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

2.5 Measures to increase gas gap breakdown voltage

2.5.1 Improving electrode profile

- Improving electric field structure, suppress discharge initiation and development

For slightly non-uniform fields:

Increase the of the electrode and improve the uniformity of the electric field to increase the gap breakdown voltage;

For extremely non-uniform field:

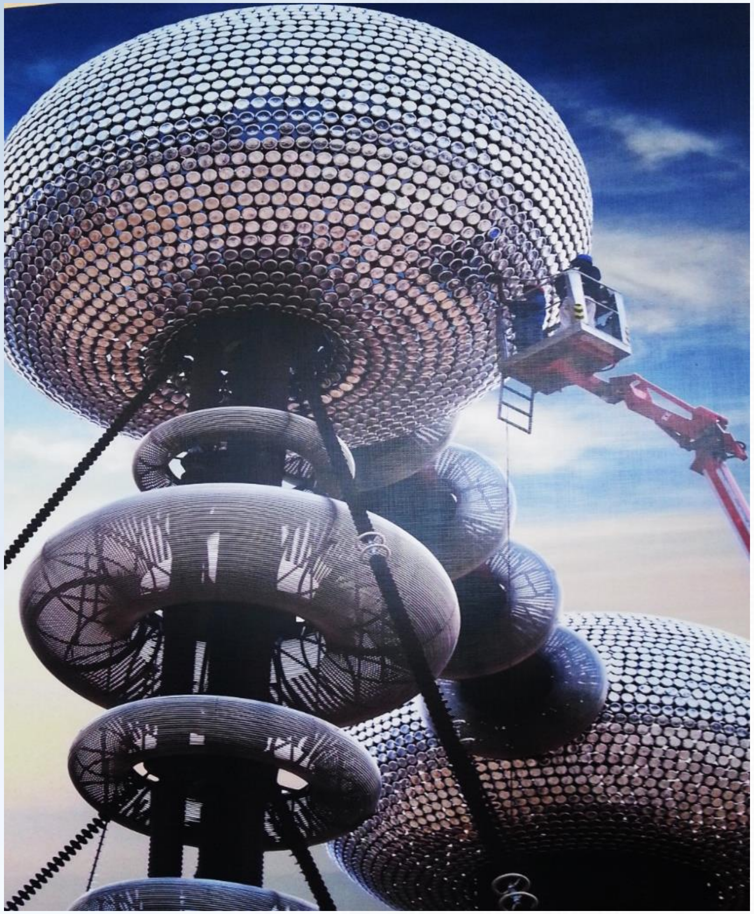
Change the electrode profile to avoid asymmetric electric fields distribution as much as possible to increase the gap breakdown voltage;

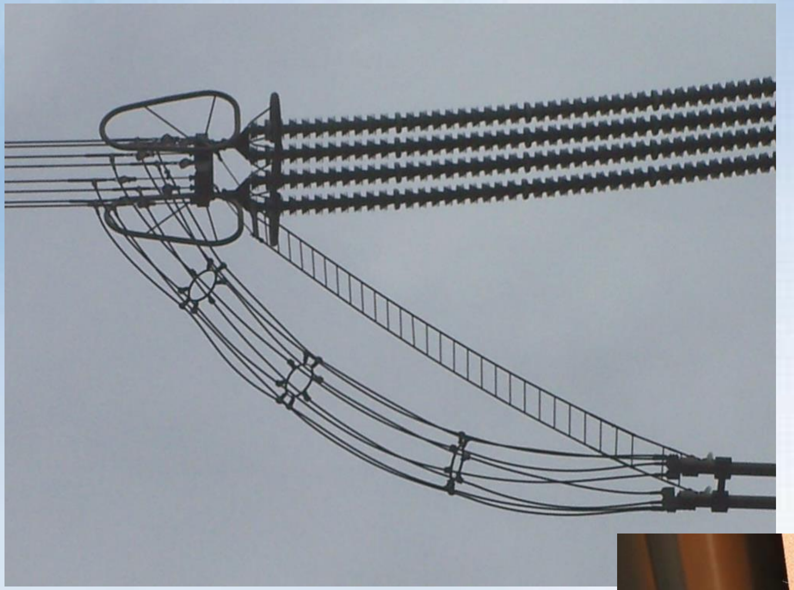
Or increase the curvature radius of the electrode, increase the inception voltage of corona, and reduce corona (with little effect on breakdown voltage)

- To reduce the discharge voltage and increase the discharge effect, vice versa

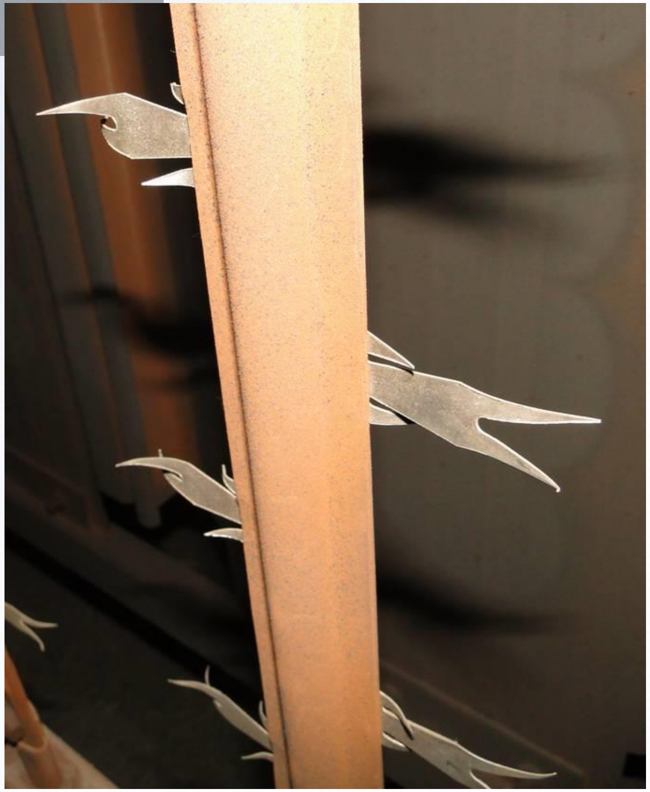
;

Increase the curvature radius of high electric field electrodes to avoid corona initiation





Adjust electric field distribution and control local high electric field (left and top)



Reduce the curvature radius of high electric field electrodes to induce earlier inception of corona (right)

Discharge show using Tesla transformers
(Hope to get the discharge spark as long as possible)

Discharge show using Tesla transformers
(Hope to get the discharge spark as long as possible)

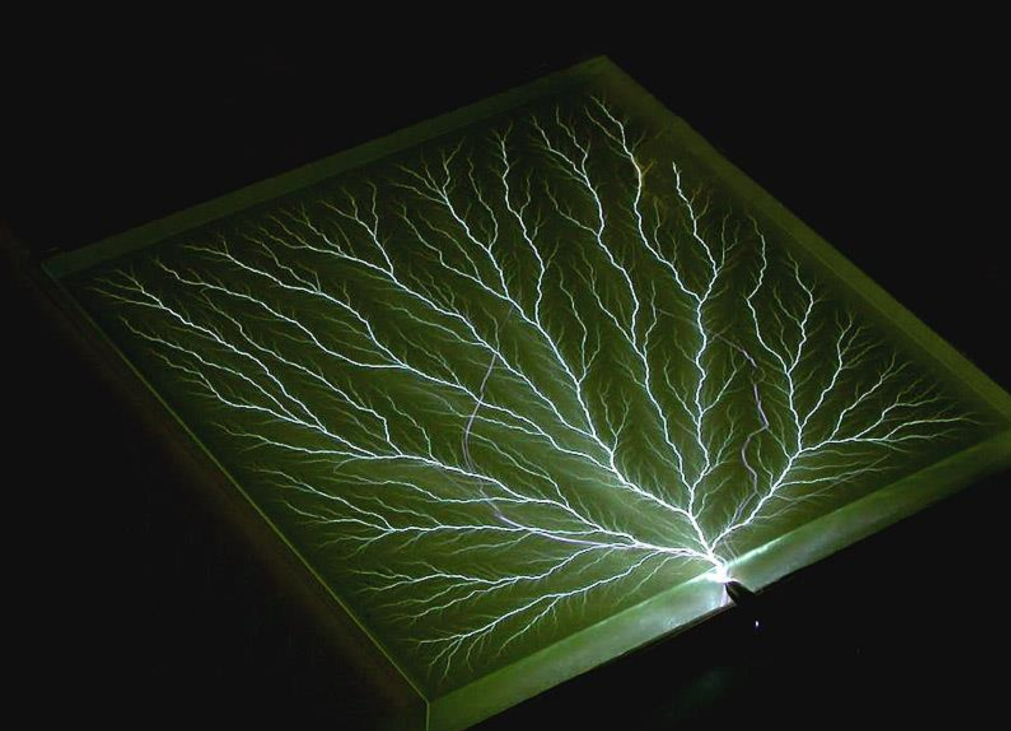
Hope to get the discharge spark as long as possible

