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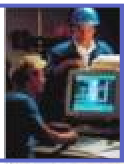
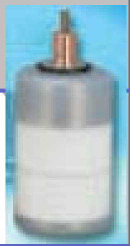
ABB Inc.

Vacuum Switching TUTORIAL



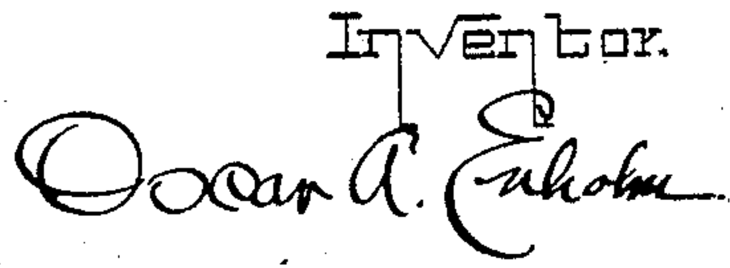


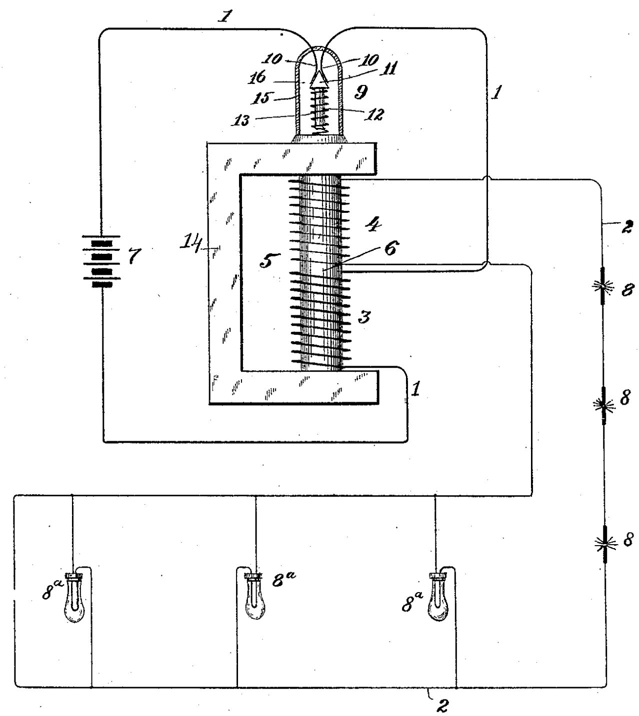

Vacuum interrupters.

Their Design, Mechanical and Electrical Characteristics

Presented at the IEEE Tutorial – Design & Application of Power Circuit Breakers, July 2008

First patent for Vacuum switching- Feb. 1890





matic electro-magnetic rheotome. The difficulty which has attended the use of such a system is the destructive sparking which takes place between the terminals of the automatic rheotome. With the large currents necessary for commercial purposes—such as electric lighting—this sparking gives rise to an arc which is maintained until the circuit-breaker is destroyed. To obviate this I cause the primary circuit to be broken in a vacuum between solid conducting-electrodes. This is found to prevent sparking and enables the automatic rheotome to be used with currents of great energy without injury to the terminals.

Other advantages of this improved circuit-breaker, in connection with inductive coils generally, is that by shortening or sharpening the break it increases the electro-motive force set up in the secondary by the break in the primary circuit.

That part of my invention which relates to placing the terminals in a vacuum is of utility in connection with circuit-breakers generally, and I do not limit myself to the particular application of it here shown.

First Power Vacuum Device - 1926

R. Sorensen (Prof.)
H. Mendenhall
CalTech, Pasadena
Sept. 1926

Vacuum-tight joints between the lead-in conductors

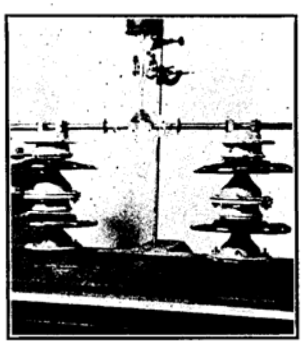


FIG. 2—VACUUM SWITCH NO. 2

and the glass envelope of the switch were easily obtained by means of W. G. Houskeeper's disk seals.[5]

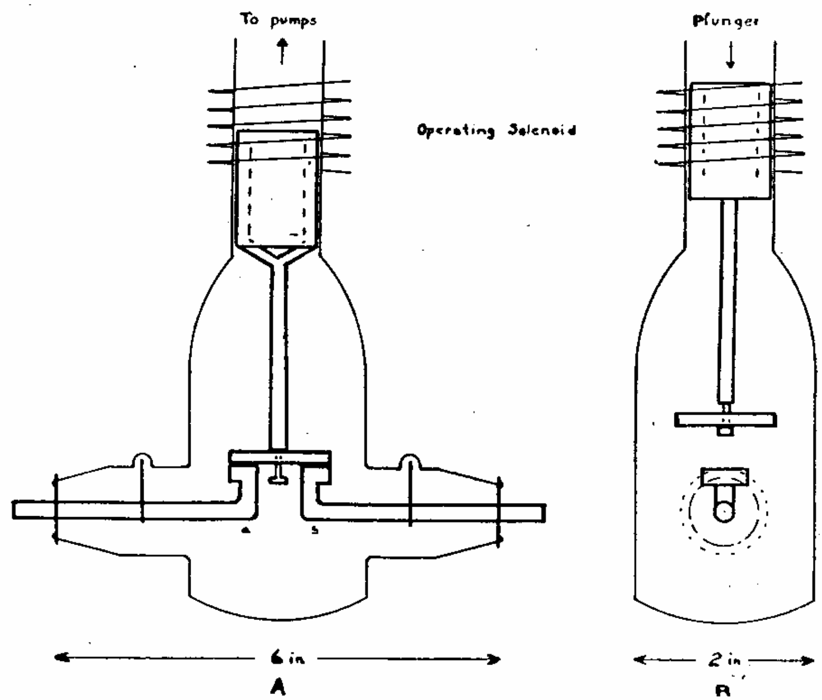
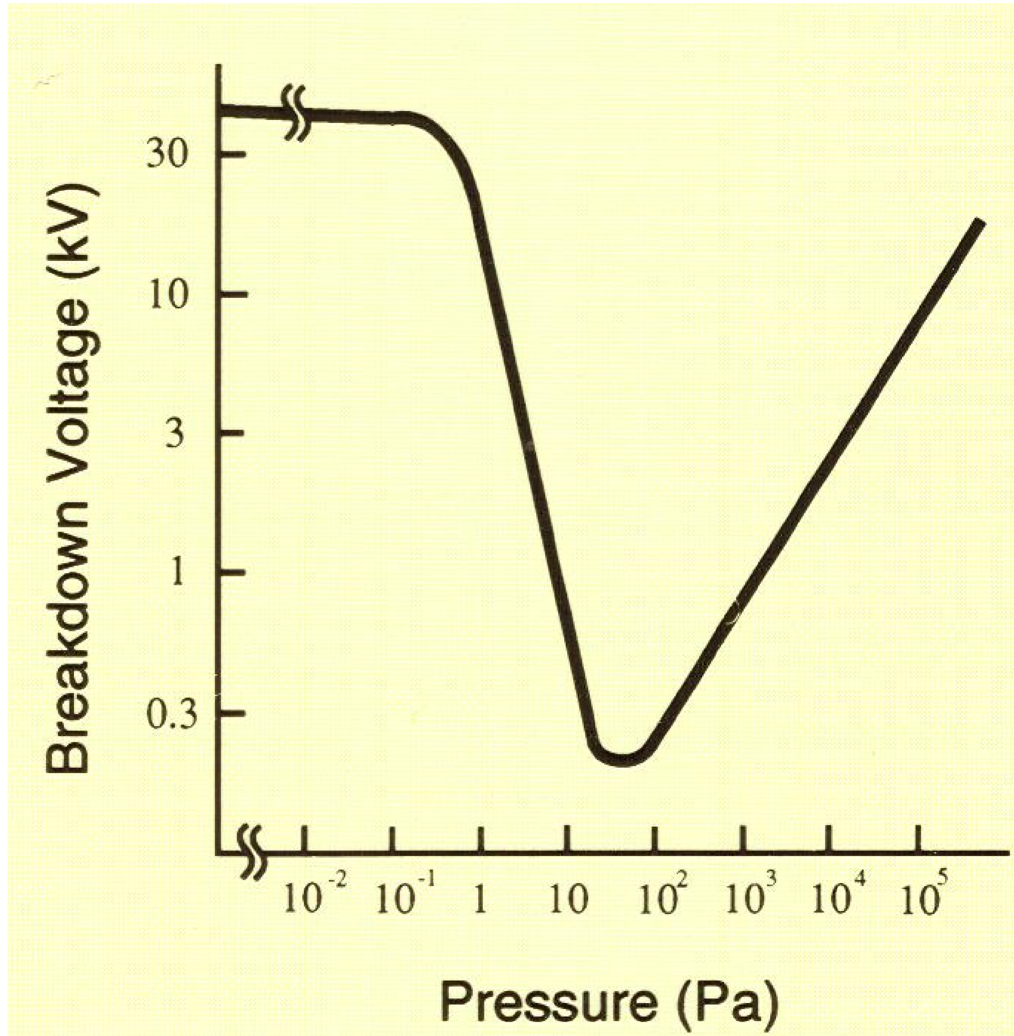


