Dielectric Insulation & High Voltage Issues

Davide Tommasini
CERN

- Basic principles
- Conduction and breakdown in dielectrics
- Materials for electrical insulation
- Electrical insulation systems
- Damage and failure mechanisms
- Ageing
- Tests
- Conclusions

Electric Field

Electric field : physical entity producing forces on electric charges

$$F = q \cdot E$$

An electric field is generated by :

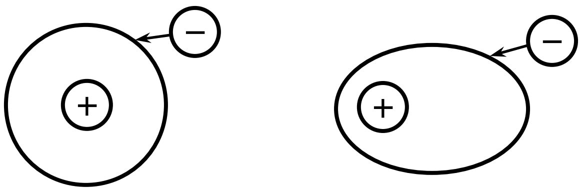
$$E = -\nabla V - \frac{\partial A}{\partial t}$$

where V is the electric potential and A is the magnetic potential

As the Earth surface is equipotential, it is convenient to set $V_G=0$

Polarization

In insulating materials the distribution of charges or electrical dipoles can be modified by an external electrical field

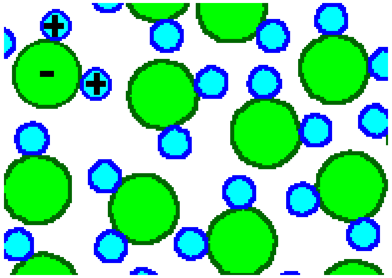


ELECTRONIC POLARIZATION

The electric field modifies the electron density.
Important in certain crystals as Si and round noble gases.
Quick response to applied field E.

ORIENTATION POLARIZATION

Important for example in water
Orientation is disturbed by thermal noise viscosity.
Slower and dissipative response to E.



IONIC POLARIZATION

It includes bulk and interfacial effects.
Slow and dissipative.
Important in ionic crystals as NaCl and heterogeneous systems

Electric susceptibility & Dielectric constant

The **electric susceptibility** χ describes the ability of a material to polarize when submitted to an electrical field

If **P** is the density of electrical dipole moments, we define :

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the "dielectric constant of free space"

This polarization of the material goes **in supplement** to the polarization effect given by the electric field in free space.

The total polarization effect is :

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 (1+\chi)\mathbf{E} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

ε_r is the **dielectric constant or permittivity** of the material

D is the **electric displacement field**

As for magnetic field density, across an interface the normal component of D and the tangential of E do not change

Dielectric losses

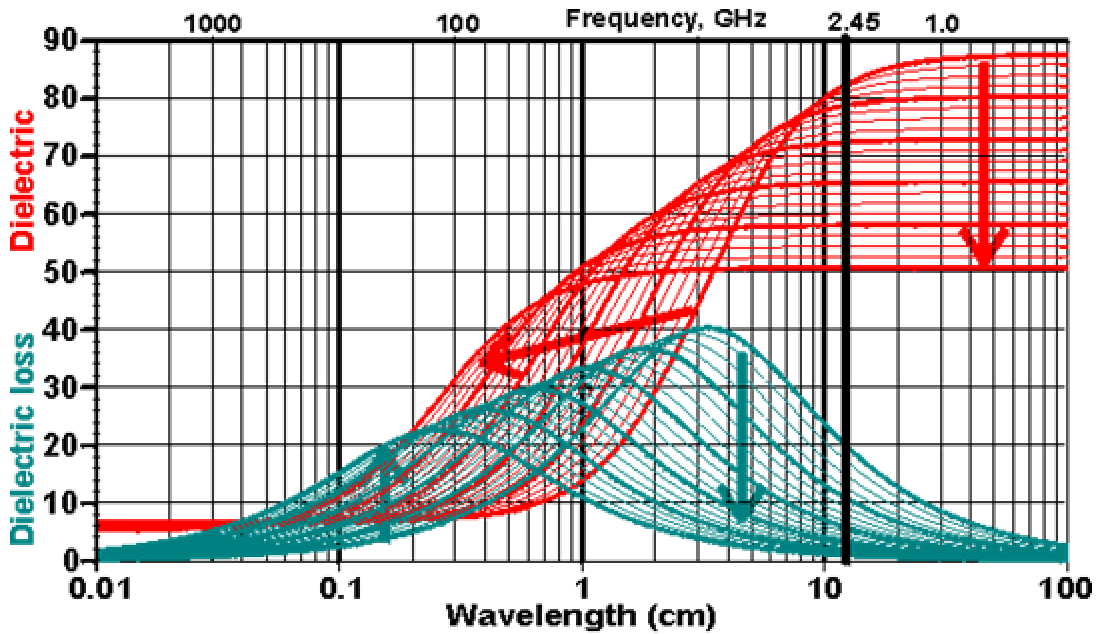
Deforming a charge distribution needs energy.

Every time you change the distribution you spend energy

When you apply a variable electric field to a dielectric you heat it !

You are creating a "displacement current" in dissipative medium

$$J_{tot} = \sigma E + \frac{\partial D}{\partial t}$$



Dielectric constant and loss of water

From : http://www.lsbu.ac.uk/water/

Based on : J. B. Hasted, Liquid water: Dielectric properties, in *Water A comprehensive treatise*, Vol 1, Ed. F. Franks (Plenum Press, New York, 1972) pp. 255-309.

Dielectric Constants and Loss Factors @ 50 Hz

Material	Relative permittivity	Loss factor tangδ $[x10^4]$
Air	1	0
Polyethylene and polypropylene	2	0
Epoxy	3	3
Fiberglass	6	10
Nylon (polyamide)	5	15
Polyimide	4	3
Polyester	4	10
PVC	3	1
Mica	5	5
Transformer oil	2	10
Teflon (PTFE)	2	0
Butyl rubber	3	15
Alumina	9	1
Water	80	
Barium titanate	1500	15