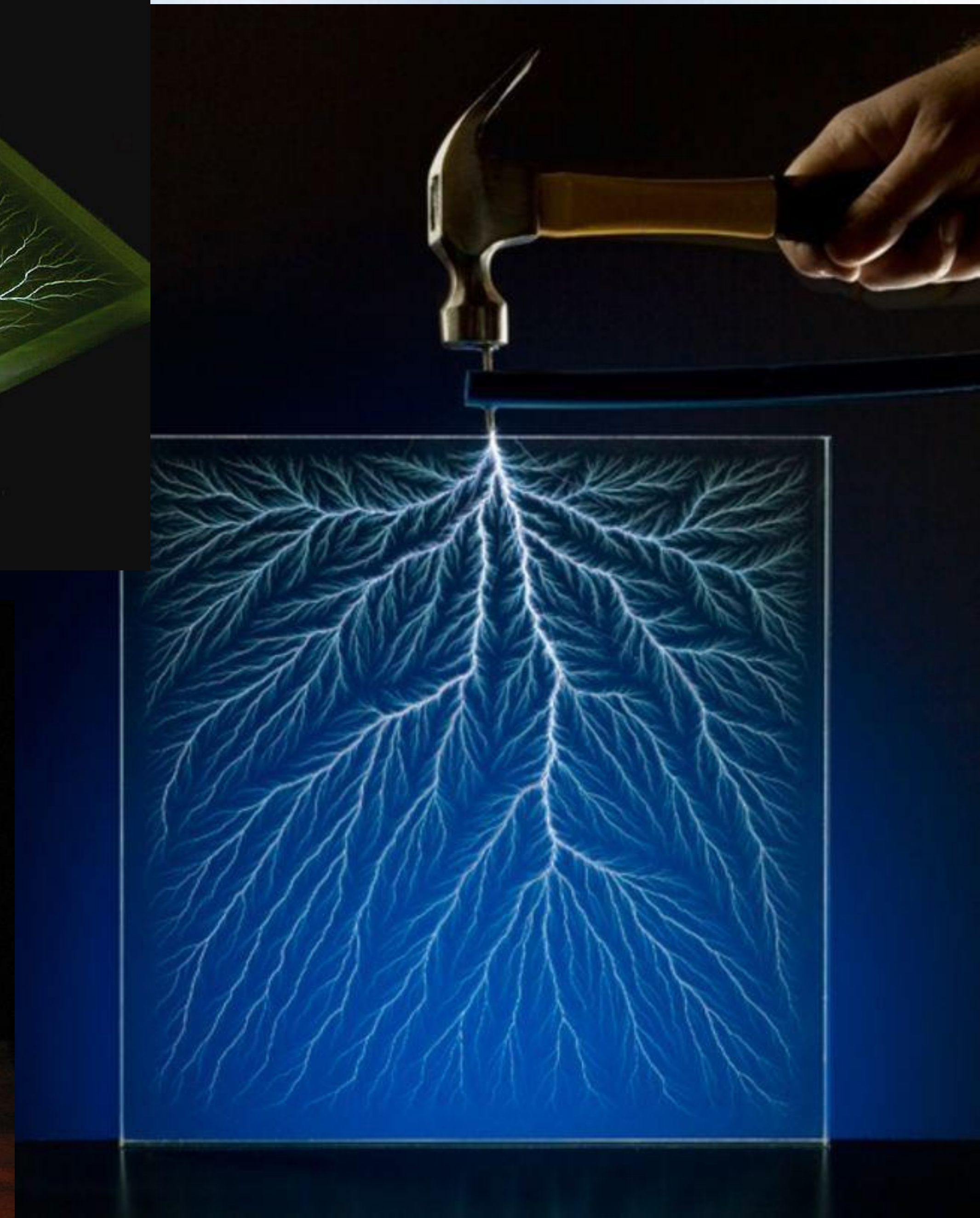
A model wearing a metal mesh (Faraday cage) danced with Tesla coil at the Paris fashion show

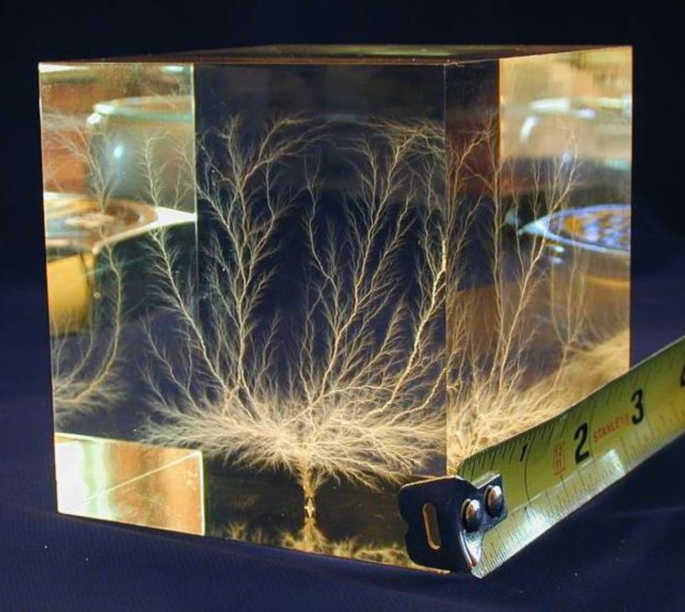
Violin players wearing protective clothing

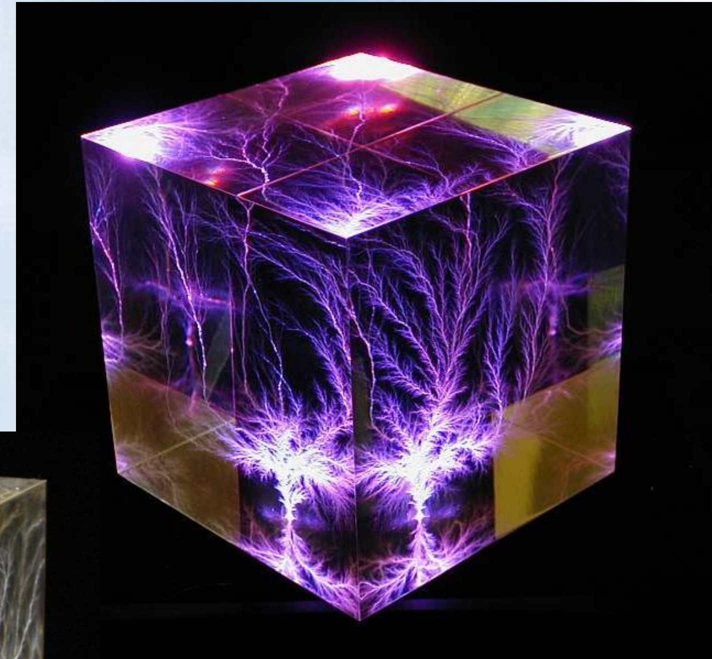
Peter Trent from Australia used 500kV to create a modern version of *The Thinker*:

Lichtenberg figure





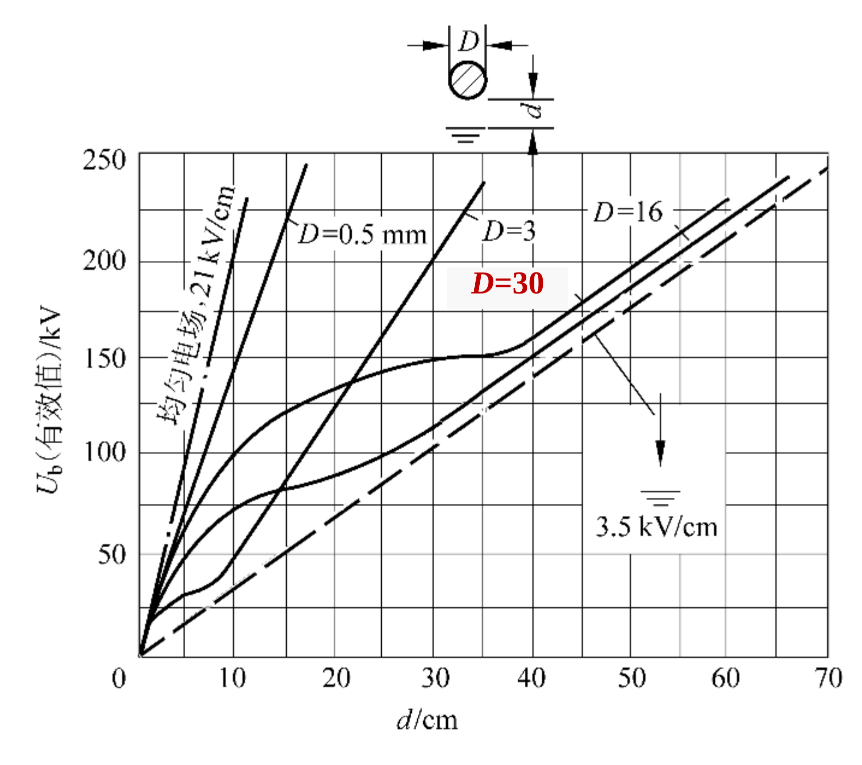




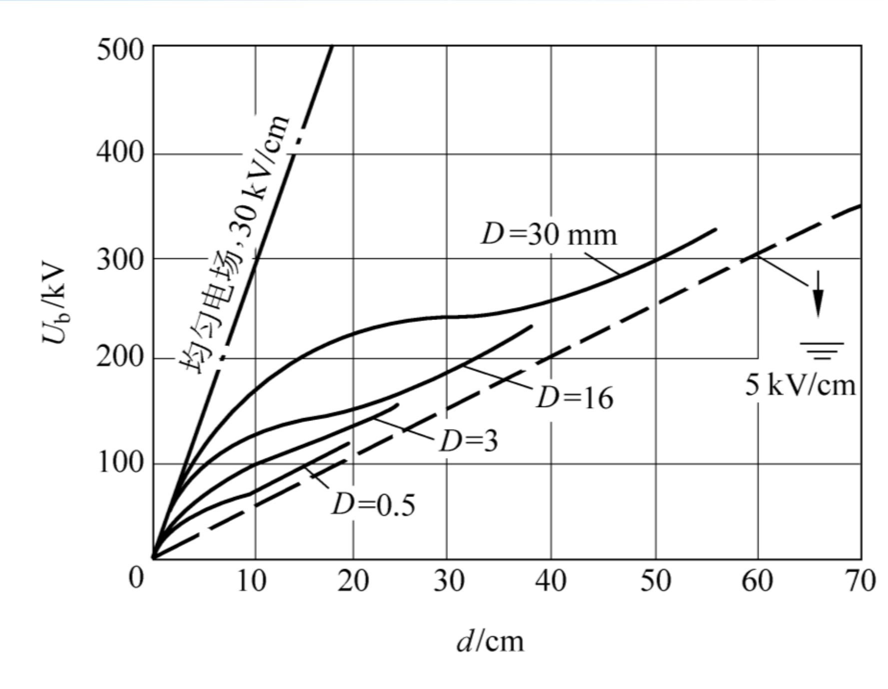
Lichtenberg
Figure
Sculpture

2.5 Measures to increase gas gap breakdown voltage

2.5.2 Utilizing Space Charge



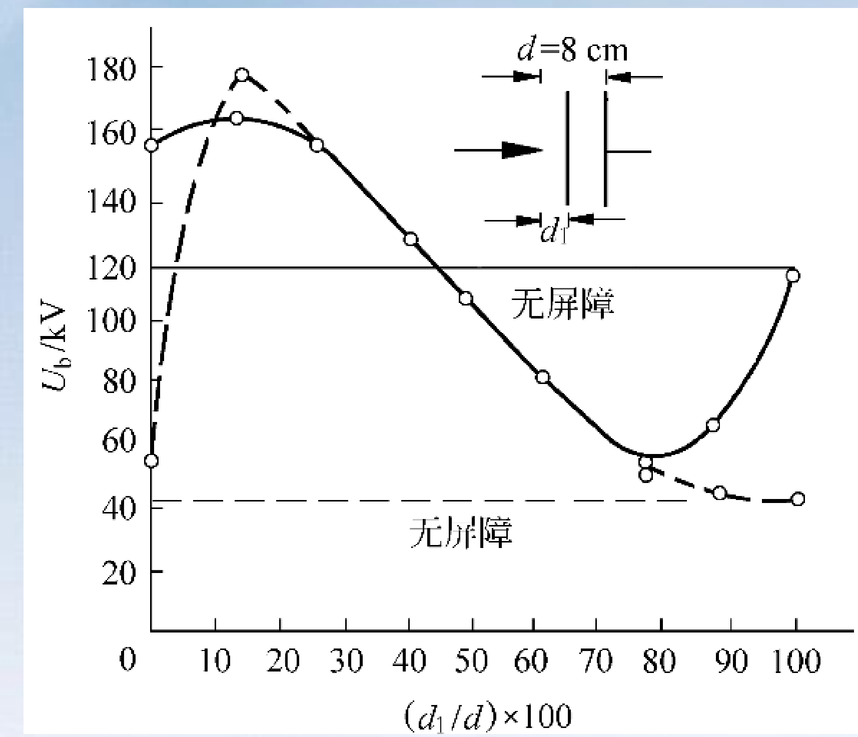
Power frequency breakdown voltage and gap distance of conductor-plane air gap



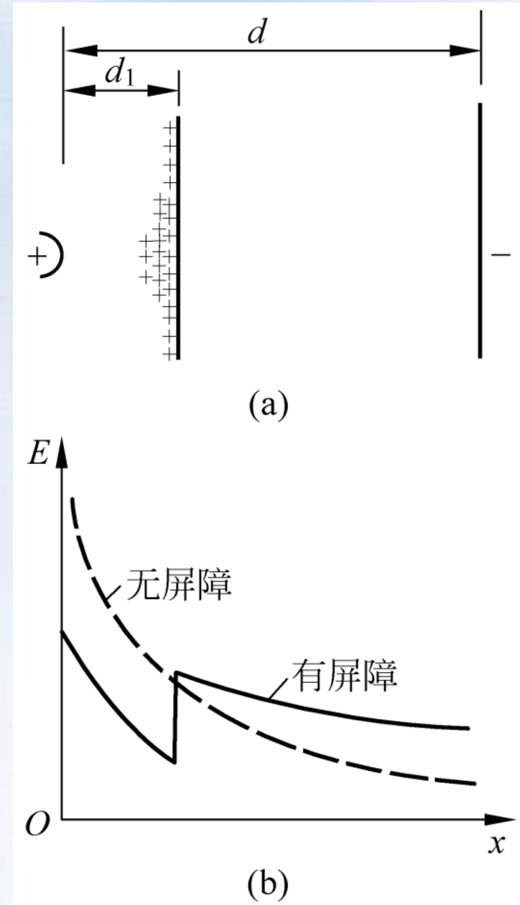
Lightning impulse breakdown voltage and gap distance of conductor-plane air gap

2.5 Measures to increase gas gap breakdown voltage

2.5.3 Application of shielding in extremely non-uniform fields



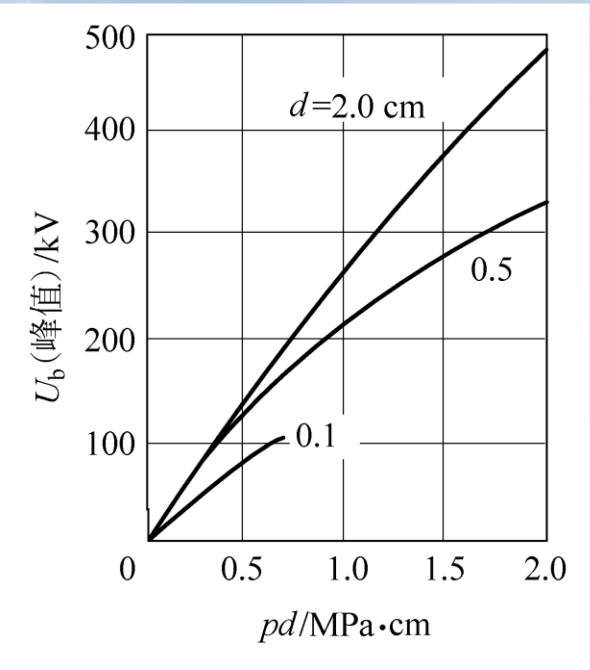
The influence of barriers on the DC breakdown voltage of the positive point-plane air gap
(Solid line-negative; dashed line-positive)



The influence of barriers on the electric field distribution in positive point-plane gap

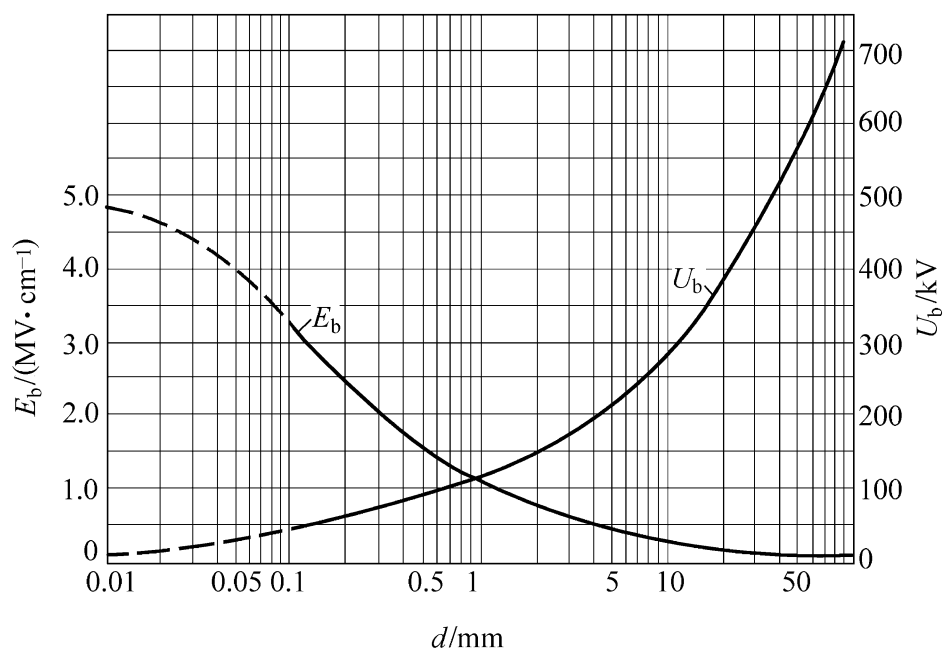
2.5 Measures to increase gas gap breakdown voltage

2.5.6 Application of high pressure



The relationship between breakdown voltage and *pd* of air under different gap distances in a uniform electric field

2.5.6 Application of high vacuum



Under DC voltage in vacuum, the breakdown voltage of the sphere-plane gap and the relationship between breakdown field strength and gap distance

2.5 Measures to increase gas gap breakdown voltage

2.5.6 Application of high vacuum

Vacuum circuit breakers were previously used for 10-35kV and are developing towards higher voltage levels now

2.5 Measures to increase gas gap breakdown voltage

2.5.6 Application of high vacuum

Siemens 245kV/63kA and 170kV/50kA single break vacuum arc extinguishing chambers
2018 CIGRE Exhibition

2.5.7 Application of High Electrical Strength Gas (SF_6)

Gas compounds containing halogen elements such as SF_6, CCl_4, and Freon CCl_2F_2 are commonly referred to as high electrical strength gases

Why is SF_6 the most commonly used in power equipment?

- Basic physical properties of SF_6
- Excellent electrical insulation performance, arc extinguishing ability, and is easy to liquefy and transport
- The biggest problem with SF_6

Think about Townsend's discharge theory, which gases present higher electrical strength and better insulation performance?
How to use Townsend's discharge theory to find new gases with better electrical performance?

2.5.7 Application of High Electrical Strength Gas (SF_6)

Gas compounds containing halogen elements such as SF_6, CCl_4, and Freon CCl_2F_2 are commonly referred to as high electrical strength gases

Table 2-1 Relative Electrical Strength of Several Gases

Gas	N_2	SF_6	CCl_2F_2	CCl_4
Relative electrical strength	1.0	2.3 ~ 2.5	2.4 ~ 2.6	6.3
Liquefaction temperature at 1 atmospheric pressure (°C)	-195.8	- 63.8	- 28	76

SF_6 was first synthesized in 1900 and is a colorless, odorless, non-toxic, and non flammable inert compound. It has no corrosive effect and does not decompose when heated to 500 °C.

Under moderate pressure, SF_6 gas can be liquefied for easy storage and transportation.

High electrical strength and good arc extinguishing performance, but its price is high, and the GWP value is as high as 22800, which must be with very high equipment sealing requirements.

