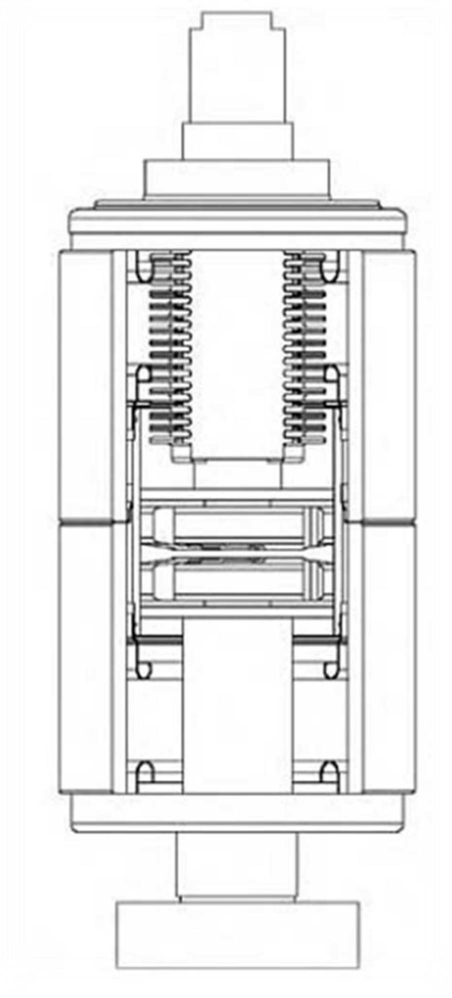

Paul G. Slade

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THE VACUUM INTERRUPTER

Theory, Design, and Application

High-Voltage Vacuum Interrupter Insulation Design

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CONTENTS

1. INTRODUCTION

High voltage vacuum interrupter insulation design

Withstand an ac voltage for 1 min across the open vacuum interrupter.

Withstand the basic impulse level (BIL) or lightning impulse withstand voltage (LIWV).

1. INTRODUCTION

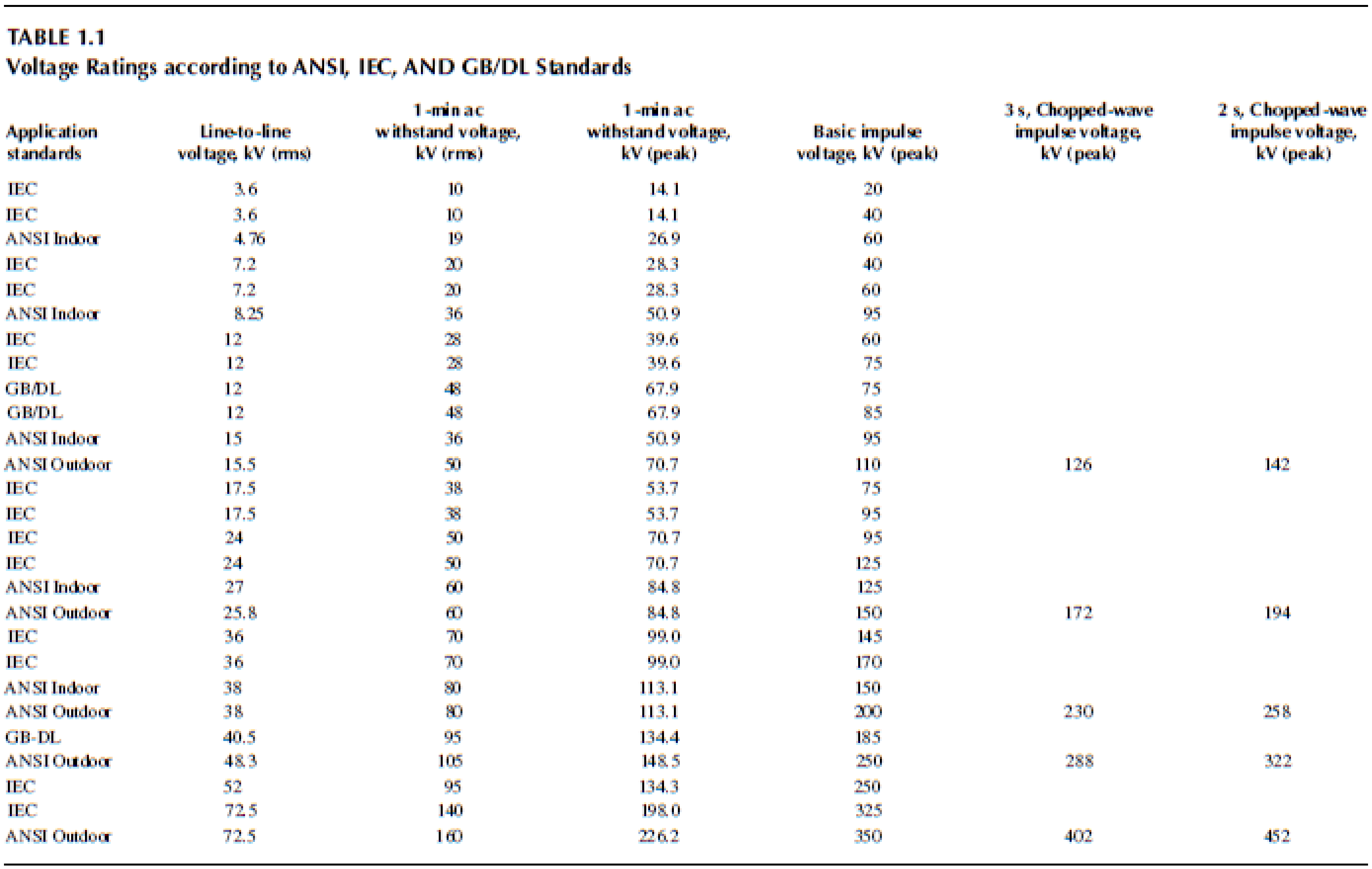
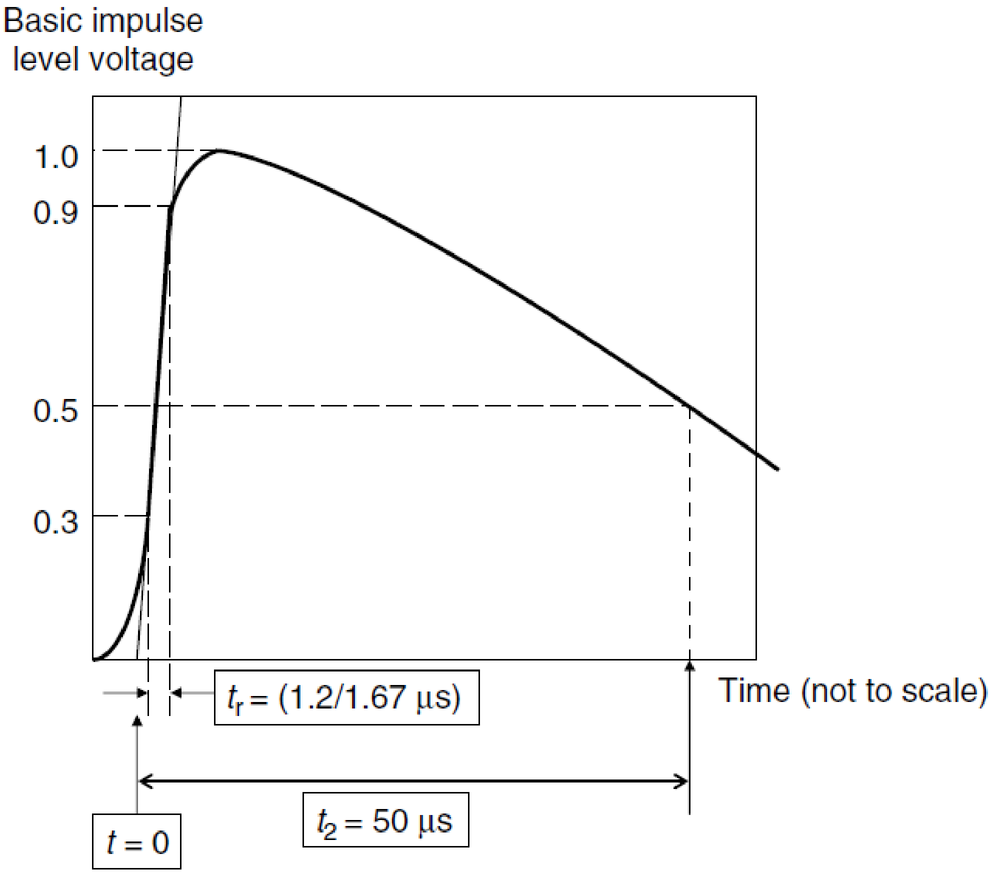


TABLE 1.1
Voltage Ratings according to ANSI, IEC, AND GB/DL Standards

Application standards	Line-to-line voltage, kV (rms)	1-min ac withstand voltage, kV (rms)	1-min ac withstand voltage, kV (peak)	Basic impulse voltage, kV (peak)	3 s, Chopped-wave impulse voltage, kV (peak)	2 s, Chopped-wave impulse voltage, kV (peak)
IEC	3.6	10	14.1	20		
IEC	3.6	10	14.1	40		
ANSI Indoor	4.76	19	26.9	60		
IEC	7.2	20	28.3	40		
IEC	7.2	20	28.3	60		
ANSI Indoor	8.25	36	50.9	95		
IEC	12	28	39.6	60		
IEC	12	28	39.6	75		
GB/DL	12	48	67.9	75		
GB/DL	12	48	67.9	85		
ANSI Indoor	15	36	50.9	95		
ANSI Outdoor	15.5	50	70.7	110	126	142
IEC	17.5	38	53.7	75		
IEC	17.5	38	53.7	95		
IEC	24	50	70.7	95		
IEC	24	50	70.7	125		
ANSI Indoor	27	60	84.8	125		
ANSI Outdoor	25.8	60	84.8	150	172	194
IEC	36	70	99.0	145		
IEC	36	70	99.0	170		
ANSI Indoor	38	80	113.1	150		
ANSI Outdoor	38	80	113.1	200	230	258
GB-DL	40.5	95	134.4	185		
ANSI Outdoor	48.3	105	148.5	250	288	322
IEC	52	95	134.3	250		
IEC	72.5	140	198.0	325		
ANSI Outdoor	72.5	160	226.2	350	402	452

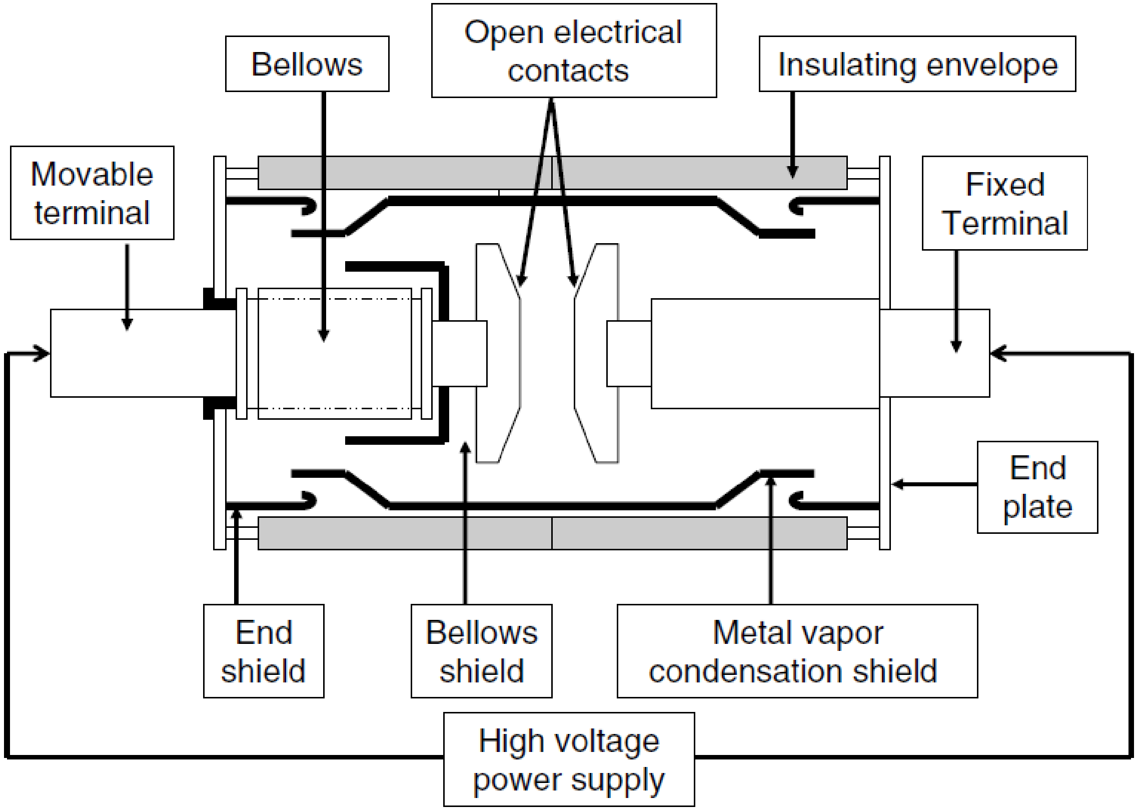
Voltage Rating according to ANSI, IEC, and GB/DL Standards

1.INTRODUCTION



The basic impulse level (BIL) or lightning impulse withstand voltage (LIWV) voltage wave shape.

2.EXTERNAL DESIGN



The external design of vacuum interrupters

2.EXTERNAL DESIGN

(1) The theory of breakdown in gas.

The electron collides with the gas in two ways:

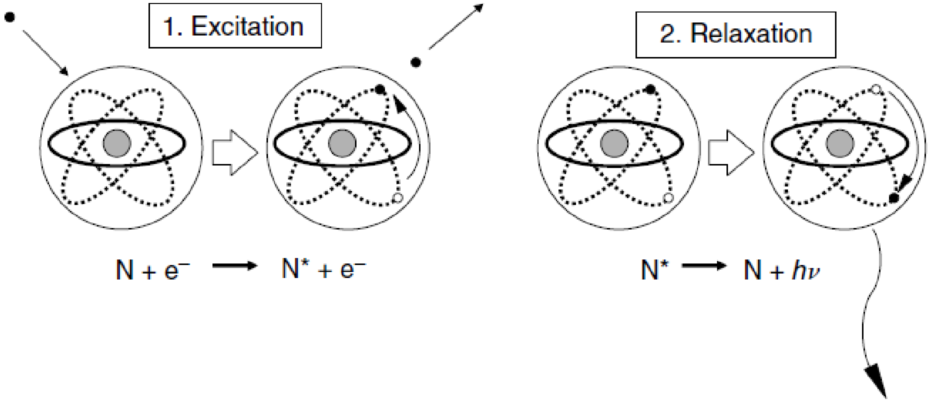
- **An elastic collision**
- **An inelastic collision**

1. **Dissociation (解离) : the process of splitting a molecule.**

$$e + N_2 \rightarrow \mathrm{e} + \mathrm{N} + \mathrm{N}.$$

2. **Excitation and Relaxation (激励和弛豫) : the process by which light is emitted from the gas.**

$$e + \mathrm{N} \rightarrow \mathrm{N}^* + \mathrm{e}, \qquad \mathrm{N}^* \rightarrow \mathrm{N} + h\nu,$$

