Vacuum 101

Prof. Leslie T. Falkingham PhD

Vacuum Interrupters Limited

Falkingham@vil.org.uk

Vacuum 101

(Everything you ever wanted to know about Vacuum Switching but were too afraid to ask!)

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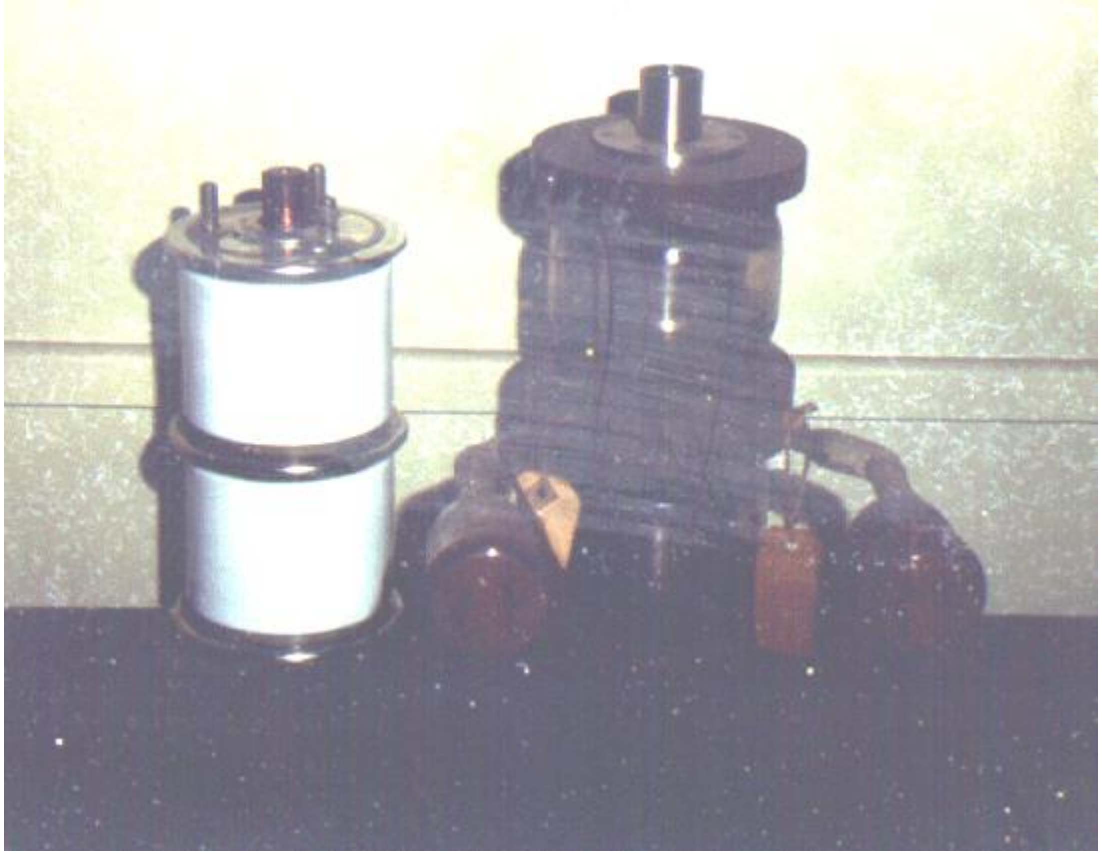
History: Origins



The world's first contrate contact vacuum interrupter prototype (right) built by Dr M. P. Reece in 1966. The Interrupter cleared 16kA @12kV. It still has vacuum and is now in the Science Museum, London.

History: Origins

The Question; Why did anyone want to use vacuum to interrupt current at high voltages?

The Answer; This is not so simple, and we need to delve into the physics and start by asking another question:

"What is a vacuum?"

What is a Vacuum?

Oxford English Dictionary Definition:

"Vacuum is space entirely devoid of matter"

(The word stems from the Latin adjective vacuus meaning "vacant" or "void")

Or, more interesting to us;

"A space or container from which the air has been completely or partly removed"

What is a Vacuum?

"A space or container from which the air has been completely or partly removed"

The point is that a true "hard" vacuum does not exist anywhere in the universe. Always there are some molecules left.

So the question becomes;

"What level of vacuum do we actually require?"

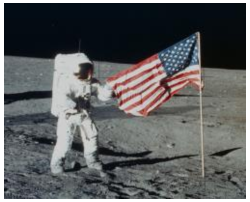
What is a Vacuum?

1,000 mbar Atmosphere

800 mbar "Vacuum" Cleaner

3×10^{-4} mbar 100 km (62 mi) altitude (Edge of Space)

1×10^{-11} mbar Surface of the Moon



$1\text{x}10^{-15}$ mbar Interplanetary Space

$1\text{x}10^{-16}$ mbar Interstellar (Deep Space)

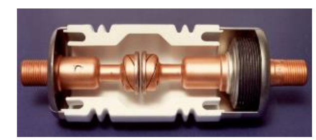
What is a Vacuum?

1,000 mbar — Atmosphere

800 mbar — "Vacuum" Cleaner

3×10^{-4} mbar — 100 km (62 mi) altitude

$1\text{x}10^{-6}$ mbar — Vacuum Interrupter



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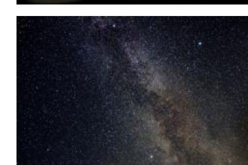


What is a Vacuum?

The Question;

"Why did anyone want to use vacuum to interrupt current at high voltages?"

The Answer; Also not so simple, and we need to delve into the physics and start by asking another question:

"What level of vacuum do we require?"

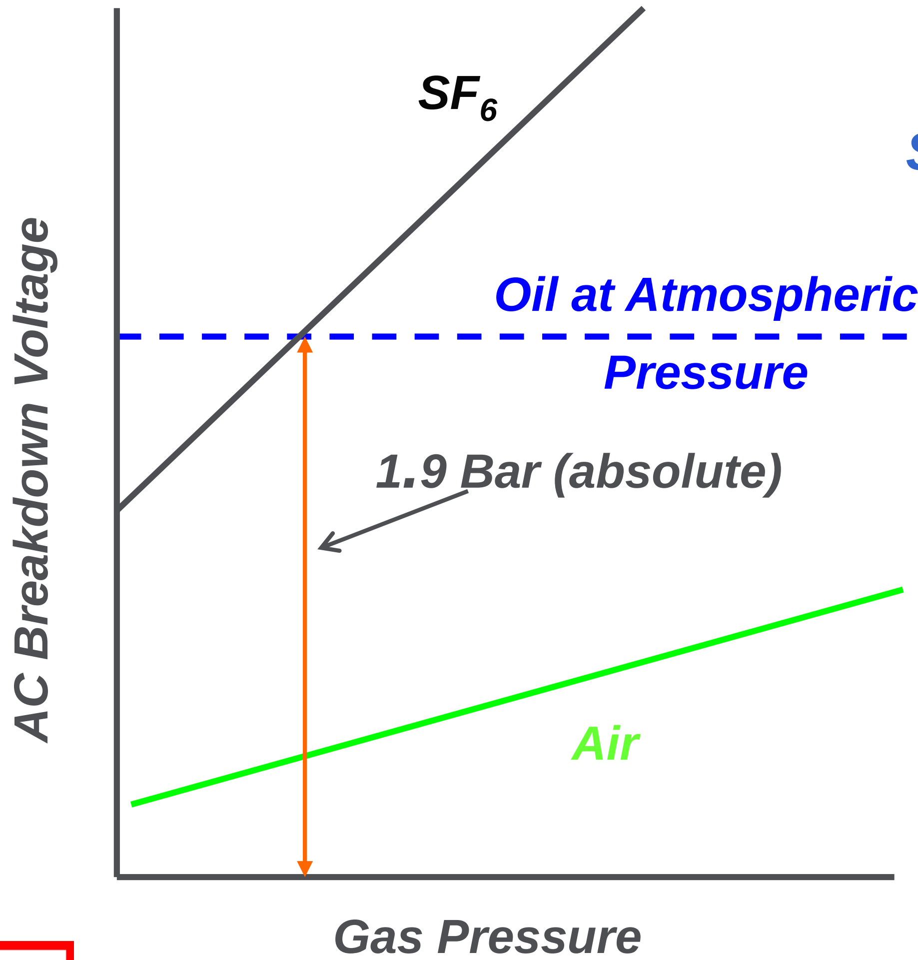
What is a Vacuum?

"What level of vacuum do we require?"

For our purposes a vacuum is a device with a pressure of around $1x10^{-6}$mbar

"Why $1x10^{-6}$ mbar?"

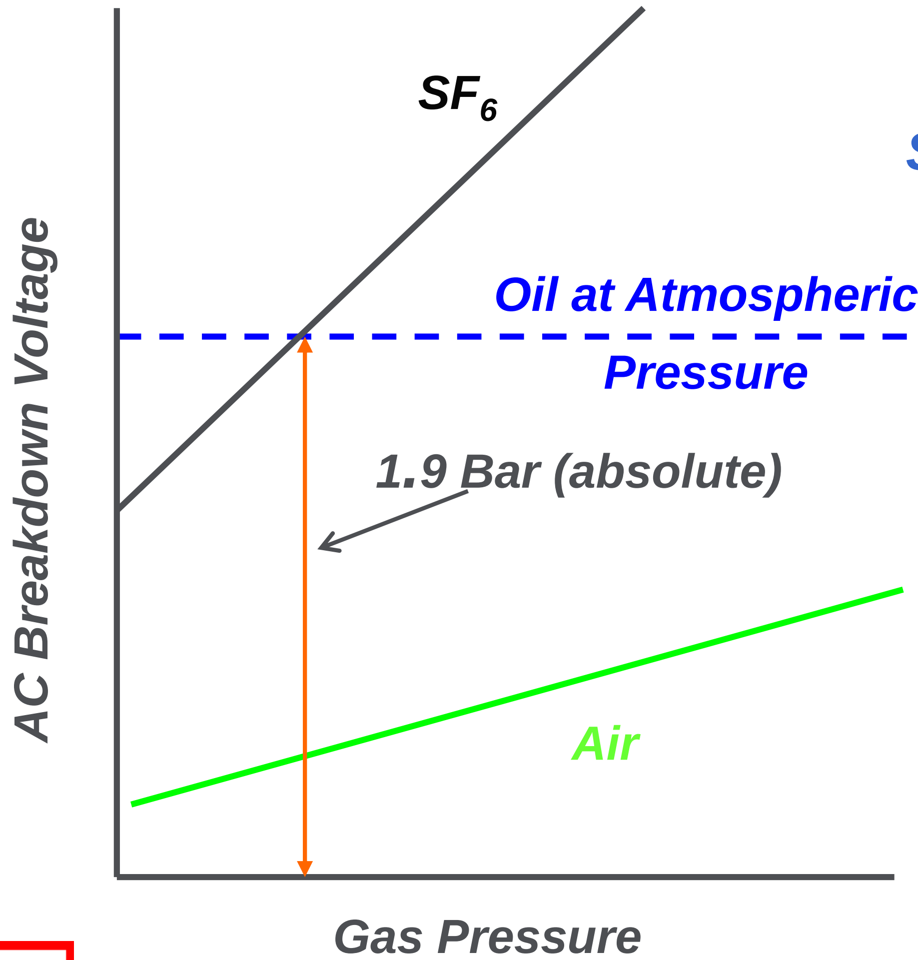
Properties of Insulators



SF_6 has the same dielectric withstand as insulating oil at a gauge pressure of 0.9bar (1.9bar absolute)

Air	*30kV/cm*
Oil	*120kV/cm*
SF_6@1.9bar	*120kV/cm*
Vacuum	*380kV/cm*

Properties of Insulators



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Vacuum Physics

Gas Pressure & Insulation:

As you increase gas pressure the dielectric strength increases

Vacuum Physics

Gas Pressure & Insulation:

As you increase gas pressure the dielectric strength increases

So how does vacuum have such a high dielectric strength?

Vacuum Physics

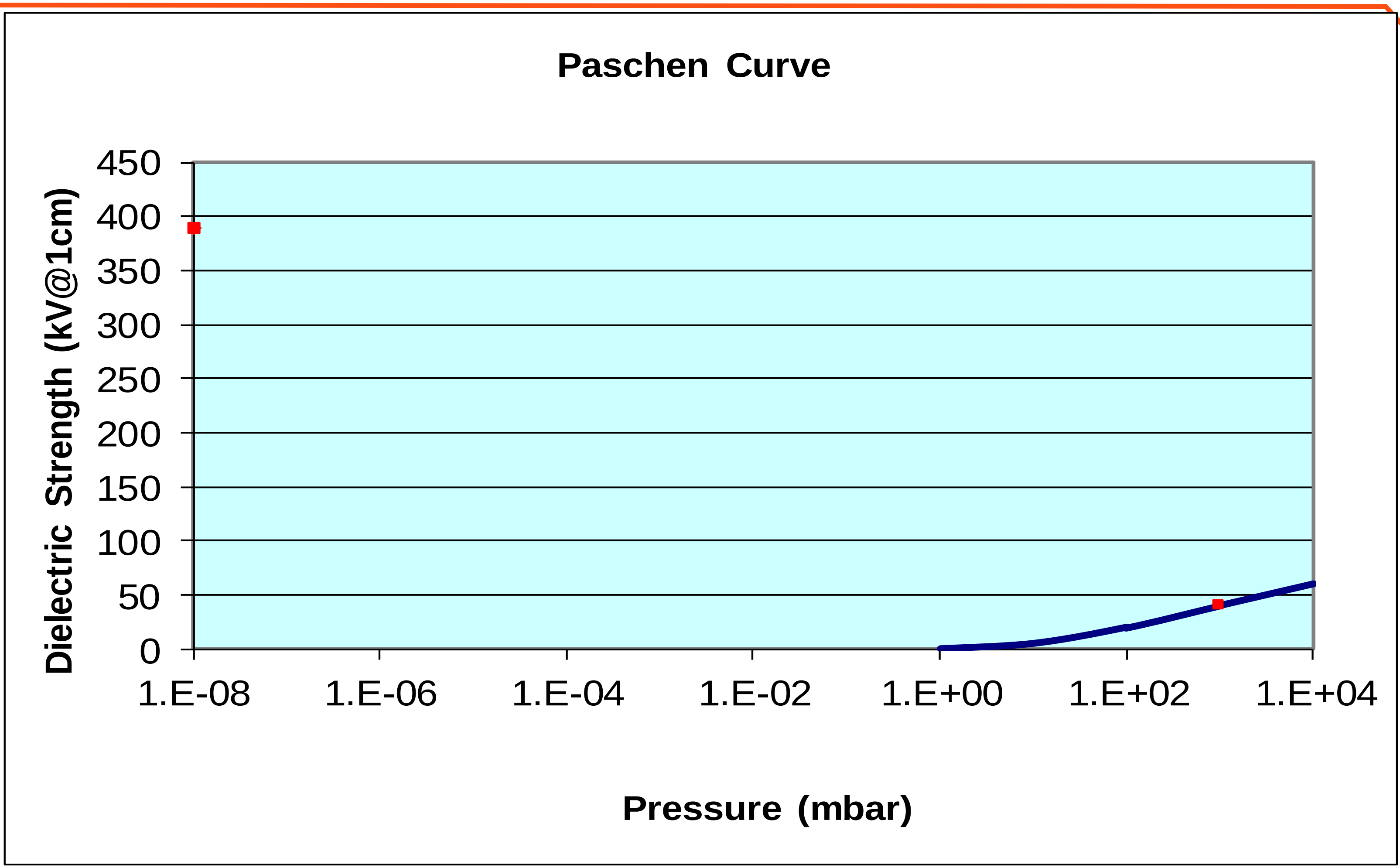
Gas Pressure & Insulation:

As you increase gas pressure the dielectric strength increases

So how does vacuum have such a high dielectric strength?

Clearly the relationship between pressure and dielectric strength is non-linear

Vacuum Physics

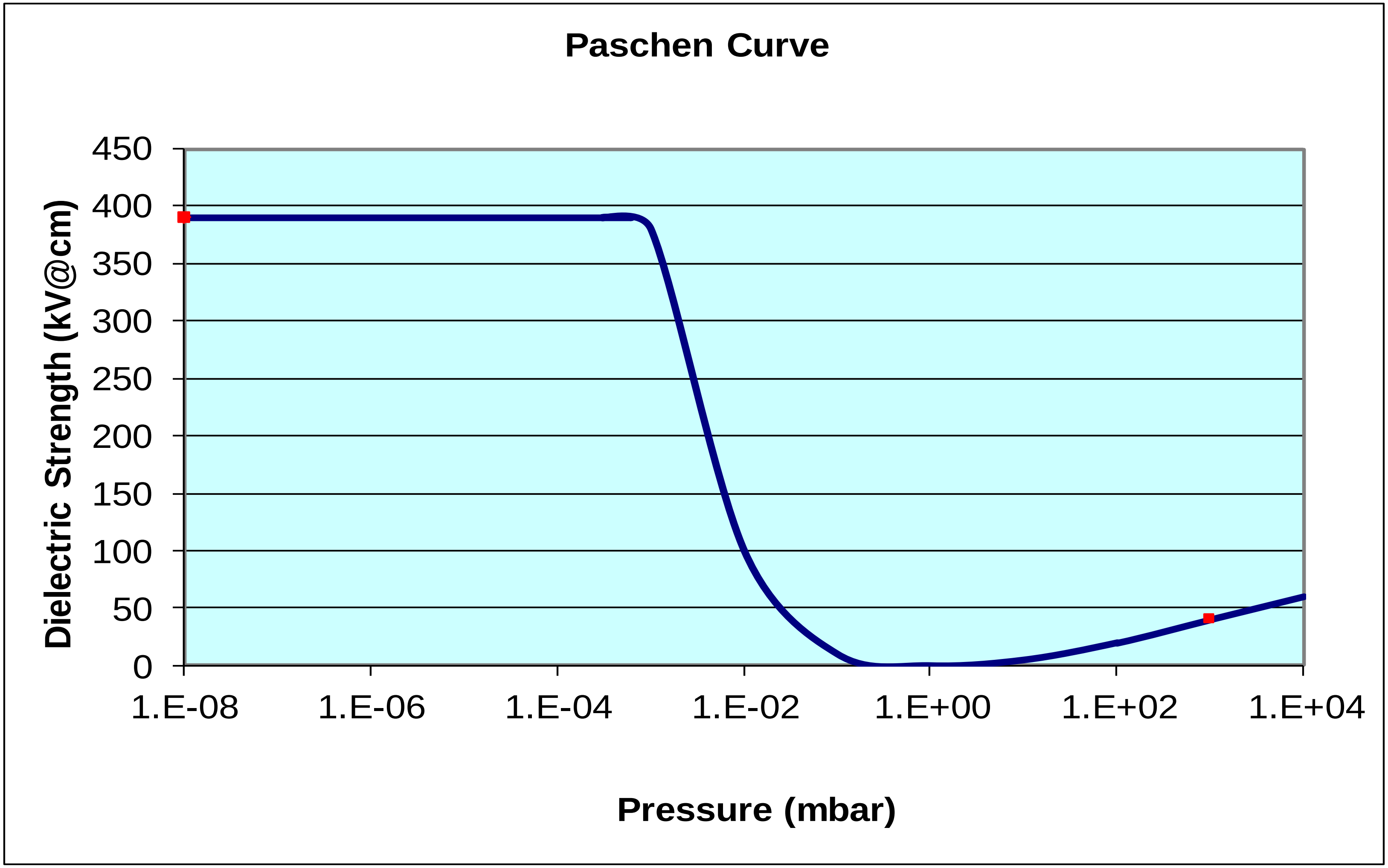


Vacuum Physics

As pressure is reduced from atmospheric, the dielectric strength of a fixed vacuum gap varies quite strangely, following the Paschen Curve

This is extremely non linear and is fundamental to the design and operation of vacuum interrupters

Vacuum Physics



Vacuum Physics

The three "zones" of the Paschen curve are dominated by different effects;

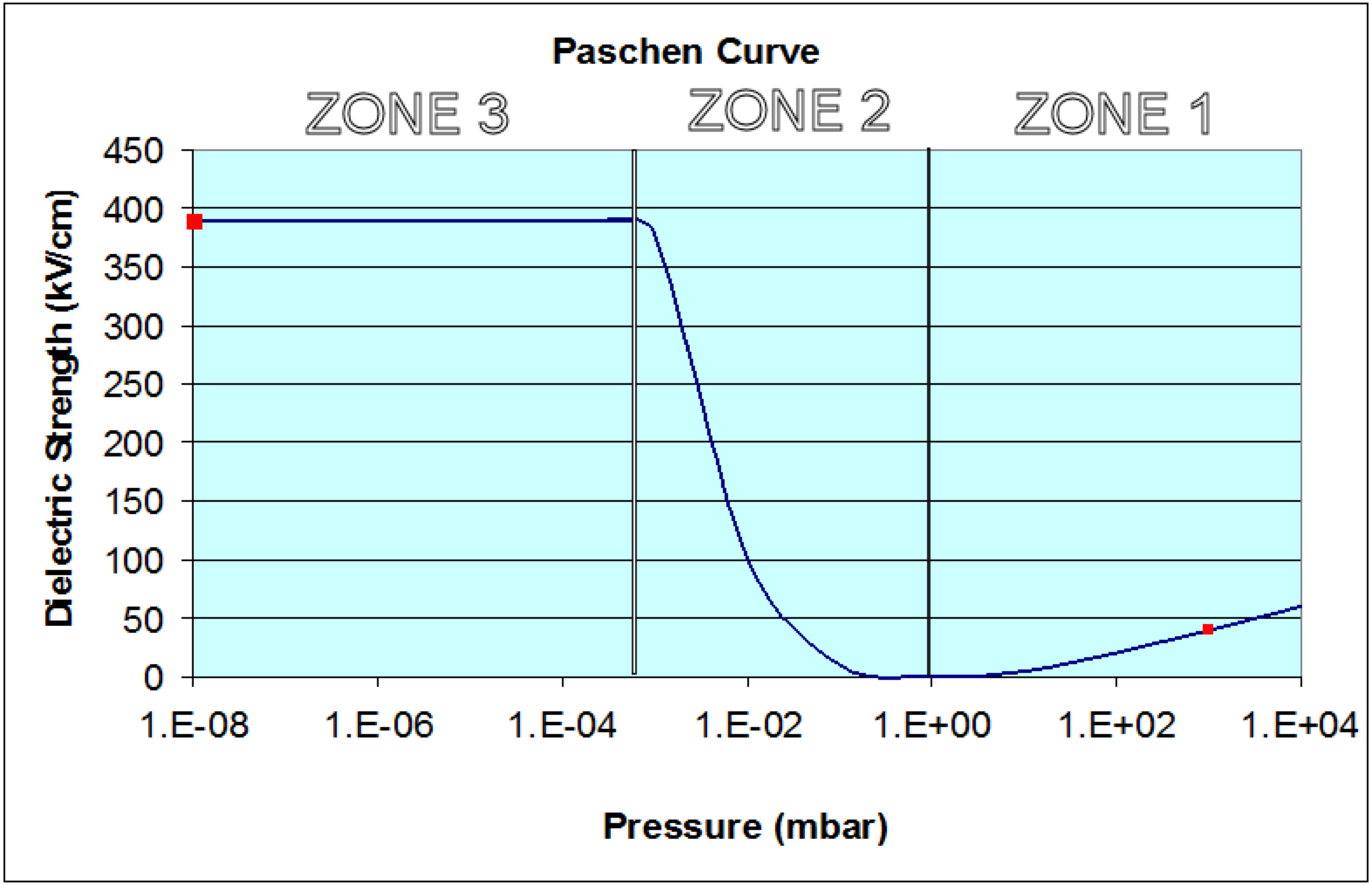
From right to left;

Zone 1: High pressure

Zone 2: Transition pressure

Zone 3: Vacuum pressure

Vacuum Physics



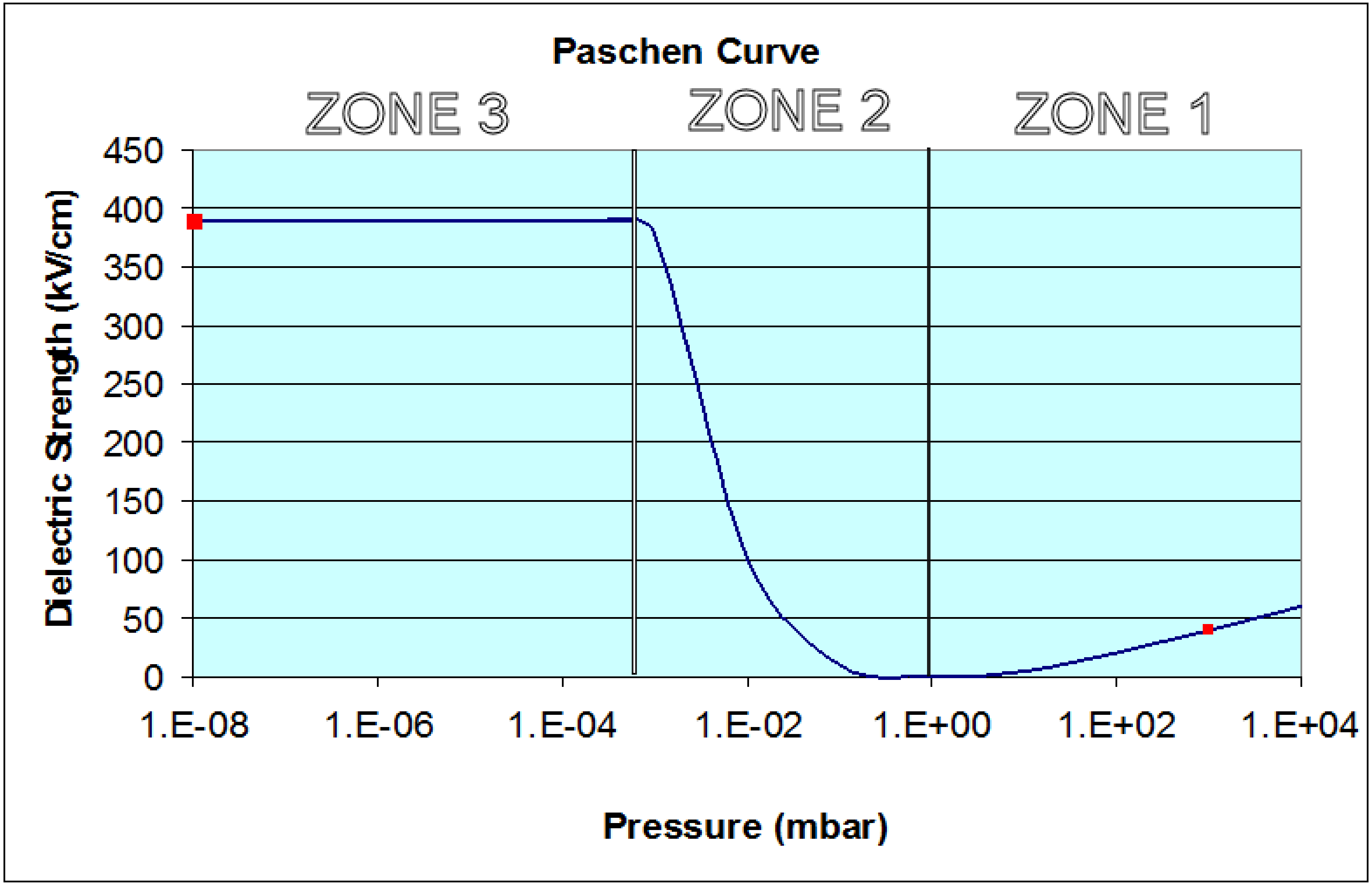
Vacuum Physics

Zone 1: High pressure ***- as the gas pressure decreases it becomes easier for electrons hitching a ride to pass from one electrode to the other – decreasing dielectric strength***

Zone 2: Transition pressure ***– as pressure continues to decrease a lack of gas molecules to act as "taxi's" leads to increasing dielectric strength***

Zone 3: Vacuum pressure ***–once there are no "taxi's" the electrons decide to walk, and decreasing the pressure further has no effect***

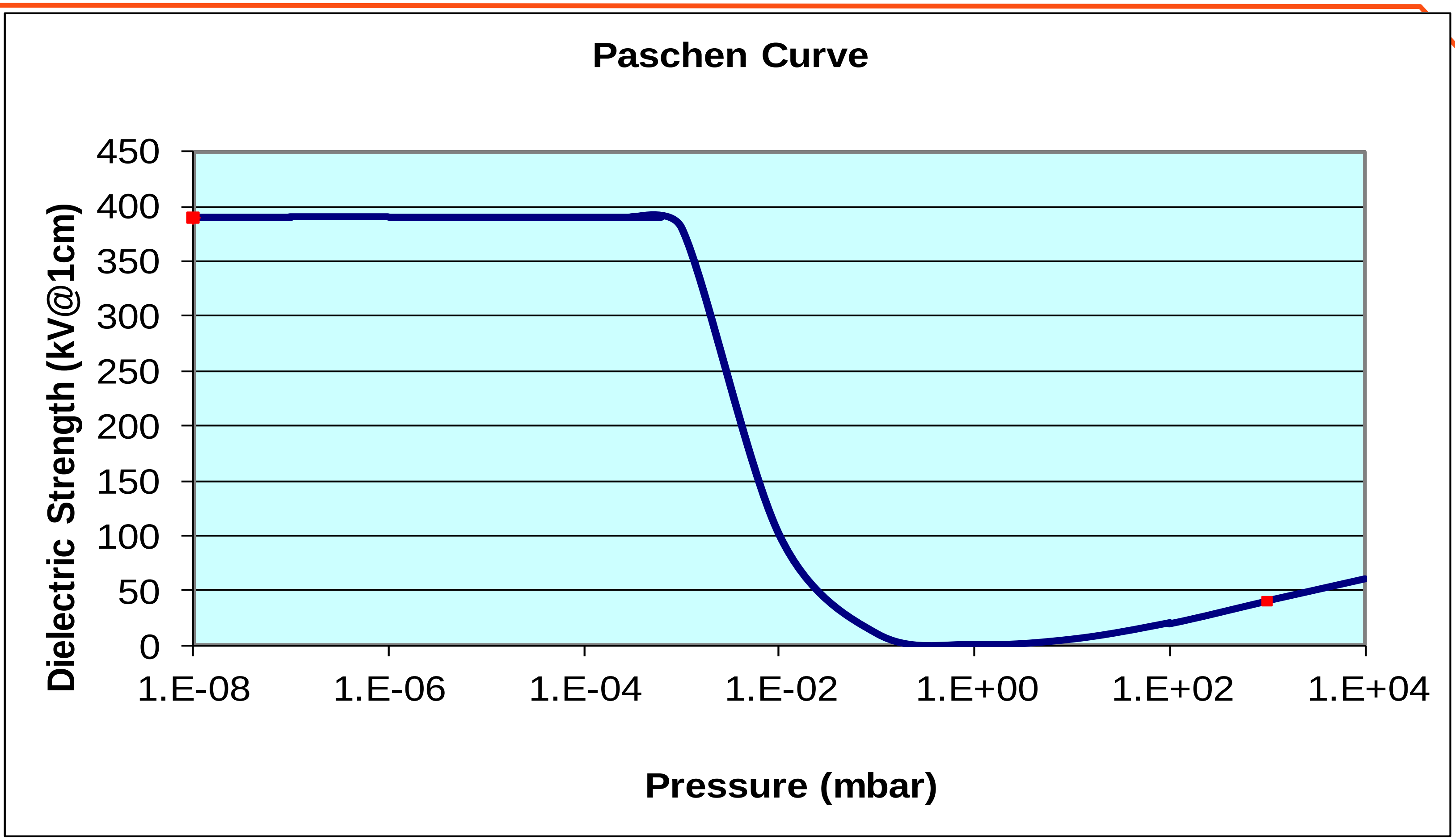
Vacuum Physics



Vacuum Physics

The Paschen curve totally dominates the vacuum interrupter technology and is the source of almost all that is both positive and negative about vacuum interrupters

Vacuum Physics



Vacuum Physics

So what does this all mean?