After the 1960s, it was widely used in high-current & high-voltage circuit breakers, high-voltage gas filled cables, high-voltage capacitors, high-voltage gas filled bushings, and Gas Insulated Substation/Switchgear GIS. The equipment size and substation land were greatly reduced.

2.5.7 Application of High Electrical Strength Gas (SF_6)

What are the advantages of the expression of the Paschen's curve?

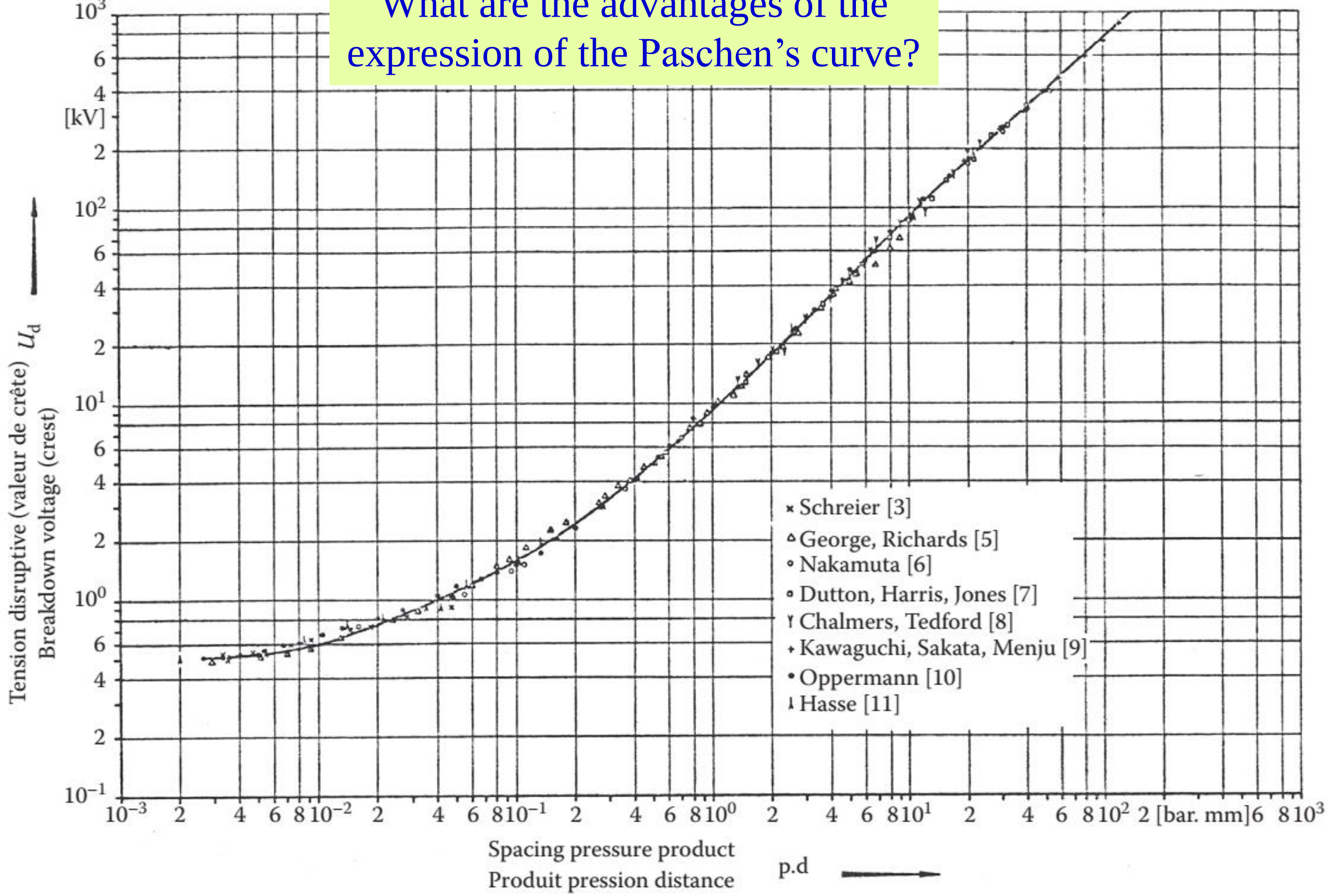


FIGURE 4.30 Paschen's curves in SF_6. (From Dakin, T.W. et al., *Electra*, 32, 61, 1974.)

2.5.7 Application of High Electrical Strength Gas (SF_6)

What are the advantages of the expression of the Paschen's curve?

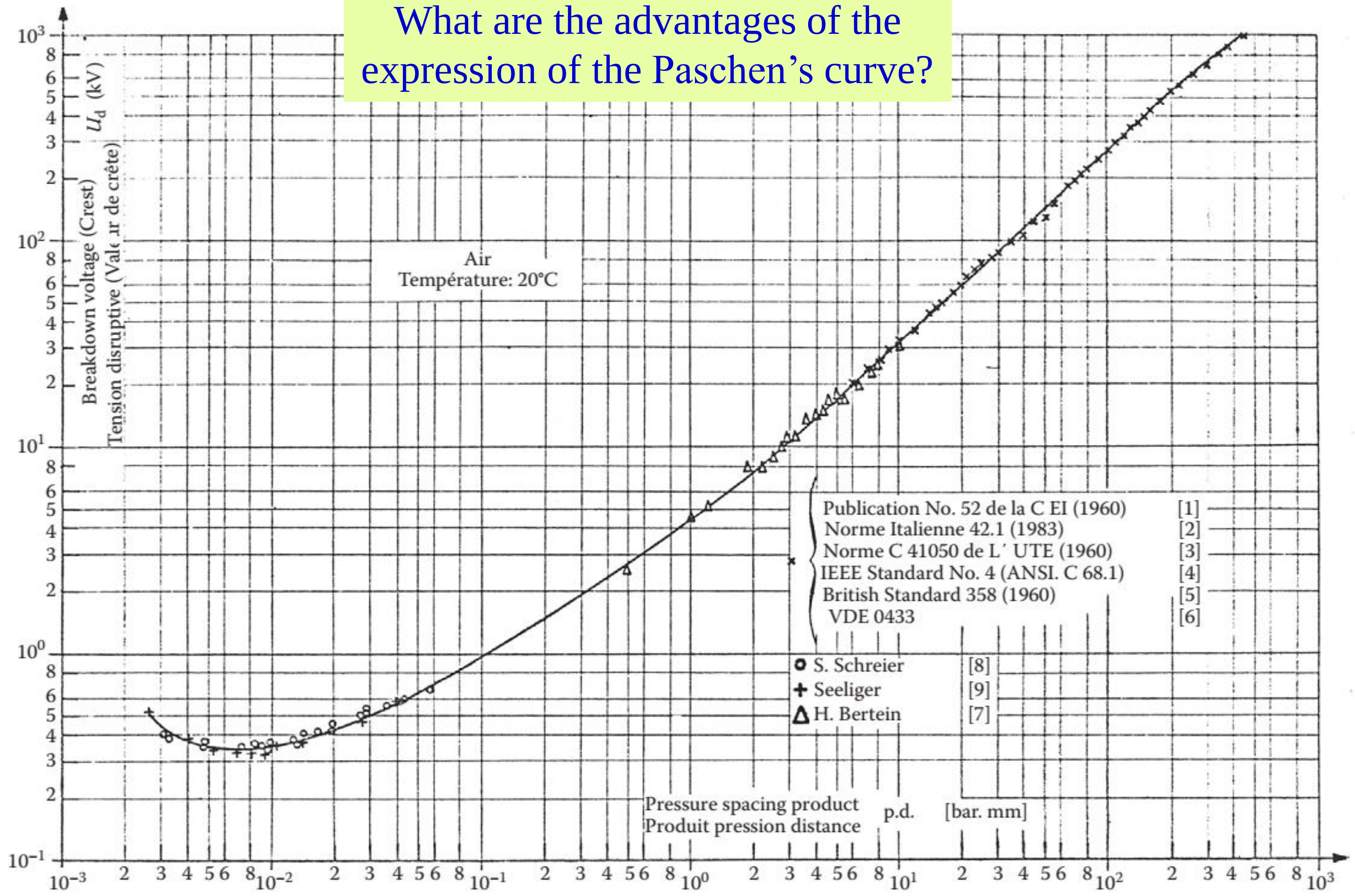


FIGURE 4.29 Paschen's curves in air. (From Dakin, T.W. et al., *Electra*, 32, 61, 1974.)

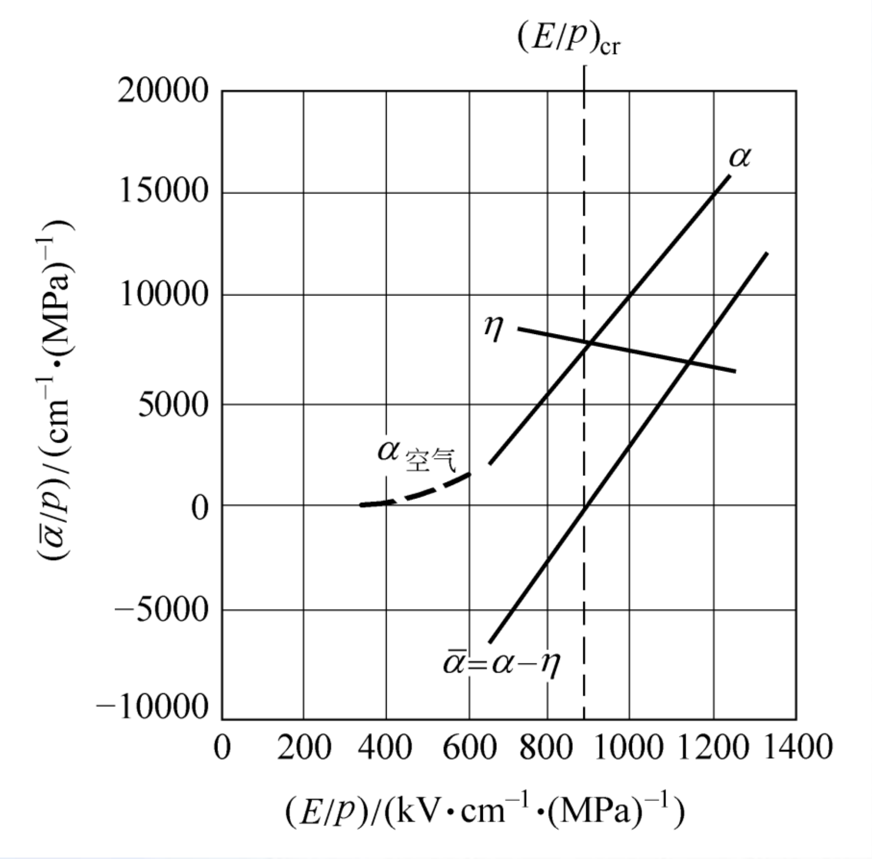
2.5.7 Application of High Electrical Strength Gas (SF_6)

Why does electronegative gas present high electrical strength?

