Please connecting to the Rain Classroom

Department of Electrical Engineering
Tsinghua University

High Voltage Engineering

Spring 2025, Lecture 6

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Chapter 3 High Voltage Outdoor Insulation and Surface Discharge

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

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 (day and clean)

3.4 Rain flashover of insulator (wet)

3.5 Pollution flashover of insulator (polluted)

master scientific principles,
know technical measures,
understand engineering specifications

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

;

3.1 The influence of atmospheric conditions on air gap discharge

- ***Standard procedure*** $U_0=U/K_t$

correct U under test conditions to U_0 under standard condition

- ***Converse procedure*** $U=U_0 K_t$

convert U_0 specified under standard conditions to the equivalent U under test conditions

Correction factor components: $K_t = k_1 * k_2$

Air density correction factor $\boldsymbol{k_1 = \delta^m}$, humidity correction factor $\boldsymbol{k_2 = k^w}$

δ、k、m、w should be obtained before atmosphere corrections

Steps for atmosphere correction

- Calculate δ and k from recorded t, p and h, $\boldsymbol{\delta = (p/p_0)(T_0/T)}$ when $0.8< k_1 <1.0$
- Obtain parameter g, $\boldsymbol{g = U_{50} / (500L\delta k)}$
- Calculate exponent m and w from parameter g, then obtain $k_1= \delta^m$ and $k_2= k^w$,

  K_t is then obtained from $K_t = k_1 * k_2$

  this called "method with parameter g"

3.1 The influence of atmospheric conditions on air gap discharge

The atmosphere pressure at different altidude $p = 101.3 \exp(-H / 8150)$

$$U = K_a U_0 = U_0 \exp\left[q\left(\frac{H-1000}{8150}\right)\right],$$ q depends on selected voltage

(q=1.0; for lightning impulse withstand voltage and short time AC withstand voltage, more information is in GB 311.1-2012）

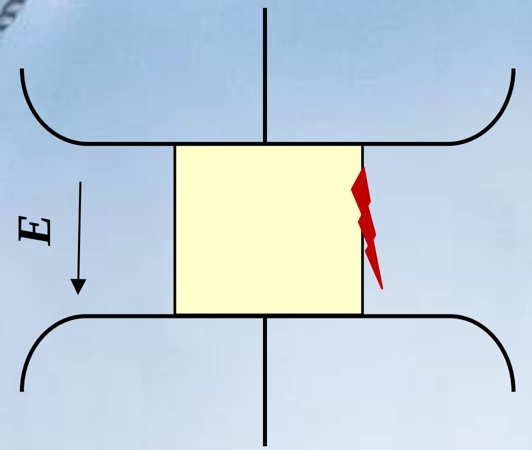
3.2 High voltage outdoor insulation and high voltage insulators

The outdoor insulation consists of two parts:
insulation along the surface of an insulator and air gap insulation

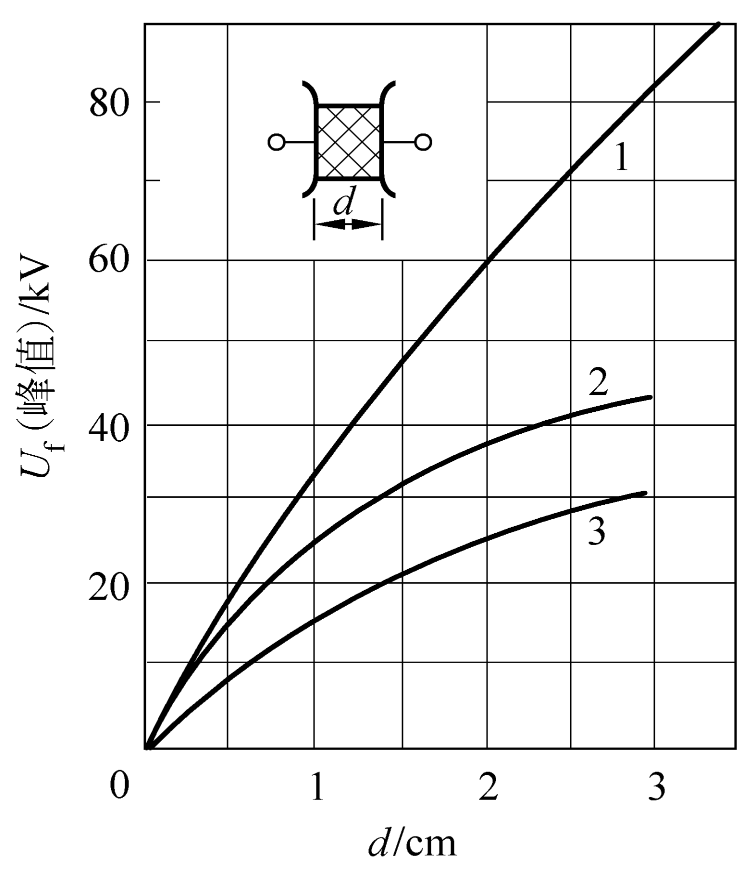
The key to outdoor insulation is insulators!
Related to: surface insulation and bulk insulation,
electrical performance and mechanical performance

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

(1) Surface discharge in a uniform field



Surface flashover voltage is very low, and can not be calculated !
It can only be obtained by testing
This type of insulation structure should be avoided or try to optimize

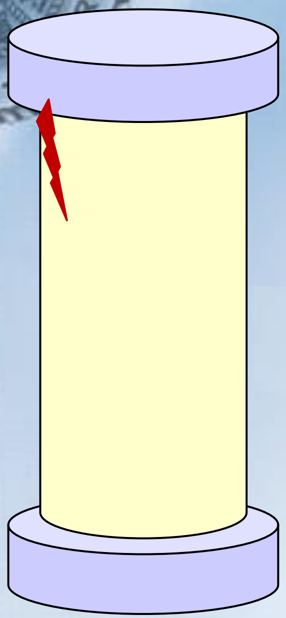


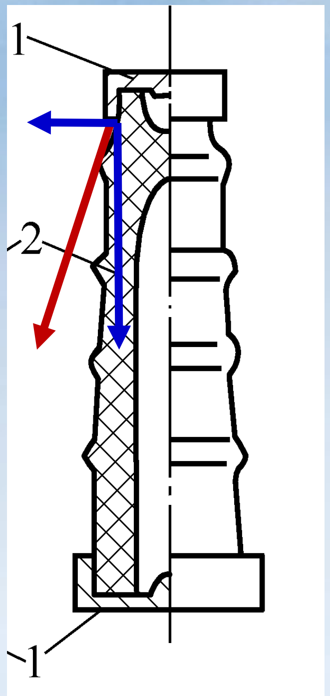
1- Air gap breakdown
2- Surface flashover under lightning impulse voltage
3- Surface flashover under AC voltage

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

The flashover voltage along the surface is much lower than air gap or solid structure breakdown voltage with the same dimensions

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





Surface flashover voltage is very low, and can not be calculated ! It can only be obtained by testing! This type of electric configuration should be optimized or using shielding

The flashover voltage along the surface is much lower than air gap or solid structure breakdown voltage with the same dimensions

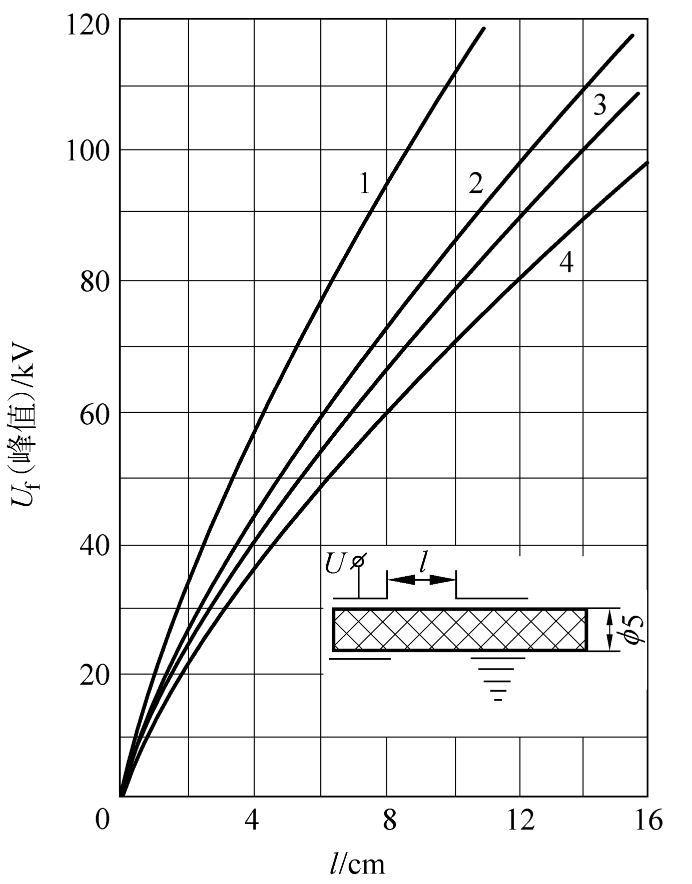
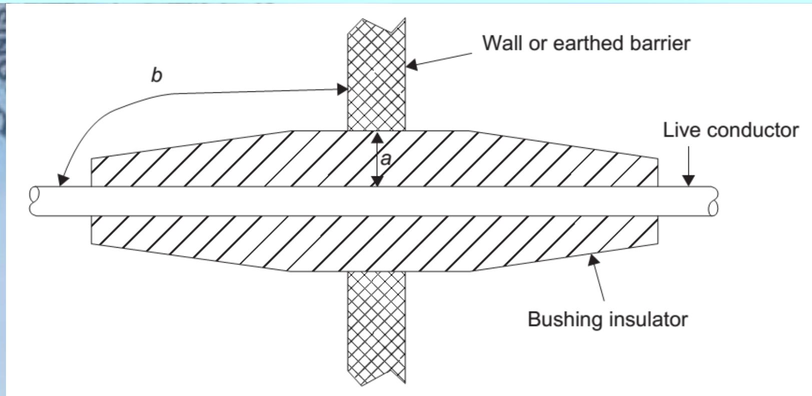


Figure 3-7: Power frequency flashover voltage vs flashover distance along the surface in extremely non-uniform field

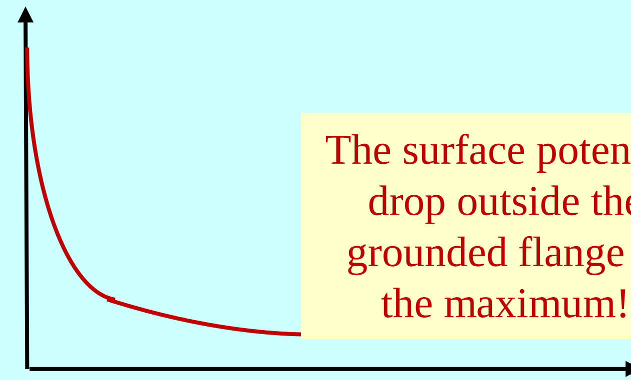
1- Pure air gap; 2- Paraffin wax
3- Resin immersed paper;
4- Porcelain or glass

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

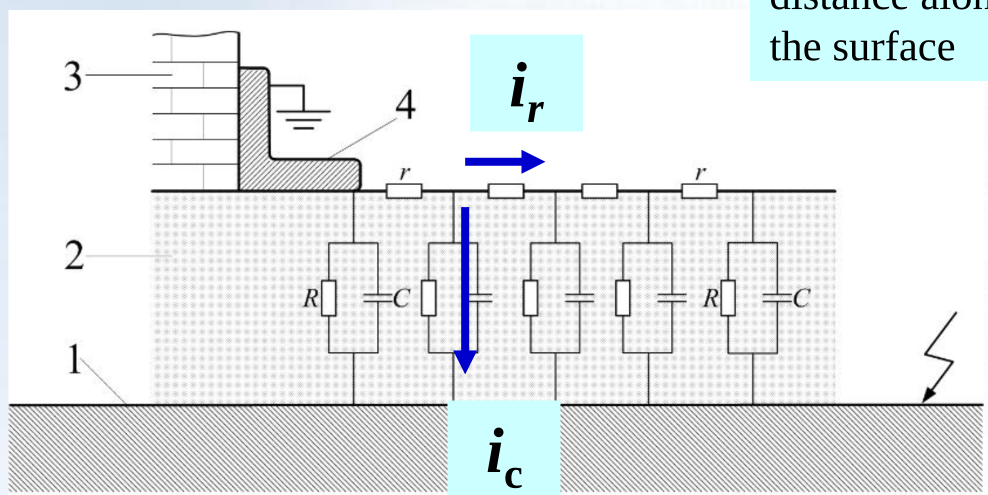


HV conductor passing through a grounded wall

Field distribution along the bushing surface



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



Equivalent circuit of wall bushing

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

Conditions for sliding spark discharge:

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

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

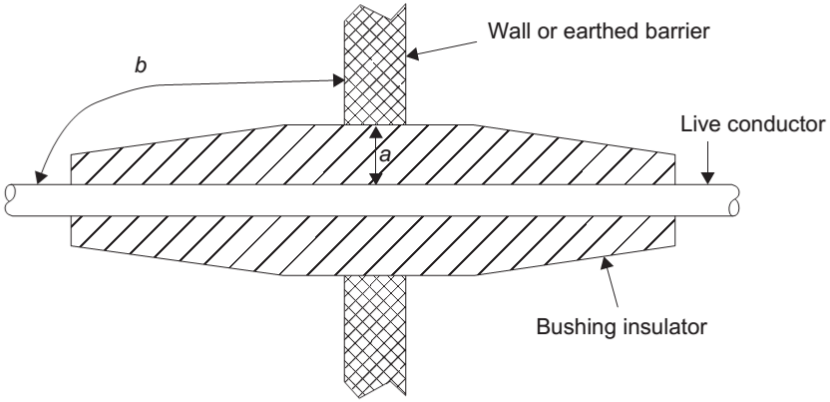


Figure 12.1 Non-condenser bushing

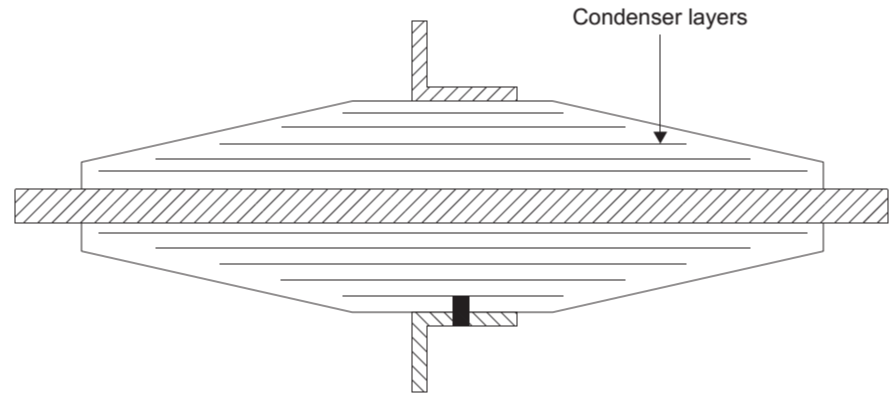
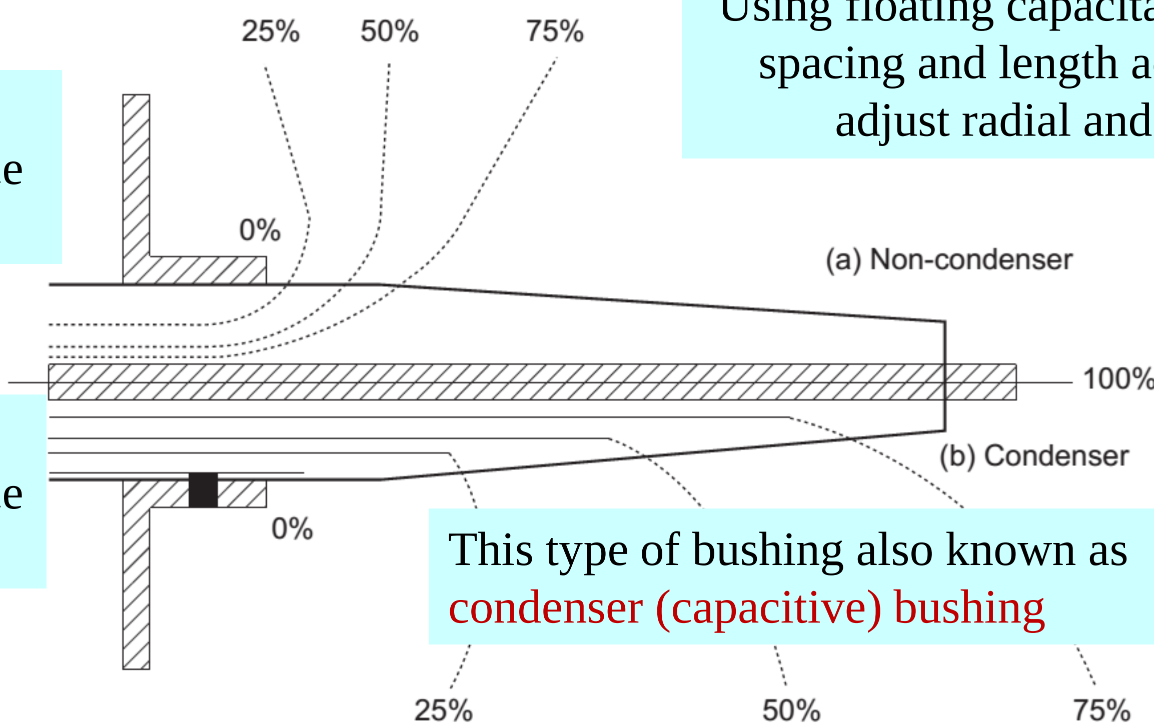


Figure 12.4 Condenser bushing

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

Without capacitance screen

With capacitance screen



This type of bushing also known as condenser (capacitive) bushing

Sliding spark discharge can be effectively avoided or controlled by using floating capacitance screen or stress cones

Figure 12.5 Field distribution in non-condenser and condenser bushings

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:

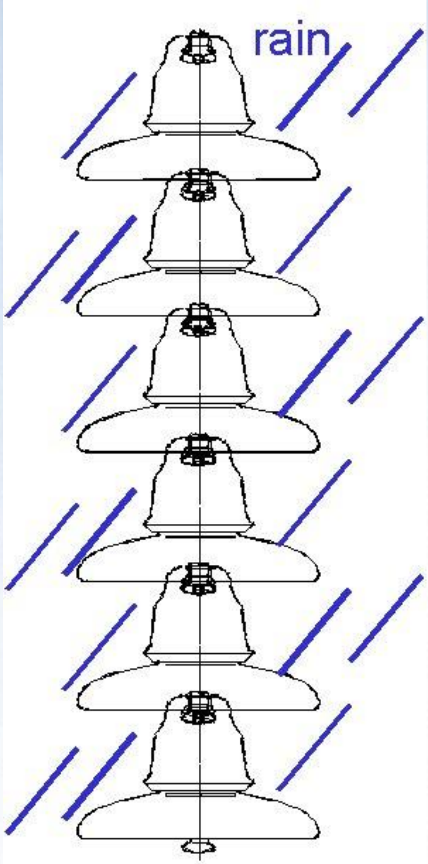
$U_{rain} = (0.50\sim0.72)\ U_{dry}$

One minute DC voltage:

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

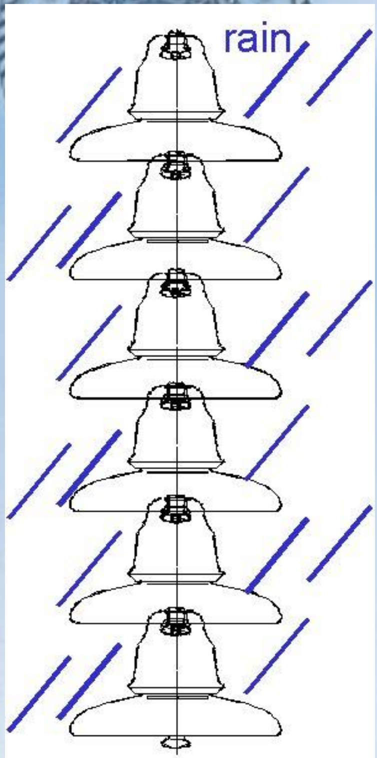
The AC and DC rain flashover voltage of insulators decreased dramatically!