Electrostatics

Potentials are computed from the **Poisson** equation :

$$\nabla^2 V = -\rho / \varepsilon$$

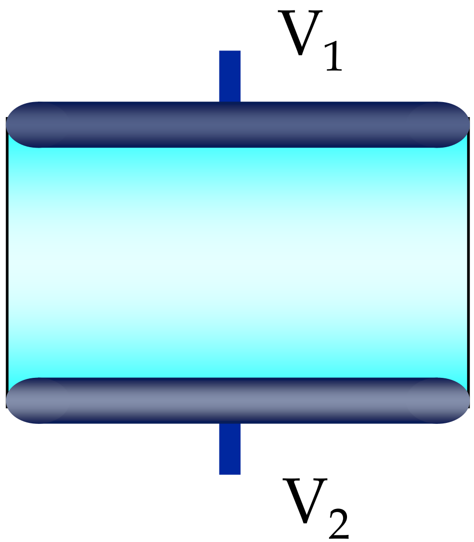
Which becomes the **Laplace** equation if no free charges :

$$\nabla^2 V = 0$$

$$\nabla^2 V = \nabla \cdot (\nabla V) = div(\overrightarrow{grad\, V})$$

$$\nabla^2 = \Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

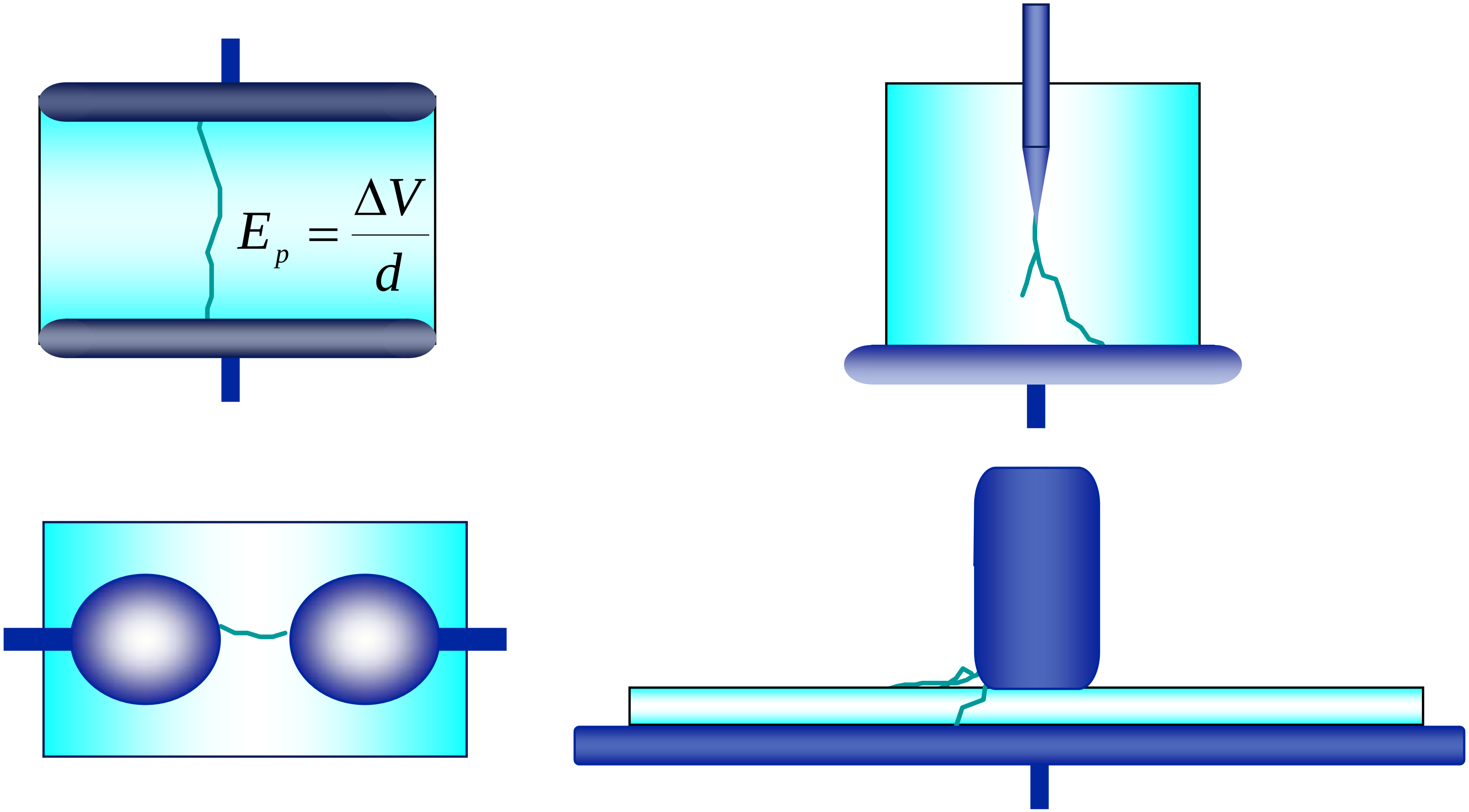
Infinite parallel electrodes at distance d, potentials V_1 and V_2



$$\frac{\partial^2 V}{\partial x^2} = 0 \Rightarrow V(x) = c_1 x + c_2 \Rightarrow c_2 = V_1; c_1 = \frac{V_2 - V_1}{d}$$