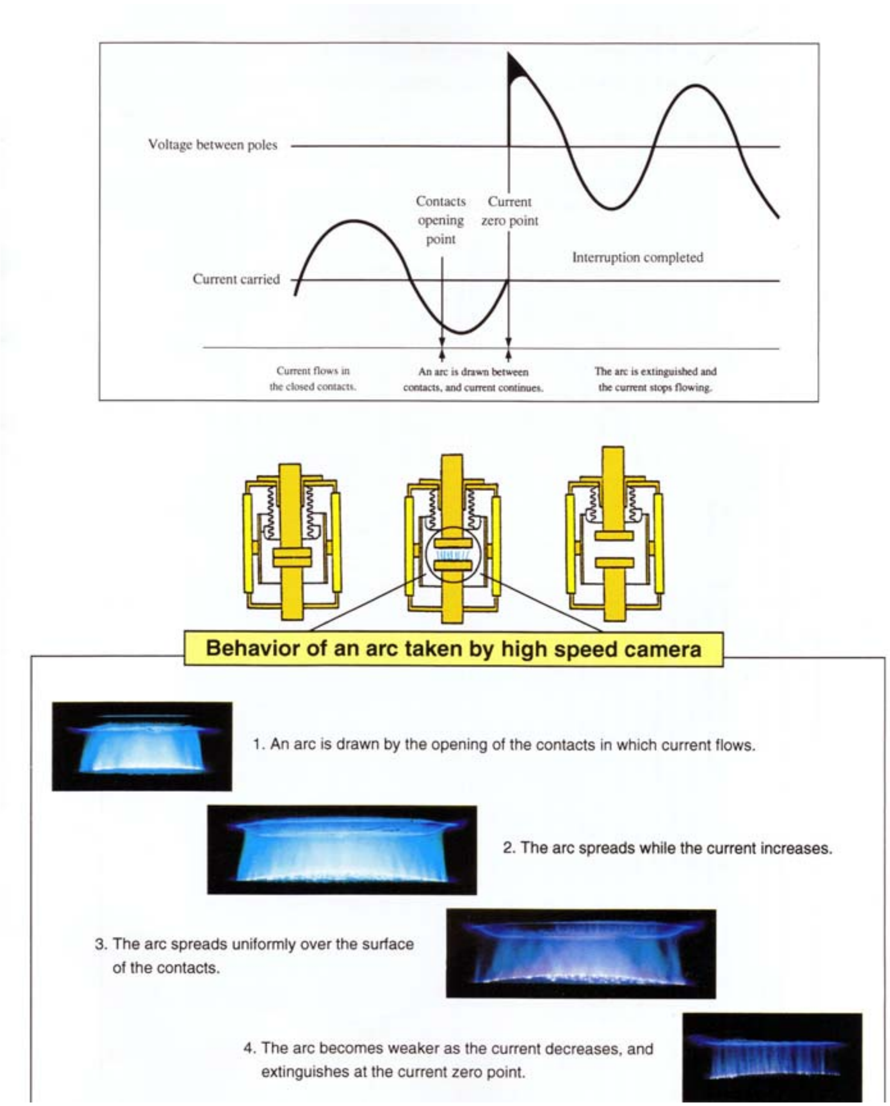
FIG. 1—CROSS-SECTION VIEWS OF SWITCH NO. 1

Vacuum as Dielectric

- Dielectric strength- 30-40 kV/mm
- short distances required to support system voltage (typical contact separation 3-15 mm)
- compact equipment
- insulating properties not altered by environment (sealed)
- do not change with time



Vacuum as Interrupting medium

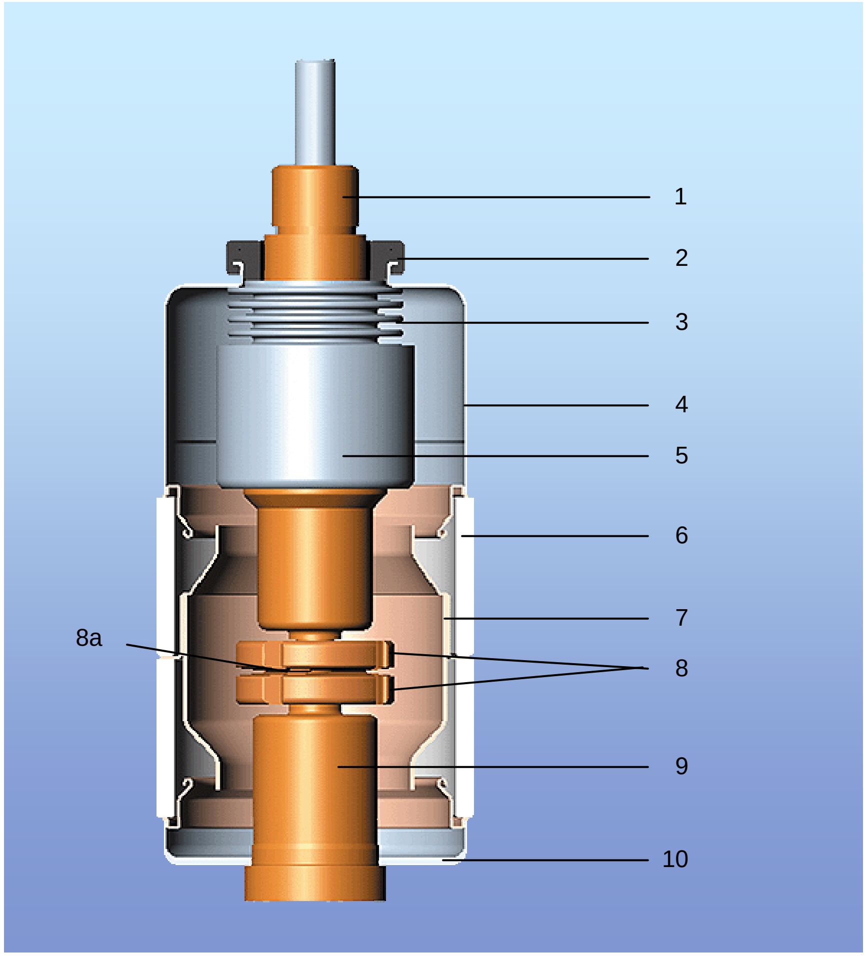


- when contacts separate the arc in vacuum is drawn
- the arc continues until the next current zero of 60 Hz
- the arc is extinguished in a very short time
- the dielectric strength across the contacts is recovered extremely quickly (in few μs (10^{-6} sec))
- vacuum arc dissipates very low energy (arc voltage only 20-80 Volts)
- no significant heating

Vacuum versus other switching technologies

Property	Vacuum	SF6, air, oil
contact travel	small (3-15 mm)	long (20-80mm)
opening/closing speed	moderate (~1 m/s)	higher (>2 m/s)
energy required to operate	low, (low mass of contacts to move, short stroke)	higher energy required to build up pressure (SF6) and move fast
contact force	required to overcome contact popping and provide low R-contact	low, to provide low R-contact
dielectric	excellent (40kV/mm)	good to very good (3-40 kV/mm)
arc interruption	excellent in the whole range of currents (from small inductive to full SC)	good to very good but blind spots exist (small inductive currents, for example)
durability	typical >10,000 mechanical operations, >30 SC operations can be extended to 100,000 or even 1,000,000 for contactors	contact inspection and service is often required
maintenance	none to interrupters, sealed for life	contacts-required periodically gas pressure checks, etc.
environmental	none	spills, gas leakage, toxic arc byproducts,.etc.

Typical design of vacuum interrupter



1 Moving contact stem
2 Bellows-twisting protection
3 Metal bellows
4 Interrupter lid (or end-plate)
5 Bellows shield
6 Ceramic insulator(s)
7 Contact shield
8 Contacts (main geometry)
8a Contacts (contact material)
9 Fixed contact stem
10 Interrupter lid (or end-plate)

The secret is in contact material and arc control geometry!