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

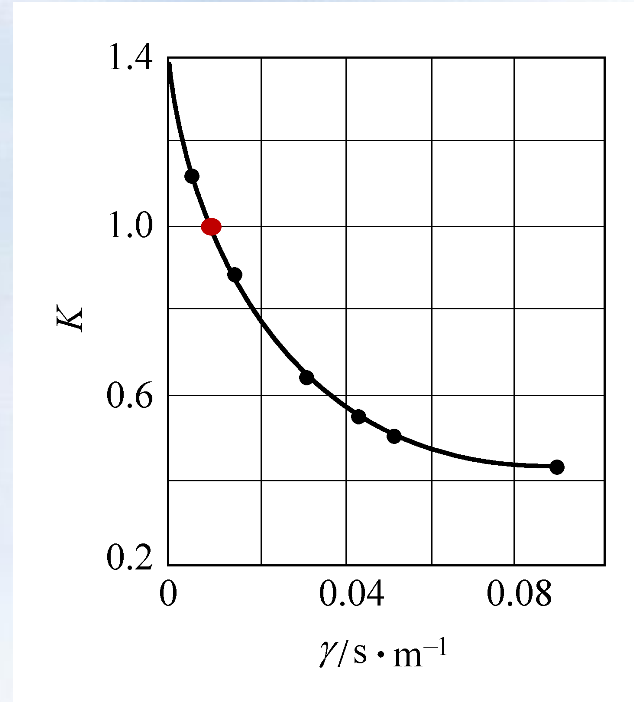


Figure 3-19 Effect of water conductivity on wet flashover voltage

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.

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

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

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From a simplified theoretical model
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Core concepts of this chapter:
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pollution flashover,   hydrophobicity transfer,
(silicone rubber) polymeric ourdoor insulation

;

3.5 Pollution discharge of insulators

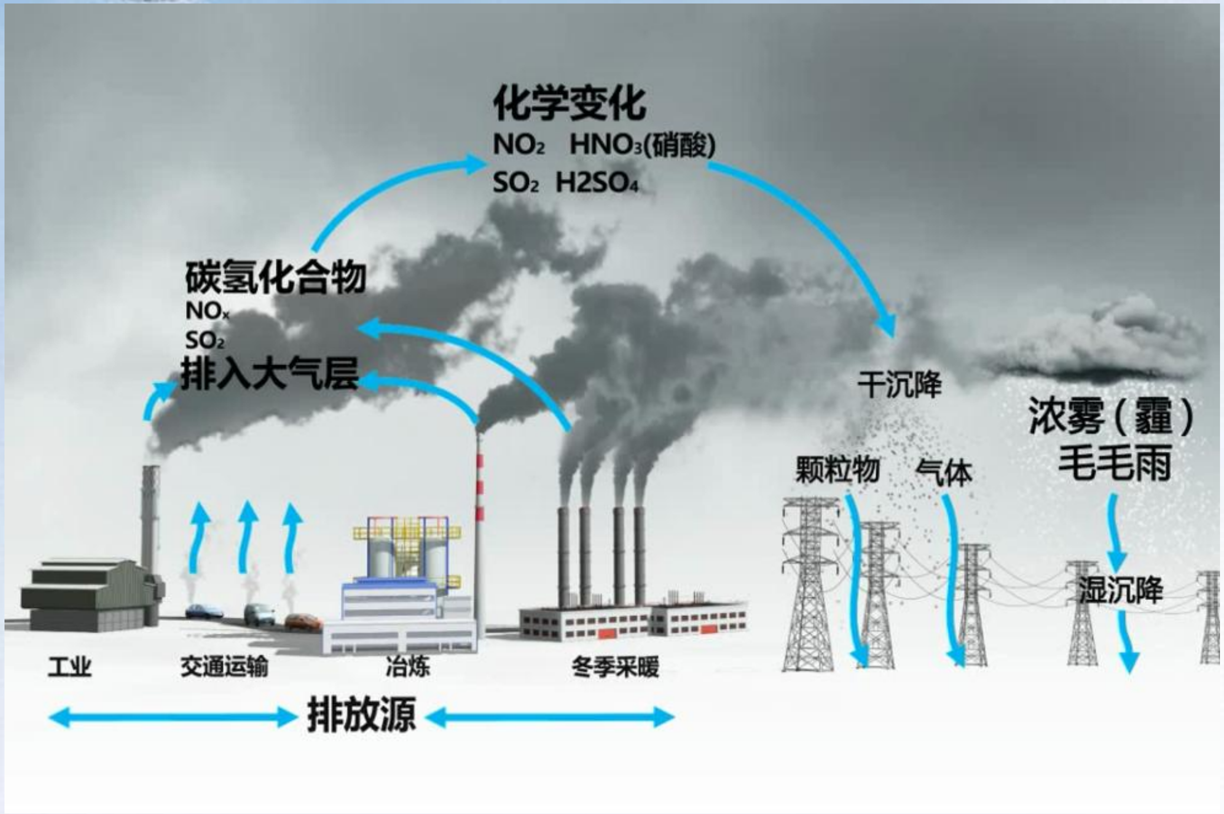
Try to ask more questions.
It will be more effective
when study with questions

3.5.1 Characteristics of pollution flashover	What is pollution flashover? How severe it is?
3.5.2 From pollution accumulation to flashover	What are the influencing factors? Why pollution flashover voltage is so low?
3.5.3 Pollution test and pollution flashover performance	Laboratory reproduction, quantitative simulation
3.5.4 Dimension of insulator in polluted areas	How to choose insulators?
3.5.5 Icing flashover of insulator	What is icing flashover, characteristics, and test method?
3.5.6 Measures for increasing the pollution flashover voltage of porcelain/glass insulators	How to increase pollution flashover voltage?
3.5.7 Silicone rubber composite insulators and organic outdoor insulation	Why organic outdoor insulation can be used to prevent pollution flashover?

The problem of clean surface flashover can be solved at the design stage by electric field control, but the pollution flashover of insulator is much more severe problem!

3.5.1 Characteristics of insulator pollution flashover

What is pollution flash? How severe it is?

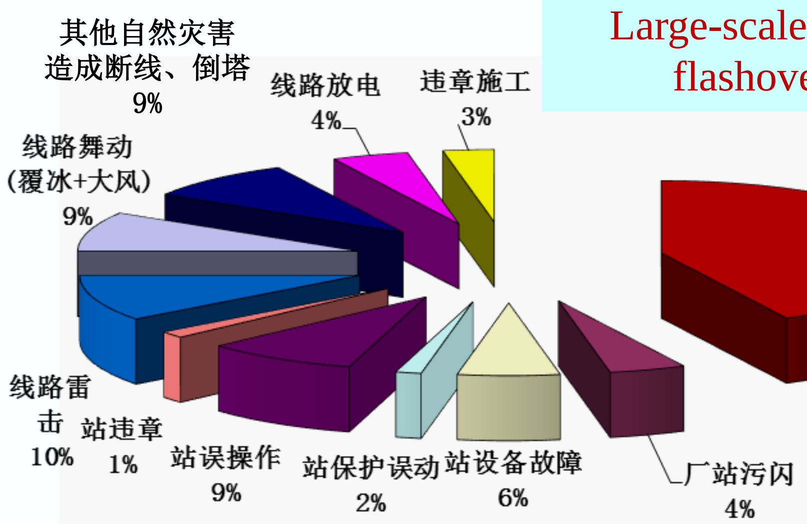


Typical pollution flashover in China (type A): pollutants in the air gradually accumulated on insulator surface, then resulting surface flashover under humid/wetting conditions

3.5.1 Characteristics of insulator pollution flashover

What is pollution flashover? How severe it is?

1981-2001, among the 68 serious power outages in China, 29 accidents is caused by large-scale pollution flashover, account for 43% of the total



Large-scale pollution flashover 43%

There have been many large-scale pollution flashovers lasting for more than 30years:

1974: Liaoning;
1976-1981: East China
1987: Shaanxi
1988-1989: Jiangsu, Shanghai, Zhejiang;
1990: Henan, Hebei, Beijing-Tianjin-Tangshan, Shanxi, Shandong, Liaoning;
1991: Qinghai, Shanghai, Zhejiang;
1992: Sichuan, Guangdong, Jiangsu;
1994: Shanxi;
1996: Hubei, Hunan, Jiangxi, Anhui, Zhejiang, Jiangsu, Shanghai, Fujian, Hebei;
1997: Shaanxi, Xinjiang;
1998: Henan, Shandong;
1999: Beijing Tianjin Tangshan;
2000: Shaanxi;
2001: Henan, Hebei, Shandong, Beijing Tianjin, Liaoning;
2004: Zhejiang, Shanghai;
2005: Guangdong and Fujian;
2006: Hebei, Henan, Shandong

Rain flashover is rare and sliding spark discharge is avoided if insulator is well designed. Why pollution flashover is still severe for many years?

Large-scale pollution flashovers are mostly concentrated in developed area and densely populated areas
The peak period of pollution flashover outage occurs every 5 to 6 years, with super large-scale pollution flashover accident acrossing multiple provinces

Beijing Tianjin Hebei Shanxi Henan Shandong Liaoning (early 1990)

- 172 lines with110kV ~ 500kV tripped, all 500kV lines tripped, 27 substations on 81 lines lost power, and 354 accident points
- Covering an area of about 320,000 km^2

Jiangsu, Zhejiang, Shanghai, Hunan, Hubei, Jiangxi, Anhui (late 1996)

- 60 lines of 220kV-500kVtripped / stopped, 3 substations (power plant) experienced power outages, 367 accident points.
- Covering an area of about 140,000 km^2
- 96-97 North China, Northwest China, Shandong

Beijing Tianjin Hebei Liaoning Henan Shandong (early 2001)

- 238 lines of 66kV~500kV tripped and 34 substations experienced power outages, with 433 accident points
- Covering an area of about 300,000 km^2

Guangdong Fujian Pearl River Delta (early 2005)

- 12 lines of 500kV with pollution flashovers
- Guangdong 500kV southern ring network disconnection

Large scale pollution flashover and power outage accidents in developing countries:

✓ In 1989, 177 pollution flashover occurred in eastern South Africa within two days
✓ From 2006 to 2010, there were four large-scale pollution flashovers in the Indian power grid, with three consecutive days of widespread power outages in New Delhi and its surrounding areas in 2008

Large scale pollution flashover and power outage accidents in developed countries:

✓ In the early 1950s, southeastern England and Scandinavia
✓ Donbass, Soviet Union in the 1960s
✓ 1965-1968 North American Great Lakes, Southern California Industrial Zone
✓ In the 1970s, coastal industrial zones in Japan
✓ 1991 Florida Peninsula, USA

Flashover: voltage increase or insulation decrease

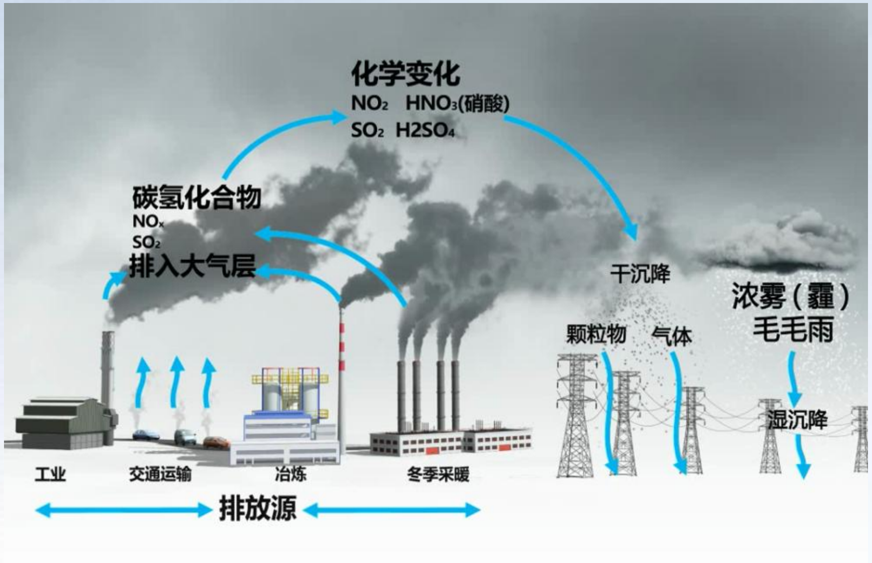
The characteristics of power grid pollution flashover:

- ✓ All insulator strings in large area face the same pollution and wetting condition;
- ✓ Pollution flashover occurs under operating voltage (lasting enough long time), not like lightning strikes disappear very quick;
- ✓ After the pollution flashover tripout, the wet condition and pollution layer still exist, and the reclosing success rate of switchgear is low.

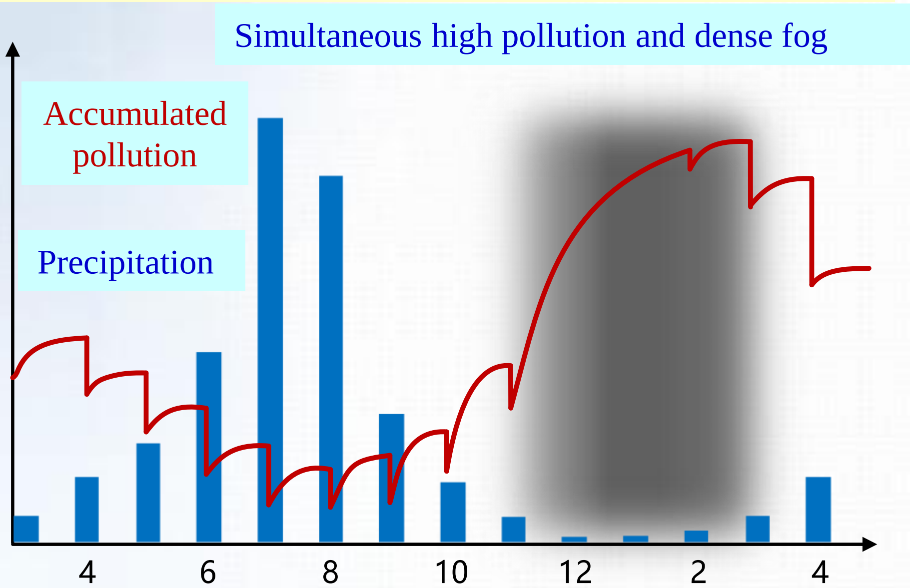
Large-scale pollution flashover:

- ✓ multiple accident points, happens in alrge area, and long time for restore power supply

The practical reasons for large-scale pollution flashovers once again in China's power grid: severe air pollution and overlapping of heavy pollution and humidity



Air pollution accumulated on insulator surface



Changes in pollution accumulation and precipitation, heavy fog period

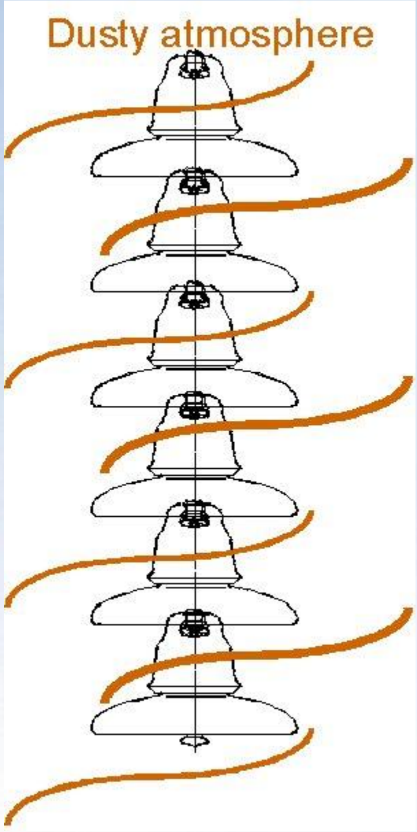
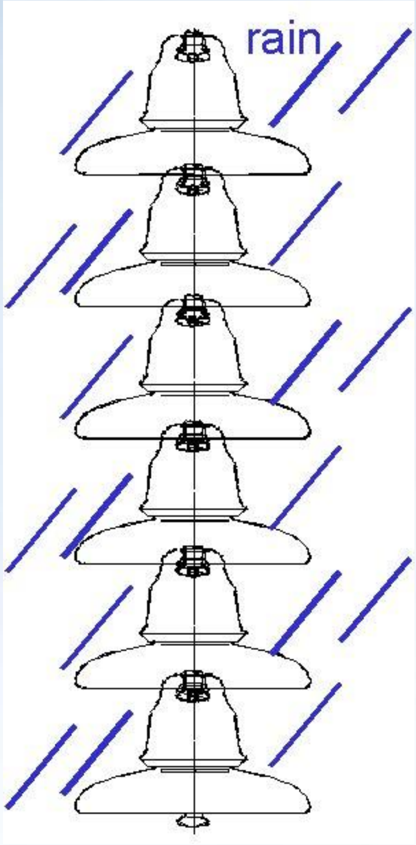
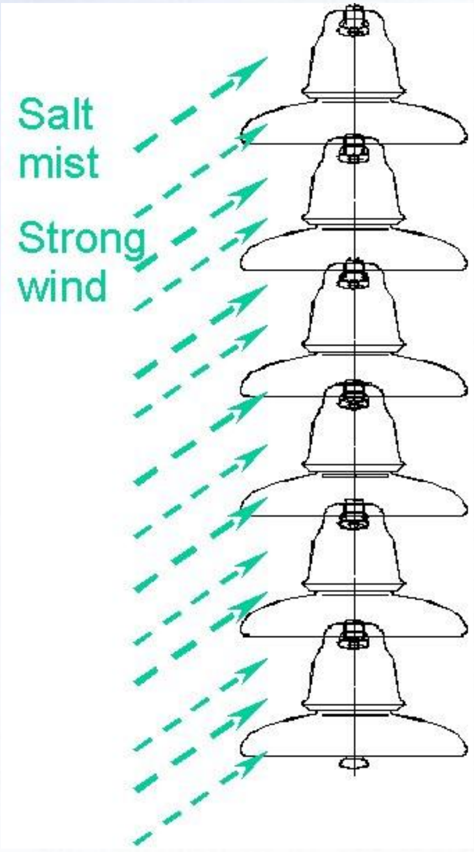
3.5.2 From pollution accumulation to pollution flashover

What are the influencing factors?
Why pollution flashover voltage is so low?