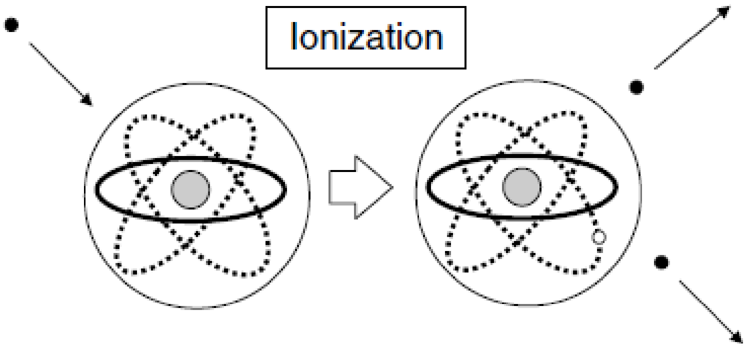


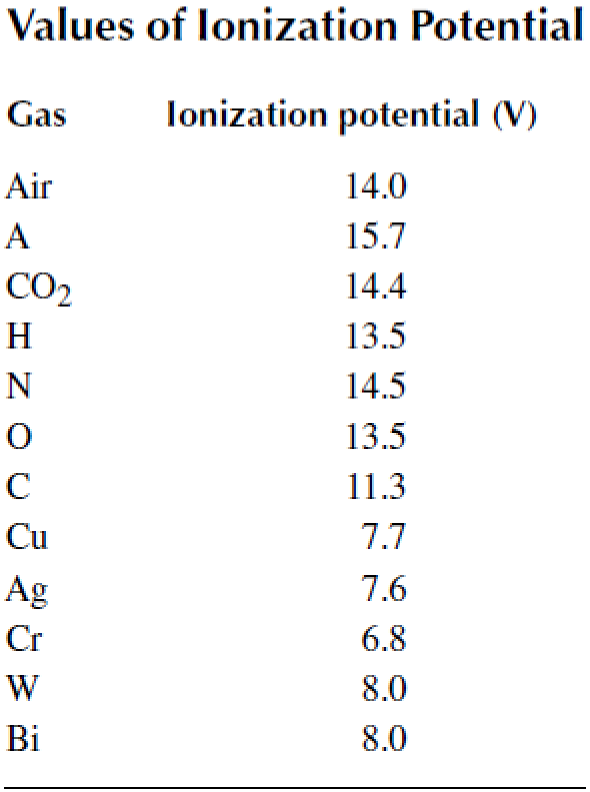
2.EXTERNAL DESIGN

The theory of breakdown in gas

3. **Ionization: the process that directly results in an electric arc.**

$$e + \mathrm{N} \rightarrow 2\mathrm{e} + \mathrm{N}^{+}.$$

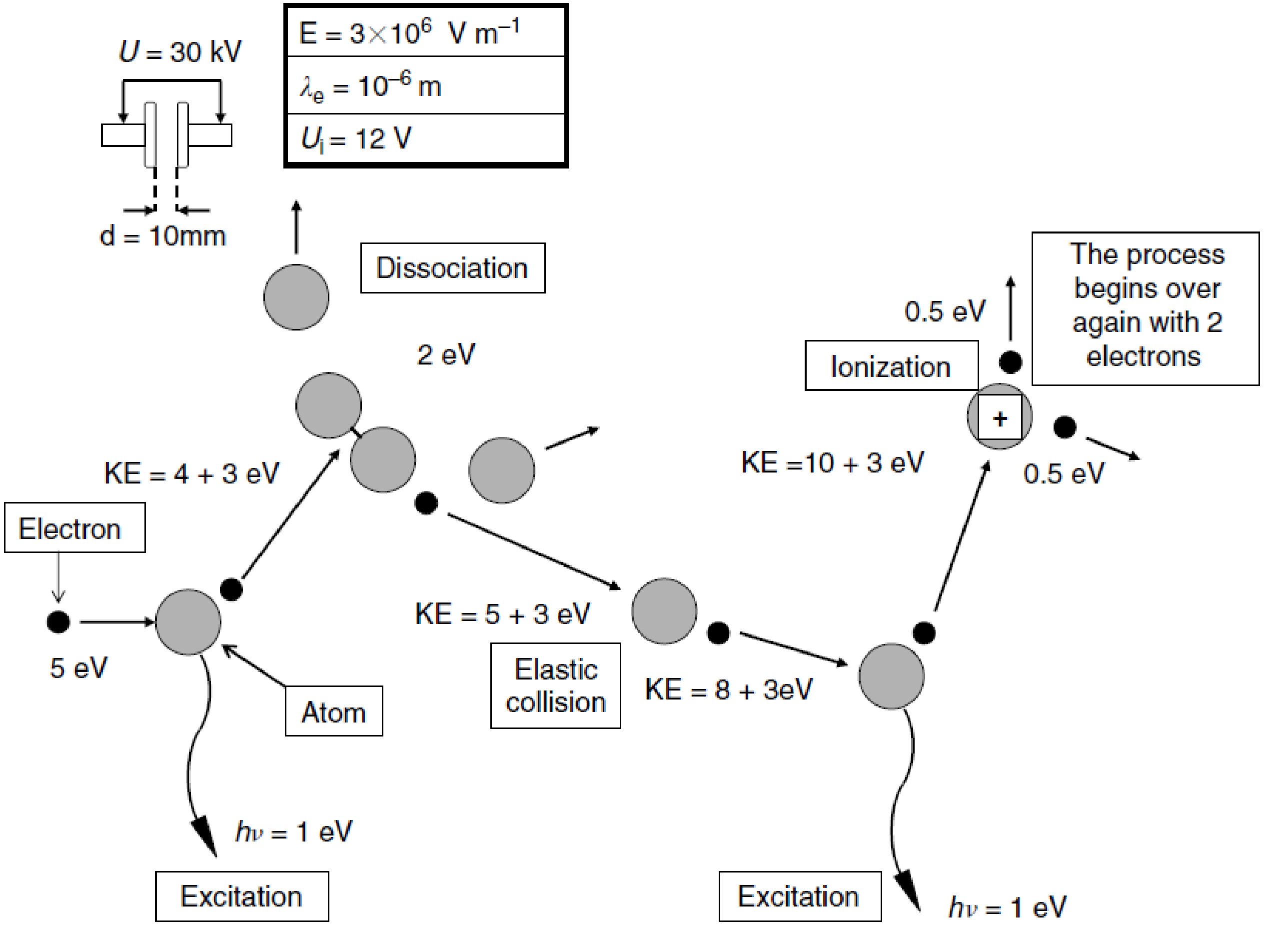




Values of Ionization Potential

Gas	Ionization potential (V)
Air	14.0
A	15.7
CO_2	14.4
H	13.5
N	14.5
O	13.5
C	11.3
Cu	7.7
Ag	7.6
Cr	6.8
W	8.0
Bi	8.0

2.EXTERNAL DESIGN



The theory of breakdown in gas.

Possible interactions with a gas of an electron accelerated by an electric field.

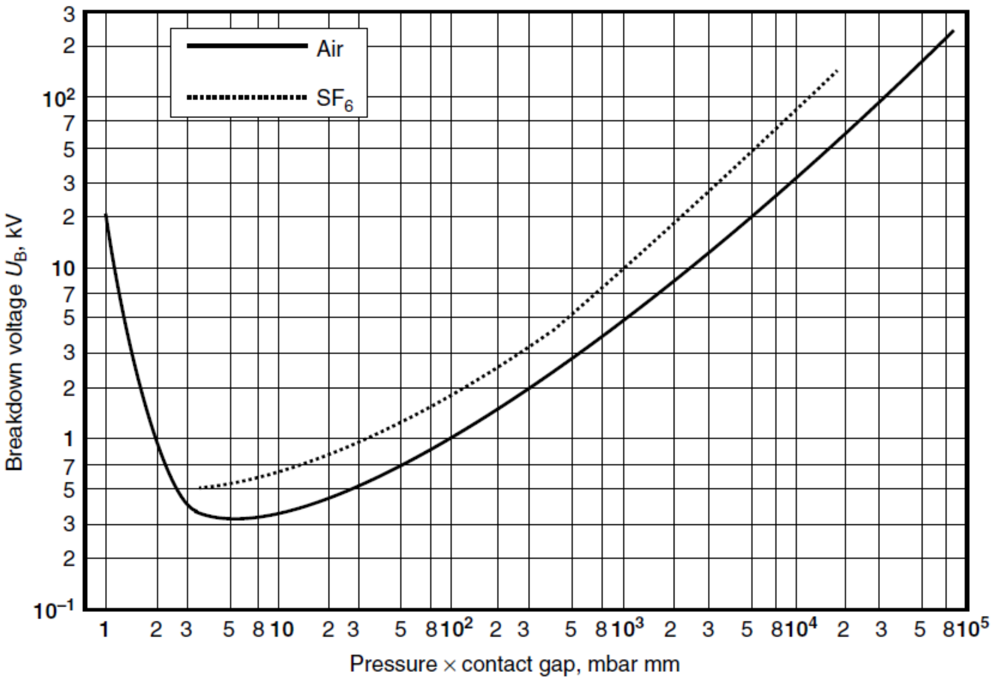
2.EXTERNAL DESIGN

(2) The breakdown voltage of the gas gap.

The breakdown voltage U_B for a given gas with an ionization potential U_i *is a function of the* gas pressure multiplied by the contact gap (*pd) alone.*

$$U_B = f(pd)$$

This is known as Paschen's law. An example of Paschen curves in air and SF6 for contacts with a uniform electric field between them.

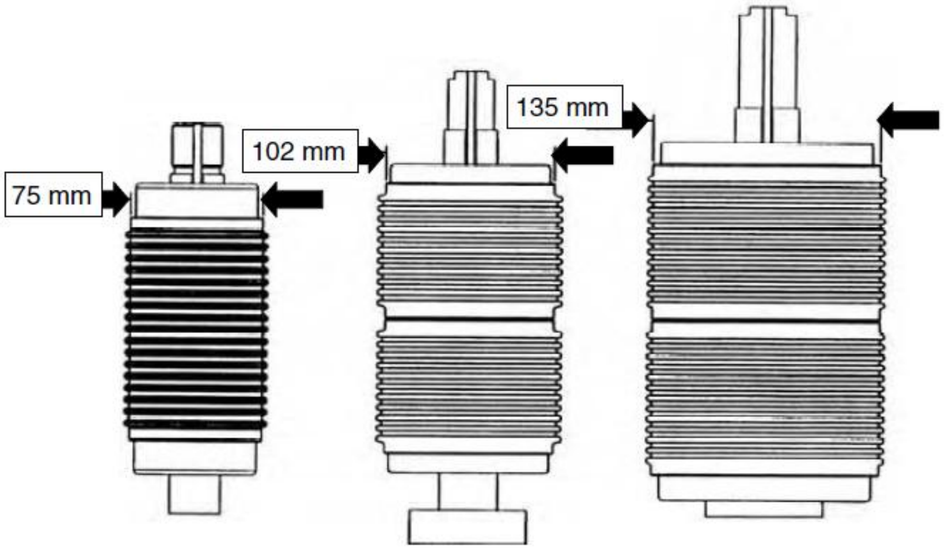


2.EXTERNAL DESIGN

(3) Creepage distance

The ceramic lengths required to support different BIL voltages are for clean cylinders in a relatively clean and low-humidity environment. The distance along the ceramic between the end plates, d_c, is called the *creepage distance*. In circuit breaker standards it is usual to specify a creepage d_{creep} as: d_c/maximum-rated voltage (rms), line to ground (in mm kV^{-1}), that is,

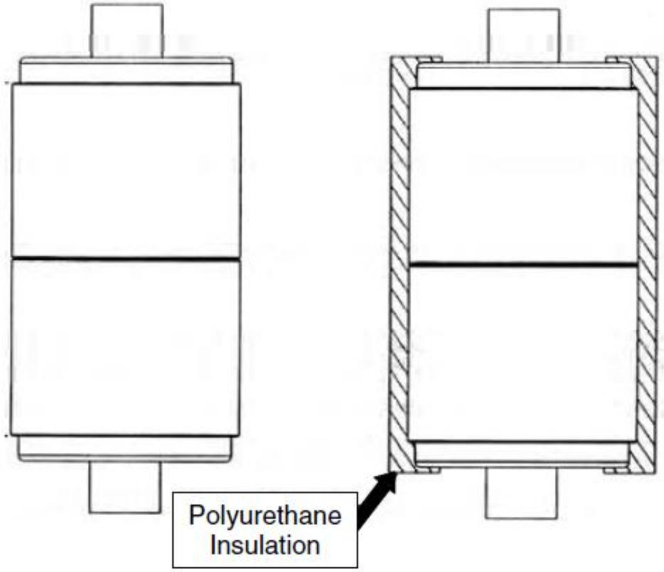
$$d_{\text{creep}} = \frac{\sqrt{3} \cdot d_c}{U_{\text{circut}}(\text{rms})} \cdot \text{mm kV}^{-1}.$$

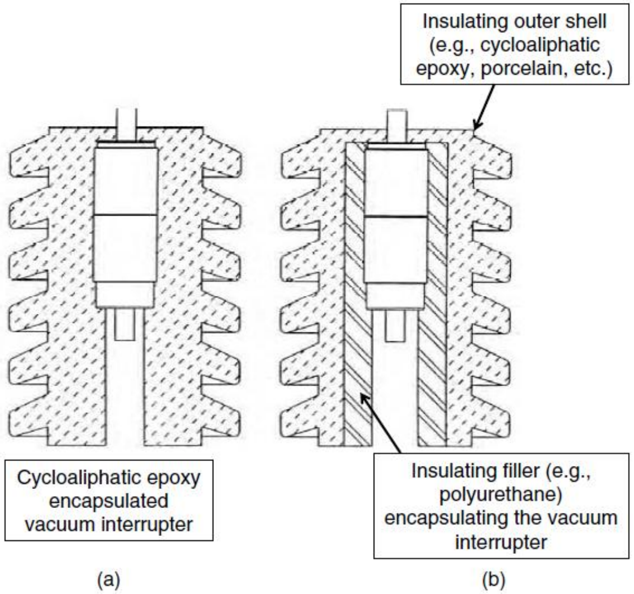


Contour wave ceramic vacuum interrupter designs for 12 kV application in air, manufactured by Eaton's electrical business.

2.EXTERNAL DESIGN

(4) Insulation ambient and encapsulation



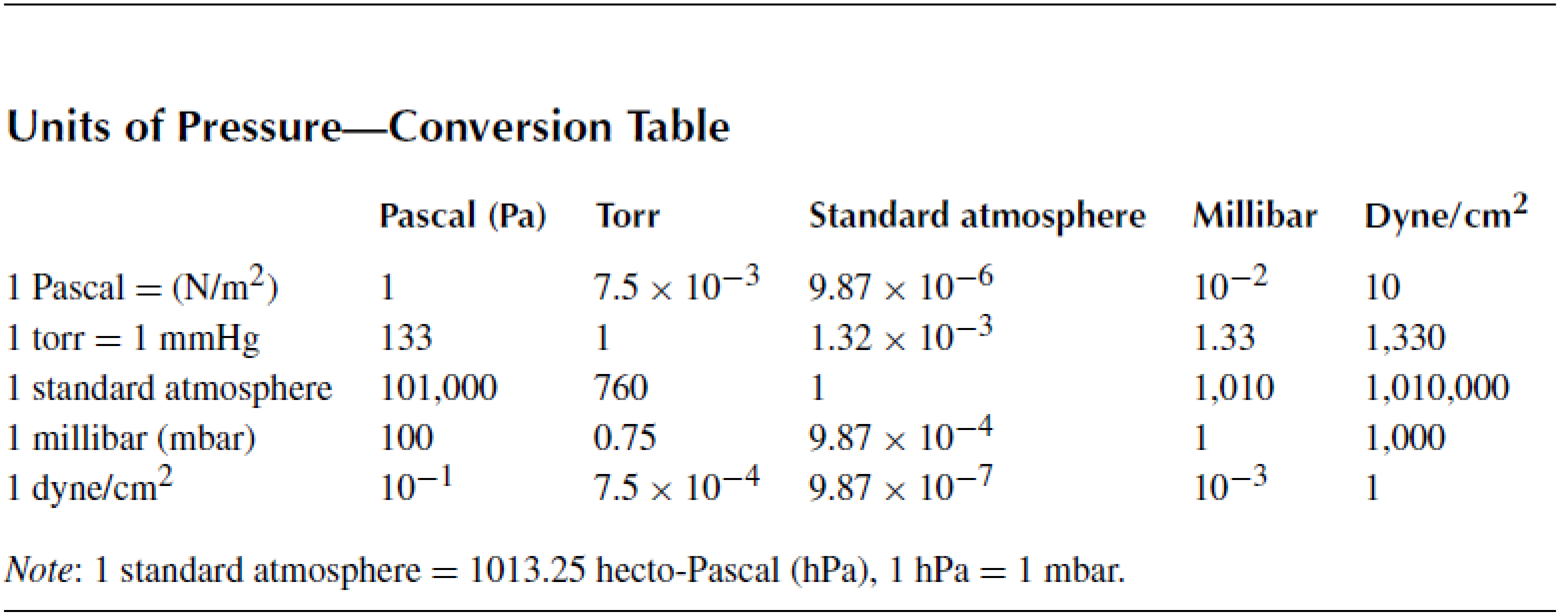


A vacuum interrupter encapsulated in a polyurethane material （聚氨酯）

(a) A vacuum interrupter directly encase in an insulated housing; （脂环族环氧树脂）

(a) A vacuum interrupter encapsulated inside an insulated housing with a secondary potting material

3.ELECTRICAL BREAKDOWN IN VACUUM



Units of Pressure—Conversion Table

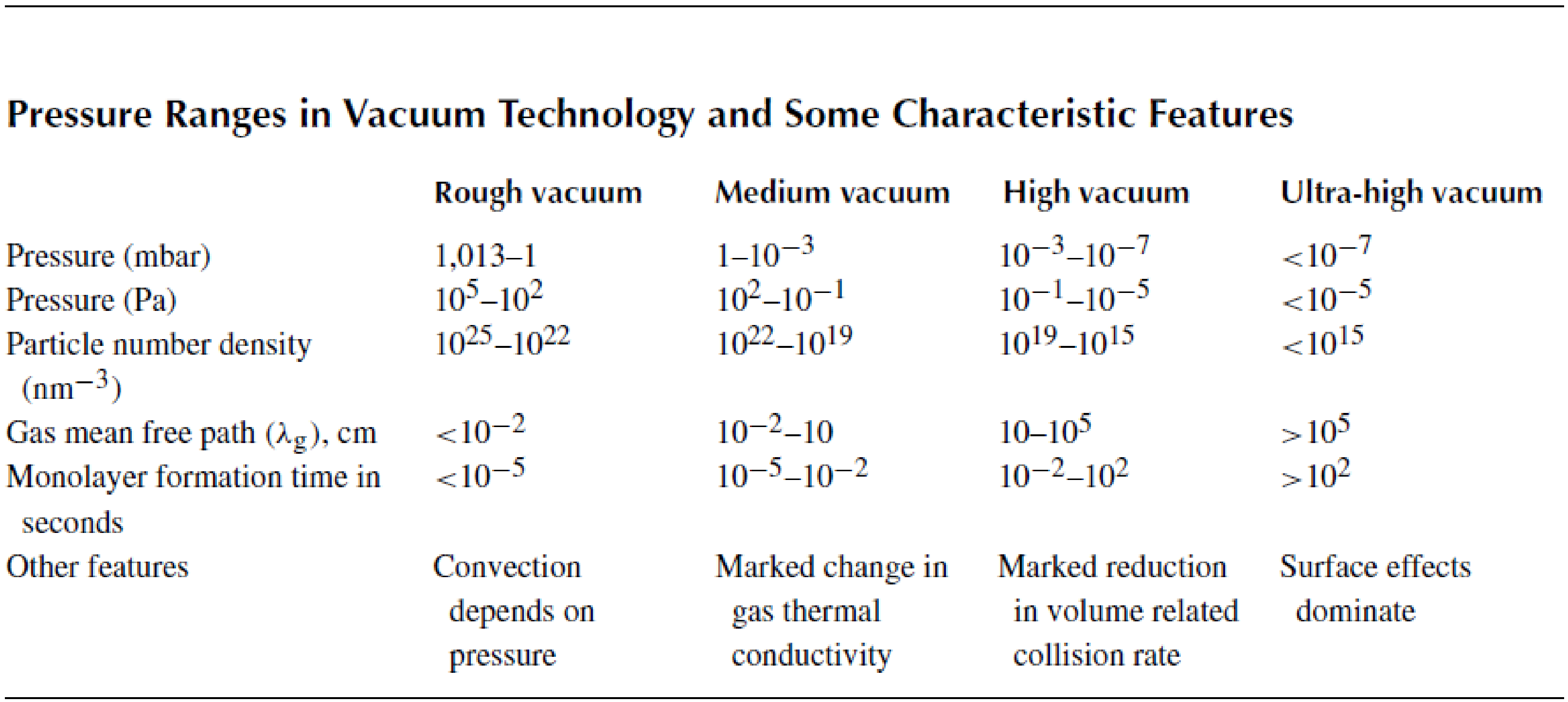
	Pascal (Pa)	Torr	Standard atmosphere	Millibar	Dyne/cm^2
1 Pascal = (N/m^2)	1	7.5×10^{-3}	9.87×10^{-6}	10^{-2}	10
1 torr = 1 mmHg	133	1	1.32×10^{-3}	1.33	1,330
1 standard atmosphere	101,000	760	1	1,010	1,010,000
1 millibar (mbar)	100	0.75	9.87×10^{-4}	1	1,000
1 dyne/cm^2	10^{-1}	7.5×10^{-4}	9.87×10^{-7}	10^{-3}	1

Note: 1 standard atmosphere = 1013.25 hecto-Pascal (hPa), 1 hPa = 1 mbar.

Units of the vacuum:

The units by which vacuum pressure are given are somewhat confusing. The table gives the conversion factors which were used in vacuum.