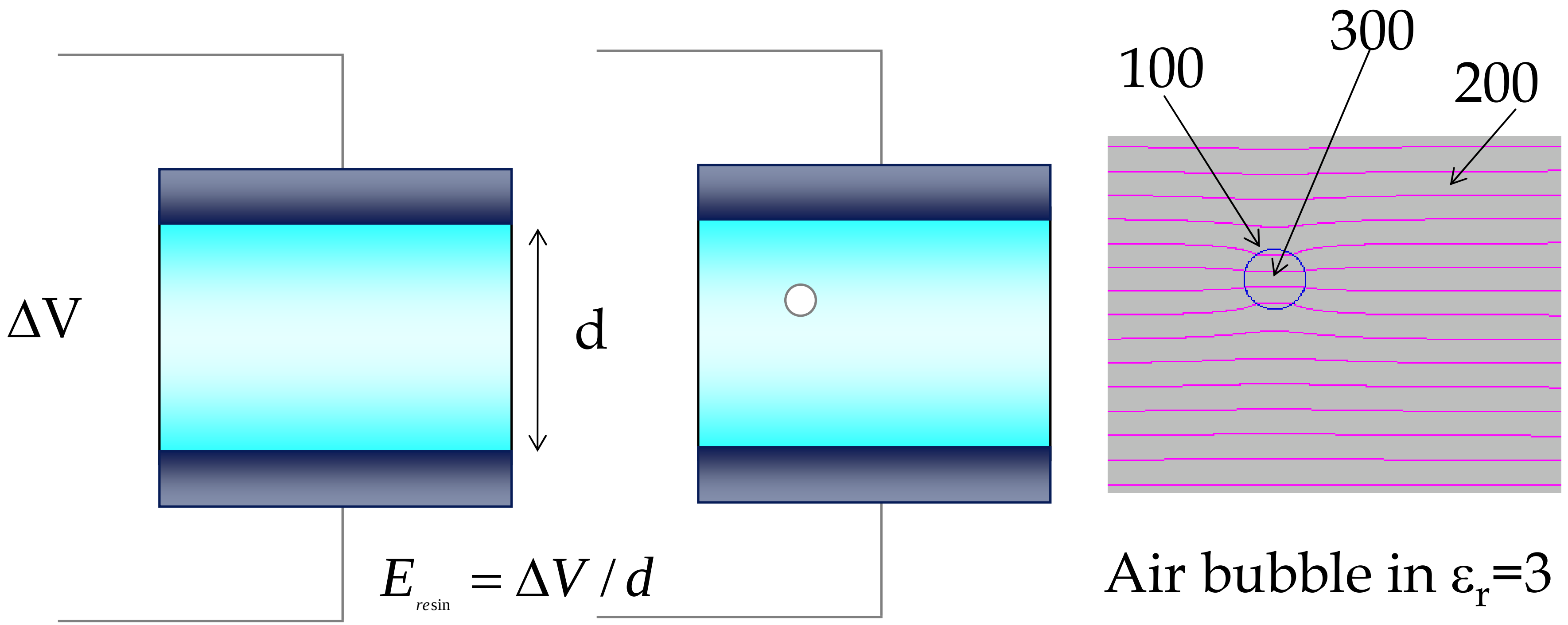
$$\Rightarrow E = \frac{\partial V}{\partial x} = \frac{V_2 - V_1}{d}$$

Electrode configurations



Electric field in an air bubble of a dielectric

Let's consider an electrical insulation composed by 1 mm of epoxy resin between two parallel electrodes, submitted to a voltage ΔV



$$E_{resin} = \Delta V / d$$

Air bubble in $\varepsilon_r=3$

As $\varepsilon_{resin} > \varepsilon_{air}$ the electric field in an air bubble can be much higher than the average one in the dielectric medium !
Also, as in general air is less insulating than a good dielectric, easily electrical discharges can appear in the bubble (see later).

Conduction in dielectrics

A **dielectric** is, by definition, a *non-conducting* material, in which macroscopic currents are mainly due to the displacement current

$$J_{tot} = \sigma E + \frac{\partial D}{\partial t}$$

The term was invented by William Whewell, a British philosopher of science who also coined : scientist, physicist, catastrophism, anode, cathod …

When the electric field is high enough a dielectric may suddenly loose its property of *non-conduction*, permanently or temporarily, showing an **electrical breakdown**.

Breakdown in dielectrics

It consists in the abrupt rise of electrical current under the effect of an electric field. Its causes depend on the medium, the geometry and the type and amplitude of the electric field.

- Medium
    - gas (ionization, avalanche, corona, Pashen)
    - liquid
    - solid (intrinsic, surface, thermal, partial discharges …)
    - vacuum
- Geometry
- Voltage
    - distribution (electric field)
    - type (dc, ac, impulse, frequency …)

An analogy

conductor
dielectric
voltage

water channel
pipe wall
pressure

dielectric breakdown :
happens above a certain

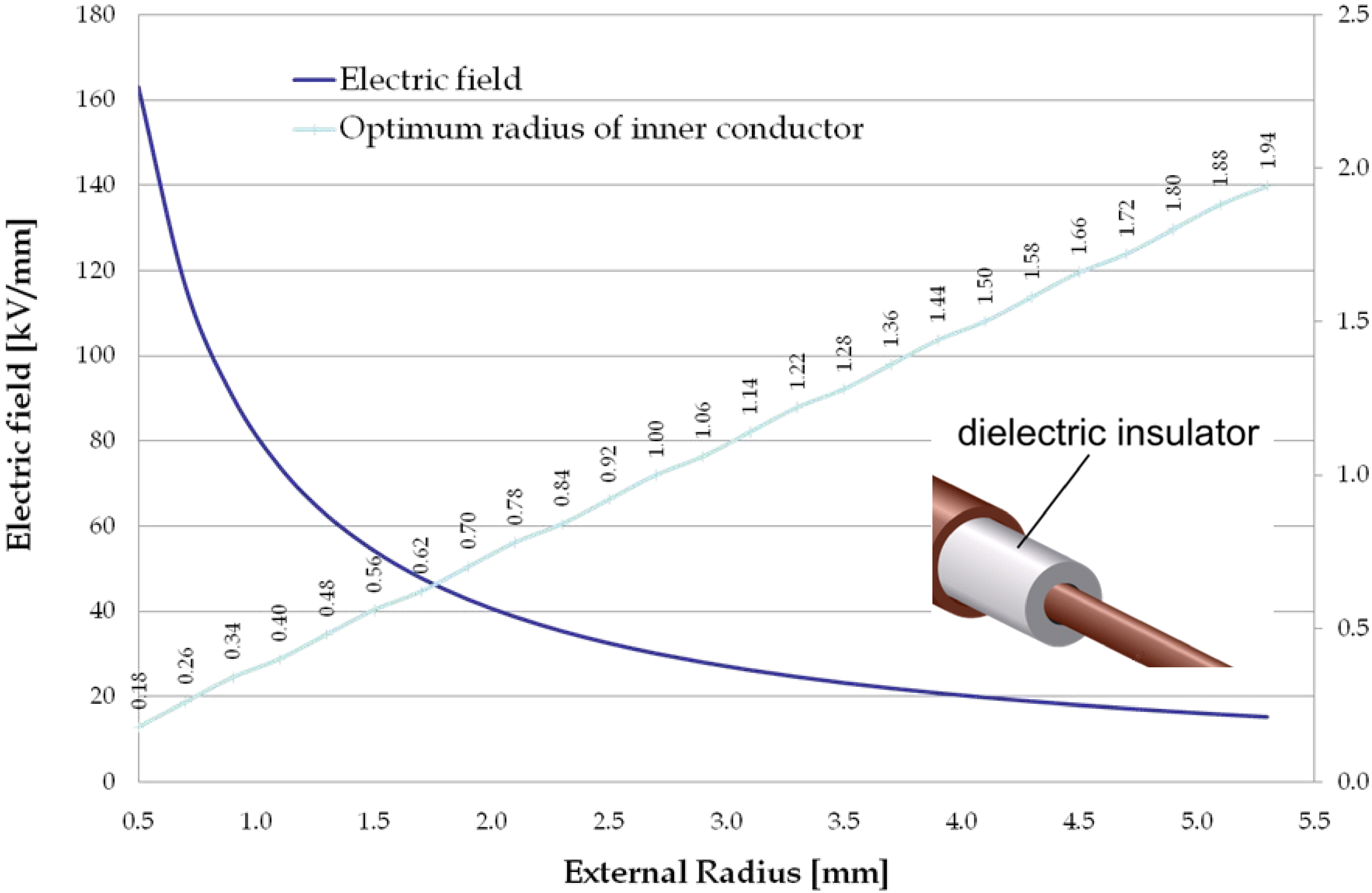
difference of voltage *
between inside and outside
the dielectric
in reality it is the electric field which counts

