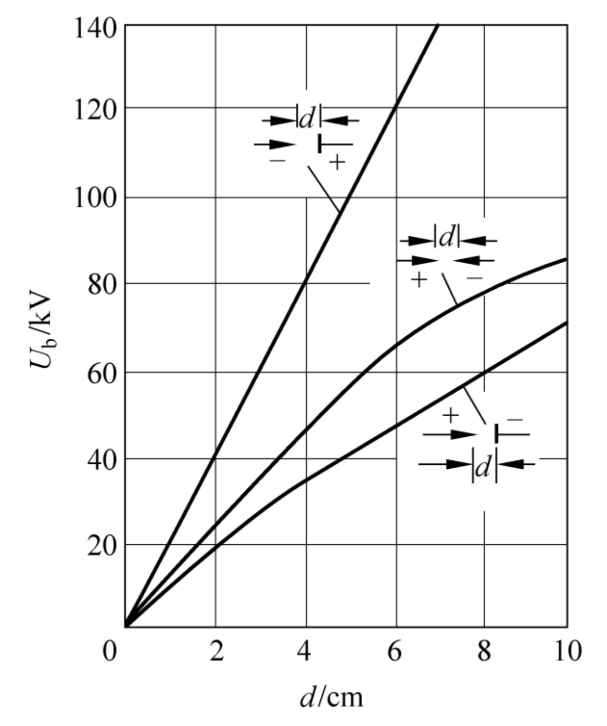


Figure 2-12 Relation between DC breakdown voltage and air gap distance of point-plane and point-point

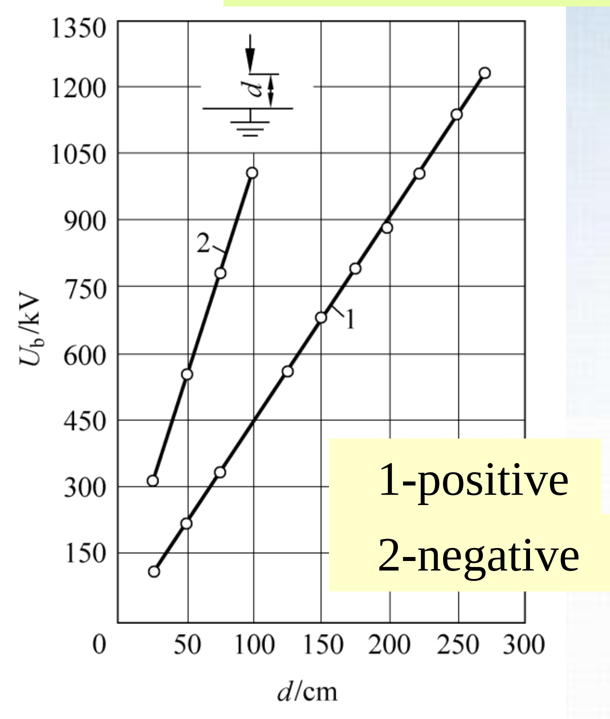


Figure 2-13 Relation between DC breakdown voltage and gap distance of rod-plane air gap

Symmetrical and voltage polarity are the two most important factors influence breakdown

- U_b cannot be calculated, **can be obtained from curves or experiment**
- Qualitative judgment and analysis are also important
- Accurate calculation and roughly estimation are all useful; In practice, "estimation + experiment" is used to determine the discharge voltage