It is inevitable for insulators to accumulate pollution during tens of years of outdoor operation

The self-cleaning effect mainly comes from rainfall

Shed profile present significant impact on pollution accumulation and cleaning

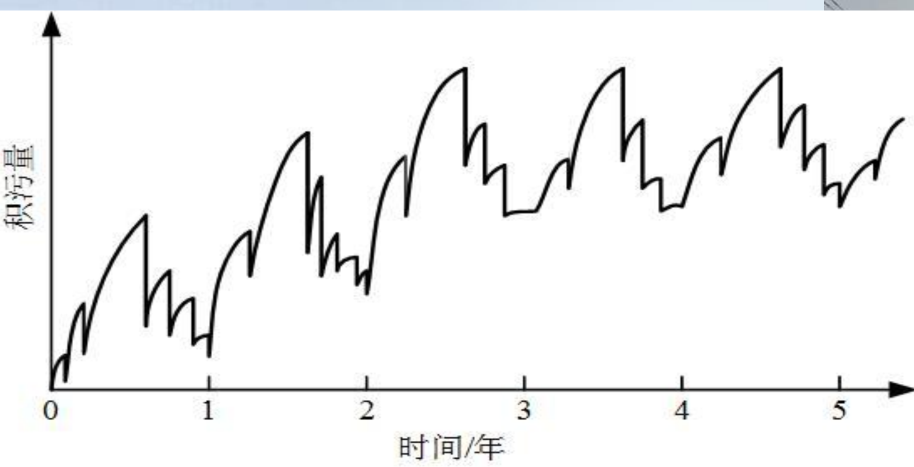
Pollution deposits	Rainfall cleaning	Rapid pollution accumulation
		

3.5.2 From accumulated pollution to pollution flashover

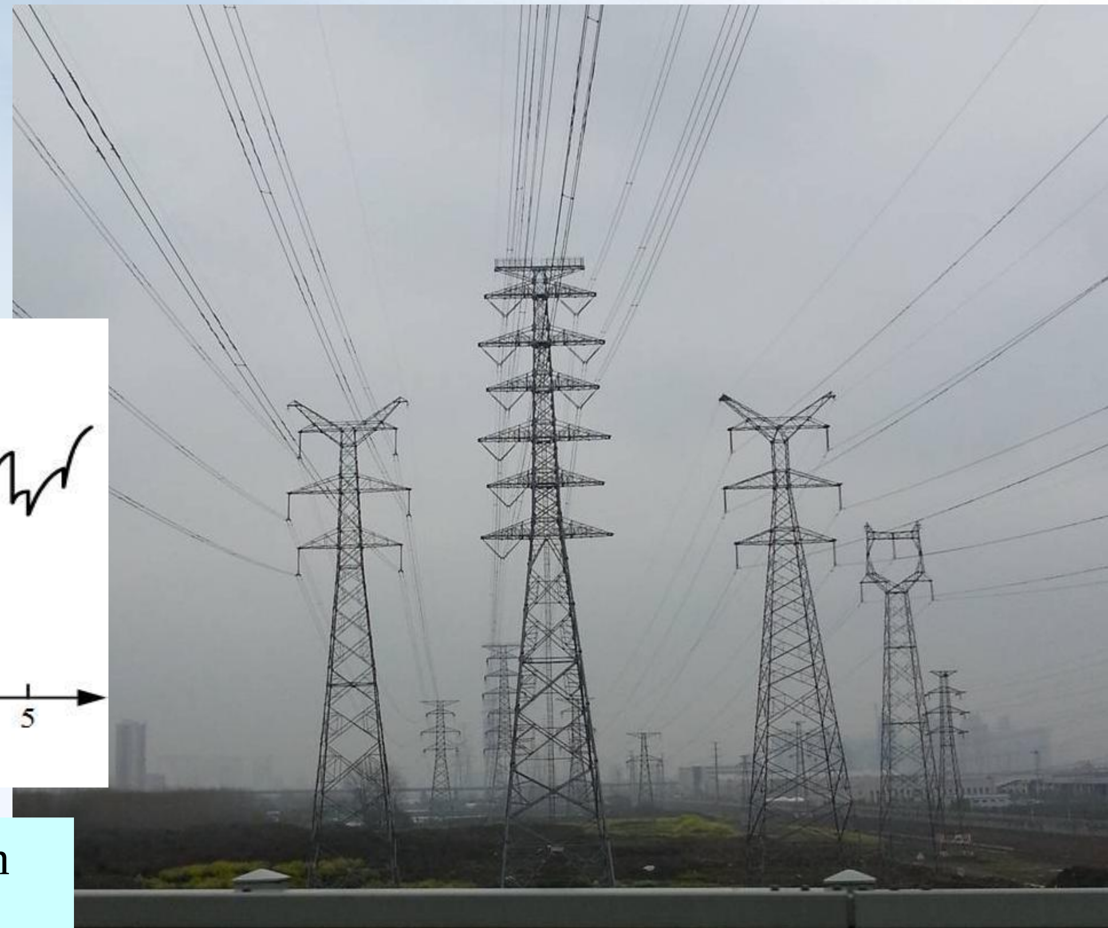
What are the influencing factors?
Why pollution flashover voltage is so low?

It is inevitable for insulators to accumulate pollution during tens of years of outdoor operation
The self-cleaning effect mainly comes from rainfall
Shed profile present significant impact on pollution accumulation and cleaning

The type of pollution source, insulator shed profile and precipitation influence the pollution accumulation all together

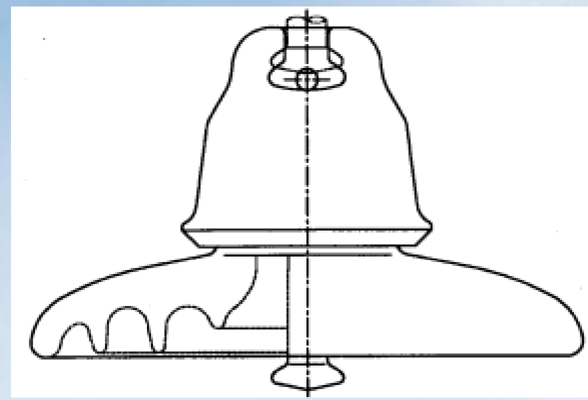


Schematic diagram of surface pollution changes on insulators

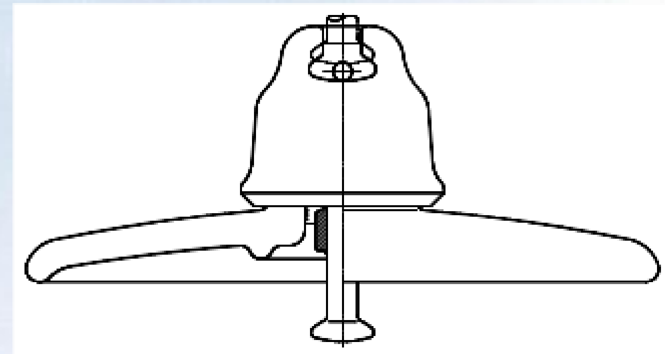


Choose different shed profile to reduce pollution accumulation or moisture exposure

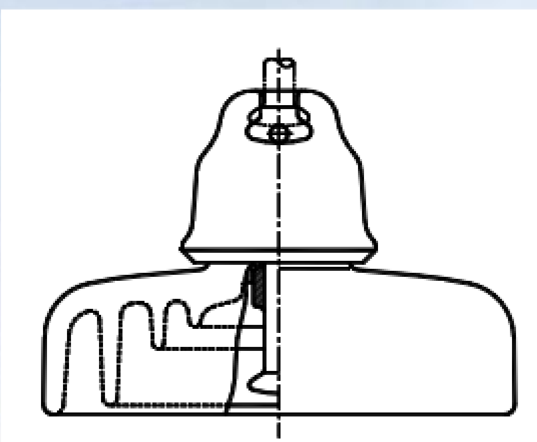
The shed profile should provide enough creapage distance, and helpful for self cleanning



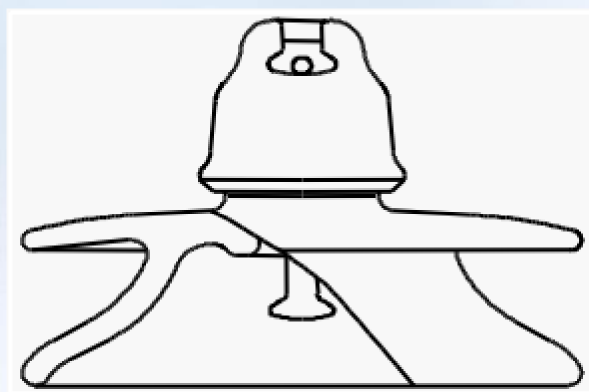
Standard



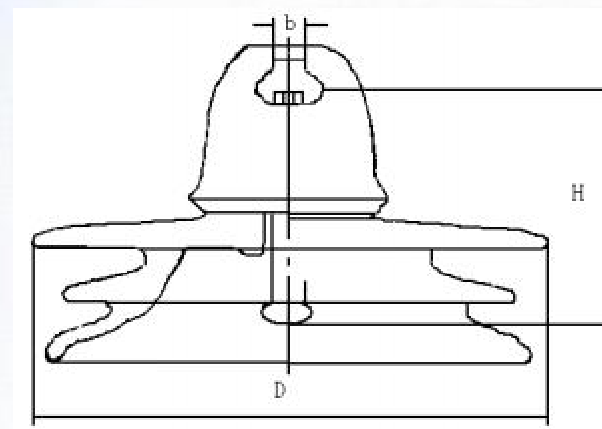
Aerodynamic



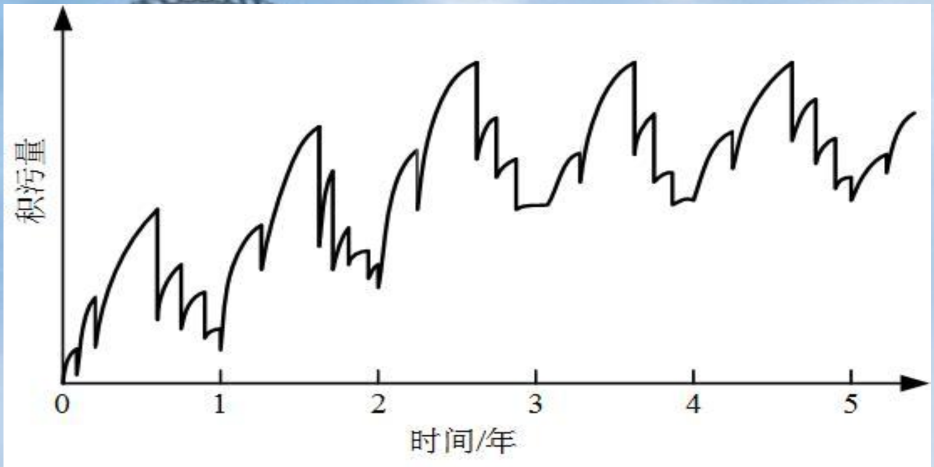
Deep under-ribs



Double shed



Alternating shed

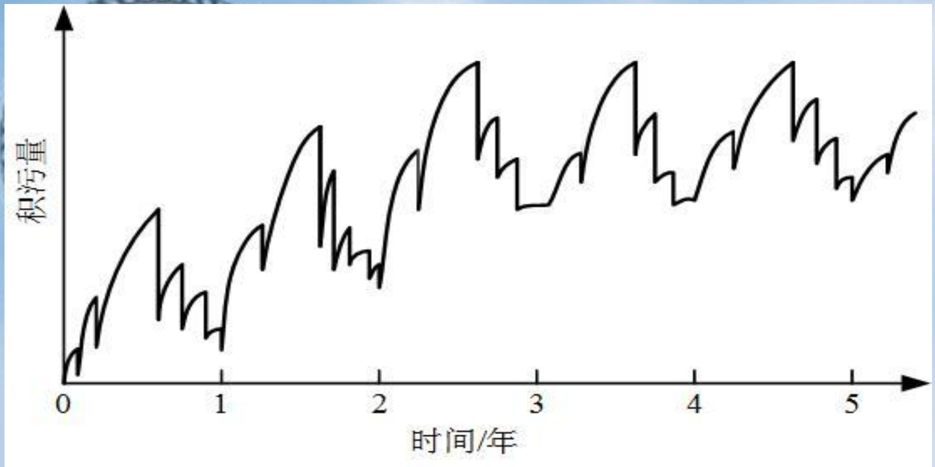


surface pollution changing over years

Quantitative evaluation of insulator contamination:

Equivalent salt deposit density ESDD (mg NaCl/cm^2)

Non-soluble deposte density NSDD (mg/cm^2)



surface pollution changing over years

Quantitative evaluation of insulator contamination:

Equivalent salt deposit density ESDD (mg NaCl/cm^2)

Non-soluble deposte density NSDD (mg/cm^2)

pollution measurement on site

3.5.2 From pollution accumulation to flashover

Why the pollution flashover voltage is so low?

The process from clean to pollution flashover:
Pollution deposite, wetting, dry band arc, flashover

development of discharge on contaminated surfaces

(a) In the early stage of the wetting of pollution layer, uniform voltage distribution, leakage current appears

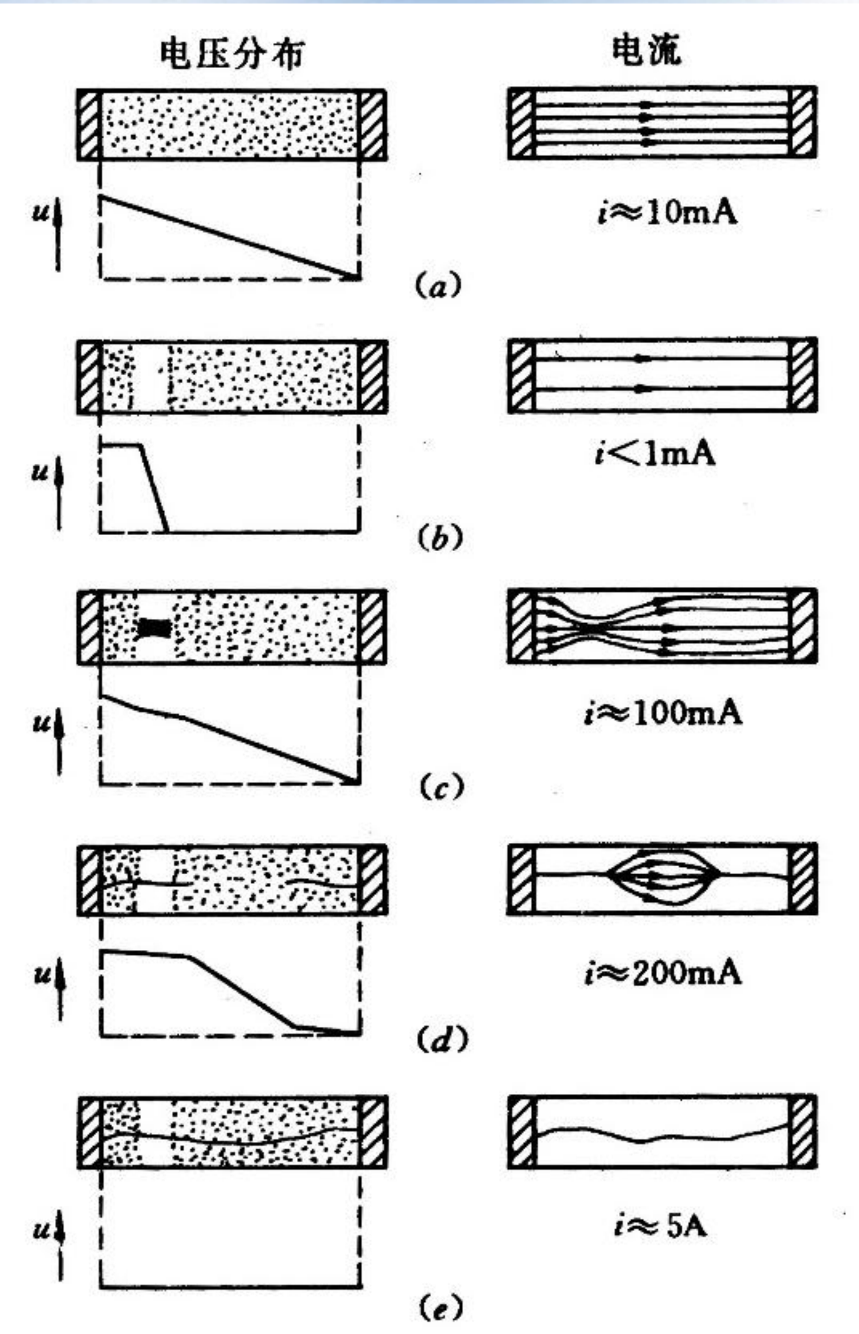
(b) Dry band emerging, voltage is mainly applied to the dry band, current then decreases

(c) Dry band arc is formed if voltage is high enough, and current greatly increased

(d) Arc propagation, voltage then applied to the remaining pollution layer, current increased further

(e) Arc interconnects the electrode and completes surface pollution flashover

The voltage to form a dry band and the dry band arc is not high
The voltage to maintain the surface arc propagation is also not high
The pollution flashover voltage is very very low!