mechanical failure :
happens above a certain

difference of pressure *
between inside and outside
the pipe wall
in reality it is the mechanical stress which counts

A pressure test of a water circuit is equivalent to a high voltage test : you want no leakage up to a given stress level

Example : HV instrumentation wires for ITER



Breakdown in Gas

In a gas free charges under a sufficiently high force can produce ionization and avalanche breakdown by hitting other atoms.

Pashen law

$$V_b = \frac{a(pd/T)}{\ln(pd/T) + b}$$

at high pressure :

increasing pressure increases density,
decreases the mean free path,
though probability of collision increases, the lower collision energy gives an increase of V_b

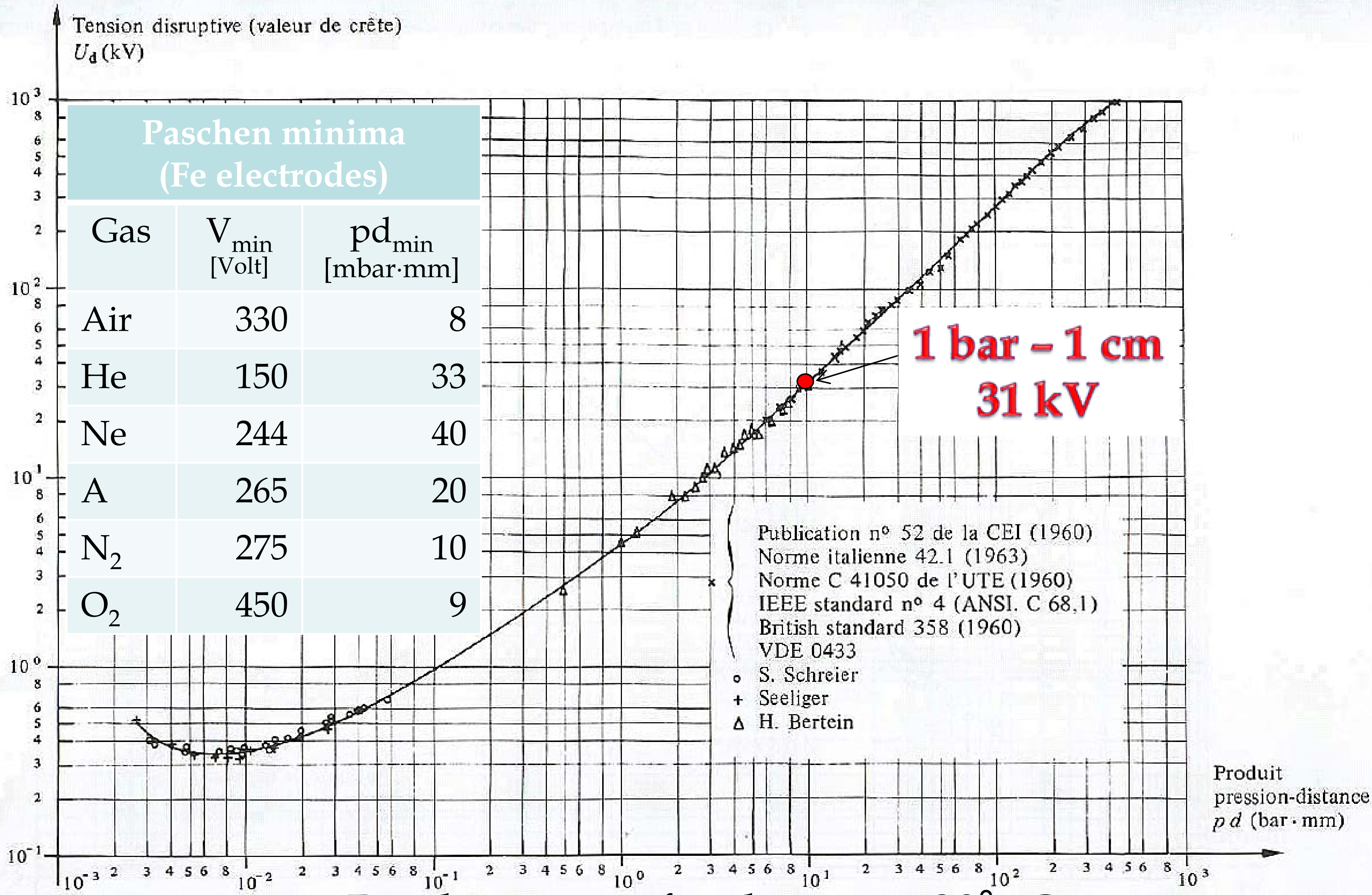
at low pressure :

decreasing pressure decreases density,
decreases the probability of collisions, though the mean free path increases,
the lower ionization gives an increase of V_b

in practice :

at high pressure the mean free path is dominant
at low pressure the probability of collision is dominant
and … there is a ***pd*** at which V_b is minimum