Contact Materials

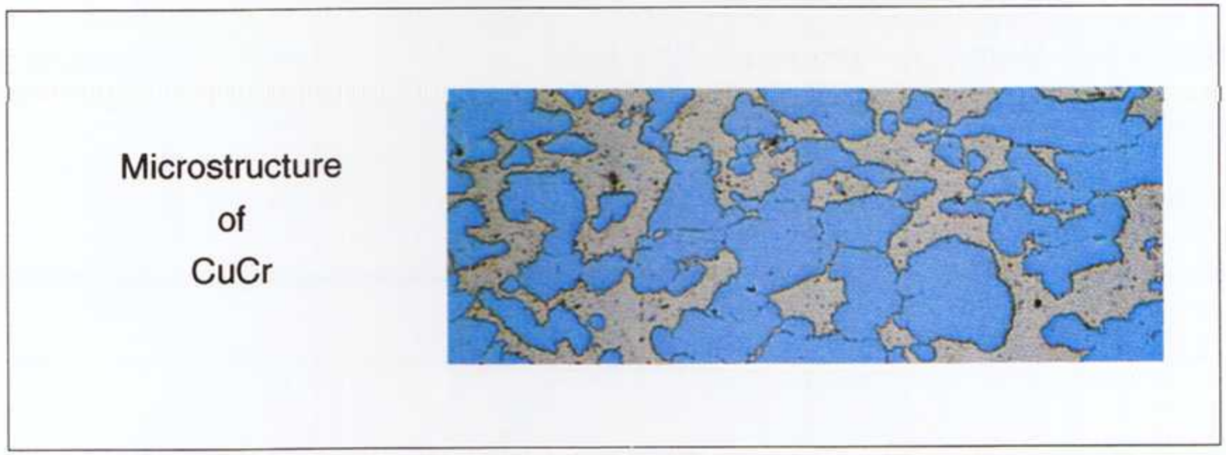
<u>Typically:</u>

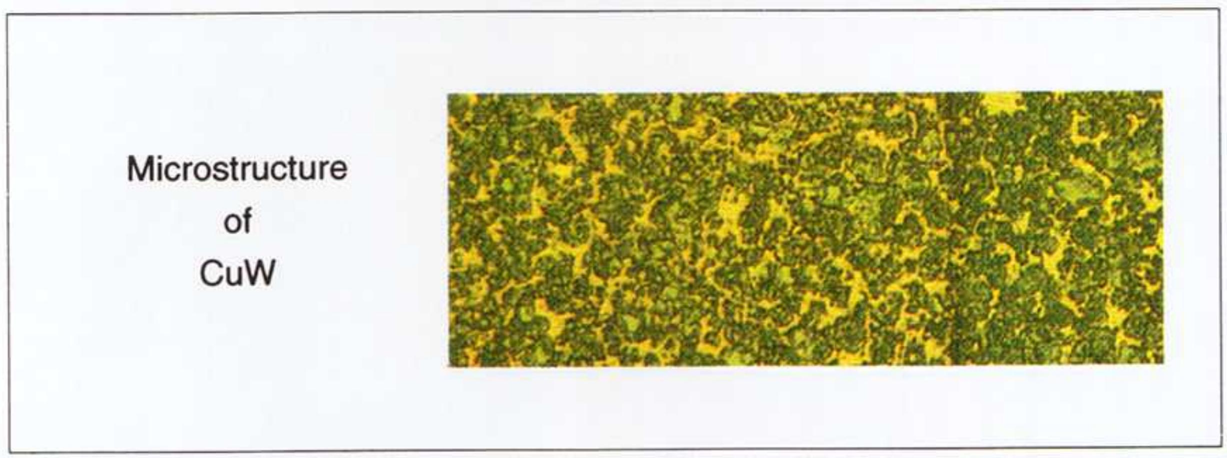
-CuCr for circuit breakers

-WCAg for LV contactors

-CuW for low current applications

-CuBi for circuit breaker (second alternative)



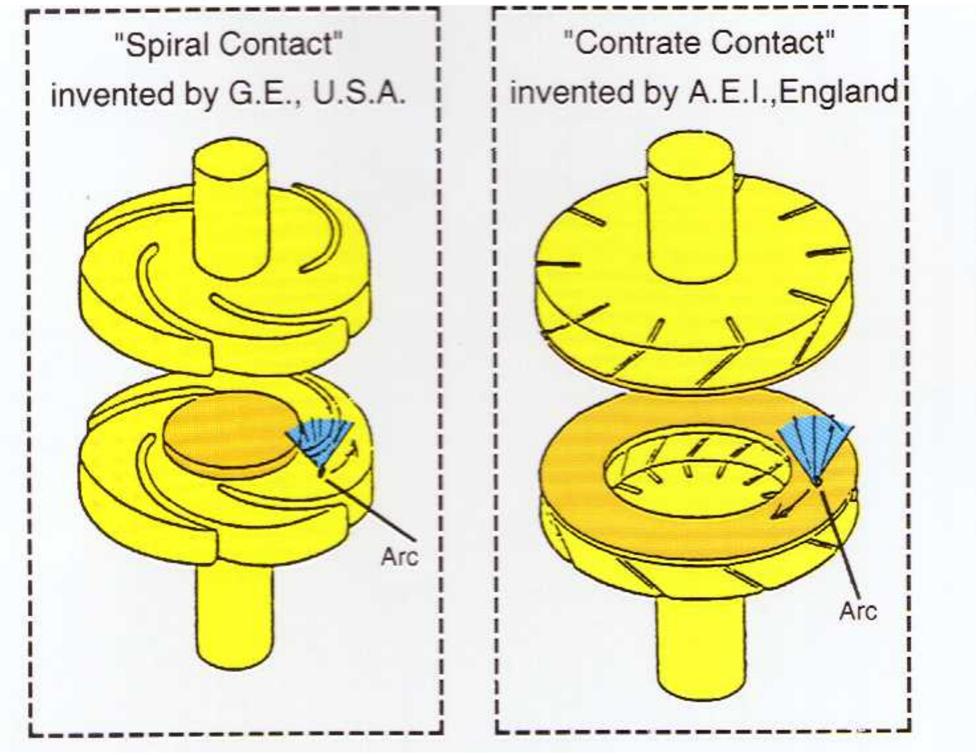


Arc Control Geometry- Radial Magnetic Field - RMF

- Arc moves around the perimeter in radial magnetic field generated by the current itself flowing through the geometry

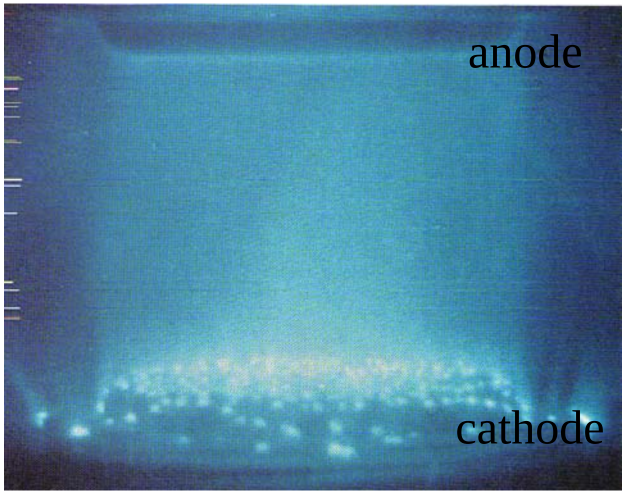
- can rotate up to 3-5 times per half cycle

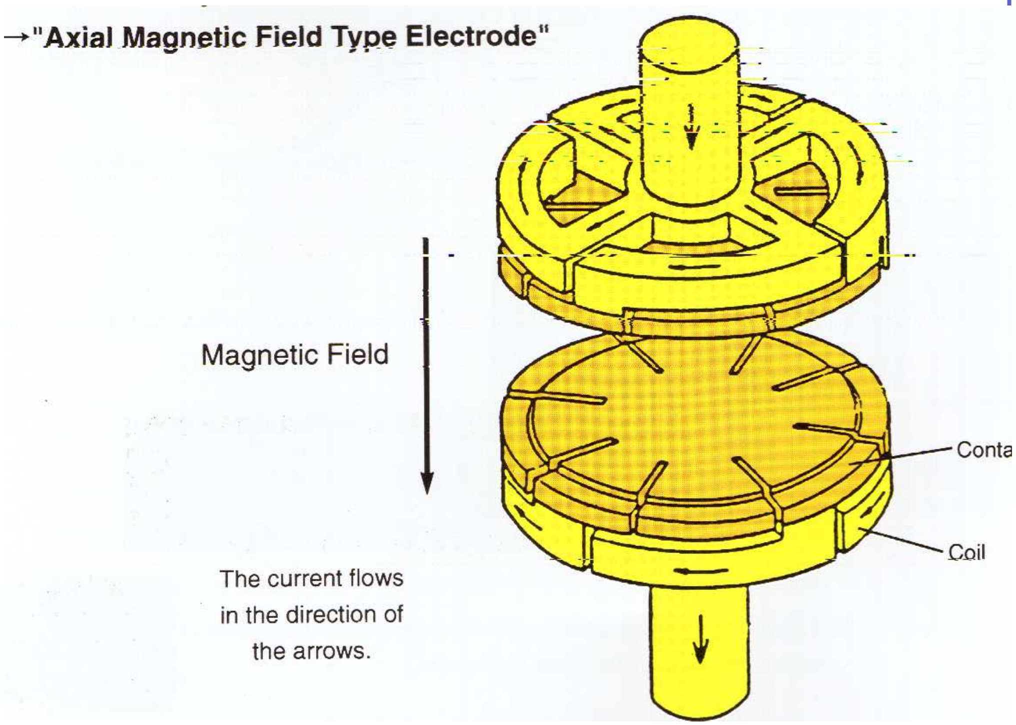
Spiral contacts   Contrate contacts

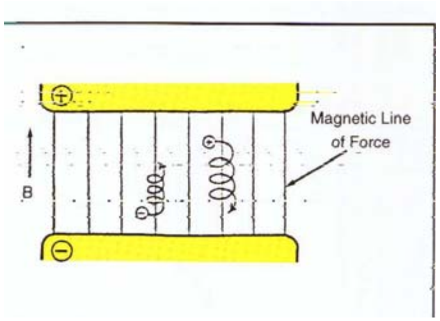


Arc Control Geometry- Axial Magnetic Field - AMF

- arc is diffused by the action of axial magnetic field generated by the current itself
- arc occupies the whole space between the electrodes uniformly







