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Department of Electrical Engineering
Tsinghua University

High Voltage Engineering

Spring 2025, Lecture 4

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March 13, 2025

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

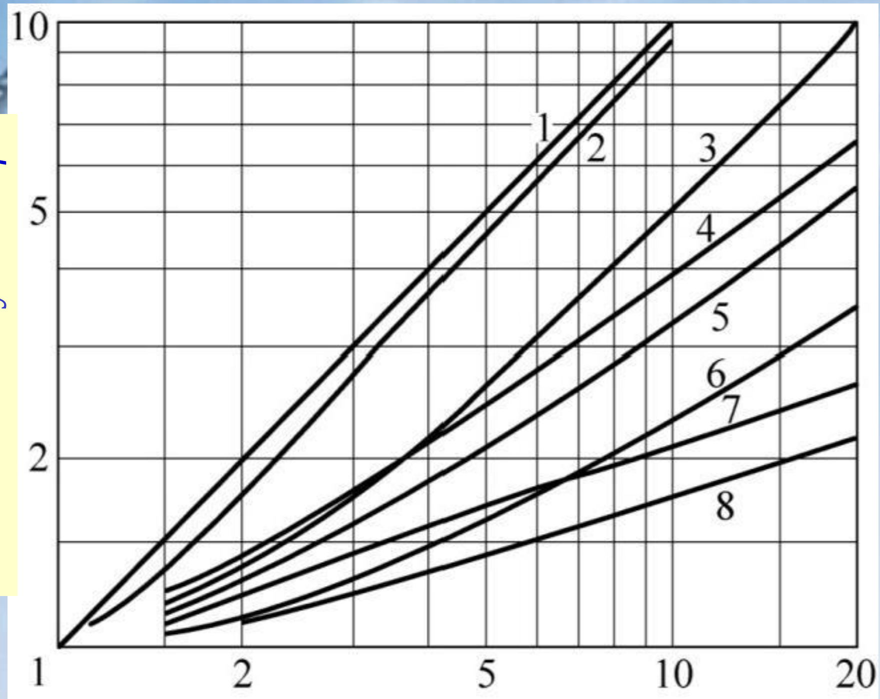
What is the difference on the focus of Chat 1 & 2?

Chat 1:Internal physical process, discharge mechanism, how discharge happens? What is the criterion of discharge? What is the factor which may influence the discharge?......

Chat 2: Apply above principle to actual situation, guide the design and predict or analyze the possible results

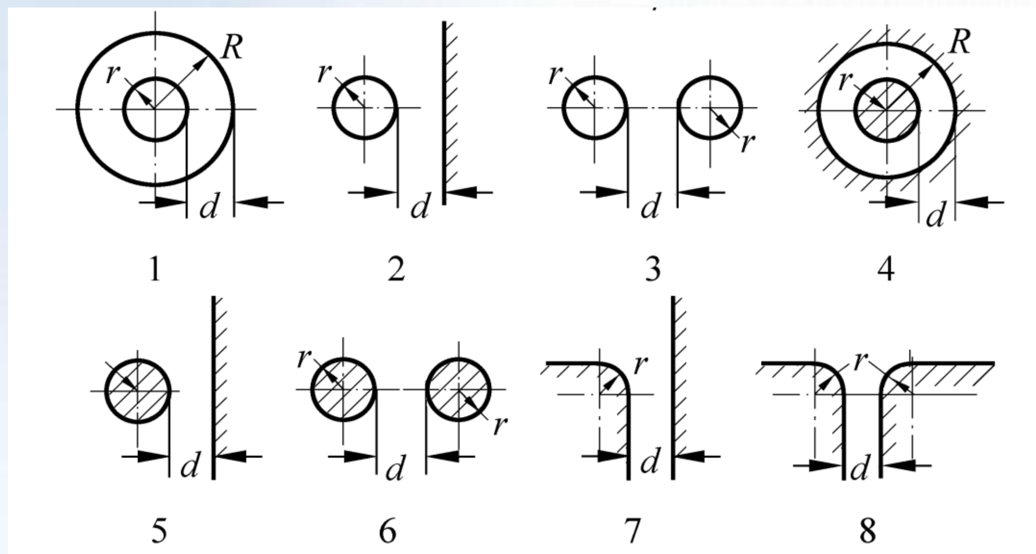
2.1 Analysis of electric field distribution and field adjustment

Non-uniformity factor f



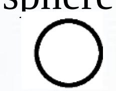
Geometric characteristic factor $p=\frac{r+d}{r}$

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



- Under the same size, **symmetric field is more uniform than asymmetric one**

sphere



cylinder

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

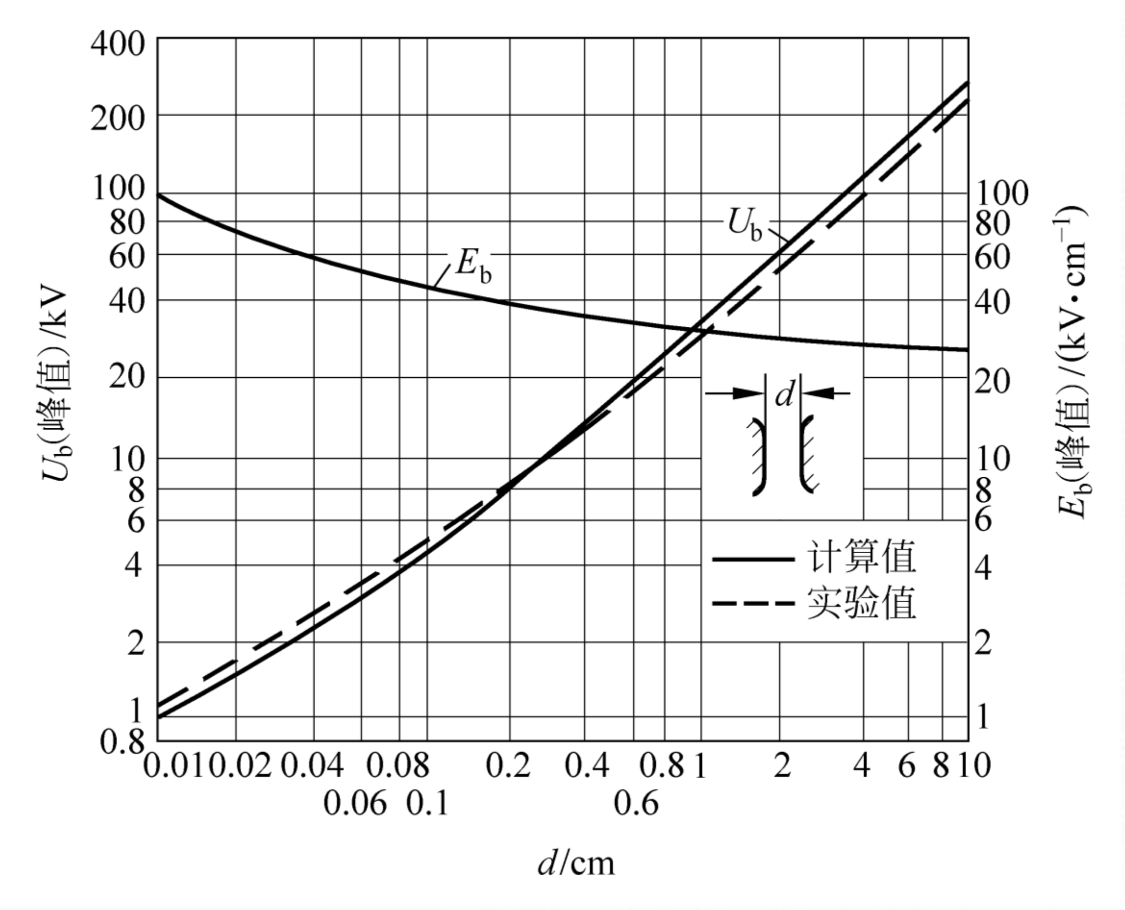
2.2.1 Insulation characteristics of air gaps in a uniform electric field

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

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

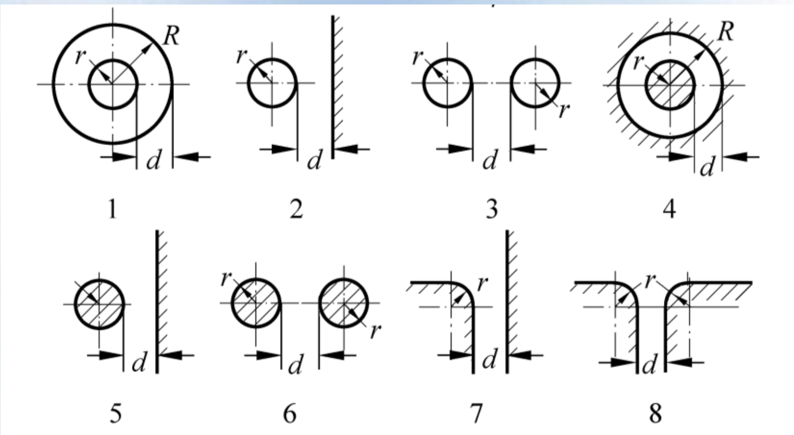
In electrical equipment, the distance of a uniform electric field is not long



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

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



- 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
- **Digital calculation** of field distribution is very helpful and powerful now!
- If no available empirical formula to obtain the E_0, **then 30kV/cm can be used** at the beginning

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.
- Obvious corona before breakdown, big difference between corona inception voltage and gap breakdown voltage.
- The empirical formula in Table 2-1 can also estimate the corona inception voltage/stress, but cannot estimate the gap breakdown voltage of extremely non-uniform fields!

The gap breakdown voltage of extremely non-uniform fields
is mainly obtained through experiments (1:1 experiment),
or by referring to curves obtained under similar experiment conditions.

The breakdown voltage cannot be calculated from discharge theory!

Extremely non-uniform fields classified into rod-rod (symmetric) and rod-plane (asymmetric)
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

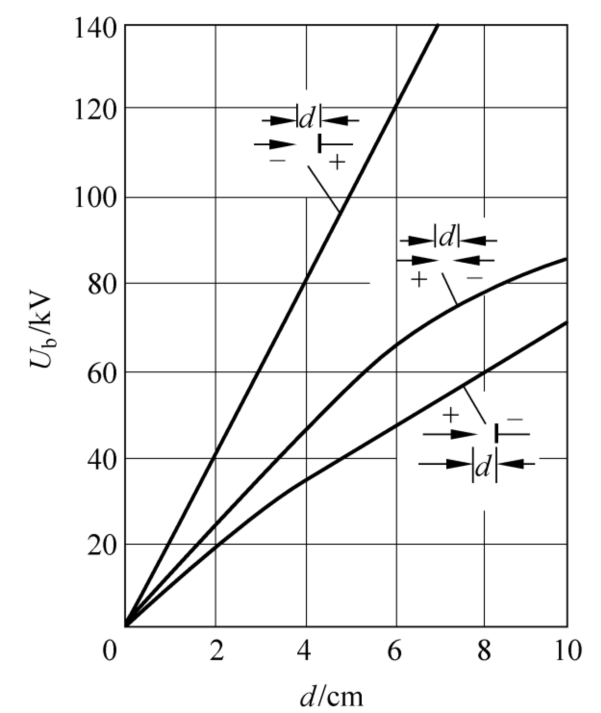


Figure 2-12 Relation between DC breakdown voltage and air gap distance of point-plane and point-point

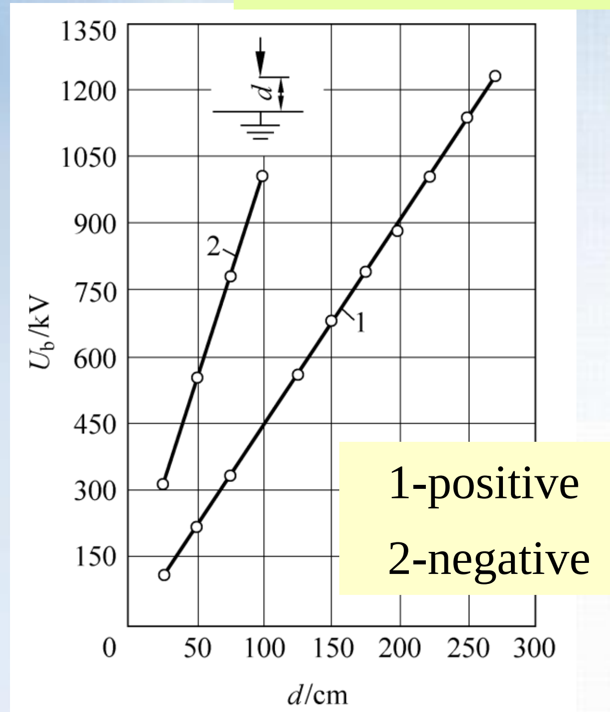


Figure 2-13 Relation between DC breakdown voltage and gap distance of rod-plane air gap

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

- U_b cannot be calculated, **can be obtained from experiment**
- Qualitative and roughly judgment and analysis are also important

2.2 Insulation characteristics of air under continuous applied voltage

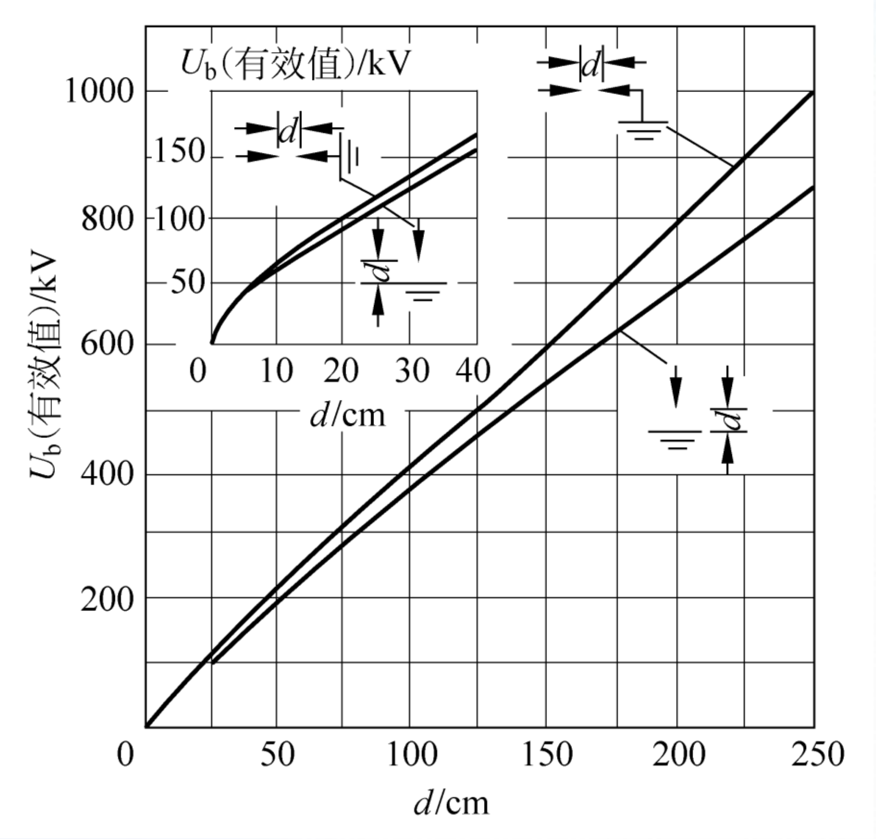
2.2.3 Insulation characteristics of air gaps in extremely non-uniform electric fields

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 experiment**

Gap breakdown under AC voltage occurs in the positive half wave

Extremely non-uniform fields classified into rod-rod (symmetric) and rod-plane (asymmetric)
voltage polarity: positive or negative polarity