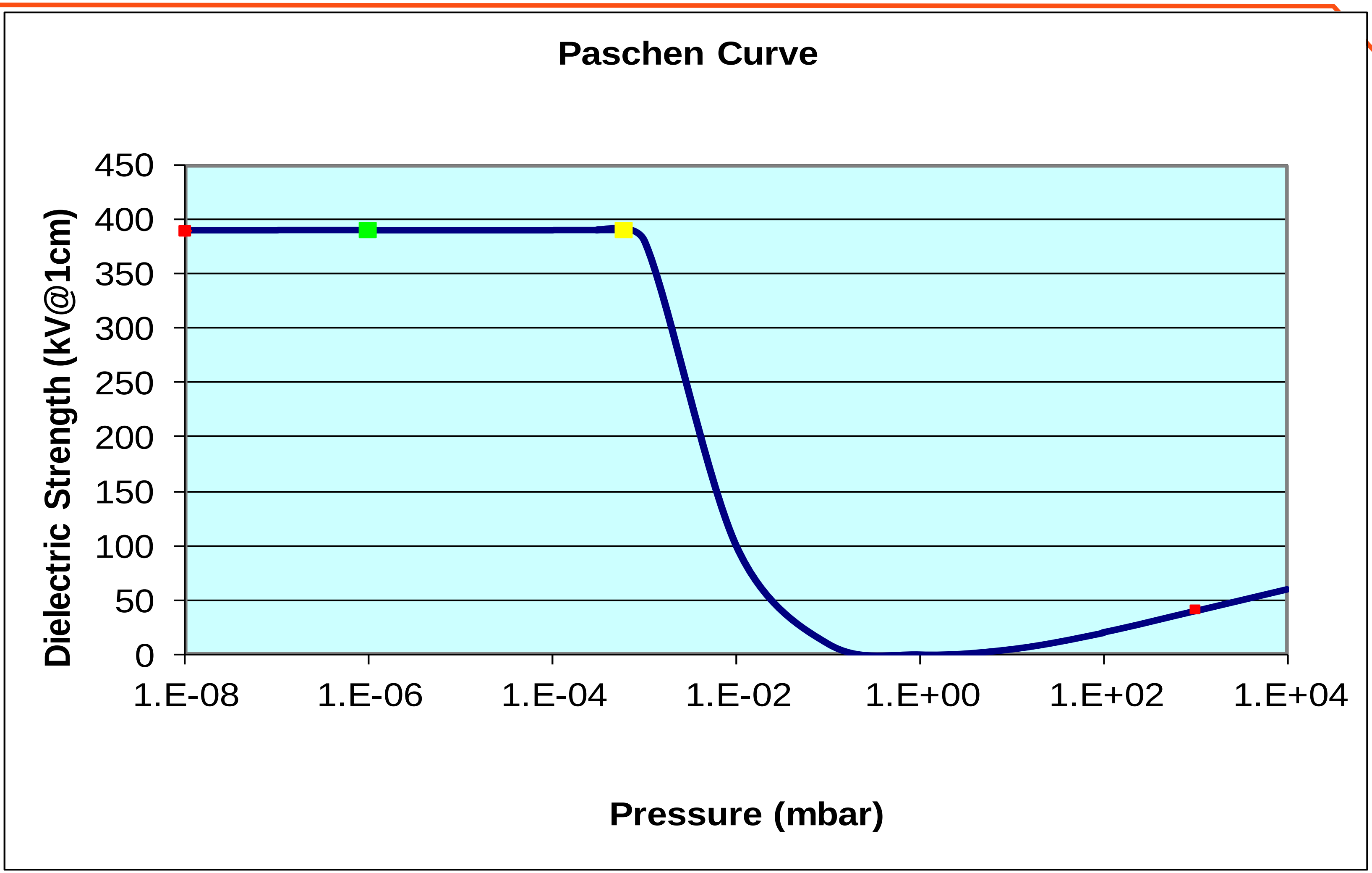
Firstly we can answer the original question:

"What level of vacuum do we require?"

Clearly it needs <u>to be less than c. 5x10^{-3}mbar</u>

Also we see that a lower (better) vacuum than this actually has no effect

Vacuum Physics



Vacuum Physics

But we have still not answered the question

"Why $1x10^{-6}$ mbar?"

This is actually much lower than the $5x10^{-3}$ we said that we needed.

The reason is to do with the life expectancy of vacuum interrupters (VI).

Vacuum Physics

But we have still not answered the question

"Why $1x10^{-6}$ mbar?"

The reason is to do with the life expectancy of vacuum interrupters (VI).

VI are sealed for life vacuum devices. That means that they are sealed with the vacuum inside and do not have a pump connected when in service. So they must maintain the vacuum for 20 years or more

Vacuum Physics

Manufacturers must ensure that each VI is both hermetically sealed and also that it does not contain sources of gasses which would evolve within the sealed device and ruin the vacuum.

Gas entering the VI from outside is termed a "Real Leak"

Gas evolved from inside is termed a "Virtual Leak"

Vacuum Physics

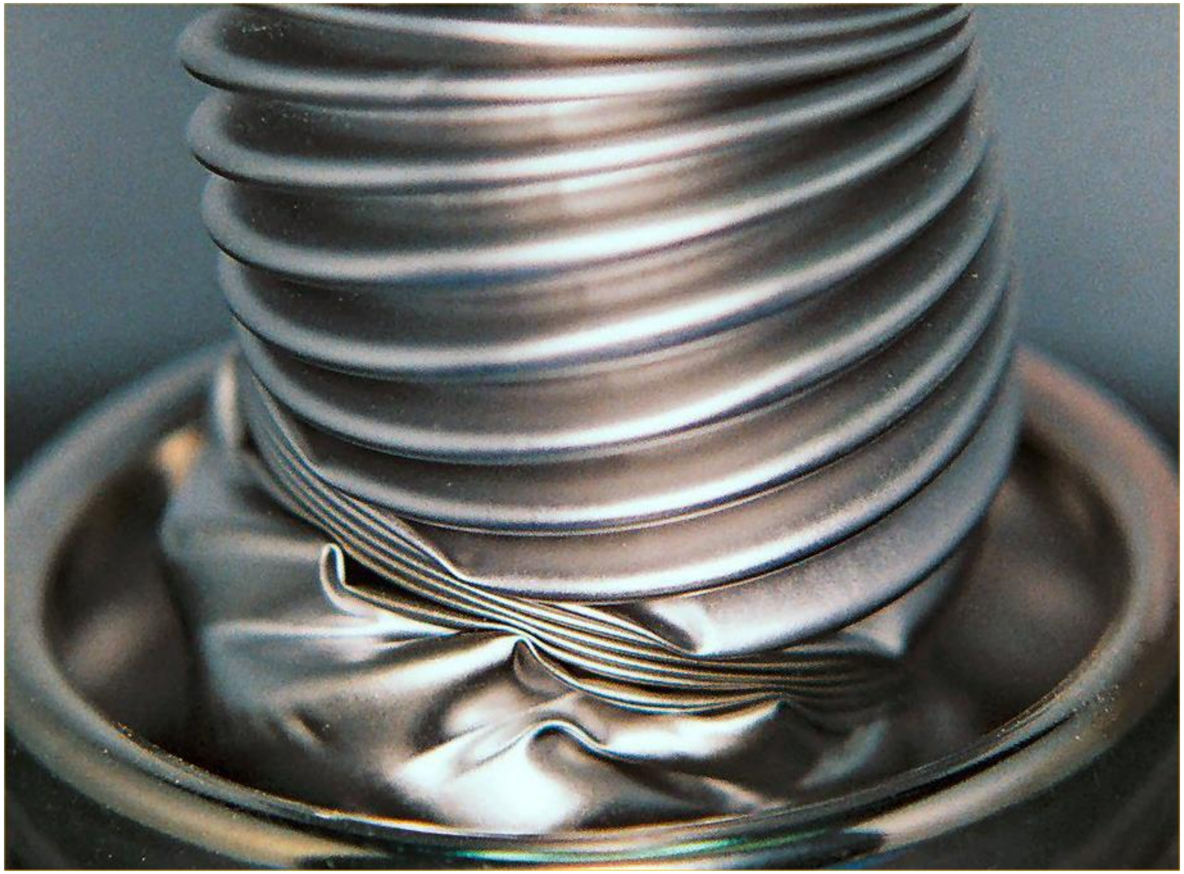
Real Leaks:

A Real Leak is either due to a defect in manufacture or damage which occurred after seal off

In Manufacture we need to ensure that the VI were properly made

How we deal with damage after manufacture will be dealt with later

Mechanical Damage - Twisted Bellows



The bellows is the mechanically weakest part of the VI and is protected in different ways by different manufacturers

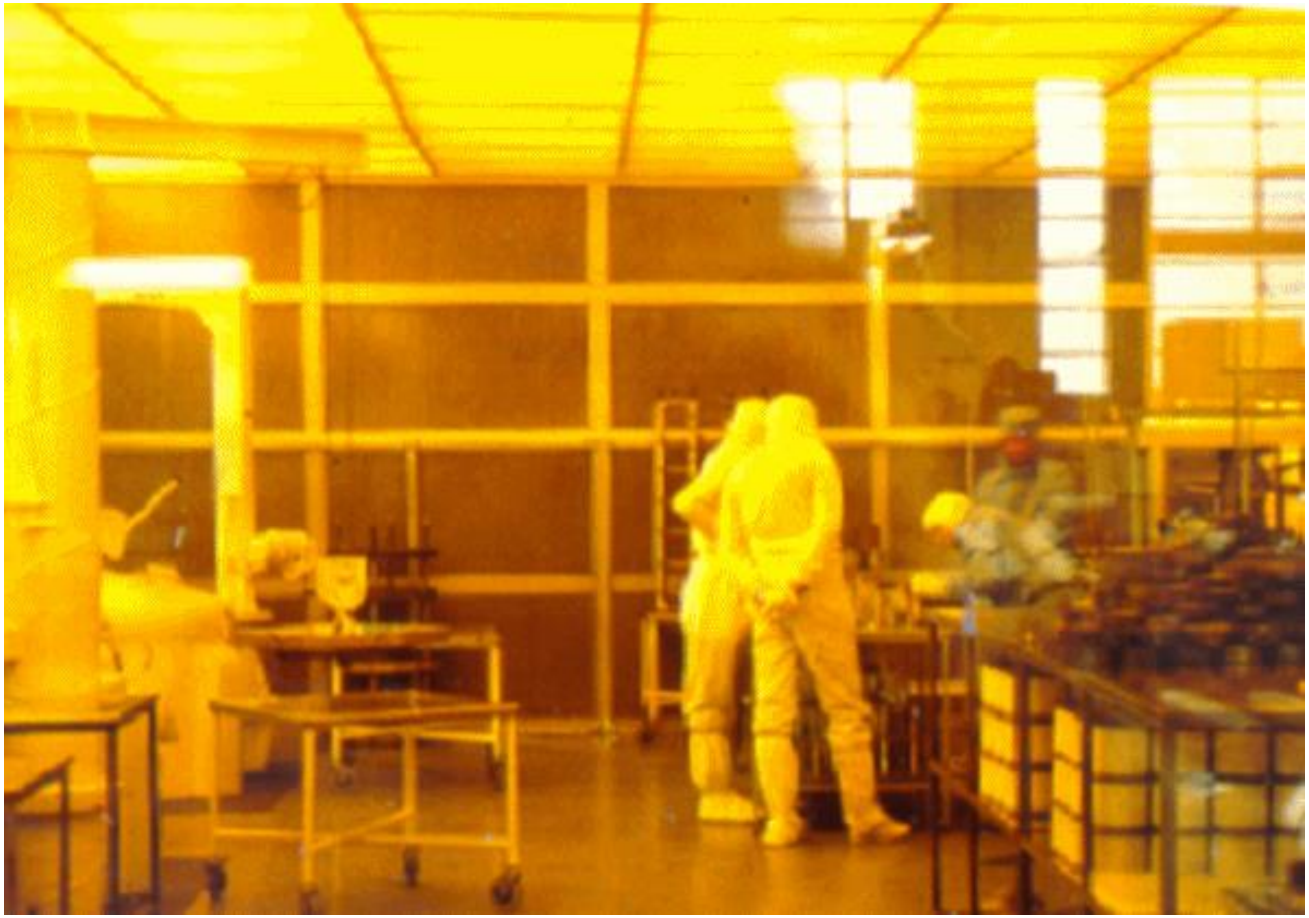
– this VI lost vacuum in service due to the bellows being twisted during installation of the VI in the circuit breaker which seriously reduced its mechanical life

Vacuum Physics

Virtual Leaks:

A Virtual Leak can only be created during manufacture, but can continue to evolve gas for the life of the VI, and is due to wrong/defective materials, or contamination trapped within the VI

Clean Assembly



Vacuum Interrupter manufacture requires Clean Room assembly in order to reduce any contamination in the sealed for life devices and thereby reduce the reject rate

Main horizontal laminar flow clean room at VIL Finchley, London, 1978.
(Slimmer & younger Author second from left)

Vacuum Physics

Leak Determination:

In order to be sure that the VI will be good for its design vacuum life (normally at least 20 years), we need a system to detect both Real and Virtual Leaks

Leak determination is actually quite easy in principle for all pressure vessels. You measure the pressure (P) of a sealed device , wait a fixed period, and measure the pressure again.

Delta P will give you the leak rate.

Vacuum Physics

Leak Determination:

This principle also is used for vacuum devices.

You measure the pressure, wait a fixed period, and measure it again, and then check the leak rate against the design vacuum life.

However this poses the next question:

"How do you measure the vacuum level of a sealed Vacuum Interrupter?"

Vacuum Physics

"How do you measure the vacuum level of a sealed Vacuum Interrupter?"

Not so easy. We could fit a vacuum gauge to each VI. These are commercially available, and cost about the same as the present cost of a VI, leading to a significant cost increase for the breaker.

However it would meet demands from users to have a gauge fitted to the VI giving the actual pressure or a pressure warning, just like on gas breakers.

Vacuum Physics

But cost is not the real reason why we don‘t do this. Neither is size.

Vacuum Physics

The real reason we do not add a vacuum gauge is actually based on statistics.

MTTF Vacuum Interrupter - 44,000 VI years

MTTF Vacuum gauge – 100 gauge years?

If you fit a vacuum gauge then the MTTF of the system drops by 440x

So by fitting a gauge we would make the VI much less reliable, because if the gauge fails we then need to replace the VI and the gauge is much less reliable than the VI.

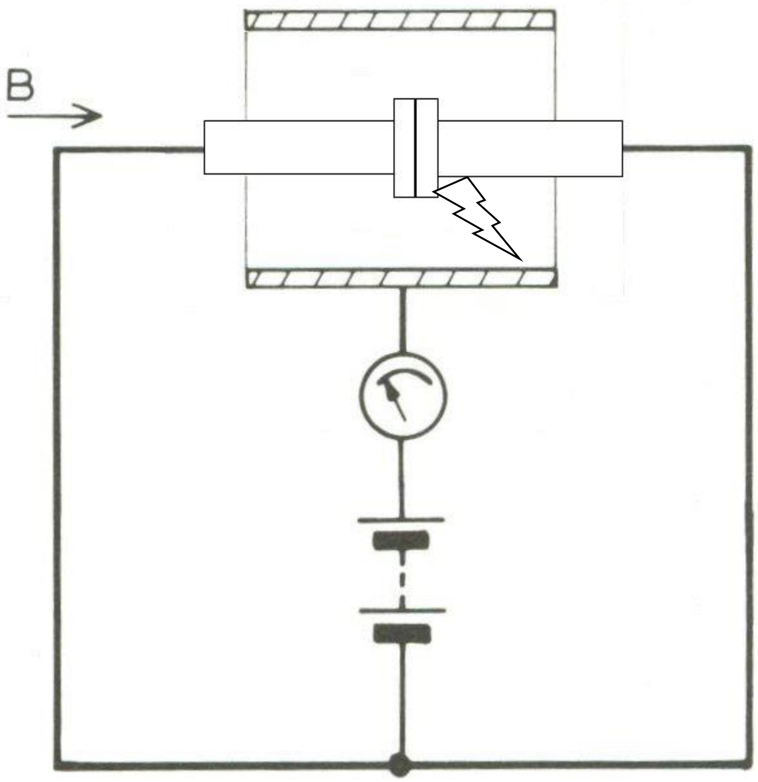
Vacuum Physics

So what we actually do is design the VI to be its own gauge!

We use what is known as a Penning or Inverse Magnetron gauge effect.

This uses the same effects as commercial gauges but without the need for an additional gauge!

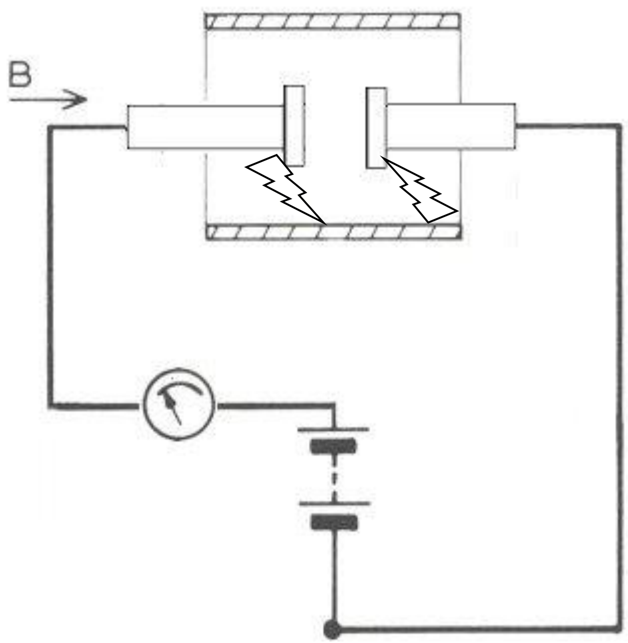
Pressure Measurement (Inverse Magnetron discharge)



This schematic shows the principle of operation of an Inverse Magnetron crossed field vacuum gauge (Magnetic Field Coil omitted)

A very small discharge occurs between the shield and the closed contacts, and the current carried is proportional to the pressure

Vacuum Physics



This schematic shows the special Pressure Measuring Machine for measuring the Vacuum within Sealed Vacuum Interrupters (Magnetic Field Coil omitted).

A very small discharge occurs between one of the contacts and the shield, and a second discharge then occurs from the shield to the other contact. Again the current carried is proportional to the pressure.

.

Vacuum Physics

V204 interrupter being loaded into the CUPE Pressure Measuring Machine. South Africa 1990's

This shows the operation of the special Pressure Measuring Machine for measuring the Vacuum within sealed Vacuum Interrupters.

This machine is used to establish the pressure and thereby the leak rate of every interrupter. As it is a true measurement of pressure, this technique monitors both Real Leaks and Virtual Leaks.

Determining the Storage Life (Vacuum Life).

- ***Leak Rate Calculation (storage period)***

  The Vacuum Life of vacuum interrupters is verified by means of a leak rate calculation using a number of vacuum measurements made over a fixed time period. This is performed on each vacuum interrupter before it is released for sale.

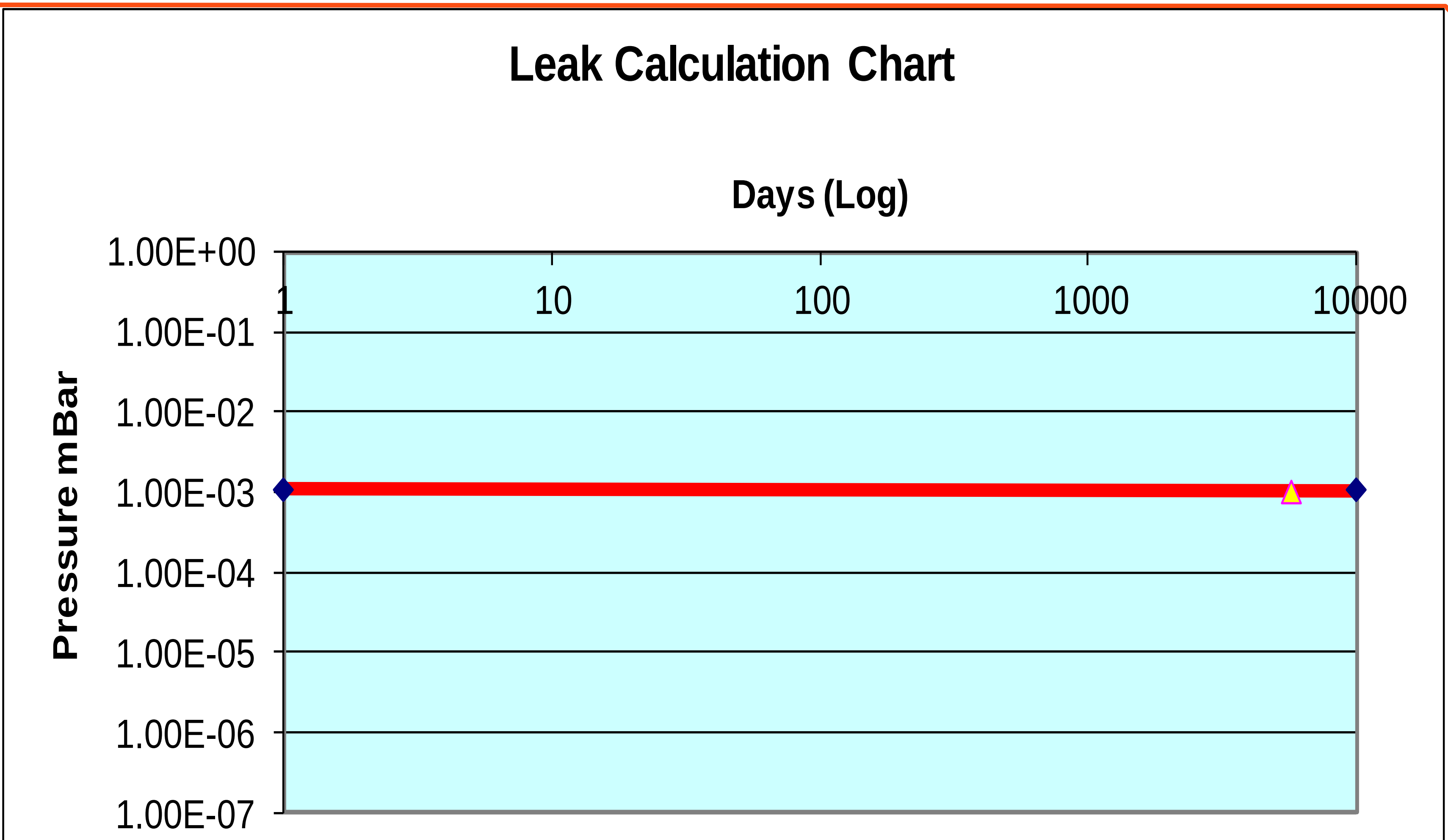
Determining the Storage Life (Vacuum Life).

- ***Leak Rate Calculation (storage period)***

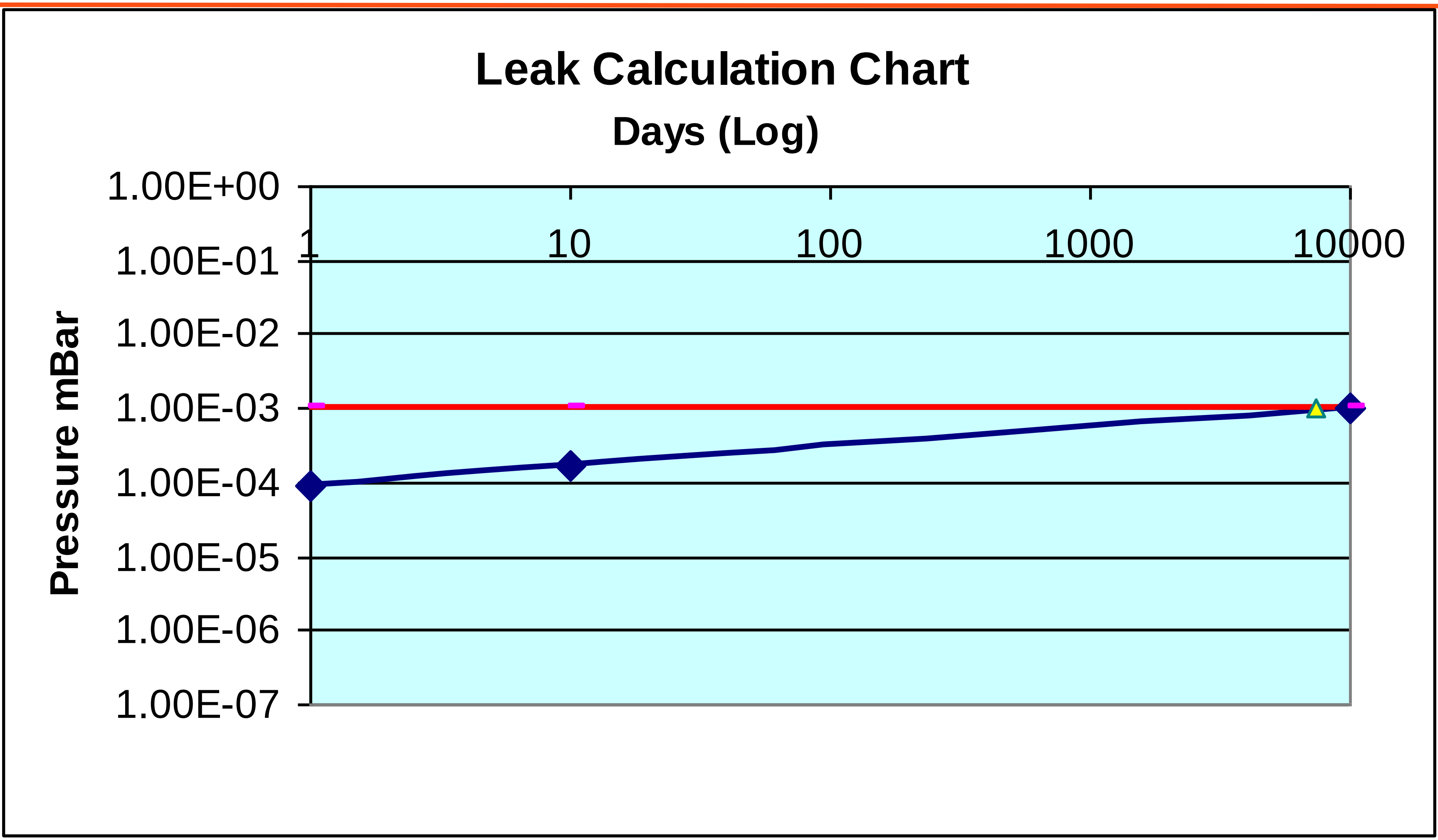
  So we measure the pressure, wait a fixed period, and measure it again. Then we calculate the leak rate, allowing for measurement resolution

  Simple, but there is a problem...