***η* Electron attachment coefficient:** The times an electron may be adsorbed per unit length of travel in the direction of electric field

$$\bar{\alpha} = \alpha - \eta$$

If (E/p) is less than the critical value $(E/p)_{cr}$ = 885 kV/(cm· MPa), the effective electron collision ionization coefficient is negative and discharge cannot develop



Relationship between $\bar{\alpha}/p$ and E/p of SF_6

The sensitivity of SF_6 collision ionization to electric field strength is much higher than that of air!

2.5.7 Application of High Electrical Strength Gas (SF_6)

The reason why halide gases (electronegative gases) present high electrical strength (compared to air):

(1) Halogen elements in the halide gas lead to strong electronegativity. Gas molecules can easily combine with electrons to form negative ions, thereby weaken the collision ionization ability of electrons and enhancing the recombination process.

(2) Halide gas has a large molecular weight, a large molecular diameter, and a large collision cross-section. The mean free path of electrons in the halide gas is greatly shortened, making it difficult to accumulate energy, thereby the ability of electrons to collide and ionize is reduced.

(3) When getting closer to electrons, these gas molecules can also be easily polarized, which increase the energy loss of electrons and weaken their collision ionization ability.

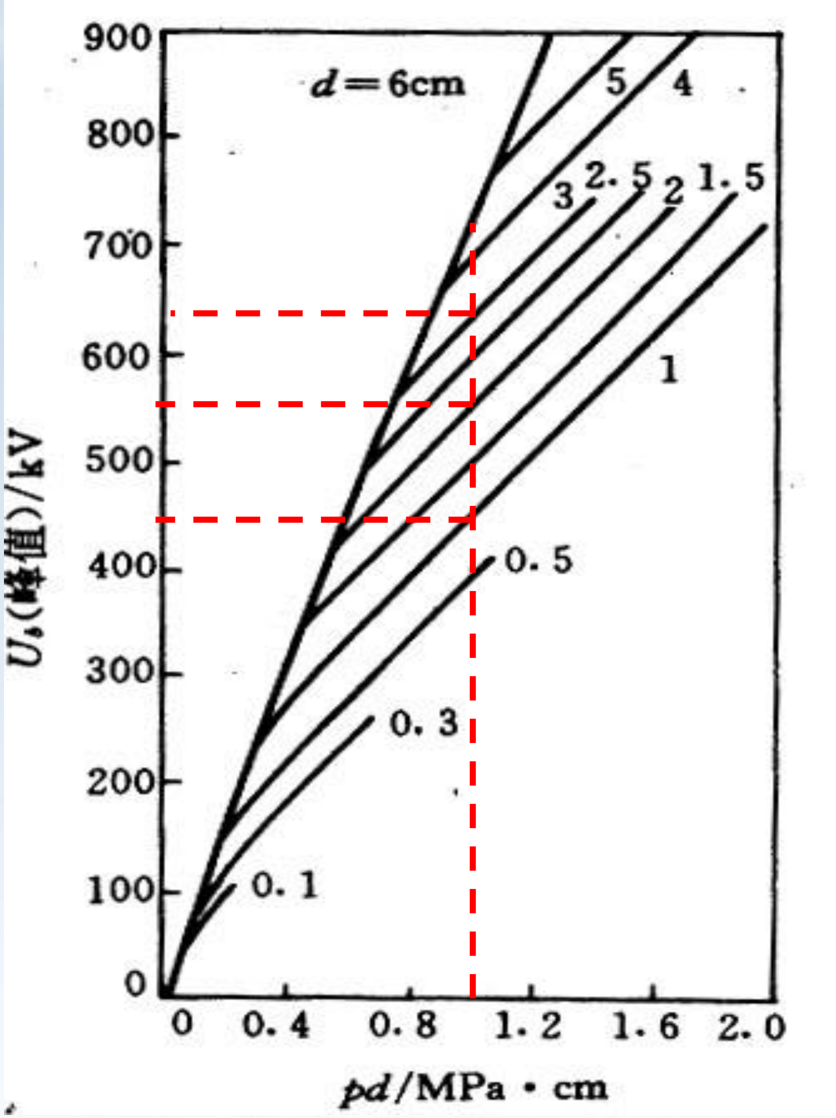
This is also the principle of exploring a substitute gas of SF_6 (molecular calculation software can now calculate!)

Large molecular weight of electronegative gases leads to smaller migration rates of positive and negative ions.

2.5.7 Application of High Electrical Strength Gas (SF_6)

- Different gaps with the same *pd* will no longer with the same breakdown voltage when the gas pressure is high, and will deviate from the Paschen's curve

- The influence of the non-uniformity of the electric field on the breakdown voltage of SF_6 is much greater than that on the air gap



The relationship between gap breakdown voltage of SF_6 and its *pd*

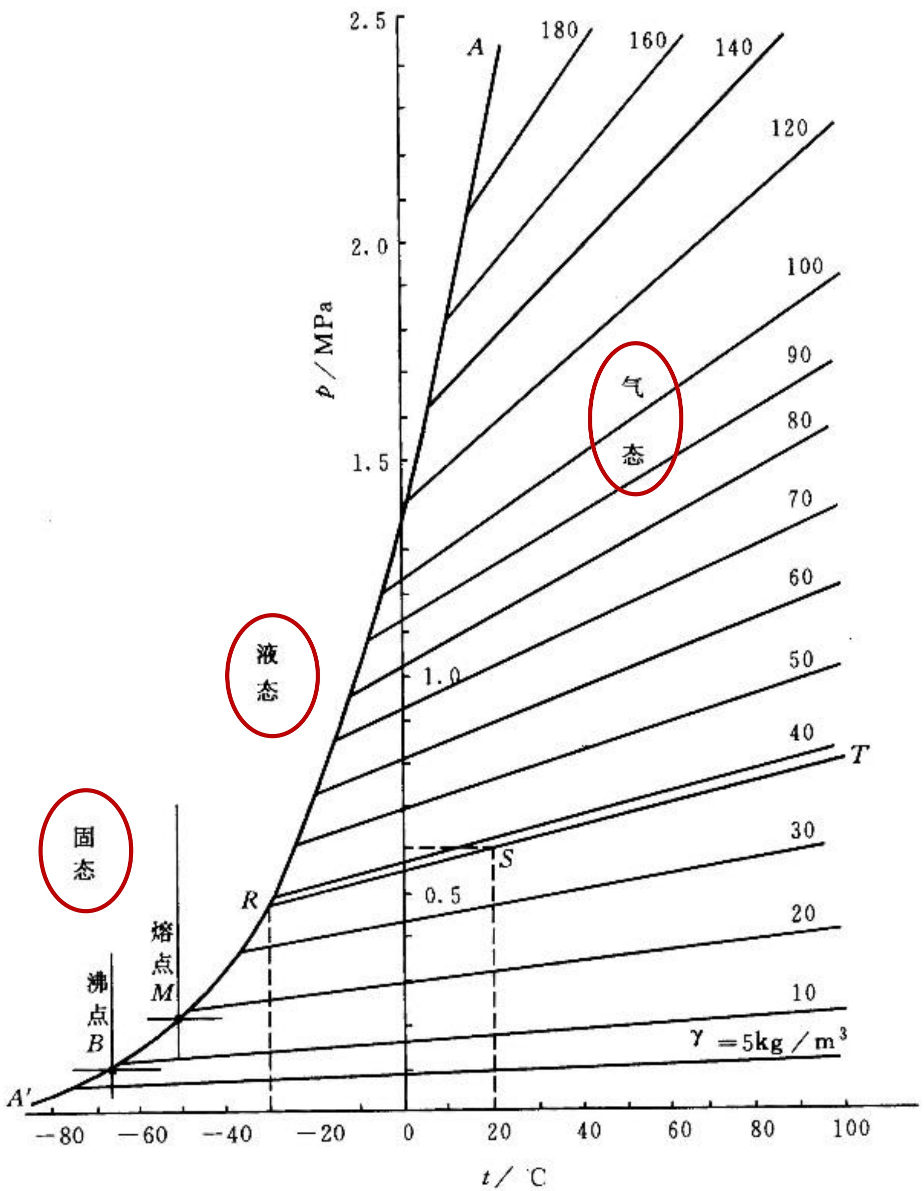
2.5.7 Application of High Electrical Strength Gas (SF_6)

Under moderate pressure, SF_6 gas can be liquefied for easy storage and transportation.

The more SF_6 is added during the manufacturing of high-voltage equipment, the higher the density and pressure,

but the higher the minimum ambient temperature at which the equipment can maintain insulation performance.

Liquefaction is another important issue that must be noted during the use of SF_6, and the pressure of SF_6 should not be too high



Gas state parameters of SF_6

2.5.7 Application of High Electrical Strength Gas (SF_6)

The biggest problem with SF_6

SF_6 is one of the six greenhouse gases banned by the Kyoto Protocol in 1997. Its Global Warming Potential (GWP) value is the highest among the six banned gases, with GWP values reaching 16300, 22800, and 32600 over 20, 50, and 100 years. Due to its extremely high chemical stability, it has a retention time of up to 3200 years in the atmosphere.