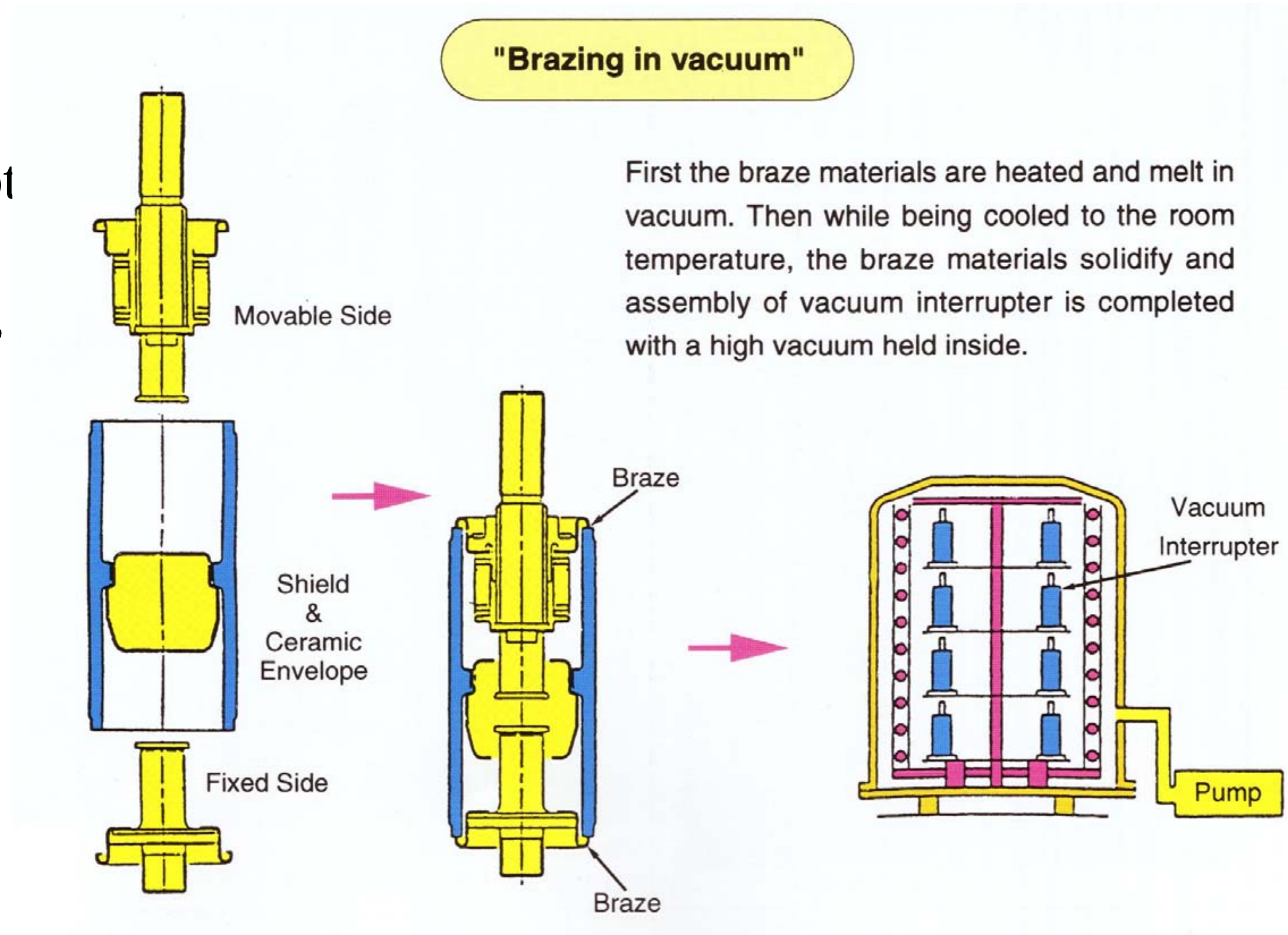
Manufacturing of Vacuum interrupters

Vacuum furnace

- Batching of pre-assembled vacuum interrupters
- Clean room conditions to US standard class 1000
- Vacuum furnaces evacuated and sealed in a single operation
- Controller monitoring of all important process parameters
- Pressure < 10^{-8} hPa (mbar)
- Temperatures > 800°C / 1472 °F

Manufacturing of Vacuum Interrupters

• one-shot brazing, pumping, and sealing



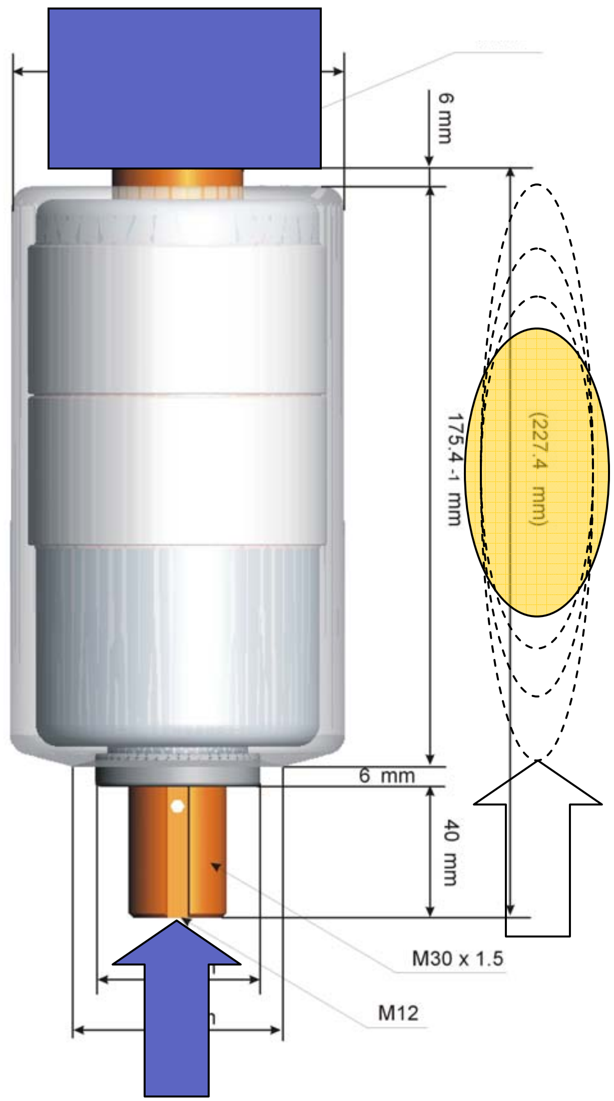
Presented at the IEEE Tutorial – Design & Application of Power Circuit Breakers, July 2008

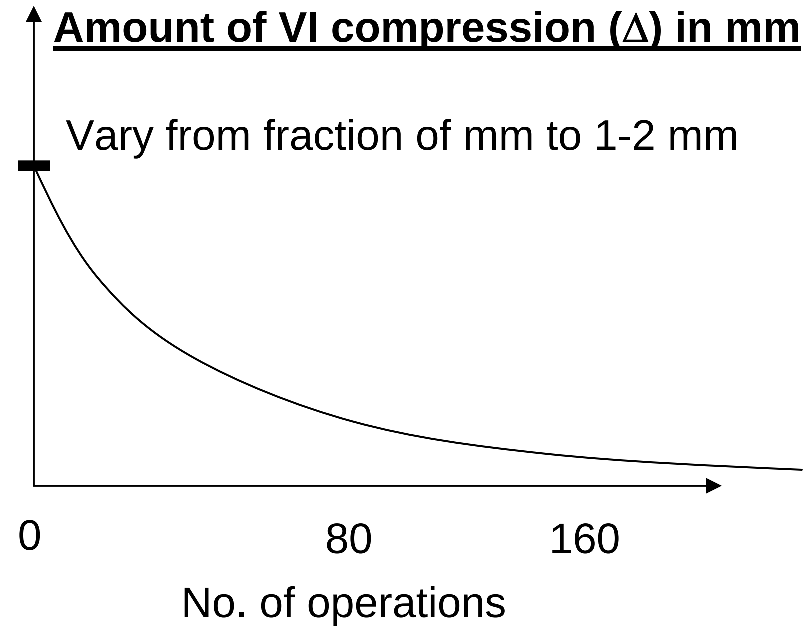
Quality control

- Essential part of vacuum interrupter manufacturing process
- All data are collected and stored
- Automatic high voltage conditioning to achieve and prove dielectric strength
- Double internal pressure measurement for the vacuum interrupters (magnetron method)
- Quarantine storage in pressure chambers filled with inert gas

Vacuum interrupter.
Design considerations.