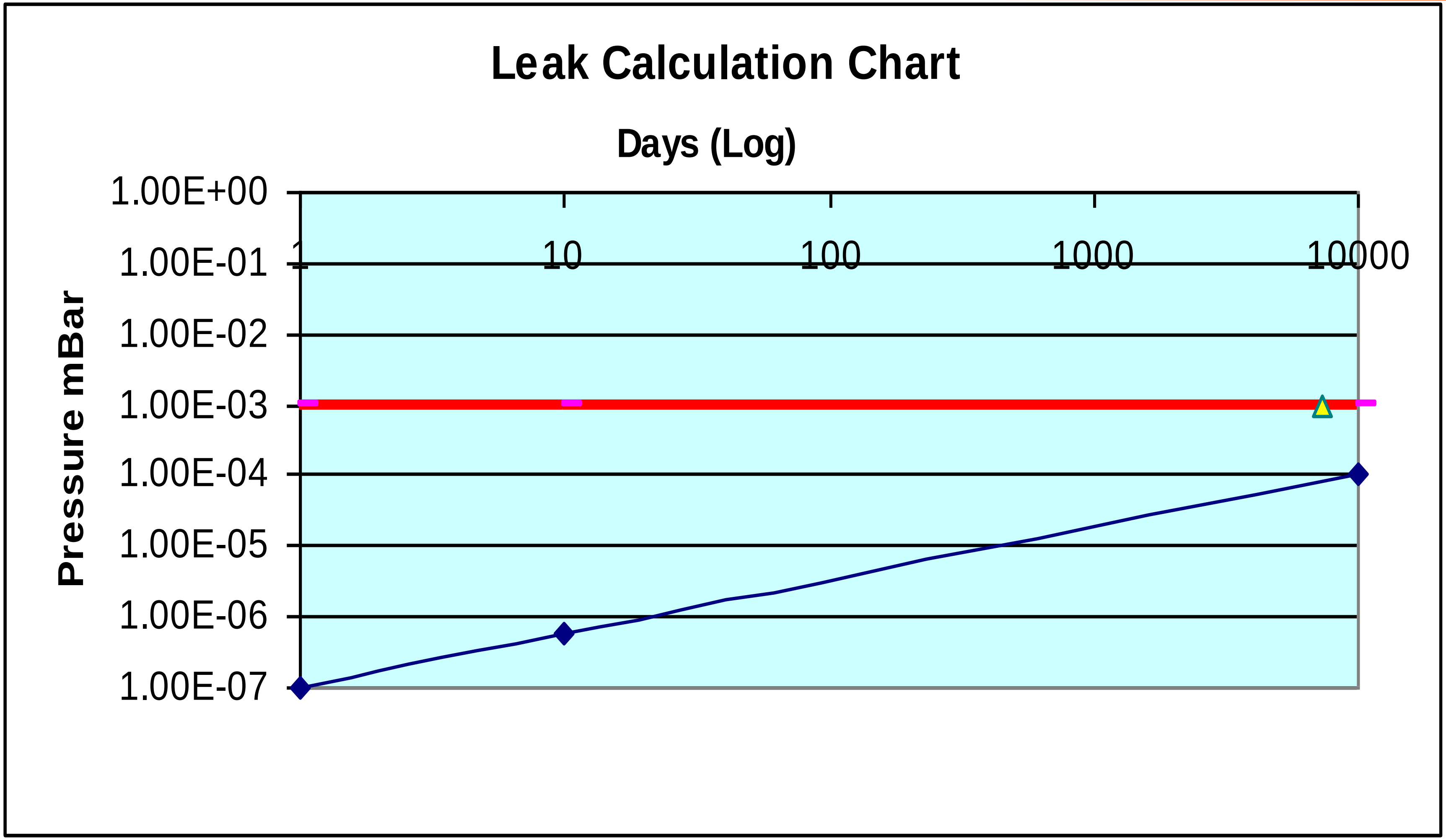
Vacuum Life Determination



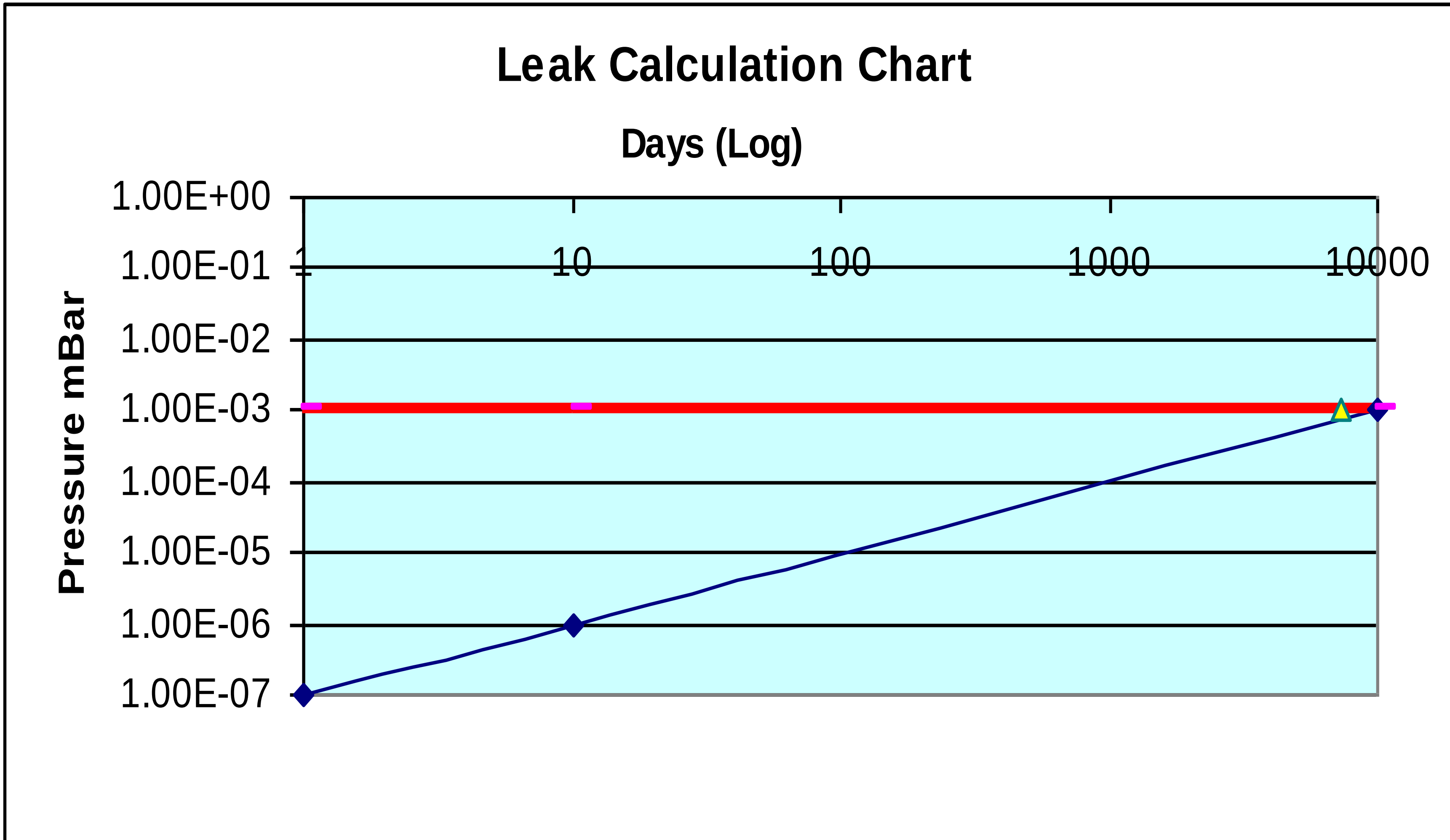
Vacuum Life Determination



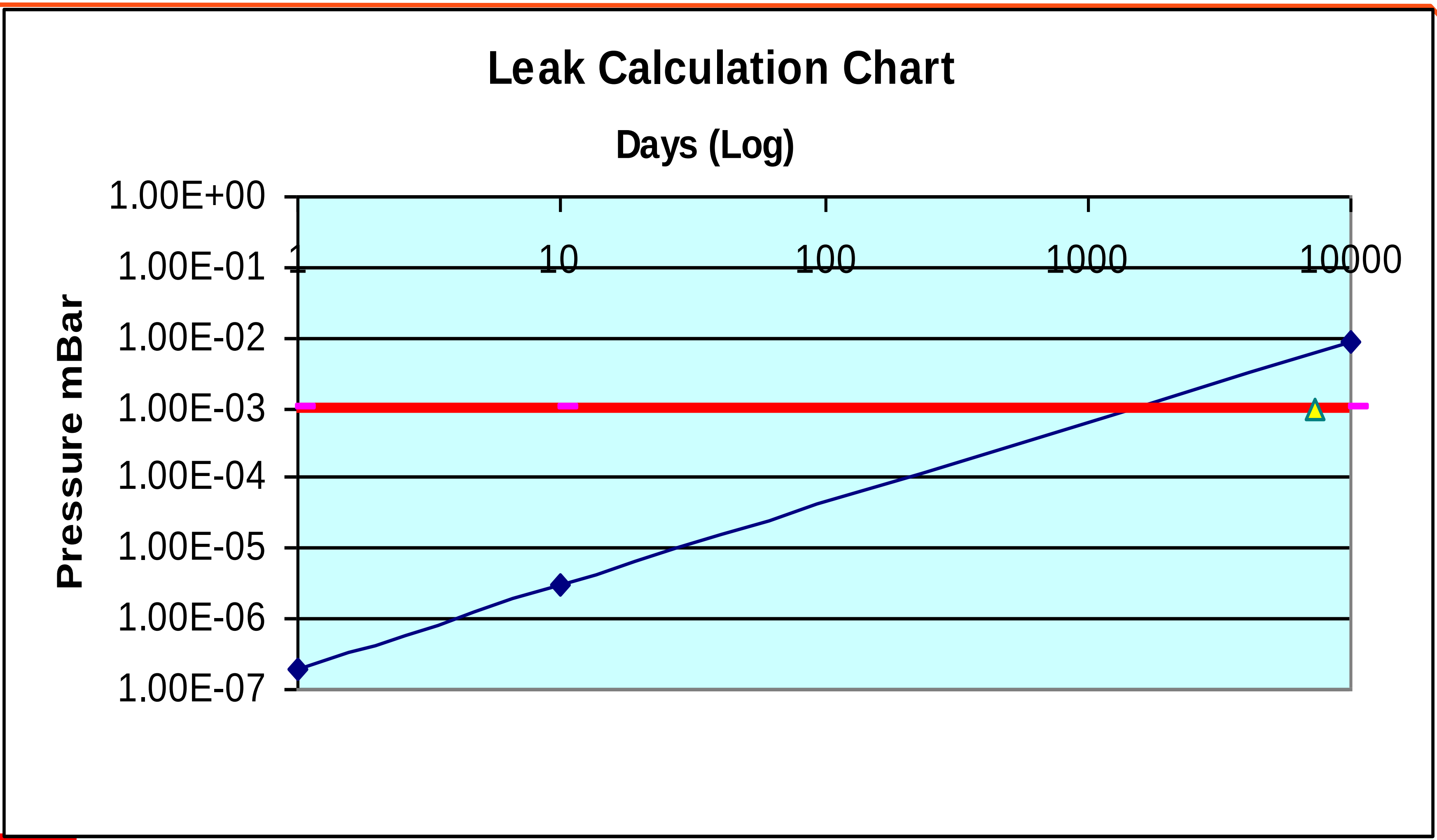
Vacuum Life Determination



Vacuum Life Determination



Vacuum Life Determination



Vacuum Physics

Put simply, If a leak is linear, i.e. so many gas molecules per second, the start pressure is $1x10^{-6}$ mbar, and the leak rate giving 1x10-6 mbar rise per day. (1 year = 7,305 days)

$1.0x10^{-6}$mbar	***1 day***
$1x10^{-5}$mbar	***10 days***
$1x10^{-4}$mbar	***100 days***
$1x10^{-3}$mbar	***1,000 days***
$1x10^{-2}$mbar	***10,000 days***

Vacuum Physics

However, the same leak, if the start pressure is $1.000x10^{-4}$ mbar;

$1.01x10^{-4}$mbar	1 day
$1.10x10^{-4}$mbar	10 days
$2.00x10^{-4}$mbar	100 days
$1.10x10^{-3}$mbar	1000 days
$1.01x10^{-2}$mbar	10,000 days

Vacuum Physics

The pressure after 10,000 days is almost the same, regardless of the start pressure. This is because it is a logarithmic scale.

The resolution of the discharge is ~ + a quarter of a decade, so that if the pressure is high (10^{-4}) we cannot easily determine the pressure rise over a small timescale. However if the pressure is low (10^{-6}), we can relatively easily find the pressure rise and determine if it will lead to too high a pressure within 20 years.

Vacuum Physics

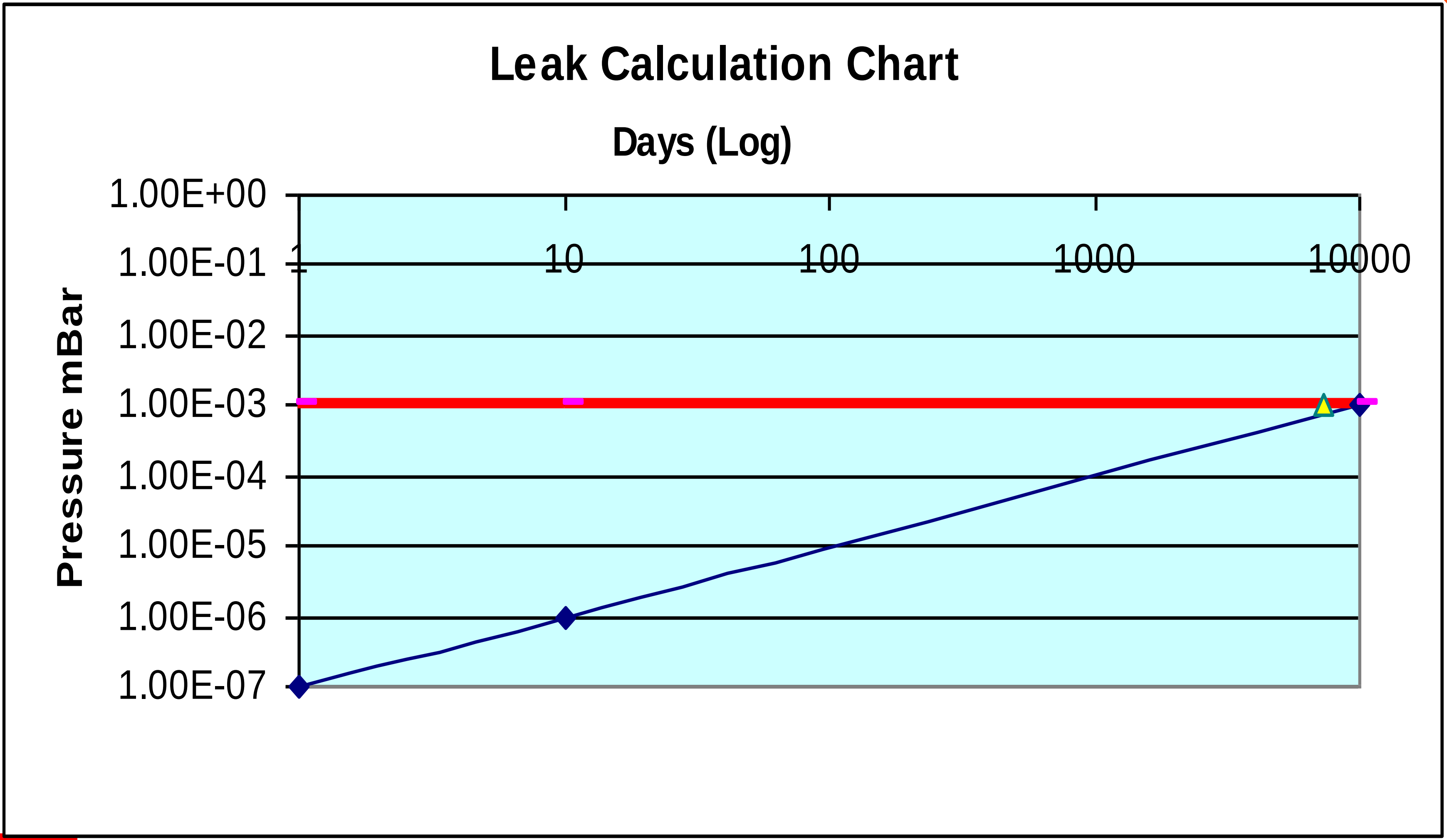
We have now answered the question

"Why $1x10^{-6}$ mbar?"

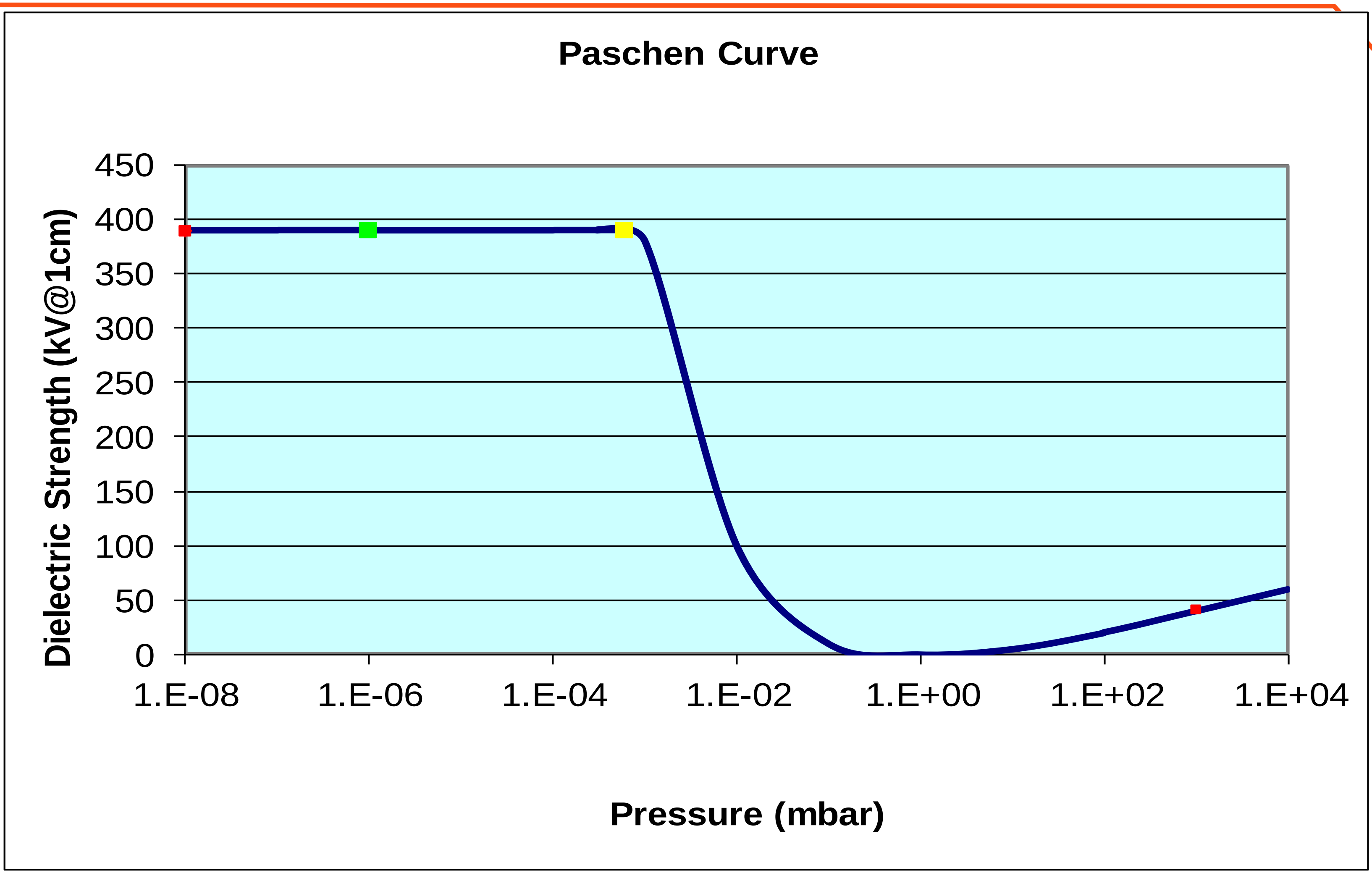
Because we are extrapolating from a small storage period to a long one, we go to very low pressures ($1x10^{-6}$ mbar) to allow space for the pressure to deteriorate, and also to allow for the sensitivity of the gauges, and make the calculation more stable.

Not all manufacturers use the same calculation but all follow a variation of this technique.

Vacuum Life Determination



Vacuum Physics



Basic Circuit Interruption

Another big question is;

"How, exactly, does a VI interrupt current?"

Switchgear of all types, not just vacuum, must perform a simple magic trick;

We must take an arc which is low resistance and almost instantaneously change it to an insulator.

This is what all switchgear does in order to interrupt a circuit.

Non-vacuum Switchgear must also change from conductor to insulator, but may also act to cool or quench the arc, effectively causing a Current Zero.

The first thing to realise is that a vacuum gap does not act to cause interruption, and has no significant cooling effect.

The Problem to be Solved

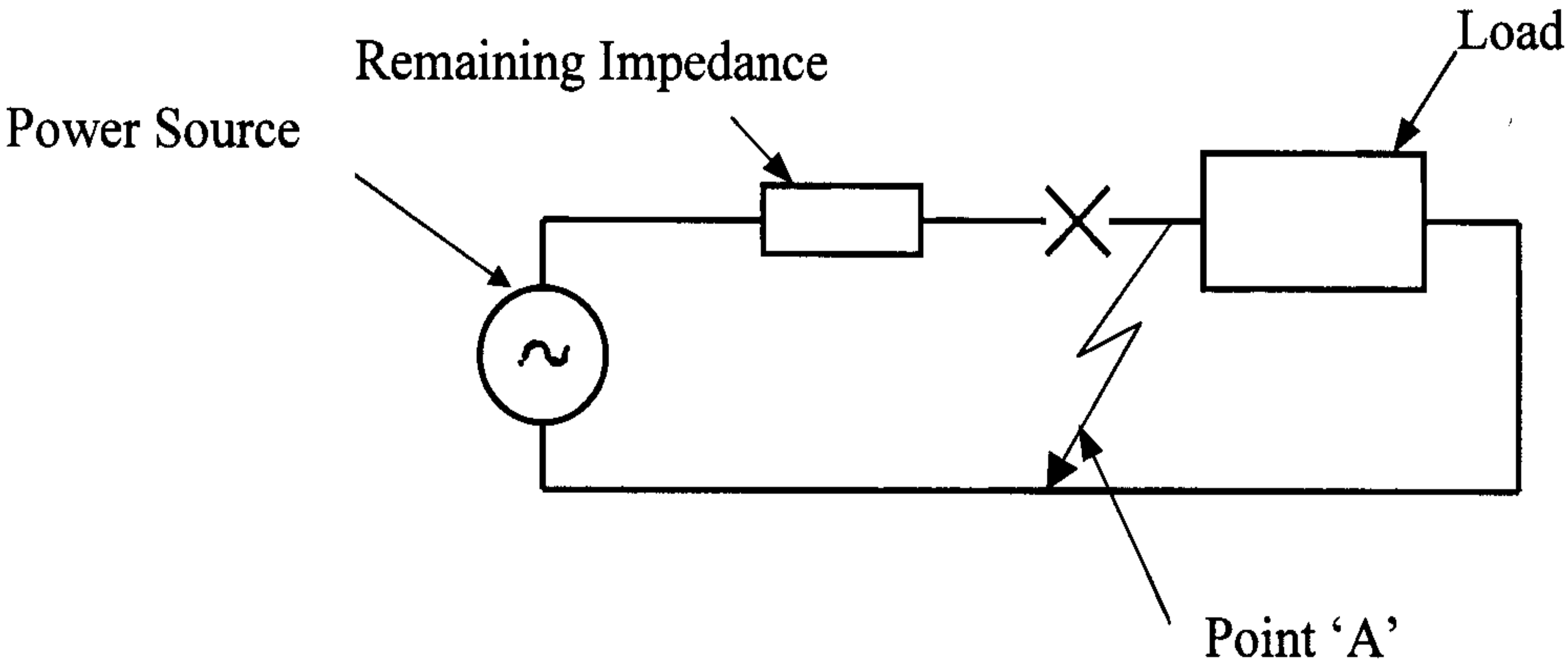


Diagram courtesy J&P Switchgear Book

The Problem to be Solved

The Problem to be Solved

Separation of conducting contacts will cause an arc to be drawn – the circuit tries to maintain itself

For interruption to take place at the instant of current zero the conductive path of the arc must become an insulating gap

This change of state from conduction to insulation is the critical part of interruption. However this is not easy to accomplish and there are a number of factors working against this

The Problem to be Solved

The flow of current generates heat, which in turn produces gas in all types of circuit breakers except vacuum interrupters

Arc temperatures are of the order of 10,000 to 20,000 Kelvin

This heat energy is the biggest problem for interruption for all types of circuit breaker

Arc Interruption Theories

There are a number of theories of arc interruption but they are all essentially based on two principal arc interruption theories;

- ***Cassie – Energy Balance***
- ***Slepian – Dielectric Race***

Cassie's Energy Balance Theory

"If the energy loss from the arc column exceeds the energy input from the external circuit, the circuit will be broken"

- ***In other words, if you can remove the energy from the arc faster than the circuit can provide it, the arc must extinguish***
- ***This is the theory based on "cooling" or "quenching" of the arc, also known as the "Arc Quenching Theory"***
- ***As the circuit breaker cools the arc it eventually creates a Current Zero, meaning that this theory can provide interruption for both AC and DC circuits***

Cassie's Energy Balance Theory – SF^6 puffer interrupter

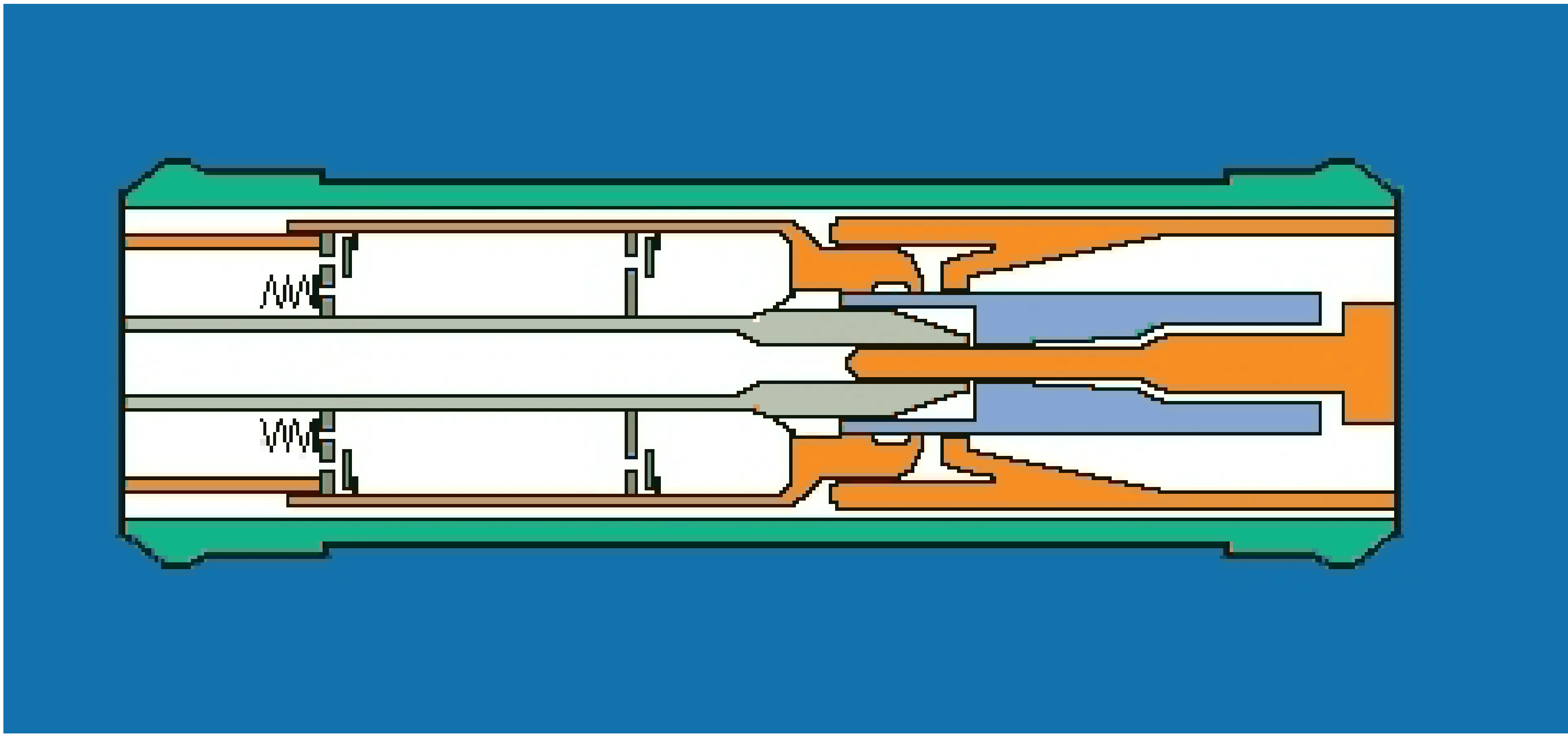


Diagram courtesy J&P Switchgear Book

Slepian's Dielectric Strength Theory

"If, after Current Zero, the dielectric strength of the contact gap increases at a greater rate than the Transient Recovery Voltage, then the circuit breaker will clear"

- ***In other words, provided that the dielectric strength of the gap after Current Zero is always higher than the instantaneous voltage, then there will be no breakdown***
- ***This is the "Dielectric Race" theory and only applies where there is a Current Zero. i.e. No Current Zero no interruption!***

Slepian's Dielectric Strength Theory

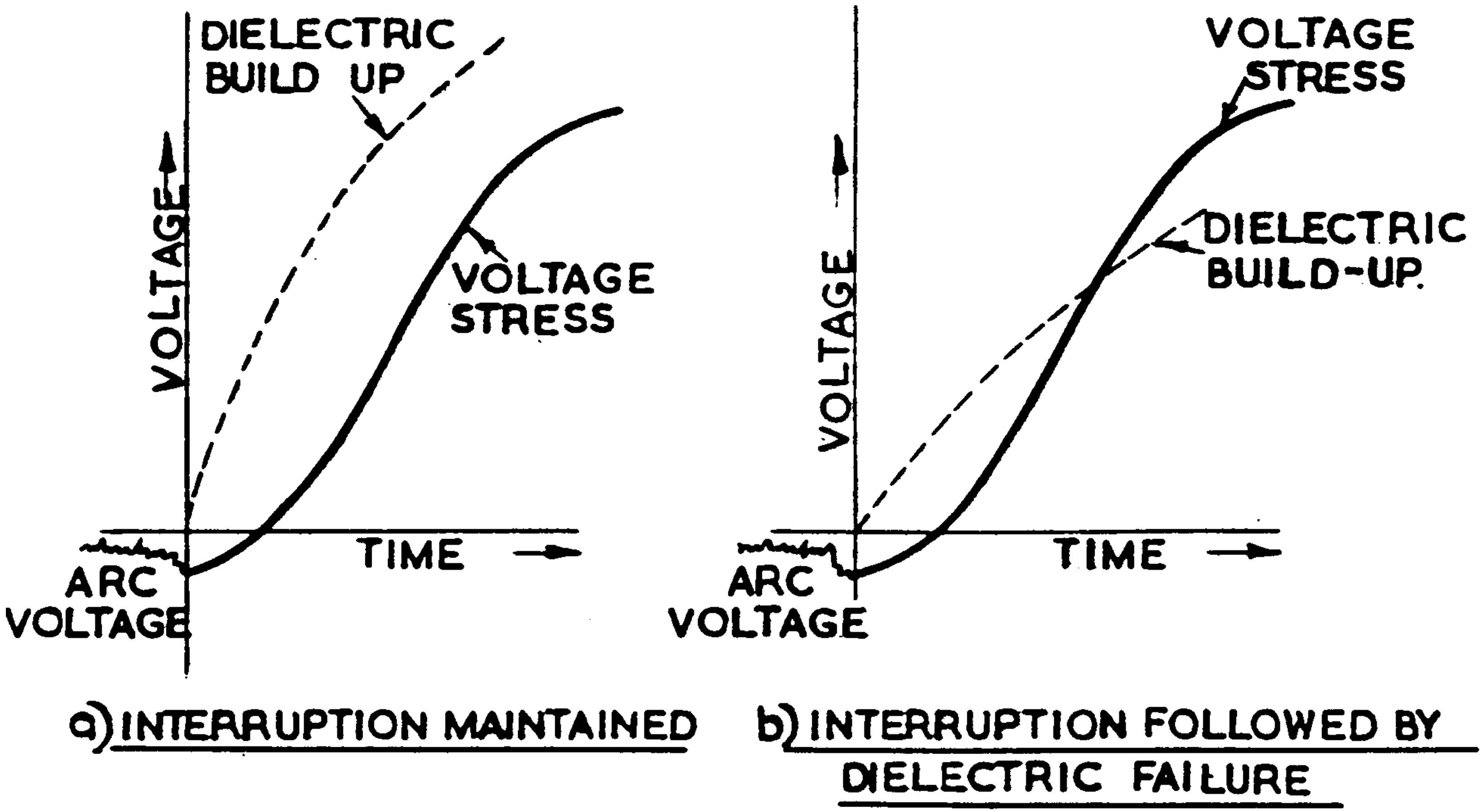


Diagram courtesy J&P Switchgear Book

The Two Interruption Theories

- ***Cassie: Energy Balance***

"If the energy loss from the arc column exceeds the energy input from the external circuit, the circuit will be broken"

- ***Slepian: Dielectric Race***

"If, after Current Zero, the dielectric strength of the contact gap increases at a greater rate than the Transient Recovery Voltage, then the circuit breaker will clear"

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The Two Interruption Theories

- ***Cassie's "Arc Quenching" theory and Slepian's "Dielectric Race" theory both apply to Gas and Oil circuit breakers. Suitably designed Gas and Oil breakers can interrupt both AC and DC circuits***

- ***However Cassie's "Arc Quenching" does not apply to Vacuum at all, as there is no significant quenching effect in vacuum.***

- ***Only Slepian's "Dielectric Race" theory applies to Vacuum circuit breakers. As a result Vacuum circuit breakers are only suitable for AC interruption. They can only interrupt DC if a false Current Zero is applied***

Vacuum Interruption

"How, exactly, does a VI interrupt current?"

It does not "quench" the arc. It simply waits until Current Zero and then wins the dielectric race.

However just waiting for Current Zero is in itself not so easy.

The Problem to be Solved

Basic Circuit Interruption

"How, exactly, does a VI interrupt current?"

Provided that we have controlled the arc correctly, after current zero the vacuum arc extinguishes naturally, and the dielectric strength of a vacuum gap recovers very quickly – far faster than the TRV can appear, resulting in interruption of the circuit.

Basic Circuit Interruption

Perhaps a better question is

“What can cause a VI not to interrupt current?”

Basic Circuit Interruption

"What can cause a VI not to interrupt current?"

The short answer is heat.

If the contact overheats then the vacuum gap does not have sufficient dielectric strength to hold off the TRV.