Therefore, SF_6 equipment has extremely strict sealing requirements and high equipment management requirements.

In recent years, the world has not only actively explored measures to reduce SF_6 leakage and reduce the volume of SF_6 equipment to use less SF_6, but also actively explored alternative SF_6 solutions, such as using mixed gases, non SF_6 gases with low GWP values, or high-voltage equipment with vacuum insulation and high pressure insulation.

Still based on Townsend's theory of collision ionization

The biggest problem with SF_6

The concentration of SF_6 gas in the global atmosphere doubled from 1973 to 2008 and increased by 20% from 2010 to 2015. According to incomplete statistics, the global electricity industry used over 10000 tons of SF_6 gas in 2010.

Based on the equipment put into operation in the past 20 years, it is estimated that the annual leakage of SF_6 is equivalent to approximately 23.5 million tons of CO_2 gas

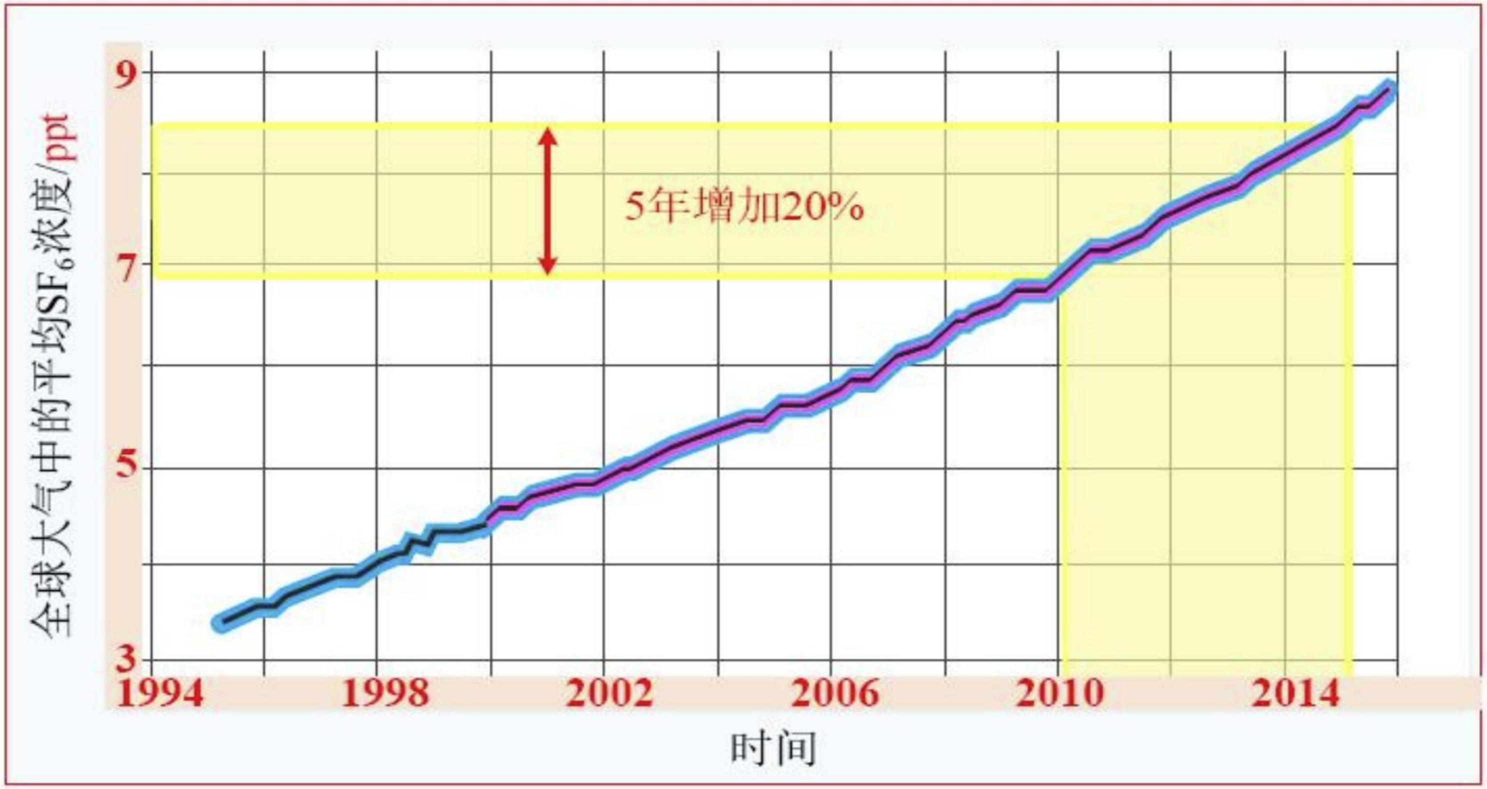


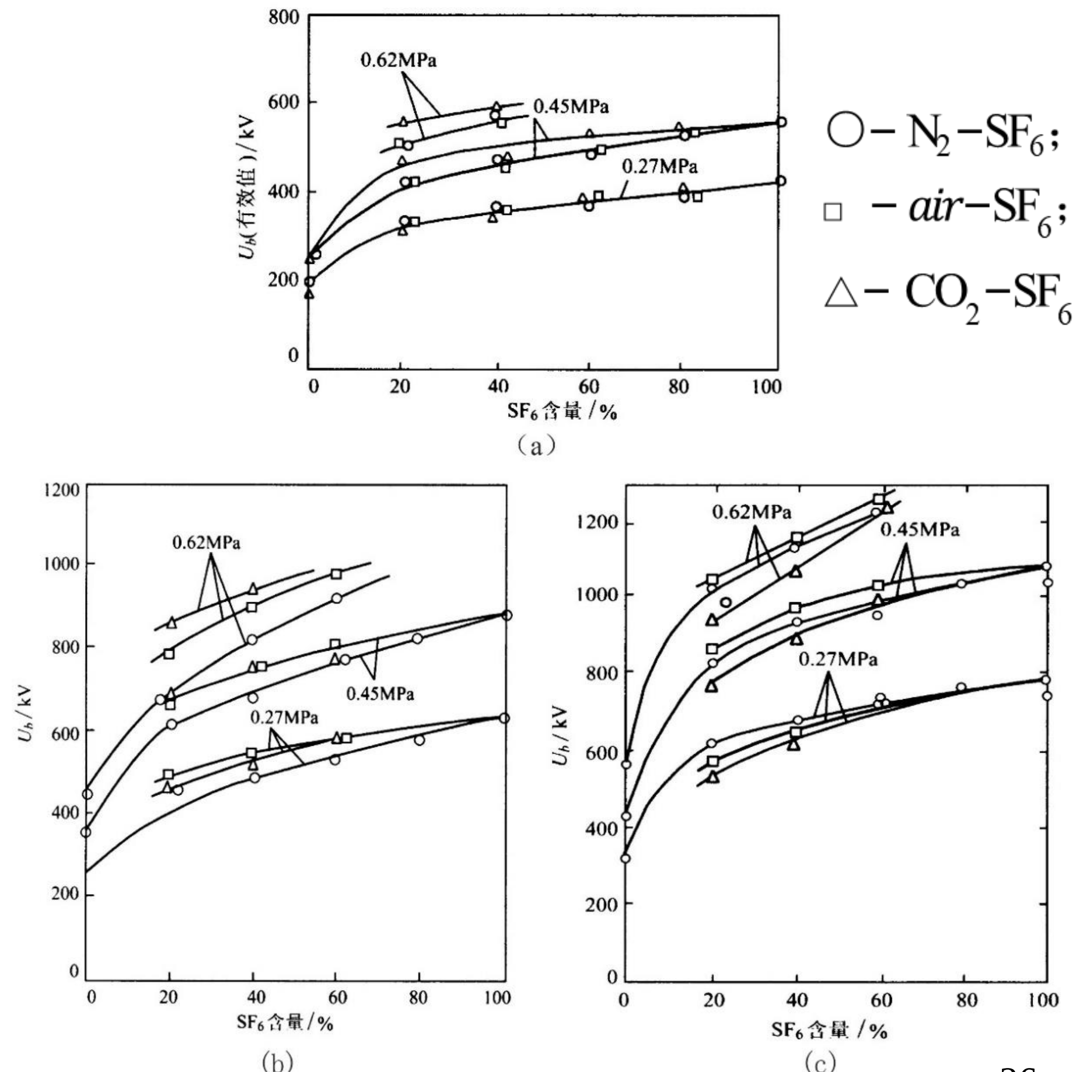
图 1.1 全球大气中的 SF_6 气体浓度

2.5.7 Application of High Electrical Strength Gas (SF_6)

(1) SF_6 mixed gas: use a small proportion of SF_6 mixed with other gases to minimize the amount of SF_6 used

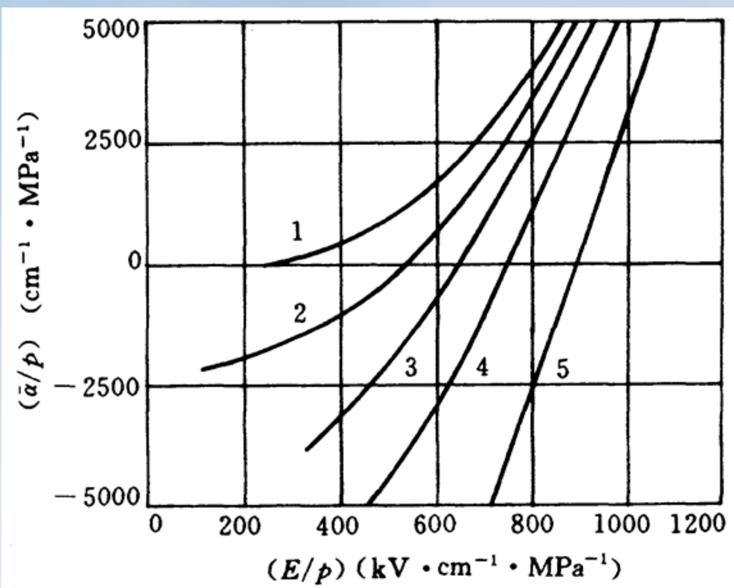
Figure 2-46 Changes in breakdown voltage of SF_6 mixed gas under slightly non-uniform field with changes in SF_6 content