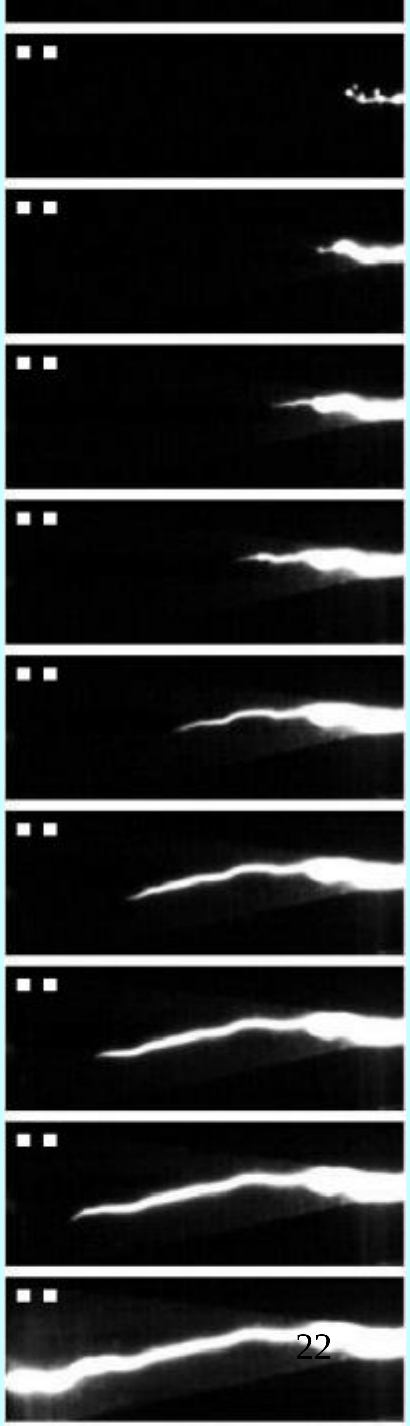
Why the pollution flashover voltage is so low?

The voltage to form a dry band and the dry band arc is not high
The voltage to maintain the surface arc propagation is also not high
Pollution flashover voltage is very very low!

Did you relating to the downwards step leader for the long air gap breakdown?

Hydrophilic surface, process of arc creap along the surface and finally flashover, captured by high-speed photography

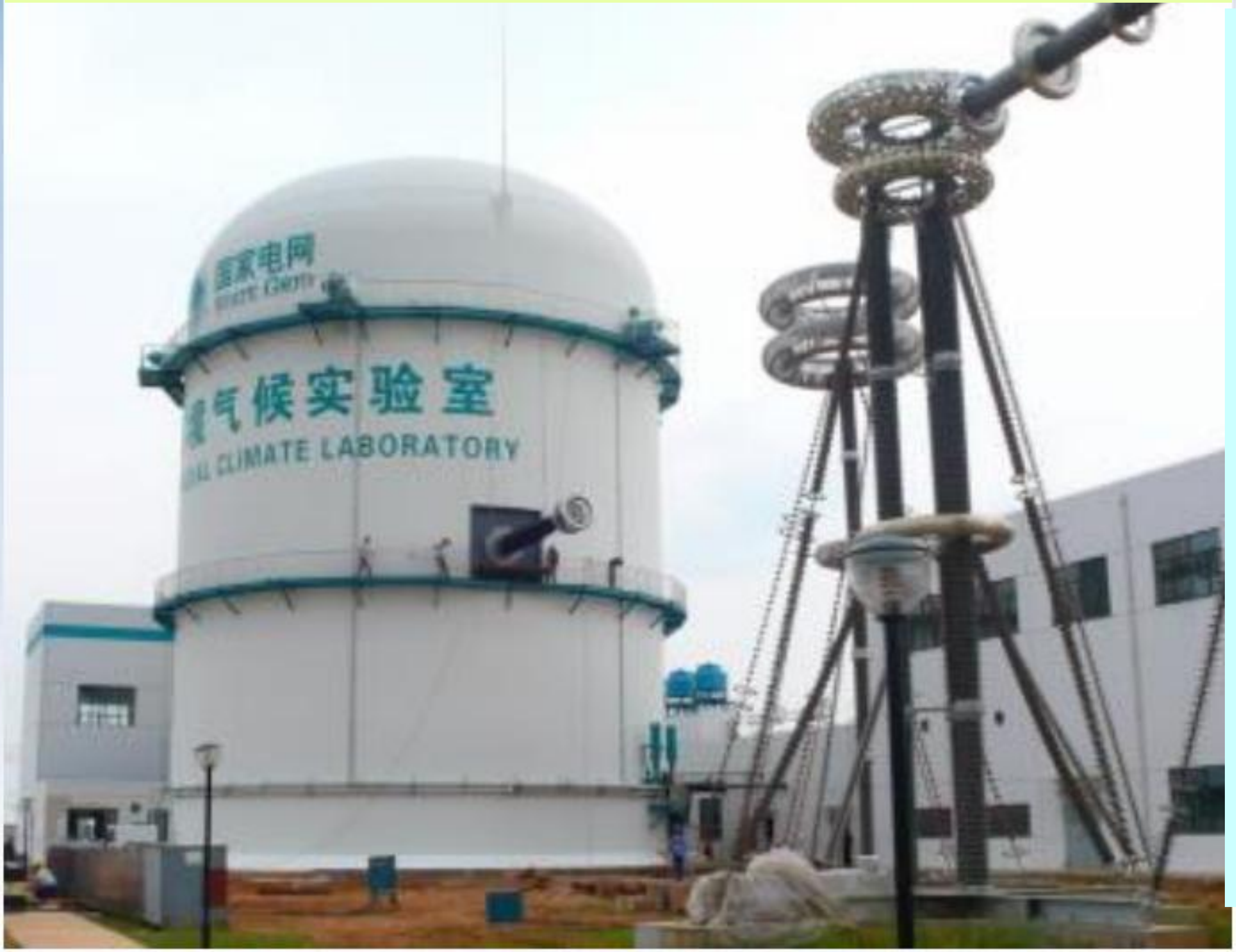
Captured under 2000 pfs with an interval of 0.5ms, with each exposure of 25us



3.5.3 Pollution test and pollution flashover performance

Laboratory reproduction, quantitative simulation

Laboratory for insulator's artificial pollution flashover test



Artificial Pollution Laboratory of China EPRI

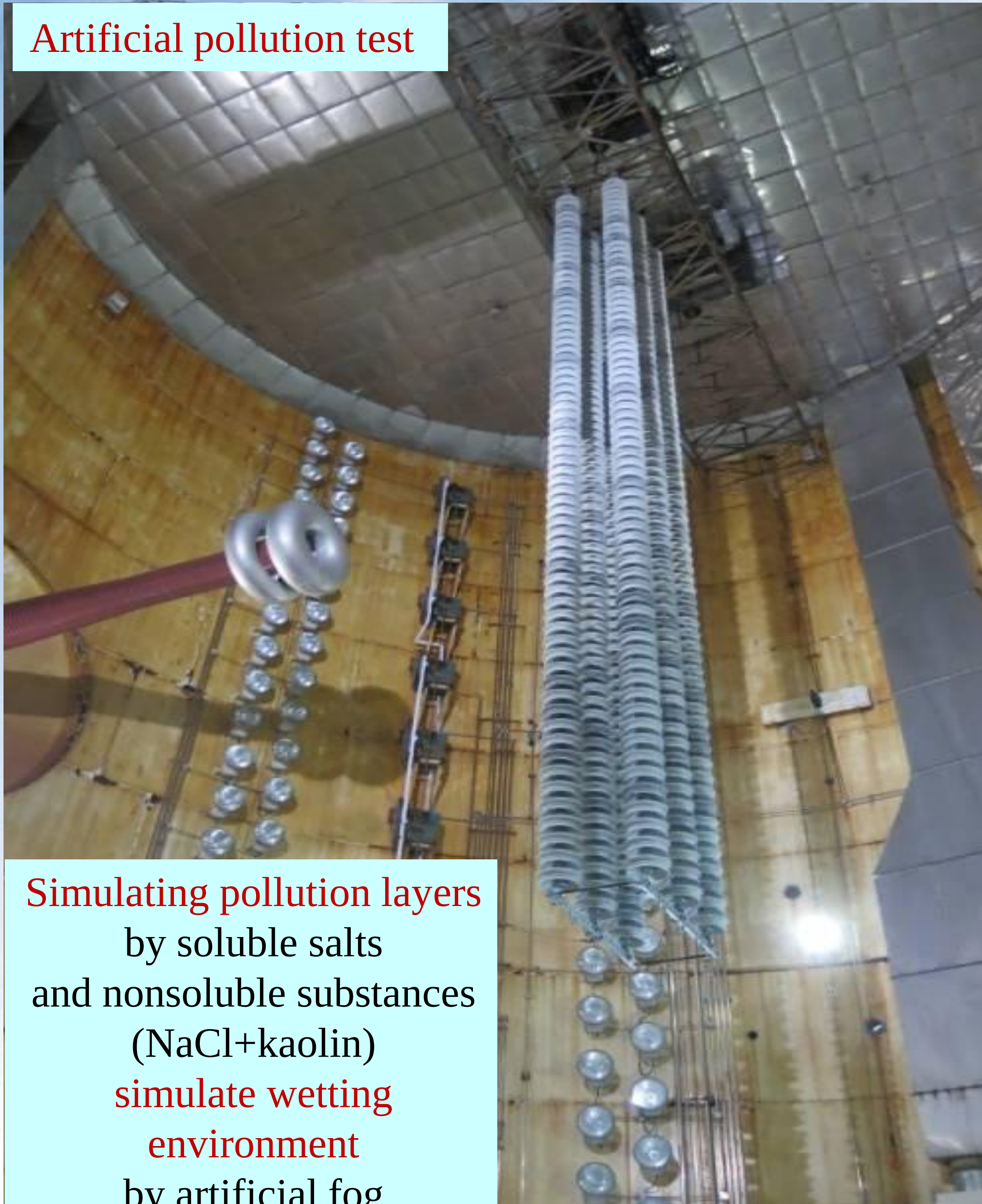
Inner diameter 20m
height 25m
800kV/6A power frequency transformer

Simulate wetting environments for polluted insulators

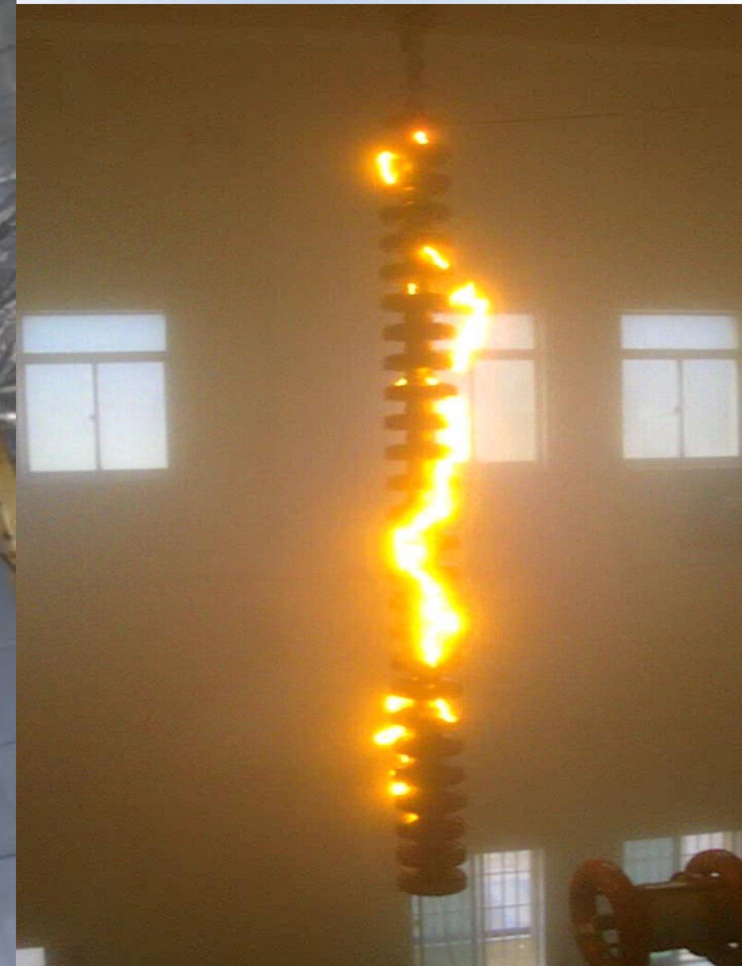
Simulate high altitude pressure up to 5000m

Simulate icing (-19℃)

Artificial pollution test



Simulating pollution layers
by soluble salts
and nonsoluble substances
(NaCl+kaolin)
simulate wetting
environment
by artificial fog

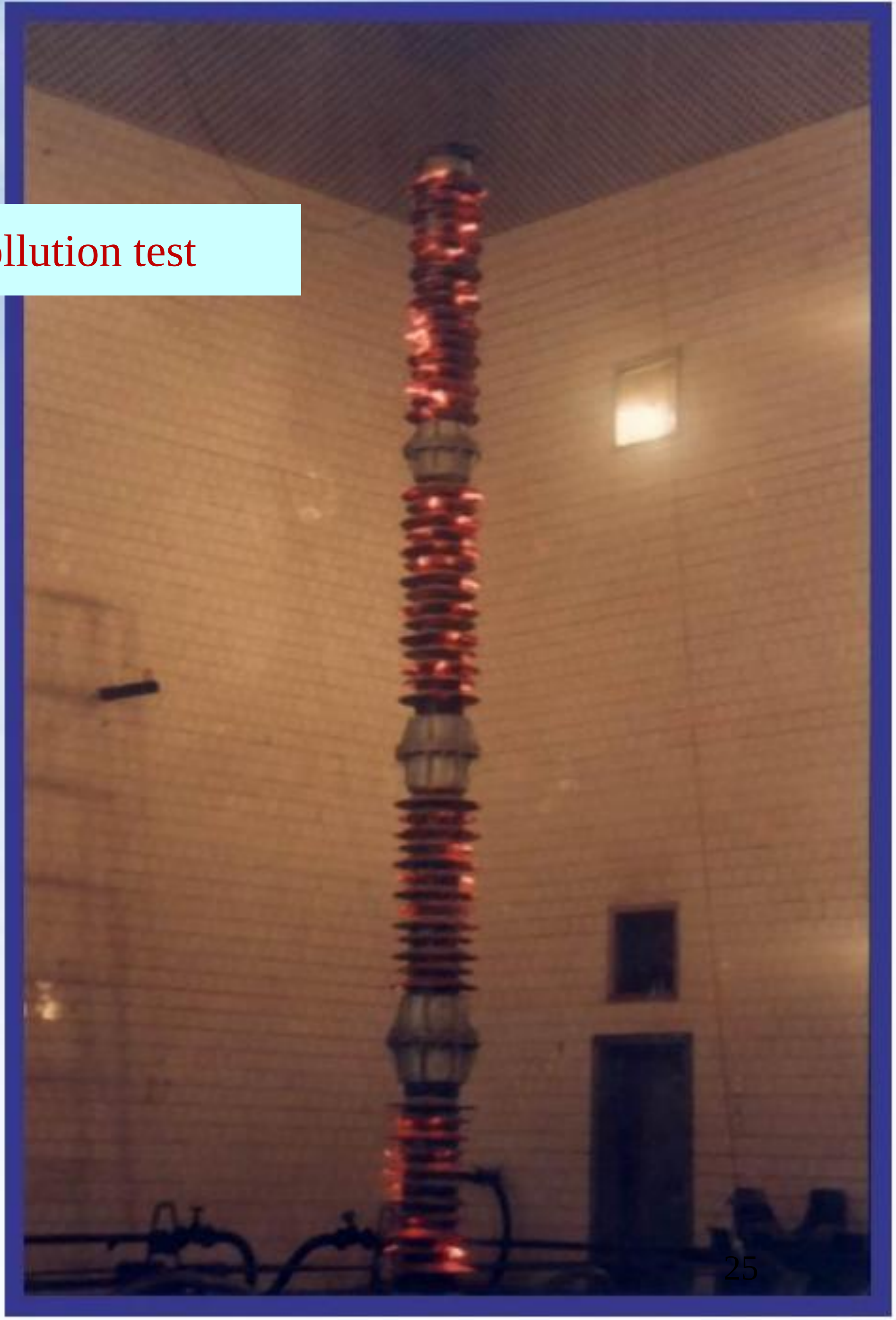


Artificial pollution test
standards:
IEC 60507-2013
GB/T 4585-2004

Artificial pollution test

Simulating pollution layers
by soluble salts
and nonsoluble substances
(NaCl+kaolin)
simulate wetting
environment
by artificial clean fog