3.ELECTRICAL BREAKDOWN IN VACUUM



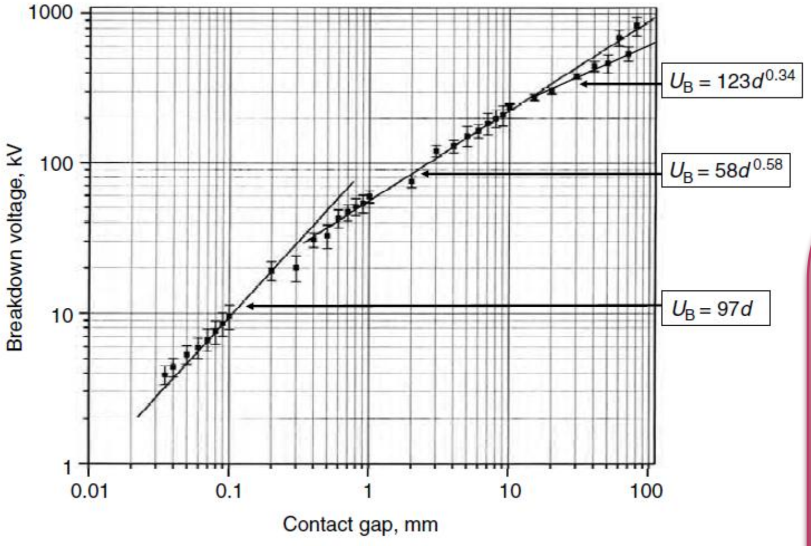
Pressure Ranges in Vacuum Technology and Some Characteristic Features

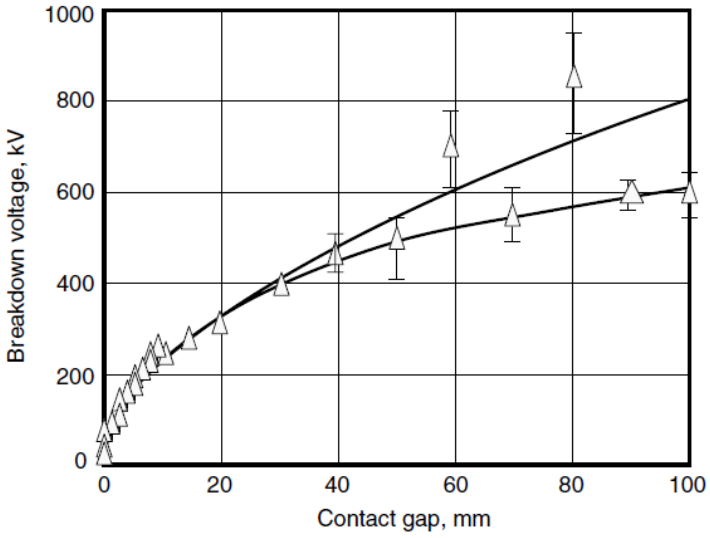
	Rough vacuum	Medium vacuum	High vacuum	Ultra-high vacuum
Pressure (mbar)	1,013–1	$1–10^{-3}$	$10^{-3}–10^{-7}$	$<10^{-7}$
Pressure (Pa)	$10^{5}–10^{2}$	$10^{2}–10^{-1}$	$10^{-1}–10^{-5}$	$<10^{-5}$
Particle number density (nm^{-3})	$10^{25}–10^{22}$	$10^{22}–10^{19}$	$10^{19}–10^{15}$	$<10^{15}$
Gas mean free path (λ_g), cm	$<10^{-2}$	$10^{-2}–10$	$10–10^{5}$	$>10^{5}$
Monolayer formation time in seconds	$<10^{-5}$	$10^{-5}–10^{-2}$	$10^{-2}–10^{2}$	$>10^{2}$
Other features	Convection depends on pressure	Marked change in gas thermal conductivity	Marked reduction in volume related collision rate	Surface effects dominate

Physical data for various ranges of vacuum:

The vacuum interrupter usually operates in the vacuum range, 10^{-2}–10^{-4} Pa.

3.ELECTRICAL BREAKDOWN IN VACUUM

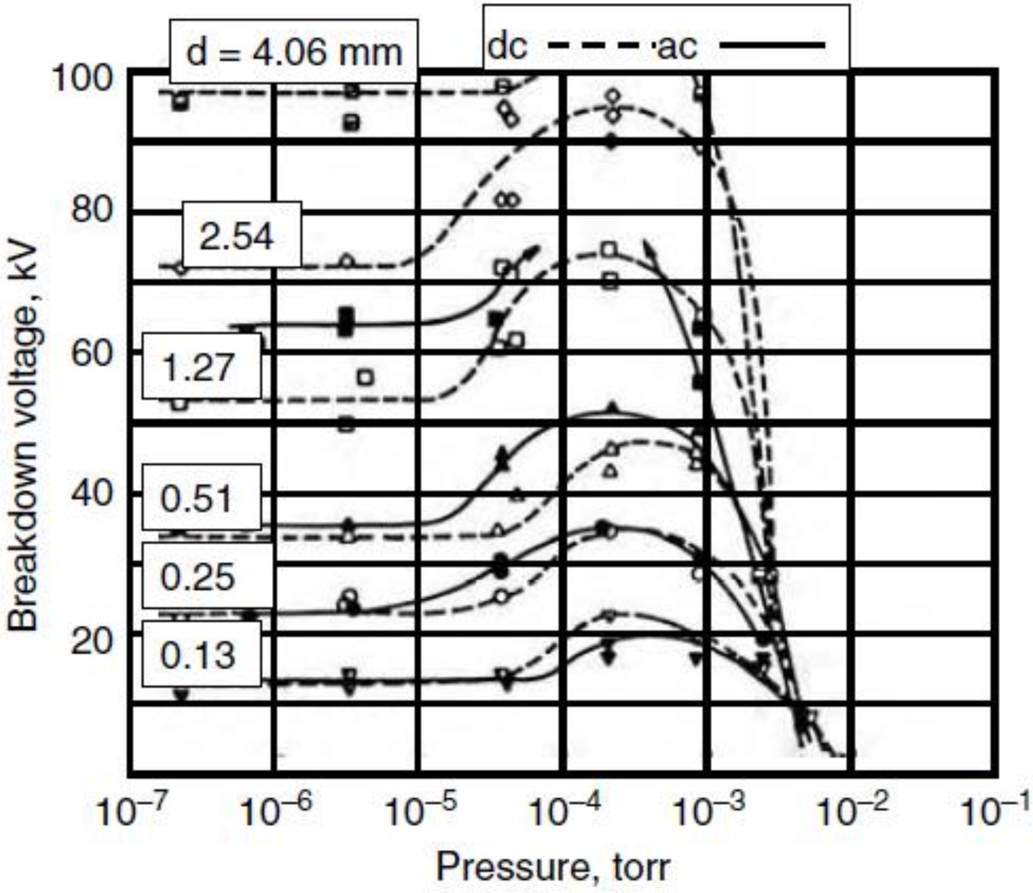




The breakdown voltage U_B as a function of contact gap in vacuum.

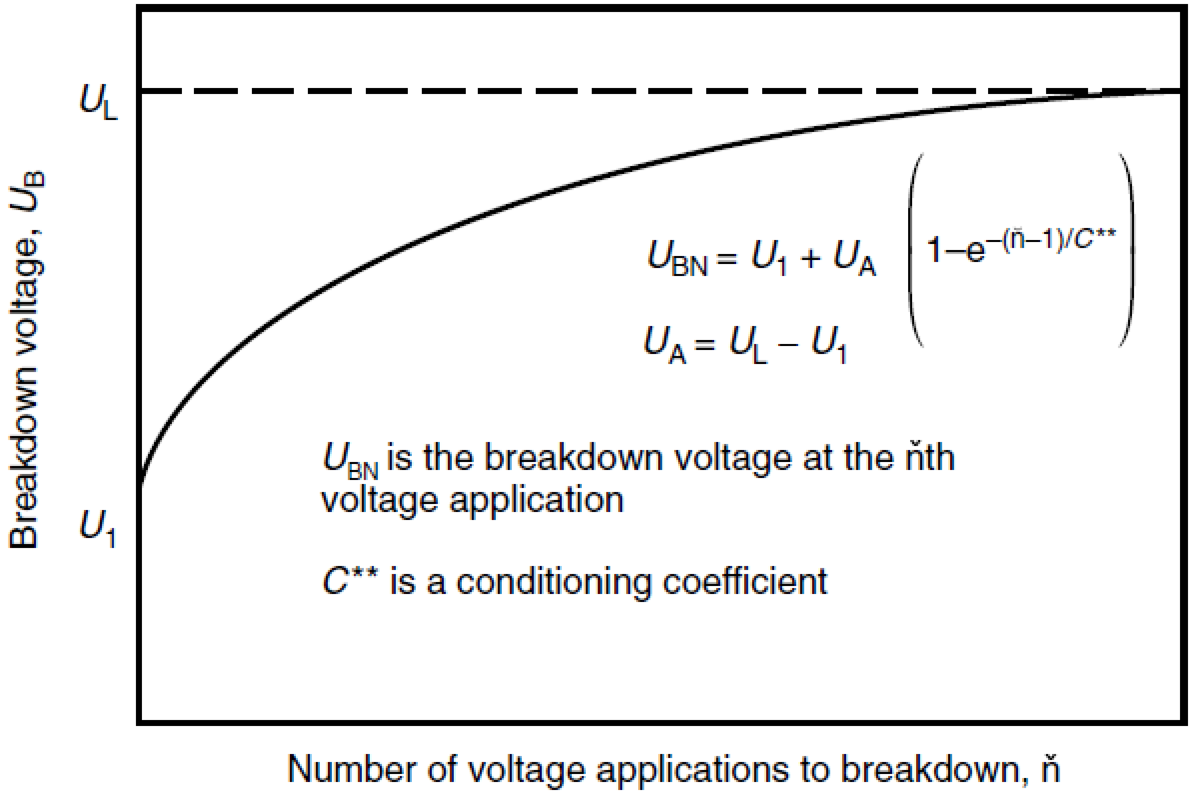
Here it can be observed that the value of U_B seems to be reaching a limiting value as the contact gap increases above 100mm.

3.ELECTRICAL BREAKDOWN IN VACUUM



The ac and dc breakdown voltage as a function of pressure and contact gaps.

3.ELECTRICAL BREAKDOWN IN VACUUM



$$U_{BN} = U_1 + U_A \left(1 - e^{-(\check{n}-1)/C^{**}}\right)$$

$$U_A = U_L - U_1$$

U_{BN} is the breakdown voltage at the ňth voltage application

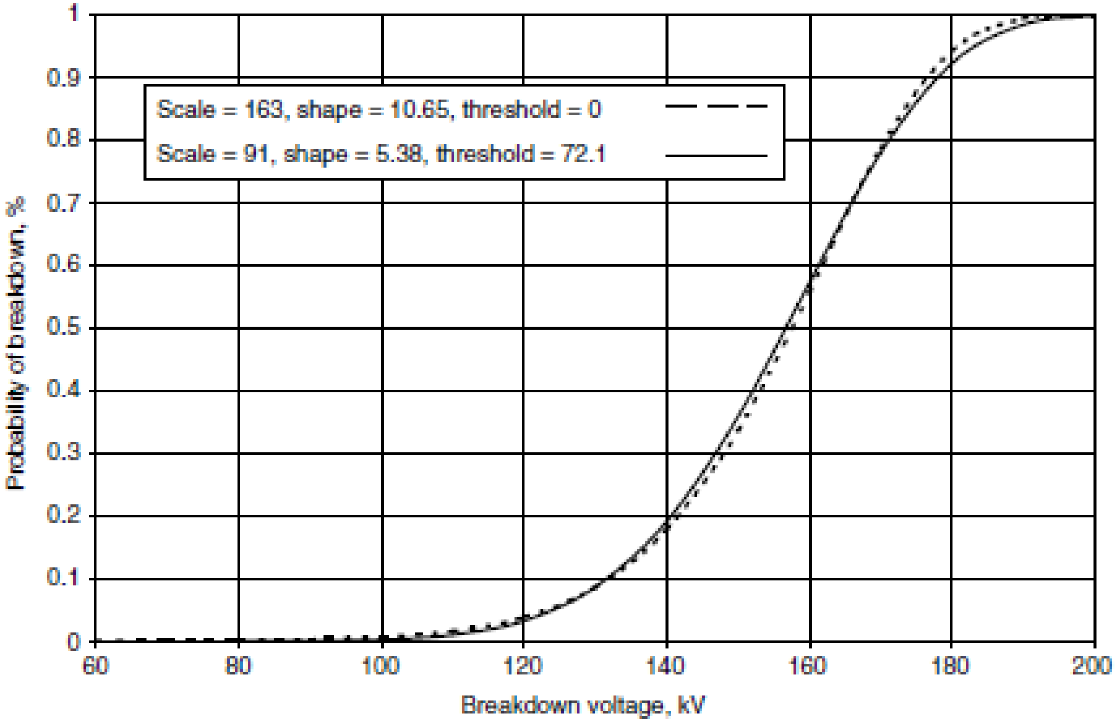
C^{**} is a conditioning coefficient

The typical characteristics of the conditioning curve

3.ELECTRICAL BREAKDOWN IN VACUUM

The 2-parameter Weibull

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\Theta}\right)^b\right].$$

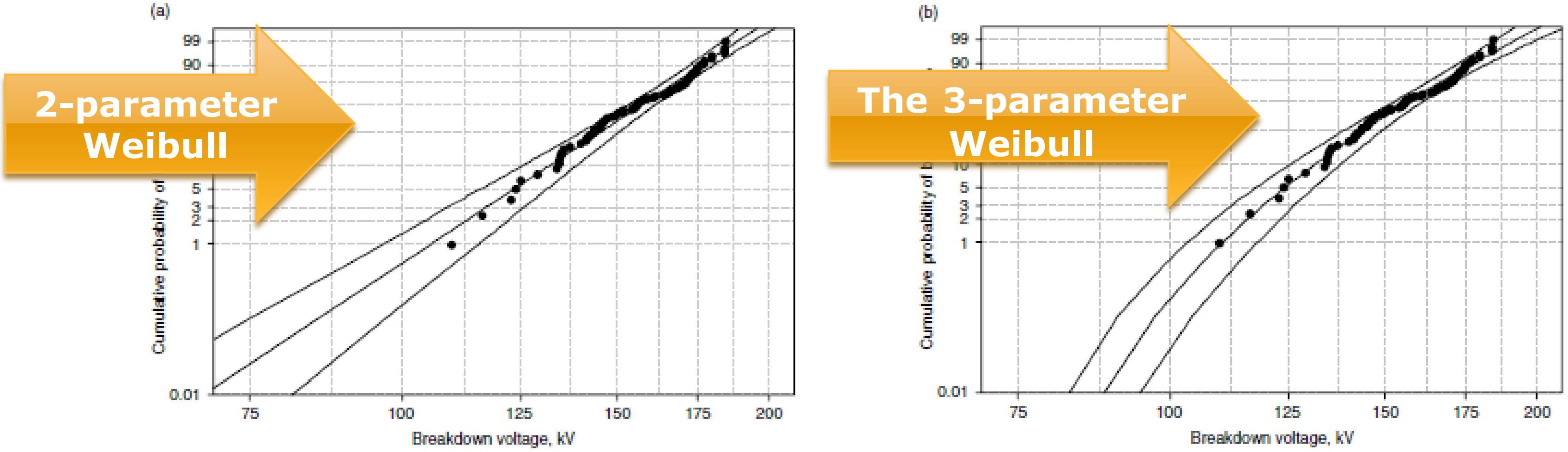


b-shape factor
Θ-scale factor
X_0-thresold factor

The 3-parameter Weibull

$$F(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\Theta - x_0}\right)^b\right].$$

3.ELECTRICAL BREAKDOWN IN VACUUM



2-parameter Weibull

The 3-parameter Weibull

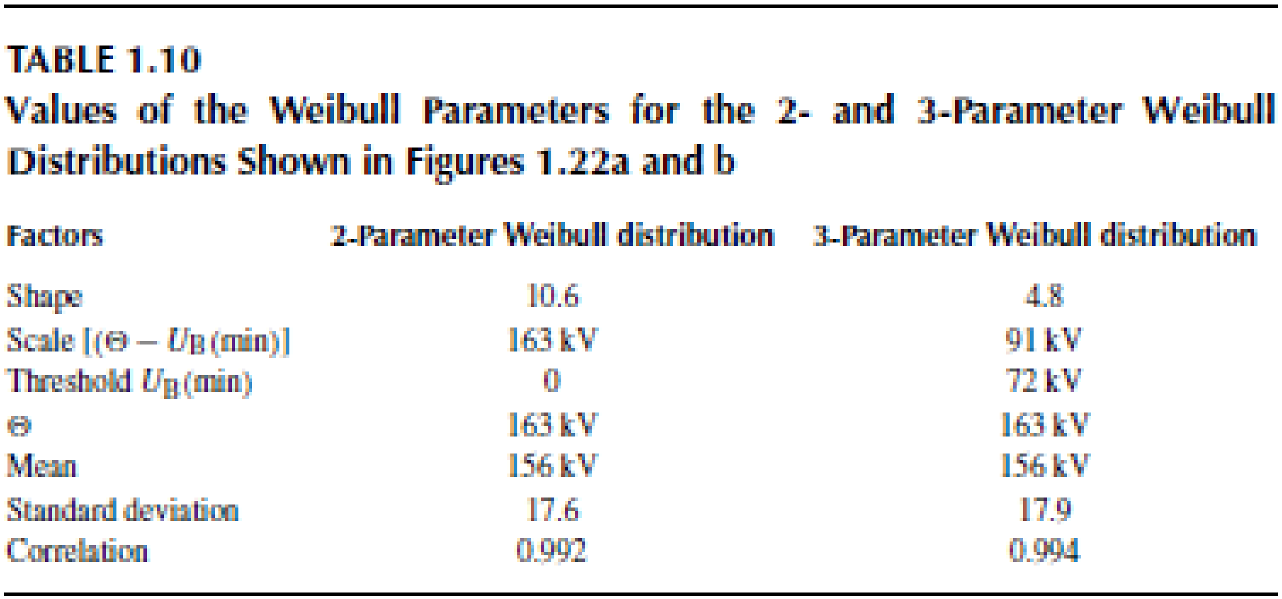


TABLE 1.10

Values of the Weibull Parameters for the 2- and 3-Parameter Weibull Distributions Shown in Figures 1.22a and b

Factors	2-Parameter Weibull distribution	3-Parameter Weibull distribution
Shape	10.6	4.8
Scale $[(\Theta - U_B(\text{min})]$	163 kV	91 kV
Threshold $U_B(\text{min})$	0	72 kV
Θ	163 kV	163 kV
Mean	156 kV	156 kV
Standard deviation	17.6	17.9
Correlation	0.992	0.994