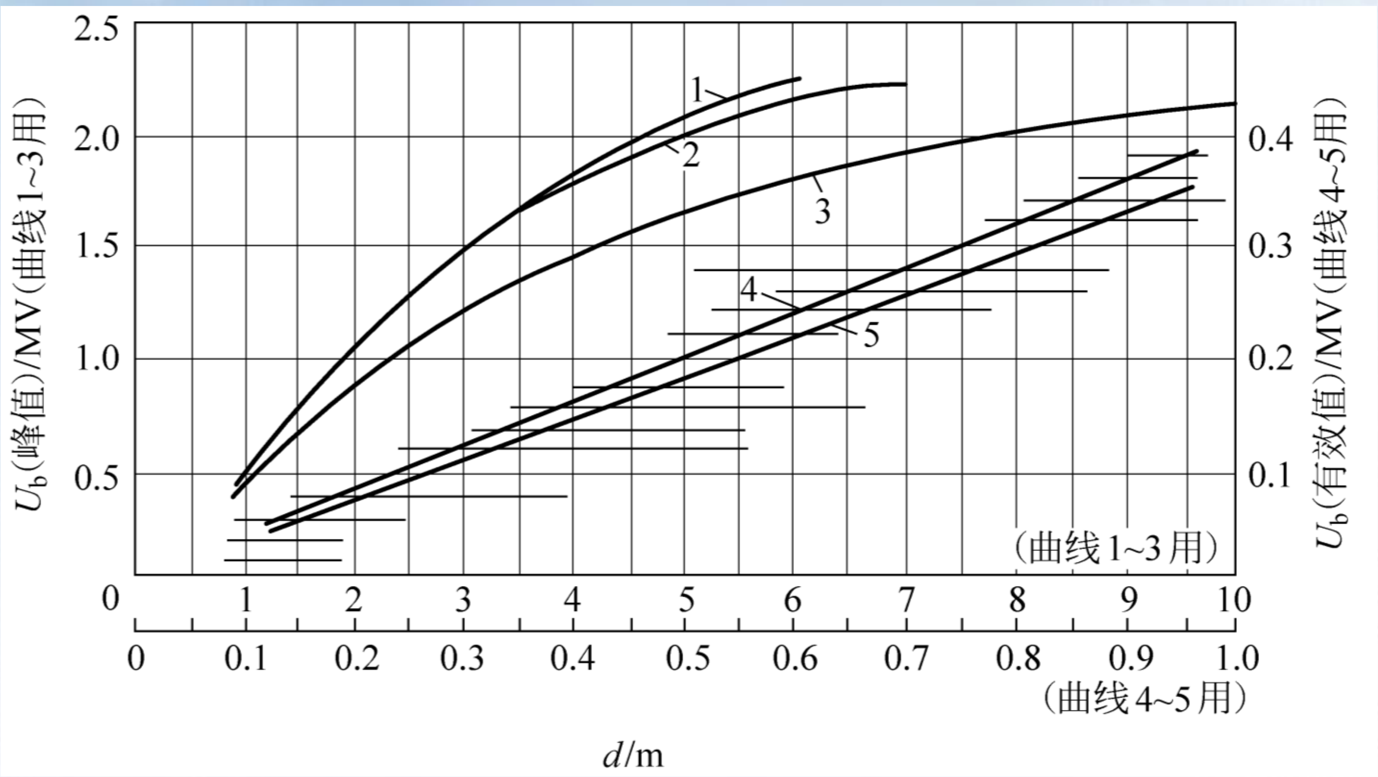
Symmetrical and voltage polarity are the two most important factors influence breakdown

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)



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

Symmetrical and voltage polarity are the two most important factors influence breakdown **for extremely non-uniform electric field**

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

2.3 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
- The development process and the stepped leader, main discharge; 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

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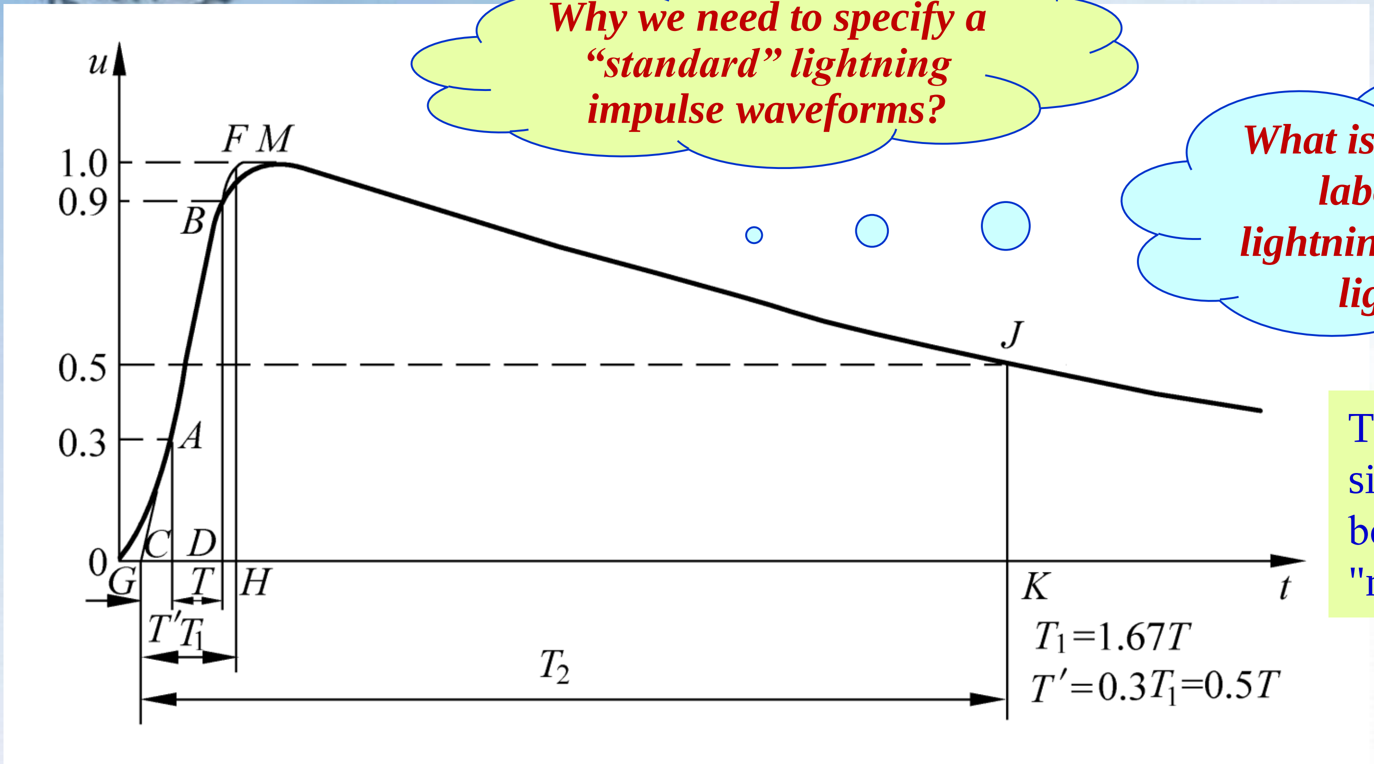
- The discharge current and electricity of lightning to the ground.
- The destructive power of lightning strikes
- Waveform of lightning impulse voltage

What are the key points when we discussing the lightning impulse voltage in Chapter 2?

2.3 Insulation characteristics of air under lightning impulse voltage

(1) Standard waveform
(2) Time lag of discharge
(3) 50% breakdown voltage
(4) v-t characteristic

Why we need to specify a "standard" lightning impulse waveforms?



What is the relation between laboratory standard lightning strikes and natural lightning strikes?

Think about the similarities and differences between "simulation" and "reproduction"

The full waveform of lightning impulse voltage

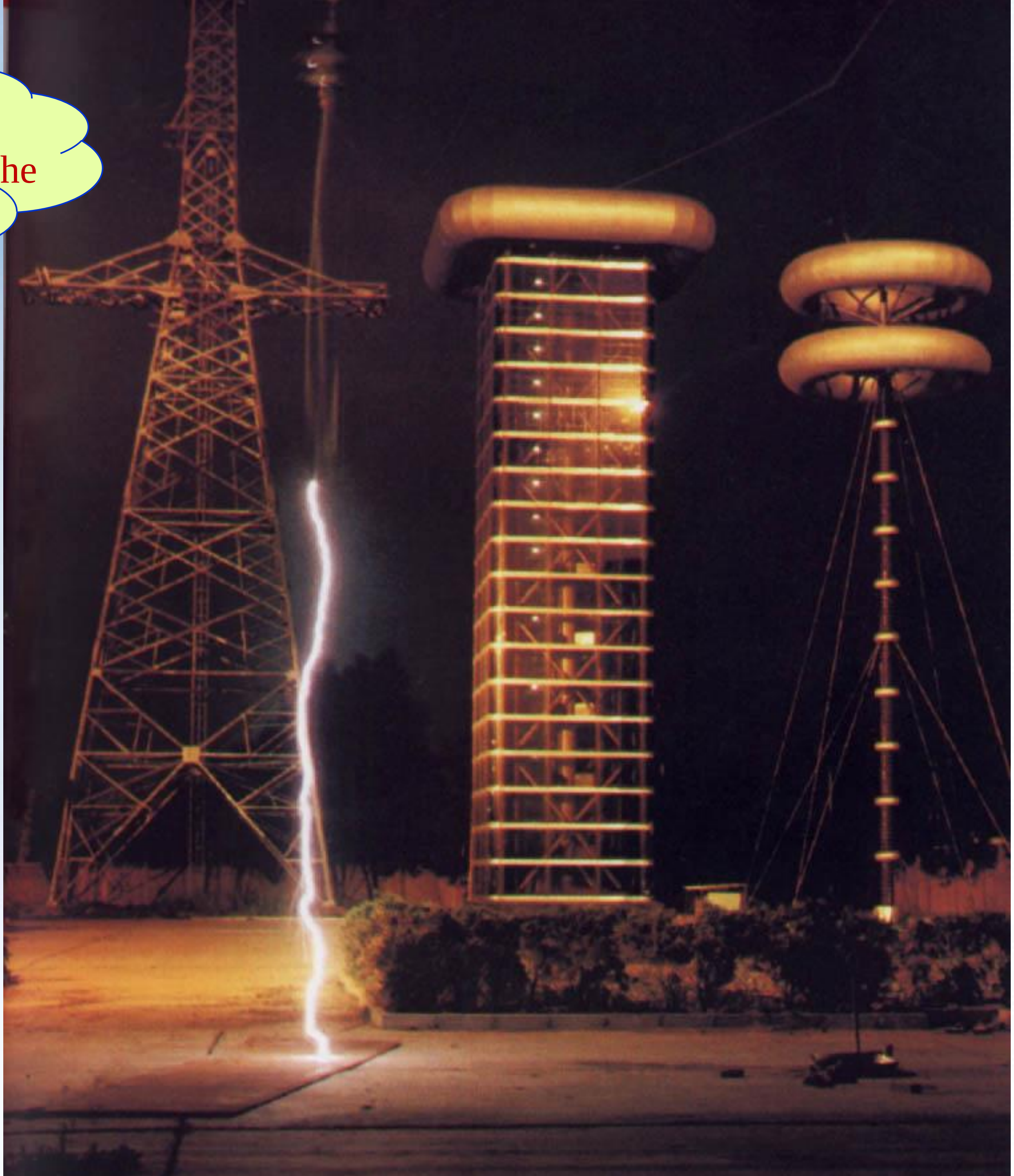
Standard waveform 1.2/50μs
(1.2±30%、50±20%)

Is laboratory "standard" lightning impulse a "standard amplitude" impulse?

How to generate simulated lightning impulse voltage in the laboratory? See Chapt 6

The air gap breakdown under artificially simulated lightning impulse voltage

Think about the similarities and differences between "simulation” and "reproduction"



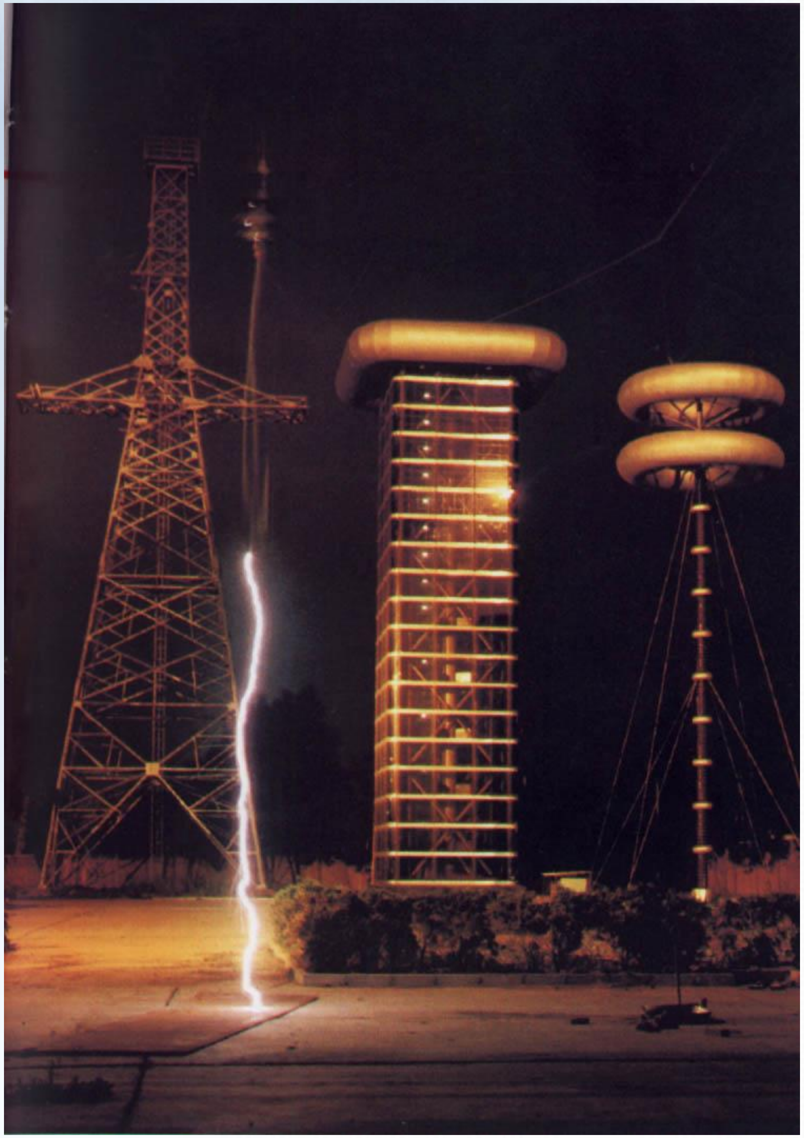
2.3 Insulation characteristics of air under lightning impulse voltage

(1) Standard waveform
(2) Time lag of discharge
(3) 50% breakdown voltage
(4) v-t characteristic