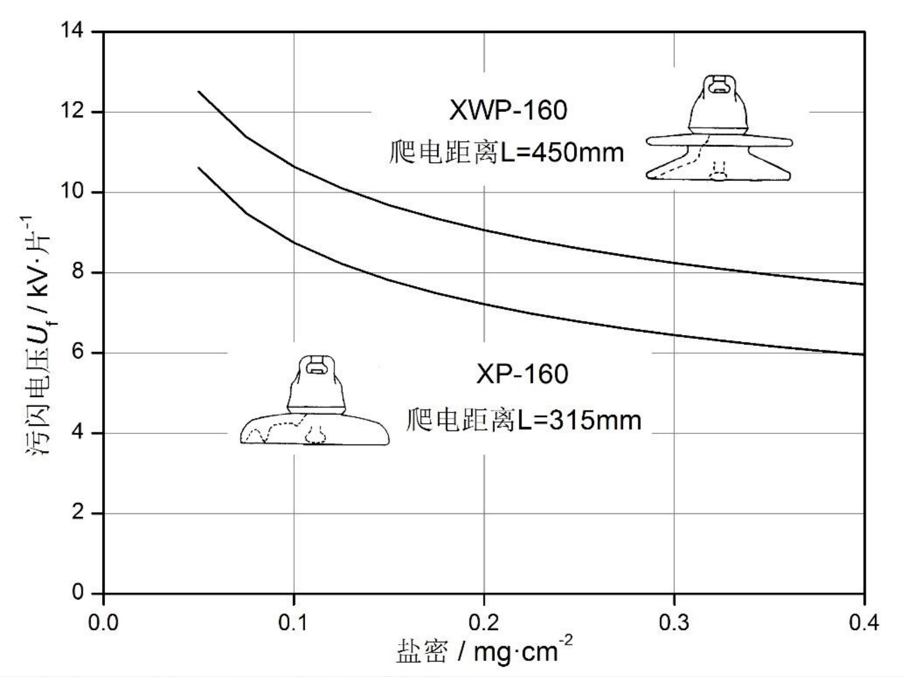
Artificial pollution test

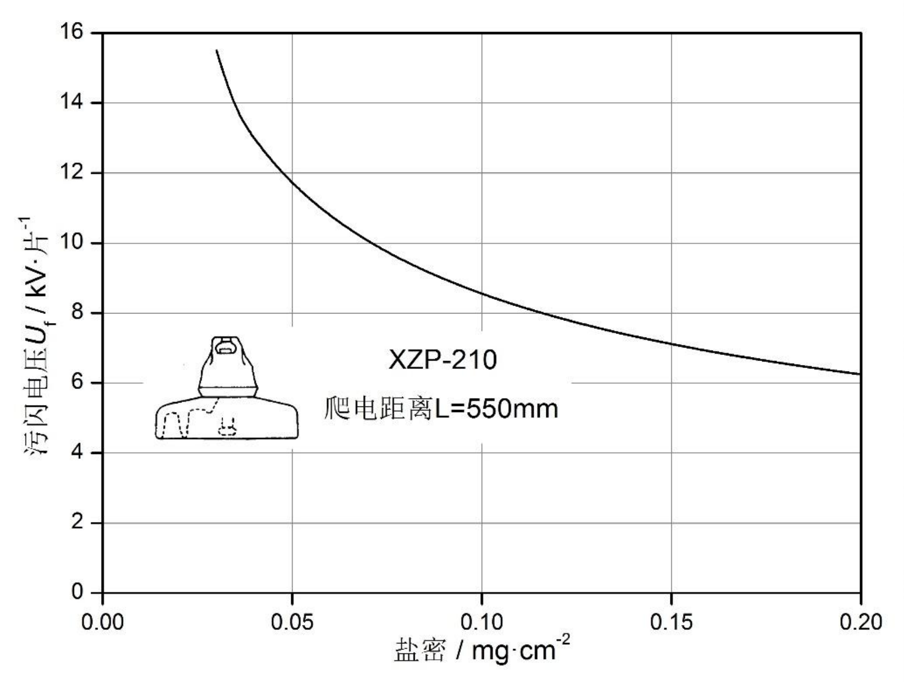


3.5.3 Pollution test and pollution flashover performance

Laboratory reproduction, quantitative simulation

Insulator pollution flashover characteristic curve obtained from artificial pollution test





(a) Pollution flashover voltage under AC voltage (rms value)

(b) Pollution flashover voltage under negative DC voltage

Artificial pollution flashover voltage vs salt deposit density on disc porcelain insulators negative power exponential relationship between pollution flashover voltage/pollution withstand voltage and pollution degree

Flashover: voltage increase or insulation decrease

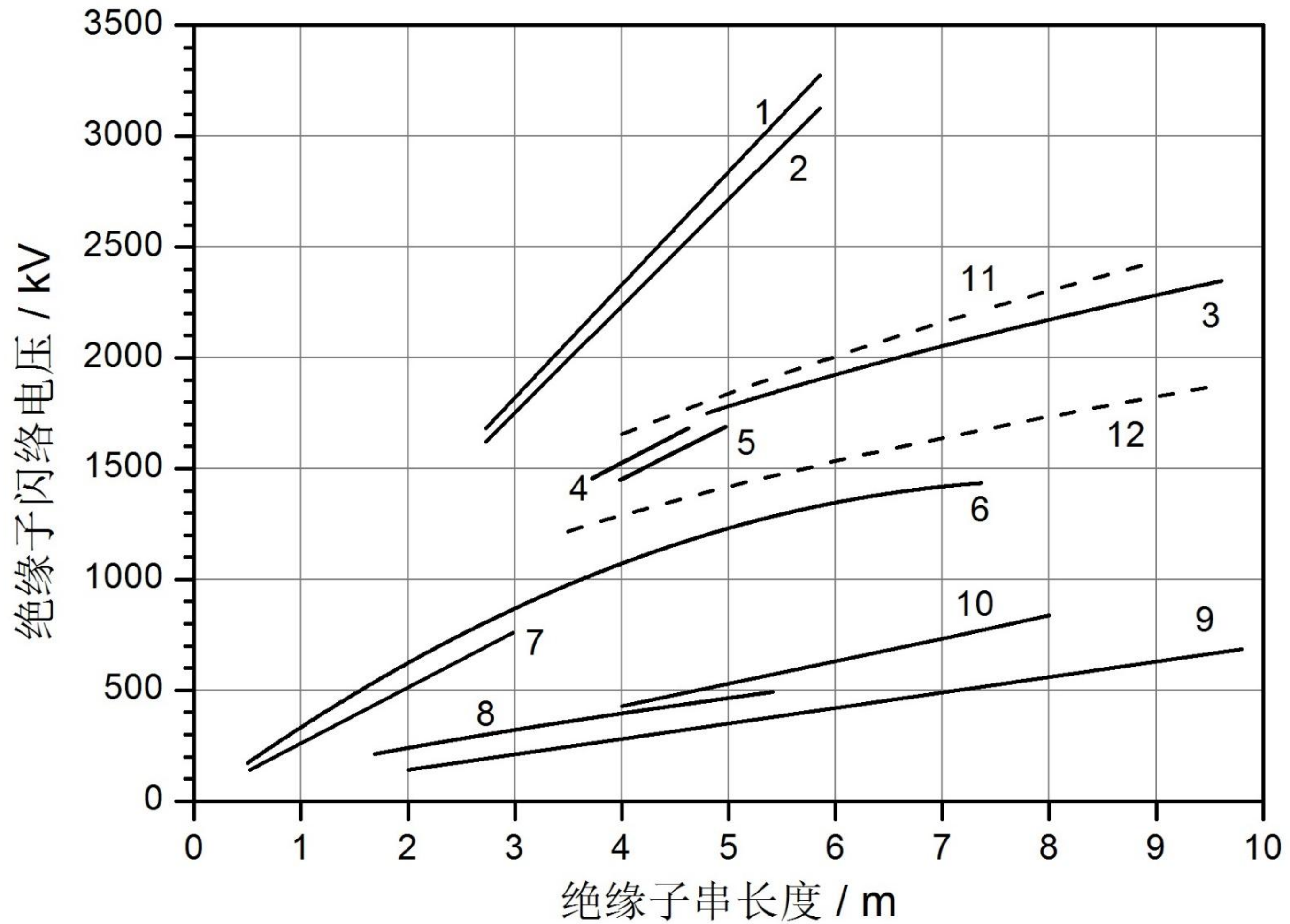
The pollution flashover of insulator occurs under operating voltage, not due to voltage rise. It is a typical insulation decreasing problem.

Why do insulators experience flashover at very low operating voltages? Why is the surface pollution flashover voltage gradient much lower than the breakdown electric field strength of air gaps?

- Uniform electric field air gap breakdown field strength: 30 kV/cm
- Positive rod-plane air gap (including power frequency): 5 kV/cm
- Switching impulse breakdown with a long air gap of over 10m on the positive rod-plane: 200 kV/m
- AC porcelain/glass insulator pollution flashover gradient: 0.3 kV/cm
- DC porcelain/glass insulator pollution flashover gradient: 0.2 kV/cm

(The above values are all peak values)

Insulator string length vs flashover voltage under different conditions



1,2- Negative and positive lightning dry flashover for disc insulator; 3- Positive switching dry flashover for post insulator;
4,5-XP-16 Positive switching dry and wet flashover; 6,7-XP-10 Power frequency dry and wet flashover (rms);
8- DC artificial pollution+ice flashover for disc insulator (0.02/1.0mg/cm^2, 50 μS/cm, ice thickness>2.5cm);
9-XP-300 AC artificial pollution flashover (rms) (0.05/1.0mg/cm^2);
10- Negative DC artificial pollution of longrod SiR composite insulator (0.05/(0.3-0.4) mg/cm^2, HC6);
11, 12- Positive switching breakdown voltage for rod-rod and rod-plane air gap

Natural pollution test

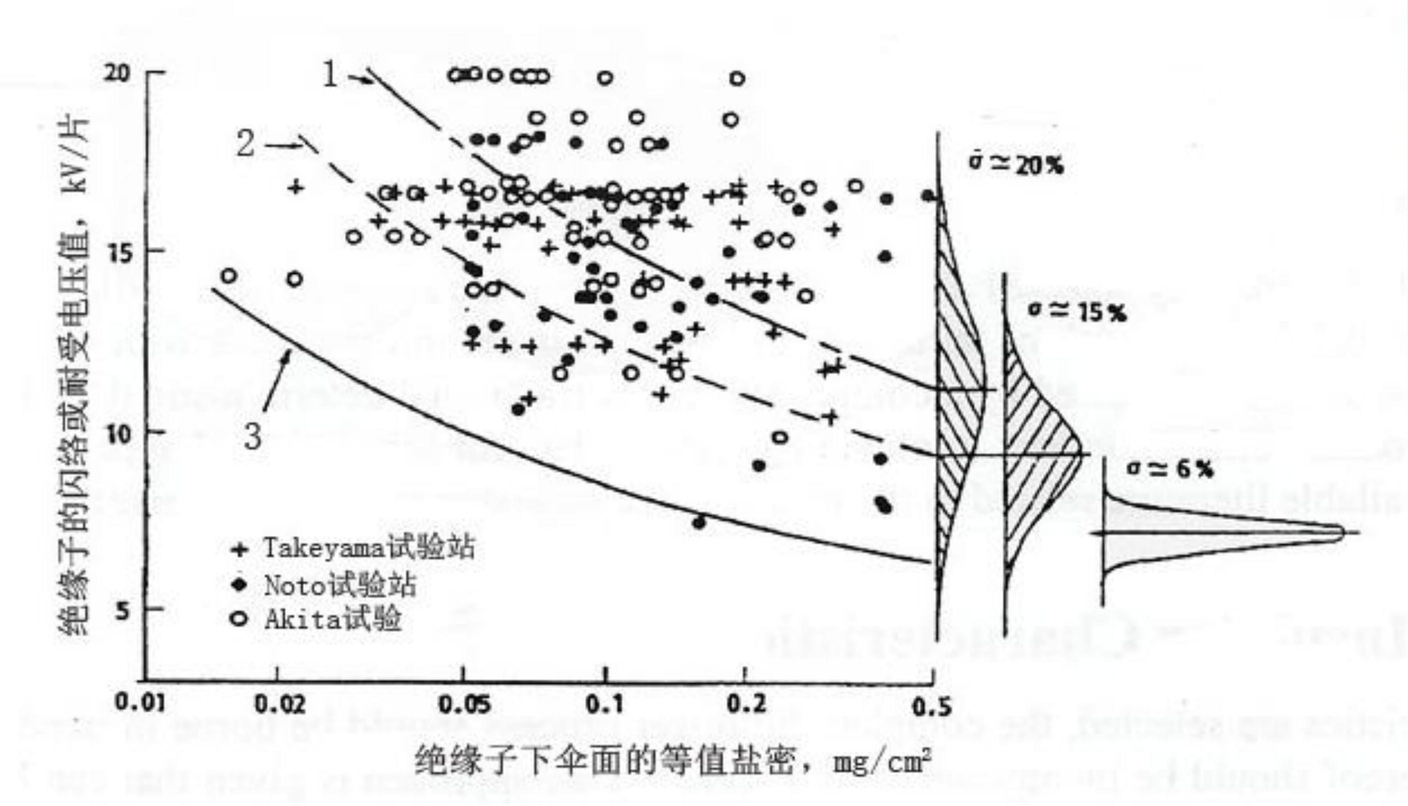


Figure 3-23 Comparison of artificial and natural pollution test results under AC voltage

Samples are standard disc porcelain insulator with diameter of 250mm

Takeyama, Noto and Akita are the natural pollution test stations in Japan

1—Natural pollution flashover voltage U_{50}, normal deviation $\sigma \approx 20\%$

2—Natural pollution flashover voltage under artificial fog U_{50}, $\sigma \approx 15\%$

3—Artificial pollution withstand voltage, Tonoko NSDD=0.1mg/cm^2, $\sigma \approx 6\%$

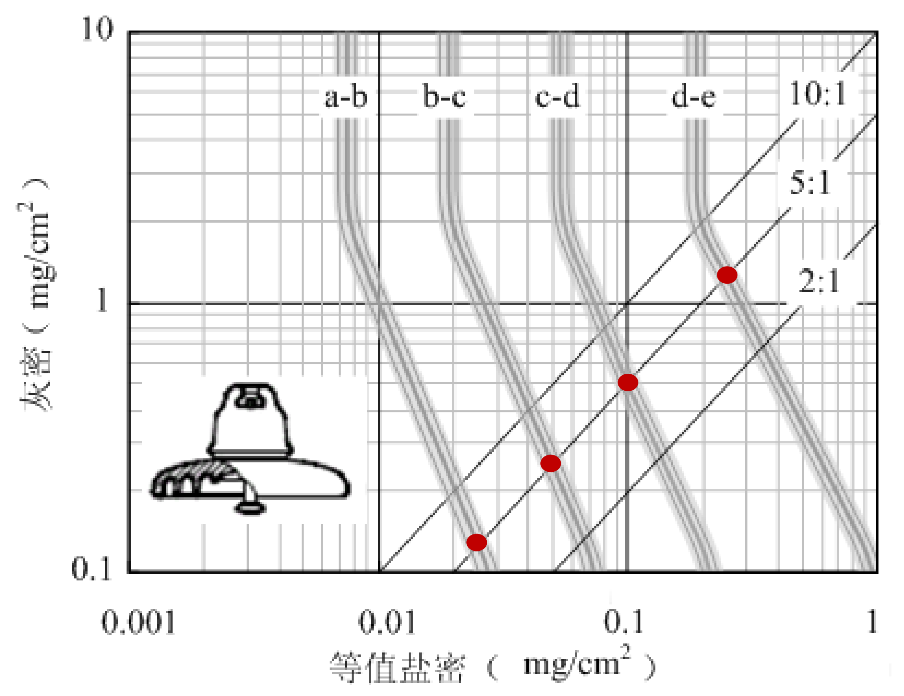
3.5.4 Dimension of insulators in polluted areas

How to deal with the pollution flashover problem of insulators in OHLs and substations?

Dimensioning of insulators in polluted areas

- The site pollution severity (SPS) is classified as a-e five classes based on the measured ESDD and NSDD value on standard disc insulators
- Unified specific creepage distance (USCD) for each pollution level is then determined accordingly

The measured NSDD to ESDD ratio in China is generally within 2:1-10:1, typically 5:1



Relation between ESDD/NSDD and SPS class for the standard disc insulator for AC condition

Table 3-5 Required USCD of standard porcelain/glass and polymer insulators in different SPS class

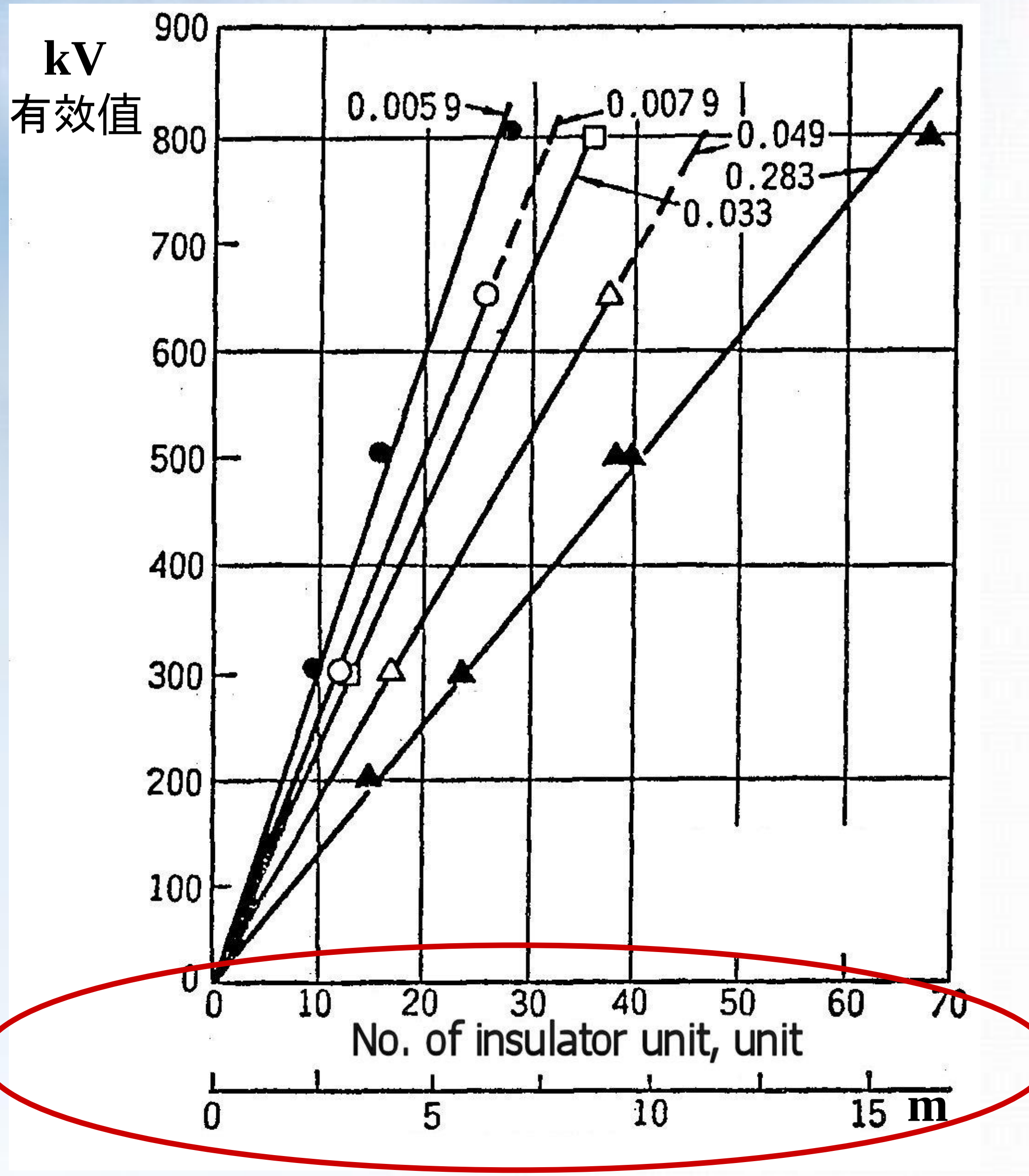
SPS class	a very light	b light	c medium	d heavy	e very heavy
Required USCD mm/kV	22.0	27.8	34.7	43.3	53.7