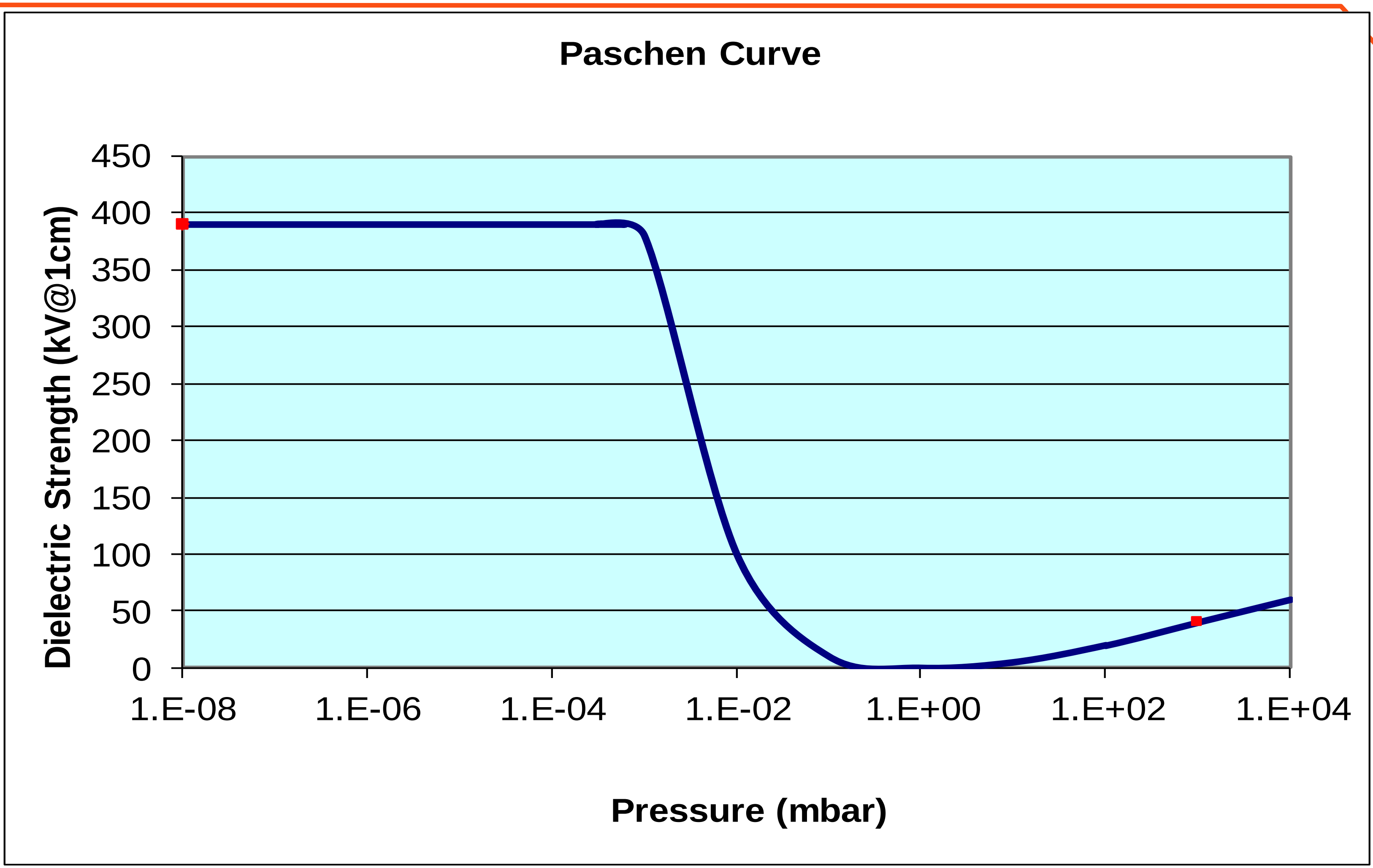
Basic Circuit Interruption

Overheating causes the contact surface to melt, this gives off gasses and metal vapour

Which means that the space between the contacts is no longer vacuum. It has a pressure derived from the outgassing and the metal vapour.

If the pressure gets high enough we fall down the Paschen cliff and the dielectric strength disappears.

Vacuum Physics



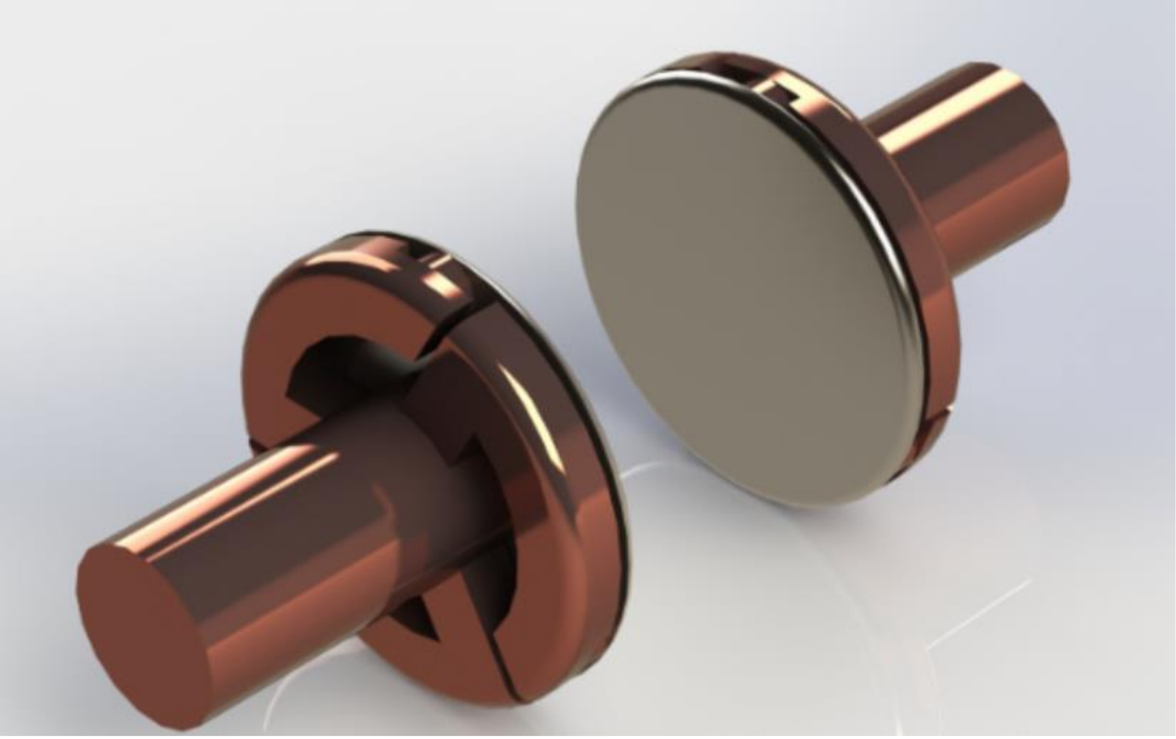
Basic Circuit Interruption

The VI does not "quench" the arc. It simply waits until current Zero. But the energies and arc temperatures are very high and while waiting for Current Zero we need to control the arc so that it does not damage the VI and also does not overheat the contacts.

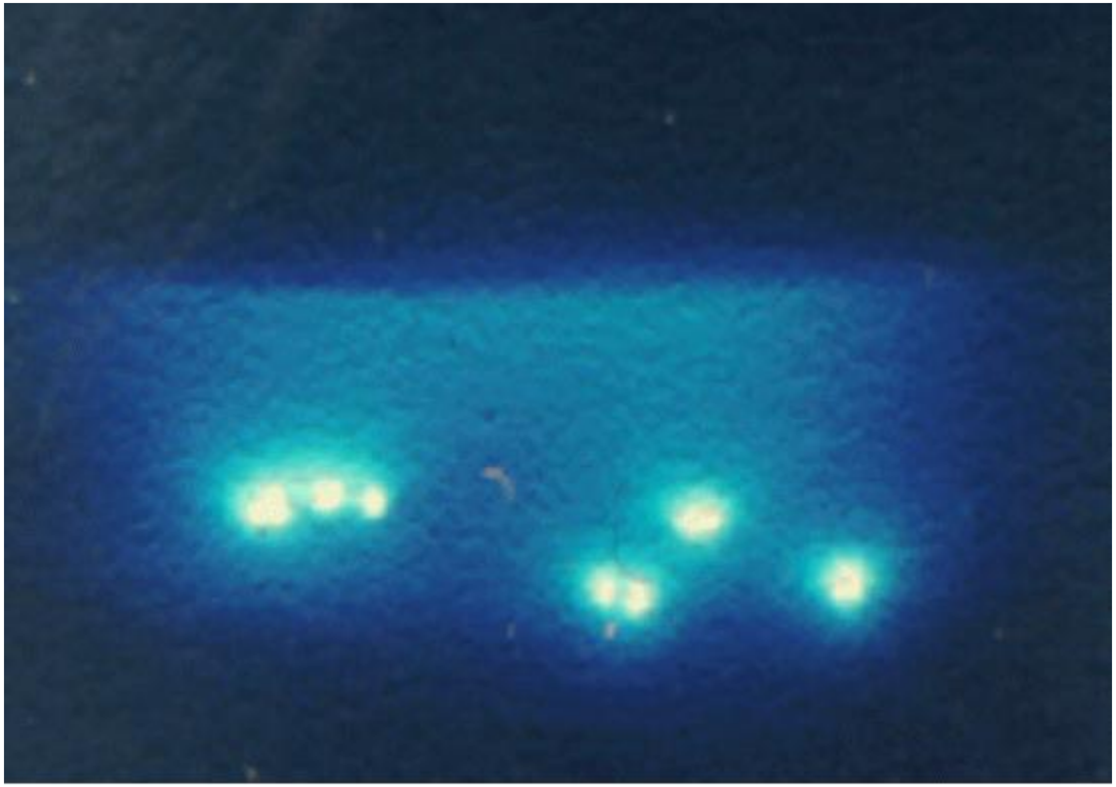
We do this by using the self induced magnetic fields generated by the large currents.

Vacuum Interrupter Contacts

VI contacts



Arc Control: Natural Diffuse Mode

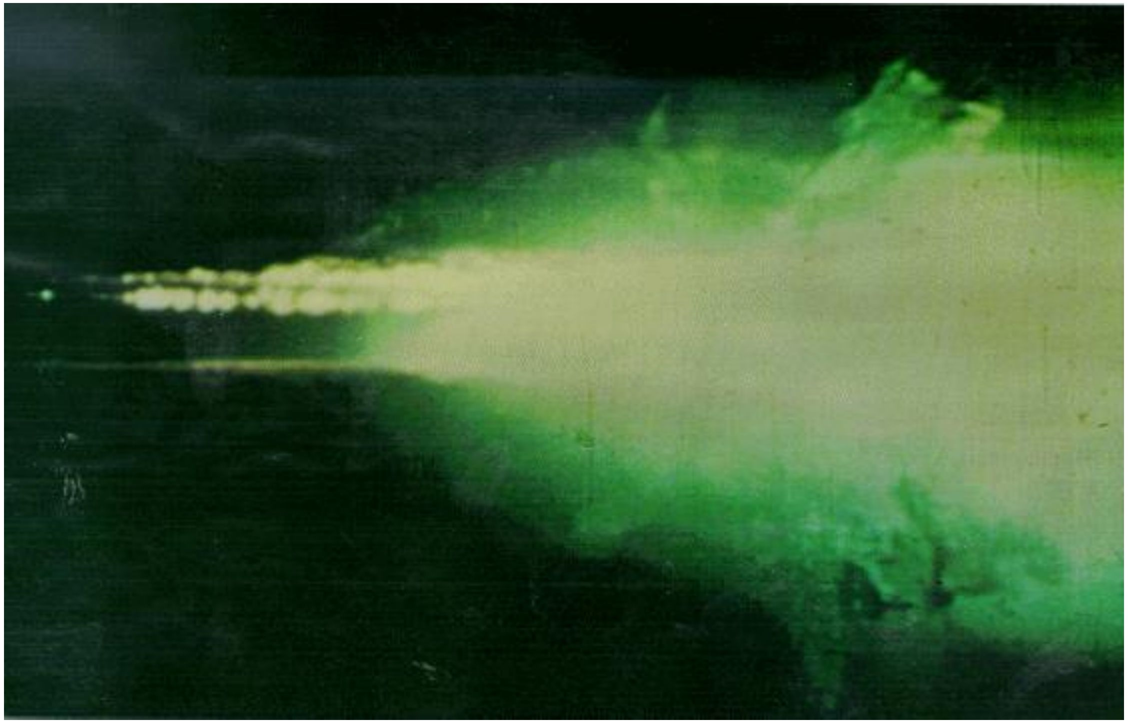


Still photo from High Speed film @ 10,000pps showing cathode spots on plain contact geometry (55mm diameter disc) CLR carrying @200A

A plain butt contact can interrupt up to ~ 9kA(pk) without any arc control.

The arc is split naturally into a number of cathode spots which repel each other and spread the energy over the contact surface.

Arc Control: Natural Diffuse Mode



Still from HS film @ 10,000pps showing constricted arc on plain contact geometry CLR carrying @15000A. The liquid spilling over the edge of the contact is boiling chromium and copper

However over the current limit the arc naturally constricts to form a concentrated column arc

This column delivers a large amount of energy into a very small area of the contact resulting in local overheating and failure to interrupt

VIL

Arc Control: Natural Diffuse Mode

If the contact overheats at any point on the surface, at Current Zero the surface is still emitting gas and vapour, and so the vacuum level between the contacts is degraded and breakdown occurs

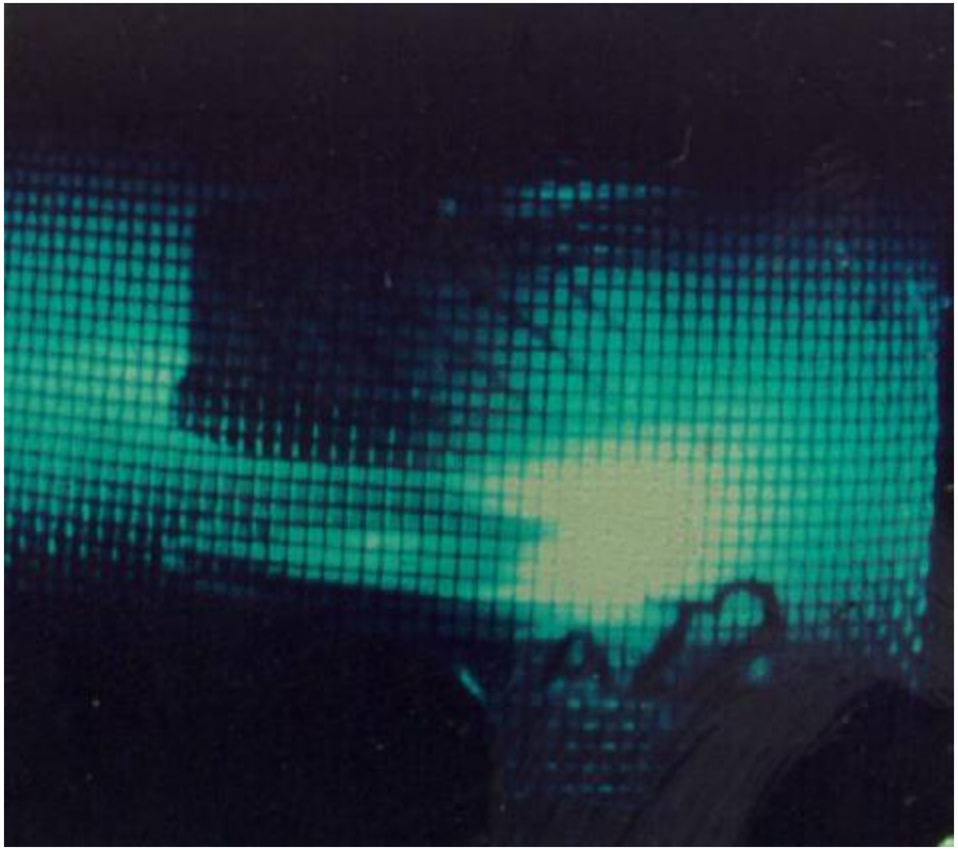
Arc Control Geometries

Vacuum Interrupters and Switches use two forms of arc control, generally using self induced magnetic fields to obtain successful interruption of high currents*;

- ***Radial Magnetic Field (RMF)***
- ***Axial Magnetic Field (AMF)***

****See "Recent Advances in Vacuum Interrupter Design" L.T.Falkingham, CIGRE paper 13.01 1986***

Arc Control: Radial Magnetic Field (RMF) Contact Geometry

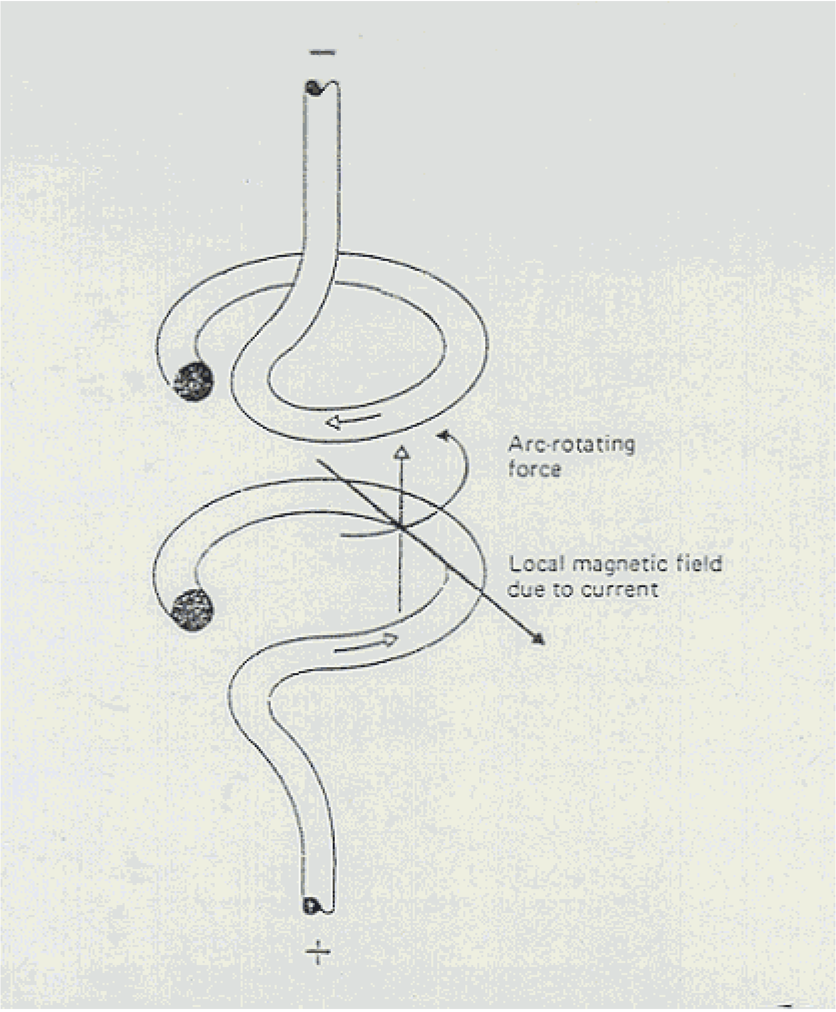


Still from HS film @ 5,000 pps showing 55mm diameter RMF contact interrupting 31.5kArms @12kVrms.

This works by using a self induced Radial Magnetic Field to make the arc move over the contact surface, reducing local heating, shown by the "Contrate" geometry here.

The contact material must allow the arc to move freely over the surface.

RMF Principle:



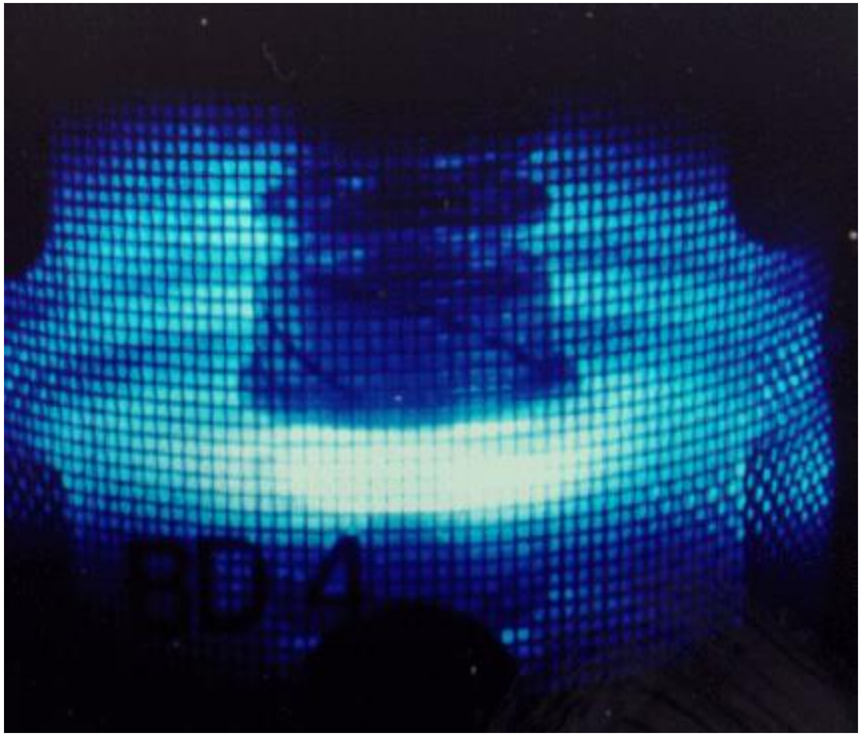
The Radial Magnetic Field generated by the contact geometry acts as an electric motor, driving the arc around the periphery of the contact, and preventing local overheating of the surface.

In Germany RMF is also known as TMF (Transverse Magnetic Field)

RMF Principle:

The RMF principle illustrated by the current flow in a "Folded Petal" Contact geometry.

RMF-Folded Petal

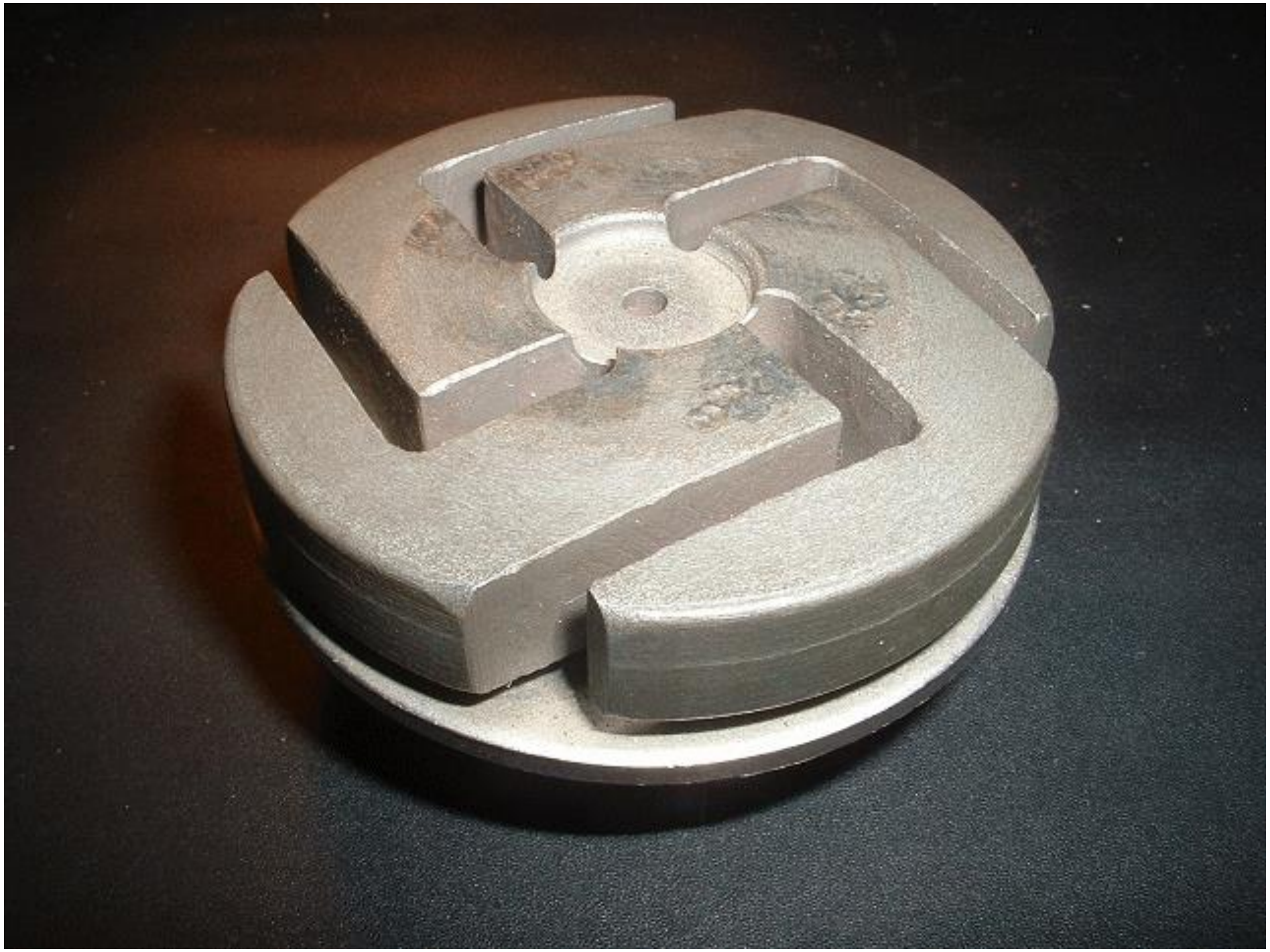


Folded Petal Contact 35mm diameter interrupting 20kA @12kV
Radial Magnetic Field (RMF)

RMF-Folded Petal

Folded Petal Contact 35mm diameter interrupting 20kA @12kV Radial Magnetic Field (RMF)

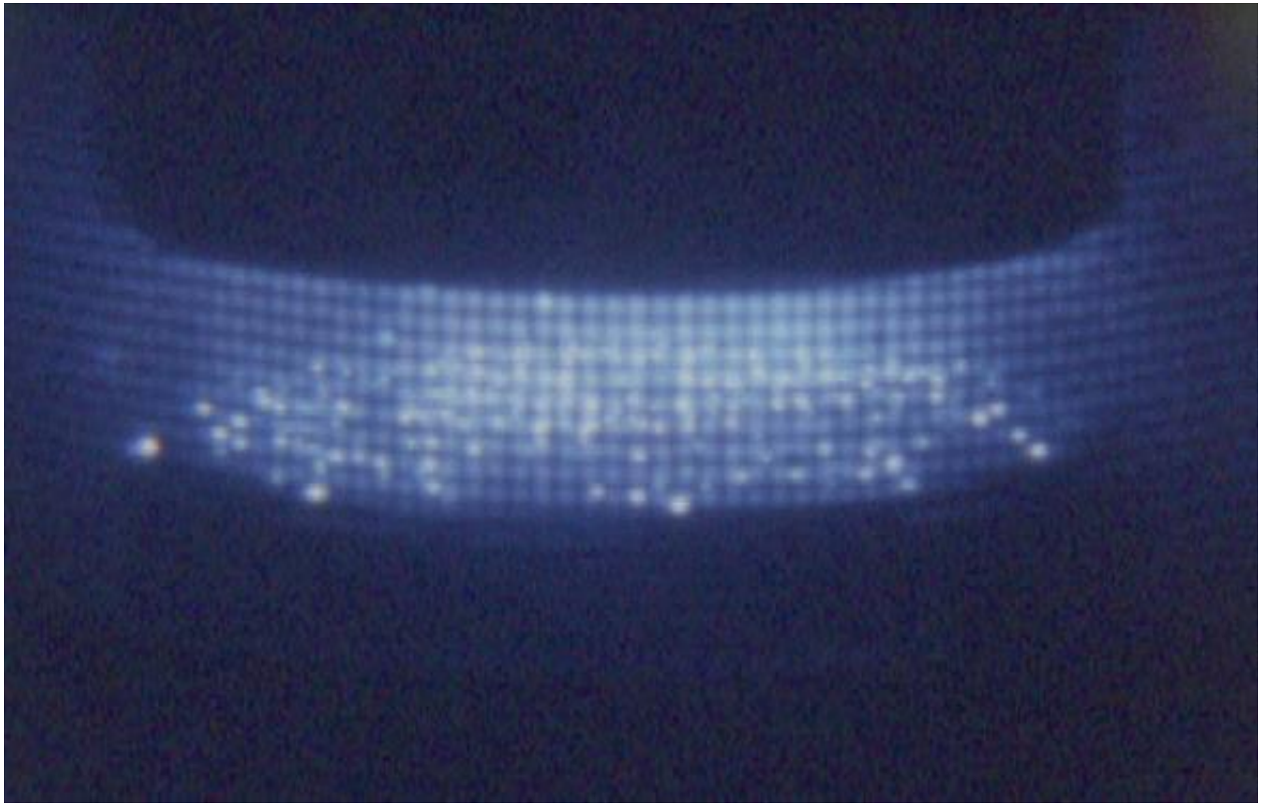
RMF-Spiral Petal



Ten Years of Development in RMF Contacts

Two RMF contacts. Right "Contrate" 1970's, Left "Folded Petal" 1980's. Both rated at 20kA@12kV.

Arc Control: Axial Magnetic Field (AMF) Geometry

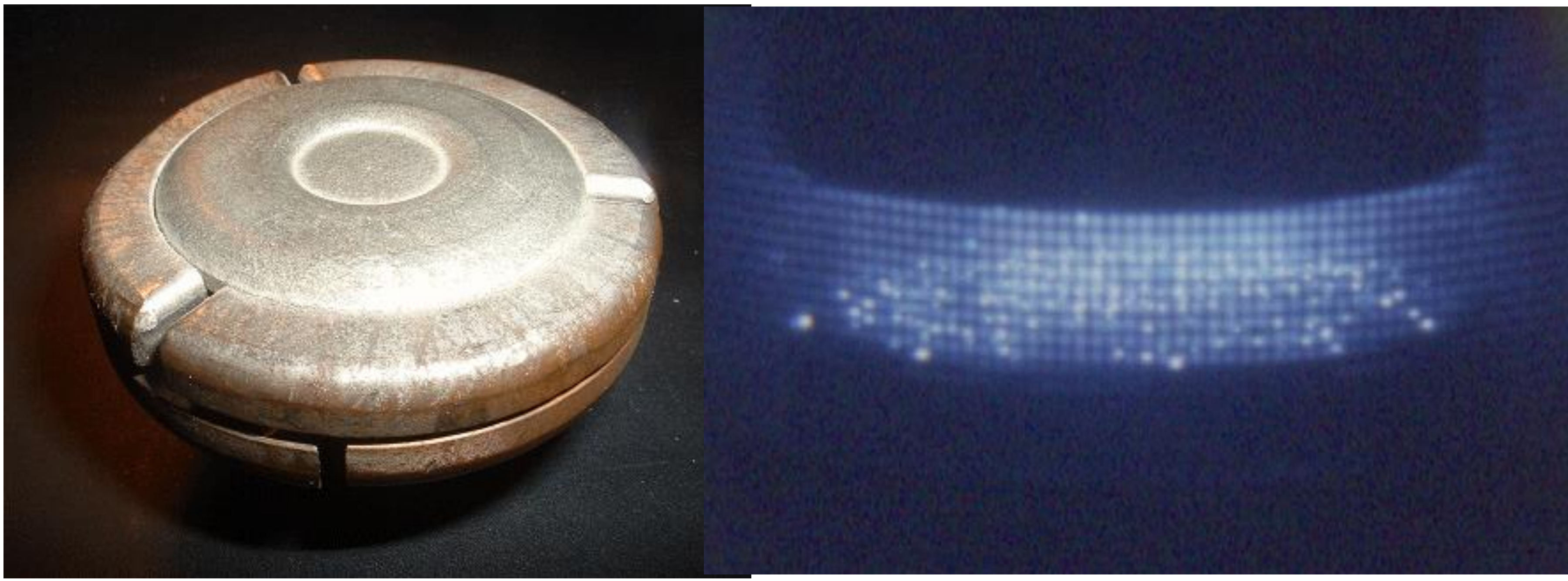


Still from HS film @ 9,000pps showing an AMF contact interrupting 40kArms @12kVrms.

This works by using a self induced magnetic field in the axis of the arc which prevents the arc from constricting and reduces local heating by spreading the energy over the surface.