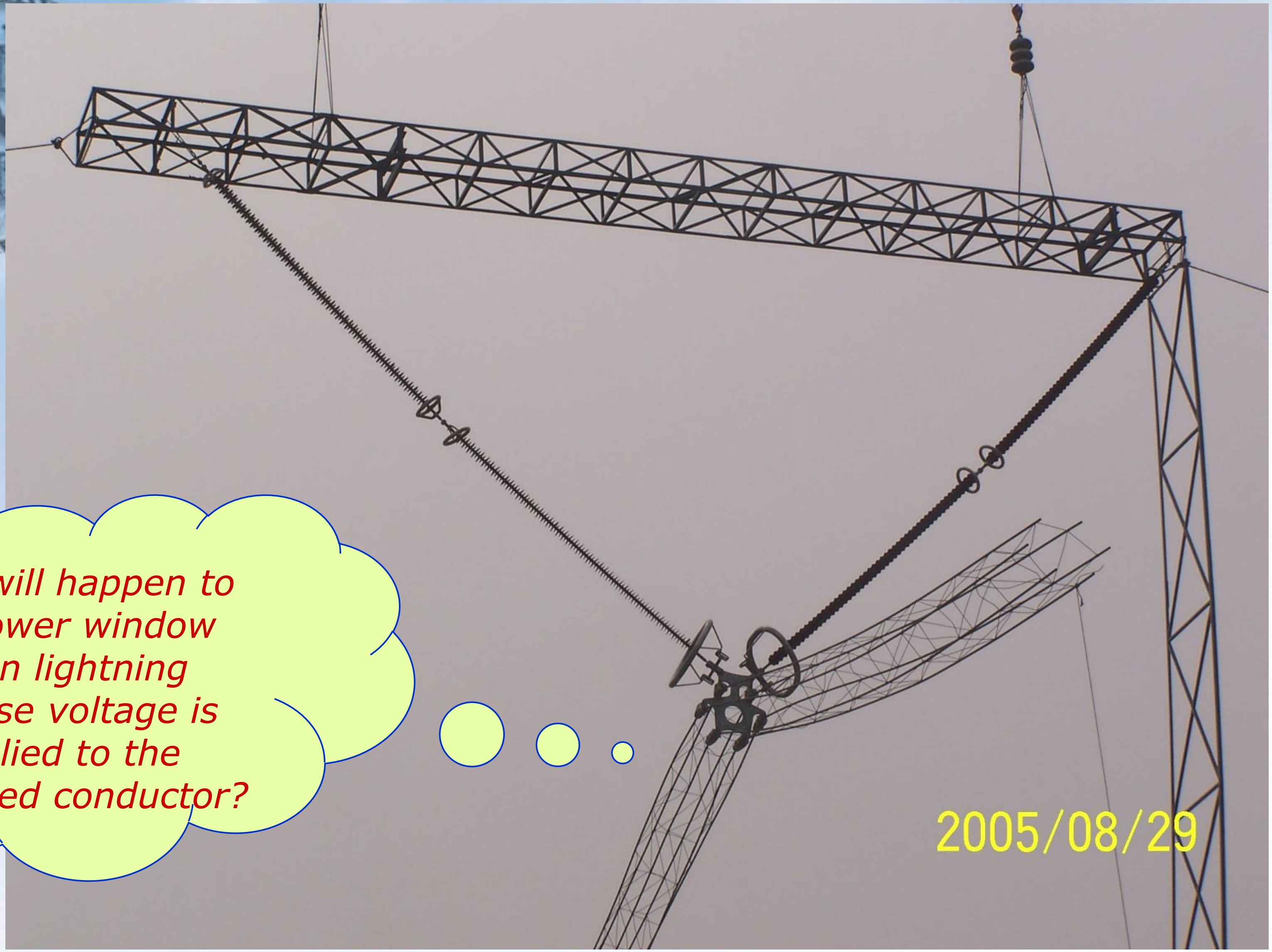
When a standard impulse voltage applied to an air gap, what is the measured voltage waveform of the gap if breakdown occurs

What is the measured voltage waveform if three is no breakdown

How to define the breakdown voltage?



What will happen to the tower window when lightning impulse voltage is applied to the simulated conductor?

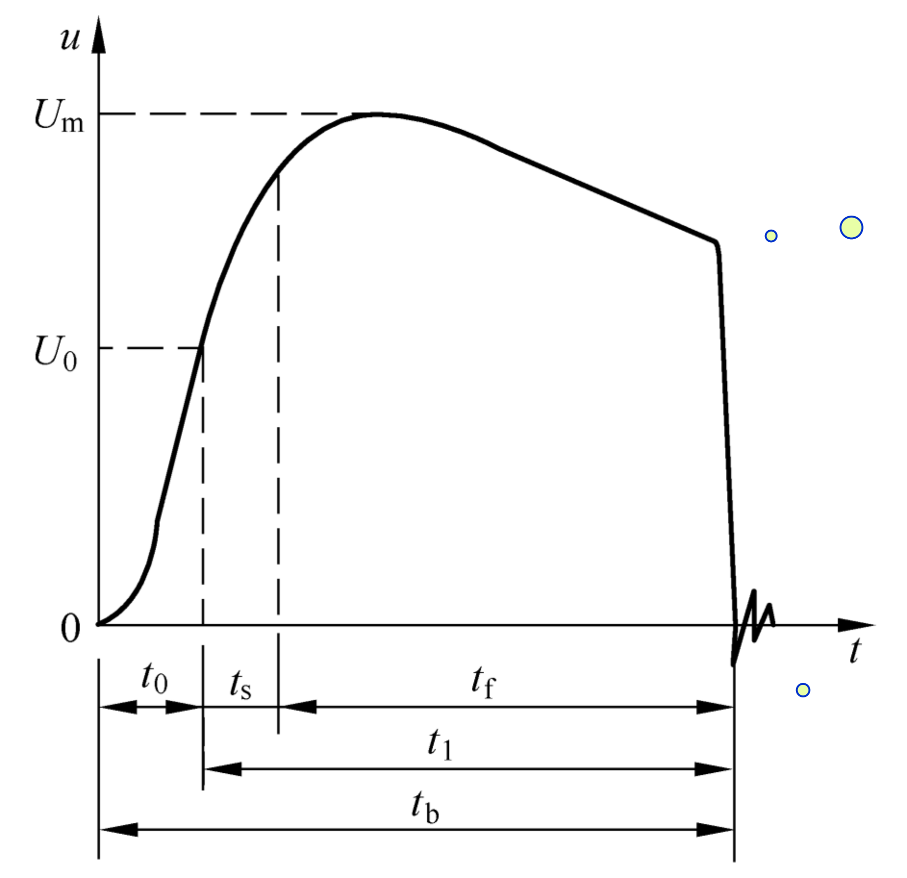


Simulated tower window and simulated conductor

Typical lightning impulse discharge path

2.3 Insulation characteristics of air under lightning impulse voltage

(1) Standard waveform
(2) Time lag of discharge
(3) 50% breakdown voltage
(4) v-t characteristic



How to define the breakdown voltage?

Why is there a discharge time lag in impulse voltage?

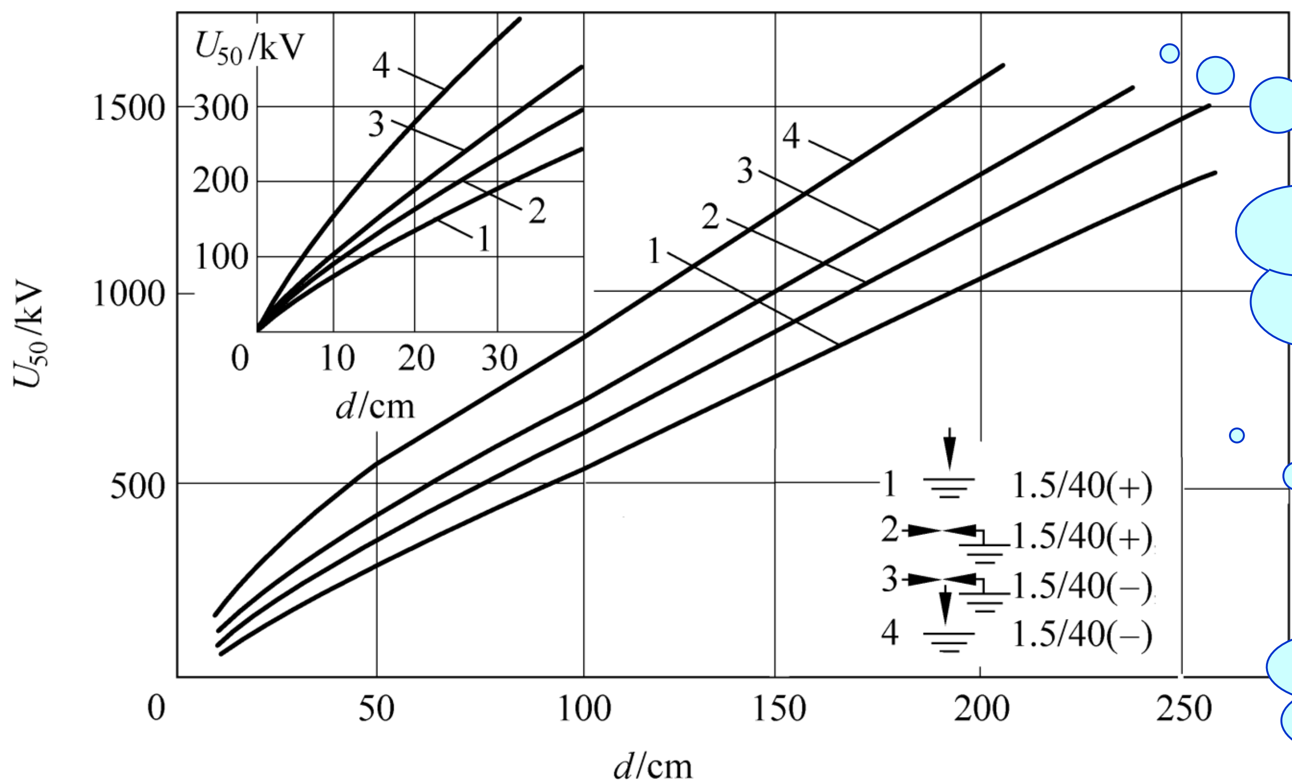
What's the influence of field distribution to time lag, and time lag to breakdown voltage?

Time lag of discharge t_d = statistical time lag t_s + formation time lag t_f

Uniform/slightly non-uniform electric fields are dominated by t_s with short time lag, while extremely non-uniform electric fields are dominated by t_f with long time lag

2.3 Insulation characteristics of air under lightning impulse voltage

(1) Standard waveform
(2) Time lag of discharge
(3) 50% breakdown voltage U_{50}
(4) v-t characteristic



When several standard LI voltage applied to an air gap, how to define the U_b ?

What is U_{50}?
Why to use U_{50}?
How to obtain U_{50}?

Figure 2-22 Relation between lightning impulse 50% breakdown voltage and gap distance of rod-rod and rod-plane air gap

1−1.5/40(+), d >40cm, $U_b = 40+5d$; 2−1.5/40(+), d >40cm, $U_b = 75+5.56d$

3−1.5/40(−), d >40cm, $U_b = 110+6d$; 4−1.5/40(−), d >40cm, $U_b = 215+6.7d$

2.3 Insulation characteristics of air under lightning impulse voltage

- For impulse voltage, **50% breakdown voltage U_{50}** is generally used to represent the insulation characteristics of a gap
- The simplest method to determine the U_{50} for a gap: Keeping the standard waveform unchanged, stepwise increase the voltage magnitude, apply per level of voltage for 10 times, until 4-6 breakdown occurs, then this voltage can be used as the approximate U_{50} of the gap
- The more impulse in each voltage level is applied, the more accurate the U_{50} will be
- Another method to obtain U_{50} by experiment is called “Up-and-Down”(Chapter 7)

- When using U_{50} to determine gap insulation distance, necessary margin should be left
- The discharge probability of impulse voltage is generally considered to follow a Gauss distribution, and the relative standard deviation σ of lightning impulse voltage is ≈ 3%

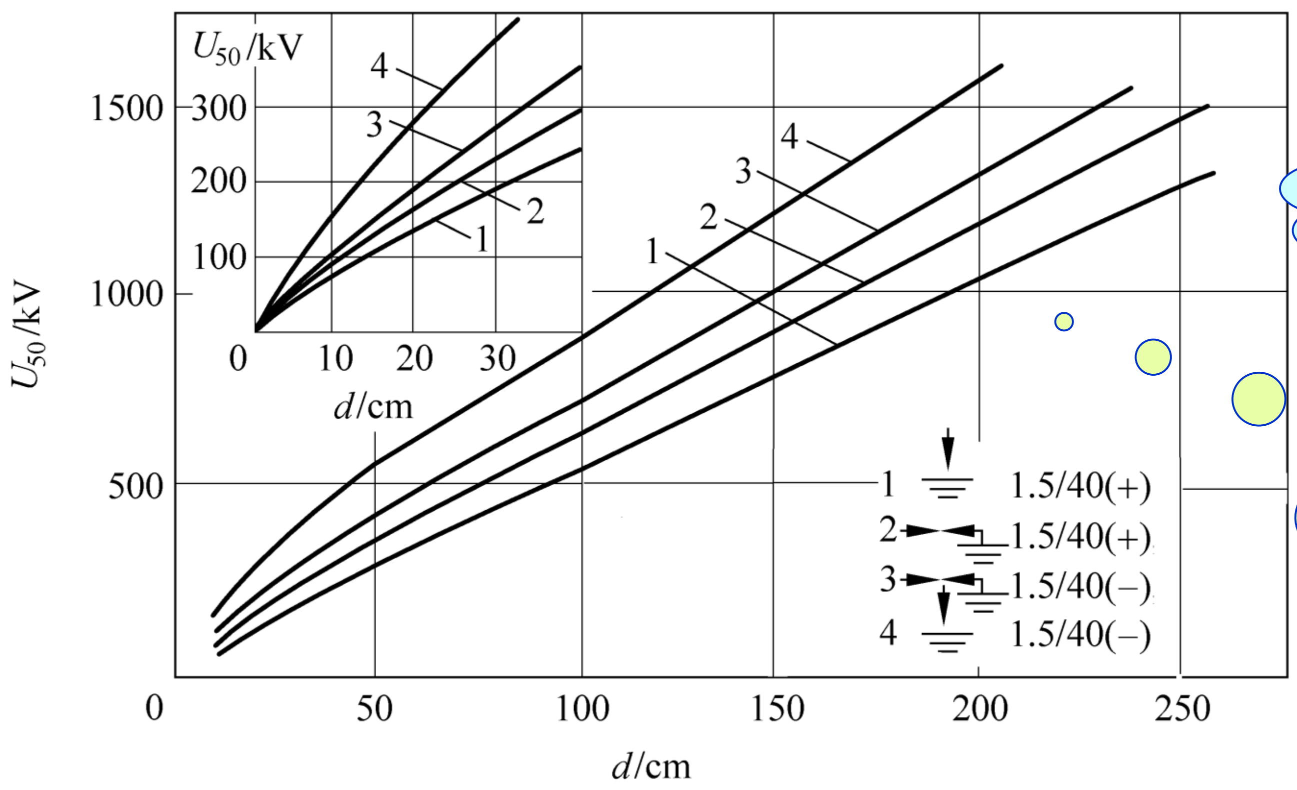
- U_{50} (1-1.3σ) = 0.96U_{50} is commonly used as the withstand voltage for self recoverable outdoor insulation gaps, with a withstand probability of 90%. For occasions with higher safety requirements, U_{50} (1-3σ) = 0.91U_{50} can be used as the withstand voltage of the gap with a withstand probability of 99.85%.