Insulator pollution flashover performance curve obtained from artificial pollution test

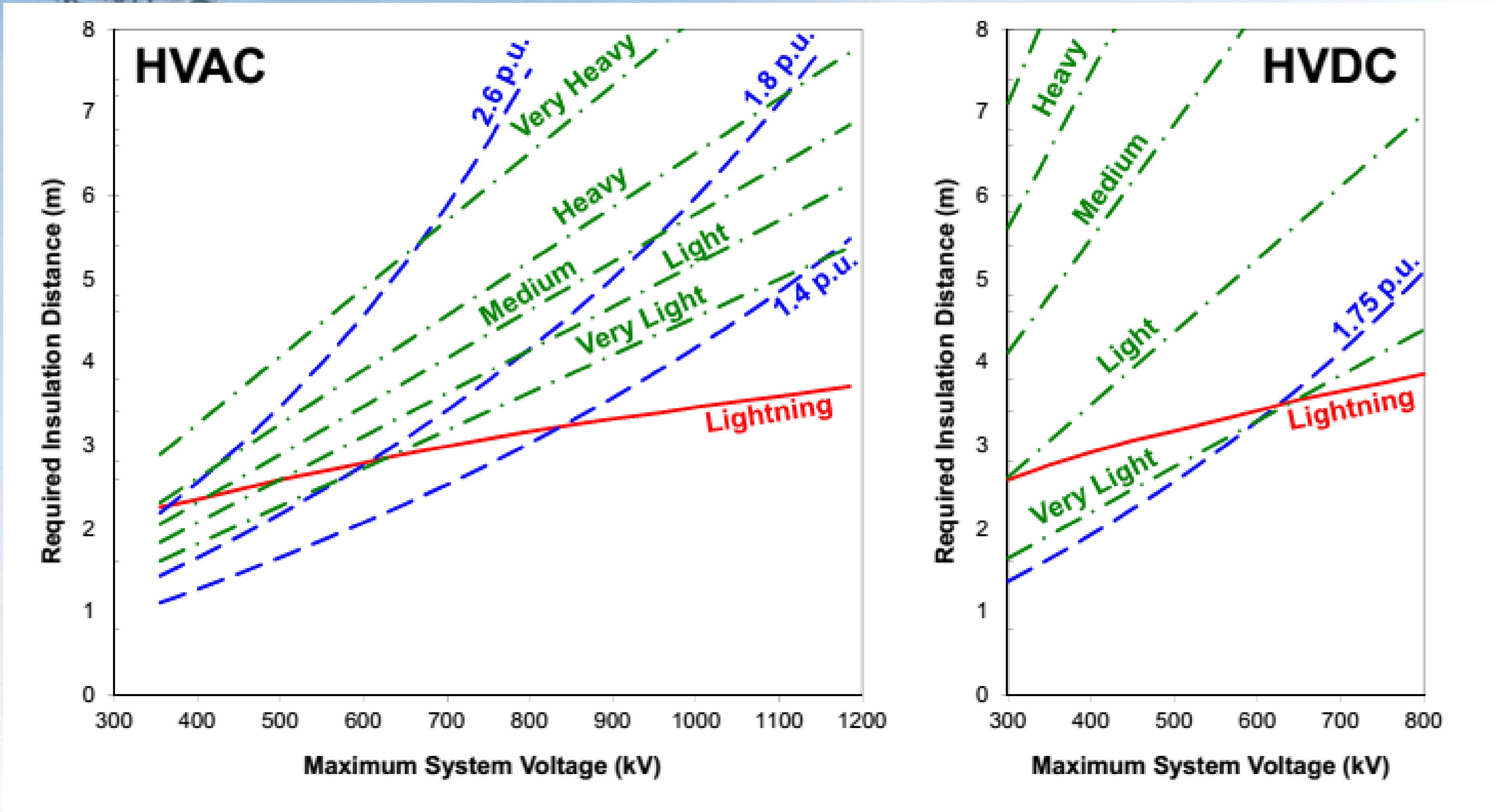
Relation between artificial pollution withstand voltage and insulator string length of disc porcelain insulator

There is a linear relationship between pollution flashover/withstand voltage and creapage distance/string length/number of disc insulators

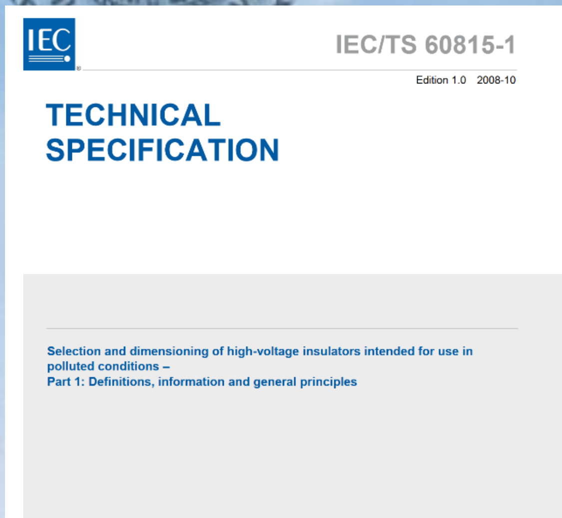
The proportional relationship between pollution flashover voltage and the creepage distance of insulators becomes the engineering basis for the dimensioning of insulators in polluted areas



Environmental pollution greatly increase the cost of outdoor insulation
and still with risk of flashover and power outage
The problem is more severe under UHV! The problem is more severe under DC!



Important documents: IEC TS 60815

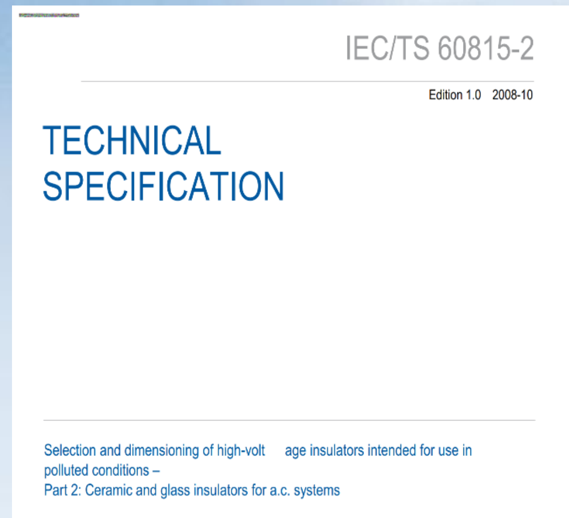

IEC

IEC/TS 60815-1

Edition 1.0 2008-10

TECHNICAL SPECIFICATION

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –
Part 1: Definitions, information and general principles

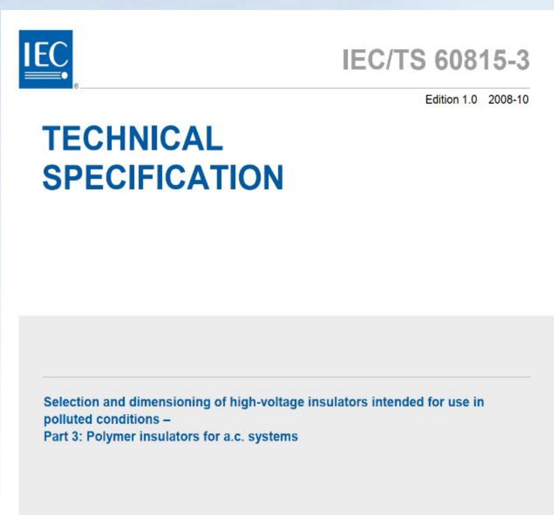

IEC/TS 60815-2

Edition 1.0 2008-10

TECHNICAL SPECIFICATION

Selection and dimensioning of high-volt age insulators intended for use in polluted conditions –
Part 2: Ceramic and glass insulators for a.c. systems

- Revision of -1/-2/-3
- Start from 2017
- Completed in 2025


IEC

IEC/TS 60815-3

Edition 1.0 2008-10

TECHNICAL SPECIFICATION

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –
Part 3: Polymer insulators for a.c. systems


This is a preview - click here to buy the full publication

IEC

IEC TS 60815-4

Edition 1.0 2016-10

TECHNICAL SPECIFICATION

colour inside

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –
Part 4: Insulators for d.c. systems

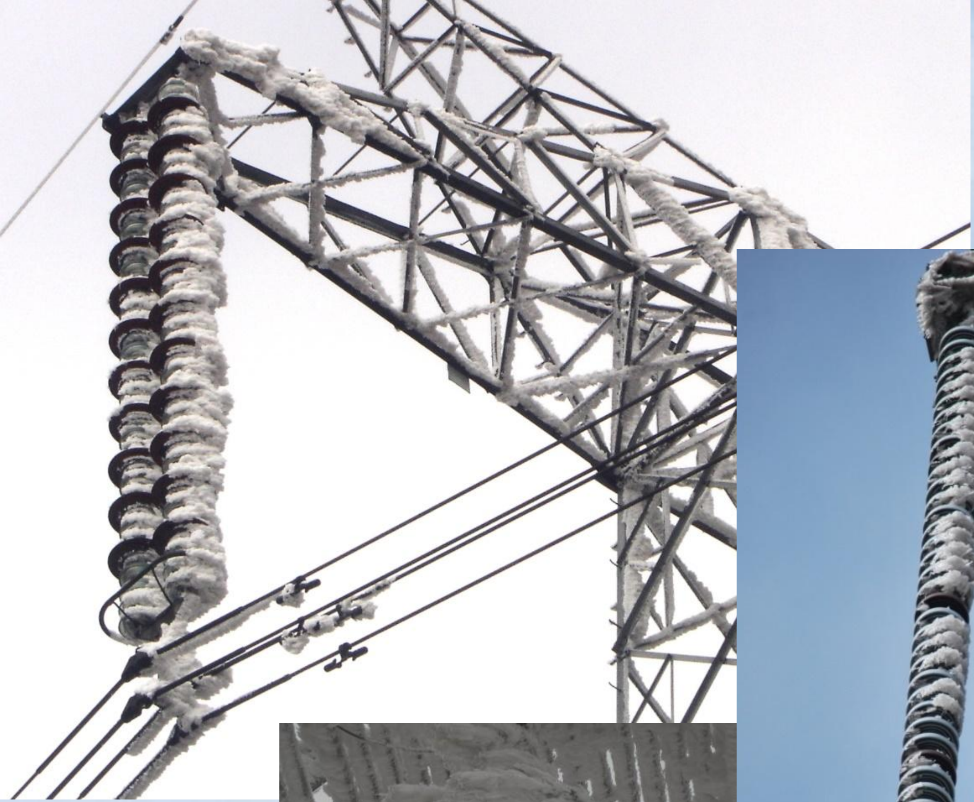
3.5.5 Icing flashover of insulators

Icing flashover process, characteristics, and test method

In artificial climate chamber, spray in sub zero ambient temperature; Warm up after icing to expected amount; Then ice melting, flashover

If insulator surface is polluted and covered with ice, the flashover voltage will be lower!

- ✓ Using water with a certain conductivity?
- ✓ Insulators should be covered with a pollution layer first and then icing? Or icing on clean insulator?
- ✓ Is it energized or not during the icing process?




Insulators icing

3.5.6 Measures for increasing pollution flashover voltage of porcelain insulators

Measures to increase pollution flashover voltage and decrease pollution flashover accidents

- Reduce pollution accumulation

Choose shed with open profile, or cleaning pollution with and without energized

- Reduce the wetting of insulators

Choose an anti-fog shed profile, or use semiconducting glaze

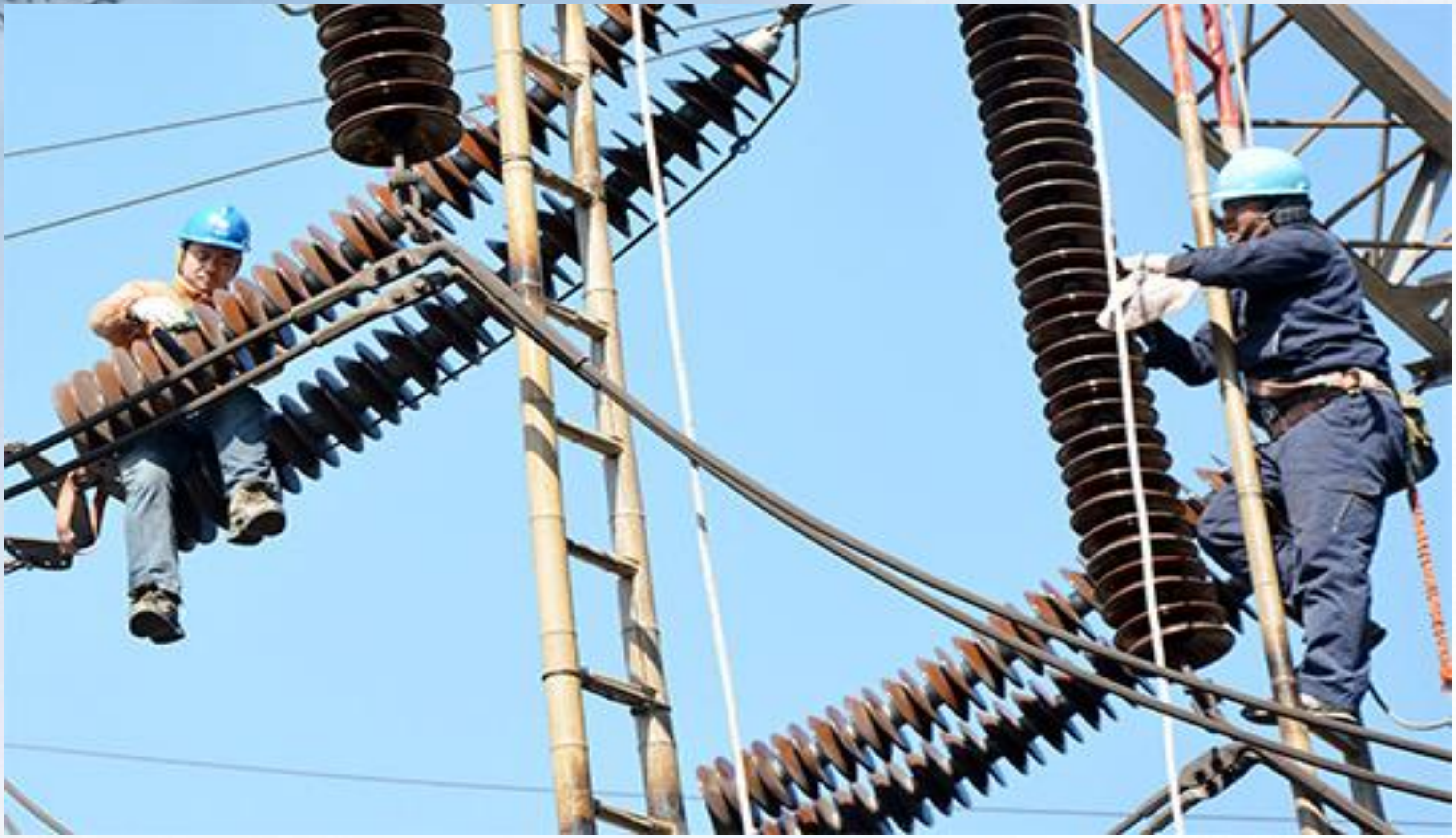
- Increase the total creepage distance of insulator string

Choose insulators with large creepage distance, or adding more insulator pieces

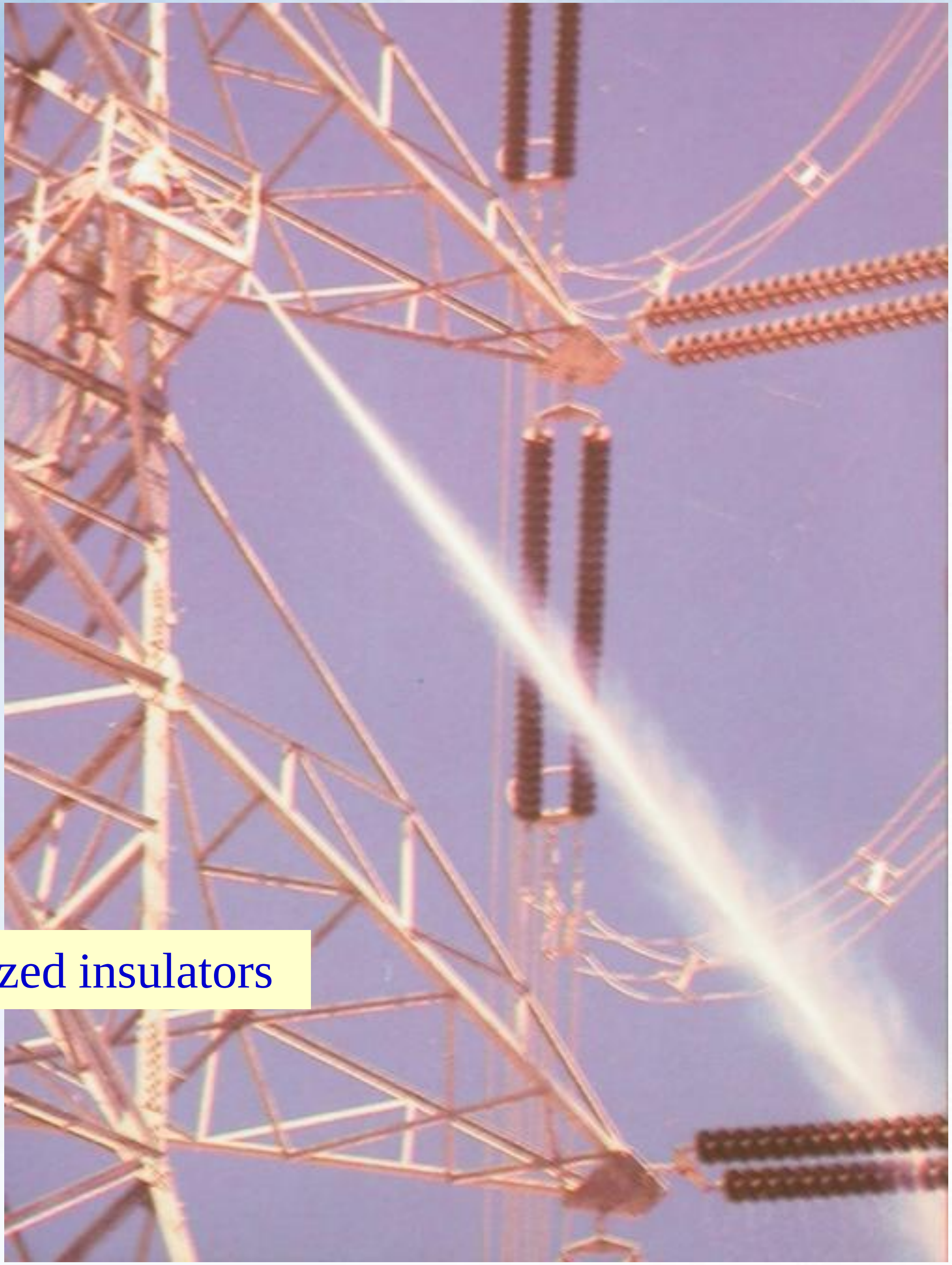
- Using hydrophobic coatings

Silicone oil, silicone grease, (long-lasting) wax, RTV coating, (Asphalt)

cleaning pollution for non-energized insulators



washing pollution for energized insulators



washing pollution for energized insulators

3.5.6 Measures for increasing pollution flashover voltage of porcelain insulators

Measures to increase pollution flashover voltage and decrease pollution flashover accidents