3.ELECTRICAL BREAKDOWN IN VACUUM

Four parts to understand vacuum breakdown phenomena in vacuum interrupters

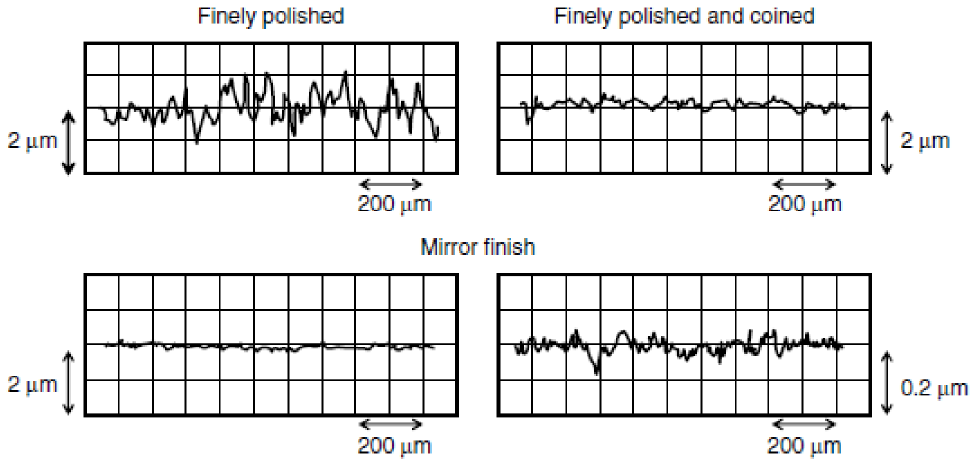
1. The electric field
2. The conditions that lead up to the vacuum breakdown, that is, the prebreakdown effects
3. The breakdown processes and the transition to the vacuum arc
4. The transition to a self-sustained vacuum arc

3.1 ELECTRIC FIELD

$E=U/d$

$E=\beta U/d$

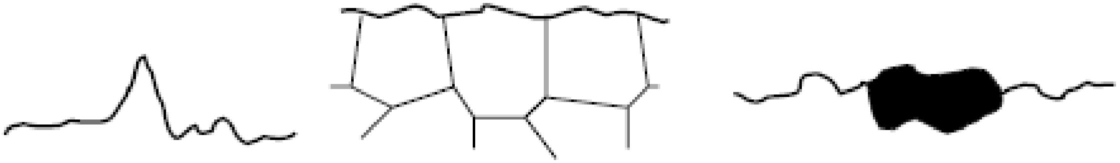
$\beta=\beta_m X \beta_g$



(a) β_m is an enhancement factor resulting from microscopic surface projections;

(b) β_g a geometric enhancement factor resulting from a nouniform field distribution

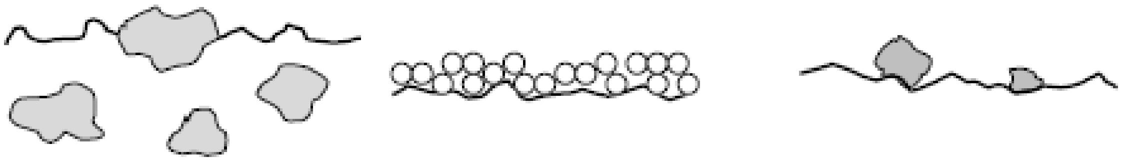
3.1 ELECTRIC FIELD



(a) Microprojections

(b) Grain boundaries at the surface

(c) Surface inclusions (insulating)



(d) Surface inclusions (metallic; e.g., from composite contacts)

(e) Adsorbed gas layers

(f) Microparticles

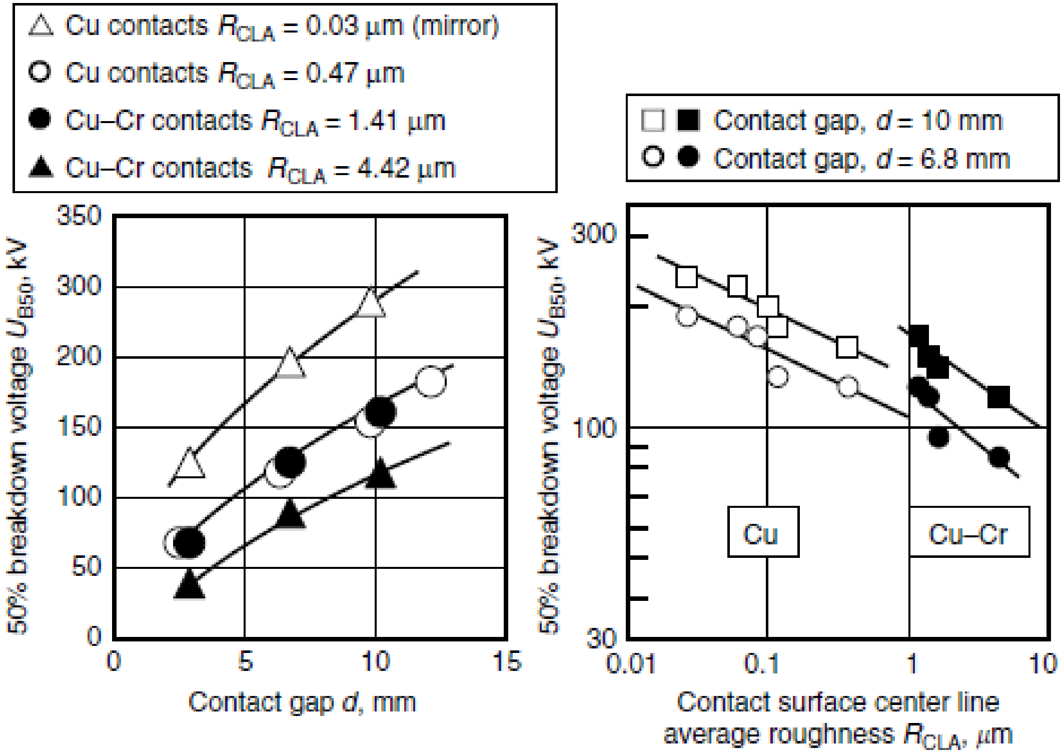
(g) Edge of craters

(h) Pores and cracks

(i) Inorganic films (e.g., oxides)

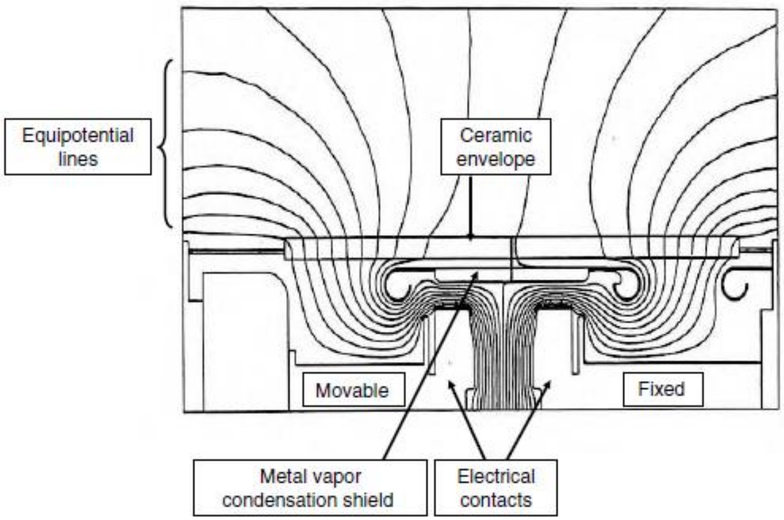
Examples of other surface effects that can give rise to a microscopic enhancement factor

3.1 ELECTRIC FIELD

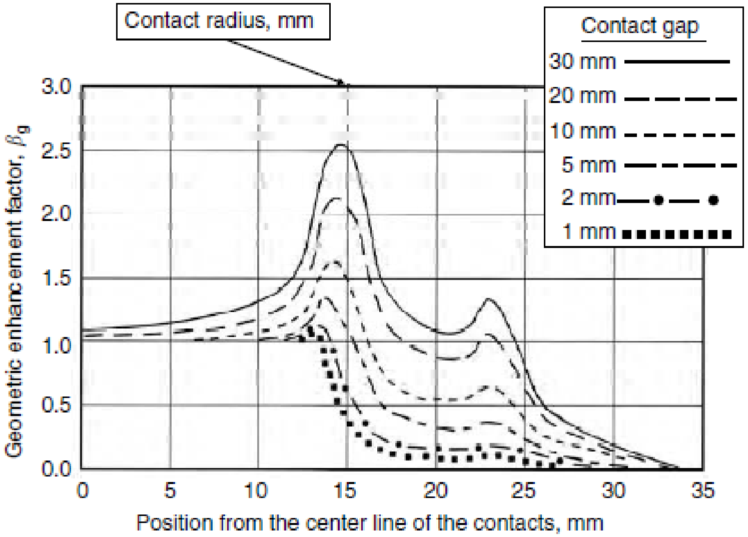


The 50% breakdown voltage U_{50} as a function of contact gap and the contact's surface center-line average roughness for Cu and Cu-Cr contacts.

3.1 ELECTRIC FIELD



The potential lines when a voltage is applied across the open.



Geometric field enhancement factor *βg* *as a function of the distance from* the center of the contact and the contact gap for the structure shown in left Figure .

The breakdown voltage in contact gap d can be calculated by the equation.

$$E(d) = \beta_{\mathrm{m}}\beta_{\mathrm{g}}(d) \cdot K_2 d^{(\eta-1)}$$

$$\frac{E_{\mathrm{C}}(d)}{E_{\mathrm{C}}(1)} = \beta_{\mathrm{g}}(d) \cdot d^{(\eta-1)}$$

3.2 PREBREAKDOWN EFEECTS

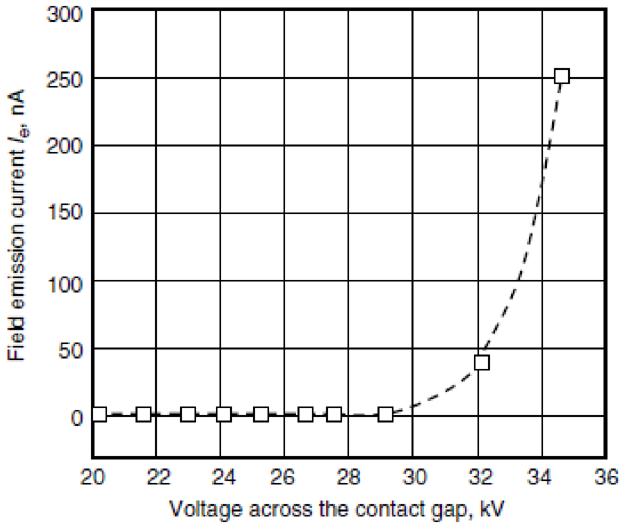
Pre-breakdown effects →

- **Field emission from the cathode**
- **Anode phenomena**
- **Micro-particles**
- **Micro-discharges**

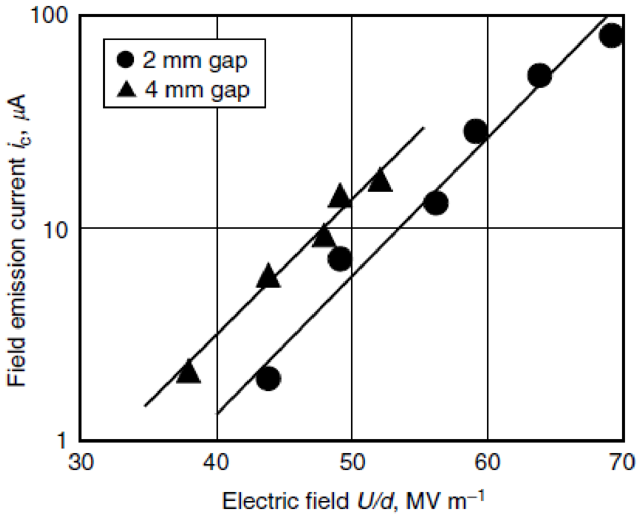
3.2 PREBREAKDOWN EFEECTS

Field emission from the cathode

Field emission current as a function of the applied voltage.



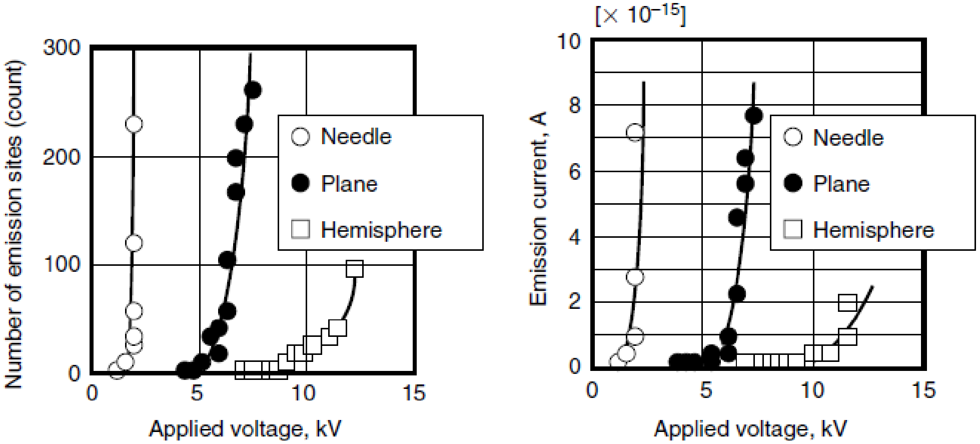
Field emission current as a function of the contact gap field (U/d).



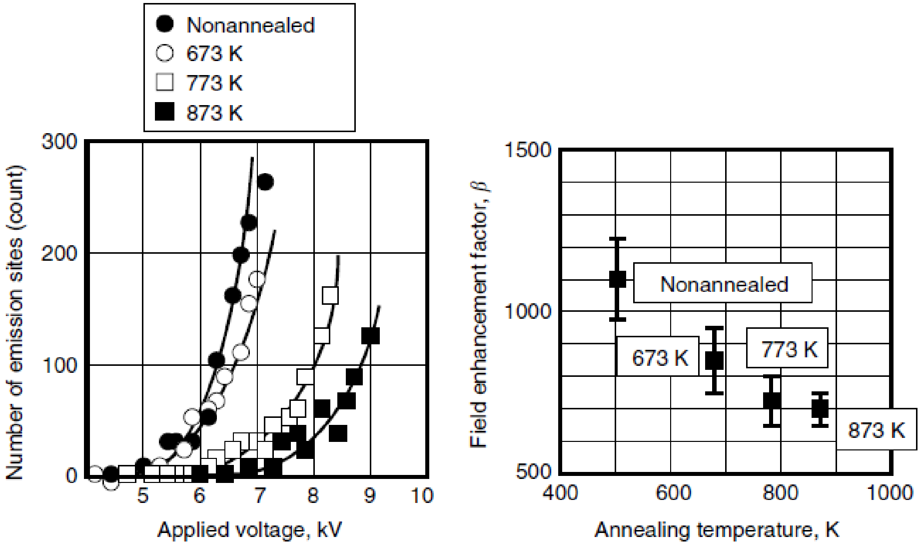
3.2 PREBREAKDOWN EFEECTS

Field emission from the cathode

The number of emission sites as a function of the voltage applied

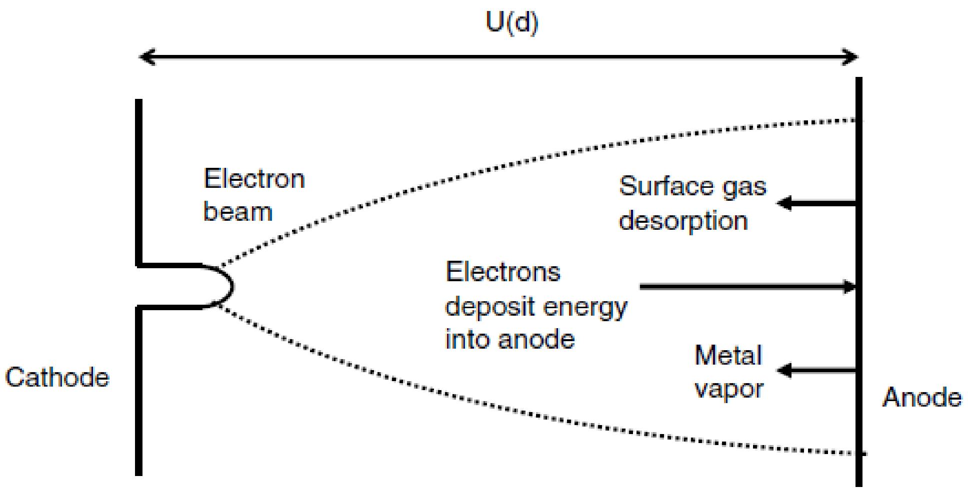


The number of emission sites as a function of the annealing



3.2 PREBREAKDOWN EFEECTS

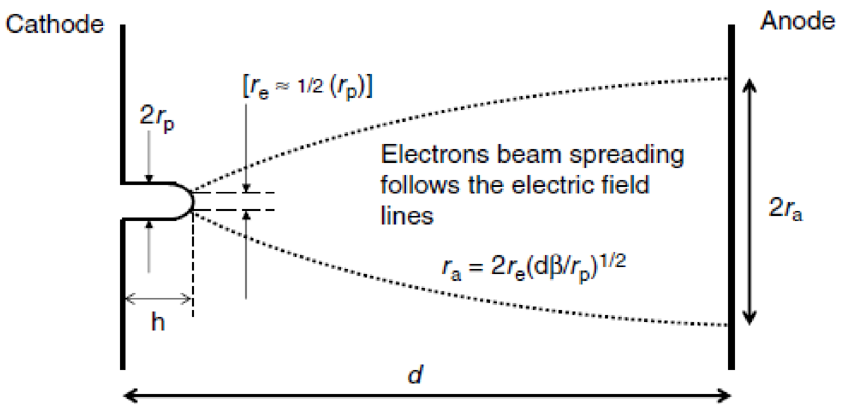
Anode phenomena



One of the earliest hypotheses for the source of gas originated from considering a narrow electron beam from the cathode impinging on a small anode area, heating it, releasing absorbed gases and eventually evaporated metal into the contact gap.