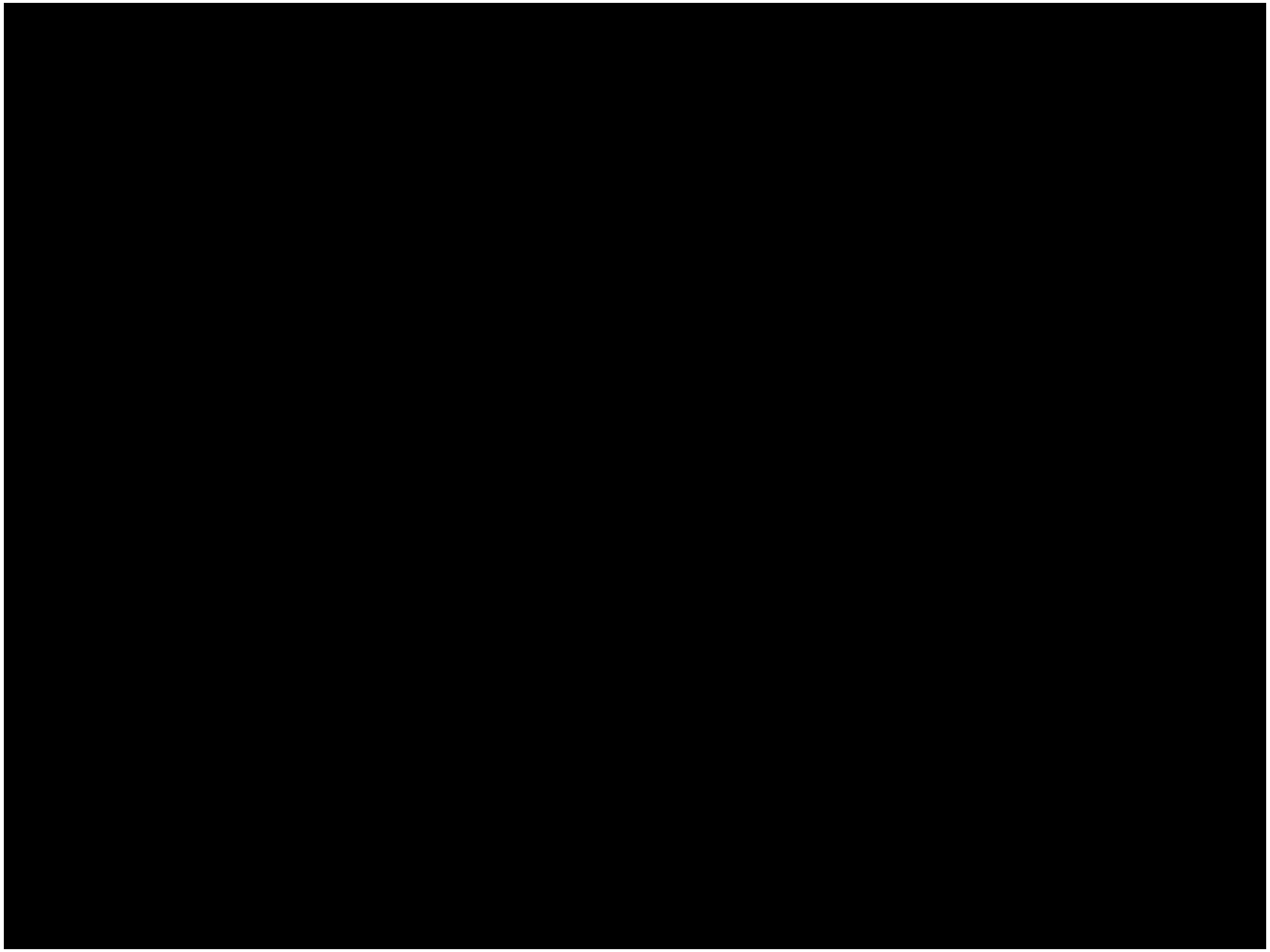
The contact material does not have to allow the arc to move freely.

Arc Control: Axial Magnetic Field (AMF) Geometry



AMF Contact 75mm diameter interrupting 40kA @12kV
Axial Magnetic Field (RMF)

Arc Control: Axial Magnetic Field (AMF) Geometry



Arc Control

For fault interruption of over a few kA all vacuum interrupters use either RMF or AMF arc control.

There are a number of different ways of achieving the fields, but all use the magnetic field of the short circuit current to generate the appropriate field.

All contacts rely on a natural Current Zero, and control the arc until this occurs.

VIL

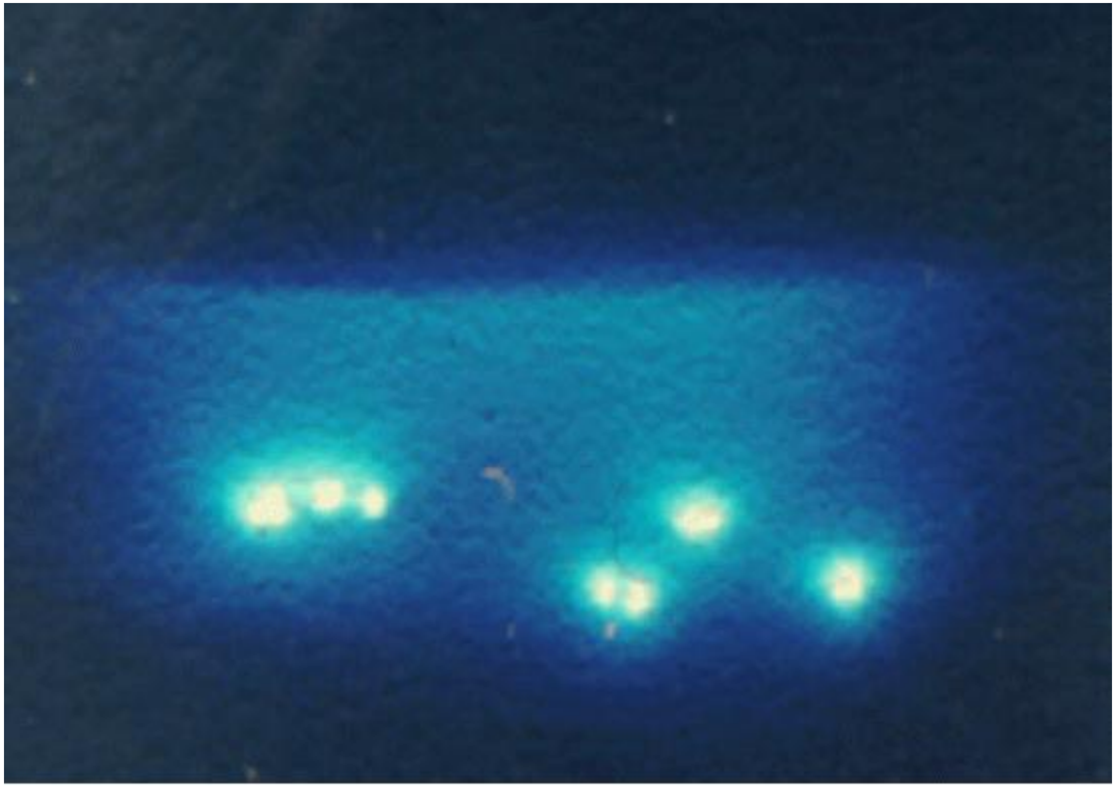
Vacuum – Retrograde Motion

Cathode spots move in the presence of a magnetic field. This is the principle of arc control, which as we have seen works very well.

However what was not mentioned was the fact that when we resolve the electric and mangnetic fields, they move in the wrong direction! There are theories to explain this, but not so convincing.

But it is a reliable effect, so rather than completely understanding it we name it "Retrograde Motion" and move on.

Arc Control: Natural Diffuse Mode



Still photo from High Speed film @ 10,000pps showing cathode spots on plain contact geometry (55mm diameter disc) CLR carrying @200A

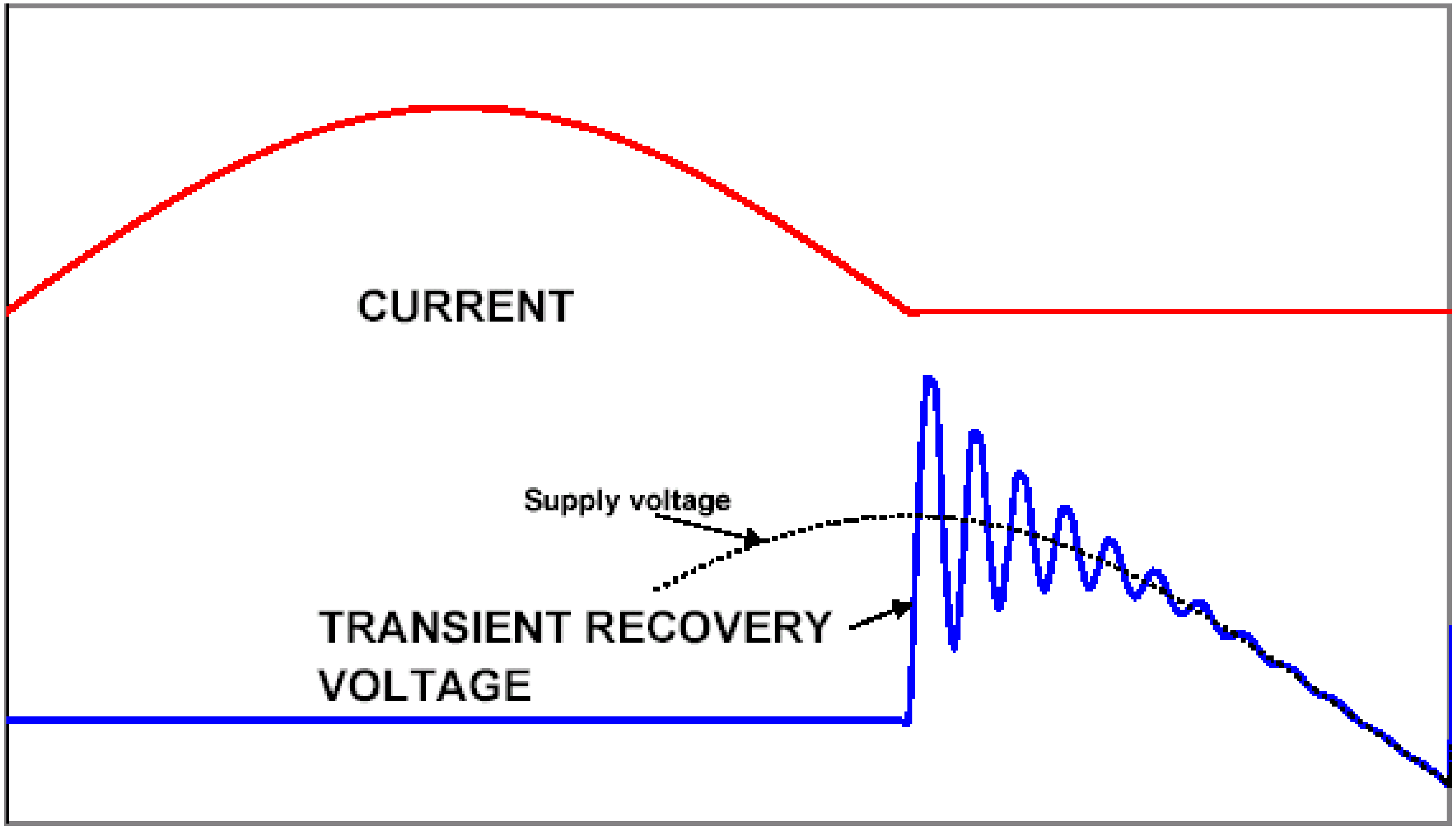
Current chopping

All types of switchgear Air, oil, SF_6 & Vacuum, exhibit current chopping.

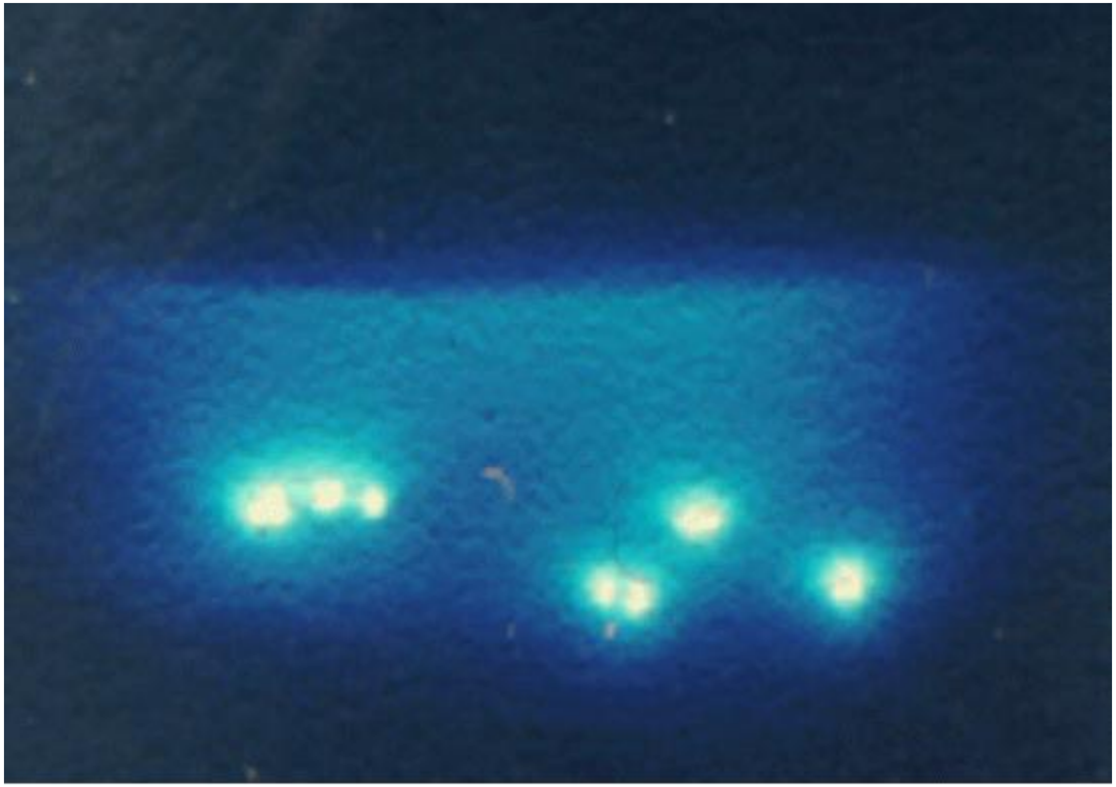
When the energy in the arc is insufficient to maintain the arc then the arc will collapse. This occurs before the natural Current Zero, and depends on the type of arc and the energy required. In vacuum this depends on the cathode spot which carries the current. Simply put the number of cathode spots depends upon the level of current being carried. More current = more spots. As current approaches Zero, eventually one spot is left.

Current chopping

All types of switchgear exhibit current chopping.



Arc Control: Natural Diffuse Mode



Still photo from High Speed film @ 10,000pps showing cathode spots on plain contact geometry (55mm diameter disc) CLR carrying @200A

The number of spots reduces as the current approaches Zero, until there is one spot left.

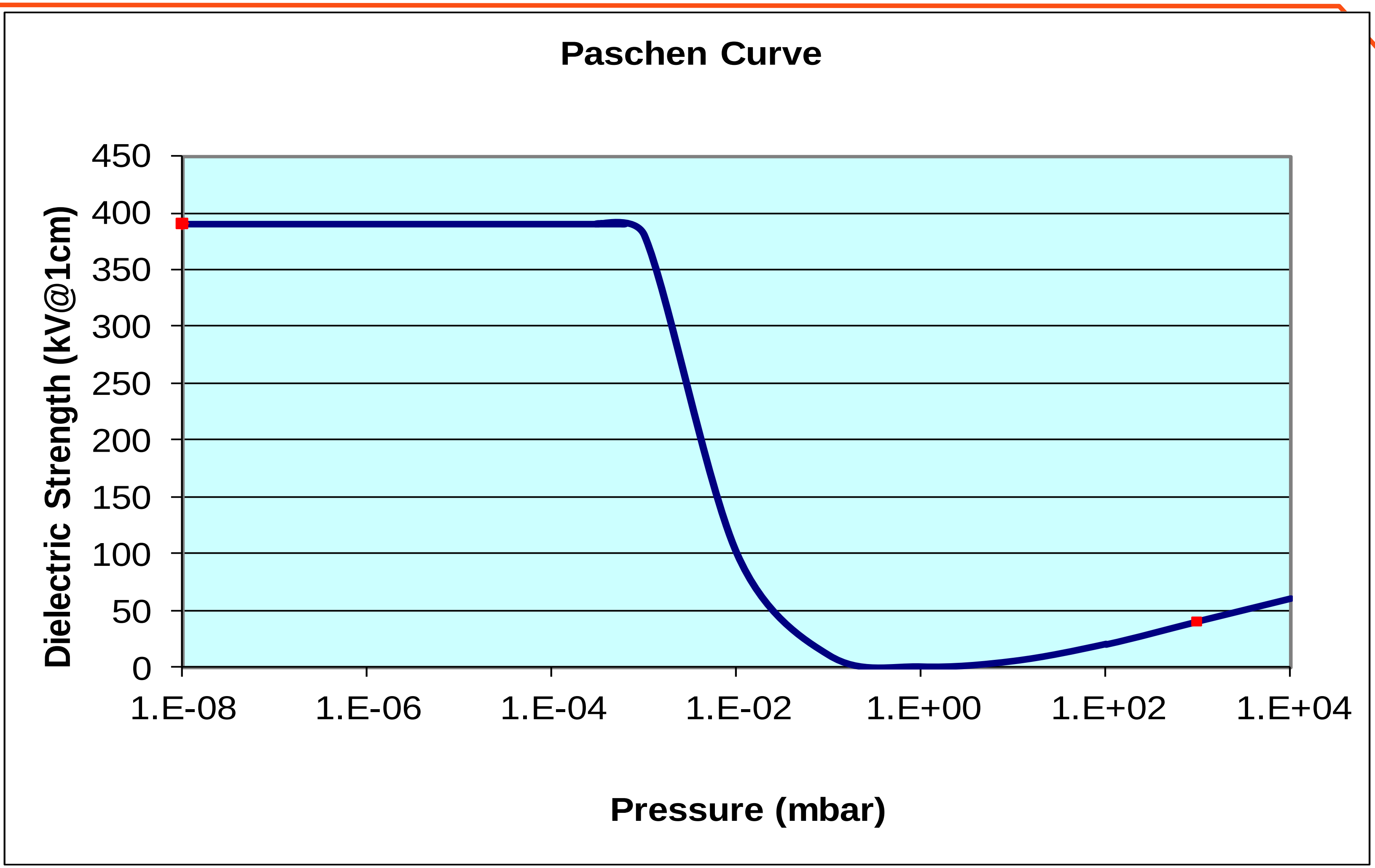
Then when there is not enough energy to maintain the arc, it collapses and extinguishes

Arc Control

The collapse of the arc is very quick, and the plasma and metal vapour quickly vanish – they condense on the contacts or escape into the VI.

Either way, the local pressure goes from Paschen minimum value to high vacuum. Which in turn changes the dielectric strength of the gap from very low resistance to very high resistance, almost instantaneously.

Vacuum Physics



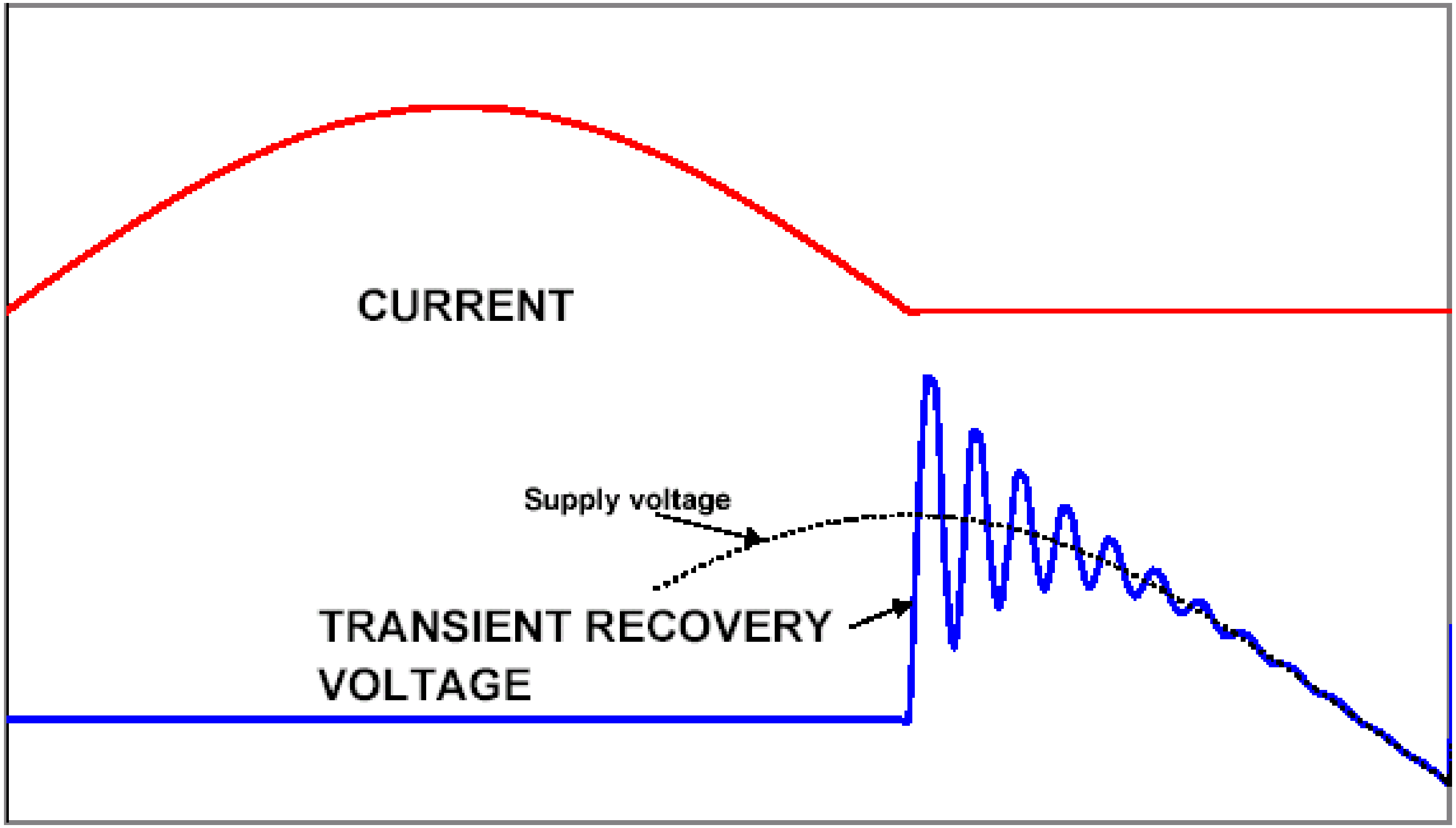
Current Chopping

Because the Current Chopping is so abrupt, the system reacts by giving a fast transient overvoltage.

But the current chopping is a property of the arc, which is made up of a metal vapour arc which comes from the contact material. If we change the contact material we can change the chopping level.

We'll deal with this later....

Current chopping



Breakdown in Vacuum

As we have seen, a cold vacuum gap has extremely high dieletric strength – up to 380kV/cm.

But what would cause it to breakdown?

Simplifying, assuming that the background vacuum is good, there are really two types of causes of breakdown:

Particulate breakdown

Electron/ion breakdown

Breakdown in Vacuum

Particulate breakdown:

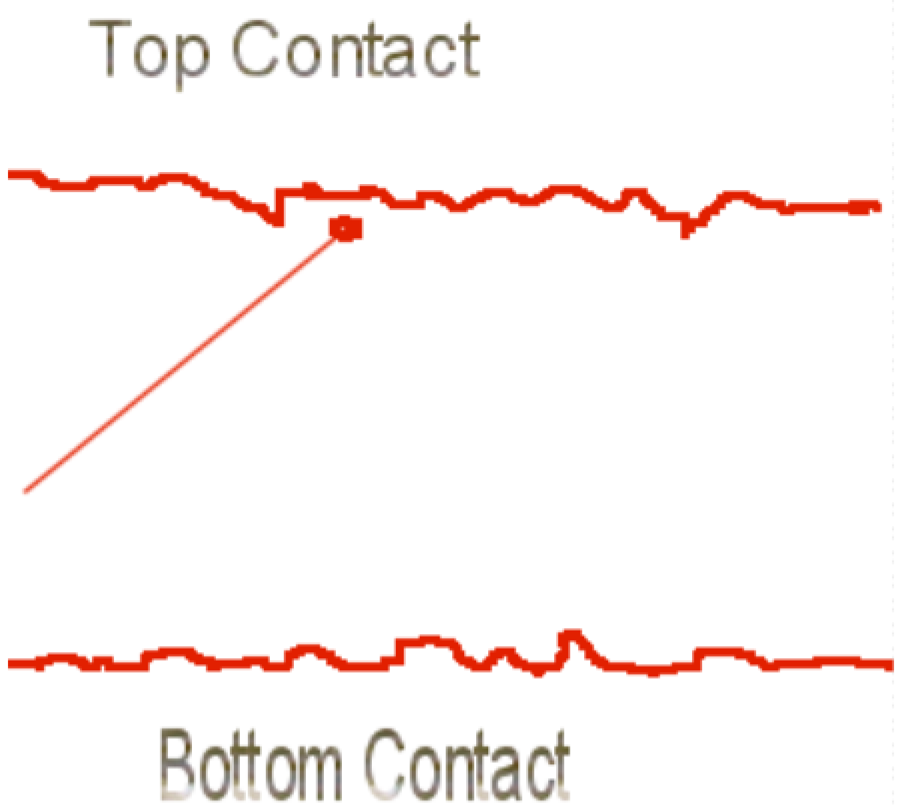
This is where a particle impacts on the surface of one of the contacts. Particles in the interrupter can be levitated into the contact gap by the electric fields between the contacts.

When a particle hits the contact surface this transfers charge, and the impact can cause local melting, and expel debris from the particle and the contact.

This can raise the local pressure to the point where breakdown can occur.

Breakdown in Vacuum

Particulate breakdown:



Breakdown in Vacuum

Particulate breakdown:

Particles can come from many sources.

- ***They can come from the manufacturing process (contamination)***
- ***They can be generated by the contacts opening or closing***
- ***They can be generated by the arcing process***

Breakdown in Vacuum

Non Sustained Disruptive Discharges (NSDD)

NSDD are phenomena generally associated with VI.

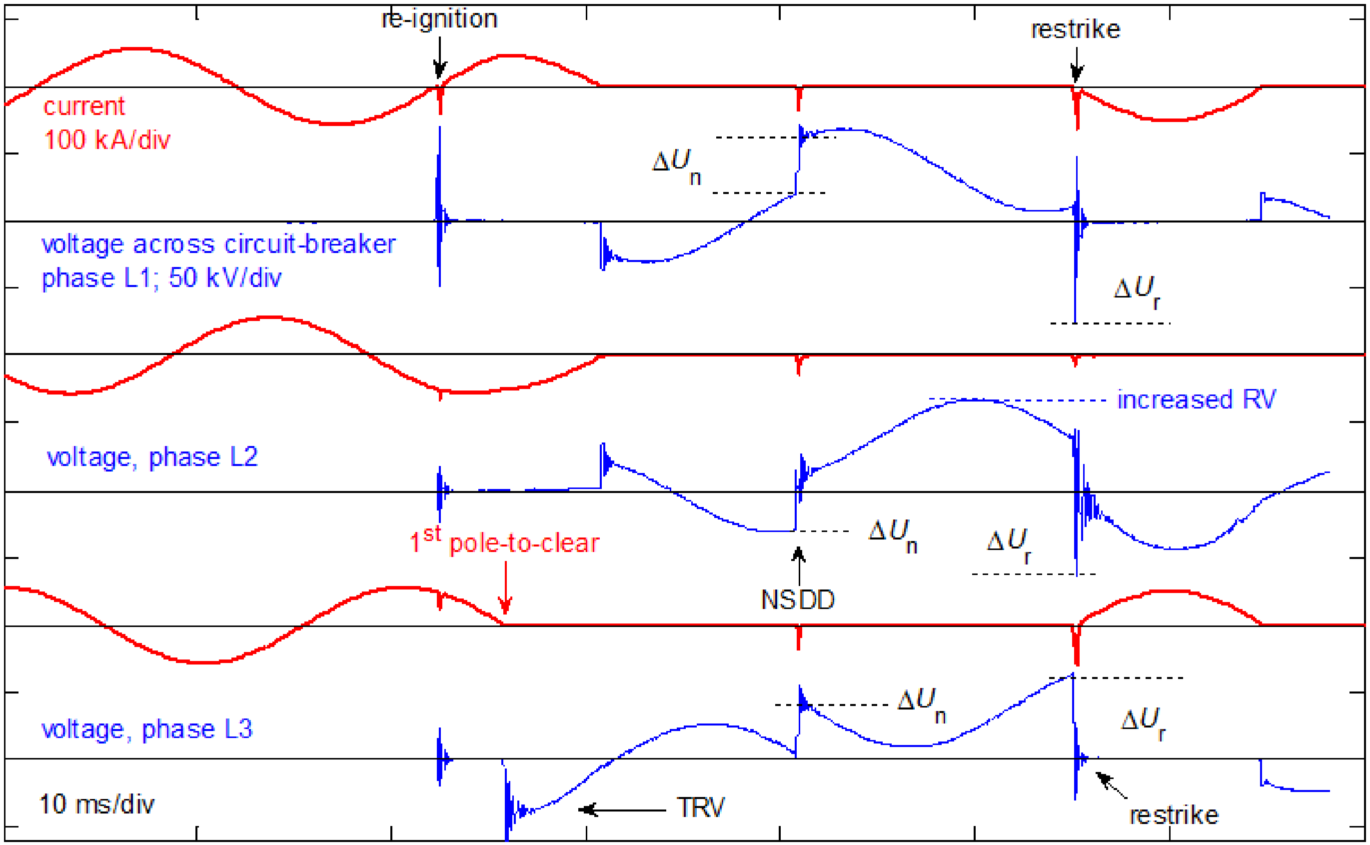
They are a little strange, as although there is a significant votage change there is no real current in the main circuit.

They are gererally associated with particules within the VI.

Breakdown in Vacuum

short-circuit current

KEMA Laboratories



Breakdown in Vacuum

Apart from NSDD, particles can cause normal breakdowns in vacuum, and the manufacturing process is designed to eliminate or at least minimise the presence of these particles, so Ultrasonic and chemical cleaning is used, as well as Clean Rooms for cleaning the components and assebling the devices.

Manufacturing - One Shot Seal Off

V204 interrupters being loaded into the furnace for seal off. South Africa 1990's.

This shows V204 vacuum interrupters being assembled in a clean room in South Africa. After assembly the interrupters are loaded into a vacuum furnace and brazed and sealed at the same time.