- Reduce pollution accumulation

  Choose shed with open profile, or cleaning pollution with and without energized

- Reduce the wetting of insulators

  Choose an anti-fog shed profile, or use semiconducting glaze

- Increase the total creepage distance of insulator string

  Choose insulators with large creepage distance, or adding more insulator pieces

- Using hydrophobic coatings

  Silicone oil, silicone grease, (long-lasting) wax, RTV coating, (Asphalt)

- Conventional anti-pollution flashover measures:

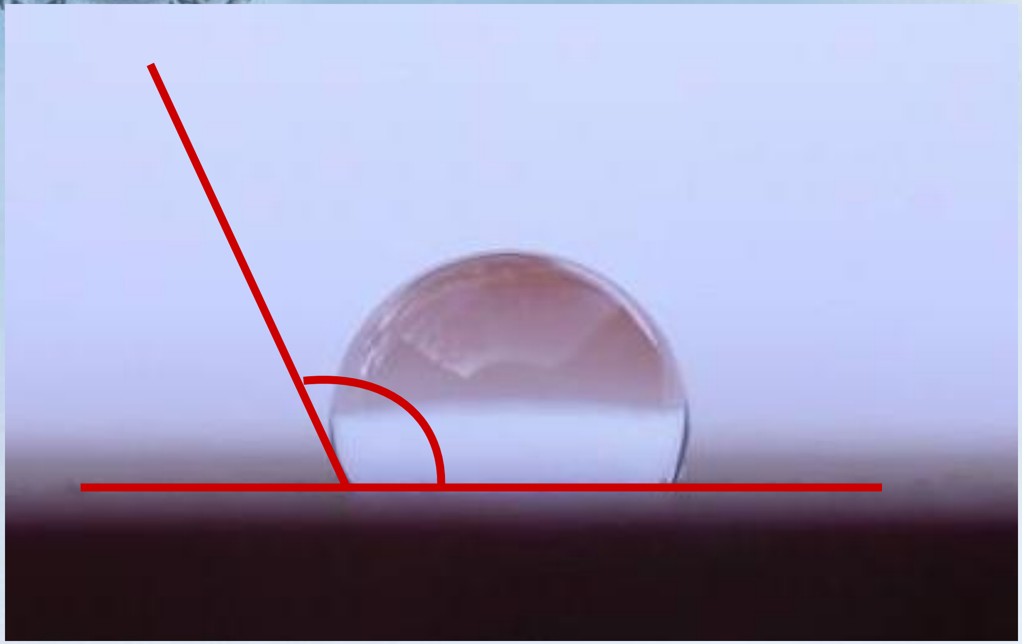
  Using longer creepage distance, hydrophobic coatings, cleaning pollution

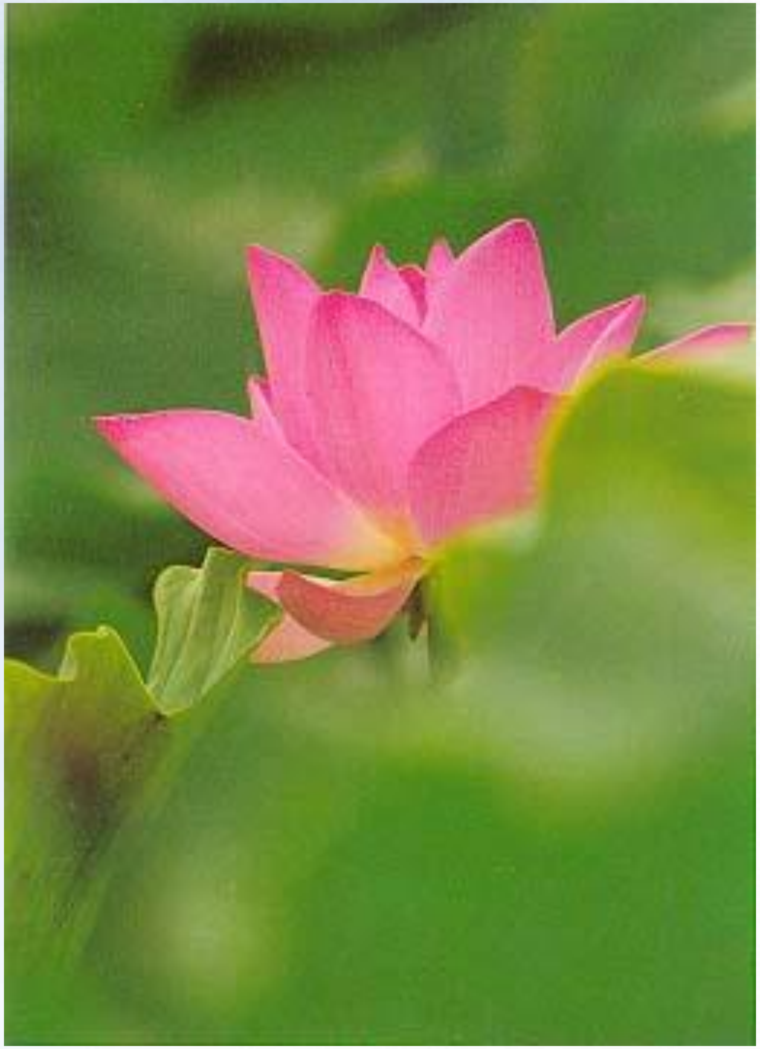
- New generation organic outdoor insulation:

  Using silicone rubber insulators

The most effective measures to solve large-scale pollution flashover accident in China

3.5.7 Silicone rubber composite insulators and organic outdoor insulation





Hydrophobic surface:
Static contact angle between water droplets and solid surface is ≧90°

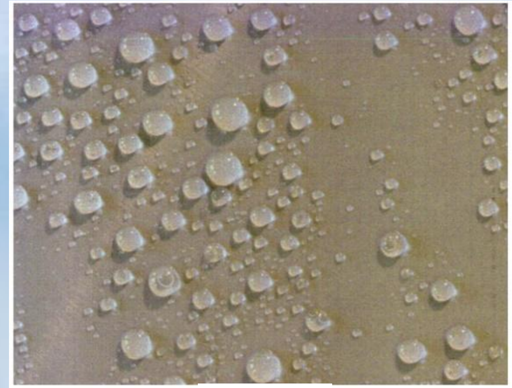
What happens if a hydrophobic surface is covered by a pollution layer?

Spraying method to evaluate surface hydrophobicity: HC1–HC7 In IEC TS 62073-2026

HC值	试品表面水滴状态描述
HC1	只有分离的水珠，大部分水珠的后退角 $\theta_r \geq 60^0$
HC2	只有分离的水珠，大部分水珠的后退角 $40^0 < \theta_r < 60^0$
HC3	只有分离的水珠，水珠一般不再是圆的，大部分水珠的后退角 $10^0 < \theta_r < 40^0$
HC4	同时存在分离的水珠与水带。完全湿润的水带面积小于 $2cm^2$，总面积小于被测区域面积的90%，$0^0 < \theta_r < 10^0$
HC5	一些完全湿润的水带面积大于 $2cm^2$，总面积小于被测区域面积的90%，$0^0 < \theta_r < 10^0$
HC6	完全湿润总面积大于90%，仍存在少量干燥区域（点或带），$0^0 < \theta_r < 5^0$
HC7	整个被试区域形成连续的水膜 $\theta_r = 0^0$

θ_r is the receding angle of water droplet on a tilted surface

What happens if a hydrophobic surface is covered by a pollution layer?



HC1

HC2

HC3

HC4

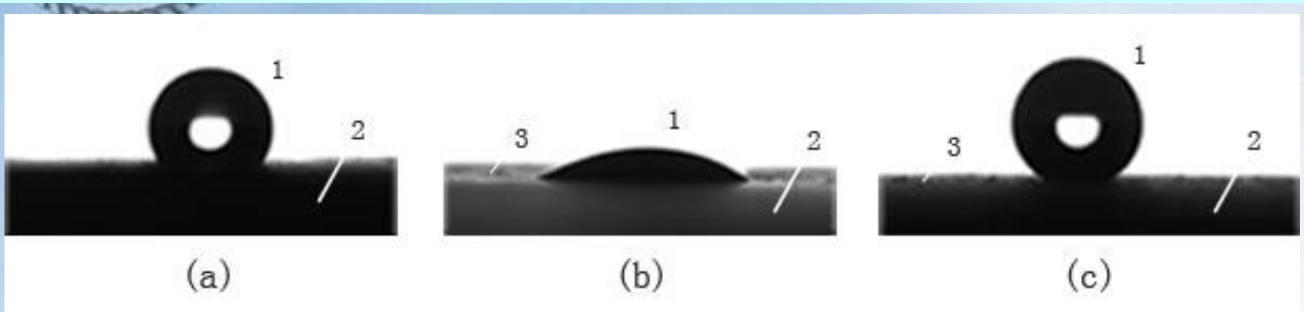
HC5

HC6

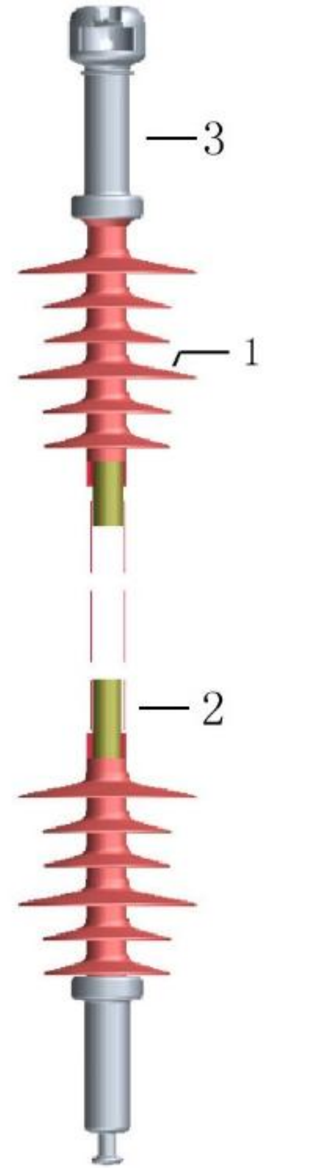
3.5.7 Silicone rubber composite insulators and organic outdoor insulation

Silicone rubber is currently the only one material found to present hydrophobicity transfer properties

Waiting some time after pollution, the pollution layer also present hydrophobicity



Hydrophobicity transfer effect on the surface of silicone rubber material
(a) Cleaned surface; (b) Hydrophilic after pollution; (c) After hydrophobicity transfer



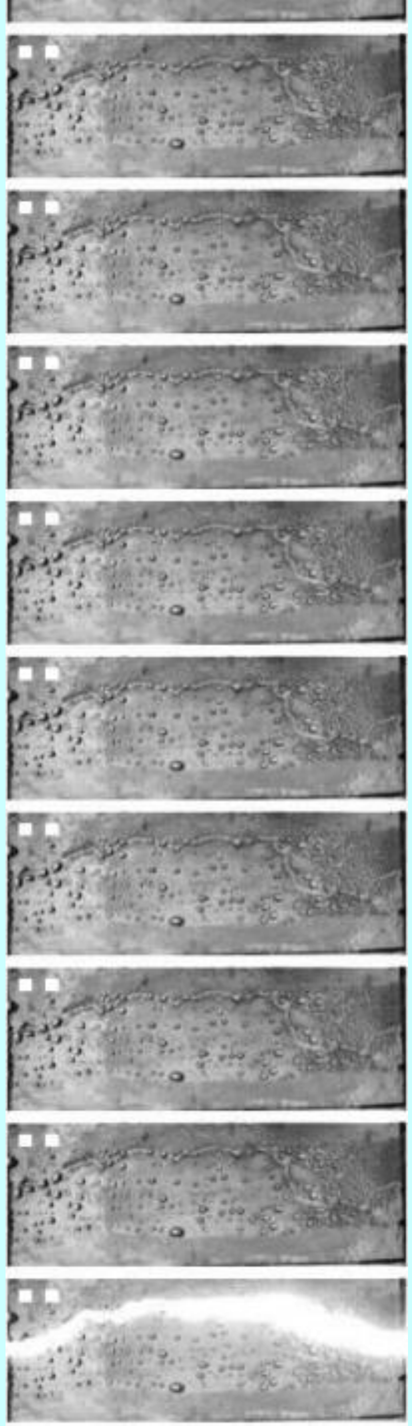
Silicone rubber composite insulator

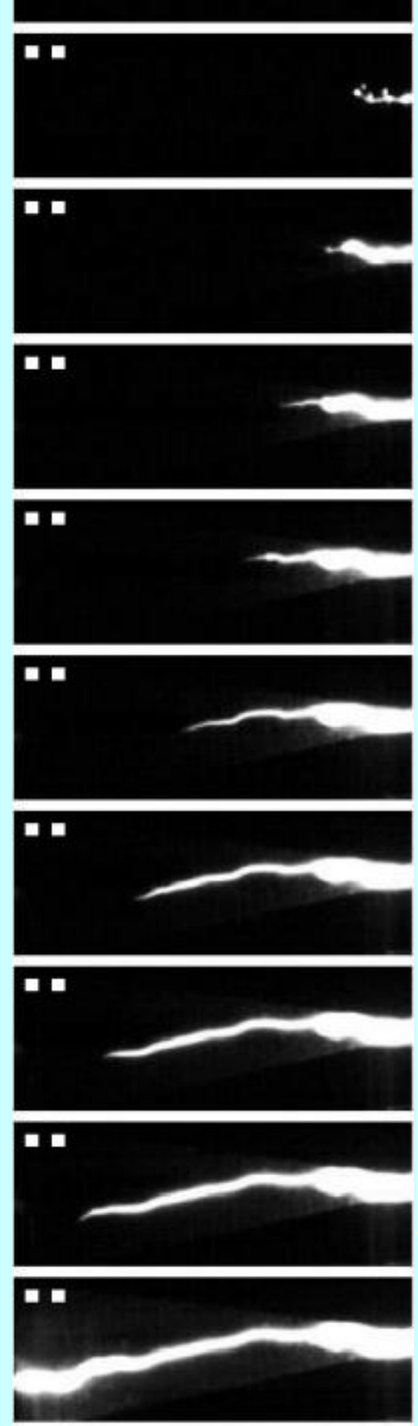
The samples on roof of Tsinghua HV lab exposed for 37 years (left) and 29 years (right) natural aging, still exhibit excellent hydrophobicity transfer property

Hydrophobic surface with high pollution flashover voltage

Sudden flashover of hydrophobic surfaces

Captured under 2000 pfs with an interval of 0.5ms, with each exposure of 25us





Hydrophilic surface with low pollution flashover voltage

Hydrophilic surface, process of arc creap along the surface and finally flashover, captured by high-speed photography

Captured under 2000 pfs with an interval of 0.5ms, with each exposure of 25us

China is the first country that organic polymer insulator dominate the HV outdoor insulation with over 10 million silicone rubber insulators installed for 110kV and above

Silicone rubber insulator is the largest used insulator, accounting for nearly half of the total, with a higher proportion of ultra-high voltage AC and DC

- The main opportunities for SiR composite insulators in China over the past forty years

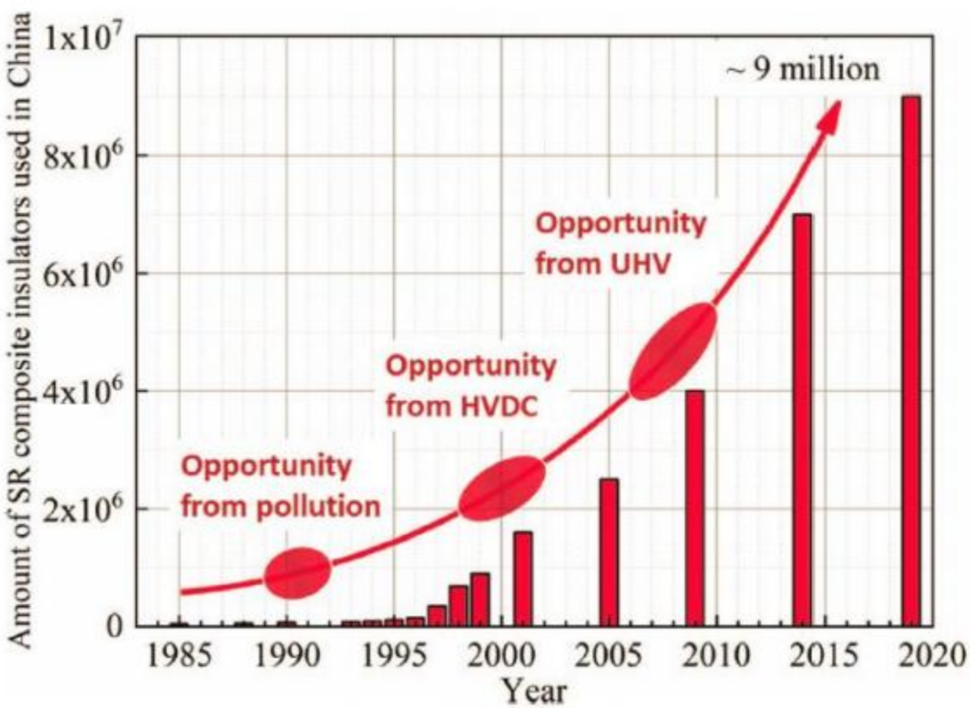


Figure 15. Amount of SR composite insulators used in China for OHLs of 110 kV to 1000 kV AC and ± 400 kV to ± 1100 kV DC.