Gas insulation can be quickly self-recovered (self-restoring insulation)

2.3 Insulation characteristics of air under lightning impulse voltage

50% breakdown voltage U_{50} (generally believed to follow a Gauss distribution)

$U_{withstand} = U_{50}(1-n\sigma)$



Lightning impulse voltage ($\sigma \approx 3\%$)

The breakdown voltage curve of impulse voltage is a strip-shaped area

Figure 2-22 Relationship between lightning impulse 50% breakdown voltage and gap distance of rod-rod and rod-plane air gap

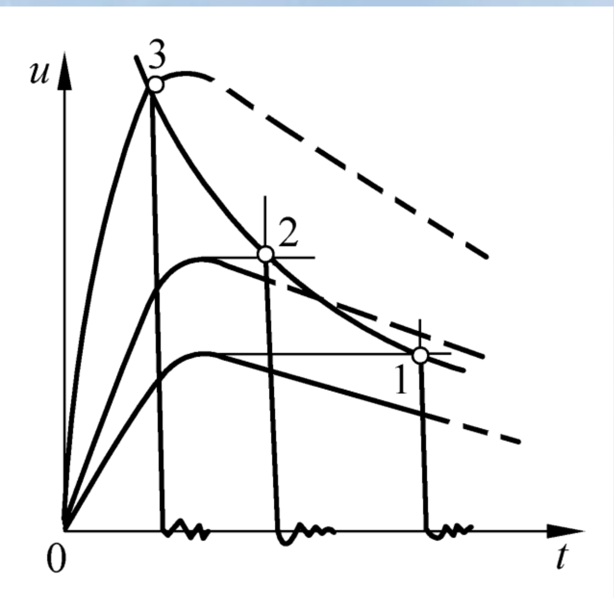
1−1.5/40(+), d >40cm, $U_b = 40+5d$; 2−1.5/40(+), d >40cm, $U_b = 75+5.56d$

3−1.5/40(−), d >40cm, $U_b = 110+6d$; 4−1.5/40(−), d >40cm, $U_b = 215+6.7d$

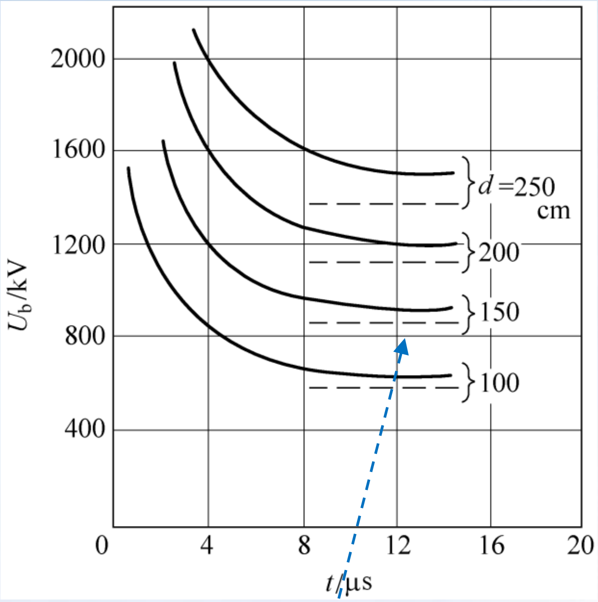
2.3 Insulation characteristics of air under lightning impulse voltage

(1) Standard waveform
(2) Time lag of discharge
(3) 50% breakdown voltage
(4) v-t characteristic

Due to the influence of time lag, the v-t curve of a uniform field are relatively flat, but tend to increase significantly when time decrease for an extremely non-uniform field

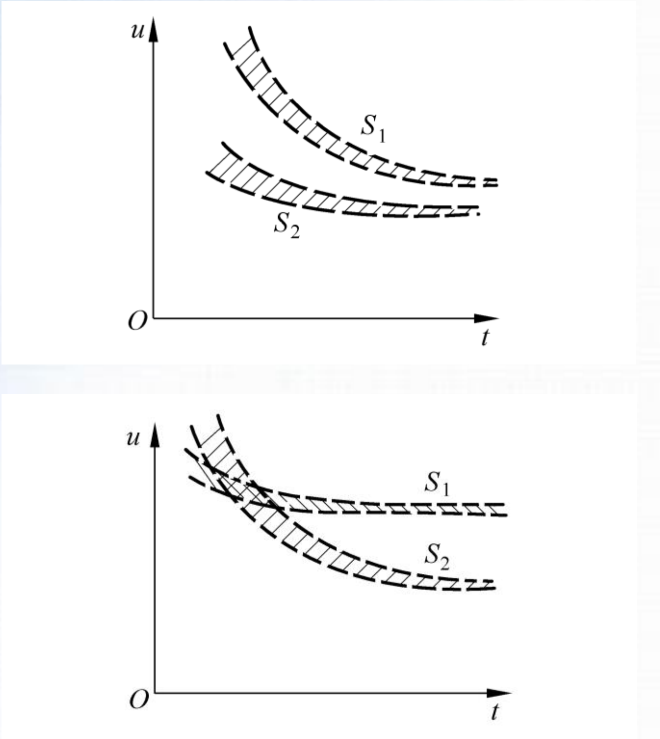


Obtaining the voltage-time characteristic curve



v-t curve of rod-rod air gap

(dotted line represents the power frequency breakdown voltage of the gap)



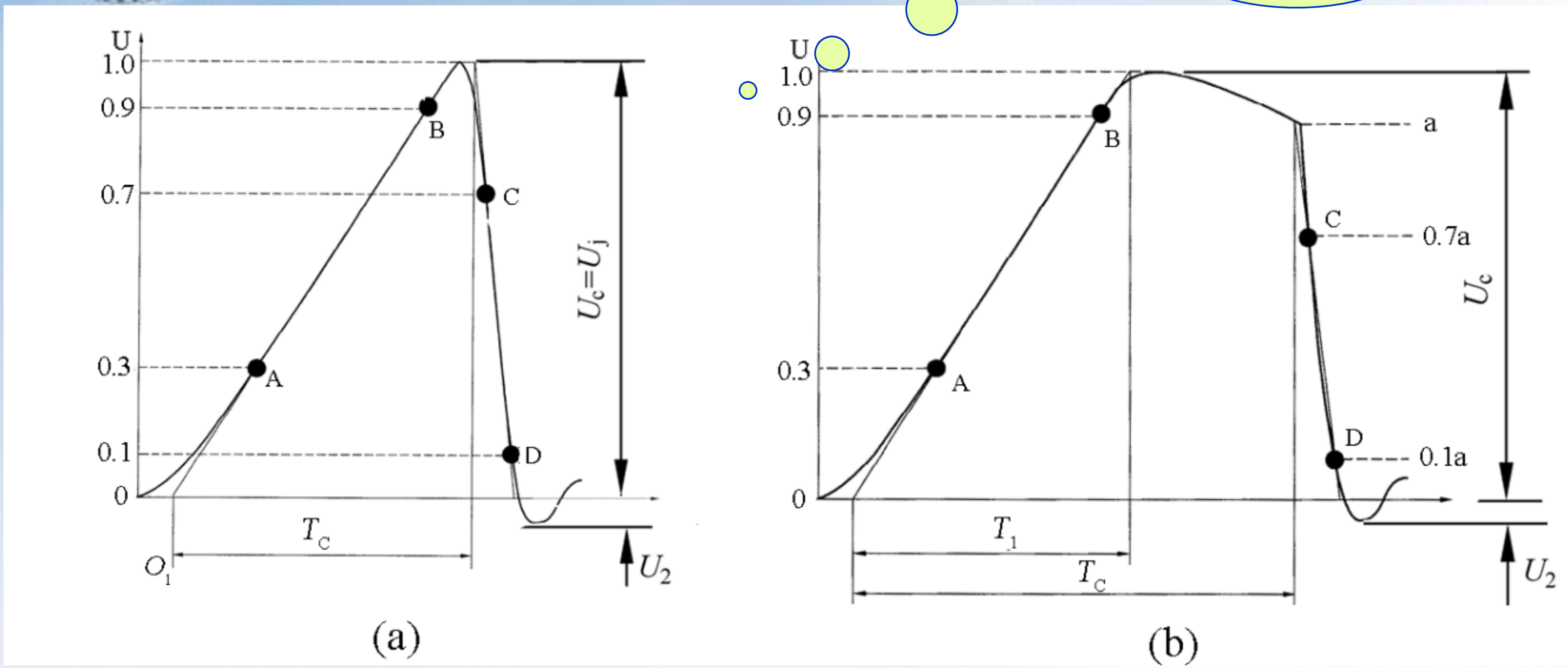
v-t curves of two parallel gap clearances

Lightning protection in Chapter 9

2.3 Insulation characteristics of air under lightning impulse voltage

Standard waveform of **chopped impulse voltage**

Some internal insulation of electrical equipment, such as transformers and motor windings, are more afraid of chopped-wave impulse and require chopped-wave tests



Schematic waveform diagram of chopped lightning impulse voltage

(a) Wave chopped at front

(b) Wave chopped at tail

Insulation is normally punctured by the amplitude of applied voltage.

But in some case, steepness of applied voltage is the most important factor.

Chapter 2 Insulation Characteristics of Air under Different Voltage Waveforms

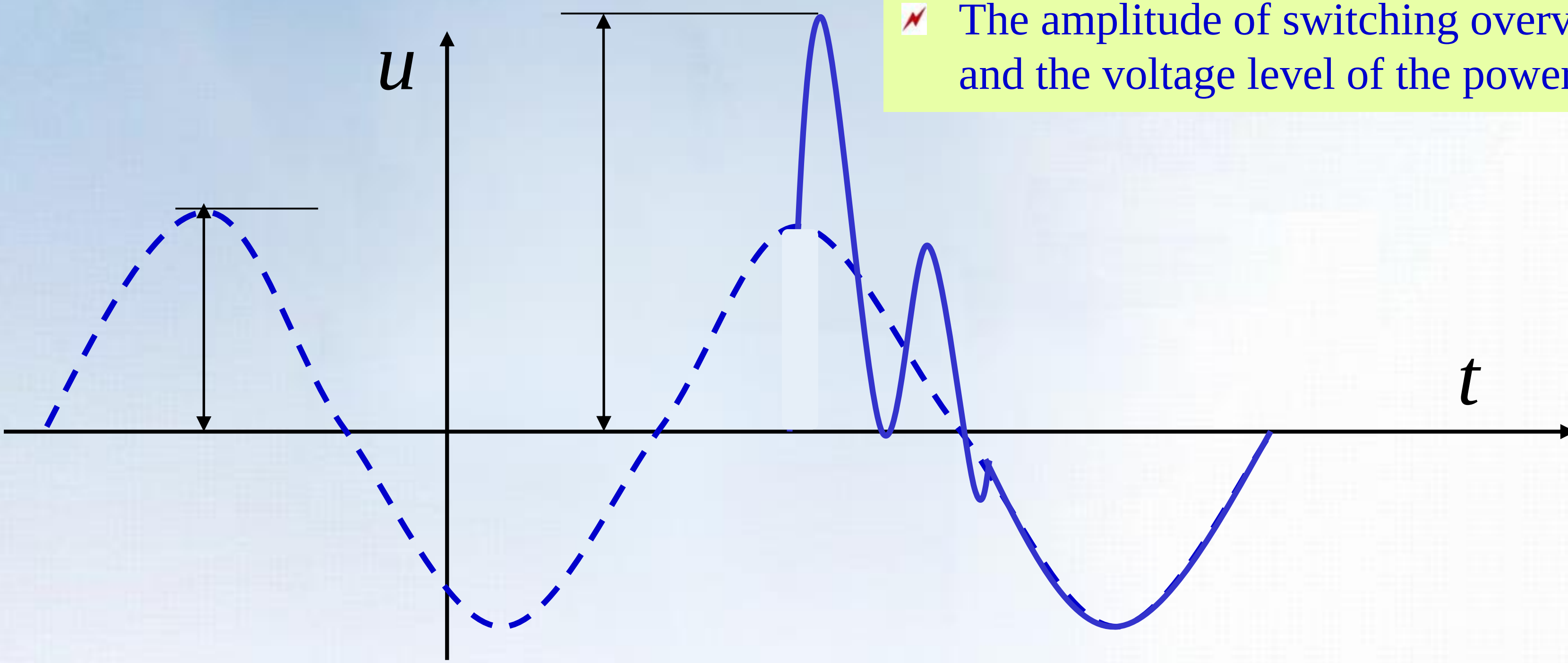
Core concepts of this chapter:

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

2.4 Insulation characteristics of air under switching impulse voltage

2.4.1 Occurrence of switching impulse voltage and its waveform

- Transition process and switching overvoltage in power system
- Waveform of switching overvoltage
- The amplitude of switching overvoltage and the voltage level of the power grid



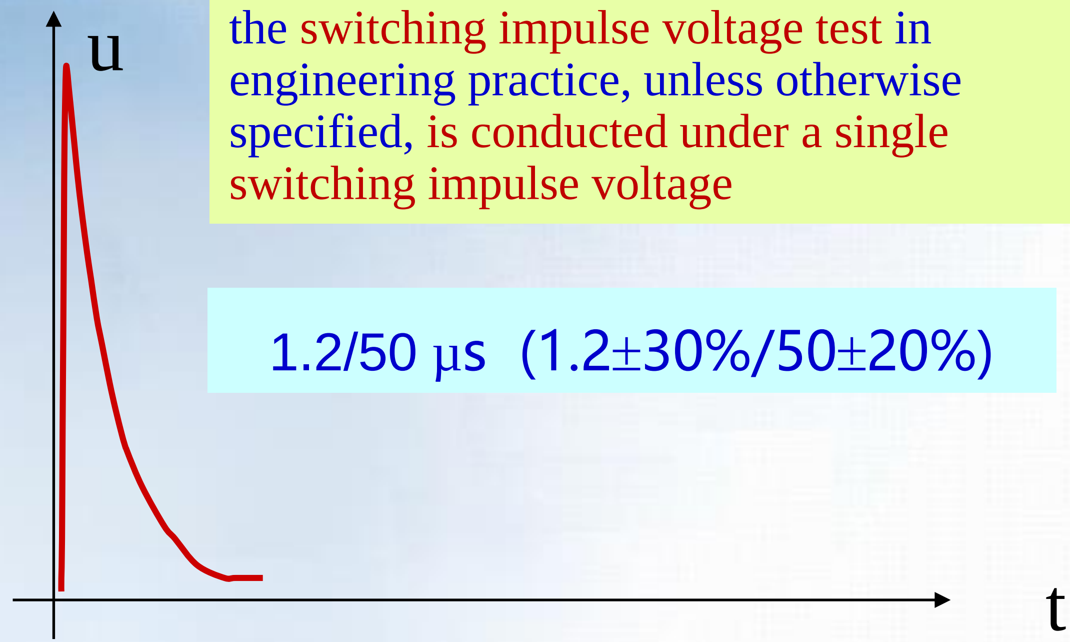
Using which type of tests to simulate switching impulse voltage, and insulation characteristics of air gaps under simulated switching impulse voltage are the main concerns in this section.

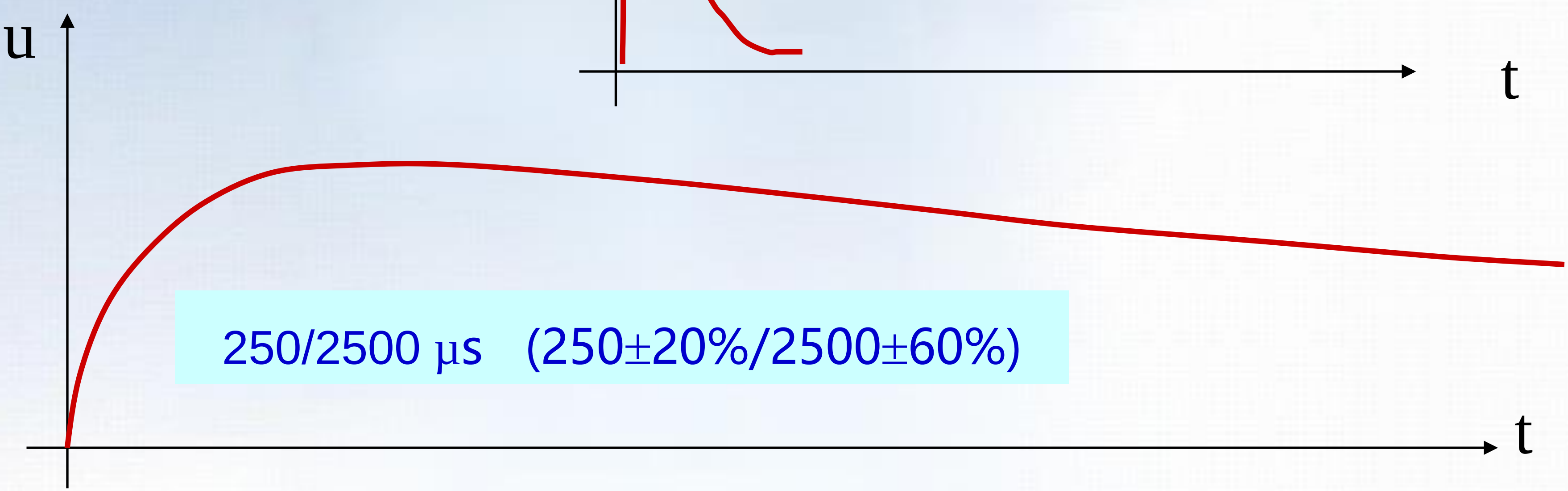
Switching overvoltage protection is described in Chapter 10.