Paschen curve and minima

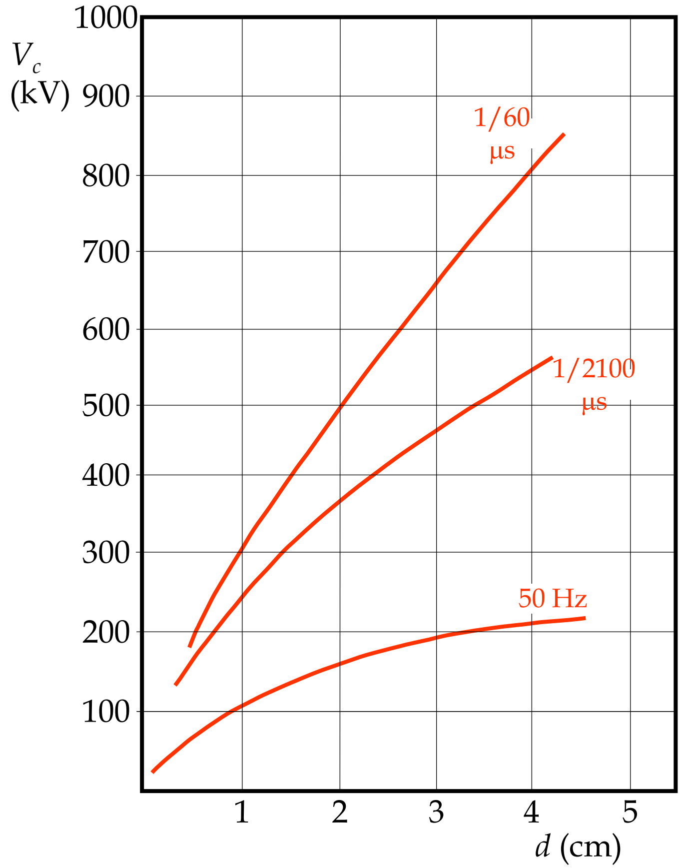


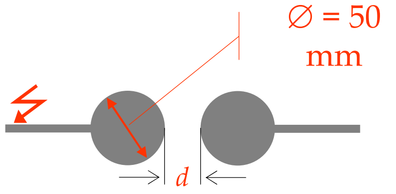
Paschen minima (Fe electrodes)

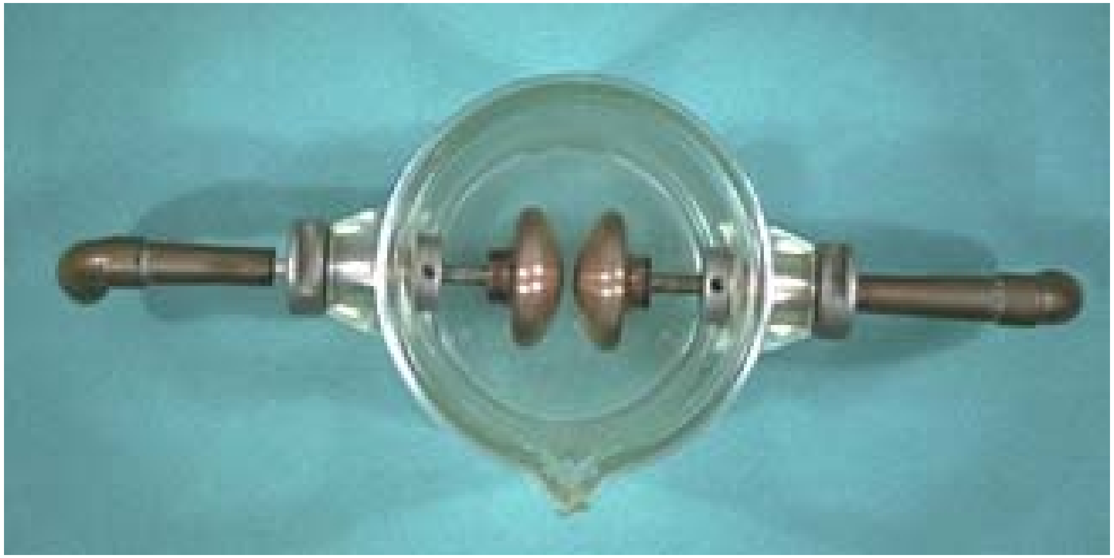
Gas	V_{min} [Volt]	pd_{min} [mbar·mm]
Air	330	8
He	150	33
Ne	244	40
A	265	20
N_2	275	10
O_2	450	9

Paschen curve for dry air at 20° C

Insulating liquids in accelerator components are for example in fast magnets pulsers for voltages above 30-50 kV.
Also in transformers, capacitors, high voltage switches and circuit breakers. In many cases they act as both dielectric and coolant.

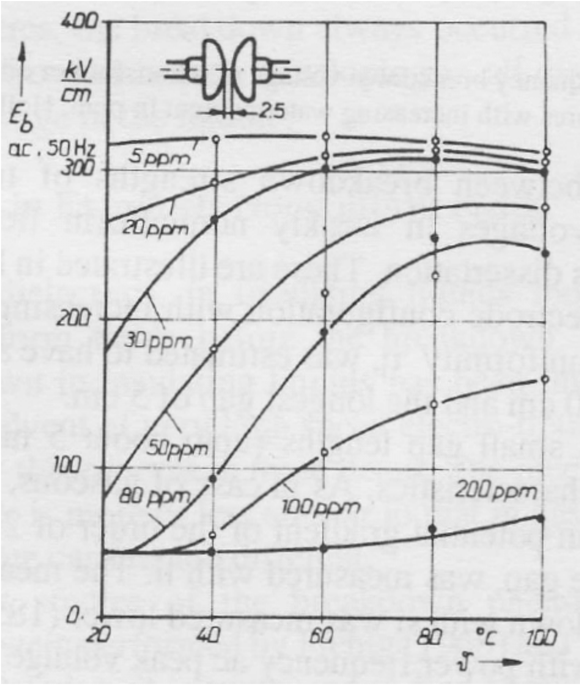






Breakdown in Liquids / 2

The most important aspect to consider when dealing with liquid insulation is its purity. When an electric field is applied to an insulating liquid, initially current is dominated by impurities. At fields higher than 100 kV/cm electron emissions can start at the interfaces of impurities and get multiplied by ionization process leading to electrical breakdown.



The breakdown mechanisms in liquids are not fully understood
Experimentally :

$$\Delta V_b = A d^n$$

where A is a constant, d the gap length, n < 1

Breakdown in Vacuum

absence of particles = no breakdown ?

practical "vacuum" still has particles, or residual gases :

remember Paschen

not only : vacuum can even create conditions for "coating" of metallic parts which are sputtered by the electric field, possibly with help of magnetic field in a magnet, on the surface of insulators leading to the catastrophic failure of the insulation.