3.2 PREBREAKDOWN EFEECTS

Anode phenomena

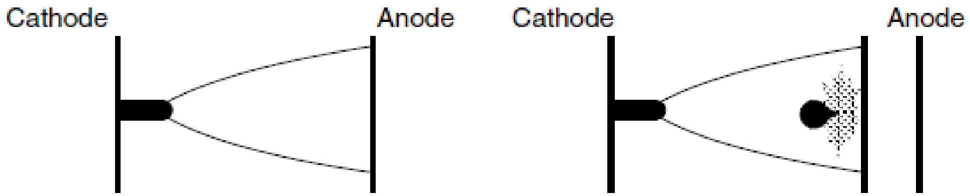


Let $\beta = 100$, $h = 0.5\ \mu m$,	$r_p = 5$ nm and $r_e \approx 2.5$ nm
$d = 10$ mm	$r_a = 70\ \mu m$ (or 0.07 mm)
$d = 20$ mm	$r_a = 100\ \mu m$ (or 0.1 mm)
$d = 30$ mm	$r_a = 120\ \mu m$ (or 0.12 mm)
$d = 50$ mm	$r_a = 160\ \mu m$ (or 0.16 mm)

The spread of the electron beam as it crosses the contact gap

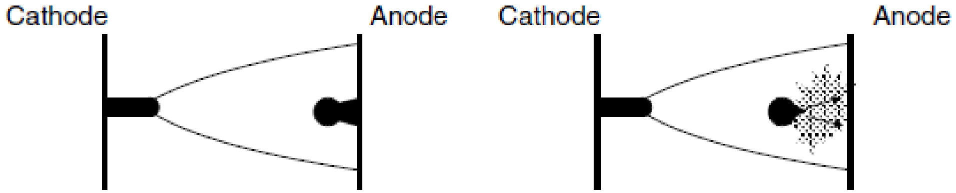
3.2 PREBREAKDOWN EFEECTS

Anode phenomena



(a) Electron beam heats small anode area, as temperature increases, yield strength of material decreases

(c) Electron beam heats microparticle to high temperature (calculated to be in excess of 2500 °C). Metal vapor from micro-particle trails behind it (for Cu at 2500 °C it is about $^1/_2$ atmosphere)



(b) Electric field exerts a force on anode surface and can pull a microparticle from it

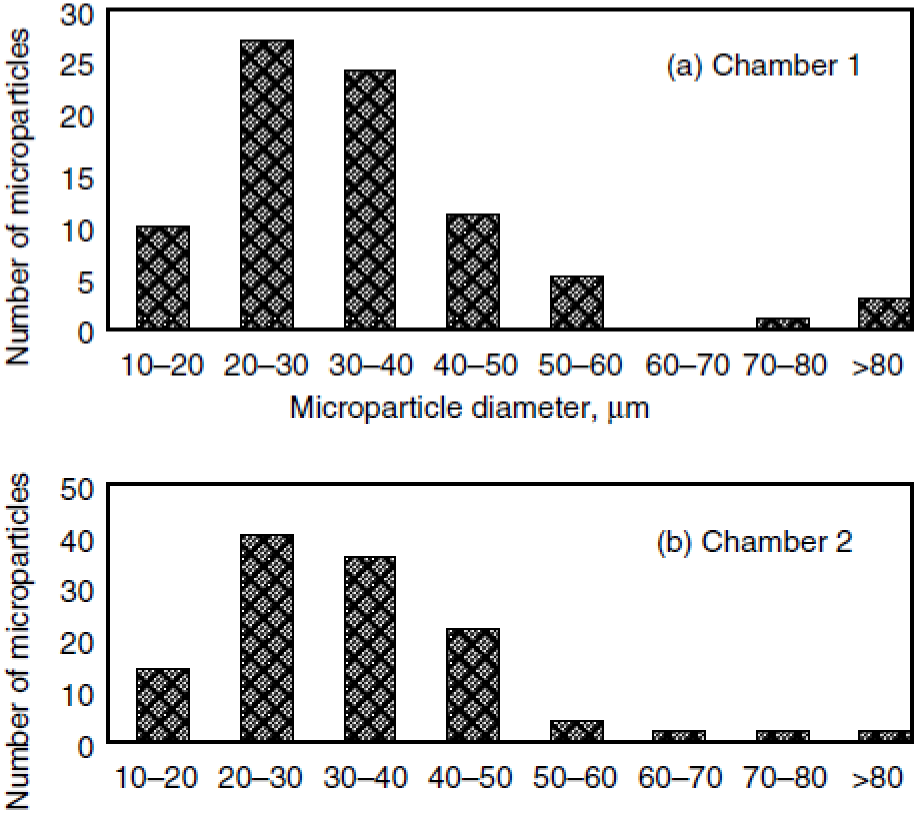
(d) Electrons emitted from micro-particle gain energies of few eV from the electric field and ionize the trailing metal vapor

Schematic diagram of electron beam heating of the anode

3.2 PREBREAKDOWN EFEECTS

Micro-Particle

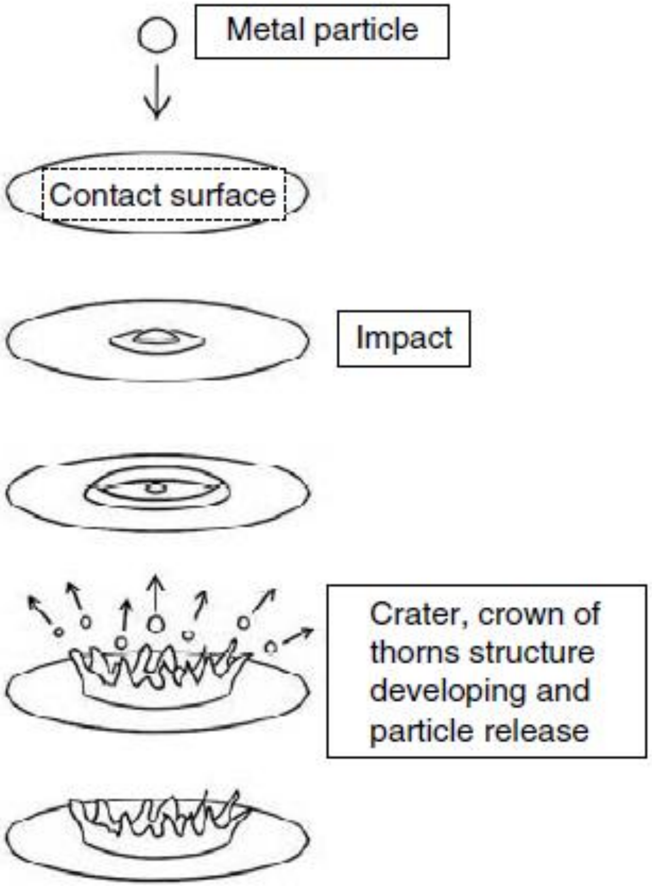
Distribution of micro-particles left on machined Cu–Cr contact surface after switching 1000 A, 100 times.



3.2 PREBREAKDOWN EFEECTS

Micro-Particle

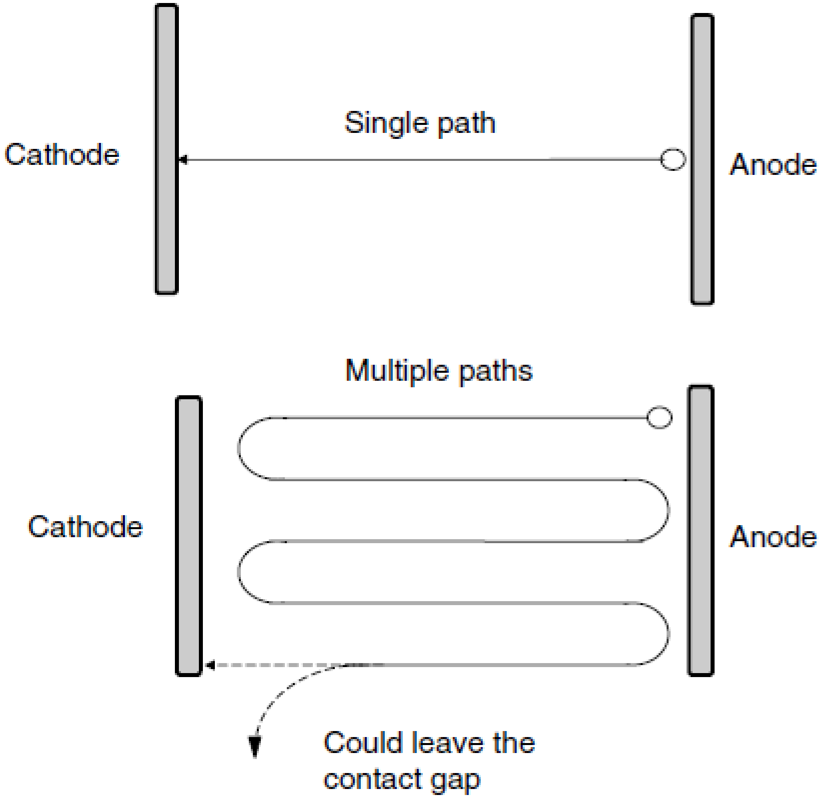
Schematic of a particle impact resulting on a crown of thorns structure on the contact surface plus the ejection of secondary micro-particles.



3.2 PREBREAKDOWN EFEECTS

Micro-Particle

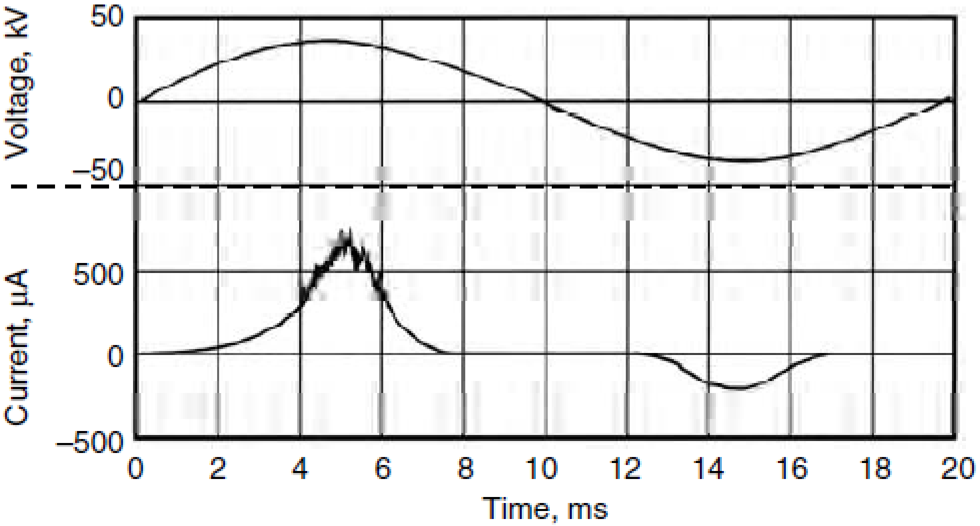
Schematic of a particle making an oscillatory passage across the contact gap.



3.2 PREBREAKDOWN EFEECTS

Micro-Discharge

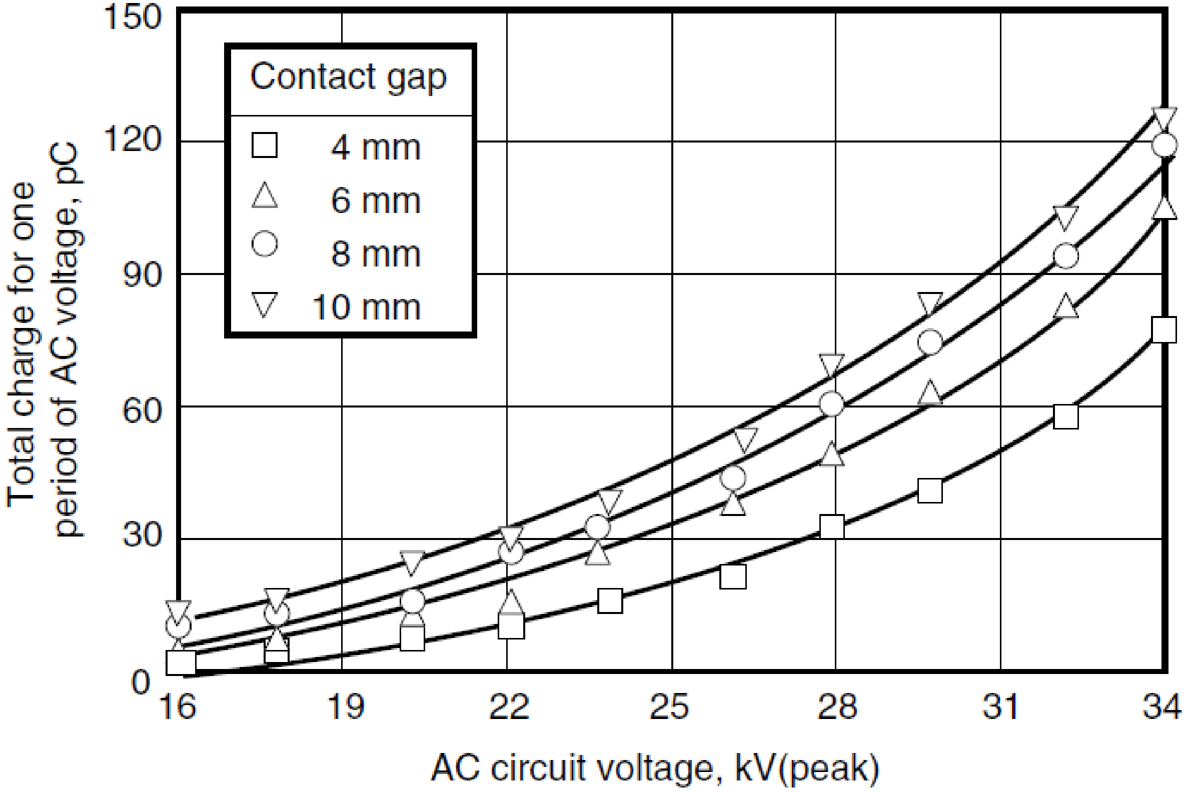
A current pulse seen during a microdischarge across a vacuum gap



3.2 PREBREAKDOWN EFEECTS

Micro-Discharge

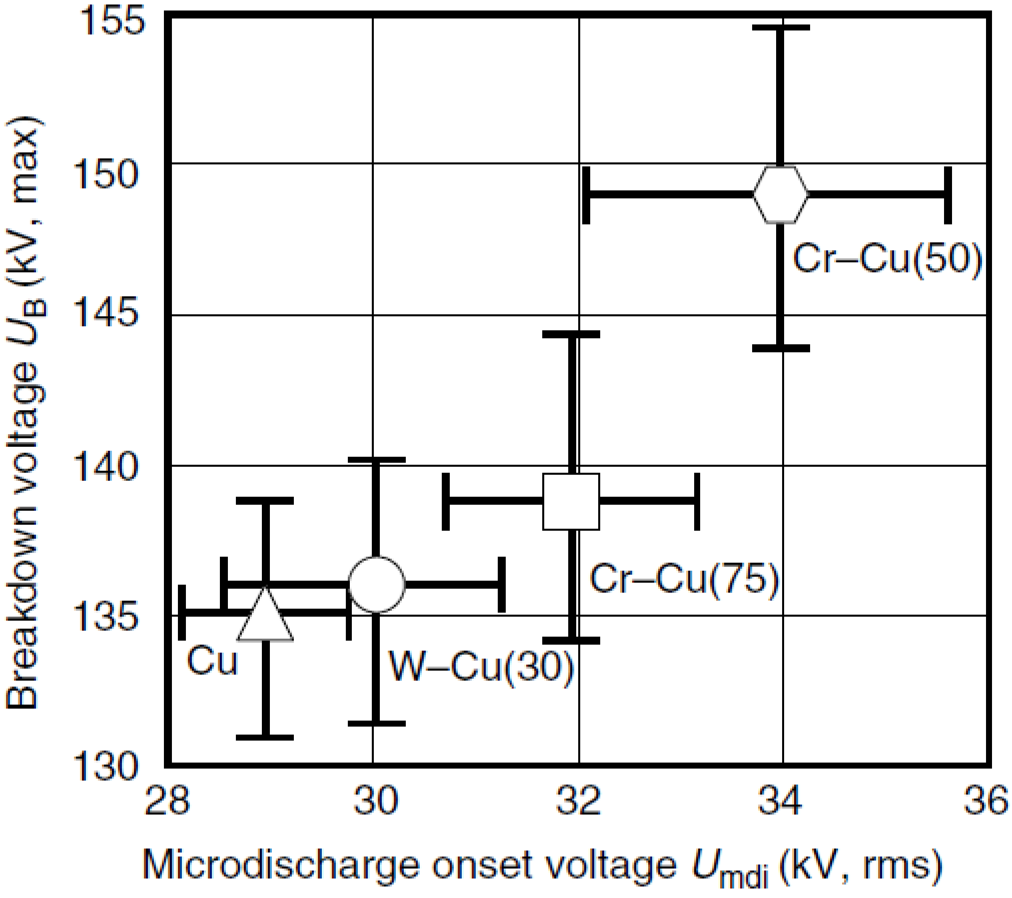
The charge passed by a mircodischarge



3.2 PREBREAKDOWN EFEECTS

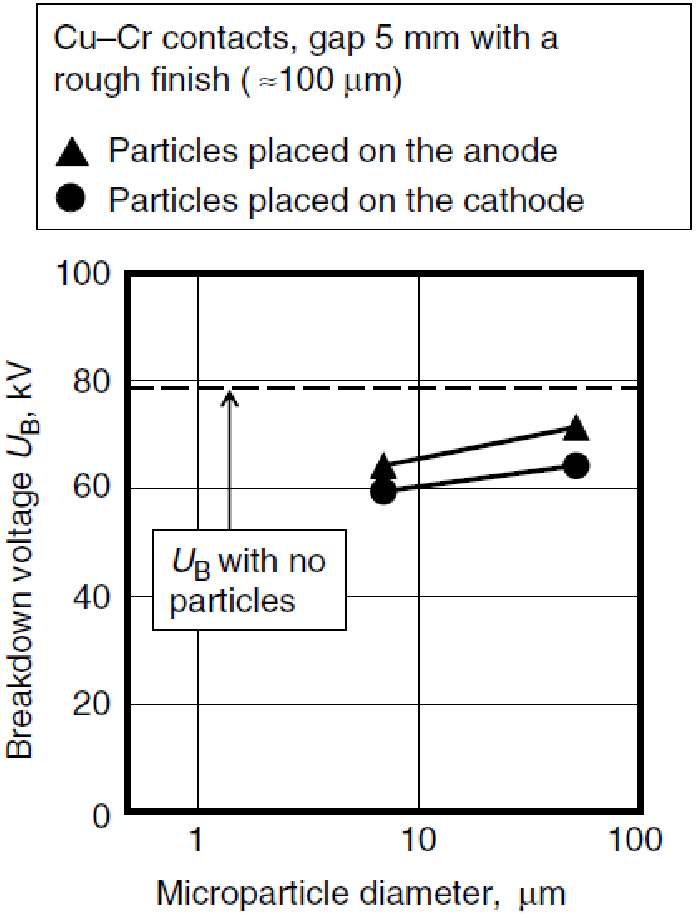
Micro-Discharge

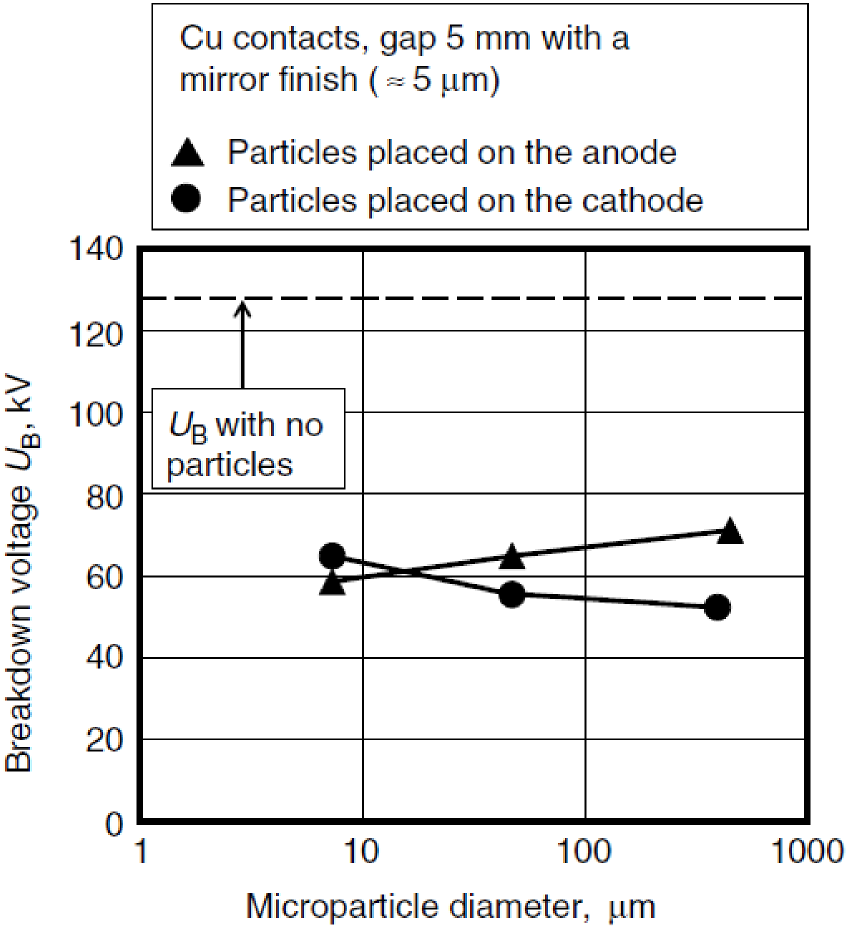
Correlation between the mircodischarge initiation voltage and the ultimate vacuum breakdown voltage