(a) Power frequency breakdown voltage
(b) Switching impulse (-250/2500 μs) breakdown voltage
(c) Lightning impulse (-1.2/50 μs) breakdown voltage



2.5.7 Application of High Electrical Strength Gas (SF_6)

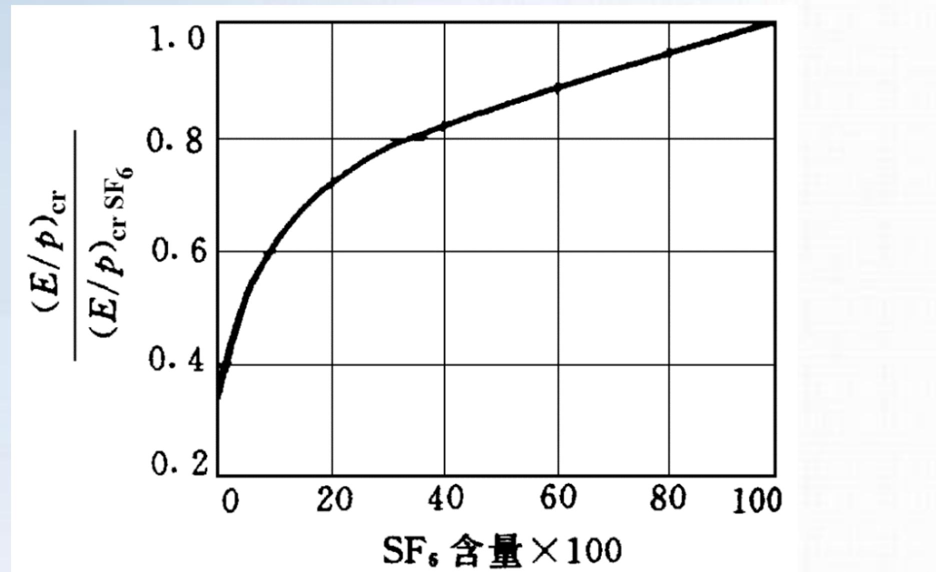
(1) SF_6 mixed gas: use a small proportion of SF_6 mixed with other gases to minimize the amount of SF_6 used



The Relationship between α/p and E/p of SF_6-N_2 Mixed Gas

SF_6 content :

1−0%; 2−10%; 3−25%; 4−50%; 5−100%



The Relationship between $(E/p)_{Cr}$ and SF_6 Content in SF_6-N_2 Mixed Gas

Several options for using less or not using SF_6:

- SF_6/N_2 mixed gas insulation, compressed air insulation, vacuum circuit breaker, alternative gas

Basic directions for screening SF_6 alternative gases:

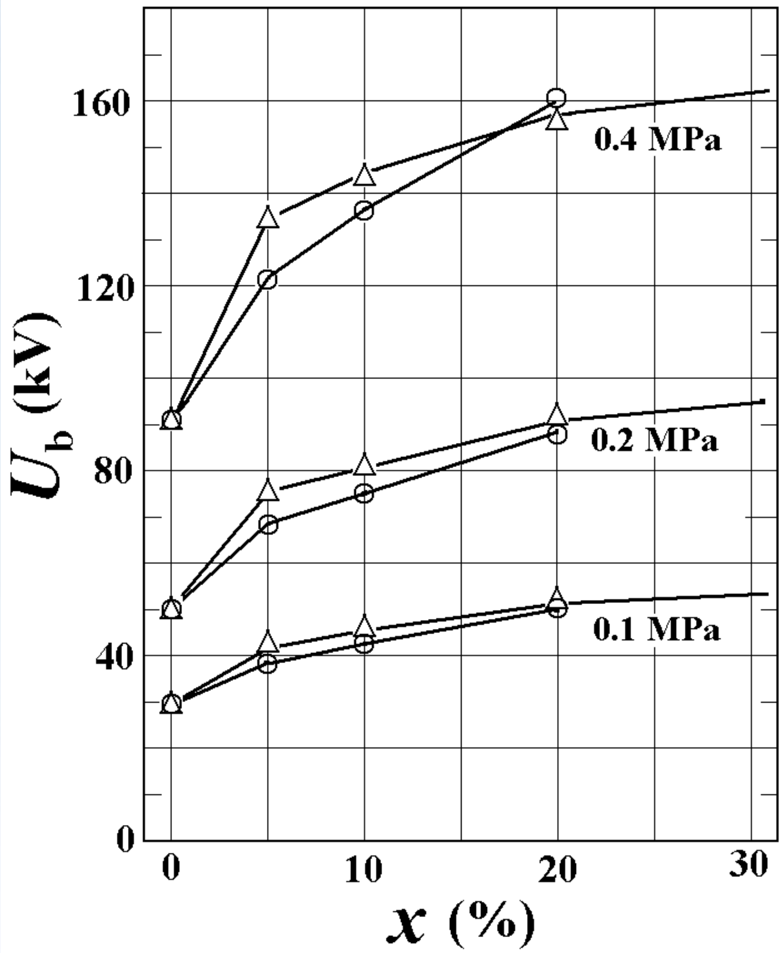
- Starting from electronegativity
- Electrical insulation performance and arc extinguishing performance
- Liquefaction temperature, stability after discharge, toxicity
- Minimize GWP value for G3 (Green Gas for Grid) gas
- New or mixed gases should have electrical performance comparable to SF_6 as much as possible

(2) SF_6 alternative gas:

Do not use SF_6 at all, instead use other artificially synthesized gases with significantly lower GWP values than SF_6.

Hope to have low GWP value, high electrical strength, high thermal conductivity, low liquefaction temperature, low toxicity, and good arc extinguishing performance.

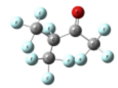
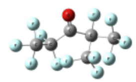
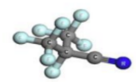
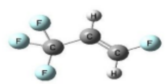
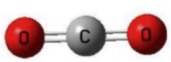
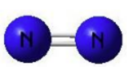
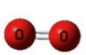
- Octafluorocyclobutane (c-C_4F_8), with high liquefaction temperature and high price, GWP8700
- Octafluoropane (C_3F_8)
- Hexafluoroethane (C_2F_6)
- Trifluoroiodomethane (CF_3 I)
- G3 (Green Gas for Grid) gas, etc



The relationship between power frequency breakdown voltage U_b of mixed gases and the content x of C_4F_8 or SF_6 in the gas

○– C_4F_8–N_2; △– SF_6–N_2

Physical and chemical parameters of several SF_6 substitute gases

气体	分子结构	GWP	大气寿命/年	液化温度/℃	相对介电强度
CF_3I		1~5	0.005	- 22.5	1.2~1.3
c-C_4F_8		8,700	3,200	- 8	1.3~1.4
$C_5F_{10}O$		1	0.042	26.5	2
$C_6F_{12}O$		1	0.014	49	2.8
C_4F_7N		2,210	30	- 4.7	2.1
HFO-1234ze(E)		<1	0.05	- 19.2	0.98
SF_6		23,500	3,200	- 63.9	1
CO_2		1	100	- 78.5	0.3
N_2		0	∞	- 195.8	0.38
O_2		0	∞	- 183	0.33
干燥空气	-	0	∞	- 193	0.36

Excerpted from Yang Yuan's doctoral thesis of CEPRI in 2022

(2) SF_6 alternative gas:

Do not use SF_6 at all, but instead use other artificially synthesized gases with significantly lower GWP values than SF_6.

The Fluoroketone series gas developed by 3M Company includes C_6FK, C_5FK, and C_4FK.

C_6FK has a high boiling point and C_4FK is highly toxic. The GWP value of C_5FK is the lowest, about 1, but the liquefaction temperature is still relatively high

C5FK(1,1,1,3,4,4,4- heptafluoro-3-(riuoroethy)bita

named 3M™ Novec5 1ioDielectricFuid(figure1).

very good dielectric performance and the boiling point of 26.9°C combined with the high vapour pressure of 94 kPa (@25°C) allows gas mixtures which are suitable for