In practice many parameters are important : pressure, distances, electrode materials, type and cleanness of insulating materials

Breakdown in solids / 1

DIELECTRIC BREAKDOWN IN SOLIDS

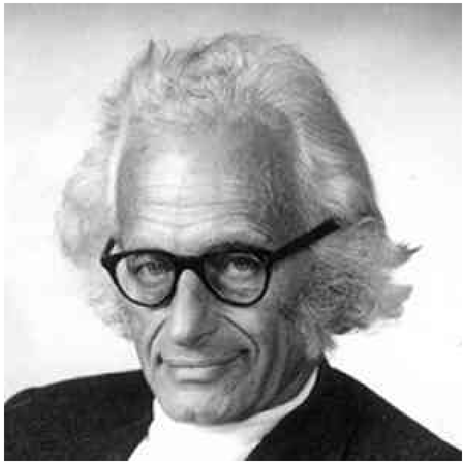
By H. FRÖHLICH

H. H. Wills Physical Laboratory, University of Bristol

Owing to its great technical importance, the dielectric breakdown in solids has for many years been a subject of experimental and theoretical investigations. Nevertheless, only in recent years has it been possible to come to a closer understanding of this phenomenon. It is the aim of this article to give an account of these recent developments.

One of the most important results of recent research has been the experimental proof of the existence of an *intrinsic electric strength*. This means that at a given temperature a maximum breakdown strength exists for each dielectric substance which is a constant of this substance, and which is obtained under ideal conditions (homogeneous field, uniform material without weak spots, etc.). Therefore it should be, and has been, possible to calculate this intrinsic electric strength from simple physical constants of the material. In this *Report* we shall deal mainly with the intrinsic electric strength. There exists

Dielectric breakdown in solids : Herbert Fröhlich 1939 *Rep. Prog. Phys.* **6** 411-43



Two principles

Electronic breakdown

With sufficient energy (above a critical field) electrons can cross the forbidden gap from the valency to the conduction band, eventually producing collisions with other electrons and leading to breakdown.

Avalanche breakdown

As in gases, with sufficient energy (above a critical field) conduction electrons gain enough energy to liberate electrons from the lattice atoms by collisions.

In both cases the breakdown permanently modifies the matter of the failing path.

Breakdown in Solids / 2

In practice electrical breakdown occurs below the intrinsic limit.

Interfaces

Thermal breakdown (thickness)

Contamination

Chemical action

Mechanical failure

Hydrolisis

Erosion (PD)

Oxydation

Radiation

Tracking

Treeing

Type & duration of applied voltage

Solid dielectrics for electrical insulation

Inorganic

Ceramics (Porcelain, alumina, …)
Glass, quartz
Cements and minerals as mica

Organic

Thermoplastic

reversibly soften on heating, typically linear chains

Rubber (natural, butyl, silicone)
Polyamide (Nylon)
Polyesther (Mylar)
Polypropylene (PP)
Polystyrene (PS)
Polyvinyl chloride (PVC)
Polymethylmetachrylate (PMMA)
Polycarbonate (PC)
Polytetrafluoroethylene (PTFE)

Polyethylene (PE,LDPE,MDPE,HDPE,XLPE)
Ethylene-Propylene (EPR)
Polyimide
Polyetheretherketone (PEEK)

Thermosetting

network structure formed by heating, cross-links

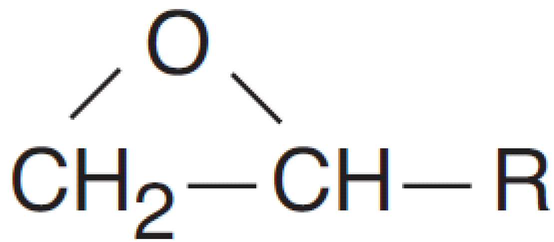
Epoxy, phenolic, silicon, polyester resins

Composites

Kevlar
Carbon
Fiber-glass
Mica

Epoxy resins

Invented in 1938 (patent by P.Castan).
They contain the epoxyde group



They are composed by :

- base resin (aromatic, cycloaliphatic, novolak or phenolic)
- hardener (amine, anhydride)
- accelerator
- flexibilizer
- fillers (Al_2O_3, MgO, quartz, Dolomite…)
- other additives (to modify the viscosity for example)

Good results in accelerator magnets are being obtained with bisphenol-A + anhydride hardener + amine accelerator.

The electrical insulation system

In an electrical machine, the electrical insulation ensures current flows only along the conductors and NOT between individual conductors or between coil and ground.

We distinguish :

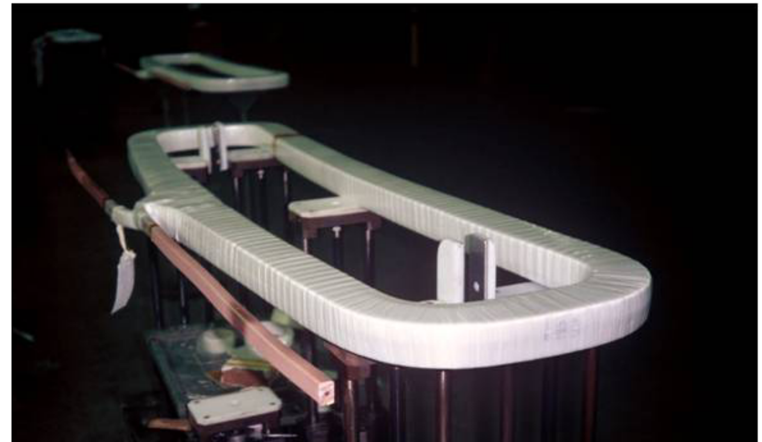
- insulation between coil turns or coil parts
- insulation between different active parts
- insulation between active parts and ground