3.ELECTRICAL BREAKDOWN IN VACUUM

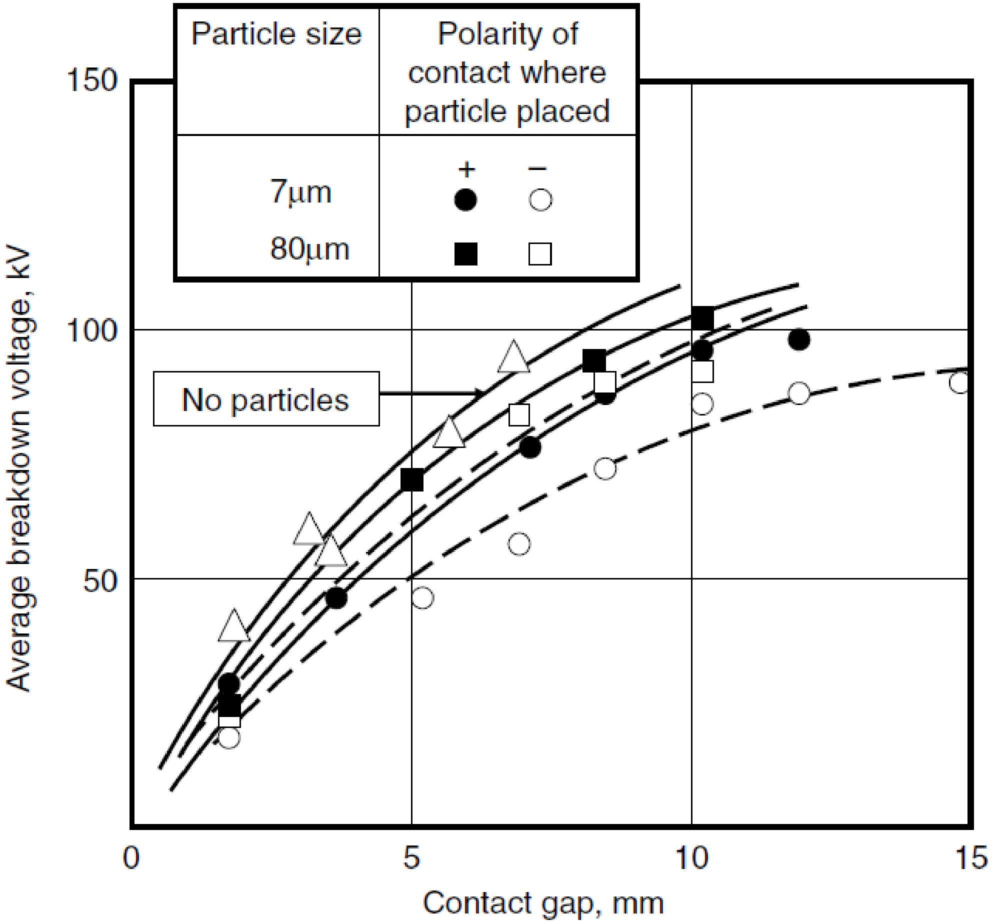
Vacuum breakdown and transition to vacuum arc





3.ELECTRICAL BREAKDOWN IN VACUUM

Vacuum breakdown and transition to vacuum arc



3.ELECTRICAL BREAKDOWN IN VACUUM

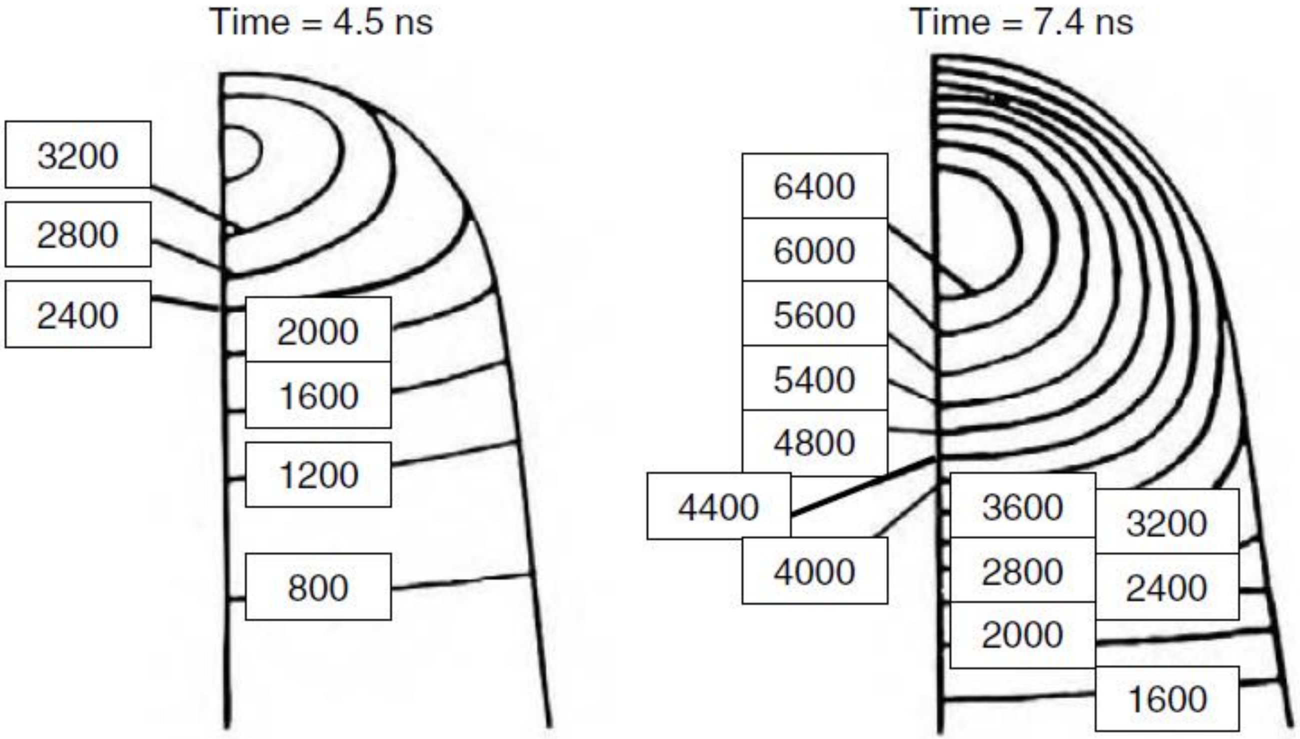
Vacuum breakdown and transition to vacuum arc

$$W_c/\pi r^2 = 6.6\epsilon_0 \beta_m \beta_g U_B^2/d.$$

$$U_B = K_c d^{1/2}$$

3.ELECTRICAL BREAKDOWN IN VACUUM

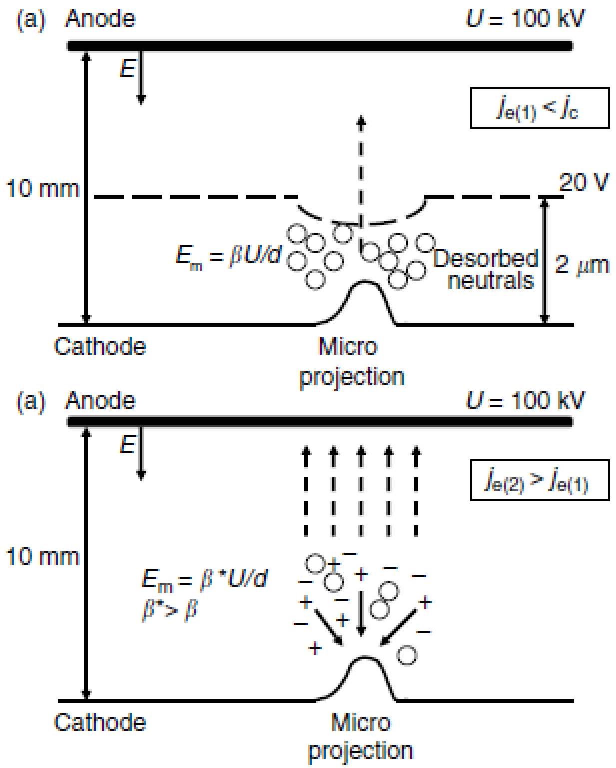
Vacuum breakdown and transition to vacuum arc



Maps of the isotherms inside a microprojection at 4.8 ns and 7.4 ns after the initiation of the high density field emission current

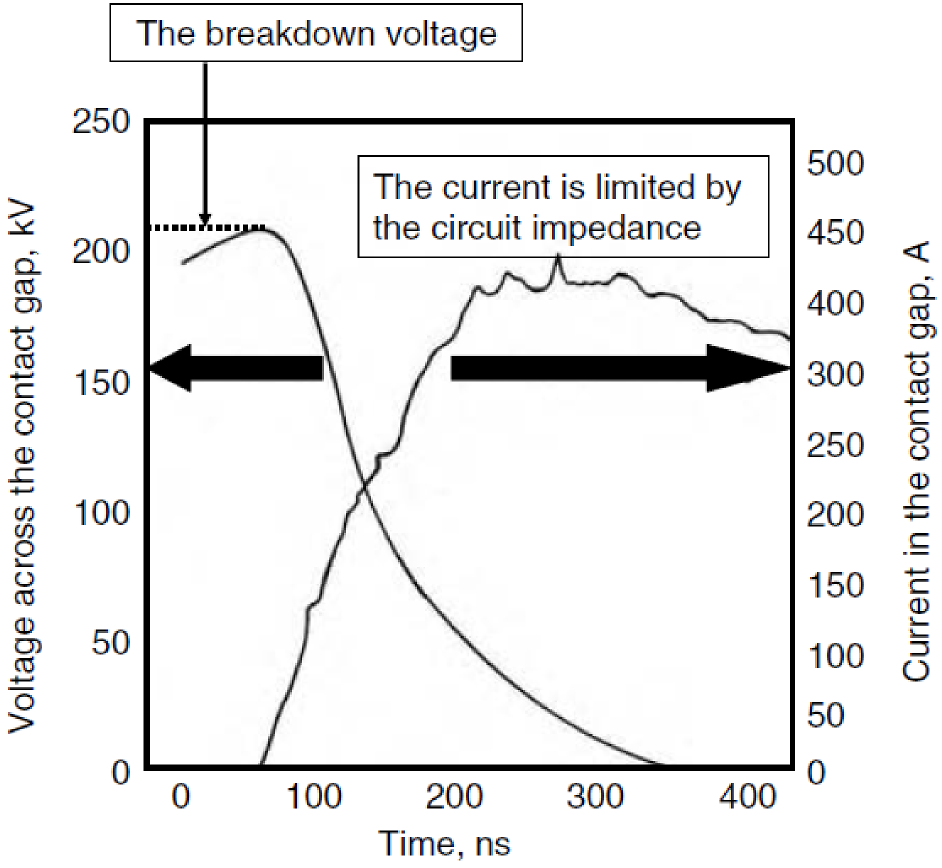
3.ELECTRICAL BREAKDOWN IN VACUUM

Vacuum breakdown and transition to vacuum arc



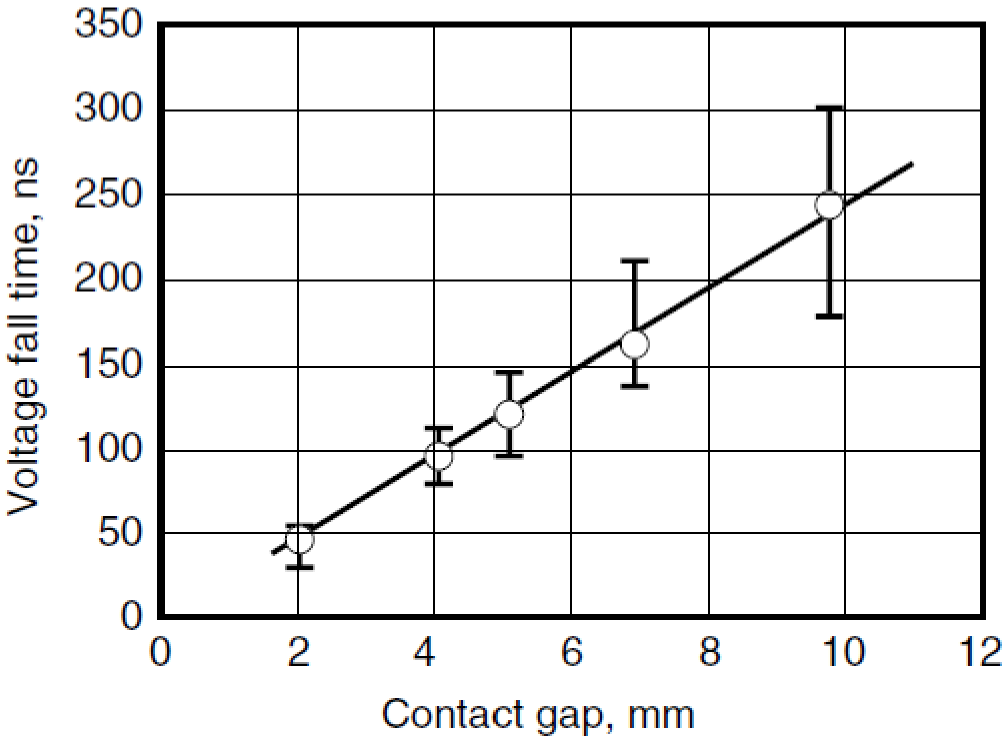
3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc



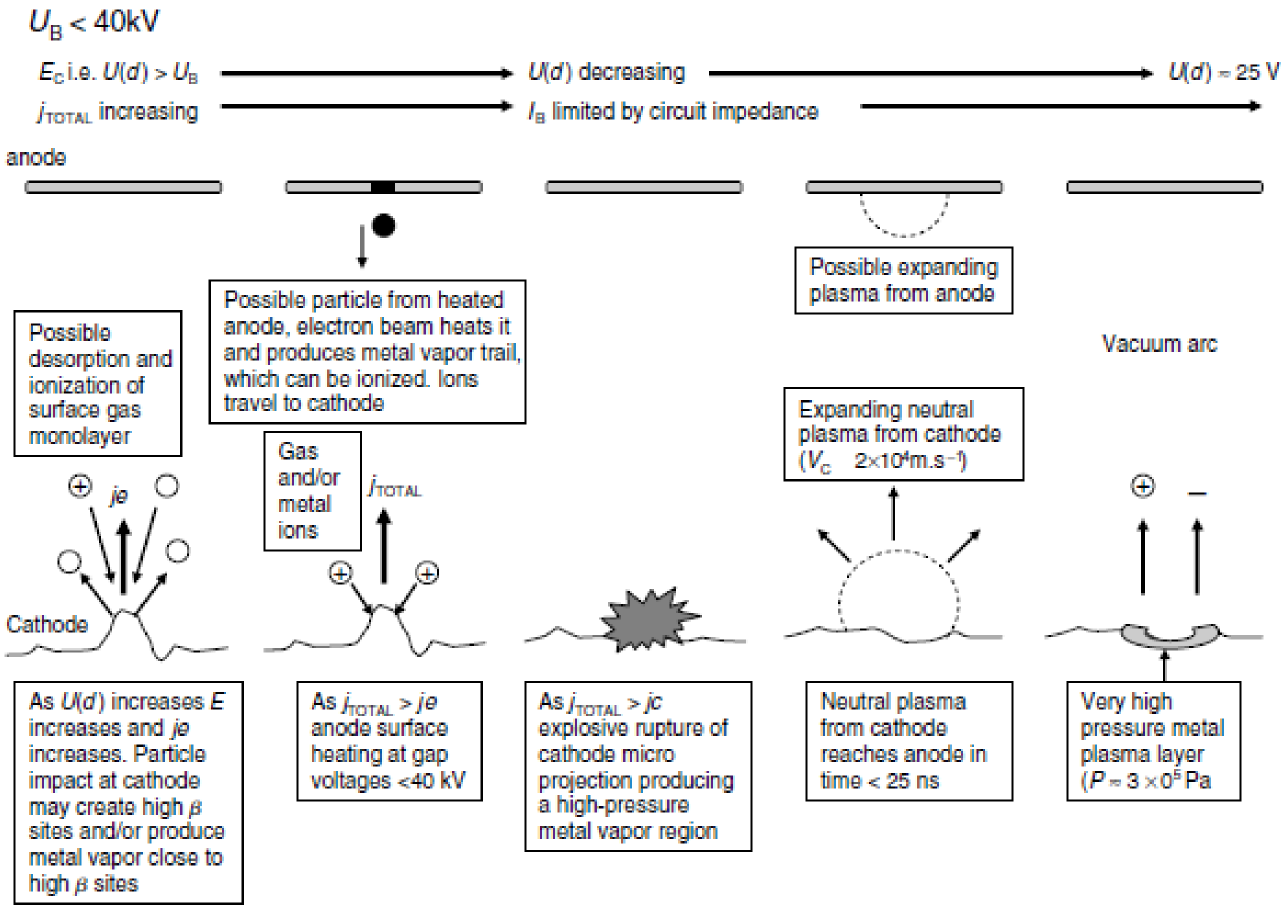
3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc



3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc



Possible desorption and ionization of surface gas monolayer

Possible particle from heated anode, electron beam heats it and produces metal vapor trail, which can be ionized. Ions travel to cathode

Gas and/or metal ions

Possible expanding plasma from anode

Expanding neutral plasma from cathode $(V_c \;\; 2\times10^4 \mathrm{m.s^{-1}})$

As $U(d)$ increases E increases and je increases. Particle impact at cathode may create high β sites and/or produce metal vapor close to high β sites

As $j_{\mathrm{TOTAL}} > je$ anode surface heating at gap voltages <40 kV

As $j_{\mathrm{TOTAL}} > jc$ explosive rupture of cathode micro projection producing a high-pressure metal vapor region

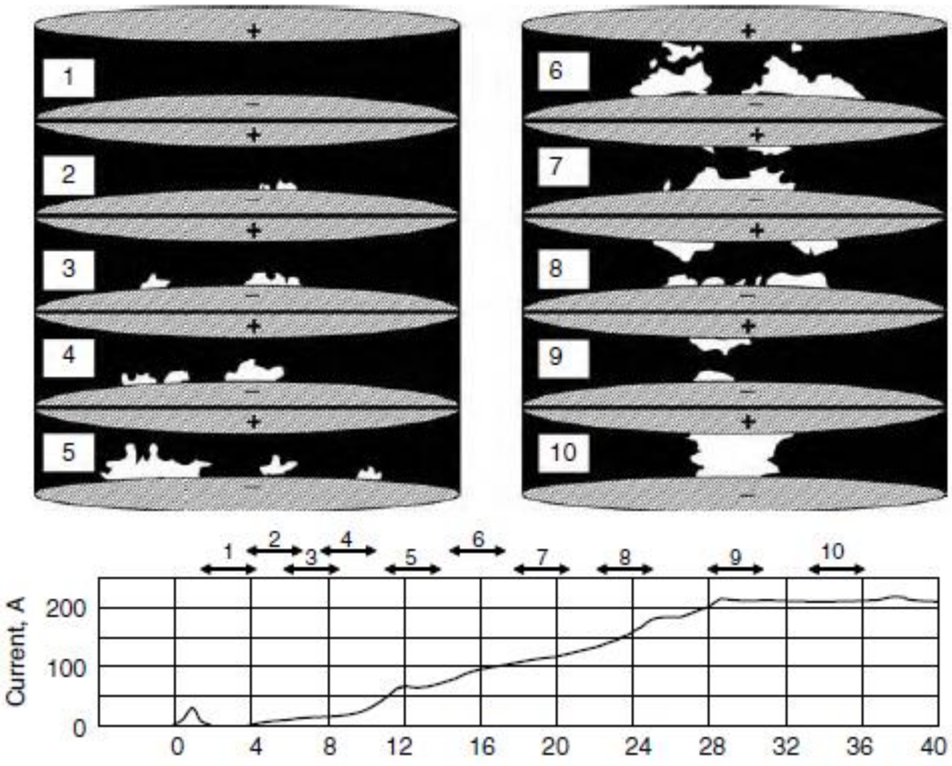
Neutral plasma from cathode reaches anode in time < 25 ns

Very high pressure metal plasma layer $(P \approx 3 \times 0^5$ Pa

FIGURE 1.74 The vacuum breakdown sequence for contact gaps <0.5 mm.

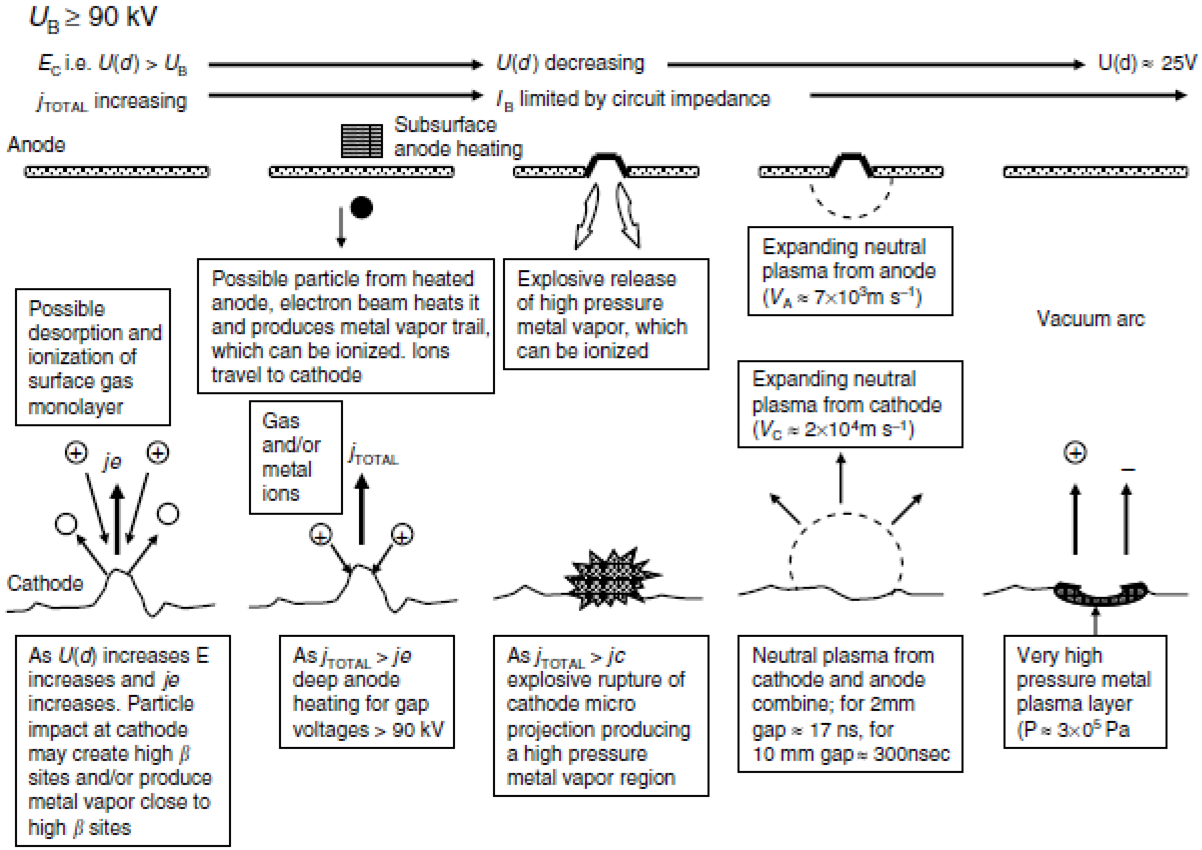
3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc



3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc



$U_B \geq 90$ kV

E_C i.e. $U(d) > U_B$ → $U(d)$ decreasing → U(d) ≈ 25V

j_{TOTAL} increasing → I_B limited by circuit impedance →

Possible desorption and ionization of surface gas monolayer

Possible particle from heated anode, electron beam heats it and produces metal vapor trail, which can be ionized. Ions travel to cathode

Gas and/or metal ions

Explosive release of high pressure metal vapor, which can be ionized

Expanding neutral plasma from anode ($V_A \approx 7\times10^3$m s^{-1})

Expanding neutral plasma from cathode ($V_C \approx 2\times10^4$m s^{-1})

As $U(d)$ increases E increases and je increases. Particle impact at cathode may create high β sites and/or produce metal vapor close to high β sites

As $j_{TOTAL} > je$ deep anode heating for gap voltages > 90 kV

As $j_{TOTAL} > jc$ explosive rupture of cathode micro projection producing a high pressure metal vapor region

Neutral plasma from cathode and anode combine; for 2mm gap ≈ 17 ns, for 10 mm gap ≈ 300nsec

Very high pressure metal plasma layer ($P \approx 3\times0^5$ Pa

FIGURE 1.76 The vacuum breakdown sequence for contact gaps >2 mm.

3.ELECTRICAL BREAKDOWN IN VACUUM

Transition to self-sustaining vacuum arc

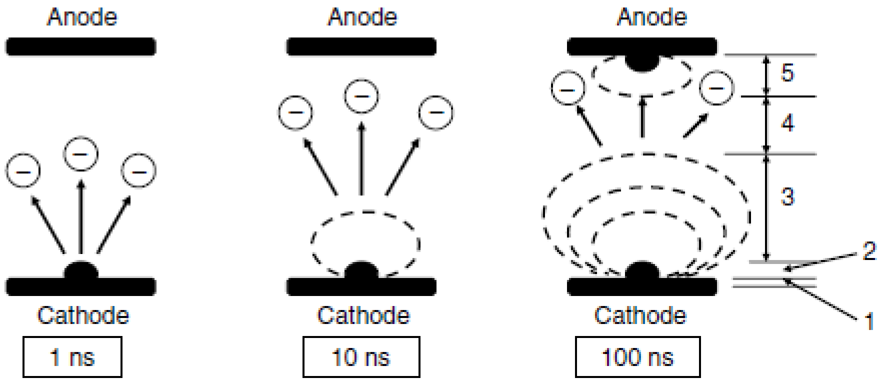


FIGURE 1.77 Schematic of the discharge zones in a vacuum gap as the vacuum breakdown process develops (1) cathode fall region, (2) cathode spot plasma, (3) expanding cathode plasma flare, (4) vacuum zone, and (5) expanding anode flare [128].

3.ELECTRICAL BREAKDOWN IN VACUUM

Time to breakdown

$$t_B = t_p + t_c,$$

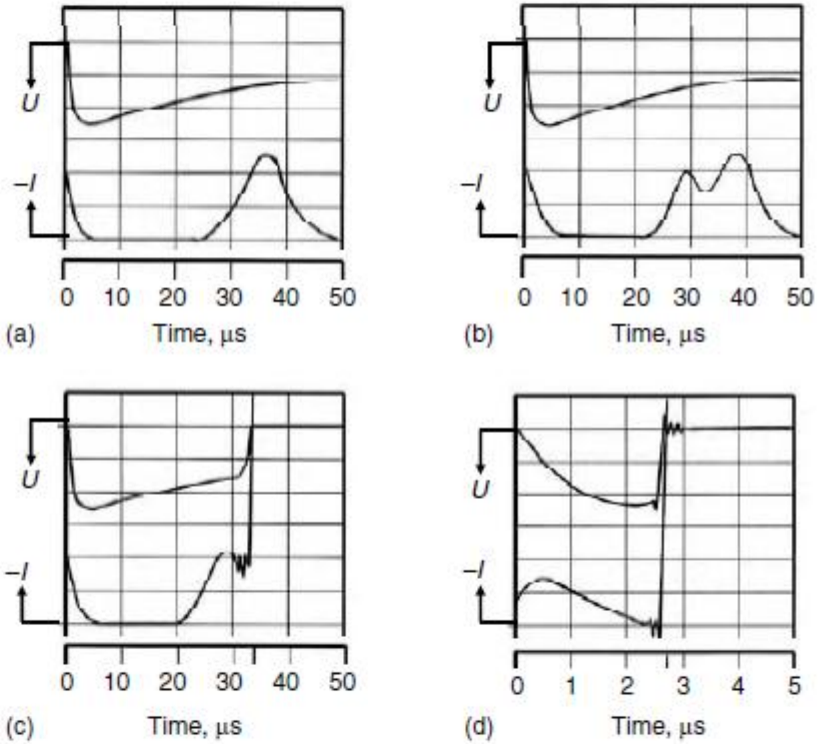
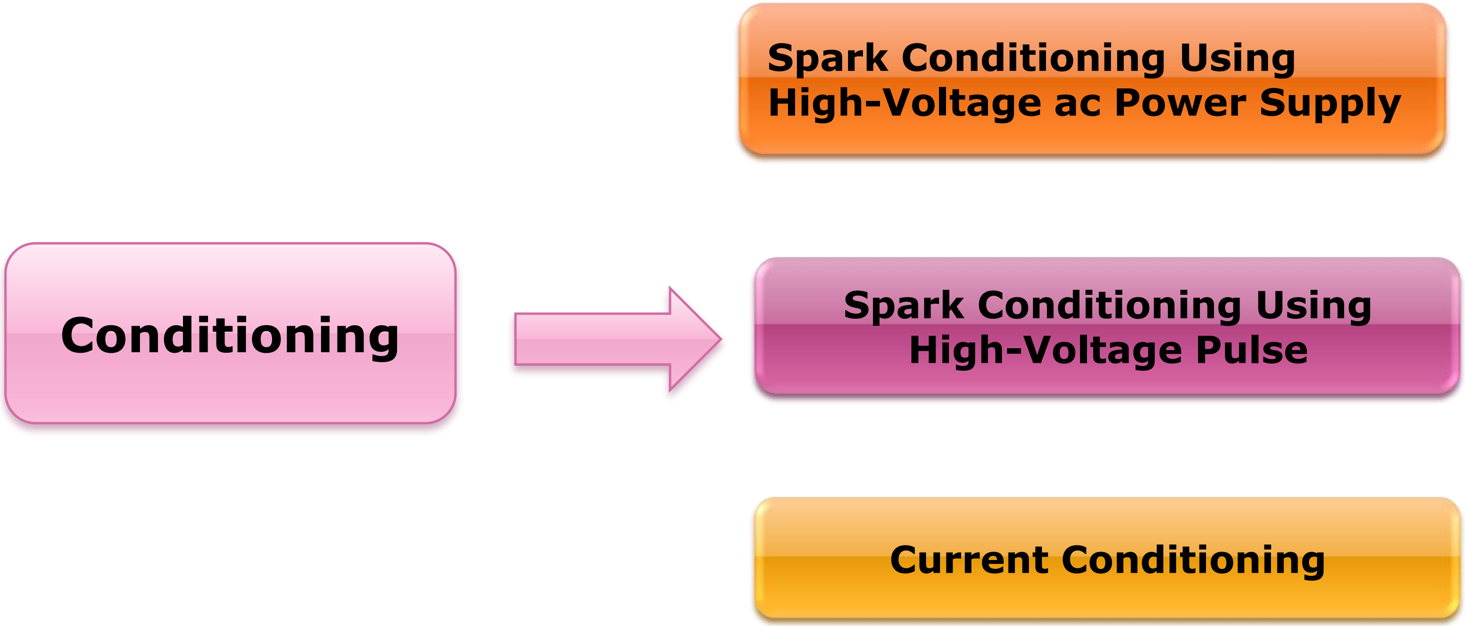


FIGURE 1.80 The variation in the time to breakdown for a pulse voltage with a peak value of 250 kV across a 20-mm copper, contact gap ($I = 2$ A/div, $U = 100$ kV/div): (a) and (b) no breakdown, (c) a breakdown after 30 µs and after the peak of the voltage pulse and (d) an immediate breakdown once the voltage exceeds a given value [136].

3.ELECTRICAL BREAKDOWN IN VACUUM



Conditioning

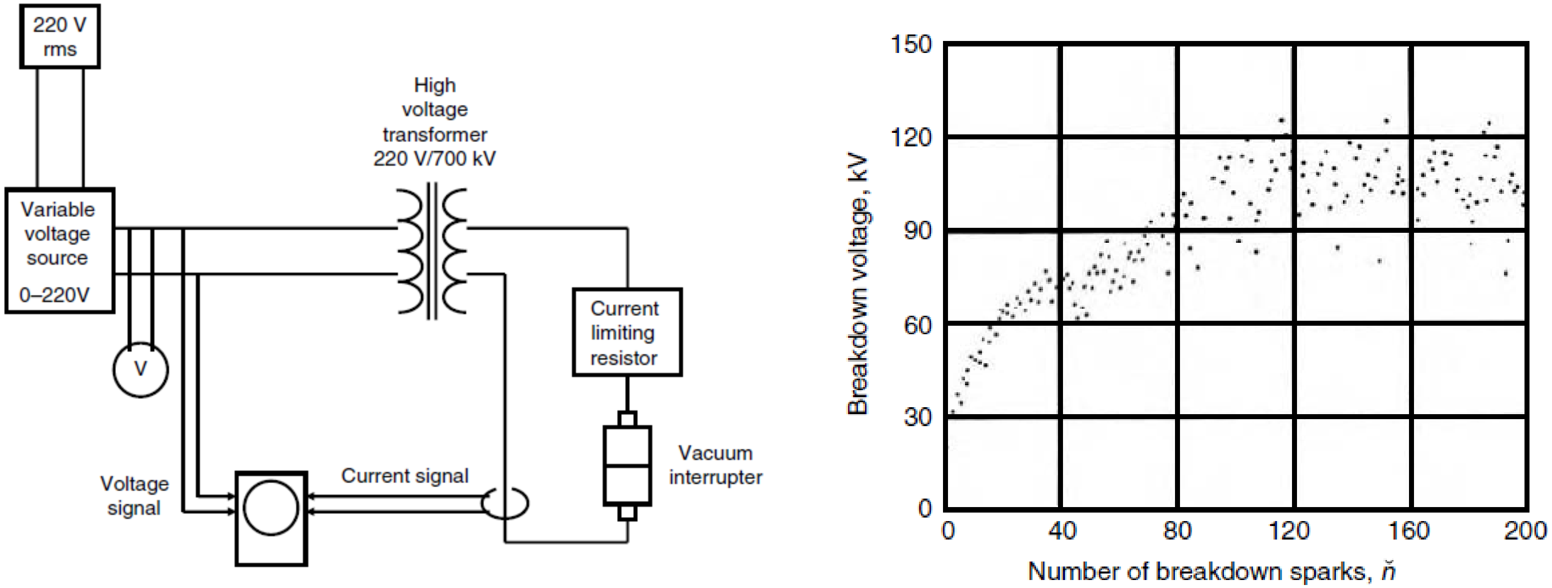
Spark Conditioning Using High-Voltage ac Power Supply

Spark Conditioning Using High-Voltage Pulse

Current Conditioning

3.ELECTRICAL BREAKDOWN IN VACUUM

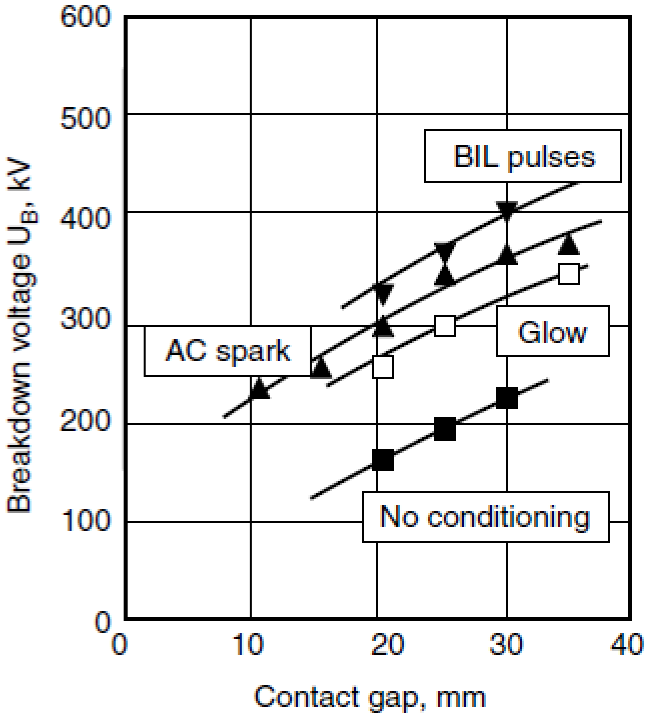
Spark Conditioning Using High-Voltage ac Power Supply