Waveform comparison:
standard lightning impulse voltage
and
standard switching impulse voltage

Although the actual switching overvoltage in the power system is superimposed on different phases of the AC voltage,

the switching impulse voltage test in engineering practice, unless otherwise specified, is conducted under a single switching impulse voltage





2.4.2 Characteristics of switching impulse voltage

Although the actual switching overvoltage in the power system is superimposed on different phases of the AC voltage,

the switching impulse voltage test in engineering practice, unless otherwise specified, is conducted under a single switching impulse voltage

(1) U-shaped curves

(2) Polarity effect of asymmetric electric field

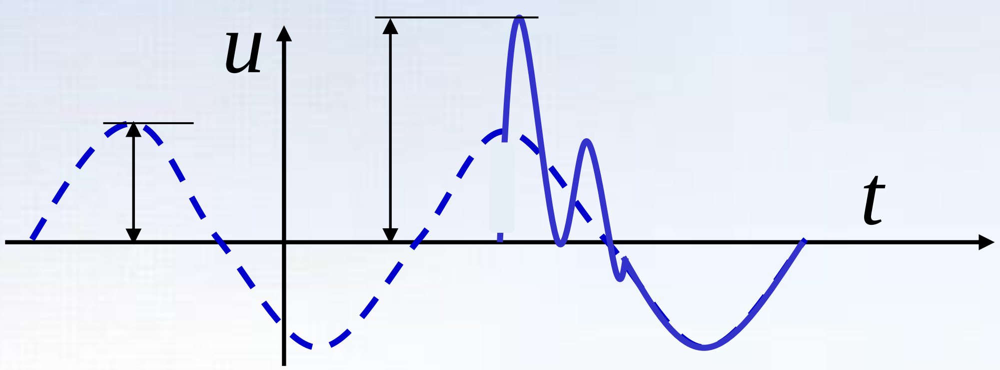
(3) The saturation phenomenon of long air gaps

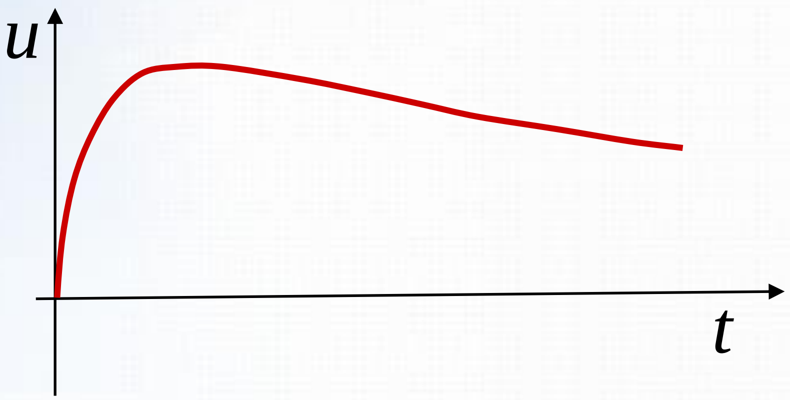
(4) 50% breakdown voltage and dispersion

(5) Effect of nearby earthed object

(6) Empirical formula for minimum air gap breakdown voltage

Think about the similarities and differences between "simulation" and "reproduction"

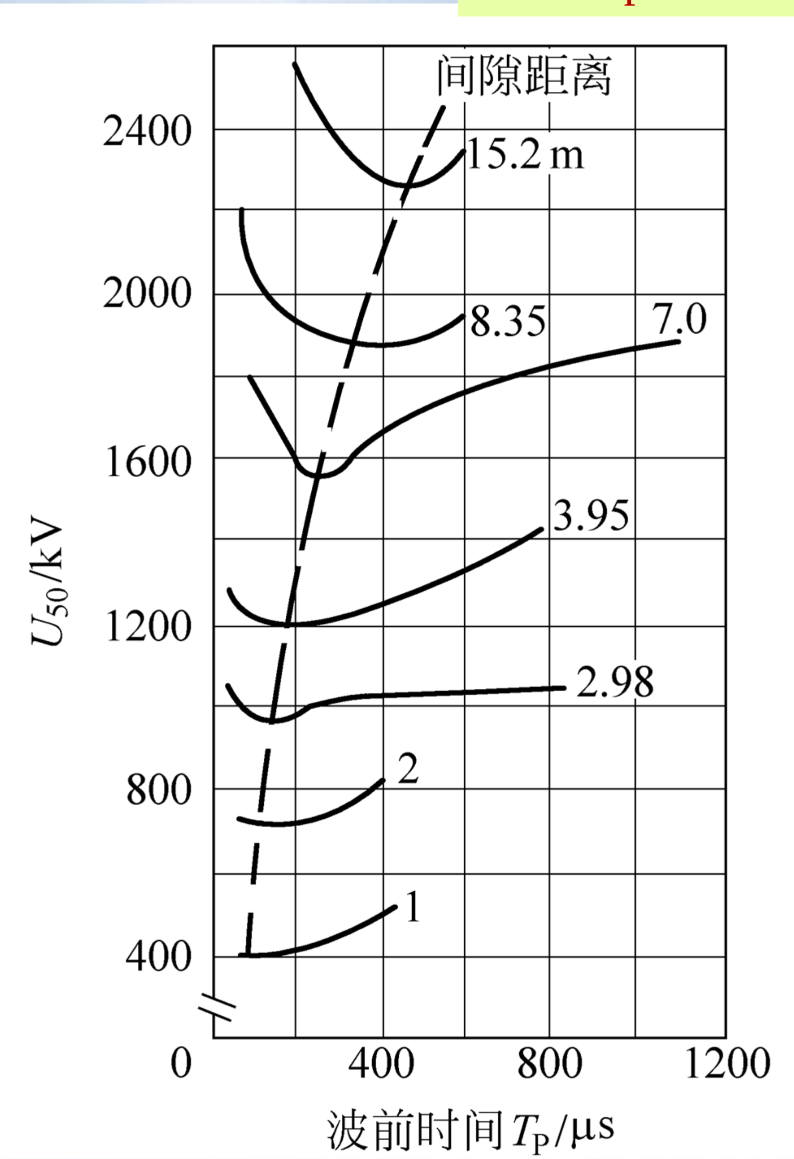




2.4.2 Characteristics of switching impulse voltage

U-shaped curves

Positive rod-plane air gap switching impulse voltage



The critical wavefront time increases with the increase of gap distance.

For gaps distance < 7m, the critical wave front time is between 100-300 μs

2.4.2 Characteristics of switching impulse voltage

Positive rod-plane air gap switching impulse voltage

The critical wavefront time increases with the increase of gap distance.

For gaps distance < 7m, the critical wave front time is between 100-300 μs

Therefore, a long gap requires a long wave front switching impulse voltage test, which cannot be done with only 250/2500 standard wave

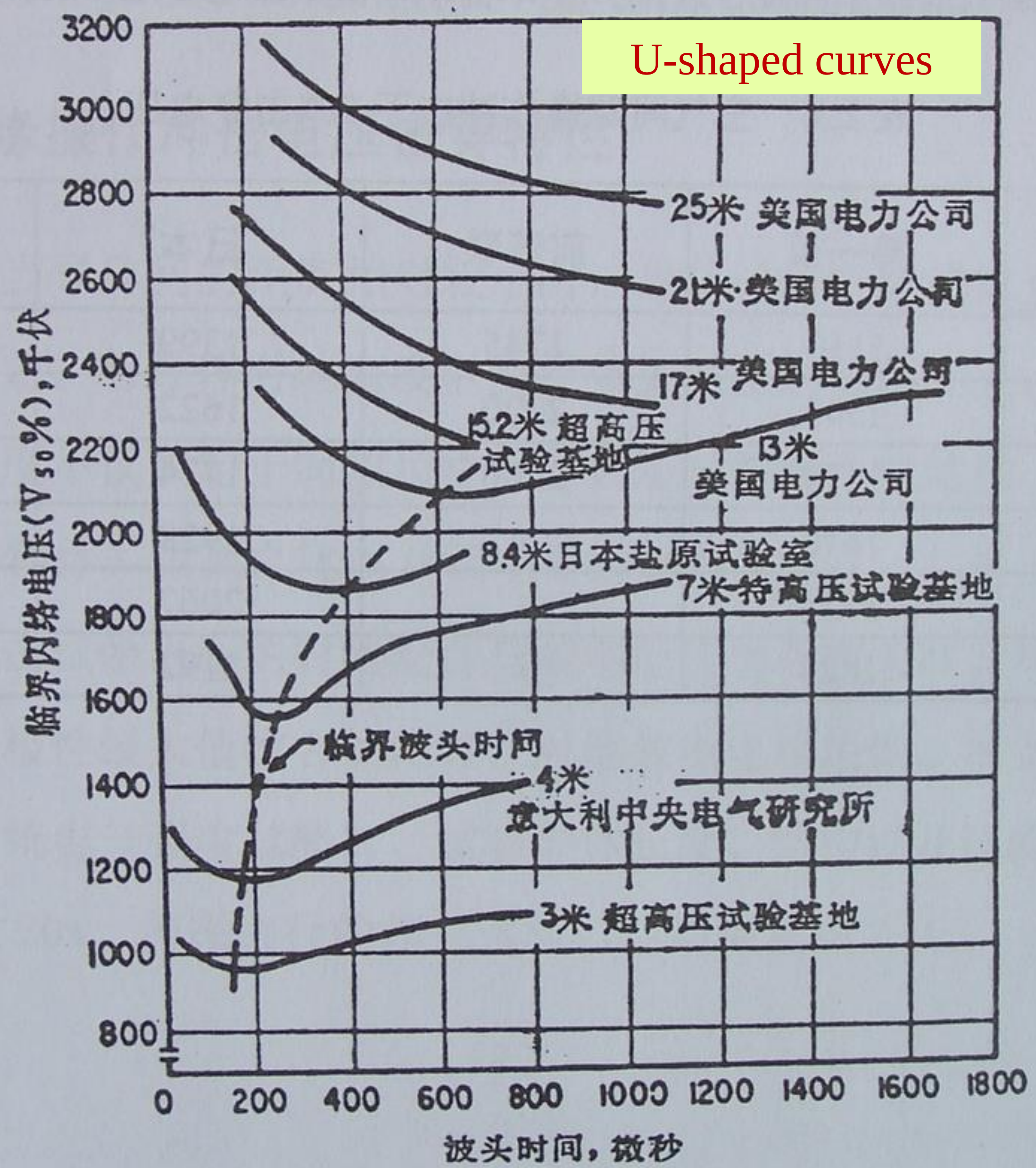


图 2-2 棒—板间隙临界闪络电压

2.4.2 Characteristics of switching impulse voltage

U-shaped curves

Positive rod-plane air gap switching impulse voltage

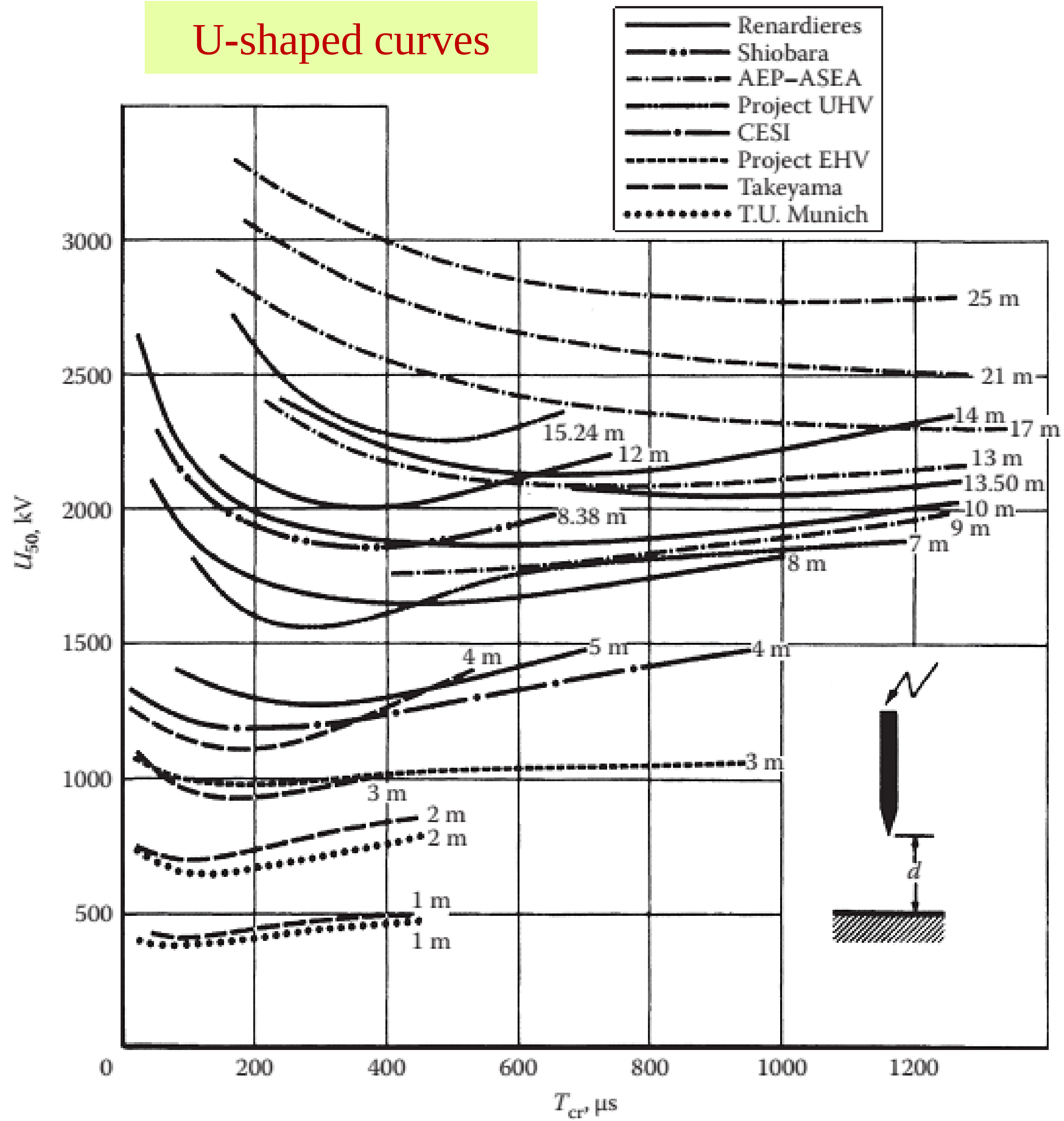


FIGURE 5.6 Data collection of 50% positive switching impulse breakdown voltage as a function of time to crest of rod–plane configuration for different spacings. (From Leroy, G., Recent developments in the physics and engineering of high voltage breakdown, in: *IEE Gas Discharge Conference* (Review Lecture, Opening Session), London, U.K., September 1974.)