The components are chemically cleaned and then assembled in Clean Rooms to reduce contamination and "Virtual Leaks"

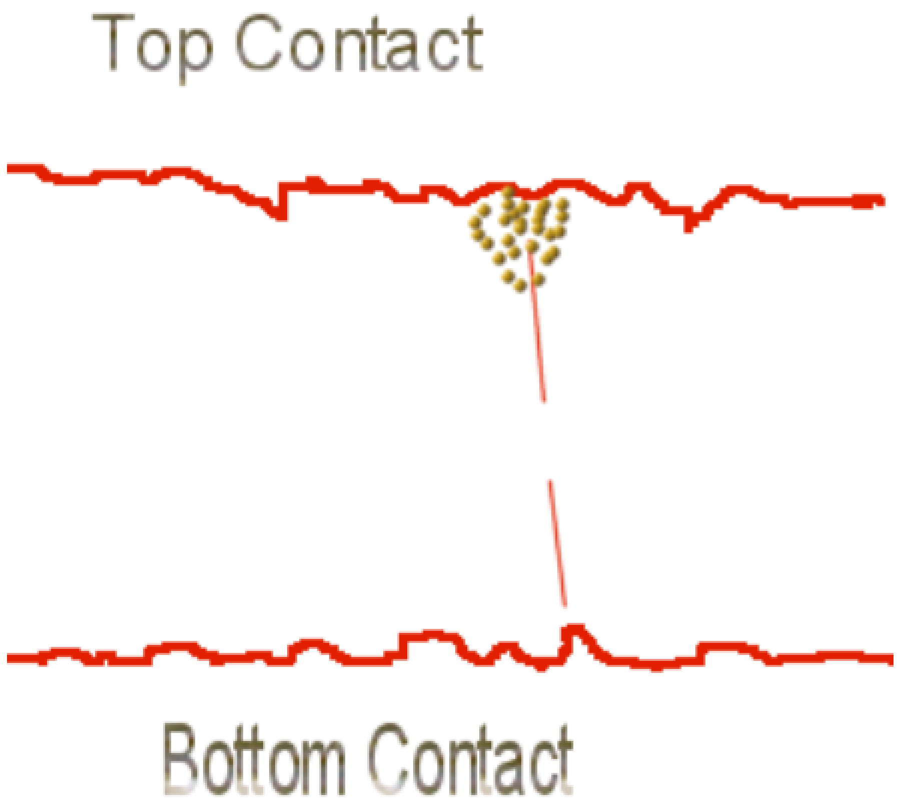
Breakdown in Vacuum

<u>Electron/Ion breakdown:</u>

In this case electrons/Ions can be emitted from the surface of one contact and bombard the other contact. This is like a laser or electron beam welder and can add significant energy to a small point on the other contact. This point can melt and emit gas and vapour and if enough is emitted can lead to vacuum pressure breakdown.

Breakdown in Vacuum

Electron/Ion breakdown:



Breakdown in Vacuum

Electron/Ion breakdown:

Why does the emission occur?

This is due to surface irregularities which give field enhancement and provides enough energy to launch the electon/ion to the other contact.

But due to the high energy density the “sharp point“ melts and becomes blunt, the field drops and the emission point switches off.

Breakdown in Vacuum

Electron/Ion breakdown:

Liquid metal surface in electric field Courtesy G. Mesyats

Breakdown in Vacuum

Electron/Ion breakdown:

Once an emission site switches off, another point will switch on and the process continues until all of the emission points have been "rounded" to a level where no point on the surface has sufficient field to launch.

At this point the VI is considered voltage "conditioned".

Manufacturers have a number of processes which they use to improve the voltage performance of VI, normally to reach the appropriate bil level.

Breakdown in Vacuum

Electron/Ion breakdown:

But, if a breakdown does occur, it can damage the surface, give sharp features, and reduce the voltage capability to much lower level.

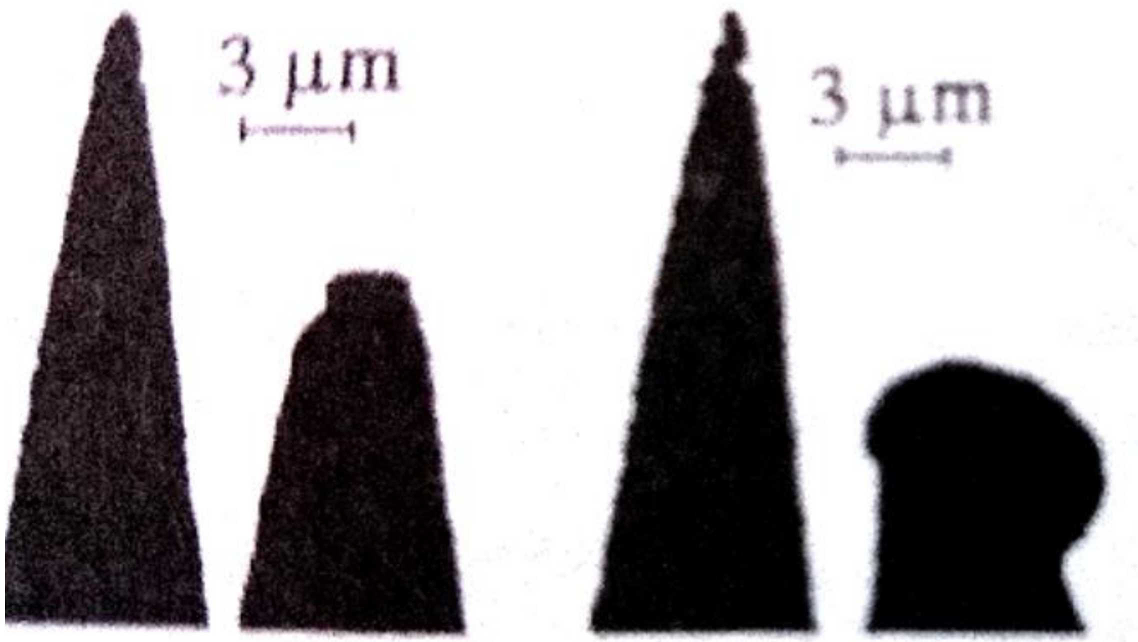
The VI then needs to be reconditioned to remove the sharp points and return to the previous voltage performance.

This means that Vacuum insulation is self restoring but can temporarily change.

If the contacts are arced by switching even load current this is normally sufficient to recondition the contacts.

Breakdown in Vacuum

Electron/Ion breakdown:



Microscopy showing effect of discharge on protrusion, each shows a spike which has melted due to emission.

Courtesy G. Mesyats

Breakdown in Vacuum

Electron/Ion breakdown:

Contact welding also can cause insulation degradation.

If a VI closes onto a fault, and then opens to break current – no problem, the arcing will melt any weld damage.

However if a VI closes onto a fault, and then opens with no current, the insulation capability will be degraded.

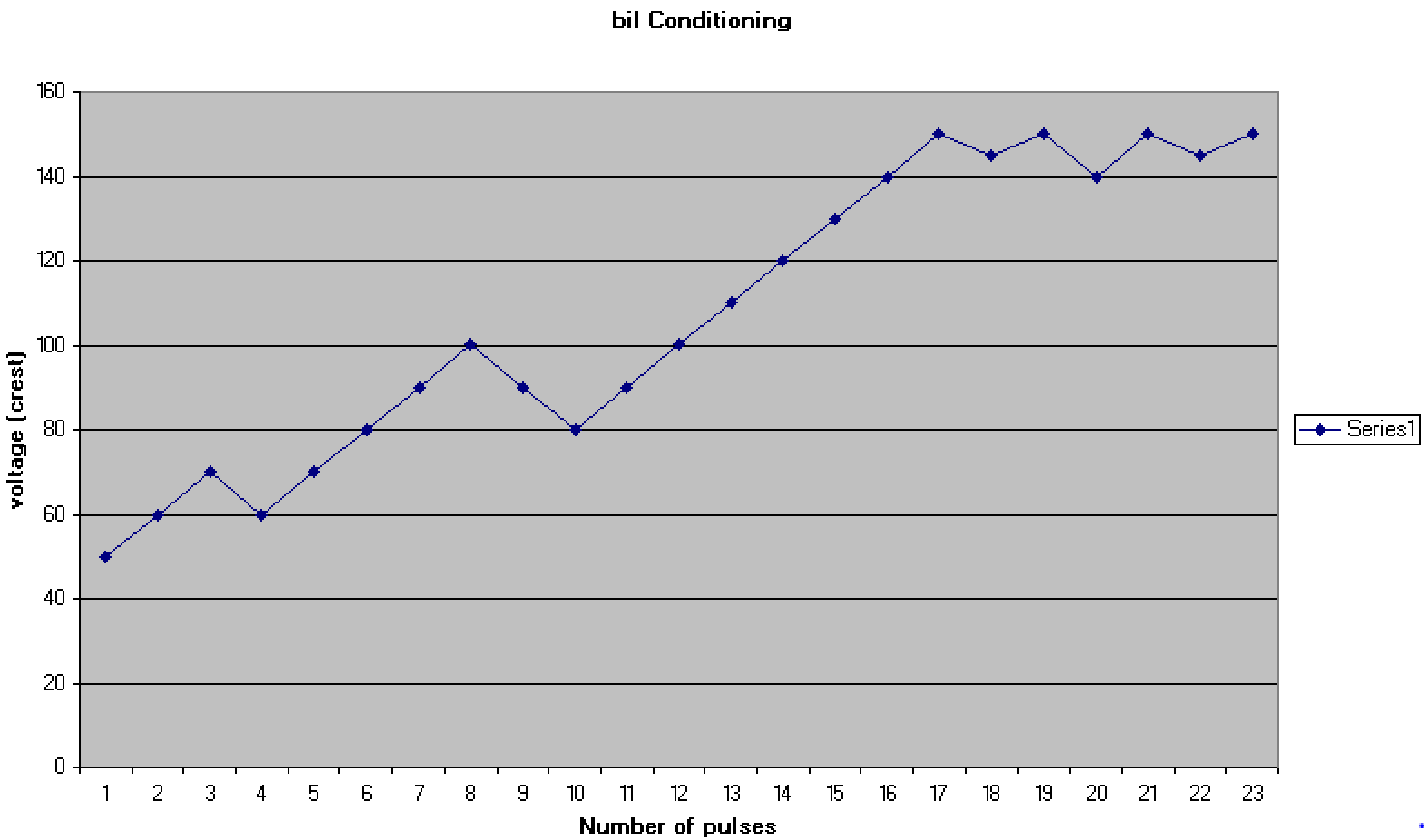
However it will recover to the orginal value after even small current switching such as load current.

Breakdown in Vacuum

Electron/Ion breakdown:

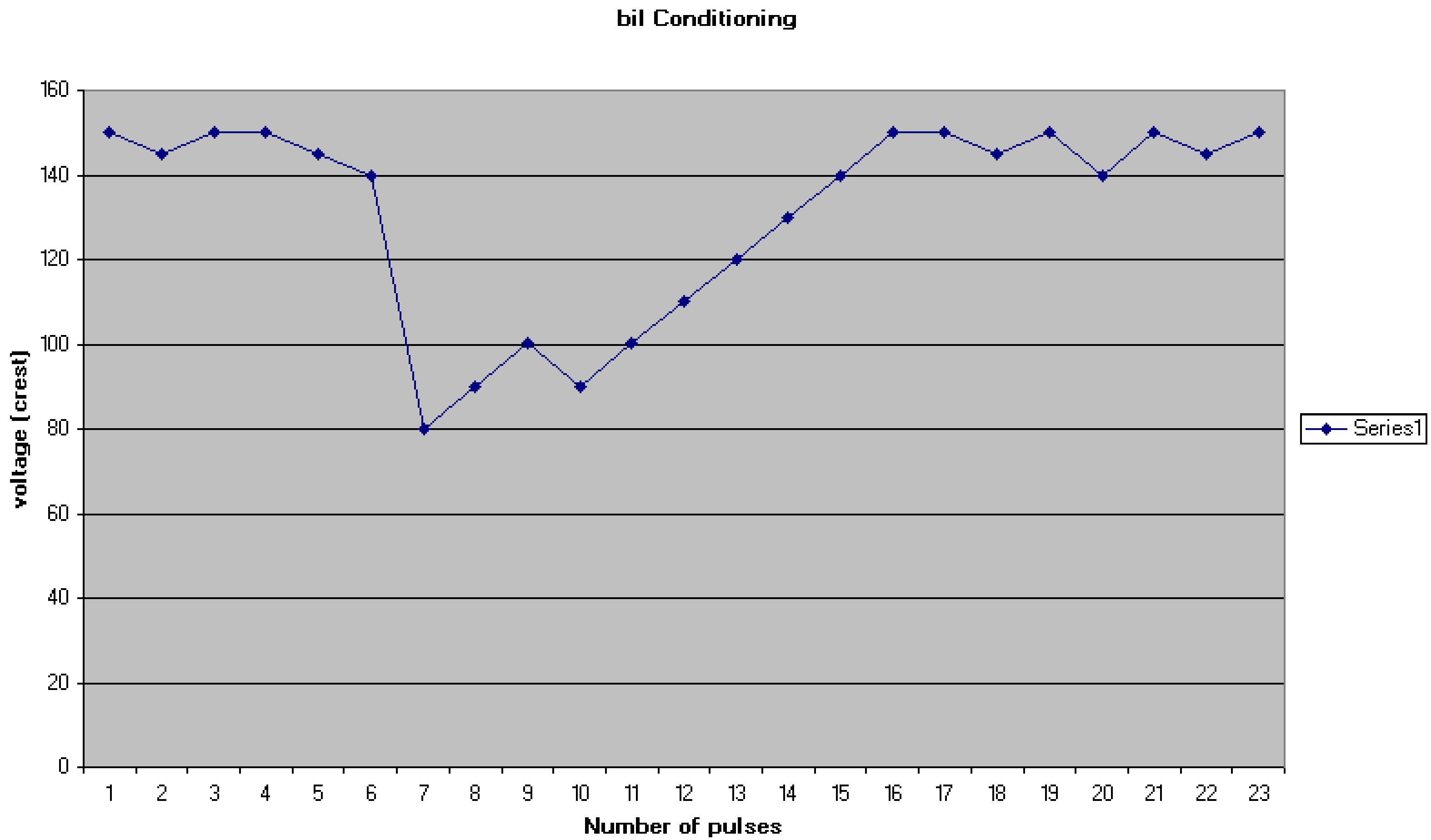
Breakdown in Vacuum

Electron/Ion breakdown:



Breakdown in Vacuum

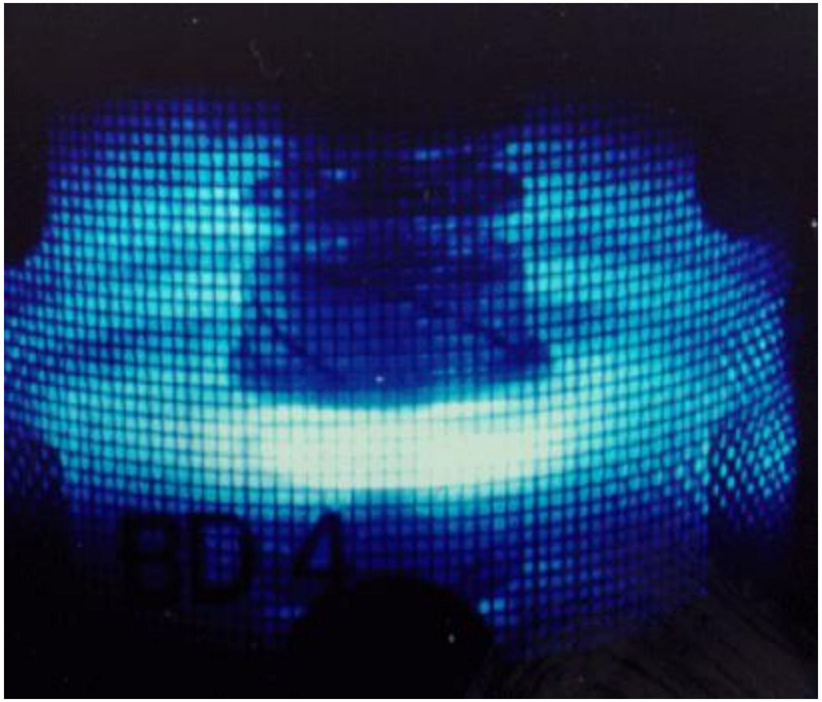
Electron/Ion breakdown:



Contact Materials

The contact breakdown effects are dependent on the properties of the contact materials. If you change the contact material you can fundamentally change the breakdown phenomena.

The Vacuum Arc – Contact Material



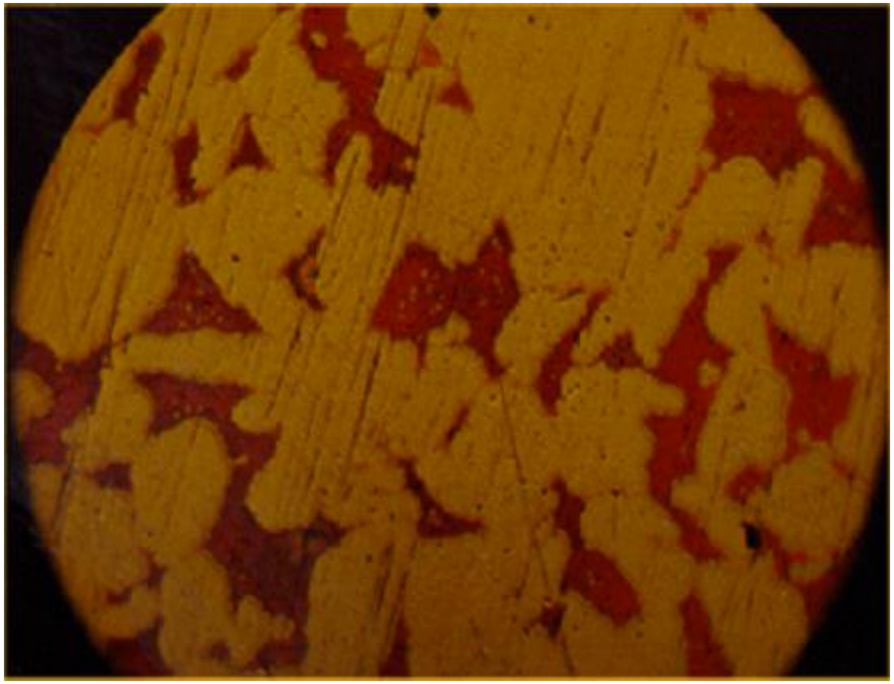
Still from HS film @ 5,000 pps showing 35mm diameter RMF contact interrupting 20kArms @ 12kVrms.

The term Vacuum Arc is a misnoma. What we have is really a metal vapour arc in vacuum.

The metal composing the arc gives the arc many of its properties.

Changing the material of the contact can fundamentally change the properties of the arc.

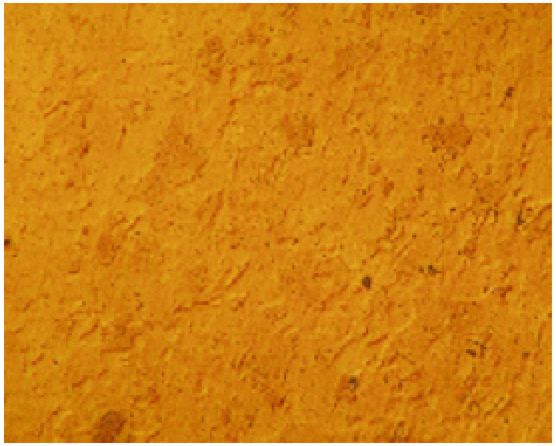
CLR

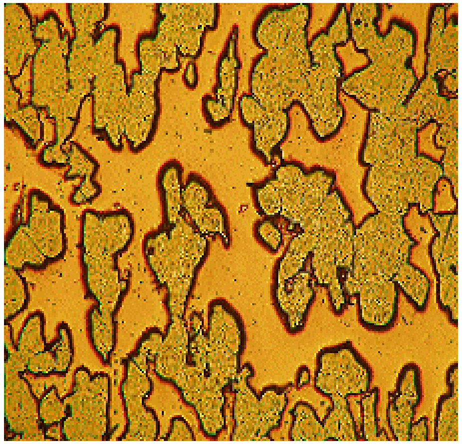


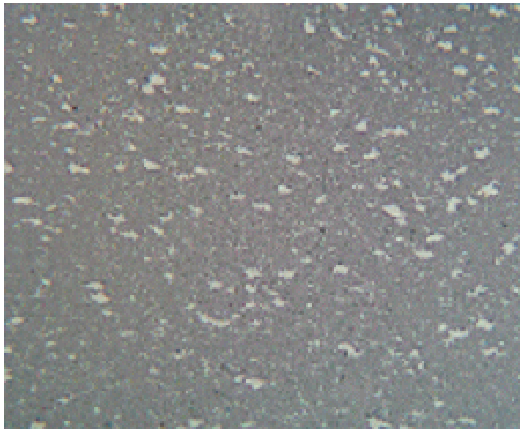
Photomicrograph of Chromium Copper (CrCu) contact material named CLR which was originally developed and patented by English Electric in the 1960's.

Chromium Copper is now the most popular contact material for MV Vacuum Interrupters in manufacture today.

Contact Materials used in Vacuum Interrupters and Switches







W Cu ***Cr Cu*** ***WC Ag***

Contact Material Effects

- ***Vacuum Compatibility***
- ***Dielectric Strength -***
- ***Current Interruption Ability***
- ***Current Chopping Level***
- ***Current Carrying Capacity***
- ***Erosion Resistance***
- ***Anti Welding Properties***
- ***Brazability***

VIL

Contact Material Requirements

Vacuum Compatibility	=	*Gas content & vapour pressure*
Dielectric Strength	=	*Melting point & ductility*
Current Interruption Ability	=	*Melting point*
Current Chopping Level	=	*Energy needed for arc*
Current Carrying Capacity	=	*Resistance*
Erosion Resistance	=	*Melting point & ductility*
Anti Welding Properties	=	*Melting point & ductility*

Contact Material Properties

Material	Structure	Vacuum	Dielectric Strength	Interruption Ability	Current Chopping	Conductivity Level	Erosion Resistance	Welding
Cu	Pure Metal	* * * * *	* *	* * *	*	* * * * *	*	*
CuBi	Alloy	* * * * *	* *	* * *	*	* * * *	*	* * * *
SbBi	Alloy in Mo	* *	*	* *	* * * * *	* * * *	*	* * * * *
CLR	Infiltrated CrCu	* * * *	* * * * *	* * * * *	* * *	* *	* * * * *	* * *
ZLR	Sintered CrCu	* * *	* * * *	* * * * *	* * *	* *	* * * *	* * * *
LR	Sintered CrCu	* * *	* * * *	* * * * *	* * *	* * *	* * *	* *
LR+	LR+Bi/Sb	* * *	* *	* * *	* * * * *	* * *	* * *	* * * *
WCu	Sintered	* * * *	* * *	* * *	* *	* * *	* * * *	* * *
WCAg	Infiltrated	* * *	* *	* * *	* * * * *	* *	* * *	* * *
			* worst	* * * * *best				

[5]Table partially based on "Advances in Material Development for High Power Vacium Interrupter Contacts" P.G.Slade, IEEE Transactions on Components Packaging & Manufacturing Technology Part A Vol. 17, No. 1 March 1994.

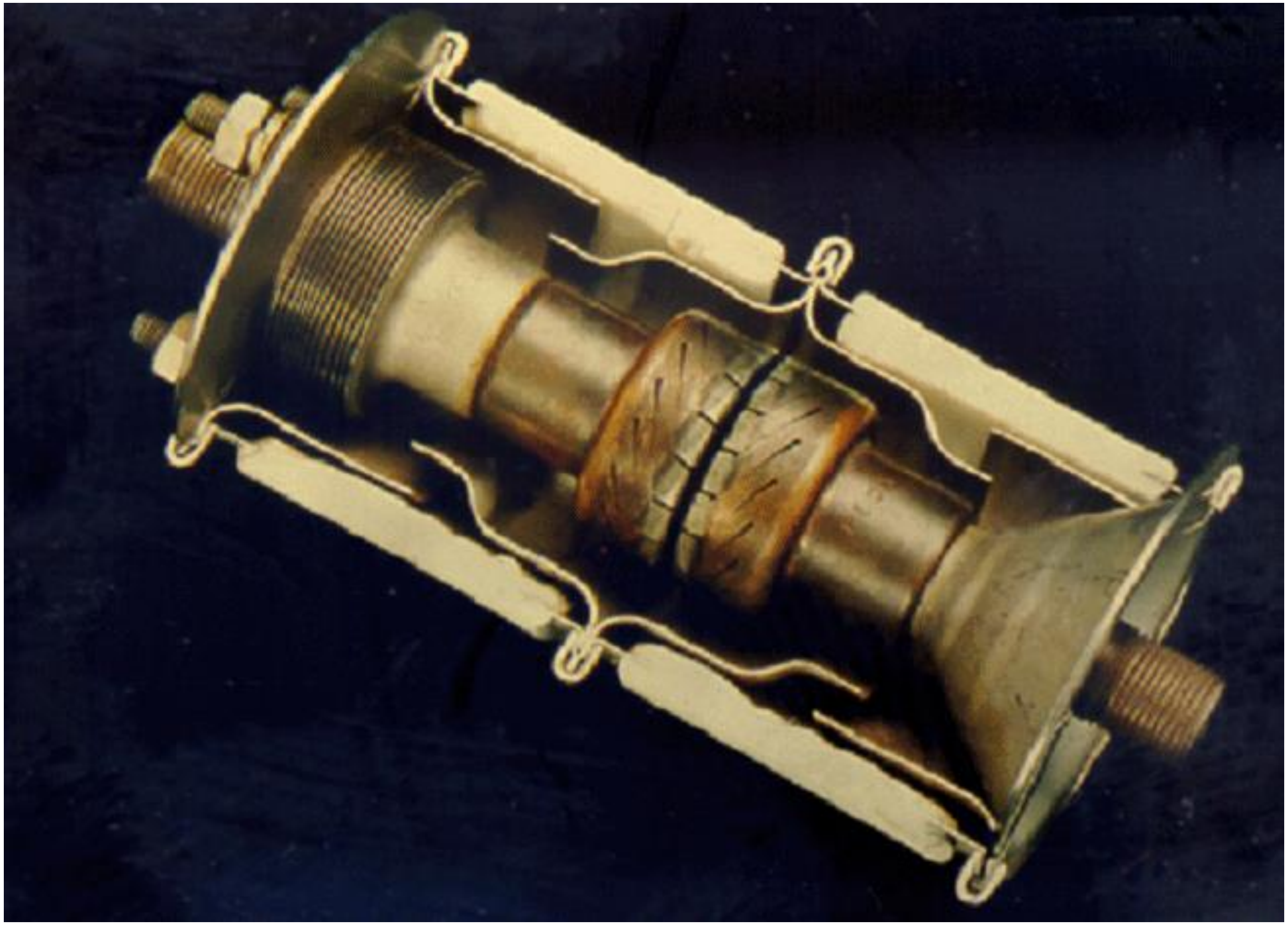
Contact Materials

The contact breakdown effects are dependent on the properties of the contact materials. If you change the contact material you can fundamentally change the breakdown phenomena.

We choose the correct materials to give the requried properties – low current chopping, high dielectric strength, low resistance, etc.

Unfortunately there are no free lunches – there is no wonder material that meets all needs, although Copper-Chromium does meet most MV requirements.

Classic Vacuum Interrupter Design



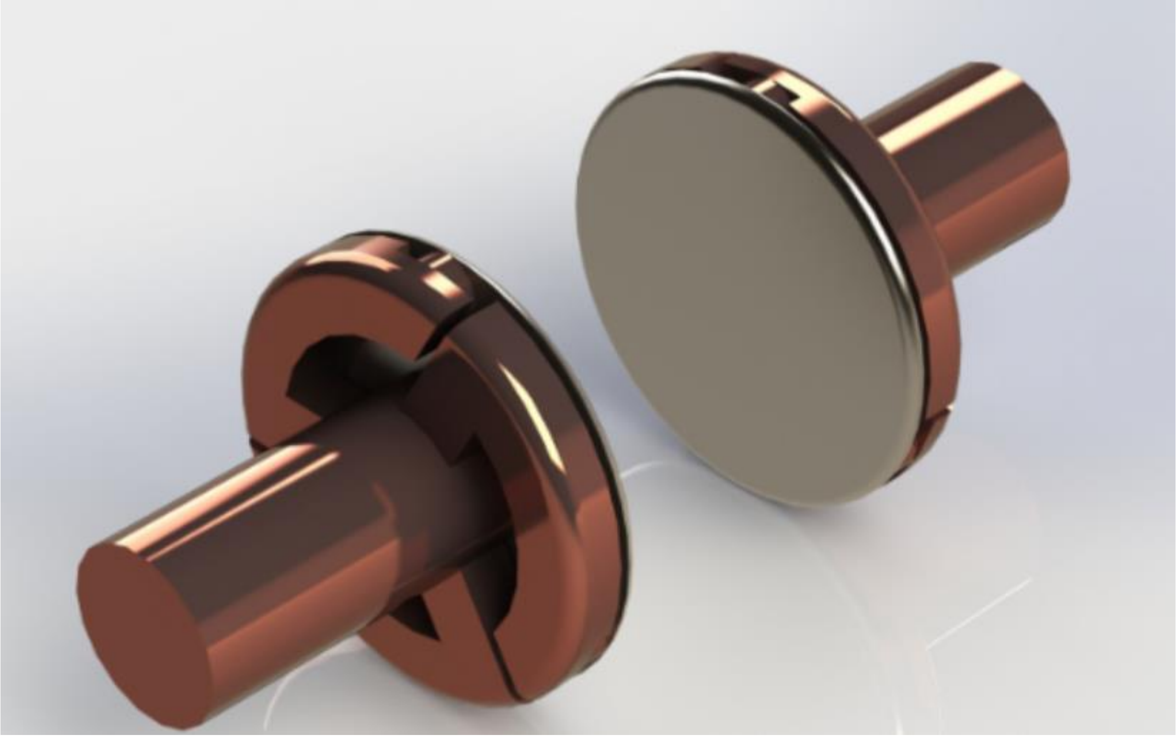
V8 1213, VIL Finchley 1970's.

The photo shows a VIL Type V8 interrupter from the 1970's.

This shows the basic design and main components of a Vacuum Interrupter.