VI Contact hardening (1)





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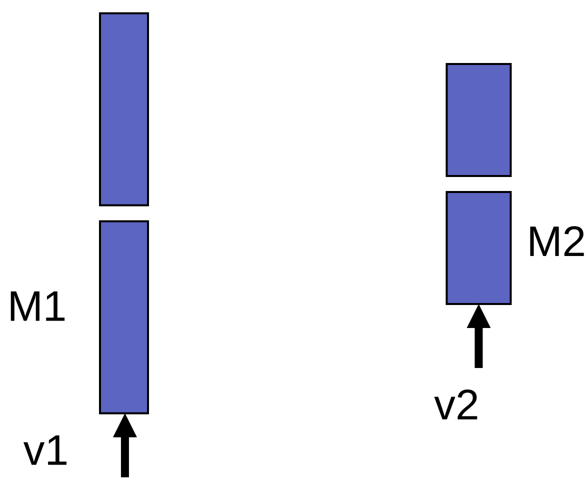
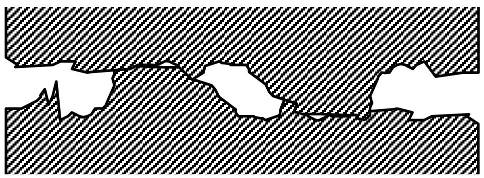
VI contact hardening (2)

- OFHC (**o**xygen **f**ree **h**igh **c**onductivity) copper used for VI contacts and stems is soft
- VIs are mechanically conditioned in the product:
  - closing the VIs on impact will harden OFHC contacts and compact the overall length of the unit
- amount of compression varies slightly with the design of contacts (geometry: length/diameter ratio...), speed of impact and moving mass



VI contact resistance (1)

• contact surface roughness - microstructure



- Typically 3-5 microscopic points of actual metallic contact (so-called a-spots)
- Typically the resistance does not (!) depend on the total surface of the contact

VI contact resistance (2) - formula

$$R_C = \frac{\rho}{2}\sqrt{\frac{\zeta \pi H}{F}}$$

- R_C is contact resistance
- ρ - electrical resistivity of the material
- ζ - empirical factor between 0.1 and 0.3
- H - material hardness
- F - contact force
- Typically: R_c=2 μΩ to 20 μΩ for F= 3,000N - 6,000N

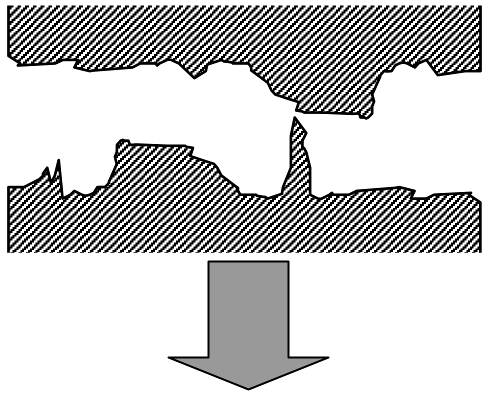
VI dielectric conditioning (1)

- **Conditioning**
- **Contact surface microstructure may enhance local electric field to cause small electrical discharges that can in turn trigger a dielectric breakdown**
- **small discharges heat the metallic tips (protrusions) due to high current concentration in small (μm areas)**
- **tips melt, smooth, reduce the discharges and increases dielectric strength**
- **opening the contacts under current (60 Hz) draws the arc; arcing smoothes the surfaces and increase dielectric strength**

Conditioning is often required to pass BIL.

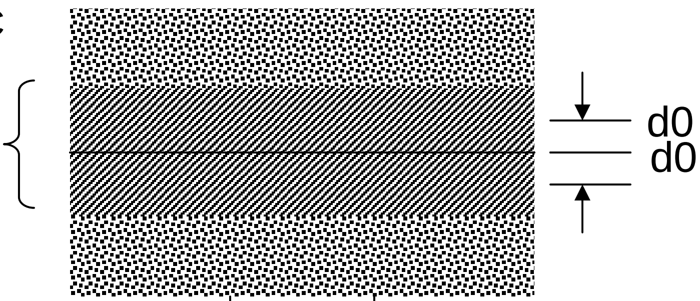
VI dielectric deconditioning (2)

- **<u>De-conditioning</u>**
- **closed contacts weld ("cold welding") - depends on time closed**
- **closing energized contacts will cause pre-strikes (hot spot welding) - depends on inrush current, frequency, dI/dt,…**
- **opening the contacts without current (breaking the welds) creates whiskers and protrusions again**
- **So… the conditioning process is not permanent but fully reversible**



VI useful life (1)

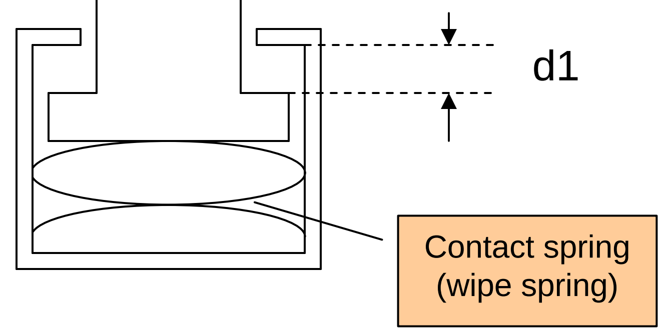
- Criteria for useful life:
  - 1. Contact erosion



  - 2. Mechanical overtravel - to maintain sufficient contact force to (a) keep the contact resistance low, (b) prevent contact popping

d1setting=d0+d0+d1min

typical VCB d0=1.5 mm
typical VCB d1=4-8 mm



  - 3. Mechanical fatigue of bellows

VI useful life (2)

- Contact erosion
  - highly non-linear with current
    - at low currents (<4-6 kAp) arc is diffuse and the erosion is low
    - at high currents (>10-16 kAp) constricted (columnar) arc, high erosion at both cathode and anode
  - function of contact design (butt, AMF or RMF), gap length, contact material, dc/ac

$$G(grams) = g(grams/Coulomb) * \int_0^{tarc} \mathrm{I(t)}dt$$

at low I	g (g/C)
CuCr	$3.1\text{x}10^{-6}$
AgWC	$2.9\text{x}10^{-6}$

- Typical minimum contact thickness ~0.5 mm

VI useful life - RMF (3)

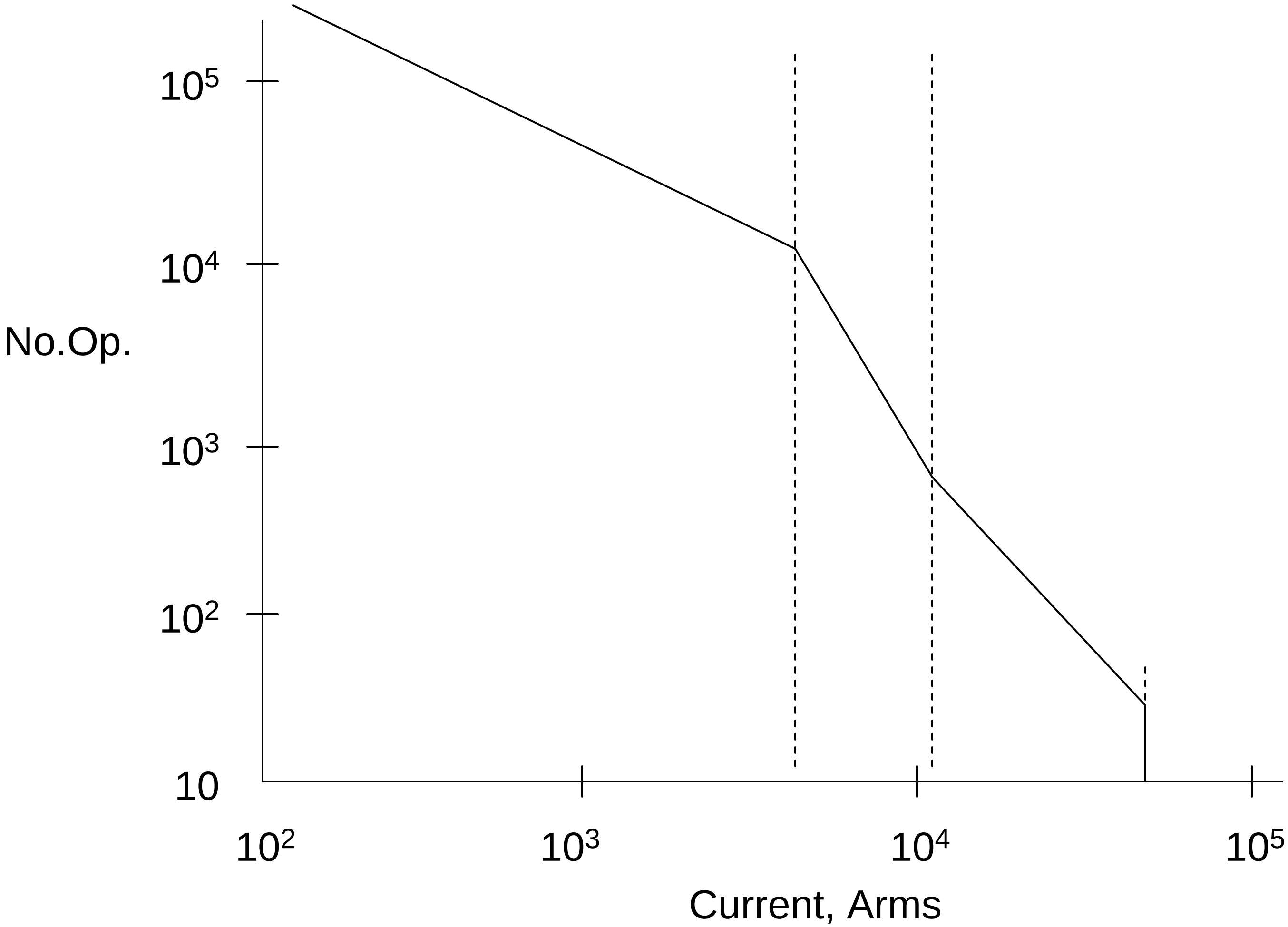
- For RMF VCB spiral contacts useful life is:
  - for low currents - more than mechanical fatigue of bellows
  - For example (for 61mm dia.) @630A N=77koperations, @ 1200A N=40koperations, @ 2000 N=24koperations (N~1/I)
  - for high (SC) currents - ~ 100 operations ($N \sim 1/I^2$)
  - end of life - slots begin to fill and there is no more RMF generated

$$2d0 = \sum 5*10^{-6} \int \frac{Idt}{A} + \sum 0.03 \left(\frac{I}{25} \right)^2 + \sum 0.0048 \left(\frac{I}{10} \right)^{3.2}$$