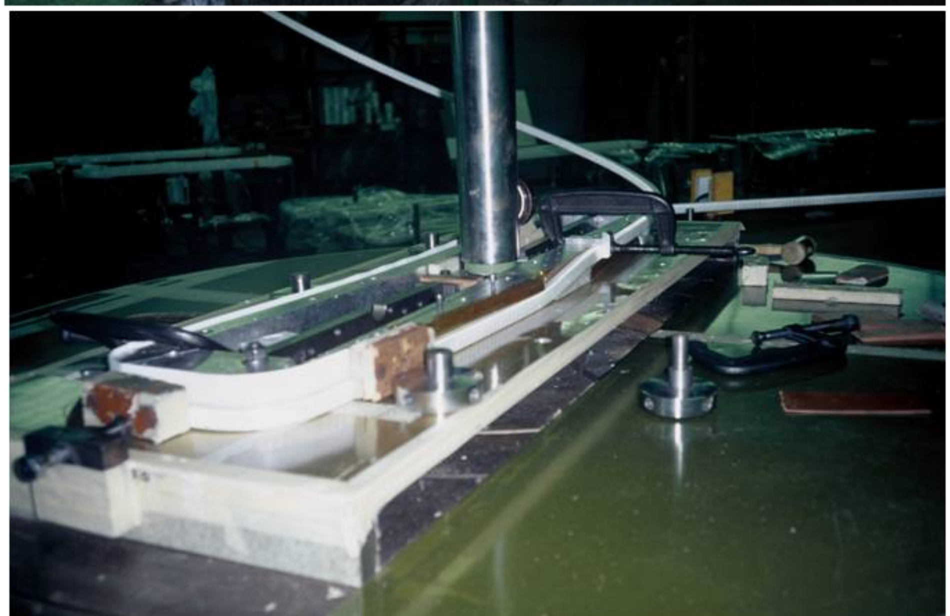
A weak insulation may produce :

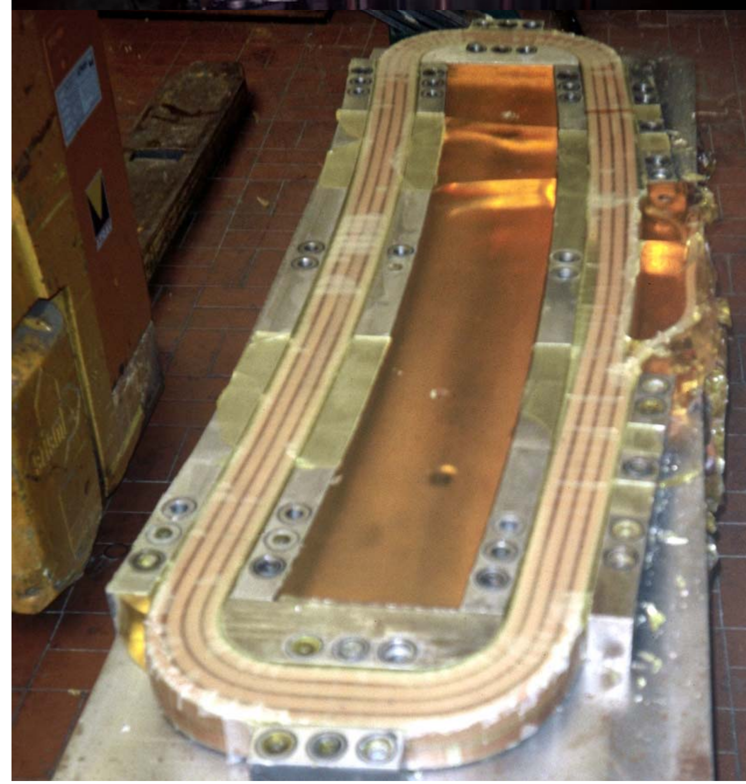
- current leak with local heating up to melting and possibly fire
- progressive damage of the leakage path up to a short circuit
- unbalance of circulating current (with magnetic field distortion)
- autotransformer effect with reduction of magnetic field
- incorrect functioning of protections

Energy stored in magnet circuits is available for any catastrophe !

Example : manufacture of coils







How an electrical insulation can fail

The electrical insulation is stressed by several factors :

dielectric thermal mechanical chemical radiations

These factor can produce short and/or long term degradation

ALSO, sometimes not considered with enough importance :

environmental conditions such as temperature, humidity, pressure can MODIFY the dielectric properties of an electrical system leading to its failure due to UNSUFFICIENT properties or DEGRADATION under that specific environmental condition (typically this is the case of surface current leaks or breakdown in proximity of magnet connections due to humidity)

Radiation : basic principles / 1

We can distinguish irradiation from :

- charged and neutral light particles
- charged and neutral heavy particles
- electromagnetic radiation

These can excite electrons or, with more than 10 eV, producing ionization. The electrons produced by the ionization can excite molecules and break bonds forming free radicals, very reactive especially when oxygen is present. New cross-links can also be formed, possibly leading to stiffer but more brittle materials.
Typically, flexural strength increases at low radiation doses (more robust material), thereafter can decrease catastrophically.

The covalent bond, typical of polymeric materials, is very sensitive to ionizing radiations.

Radiation : basic principles / 2

IEC 544-4 defines a Radiation Index as $Log_{10}(Dose[Gy])$ at which a selected property reaches the end-point criterion.

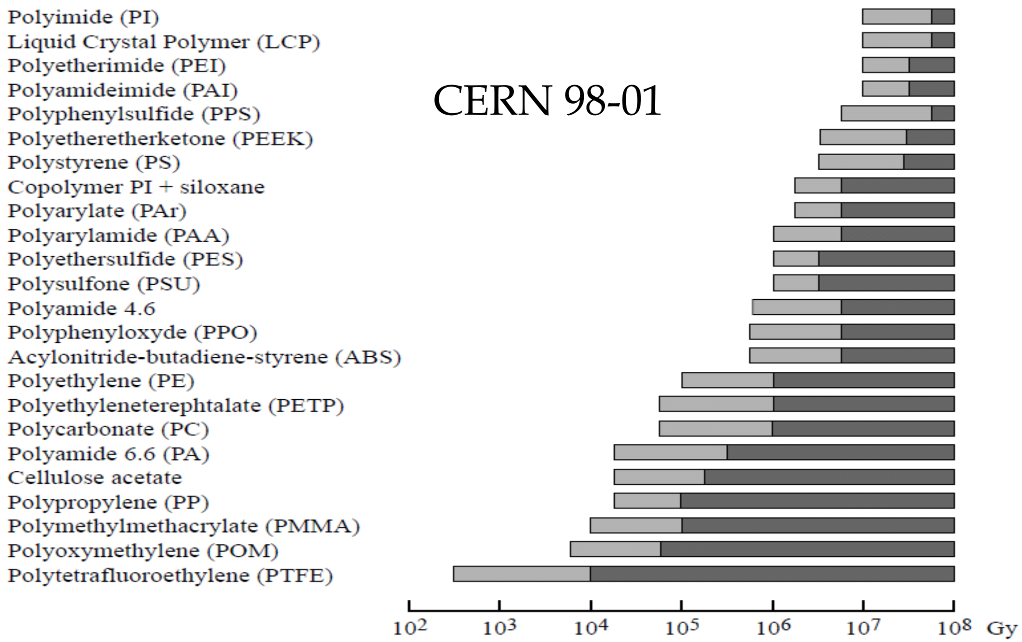
Absorbed dose is expressed in Gray :