Therefore, a long gap requires a long wave front switching impulse voltage test, which cannot be done with only 250/2500 standard wave

The switching impulse breakdown voltage of the rod-plane gap is sometimes lower than the peak breakdown voltage at power frequency

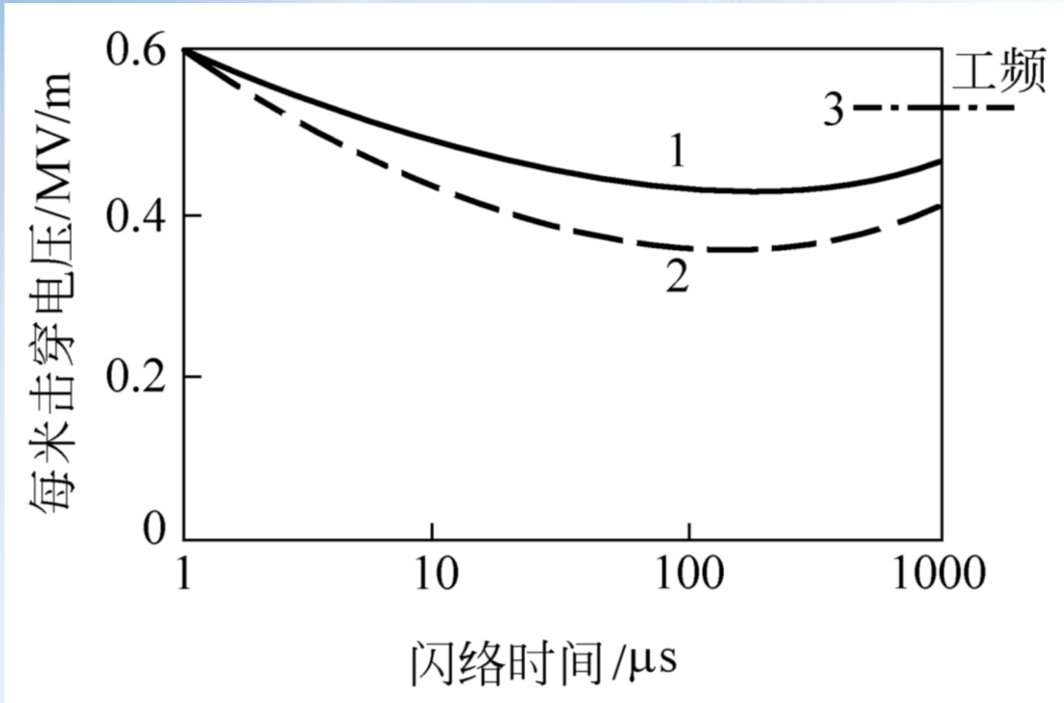
2.4.2 Characteristics of switching impulse voltage

U-shaped curves

Positive rod-plane air gap switching impulse voltage

The switching impulse breakdown voltage of the rod-plane gap is sometimes lower than the peak breakdown voltage at power frequency

- How to understand the U-shaped curve of long air gap under switching impulse voltage?
- How to understand the switching impulse breakdown voltage is lower than that of under power frequency?



Relation between switching impulse breakdown voltage and wave front time in rod-plane gap

1--Rod-rod gap; 2--Conductor-plane gap; 3--Power frequency breakdown voltage

2.4.2 Characteristics of switching impulse voltage

U_{50}, polarity effect, saturation phenomenon

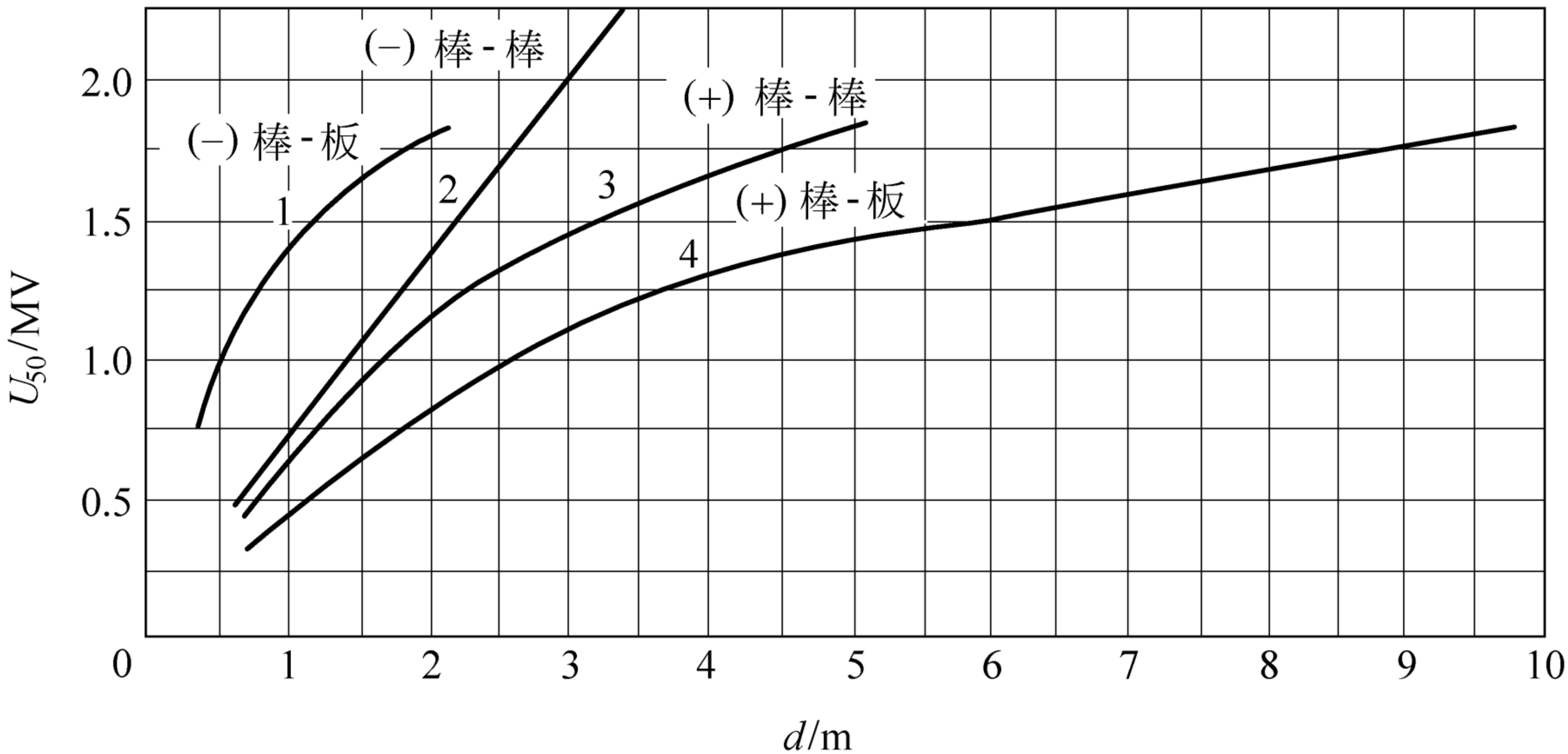


Figure 2-33 Relation between 50% breakdown voltage and gap distance in rod-plane and rod-rod air gap under switching impulse voltage (500 μs/5000 μs)

1- Rod-plane, negative polarity; 2- Rod-rod, negative polarity;
3- Rod-rod, positive polarity; 4- Rod-plane, positive polarity

2.4.2 Characteristics of switching impulse voltage

polarity effect,
saturation phenomenon

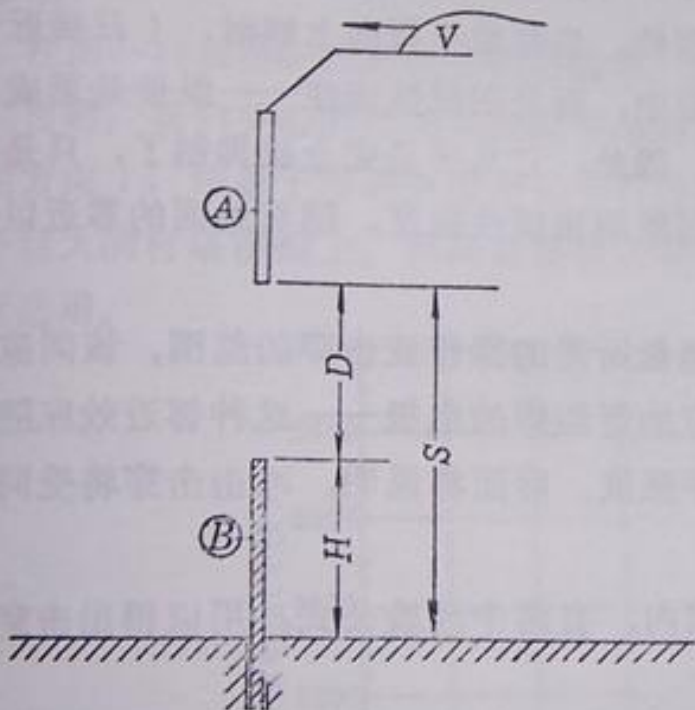


图 6-9 垂直棒对棒间隙和棒对板间隙（$H=0$）的基本间隙几何

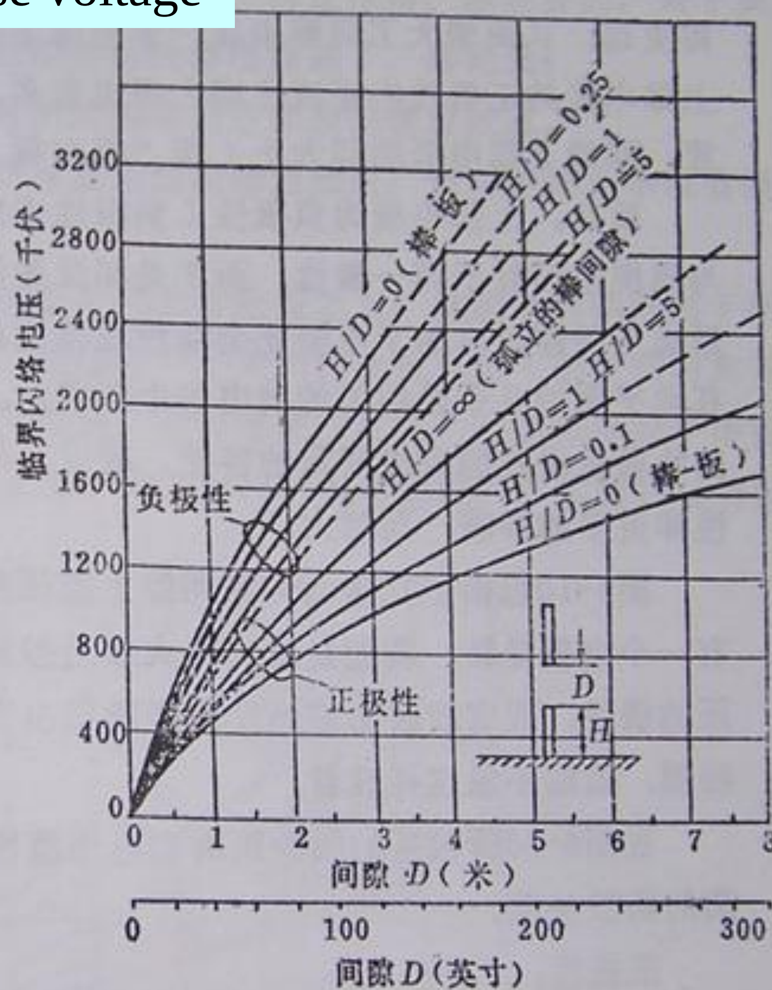


图 6-10 棒对棒和棒对板间隙的操作波闪络强度

（波头100～200微秒，蒸汽压力≈0.5英寸水银柱）

Rod-plane and rod-rod gap, switching impulse voltage curve

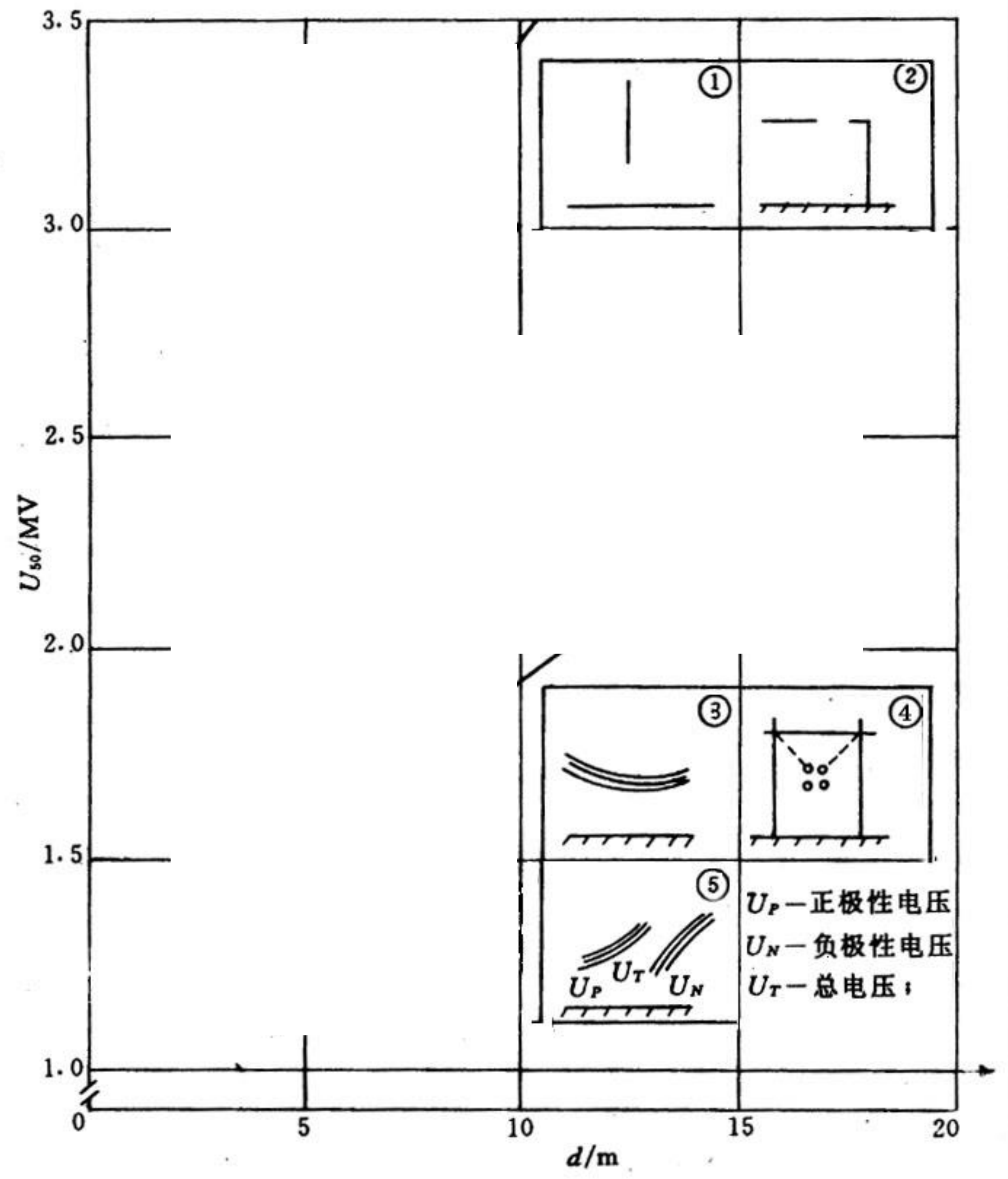
2.4.2 Characteristics of switching impulse voltage

The influence of different electrode structures

The analysis of extremely non-uniform electric fields mainly focuses on:

- Electric field is symmetric or not:
  rod-rod, rod-plane

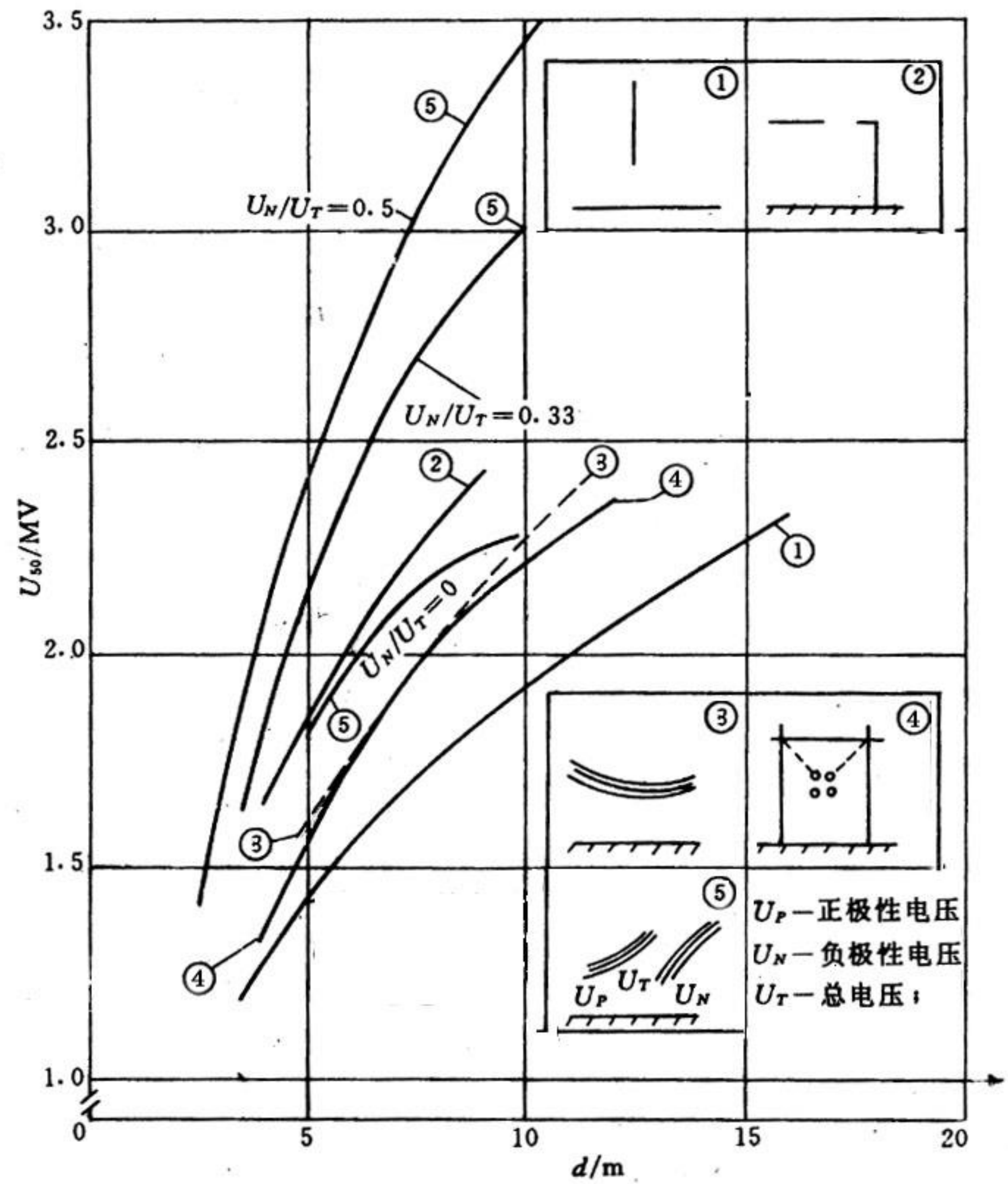
- Voltage polarity:
  positive or negative



2.4.2 Characteristics of switching impulse voltage

The influence of different electrode structures

Figure 2-34 Positive polarity switching impulse voltage curve



Positive rod-plane gap

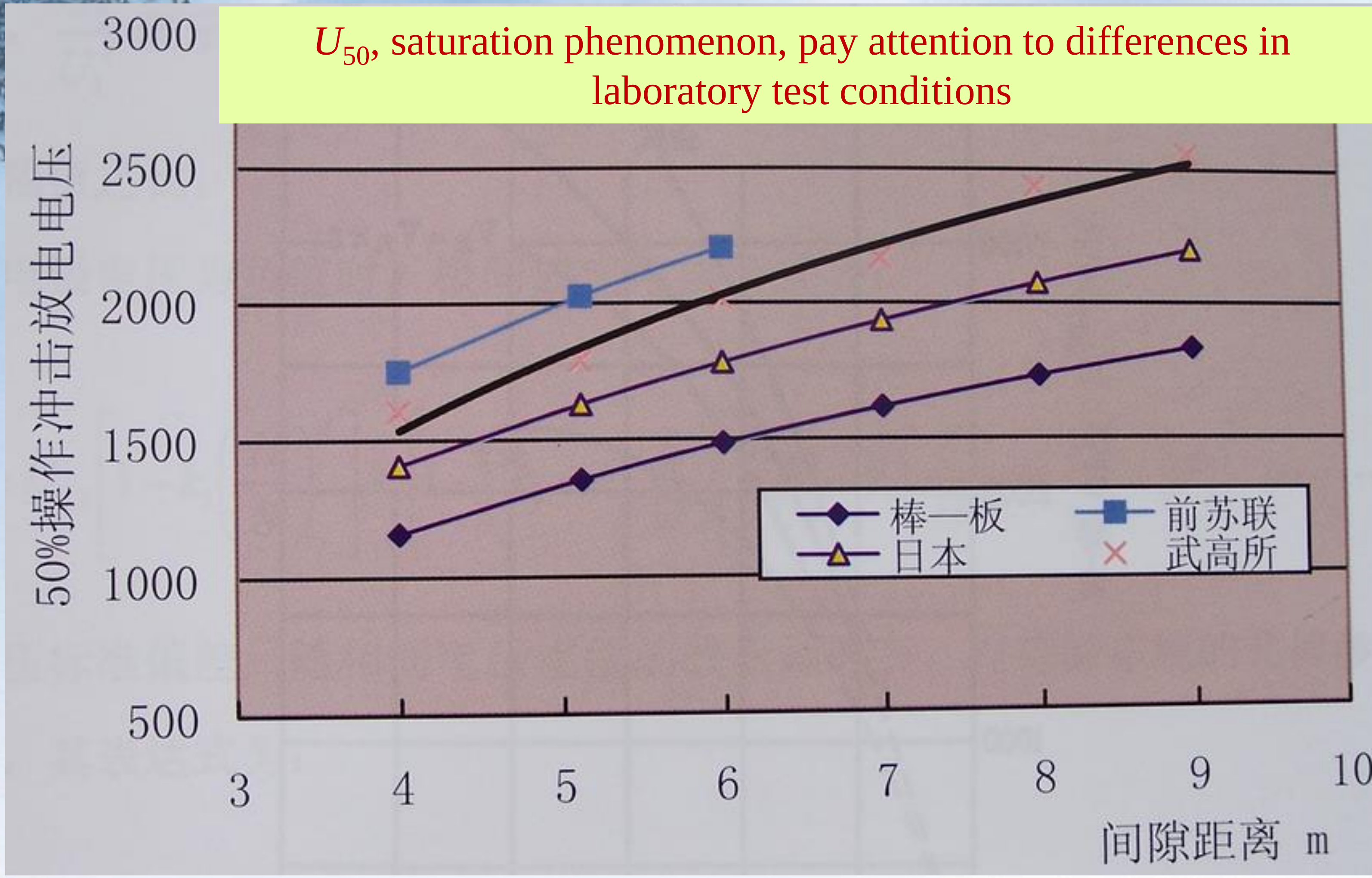
1280/5=256kV/m

1860/10=186kV/m

2220/15=148kV/m

2.4.2 Characteristics of switching impulse voltage

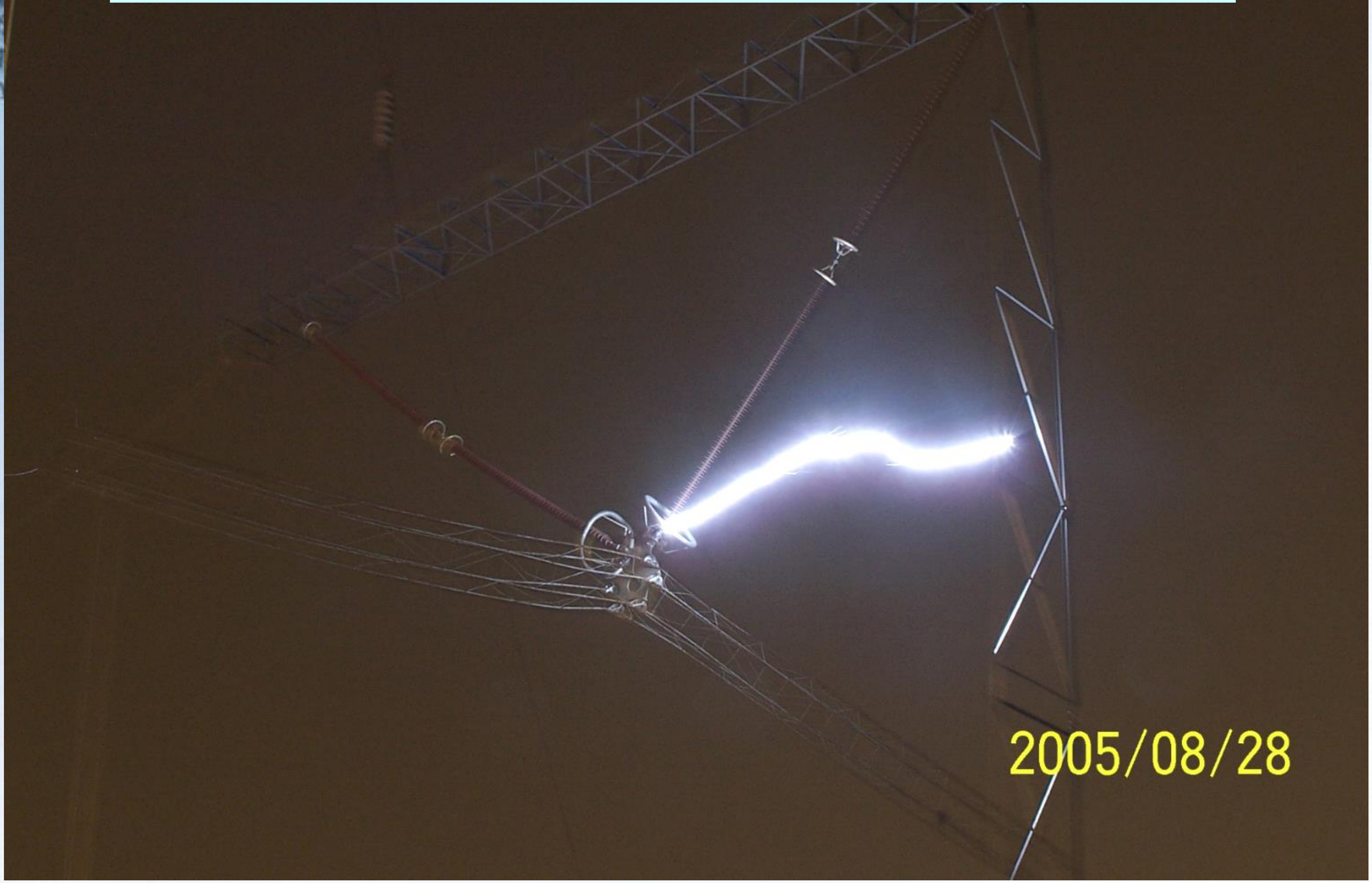
U_{50}, saturation phenomenon, pay attention to differences in laboratory test conditions



Positive polarity switching impulse voltage curve of conductor- tower

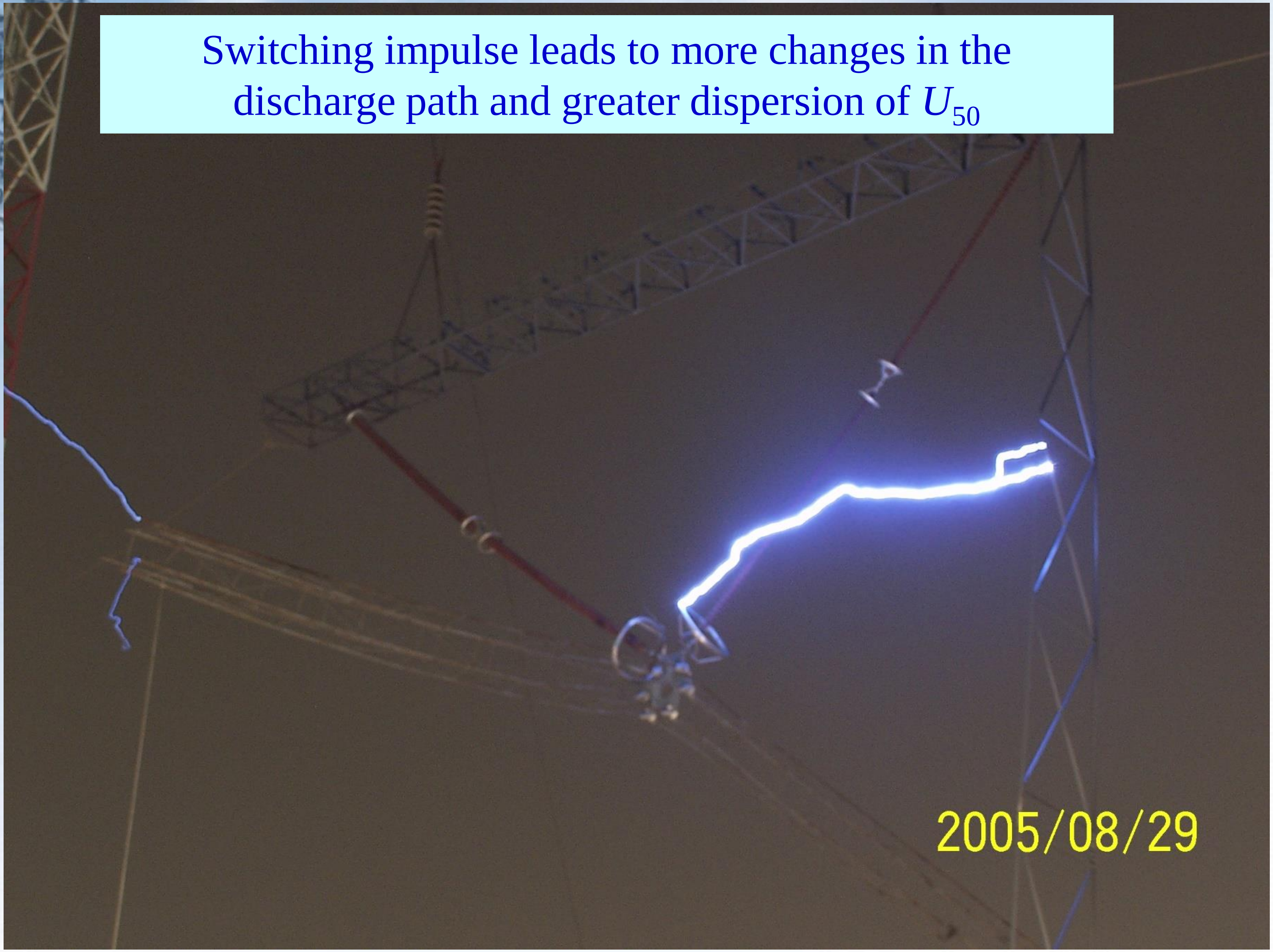
1200/4 = 300kV/m, 1500/6 = 250kV/m, 1800/9 = 200kV/m

Lightning impulse discharge almost always follows the shortest path to air gap clearance