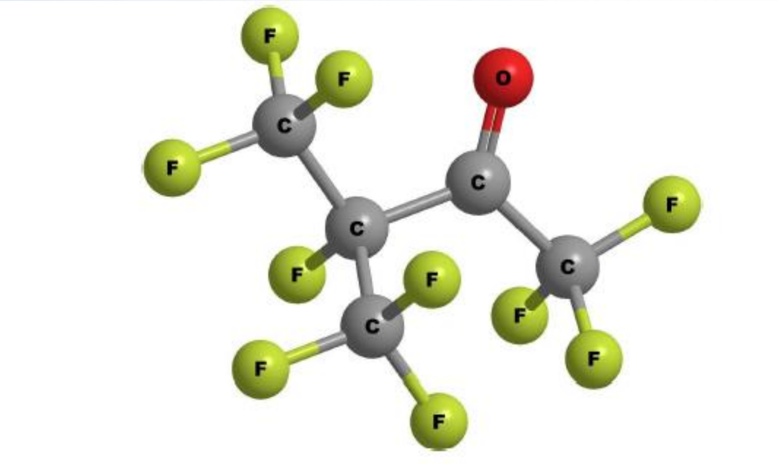
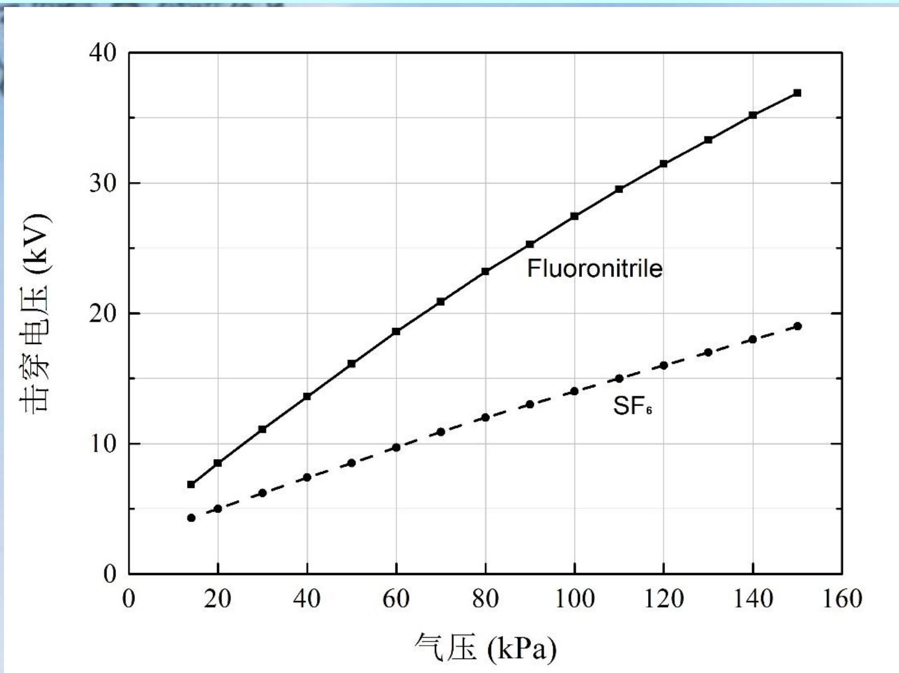


Figure 1. C5 fluoroketone 3M Novec 5110 Fluid

(2) SF_6 alternative gas:

Do not use SF_6 at all, but instead use other artificially synthesized gases with significantly lower GWP values than SF_6.



Comparison of Electrical Strength between Fluoronitrile and SF_6 under Different Air Pressure

Perfluoroisobutyronitrile $(CF_3)_2$-CF-CN, C_4F_7N. Molecular weight 195, boiling point -4.7℃, GWP_{100}=2210

The National Key R&D Program of CEPRI has selected C_4/CO_2 mixed gas, and has completed gas preparation, physical property testing, electrical testing, and ultra-high pressure mixed gas GIL model testing

tetrafluoro-2-(trifluoromethyl)-propanenitrile). As with the fluoroketones, this substance has a boiling point in the operation temperature range of electric equipment. Compared to the fluoroketones, its boiling point is significantly lower at -4.7°C and the vapour pressure is quite high at 252 kPa (@25°C). This allows for a higher concentration of the fluoronitrile in a gaseous mixture and lower operation temperatures than for the fluoroketones. The dielectric performance of the pure gas is higher than for the fluoroketones. On the other hand, the GWP of 2210 is measurably higher than for the fluoroketones but is still significantly lower than that of SF_6. 3M has developed a product based on this substance as well named 3M™ Novec™ 4710 Dielectric Fluid (figure 2).

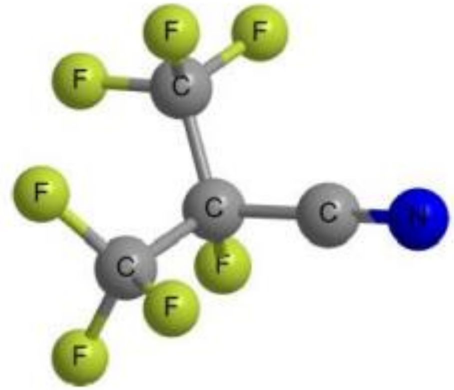


Figure 2. fluoronitrile 3M Novec 4710 Fluid

Several options for using less or not using SF_6:

- SF_6/N_2 mixed gas insulation, compressed air insulation, vacuum circuit breaker, alternative gas

Basic directions for screening SF_6 alternative gases:

- Starting from electronegativity
- Electrical insulation performance and arc extinguishing performance
- Liquefaction temperature, stability after discharge, toxicity
- Minimize GWP value for G3 (Green Gas for Grid) gas
- New or mixed gases should have electrical performance comparable to SF_6 as much as possible

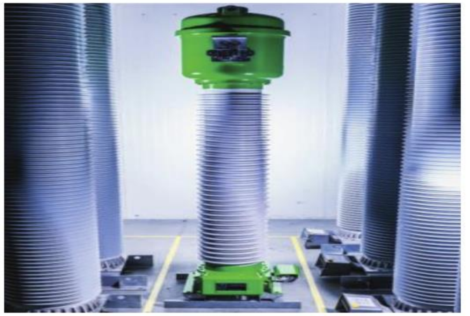
Taking into account key factors such as GWP value, insulation strength, liquefaction temperature, and toxicity of discharge by-products in engineering applications, the perfluoroisobutyronitrile/carbon dioxide C_4F_7N/CO_2 mixture gas has become a promising alternative gas solution, completely eliminating SF_6.

(a) 420kV GIL

（2017 年投运，英国）

(b) 145kV GIS

（2018 年投运，法国）



(c) 245kV CT

（2017 年投运，德国）

(d) 10kV 环网柜

（2021 年投运，国家电网）

(e) 220kV 母线

（2021 年投运，南方电网）

(f) 10kV 开关柜

（2021 年投运，南方电网）

GIS

方电网）

(h) 10kV 环网柜

（2021 年投运，国家电网）

(i) 1100kV GIL

（2021 年，国家电网）

图 1.3 C_4F_7N/CO_2 混合气体绝缘设备

Excerpted from Yang Yuan's doctoral thesis of CEPRI in 2022

On April 5, 2022, the European Commission proposed amendments to limit greenhouse gas emissions and provided a timetable for banning the use of fluorinated gases with a GWP greater than 10

On December 20, 2022, 3M Company in the United States announced its withdrawal from the production of perfluorinated and polyfluoroalkane based compounds (PFAS) by the end of 2025

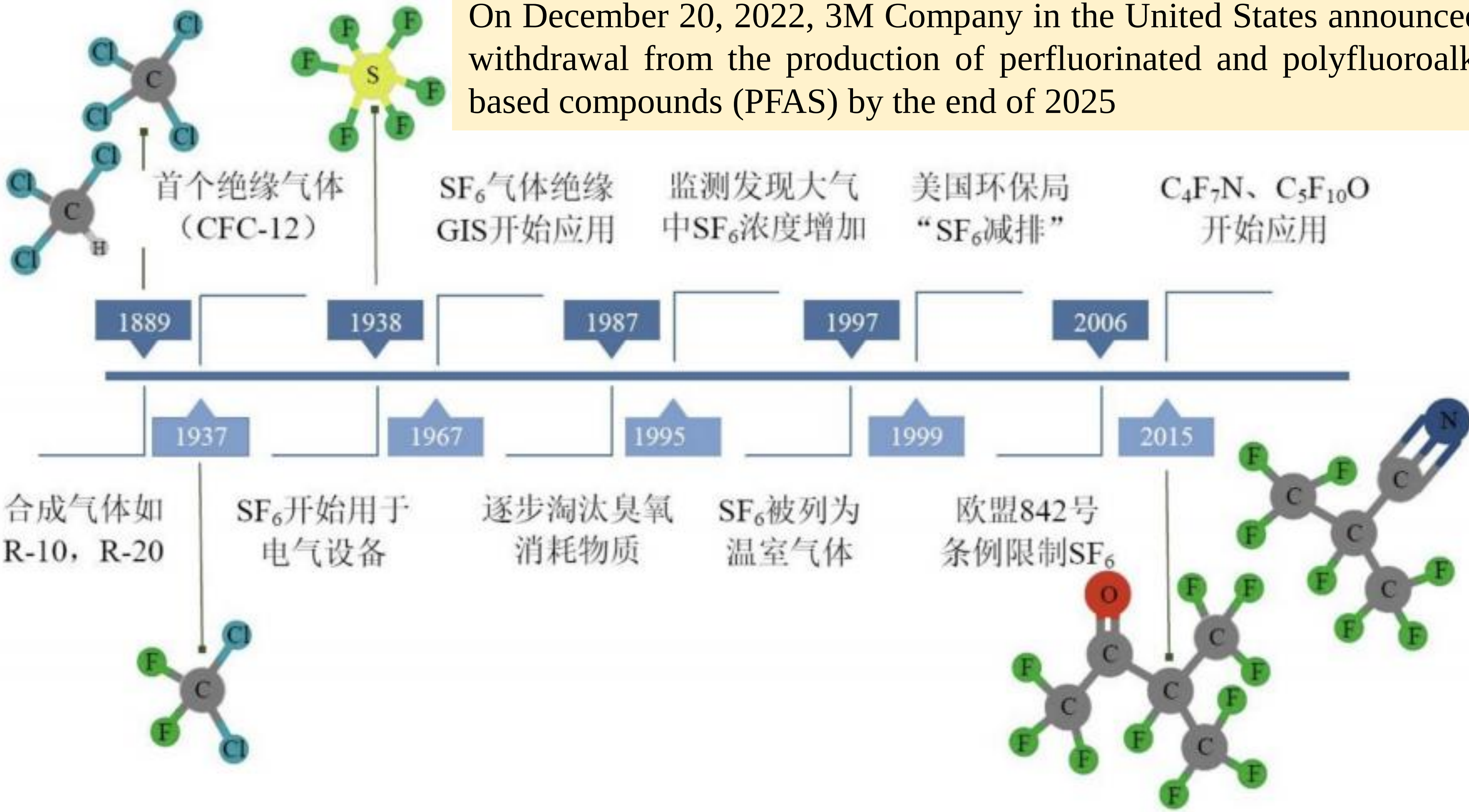


图 1.2　电力设备用绝缘气体应用进程

Excerpted from Yang Yuan's doctoral thesis of CEPRI in 2022

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

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……

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

Three types of factors affecting gap discharge