For I<4kArms I>10kA 4kA< I < 10kArms

When 2d=~3 mm contacts have reached their end of useful life

VI useful life - RMF (4)



VI useful life - AMF (5)

- Lower mechanical stresses, less contact required
- “normal” arcs are always diffuse (no columnar arc)
- only at the initial stage of opening (very short gap) the short arcs are constricted, it takes a finite time (1-3 ms) to convert the arc to diffuse mode again
- the limit for AMF is contact surface melting

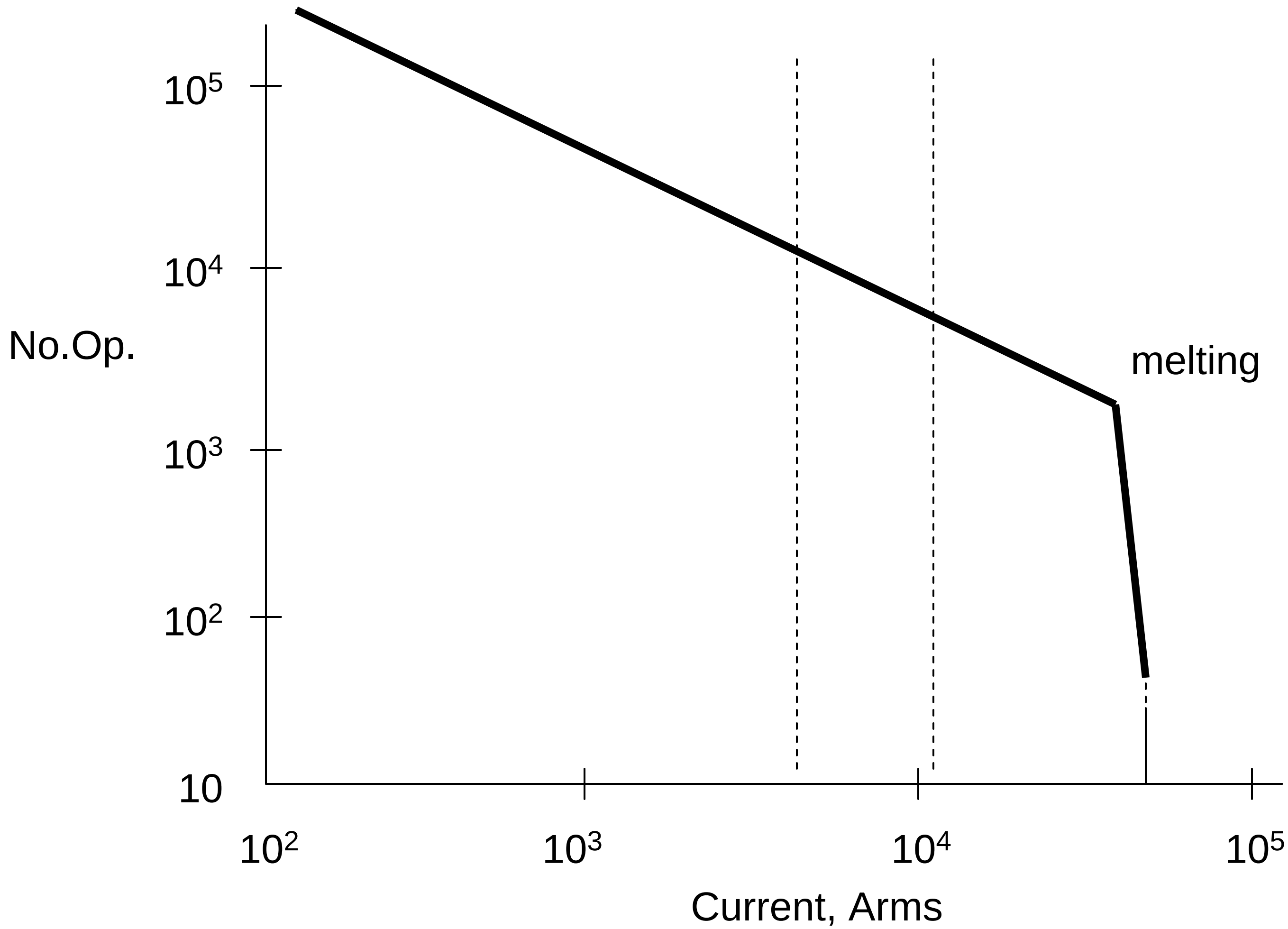
VI useful life - AMF (6)

$$2d0 = \sum 5*10^{-6} \int \frac{Idt}{A}$$

For I< I melting limit

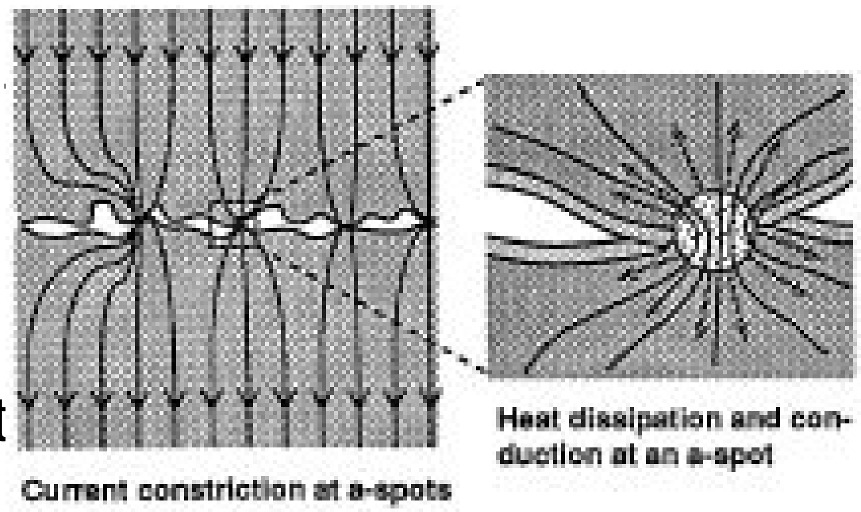
When 2d=~3 mm contacts have reached their end of useful life

VI useful life - AMF (7)