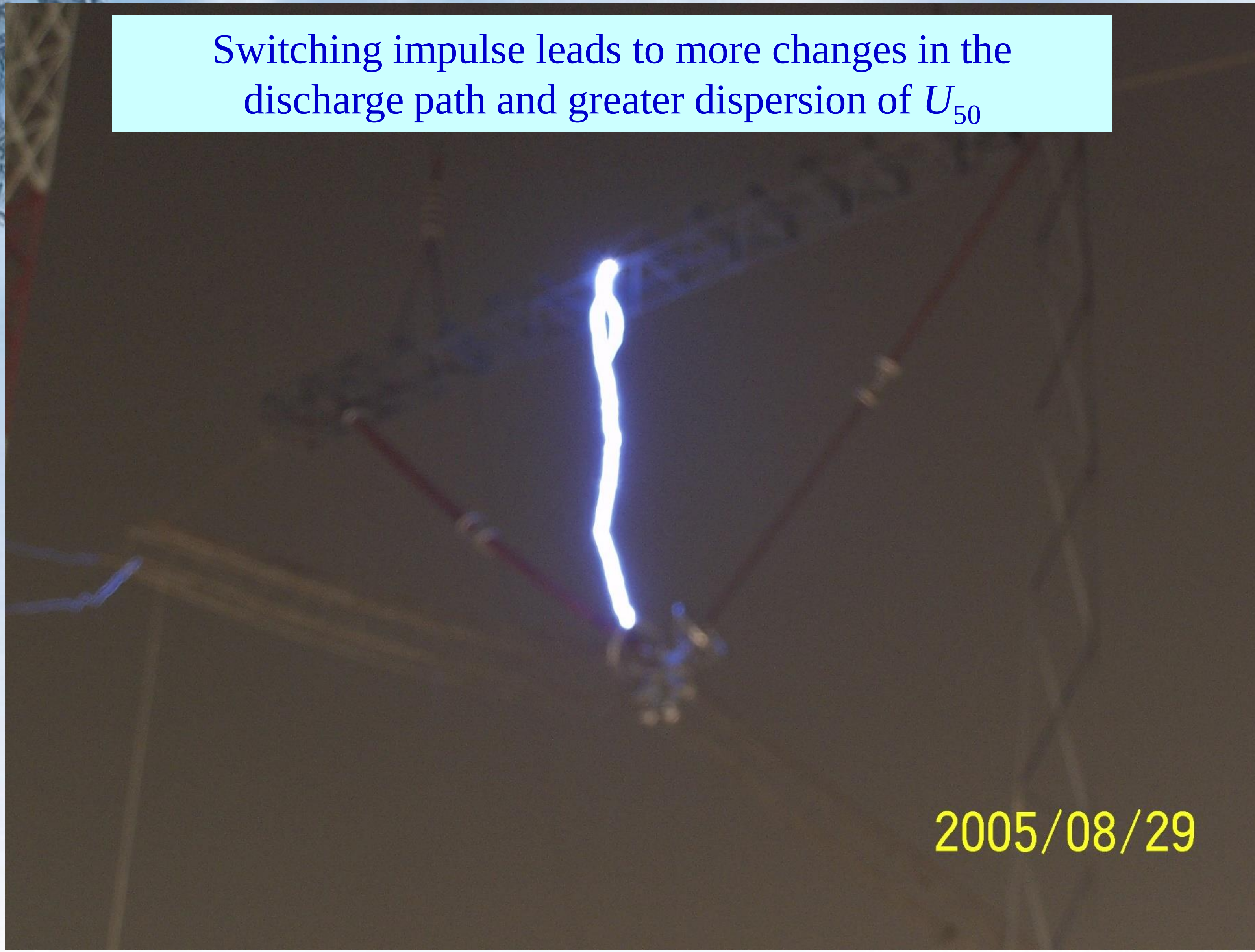
Typical lightning impulse discharge path

Switching impulse leads to more changes in the discharge path and greater dispersion of U_{50}



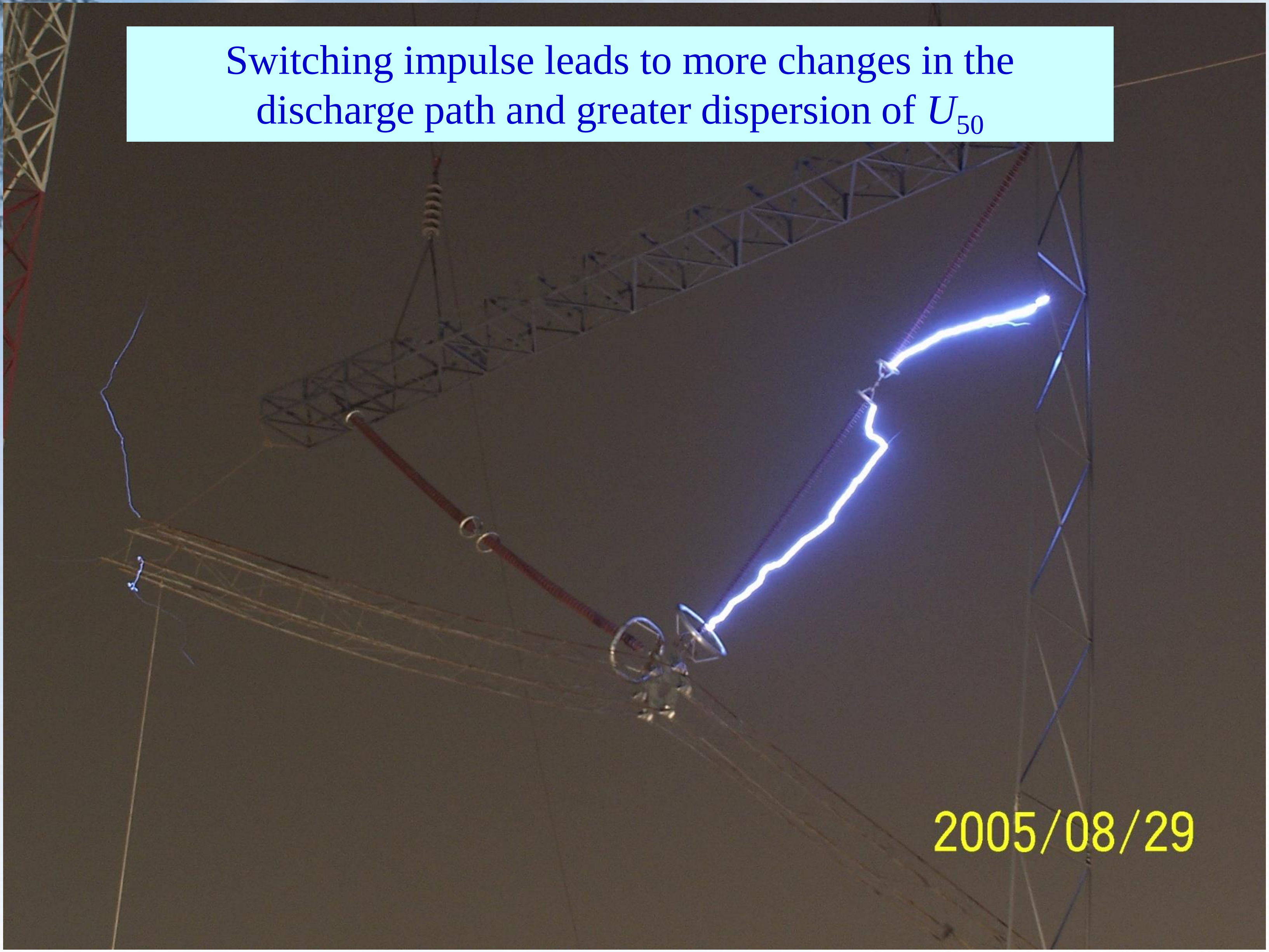
Typical lightning impulse discharge path 1

Switching impulse leads to more changes in the discharge path and greater dispersion of U_{50}



Typical lightning impulse discharge path 2

Switching impulse leads to more changes in the discharge path and greater dispersion of U_{50}



Typical lightning impulse discharge path 3

图 7-8 特高压酒杯塔边相 I 串间隙操作冲击电压试验

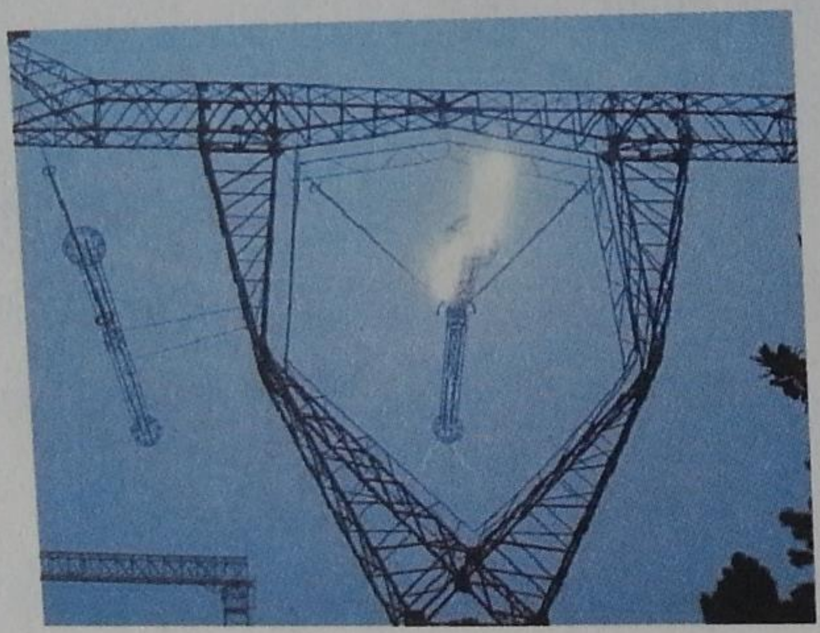


图 7-10 特高压酒杯塔中相塔窗操作冲击电压试验

4850kV switching impulse discharge

The analysis of extremely non-uniform electric fields mainly focuses on:
electric field is symmetric or not: rod-rod, rod-plane,
and **voltage polarity: positive or negative**

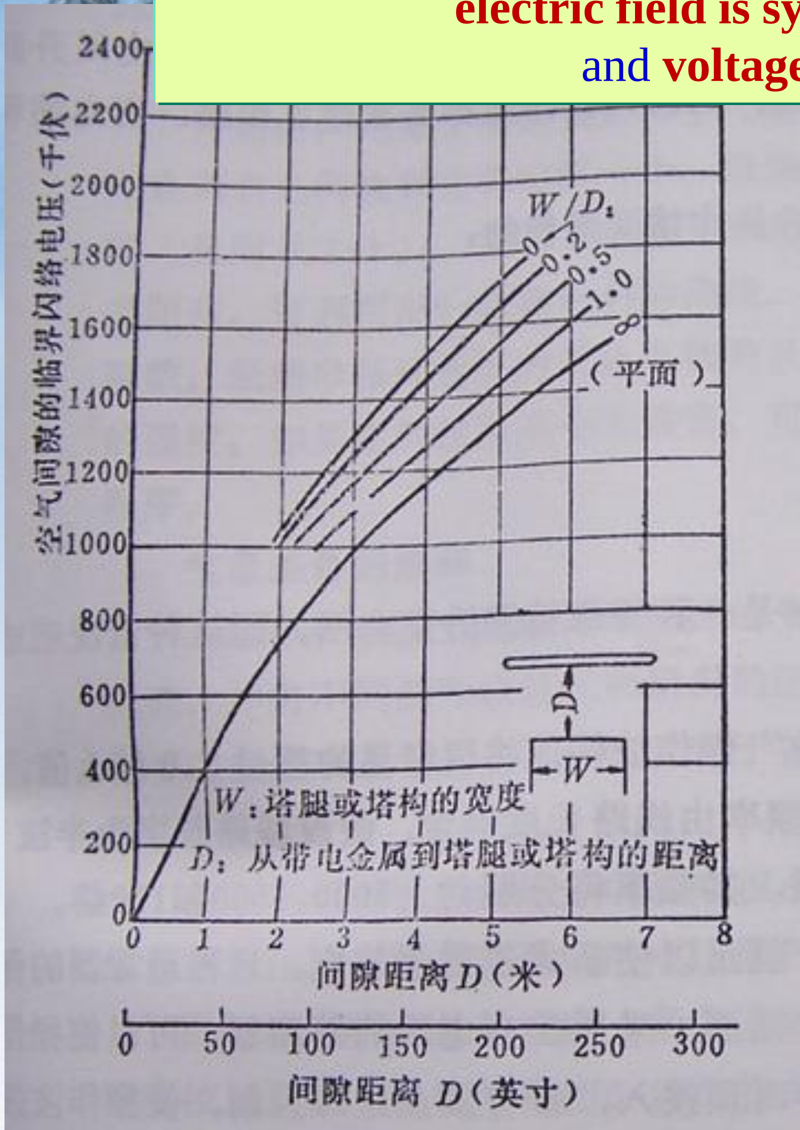
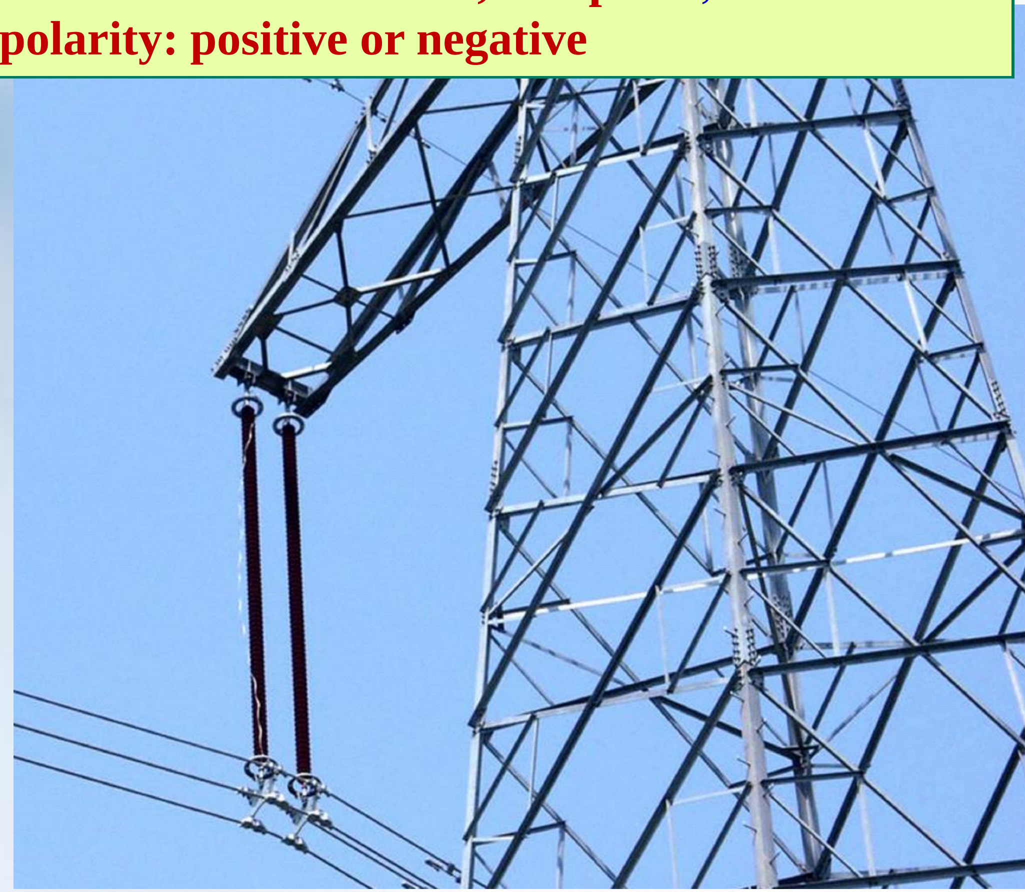


图 6-45 导线对塔腿（或塔构）空气间隙的干态正极性操作波强度



Conductor-tower positive switching impulse voltage curve

1000/3 = 333kV/m,1480/6 = 247kV/m

2.4.2 Characteristics of switching impulse voltage

(1) U-shaped curves

(2) Polarity effect of asymmetric electric field

(3) The saturation phenomenon of long air gaps

(4) 50% breakdown voltage and dispersion

(5) Effect of nearby earthed object

(6) Empirical formula for minimum air gap breakdown voltage

$$U_{50,\ \min} = \frac{3400}{1+\frac{8}{d}}$$

(d < 20m)

Electrical strength of air gaps in extremely non-uniform fields

Lightning impulse:

Positive rod-plane: ≈ 500kV/m   Negative rod-plane: ≈ 750kV/m

Switching impulse:

Positive rod-plane: ≈ 400kV/m (2m)   Negative rod-plane: ≈900kV/m (2m)

Long positive rod-plane gap:≈195kV/m (8-10m)

DC voltage:

Positive rod-plane: ≈ 4.5kV/cm   Negative rod-plane: ≈ 10kV/cm

Relatively long rod-rod gap: ≈ 4.8-5.0kV/cm

AC voltage:

Rod-rod: 5.66kV/cm (peak)   Rod-plane: ≈ 5.23kV/cm (peak)

long rod-plane gap: ≈ 210kV/m (peak)