Opportunity for large scale pollution flashover in the power grid

Applied in areas with severe pollution flashover, despite being expensive and having concerns about long-term performance.

The anti-pollution flashover effect is significant, but there are problems such as brittle fracture, decreased mechanical strength, aging of shed, and decreased hydrophobicity.

Opportunity for DC transmission

The second generation composite insulators solved the problem of brittle fracture and crimping technology. High proportion of usage in HVDC lines.

Ultra high voltage opportunity

Basic confidence build up in service life, and SiR insulators dominate the AC/DC ultra-high voltage lines.

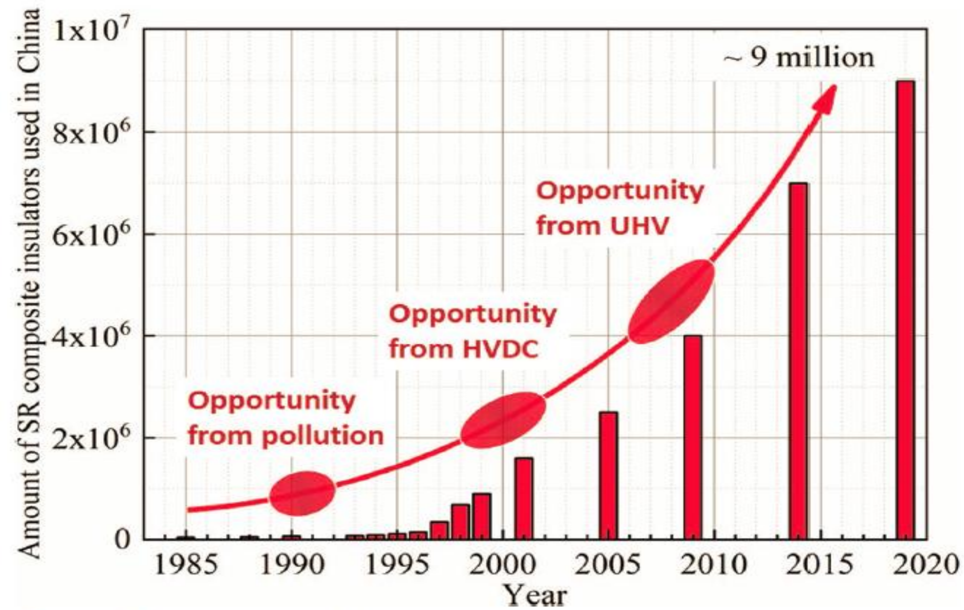


Figure 15. Amount of SR composite insulators used in China for OHLs of 110 kV to 1000 kV AC and ± 400 kV to ± 1100 kV DC.

Over the past forty years, the usage of silicone rubber composite insulators in China has grown rapidly

China became the first country to mainly use organic outdoor insulation

Insulators purchased by State Grid

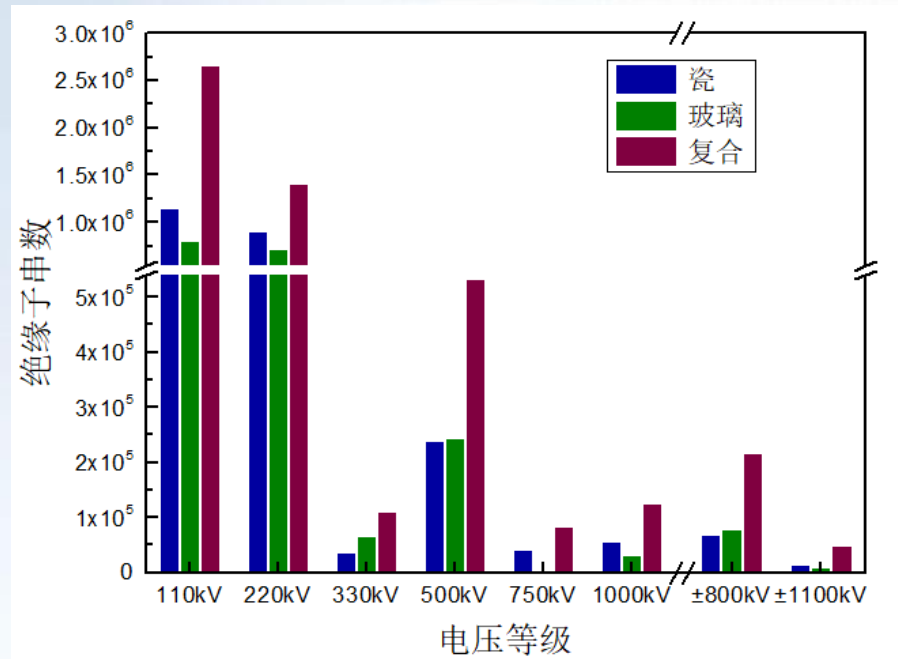
(2012. 1–2017. 12)

- **Porcelain insulators: 38050 thousand pieces (2560 thousand strings, 26. 4%)**
- **Glass insulators: 30310 thousand pieces (1940 thousand strings, 20. 0%)**
- **Silicone rubber composite insulators : 5190 thousand strings, 53. 3%**

The above data covers:

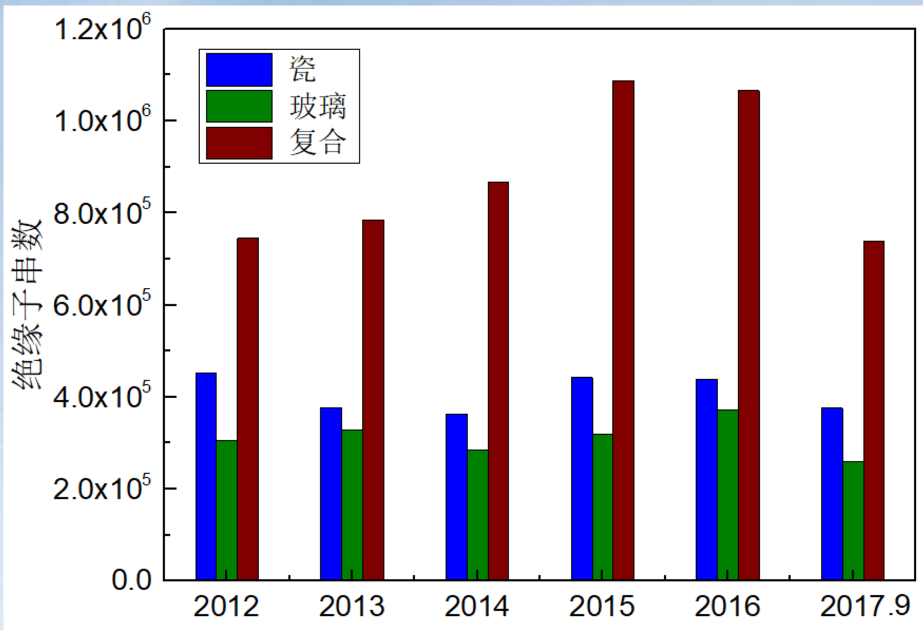
AC: 110kV ~ 1000kV, DC: ± 800kV

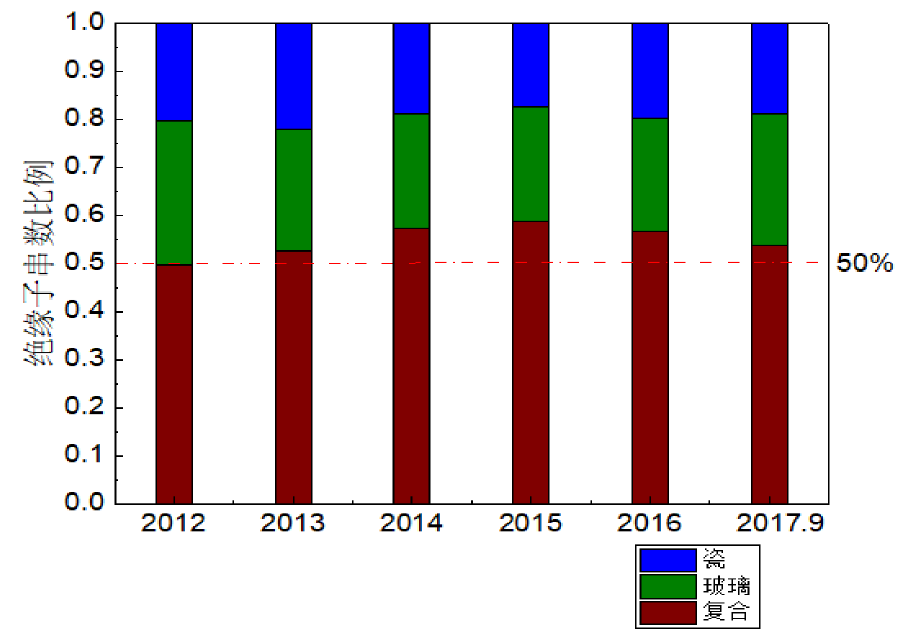
Strength level: 70kN ~ 550kN (including 1000kN composite insulators)



The usage of silicone rubber composite insulators in China has grown rapidly in the past forty years

➢ **Composite insulators have become the most widely used insulators**





- **Among the newly added insulators, the procurement volume of composite insulators remains the highest**
- **From 2012 to 2017, the proportion of composite insulator usage for 6 consecutive years was ≥ 50%**
- **From 2012 to 2017, the average annual procurement volume of composite insulators was about 800000 to 1 million strings**

China is the first country that organic polymer insulator dominate the HV outdoor insulation with over 10 million silicone rubber insulators installed for 110kV and above

Silicone rubber insulator is the largest used insulator, accounting for nearly half of the total, with a higher proportion of ultra-high voltage AC and DC

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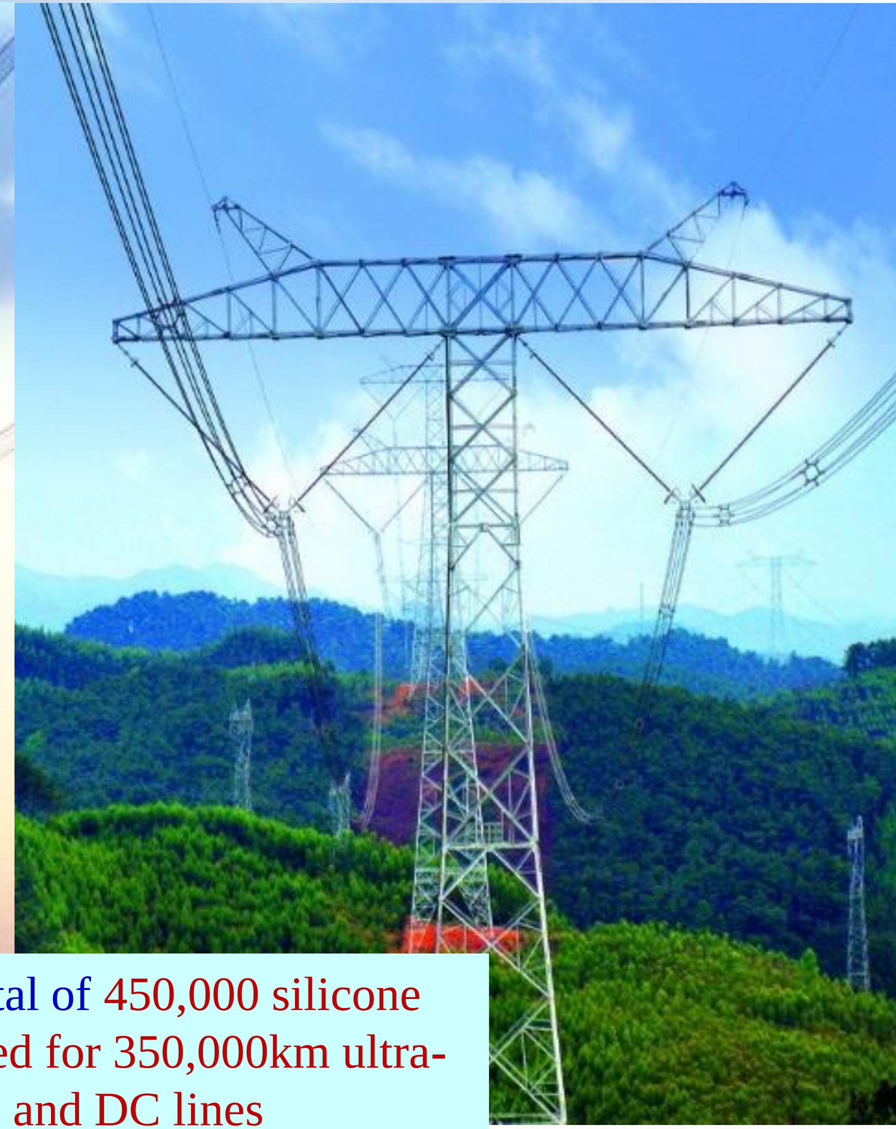


By the end of 2019, a total of 450,000 silicone rubber insulators were used for 350,000km ultra-high voltage AC and DC lines

3.5.7 Silicone rubber composite insulators and organic outdoor insulation

The large-scale pollution flashover accident in power grid no longer occurred for >18 years!

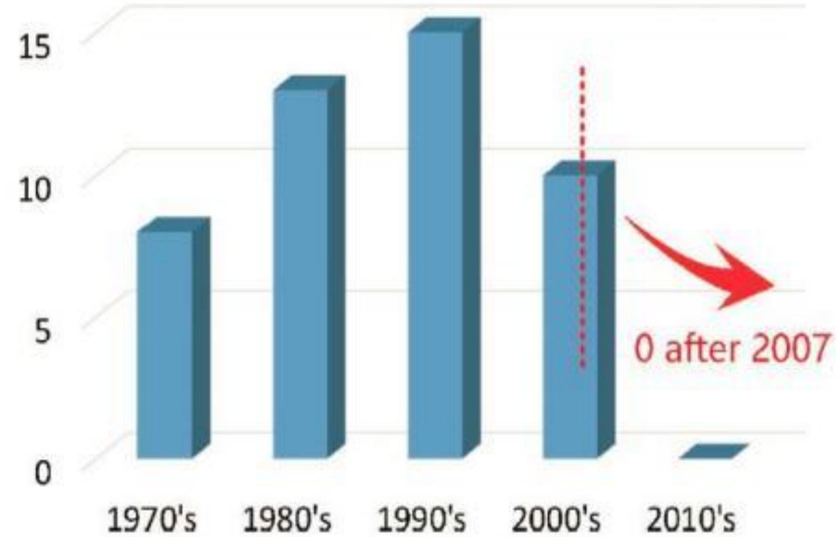
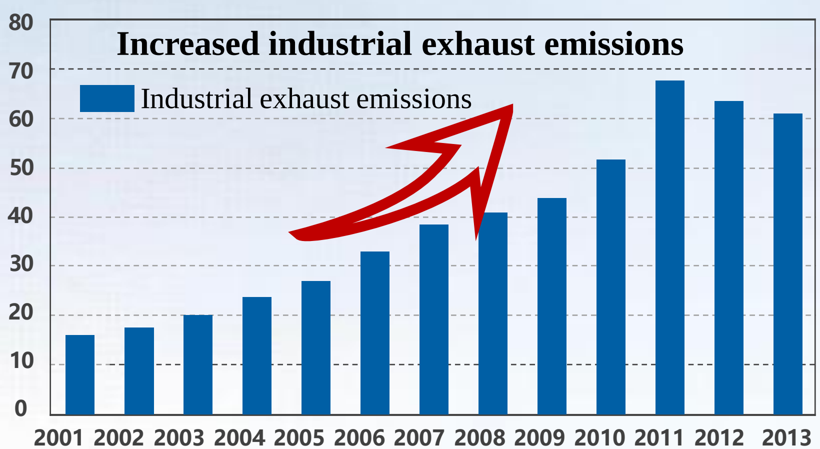
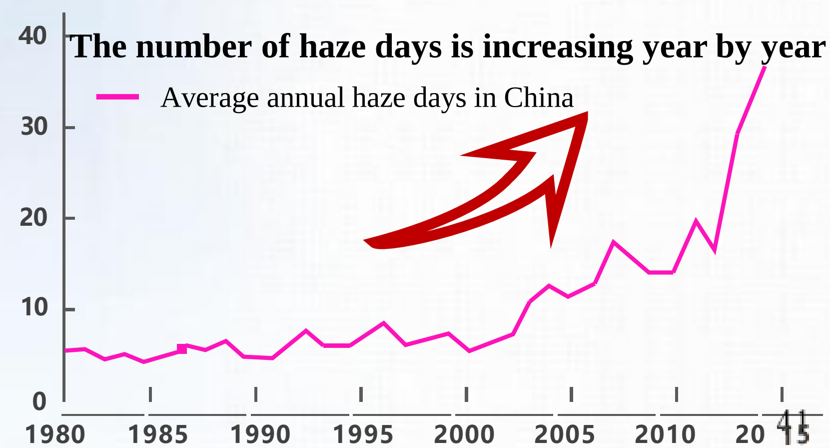


Figure 1. Number of the large area pollution flashover accidents in China from 1970s to 2010s.

With a significant increase in air pollution, the length of OHLs increased by 5-10 times, and the pollution flashover outage rate (times/100 km per year) from 0.12 in 2001 to 0.00068 since 2012, a decrease of two orders of magnitude!





Chapter 1 Analysis of gas discharge

collision ionization, self-sustained discharge, Townsend discharge, Paschen's law, electron avalanche, streamer, leader, corona discharge, polarity effect, long gap discharge

Chapter 2 Insulation Characteristics of air under different voltage forms

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

Chapter 3 High voltage outdoor insulation and surface discharge

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

Example of actual situation: What will happen to the **surface** discharge of an extremely non-uniform **field** under impulse **voltage**?

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

Voltage waveform

Lightning impulse

Switching impulse

AC

DC

Polarity effect, time lag, U_{50}, volt-time characteristics, dispersion, U-shaped curve, long gap saturation of switching impulse and AC voltage……

Three types of factors affecting gap discharge

Electric field uniformity

uniform field

slightly non-uniform field

extremely non-uniform field

collision ionization, streamer and leader, corona, typical electrode configurations of slightly non-uniform field, symmetry and asymmetry of extremely non-uniform field…

Dielectric status

Atmospheric conditions and altitude correction

Gas gap: pressure, temperature, humidity

Surface discharge: dry and clean surfaces, polluted surface

Weak/strong vertical component
Pollution flashover, Rain flashover,
Icing flashover

"material and structure" + applied voltage, determine the insulation performance and discharge characteristic.

Gas, solid, liquid and surface discharge can all be analyzed by this thinking.

(special question under HV and high stress)