2.2 Insulation characteristics of air under continuous applied voltage

2.2.3 Insulation characteristics of air gaps in extremely non-uniform electric fields

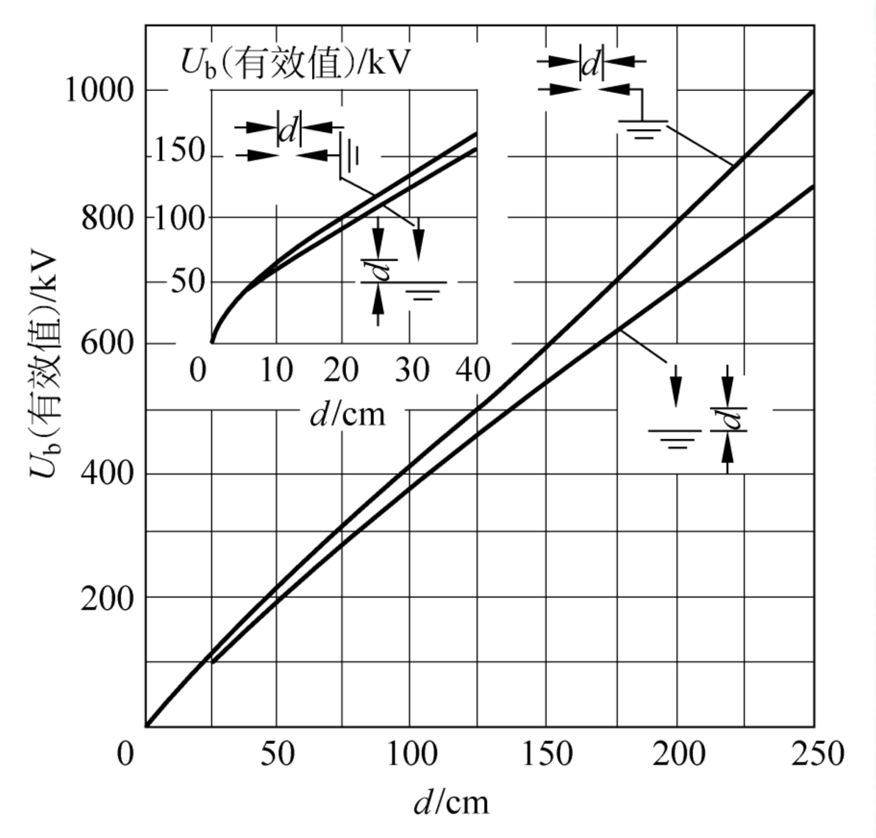
Gap breakdown under AC voltage occurs in the positive half wave

Rod-rod: $E_b \approx 4.0$ kV/cm (rms)

≈ 5.66 kV/cm (peak)

Rod-plane: $E_b \approx 3.7$ kV/cm (rms)

≈ 5.23 kV/cm (peak)



Breakdown voltage ***U_b*** can be **obtained from curves or experiment**

Figure 2-14 Relation between power frequency breakdown voltage and gap distance of rod-rod and rod-plane air gap

Analysis of extremely non-uniform fields mainly focus on the field is symmetrical or not: classified into rod-rod (symmetrical) and rod-plane (non-symmetrical)

And then check the voltage polarity: positive or negative polarity

Symmetrical and voltage polarity are the two most important factors influence breakdown

2.2 Insulation characteristics of air under continuous applied voltage

2.2.3 Insulation characteristics of air gaps in extremely non-uniform electric fields

Long gap rod-plane:

d = 10m, E_b≈210 kV/m (peak) or ≈ 150 kV/m (rms)