A typical high-voltage ac circuit for spark conditioning the contacts in a vacuum interrupter and a typical high-voltage spark conditioning curve

3.ELECTRICAL BREAKDOWN IN VACUUM

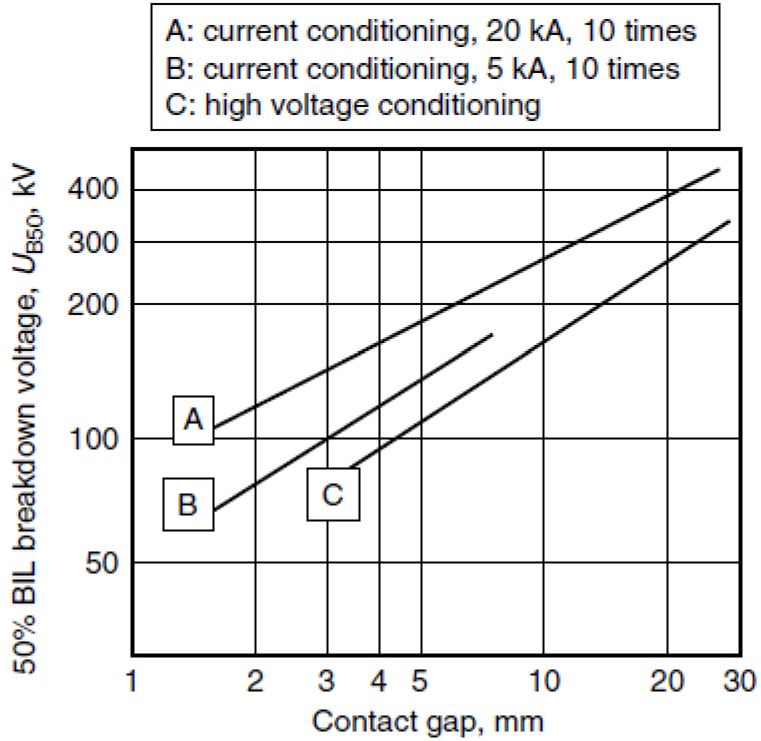
Spark Conditioning Using High-Voltage Pulse



A comparison of BIL spark conditioning, ac spark conditioning, glow discharge conditioning and no conditioning using Cu–Cr contacts

3.ELECTRICAL BREAKDOWN IN VACUUM

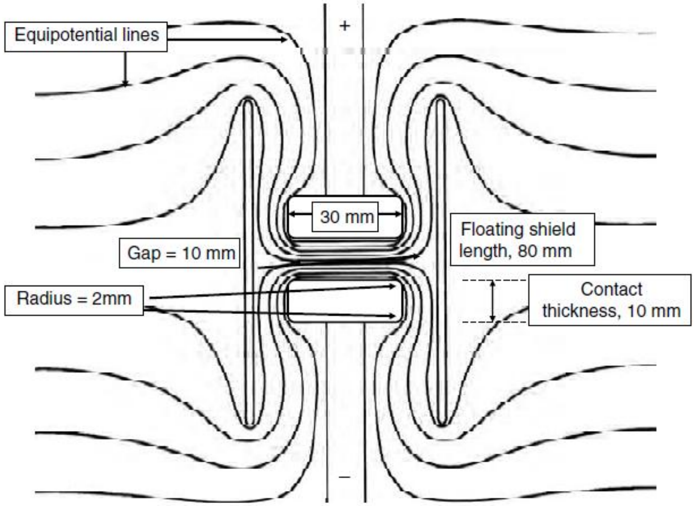
Current Conditioning

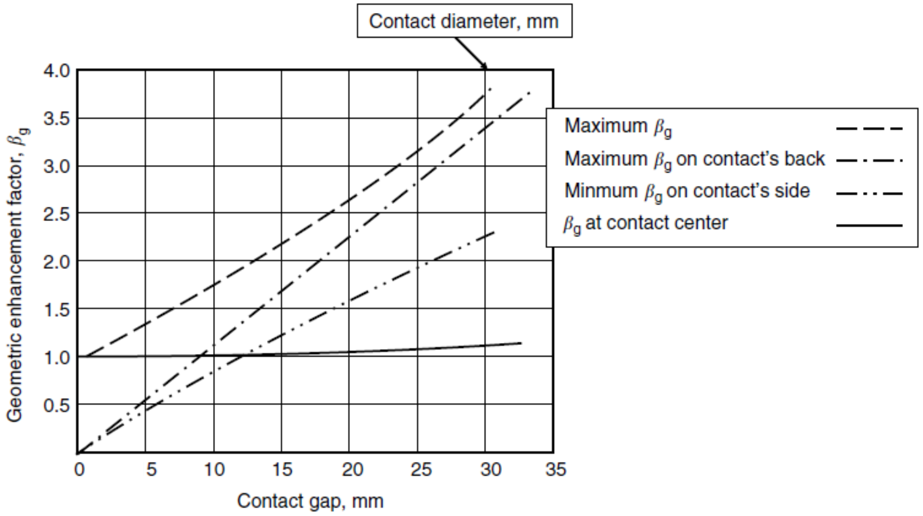


A comparison of ac spark conditioning and current conditioning using Cu–Cr contacts

4.INTERNAL VACUUM INTERRUPTER DESIGN

Control of the geometric enhancement factor ***(βg)***





The geometric enhancement factors for four places on the contact surface for the contact structure as a function of contact separation .

4.INTERNAL VACUUM INTERRUPTER DESIGN

$$E_g\ (8\ \text{mm}) = \beta_g(8\ \text{mm}) \times [110 \times 10^3]/[8 \times 10^{-3}]$$

$$E_g\ (8\ \text{mm}) = 1.6 \times [110 \times 10^3]/[8 \times 10^{-3}] = 2.2 \times 10^7\ \text{V m}^{-1}$$

Calculate the BIL voltage that can be withstood at larger contact gaps

$$U(d) = E_g(8\ \text{mm})[d \times 10^{-3}]/\beta_g(d)$$

$$U(d) = 2.2 \times 10^4 d/\beta_g(d).$$

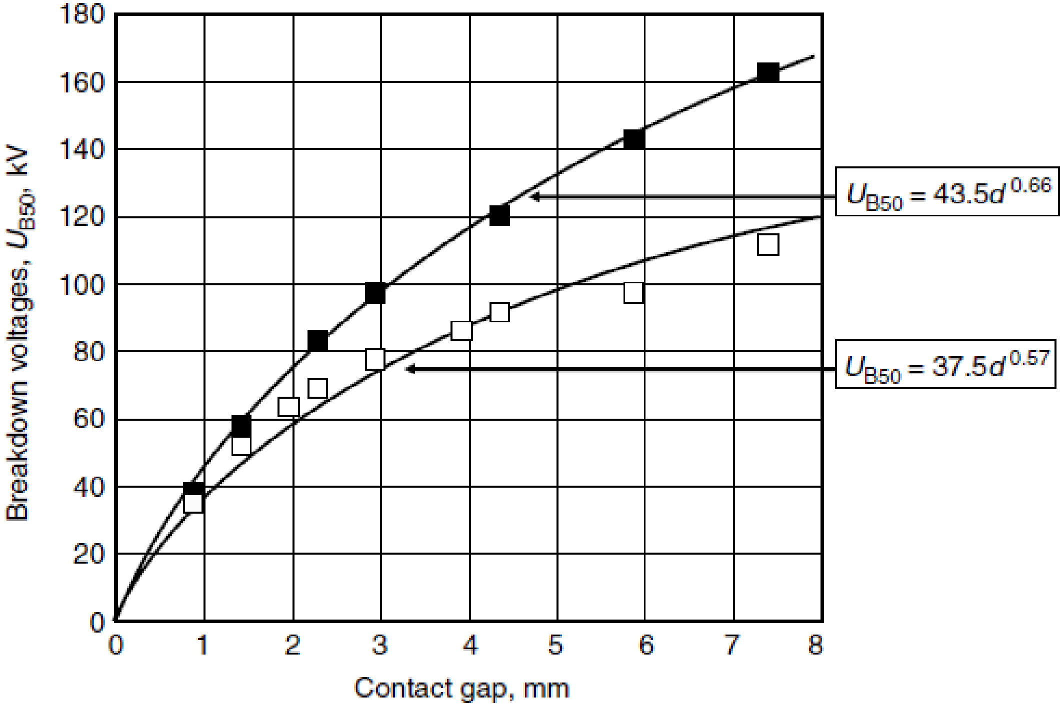
TABLE 1.15

BIL Withstand Voltage for Increasing Contact Spacing for the Contact and Shield Structure Shown in Figure 1.96

Contact spacing (mm)	Maximum $\beta_g(d)$ from Figure 1.98	$U(d)$ kV, from Equation 1.88
8	1.6	110
10	1.75	126
11	1.8	134
12	1.9	139
15	2.2	150
20	2.7	163

4.INTERNAL VACUUM INTERRUPTER DESIGN

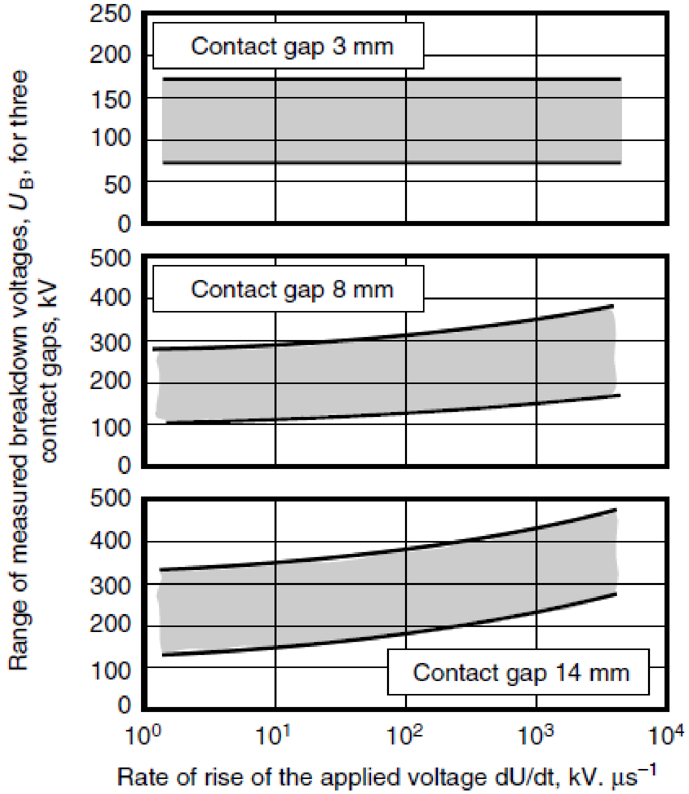
Breakdown of multiple vacuum interrupters in series for contact gaps greater than 2 mm



The breakdown voltage U_B
(1) as a function of contact gap d for a single-vacuum interrupter.
(2) as a function of contact gap d for three vacuum interrupters in series.

4.INTERNAL VACUUM INTERRUPTER DESIGN

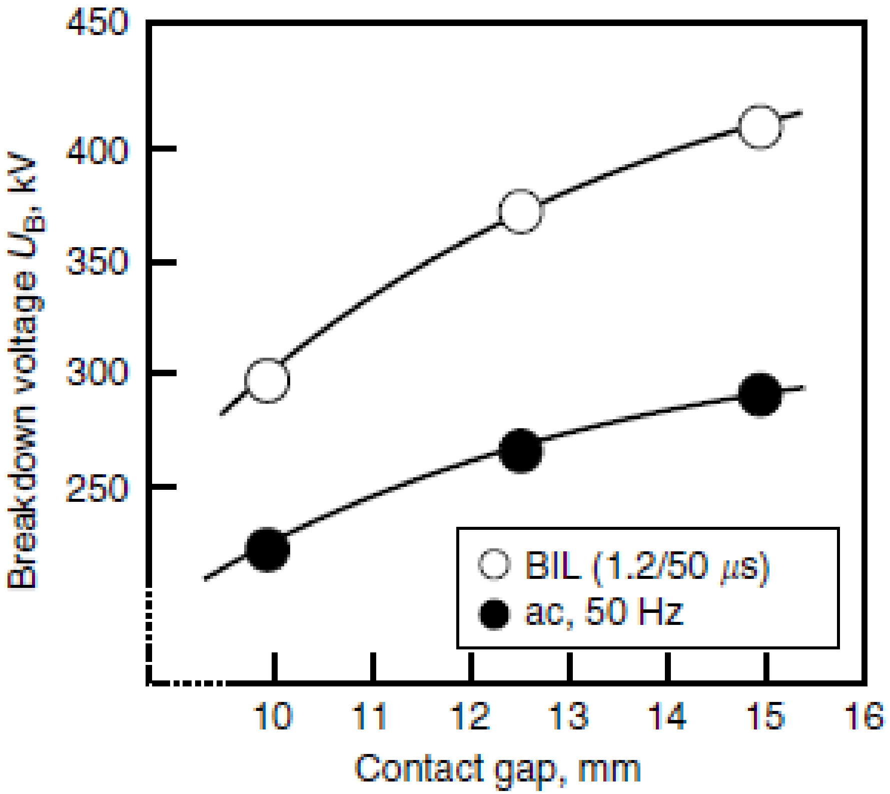
Voltage wave sharps and vacuum breakdown in vacuum interrupter



The effect on vacuum breakdown voltage of the rate of rise of that voltage

4.INTERNAL VACUUM INTERRUPTER DESIGN

Voltage wave sharps and vacuum breakdown in vacuum interrupter



4.INTERNAL VACUUM INTERRUPTER DESIGN

Testing for high altitude

$$U_B = 2440\left(\frac{293pd}{T}\right) + 61\left(\frac{293pd}{T}\right)^{1/2}$$

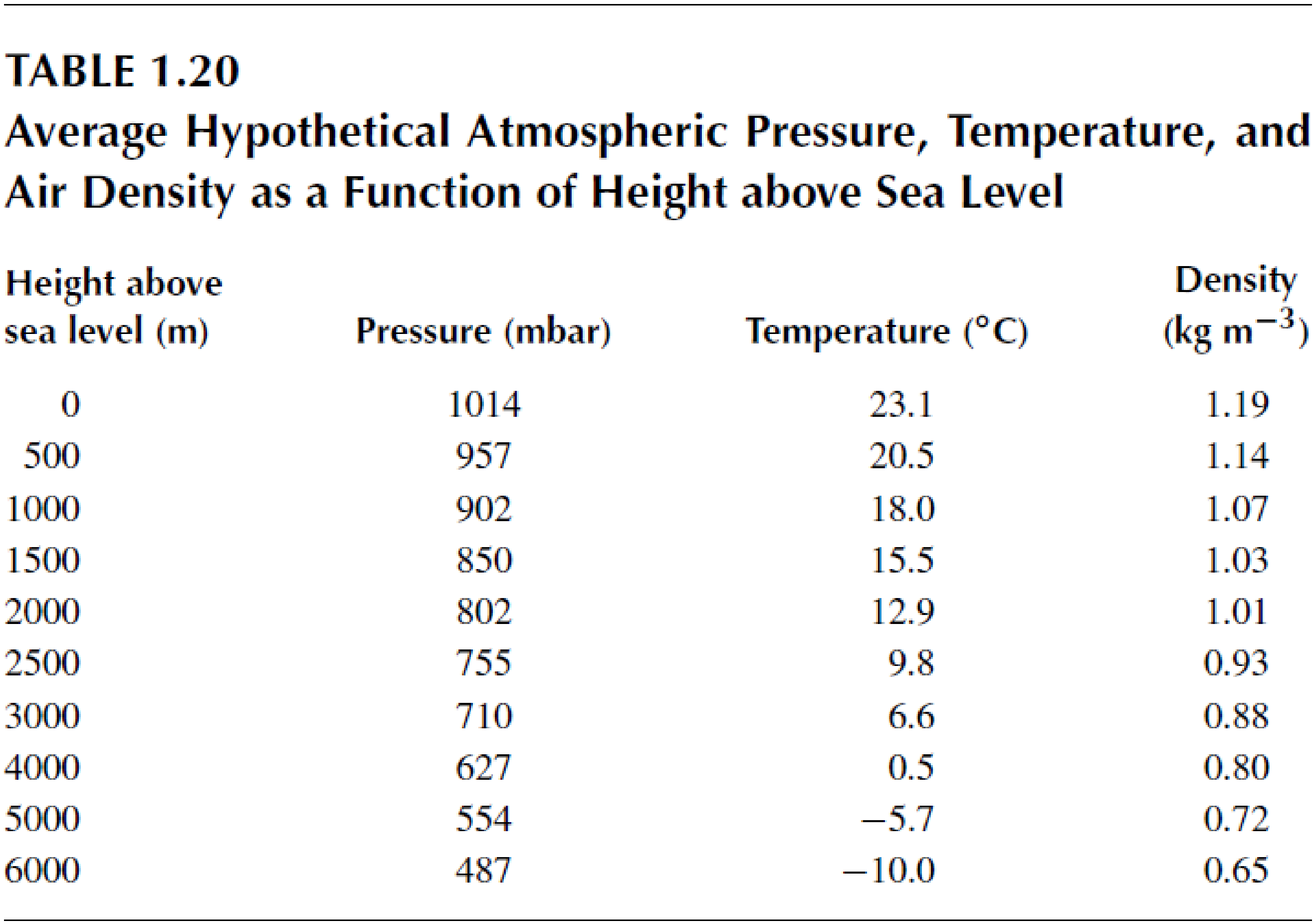


TABLE 1.20

Average Hypothetical Atmospheric Pressure, Temperature, and Air Density as a Function of Height above Sea Level

Height above sea level (m)	Pressure (mbar)	Temperature (°C)	Density (kg m^{-3})
0	1014	23.1	1.19
500	957	20.5	1.14
1000	902	18.0	1.07
1500	850	15.5	1.03
2000	802	12.9	1.01
2500	755	9.8	0.93
3000	710	6.6	0.88
4000	627	0.5	0.80
5000	554	−5.7	0.72
6000	487	−10.0	0.65

4.INTERNAL VACUUM INTERRUPTER DESIGN

Right-hand side of Pashcen’s curve

$$U_B = 2440\left(\frac{293pd}{T}\right) + 61\left(\frac{293pd}{T}\right)^{1/2}$$

T- absolute temperature in degrees Kelvin
P- atmospheres
d- breakdown gap (meter)

For d=10mm
U_B at sea level/U_B at 5000m=1.56

HAPPY IS THE PERSON WHO COULD SEARCH OUT THE CAUSES OF THINGS.