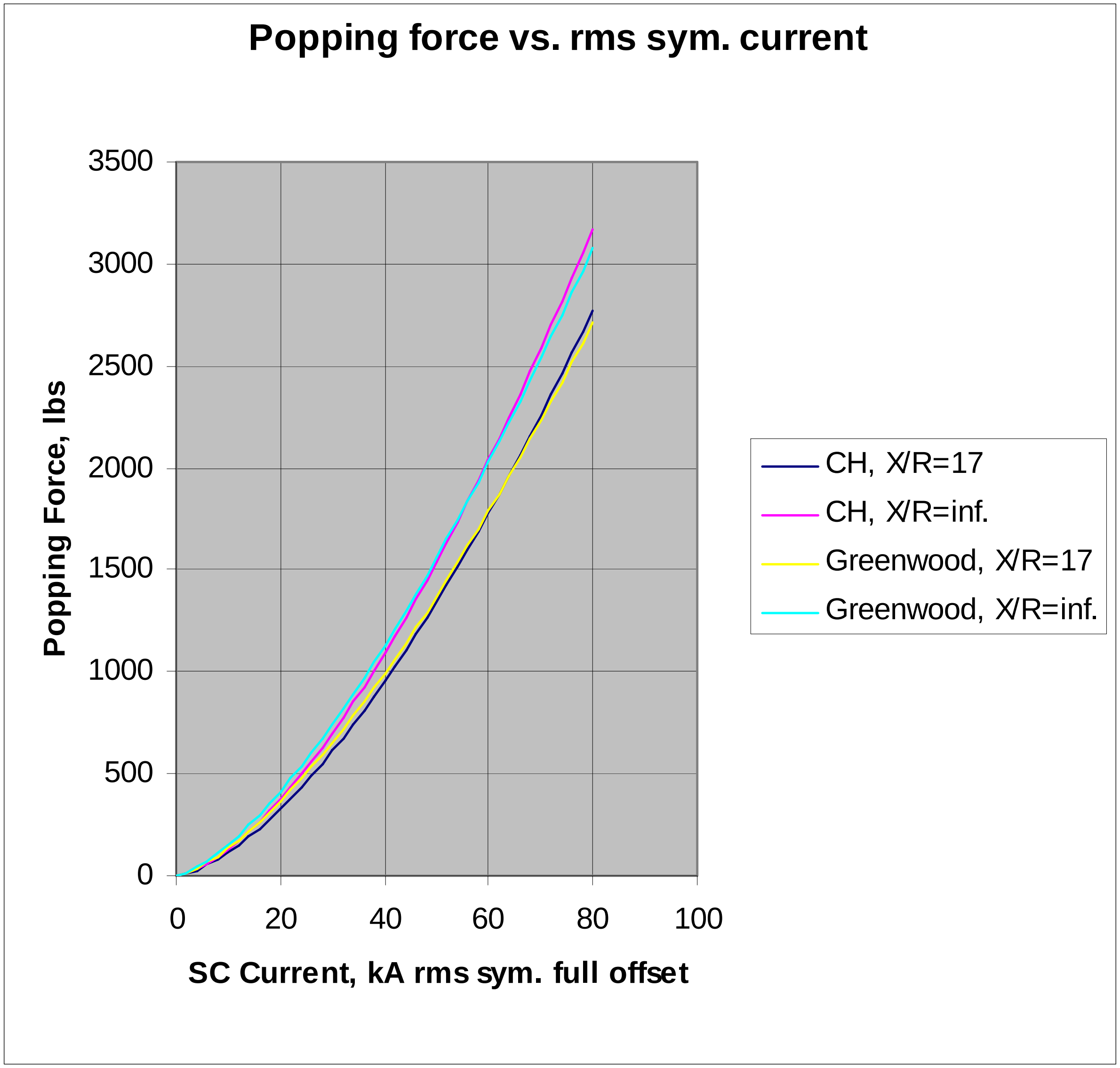
Popping forces

- Current is constricted to so called a-spots
- The constriction causes electrodynamic force repelling the contacts apart
- To counteract- a **<u>contact force</u>** has to be provided depending on the current flowing.



$$F=C*I^{(1.45\text{-}1.54)}$$

Contact force



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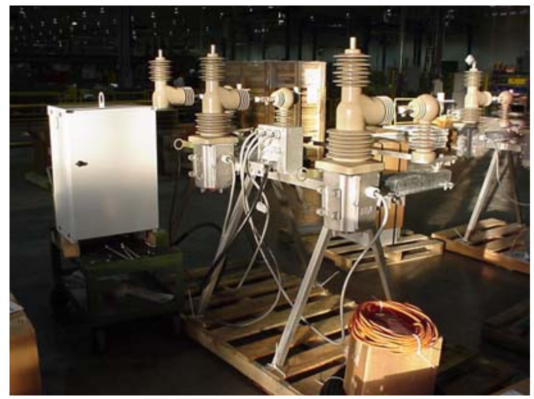
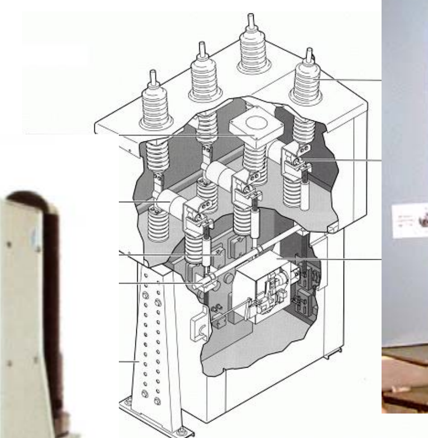
Vacuum interrupter based devices.

Vacuum Switching Equipment

- distribution circuit breakers (dead tank and live tank)
- vacuum reclosers and sectionalizers
- vacuum switches
- vacuum contactors
- …

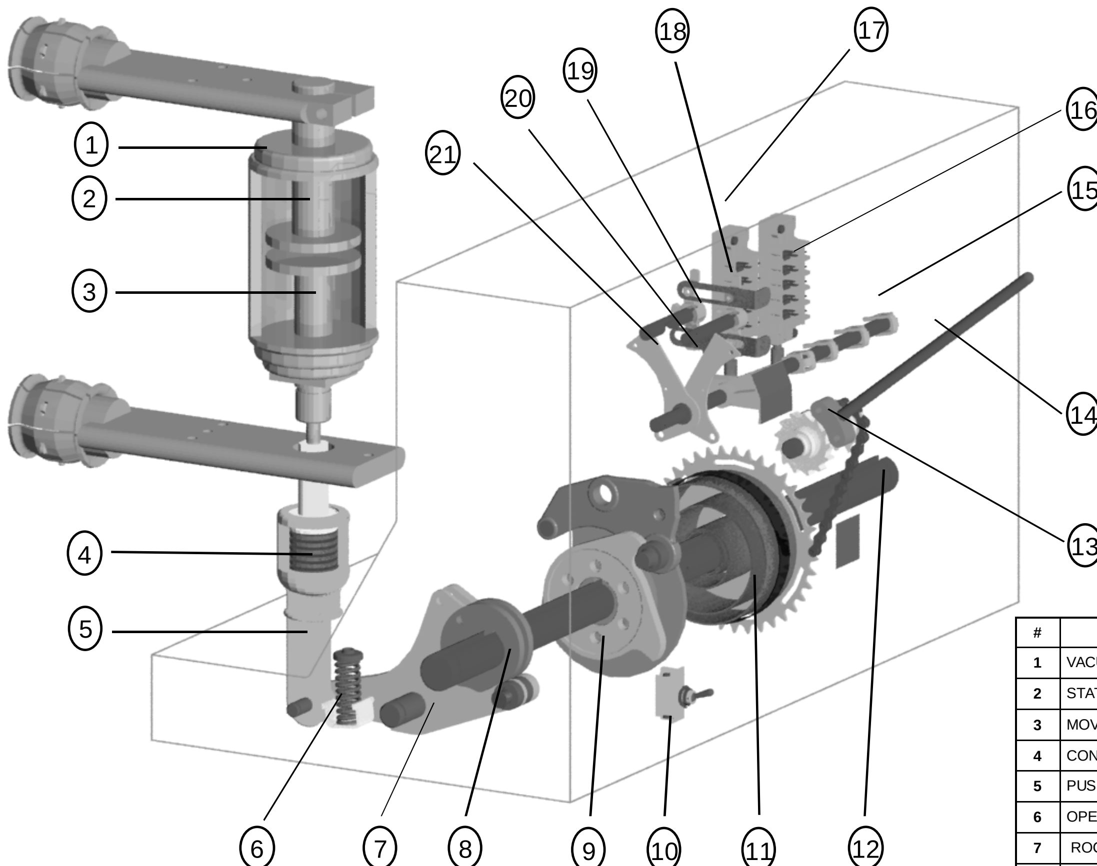







Vacuum Switchgear (Indoor, metal-clad)

Mechanical Drives for a vacuum circuit breaker



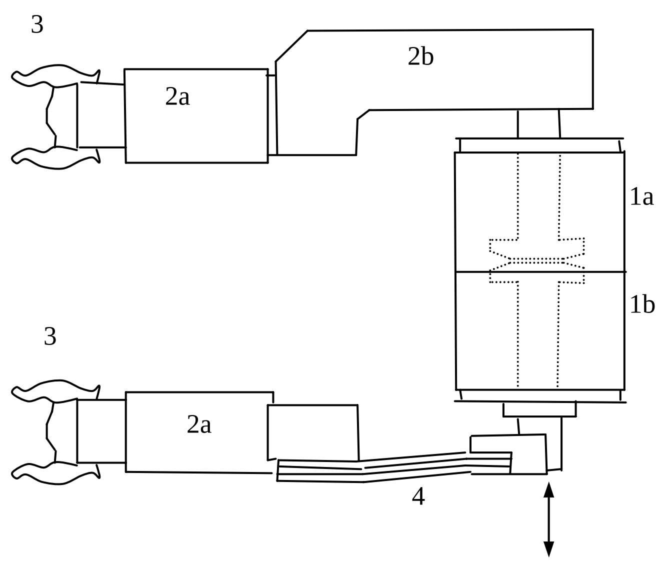
#	DESCRIPTION		#	DESCRIPTION
1	VACUUM INTERRUPTER		12	MAIN SHAFT
2	STATIONARY CONTACT		13	CHARGING PAWL
3	MOVING CONTACT		14	CHARGING HANDLE
4	CONTACT SPRINGS		15	AUXILIARY SHAFT
5	PUSH ROD		16	AUXILIARY CONTACT
6	OPENING SPRING		17	MOTOR LIMIT SWITCH
7	ROCKER ARM		18	CLOSE PUSHBUTTON
8	CAM		19	HALF SHAFT
9	STOP DISK		20	CLOSING TRIGGER
10	MOTOR DISCONNECT SWITCH		21	OPENING TRIGGER
11	CLOSING SPRING			

- low energy required
- small stroke required
- simple
- reliable

Typical characteristics of a vacuum breaker

- Contact gap (15 kV= ~ 8-12 mm)
- Mechanical energy required (typical 300-400 J)
- Contact resistance ~ contact forces$^{-0.5}$ (2-40 $\mu\Omega$)
- Contact force (VCB typical~ 3000 N-6000 N)
- Contact wipe (Mv=30-40 kg*m/s)

Typical indoor VCB pole design



Vacuum circuit breaker pole assembly showing main current carrying parts.
1a-stationary contact of vacuum interrupter,
1b- moving contact of vacuum interrupter,
2a,b- current carrying support members,
3- disconnects, 4- flexible connection.