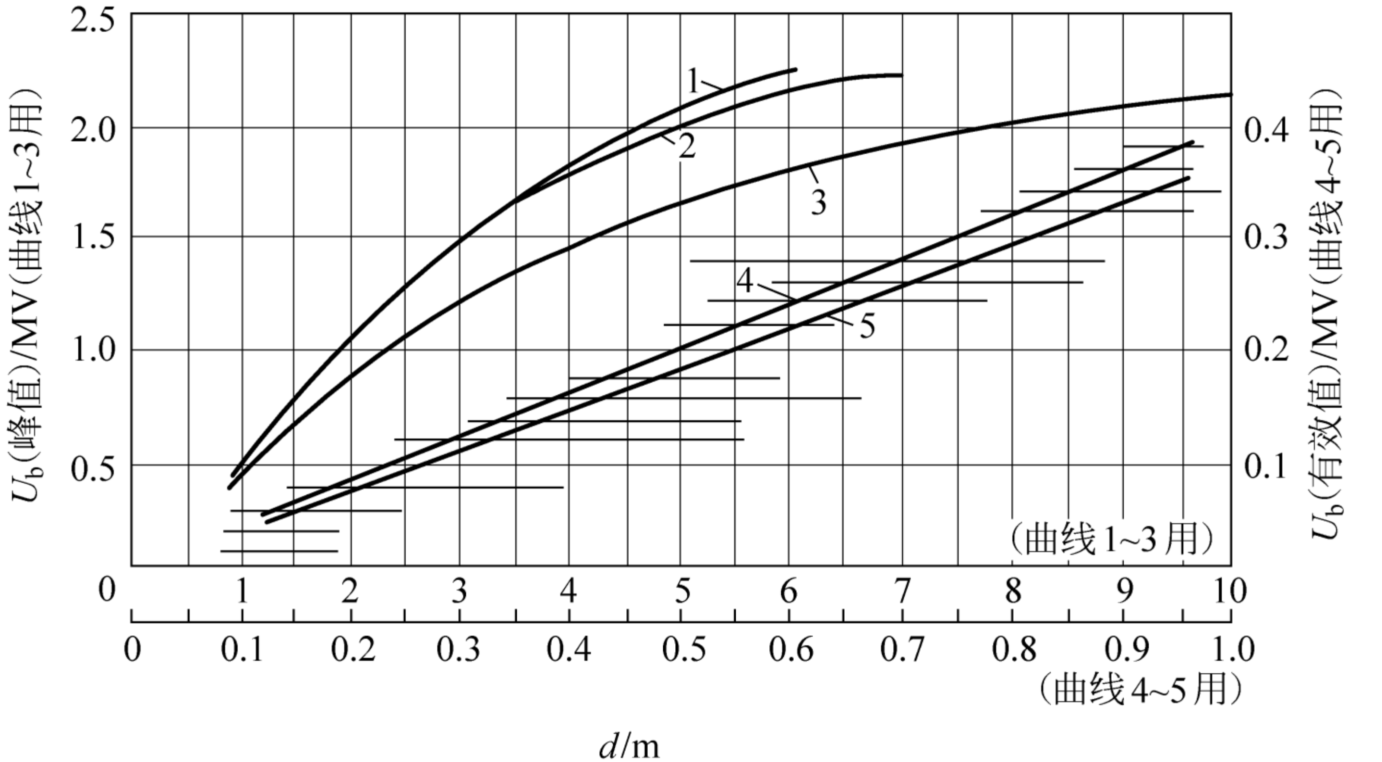


Figure 2-15 Relation between power frequency breakdown voltage and gap distance of rod-rod and rod-plane air gap 1, 2, and 4 -- rod-rod; 3,5-- rod-plane

The saturation of gap breakdown voltage with increasing gap distance is the significant characteristics of long air gap breakdown under AC voltage

Pay attention to test conditions when searching for experiment curves

Breakdown voltage U_b can be **obtained from curves or experiment**

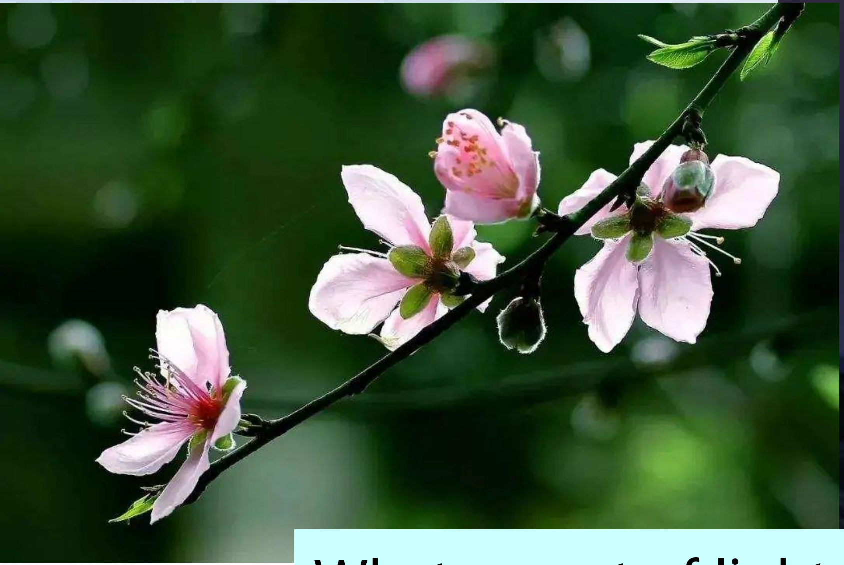
Symmetrical and voltage polarity are the two most important factors influence breakdown

2.3 Insulation characteristics of air under lightning impulse voltage

Yesterday (March 5) was the solar terms of “Jingzhe”!

Spring returns to the earth

Everything is updated



What aspect of lightning do you want most to know about?