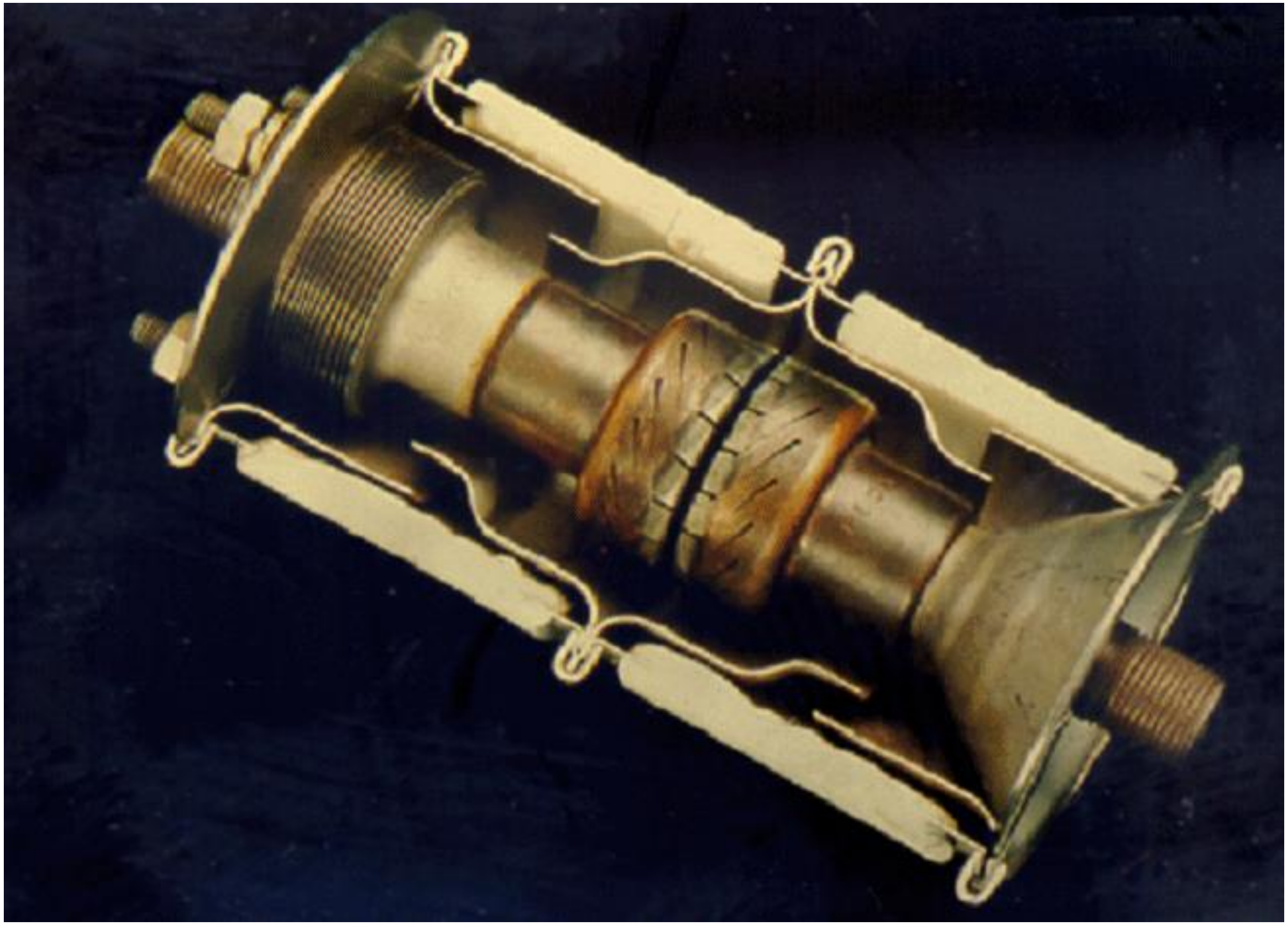
Basic Circuit Interruption

VI contacts



When the contacts arc, the metal vapour mainly condenses on the surface of the contacts, but a proportion escapes from the contact gap and moves out into the rest of the VI

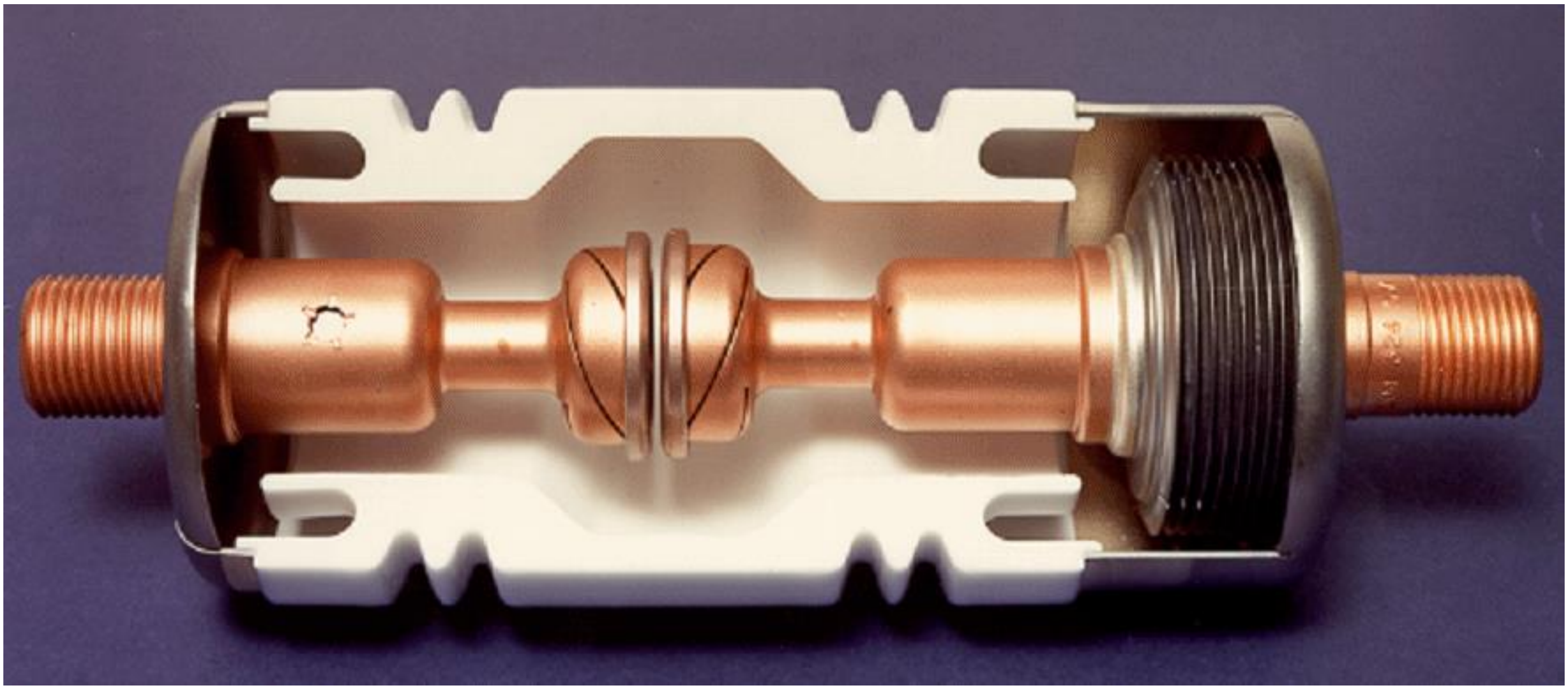
Classic Vacuum Interrupter Design



The shields protect the inner surfaces of the insulators from being metalised by the metal vapour condensing on them, which would compromise the insulation.

V8 1213, VIL Finchley 1970's.

“Shieldless“ Vacuum Interrupter Design (Self protecting ceramic insulator)



Technology & Size

Family of VIL 20kA@12kV interrupters from 1975 to 1995. Showing their respective contacts

The photo shows four interrupters ranging from a V5 of 1975 to a VI 100 of 1995. All of these are production devices and are rated at 20kA@12kV. The smallest being only 60mm in body dia., and with a 32 mm dia. contact.

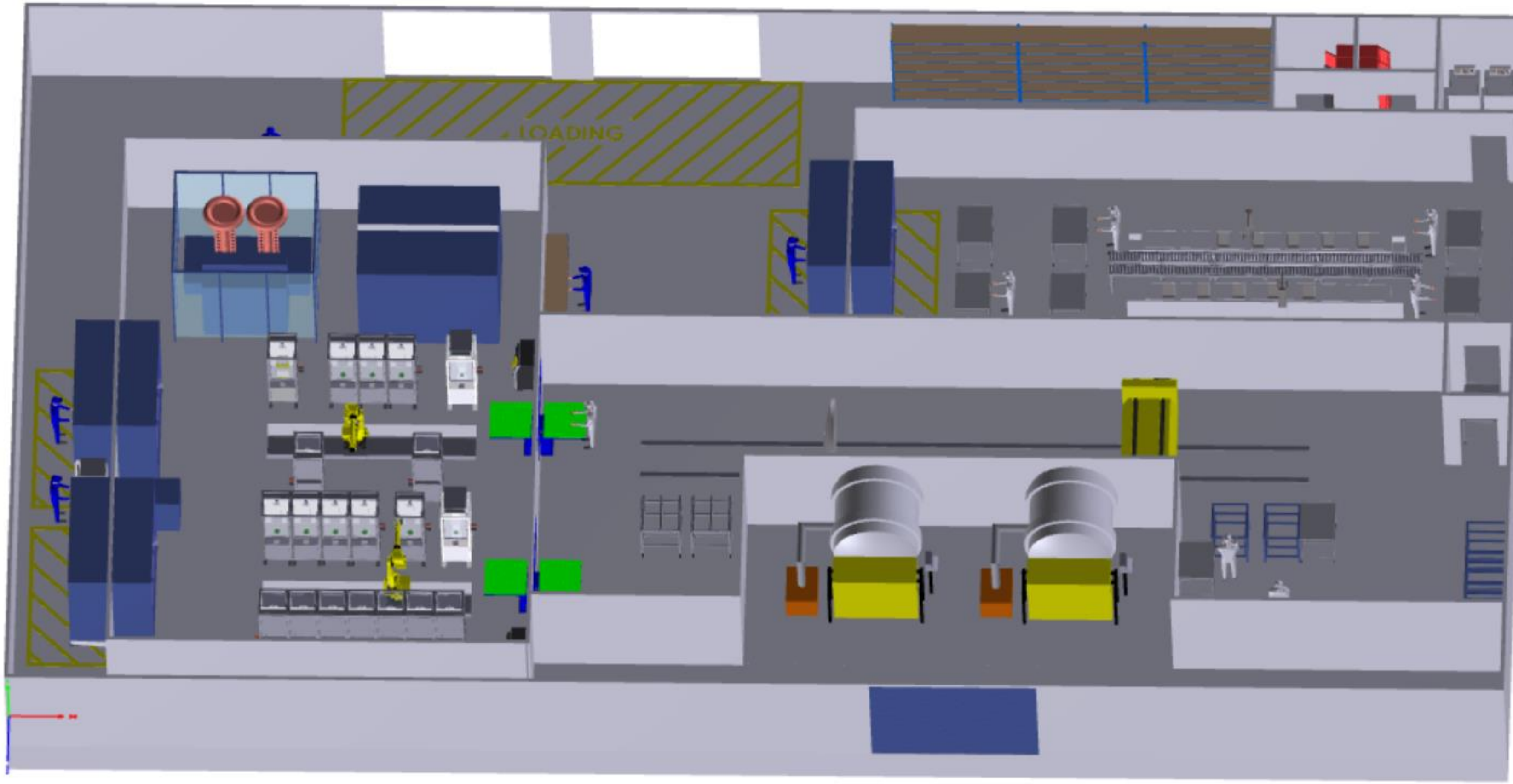
VIL

Vacuum Interrupter Families

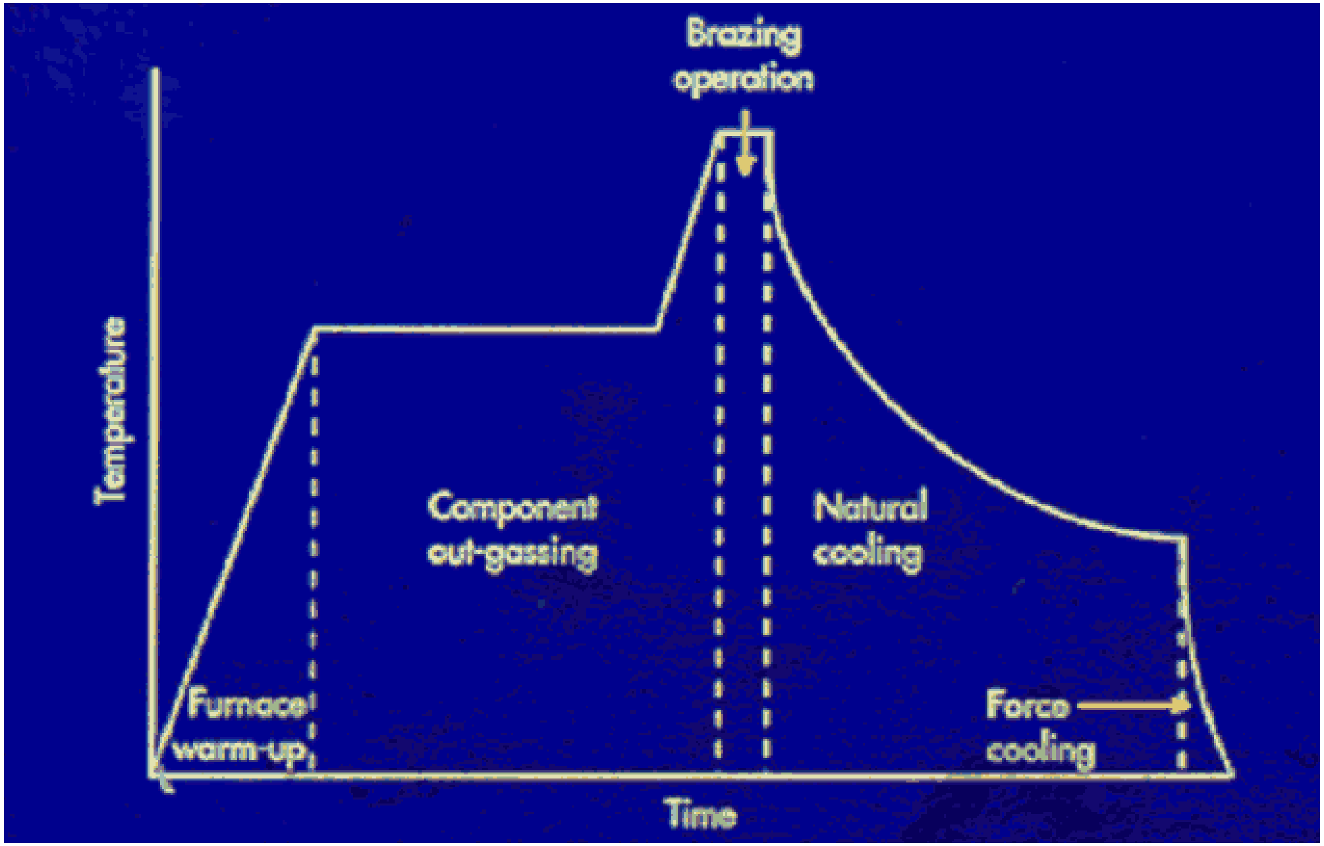
Modern vacuum interrupters are designed as a family in order to maximise benefits of standardisation both for the interrupter and the switchgear

The VG range. Just six interrupters covers 12kV:20kA to 12kV:63kA, and also 38kV:20kA to 38kV:40kA.

Manufacturing - Plant

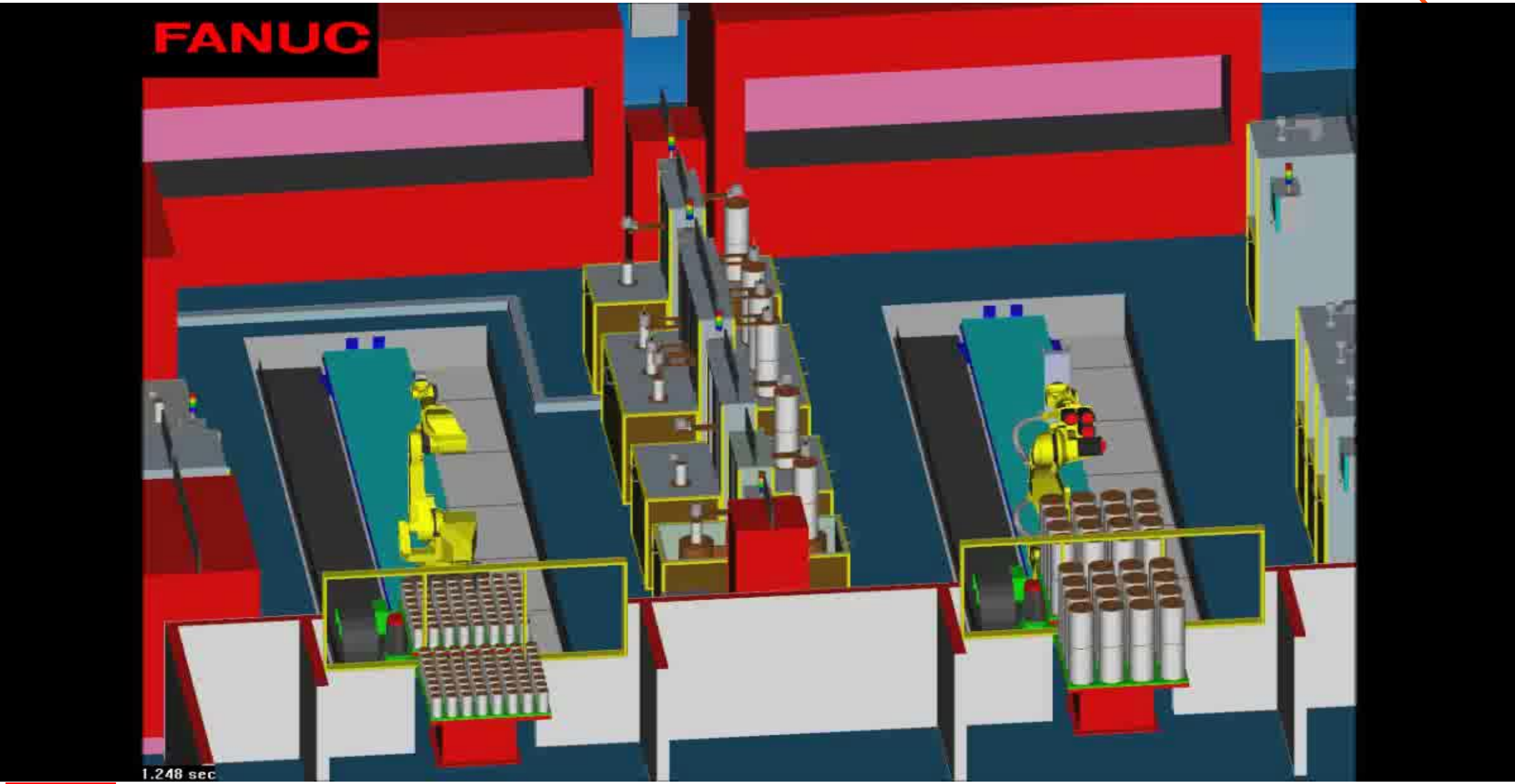


Manufacturing - One Shot Seal Off



This shows the One Shot Seal Off furnace cycle. Seal off takes place only at the highest temperature, after all components have been outgassed for several hours during the cycle. The Outgassing temperature is at over 700'C.

Vacuum Interrupter Factory Design



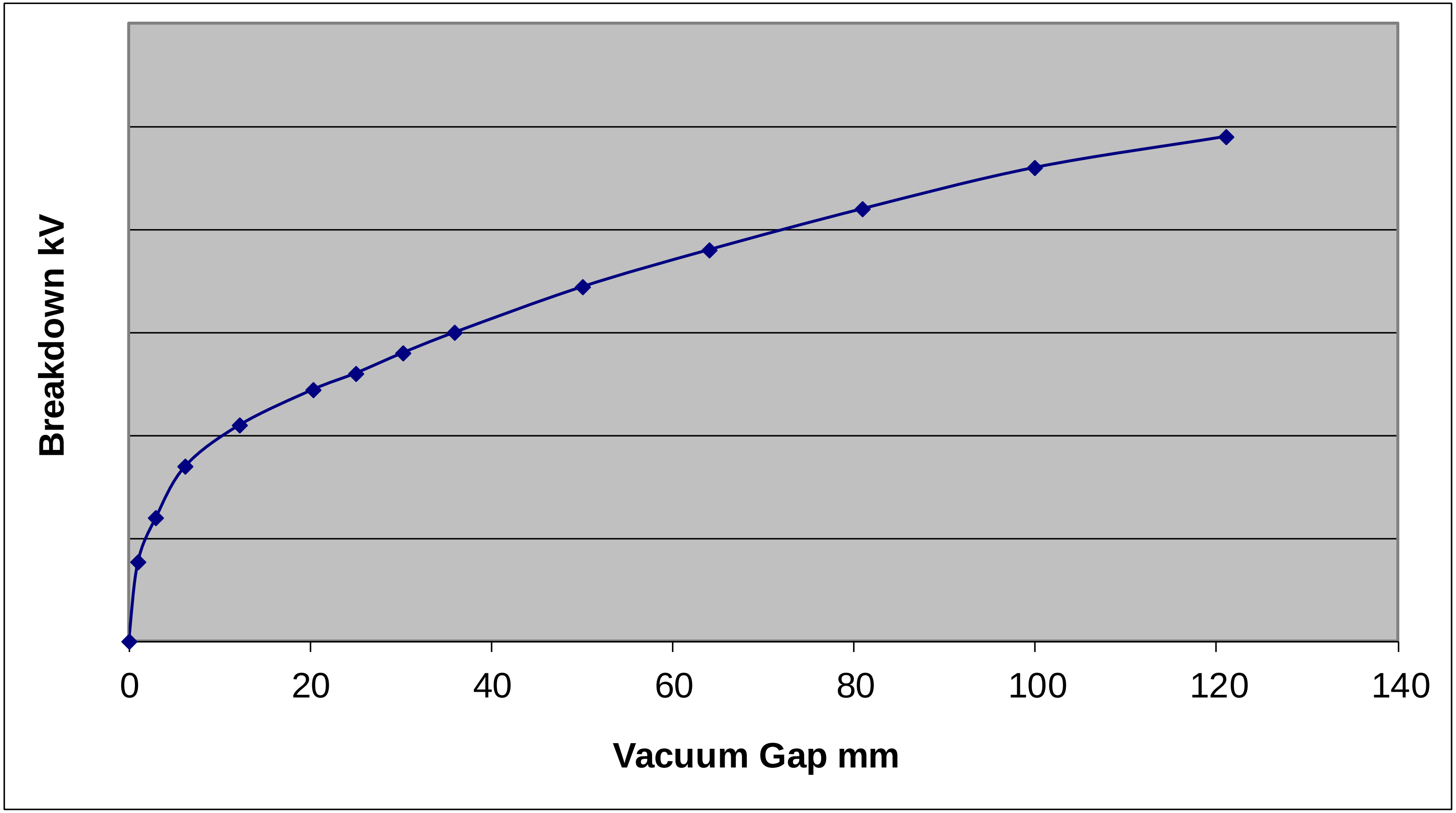
Breakdown in vacuum

Like many aspects of vacuum technology, breakdown in vacuum is not straight forward. As the vacuum gap increases the dielectric strength does not increase linearly as might be expected.

In fact smaller vacuum gaps have higher dielectric strength per mm than larger gaps!

Breakdown in Vacuum

Vacuum breakdown:



Vacuum Physics

Pressure [mbar]	Mean free path [m]
$1\cdot10^{3}$	$5.9\cdot10^{-8}$
$1\cdot10^{2}$	$5.9\cdot10^{-7}$
$1\cdot10^{1}$	$5.9\cdot10^{-6}$
$1\cdot10^{0}$	$5.9\cdot10^{-5}$
$1\cdot10^{-1}$	$5.9\cdot10^{-4}$
$1\cdot10^{-2}$	$5.9\cdot10^{-3}$
$1\cdot10^{-3}$	$5.9\cdot10^{-2}$
$1\cdot10^{-4}$	$5.9\cdot10^{-1}$
$1\cdot10^{-5}$	$5.9\cdot10^{0}$
$1\cdot10^{-6}$	$5.9\cdot10^{1}$
$1\cdot10^{-7}$	$5.9\cdot10^{2}$

The mean free path is the average distance that a particle can travel between two successive collisions with other particles.

When the MFP is bigger than the vacuum gap then the rate of change of dielectric strength with gap changes.

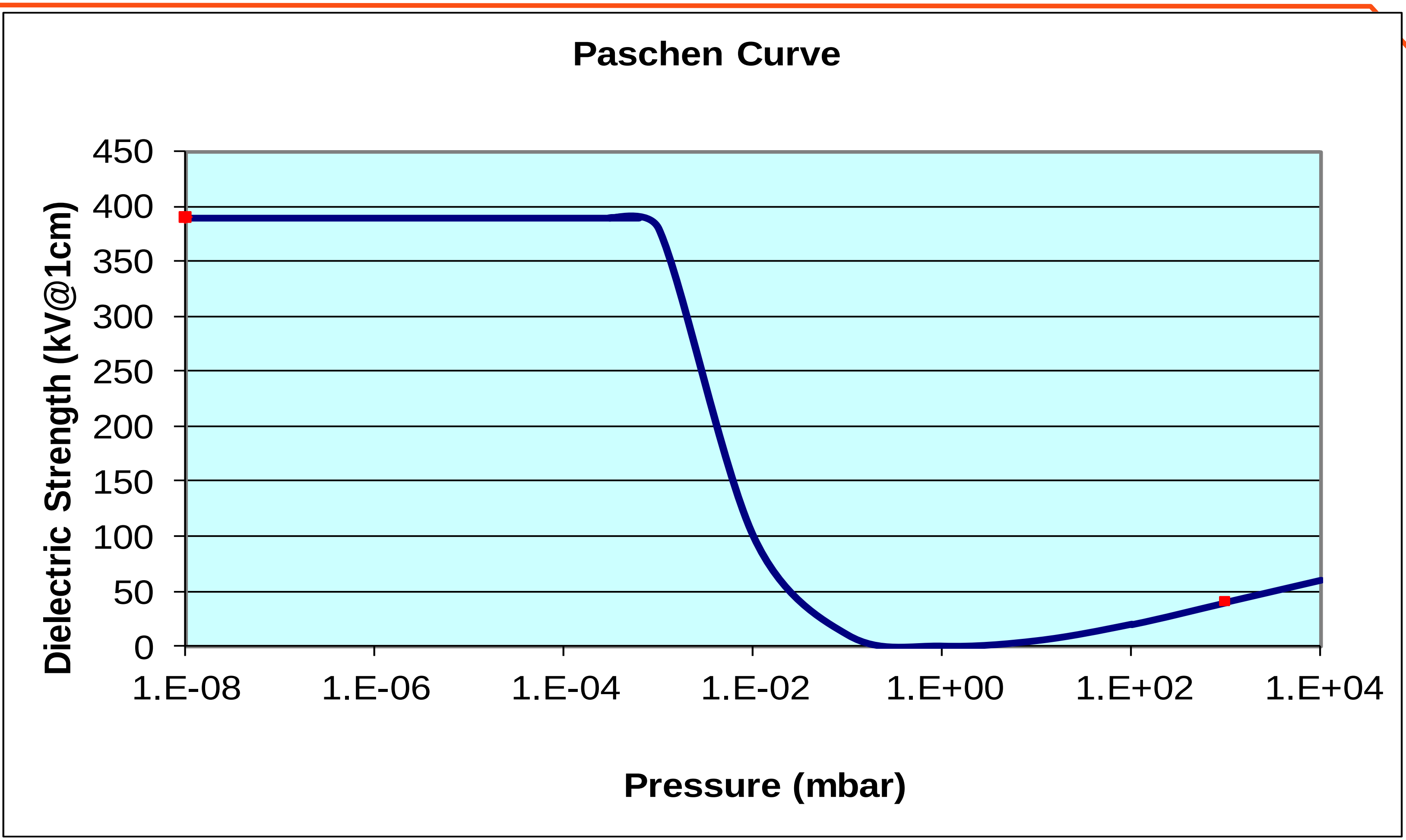
Breakdown in vacuum

Because the small gaps have higher dielectric strength it is possible, for example, to hold off around a maximum of 380kV with a 10mm gap, but to hold off 500kV with ten 1mm gaps!

This falling off of dielectric strength with gap size is a major reason why vacuum finds very high voltages (>38kV) more difficult.

It also means that multiple contact gaps have an advantage over single gaps with the same total stroke.

Vacuum Physics



Vacuum Performance in Service

The Vacuum properties we have looked at translate into a number of strengths and weaknesses when vacuum is applied in Vacuum Circuit breakers

These go some way to explaining why Vacuum & VCB behave the way that they do.

Vacuum & Contact Welding

When contacts are closed onto current there will be a breakdown at some point before contact touch.

This arcing will melt the contact surfaces and after contact touch the molten surfaces will set, and you have a weld.

If, for example, you close a vacuum breaker onto a fault current, and then open the breaker with just load current the arcing will melt any spikes on the broken surface,in effect reconditioning the surface, and restore the bil capability.

However, if you open the breaker without current the broken surfaces remain, and the bil will be greatly reduced until the next time the contacts are arced.

Vacuum & Contact Wear

When vacuum interrupter contacts switch, most of the contact material which has been vapourised recondenses back on to the contact surfaces. Material moves from one contact to the other and provided that we randomly switch polarity, the wear is evened out.

This means that contact wear in vacuum interrupters is very low.

Life expectancy in normal applications is 50 -100 full 100% short circuit interruption, and 30,000 – 50,000 load current interruptions. Much longer lives of up to 3,000,000 operation or more can be achieved by specially designed VI.

Usually interrupter life is limited by the mechanical life of the bellows.

Vacuum & Lightning Impulse testing (bil)

Vacuum is, by definition, self-restoring insulation.

However, as we have seen, conditioning and reconditioning can give the vacuum gap significantly different levels of bil capability.

This is why you can perform bil testing on a VCB and it fails the 2/15 test, but without making any changes the same VCB can then withstand hundreds of impulses without a problem.

This poses some problems for interpreting the requirements of the standards.

VIL

Vacuum Insulation & Isolation

As we have seen, a vacuum gap, although it is fully self restoring, can have a variable insulation capability depending on it's state.

Because of this, a single vacuum gap can be used to section a circuit, as in the worst case a breakdown due to a transient would result in a single half loop of current, before the VI would interrupt. Unlike other types of breakers, an open vacuum gap has full capability right up to the 100% asymmetrical short circuit rating.

An open vacuum gap is always ready to interrupt.

Vacuum Insulation & Isolation

An open vacuum gap is always ready to interrupt.

However, if the circuit needs to be isolated, then a single vacuum gap shall not be used for isolation, because, depending on the previous switching history, you cannot be sure of the bil capability at any given moment in time, and it could flash over.

Vacuum & Capacitor Bank Switching

The issues with welding, and voltage breakdown affect capacitor bank switching performance.

Added to this is the ability of Vacuum to interrupt very high frequency currents.

And the possibility of NSDD particle induced breakdowns.

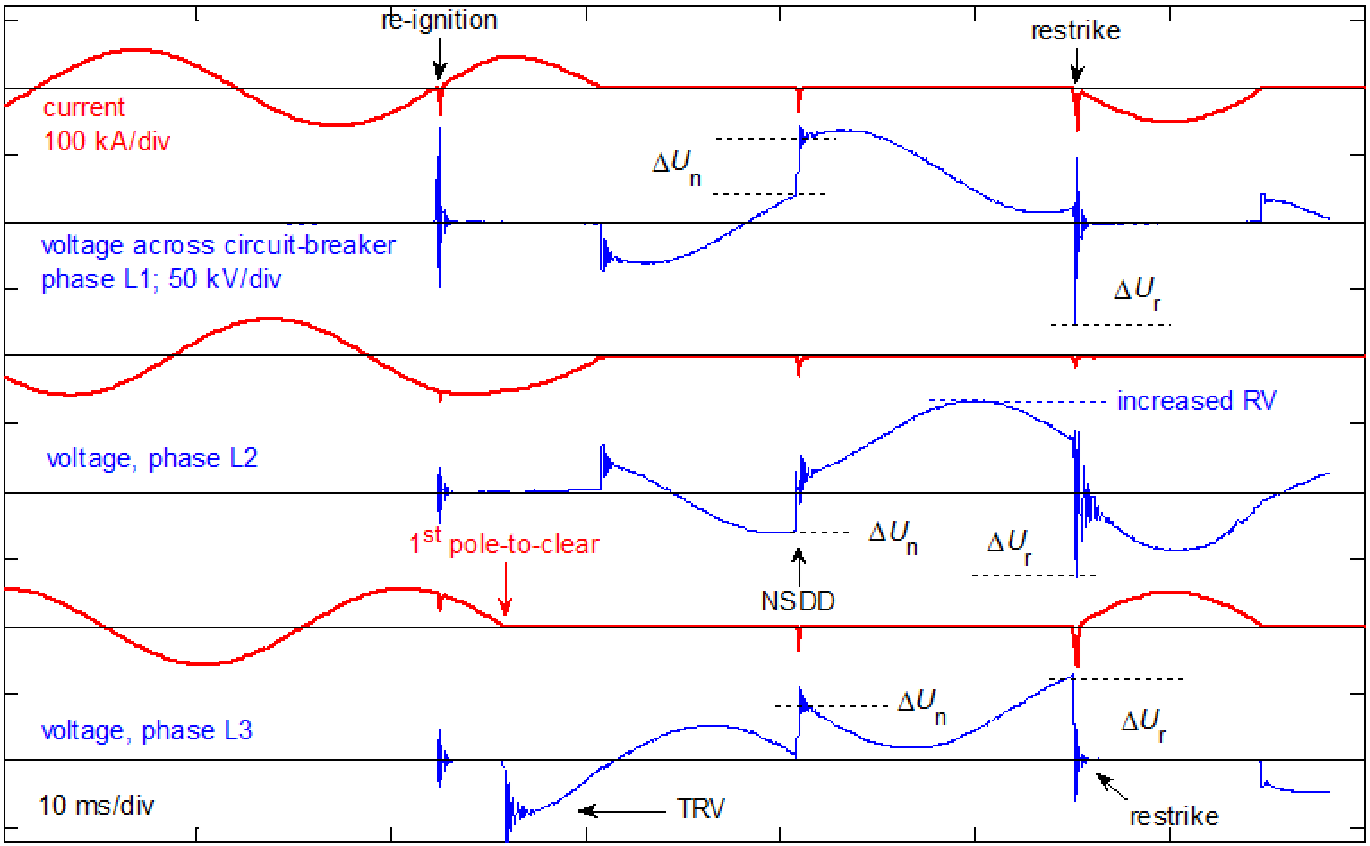
And the issue that if the polarity of the contacts is always the same the VI will have assymetrical wear of the contacts.