Summary, conclusions and future trends.

Summary of Vacuum Switchgear

- Maintenance
  - interrupters -> virtually none, occasional checks 60 Hz 1min HiPot, contact resistance and wipe
  - mechanism -> lubrication, overall integrity, timing on C and O
  - other parts -> dielectric integrity check similar to other switchgear
- Useful life of vacuum switchgear
  - shelf life of VIs -> 20-30 years, normal switching duties -> almost indefinite, limited primarily by mechanism
- Environmental compliance -> no environmental effects known
- Small size, no fire hazard, low noise, equal performance in the whole range of currents and voltages

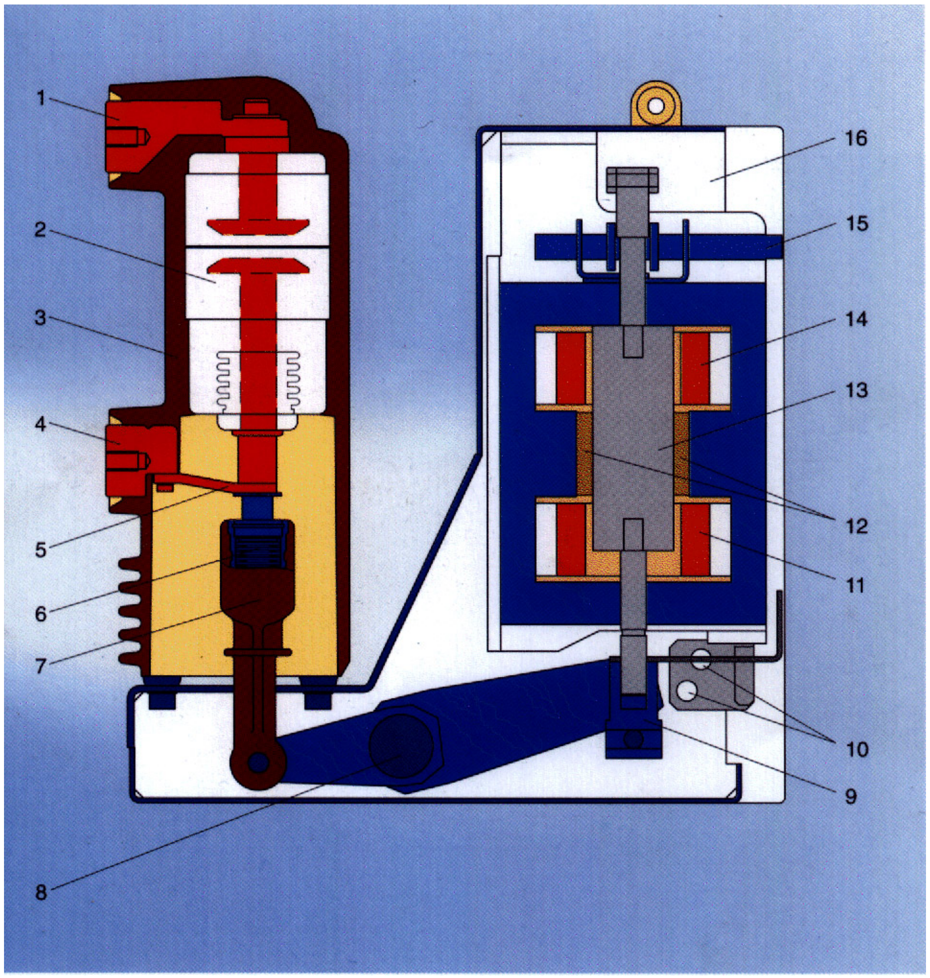
Safety and Reliability

- No exposure to arcs or arc byproducts
- If overloaded vacuum interrupter fails in benign way
- Safety
  - When high voltage is applied between two electrodes in vacuum environment a small electron emission current results. The cathodic electrons bombarding the surface of the opposite anode can generate small amount of X-ray emission. Under normal circumstances, i.e. within the voltage rating of the device and at the full open gap the X-ray emission is minimal. However, when the device is tested or operated at a fractional gap distance the excessive voltage may cause more X-rays. In such cases most manufacturers of vacuum switches warn the users of the exposure and recommend that a protective lead shield, or equivalent means, be used if any personnel be working close to the vacuum chamber for prolonged period of time. Normally, standard safety distances for electrical reasons are sufficient.
- Reliability
- Vacuum interrupters are sealed for life. Typical defect rate for good interrupters is $\sim 10^{-6}$ (1 per million)

Trends in Vacuum Switchgear Technology

- Simplified mechanical drive
  - lower energy drives, magnetic actuation, faster/more accurate operation
- Higher voltage ratings
  - trends to extend to 69/72 kV and 138/145 kV
- Higher interrupting current ratings
  - optimization of contact design, better utilization of magnetic fields (AMF and RMF), new way of utilizing magnetic fields
- Intelligent switching
  - Closing and opening on point of wave, independent pole operation, suitable for Distribution Automation, VCB controllers tailored to specific applications
- Encapsulation
  - reduce VI size (outside ceramic), no serviceable parts, better mechanical strength, resistance to shocks and weather

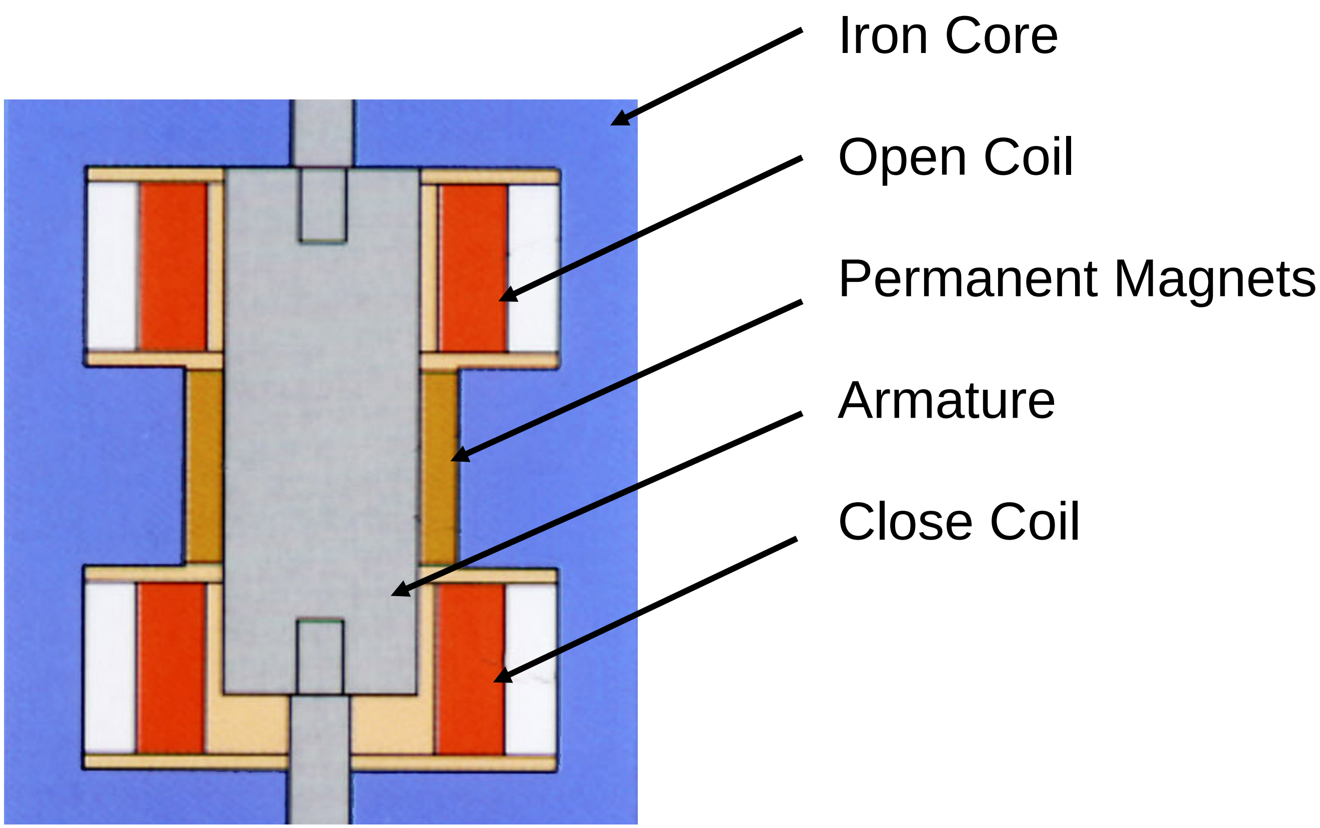
Magnetically actuated VCB



Side view of Magnetically Actuated Breaker

1. Upper Primary Terminal
2. Vacuum Interrupter
3. Epoxy Potting Compound
4. Lower Primary Terminal
5. Flexible Connector
6. Wipe Springs
7. Insulated Pushrod
8. Jackshaft
9. Stroke Adjustment
10. Position Sensors
11. Close Coil
12. Permanent Magnets
13. Armature
14. Open Coil
15. Manual Opening Actuator
16. Mechanism Enclosure

Magnetic Actuator



Magnetically actuated recloser