2.3 Insulation characteristics of air under lightning impulse voltage

2.3.1 Formation and waveform of lightning impulse voltage

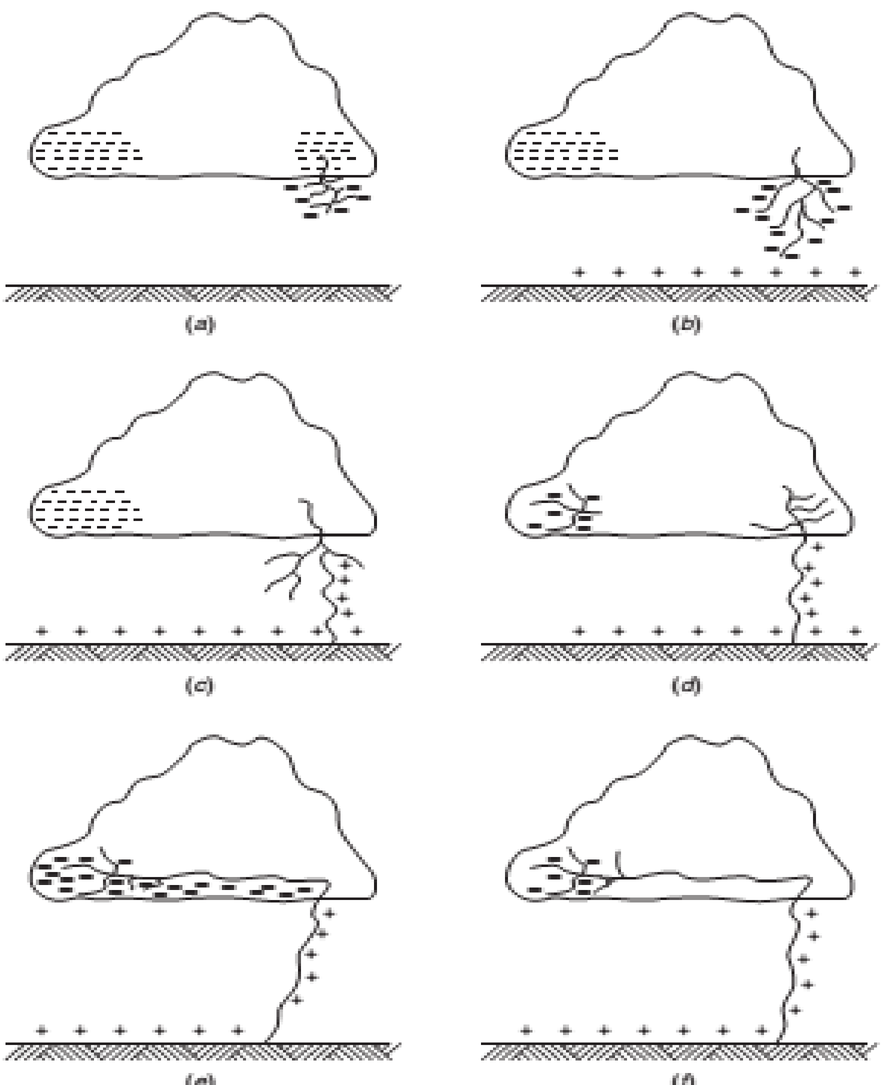
- Cloud to cloud lightning, inner-cloud lightning, and cloud to ground lightning, as well as the accumulation and distribution of electric charges inside thunderclouds
- Polarity of lightning;
- Upward and downward thunder

- Upward and downward lightning;
- The development process and speed of the stepped leader, main discharge;
- The three main stages of lightning development. The component of lightning

2.3 Insulation characteristics of air under lightning impulse voltage

2.3.1 Formation and waveform of lightning impulse voltage

- The field strength between thunder cloud and the ground;
- The potential of thunder cloud and the potential of the object being struck;



- The discharge current and electricity of lightning t

2.3 Insulation characteristics of air under lightning impulse voltage

2.3.1 Formation and waveform of lightning impulse voltage

- Cloud to cloud flash, inter-cloud flash, and cloud to ground flash, as well as the accumulation and distribution of charges in clouds
- Polarity of lightning;
- Upward and Downward Thunder
- The development process and speed of the stepped leader, main discharge;
- The three main stages of lightning development. The component of lightning
- The field strength between thunder cloud and the ground;
- The potential of thunder cloud and the potential of the object being struck;
- The discharge current and electricity of lightning to the ground.

2.3 Insulation characteristics of air under lightning impulse voltage

2.3.1 Formation and waveform of lightning impulse voltage

- Cloud to cloud flash, inter-cloud flash, and cloud to ground flash, as well as the accumulation and distribution of charges in clouds
- Polarity of lightning;
- Upward and Downward Thunder
- The development process and speed of the stepped leader, main discharge;
- The three main stages of lightning development. The component of lightning
- The field strength between thunder cloud and the ground;
- The potential of thunder cloud and the potential of the object being struck;
- The discharge current and electricity of lightning to the ground.
- The destructive power of lightning strikes

2.3 Insulation characteristics of air under lightning impulse voltage

2.3.1 Formation and waveform of lightning impulse voltage

- Cloud to cloud flash, inter-cloud flash, and cloud to ground flash, as well as the accumulation and distribution of charges in clouds
- Polarity of lightning;
- Upward and Downward Thunder
- The development process and speed of the stepped leader, main discharge;
- The three main stages of lightning development. The component of lightning
- The field strength between thunder cloud and the ground;
- The potential of thunder cloud and the potential of the object being struck;
- The discharge current and electricity of lightning to the ground.
- The destructive power of lightning strikes
- Waveform of lightning and standard waveform of lightning impulse voltage

What aspect of lightning do you want most to know about?