Together these factors conspire to make Capacitor Bank switching more onerous for VCB.

Breakdown in Vacuum

short-circuit current

KEMA Laboratories



Vacuum & Capacitor Bank Switching

Vacuum is however widely used for capacitor bank switching at voltages up to 27kV with acceptable performace, but for 38kV or above the probabilities of a breakdown build up.

The problem is statistical, and for low use switching, the probabilties of a breakdown may be acceptable, but for large numbers of operations the statistics are against you.

For these higher voltages it is normally recommended to use two VI in series, which significantly reduces the probability of an NSDD causing a breakdown, and increases the overall dielectric performance.

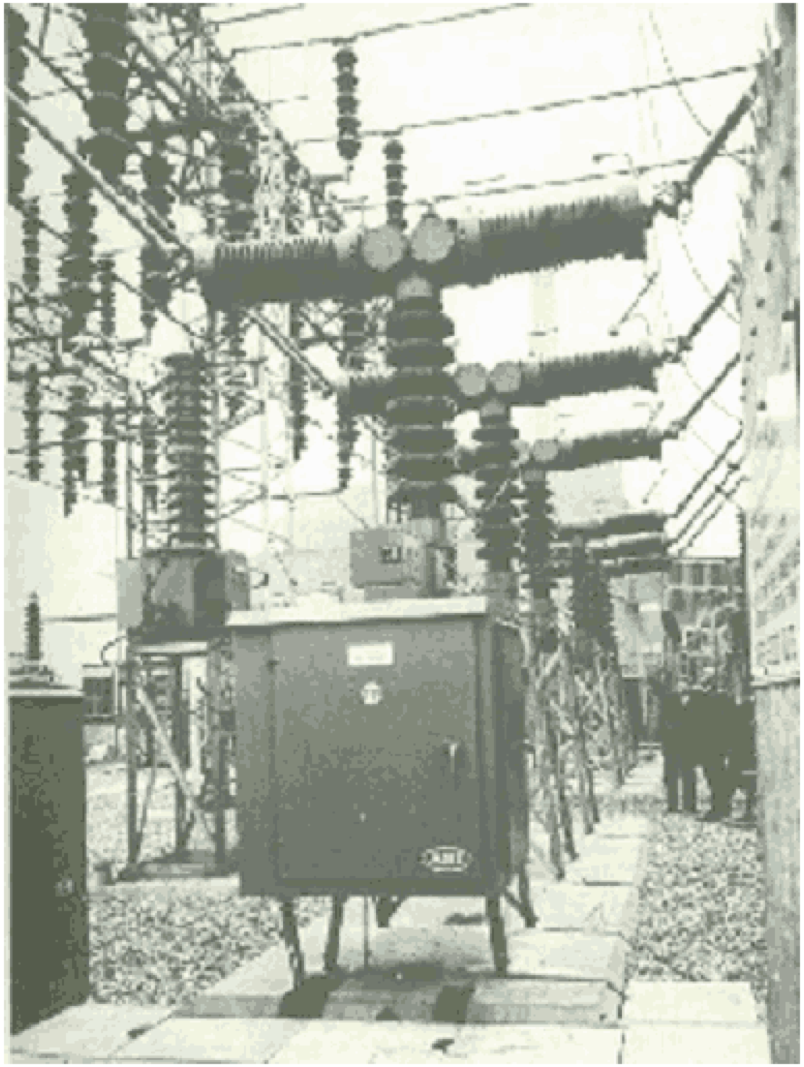
Vacuum & High Voltage Interruption

High voltage insulation fir transmission breakers (>38kV) is a problem for Vacuum as the big gaps needed for the TRV and bil ratings are in the zone where the insulation/mm is not so good.

As a result we struggle to meet these requirements. Multiple gaps helps, and is used on internal shielding, but the moving contact gap becomes increasingly difficult beyond 30 mm or so, and this limits the capability for single break vacuum at very high voltages.

145kV voltage class is probably not far from the practical limit for a single break VCB.

Early 132kV Vacuum:



The photo shows two AEI 132kV Vacuum circuit Breakers which went into service in London with the CEGB in 1967.

Others were installed in Wales and Devon. They remained in service until the late 1990's

Six breaks in series!

High Voltage Vacuum Circuit Breakers

72.5kV Live Tank Vacuum Circuit Breaker
(Courtesy Siemens AG)

A 72.5kV Live Tank Vacuum Circuit Breaker from Siemens

This has no SF_6 content and is the latest in a number of products where Vacuum is moving into voltages and applications previously dominated by SF_6

Siemens have also announced a 145kV Vacum Circuit Breaker

High Voltage Vacuum Circuit Breakers

145kV Live Tank Vacuum Circuit Breaker
(Courtesy JAEPS)

High Voltage Vacuum Circuit Breakers

145kV Live Tank Vacuum Circuit Breaker
(Courtesy JAEPS)

This is a 145kV Live Tank Vacuum circuit breaker, again with no SF_6 content

In size and performance it is very similar to SF_6 circuit breakers.

Worldwide there are now thousands of Vacuum cirucit breakers in service at 72.5 and 126/145kV voltages – CIGRE study A3-27 Technical Brochure 589

Vacuum – The Past

Vacuum switchgear has now been around for almost 60 years. (almost half of the time that we have had electricity networks!)

During that time it has come to completely dominate the medium voltage world.

Today over five million VI are manufactured every year.

Obviously the technology works, and reliability is extremely high.

Vacuum – The Past

Recently due to the SF_6 issues, vacuum is moving up into the lower transmission voltages, but as we have said vacuum is not a natural fit for this, and so there are difficulties to be solved.

After 60 years of development clearly VI technology is mature and we understand the technology very well, so surprises and radical new concepts are unlikely

Or are they?

New Technology

Vacuum technology is mature, but it still has plenty of scope for development.

The existing technology has not yet reached its full potential and as we push in new directions, the possibilities are still endless.

Here are a few examples of new technology coming to a circuit breaker near you very soon.

High Voltage Vacuum Circuit Breakers

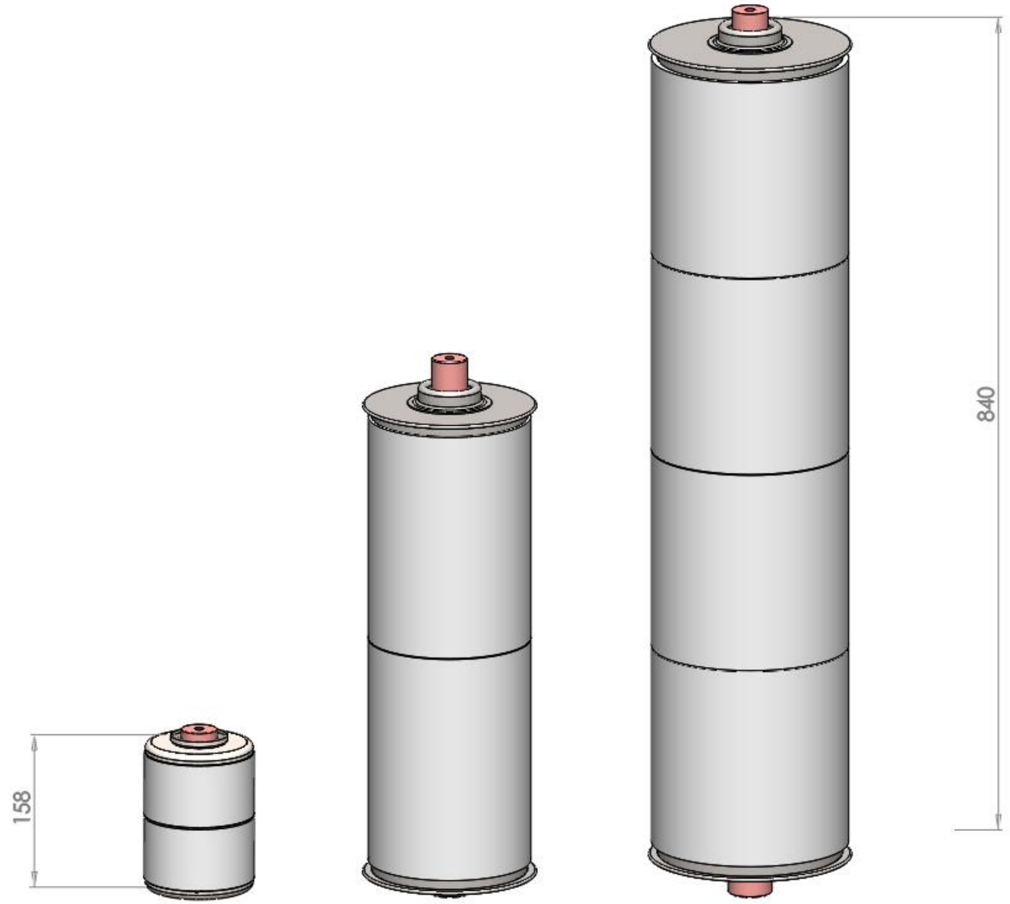
This is a 245kV Live Tank Vacuum circuit breaker design, (with no SF_6 content).

A double break Live Tank design, technically not a large step from the existing 145kV single VI VCB designs.

Dead Tank is also possible.

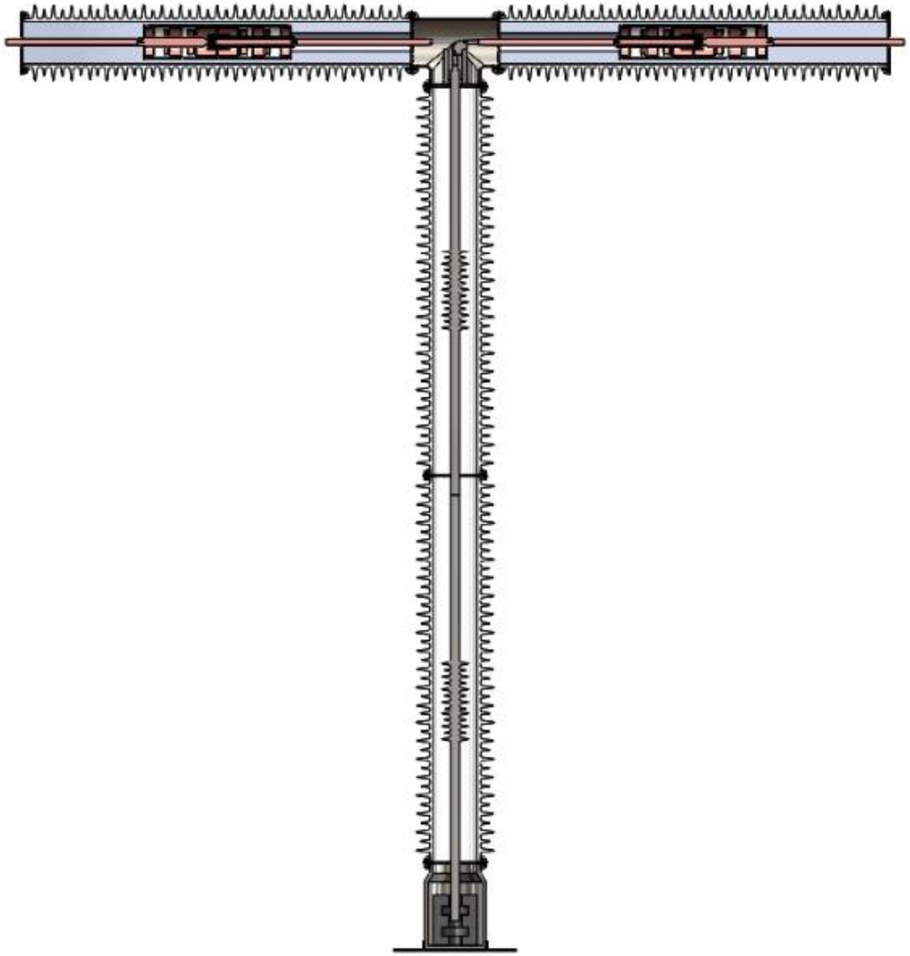
245kV Live Tank Vacuum Circuit Breaker

245kV double break vacuum circuit breaker



Size comparison: 38kV, 72.5kV, & 145kV Vacuum Interrupters

245kV double break vacuum circuit breaker



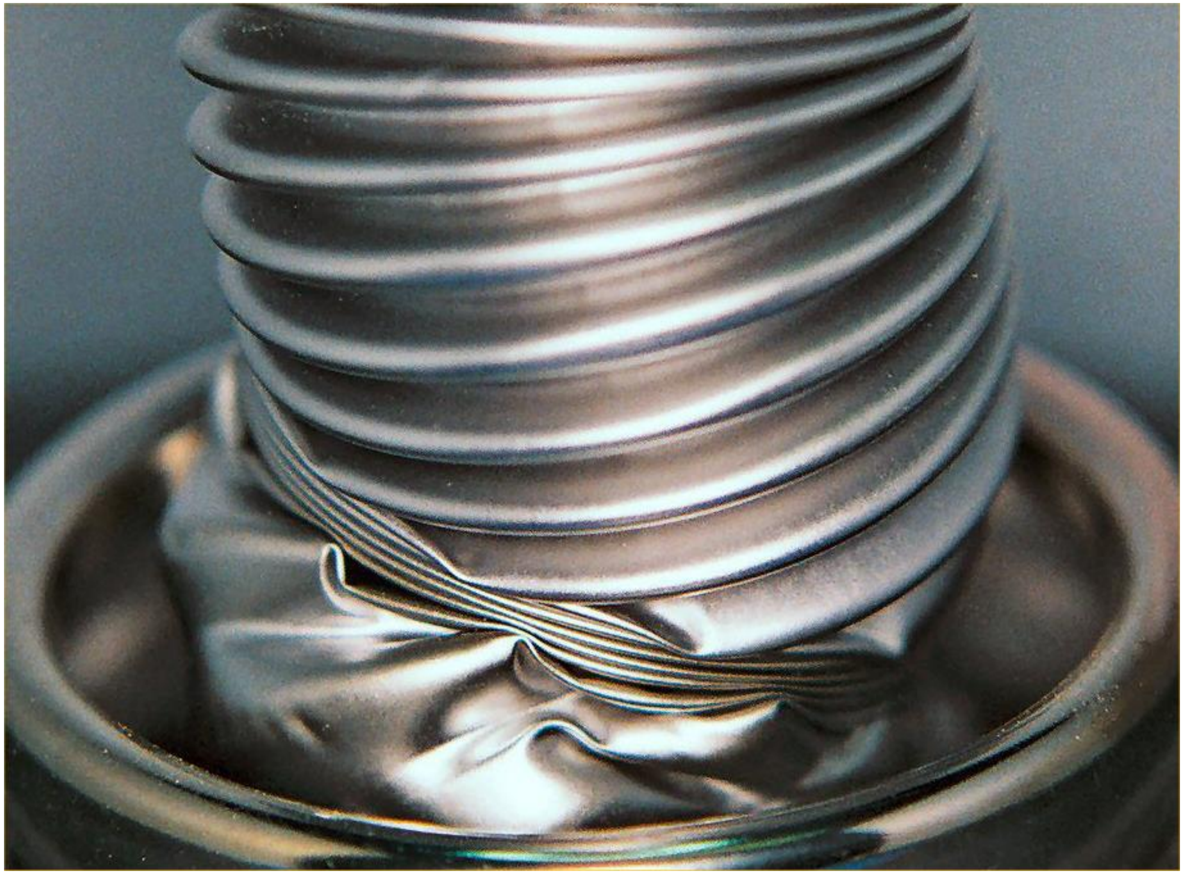
245kV double break vacuum circuit breaker

Existing Vacuum Interrupter technology can be used to move up to 245kV voltage class.

Higher voltages are more problematic, as we need more and more contact gaps to optimise the voltage withstand.

Not impossible to get to 500kV class, but increasingly difficult and probably not economic, although like most technology predictions, probably wrong. Of course, if you were desperate, you could always use two VCB in series, which brings a whole new set of problems...

Mechanical Damage - Twisted Bellows



The bellows is the mechanically weakest part of the VI and is protected in different ways by different manufacturers

– this VI lost vacuum in service due to the bellows being twisted during installation of the VI in the circuit breaker which seriously reduced its mechanical life

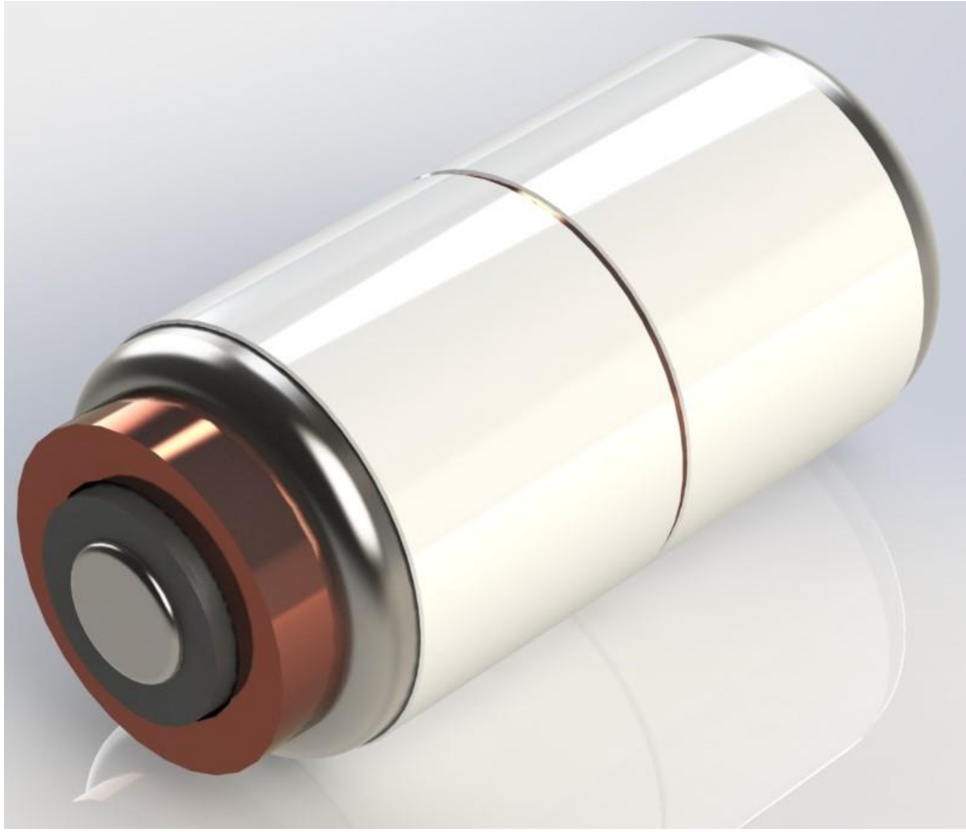
Mechanical Damage - Twisted Bellows

If we could design VI without bellows this would remove the weakest part of the design, but how to transmit the mechanical drive to the moving contact through the vacuum wall?

Self Actuating Vacuum Interrupter (SAVI)

The problem of transmitting movement through the vacuum wall without bellows is very difficult.

Self Actuating Vacuum Interrupter (SAVI)



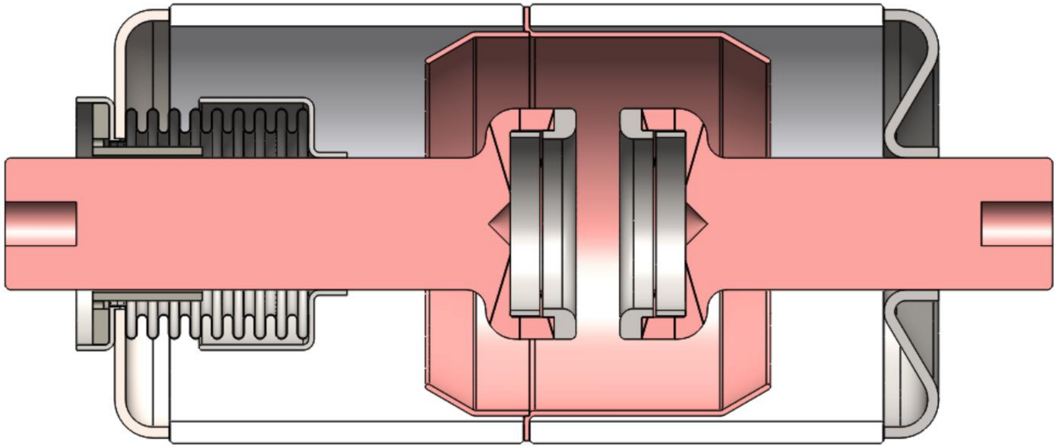
The problem of transmitting movement through the vacuum wall without bellows is very difficult.

So don‘t do it.

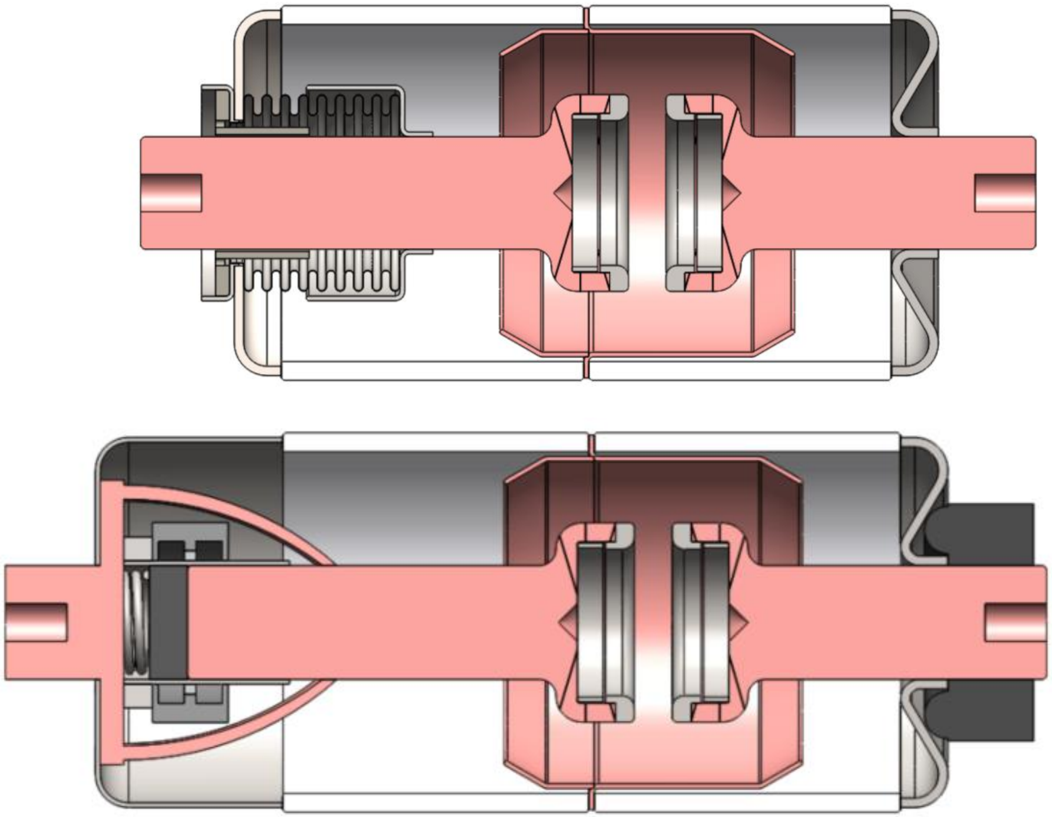
This is a vacuum interrupter with no bellows, and no external moving parts.

So how does it work?

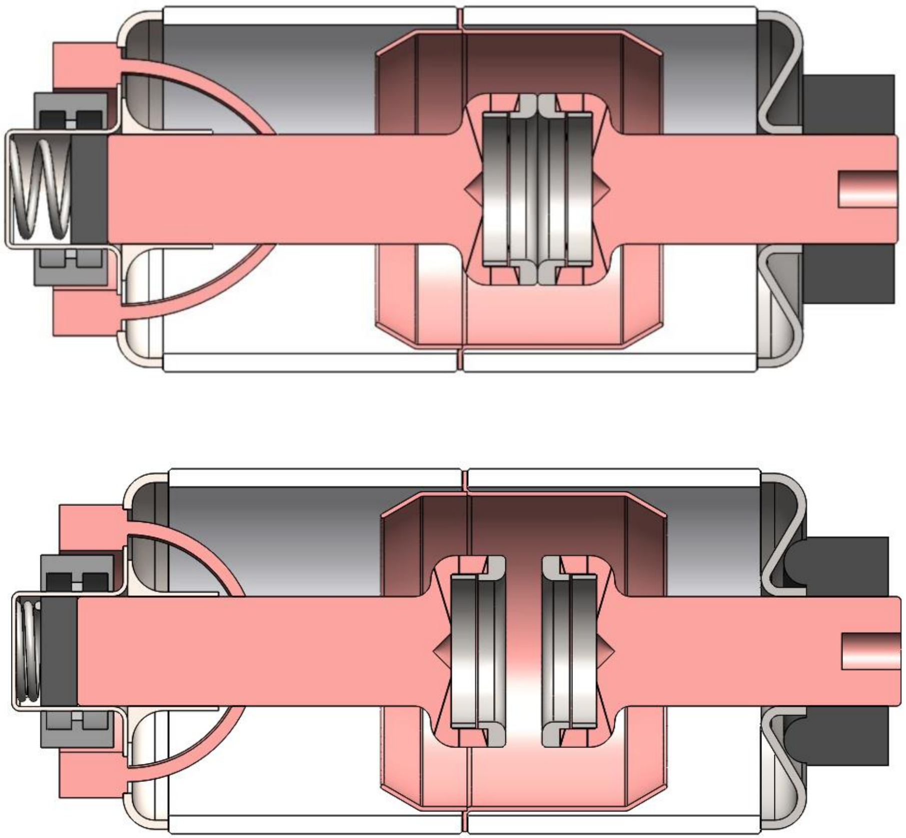
Conventional Vacuum Interrupter



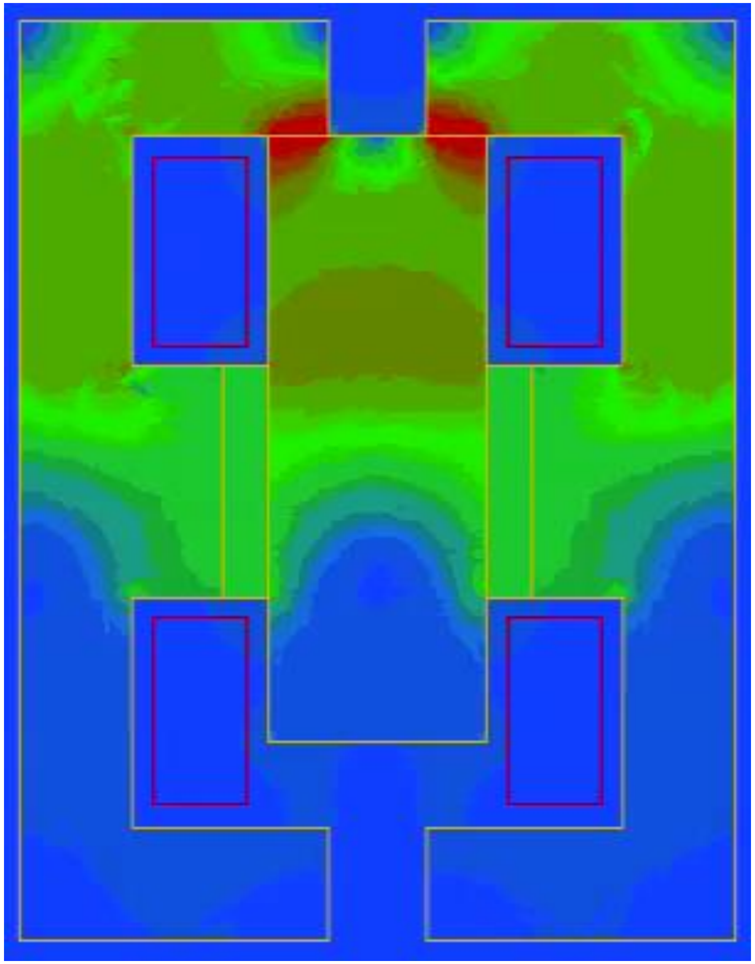
Comparison between Conventional Vacuum Interrupter and SAVI



SAVI design showing open and closed position - External coil

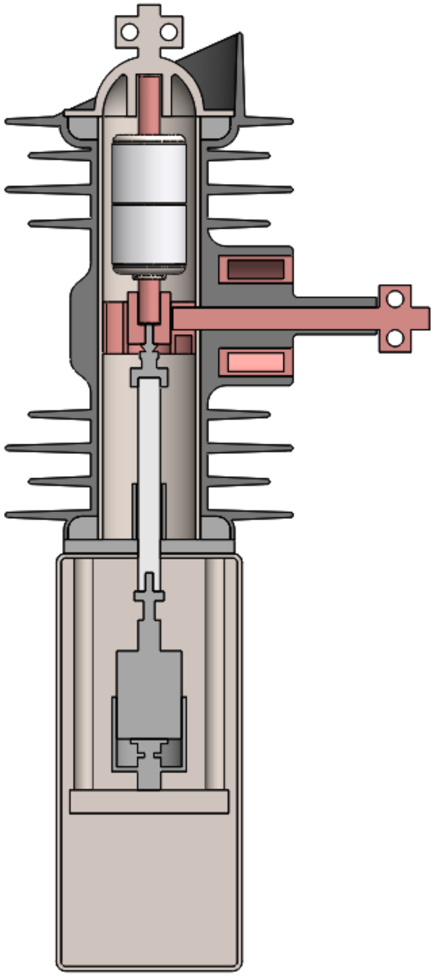


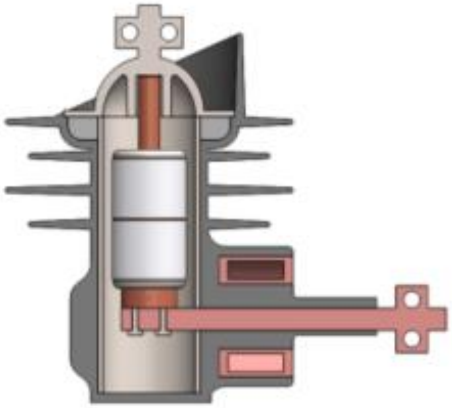
Magnetic actuator principle



Curtesy EPS (UK) Ltd

Comparison of SAVI v's Conventional outdoor VCB





Conclusion

It has been a wild ride through the ins and outs of vacuum technology, with excusions to some interesting and possibly weird places, and as I said at the beginning, much of the technology has been simplified to the extent that it is "almost true".

For example I did not mention that when you measure vacuum using a magnetron discharge, you actually change the pressure in the VI significantly, so the calculation of leak rate is much more complex than at first sight!

That explanation is for another day.

Conclusion

Hopefully this lecture has explained some of the strangeness of Vacuum & vacuum circuit breakers,

But now is the time for you to ask all of those questions you were previously too afraid to ask!

Thank you!

Further Reading

Books:

Vacuum Arcs	Lafferty	1980
Power Circuit Breaker Theory and Design	Flurscheim	1982
Vacuum Switchgear	Greenwood	1994
Explosive Electron Emission	G Mesyats	2001
Distribution Switchgear	Stewart	2004
The Vacuum Interrupter	Slade	2007

Papers:

www.vil.org.uk/library

VIL