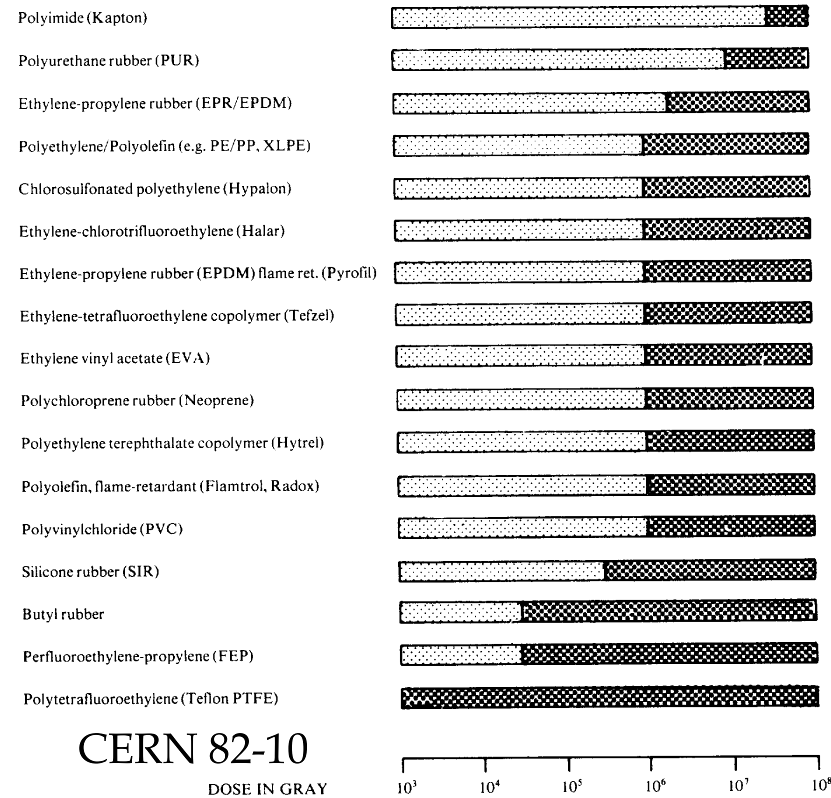
$$1\ Gy = 1\ J/kg\ (= 100\ rad)$$

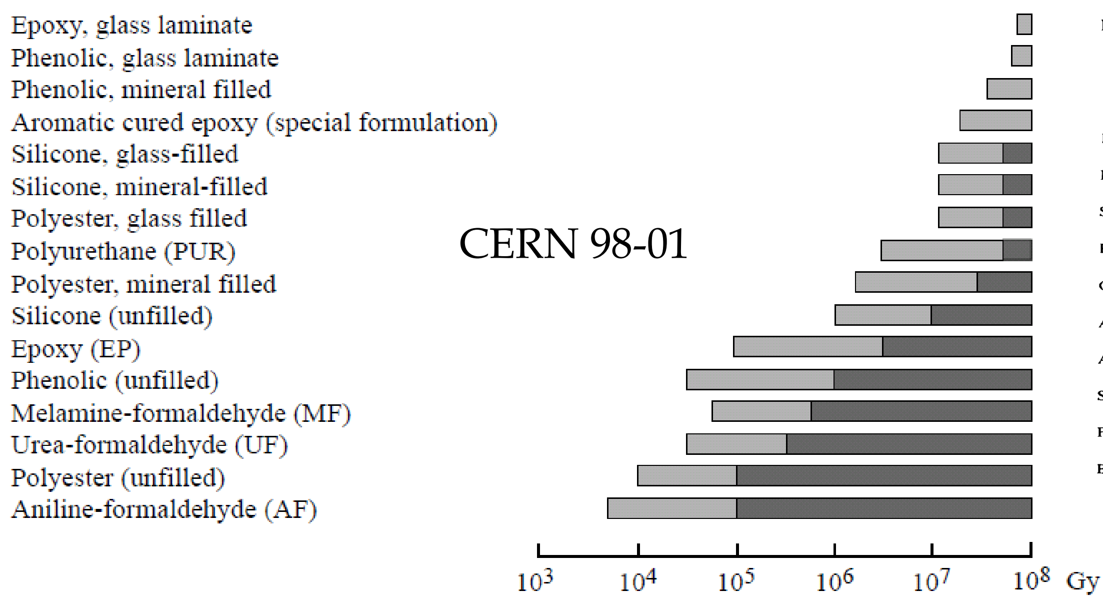
In general, relatively to radiation, failure of a dielectric insulation is due to loss of mechanical properties (in particular fragilisation) or the evolution of gases inside the material.

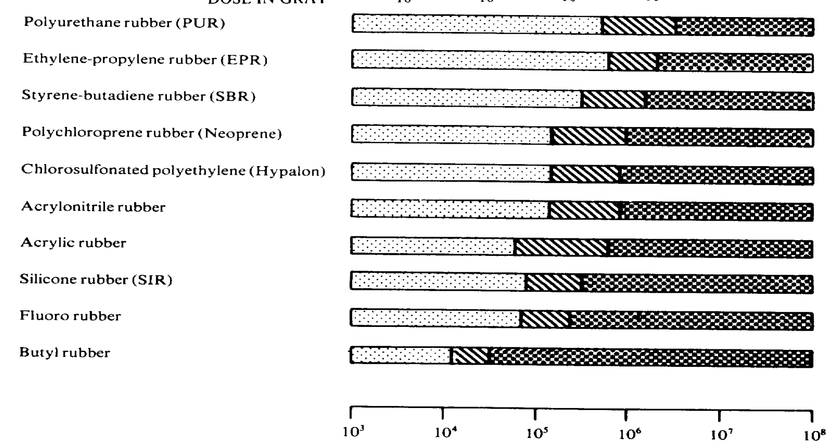
In principle, electrical properties can also be affected by ionizing radiation, because of formation of free charges or change of energetic levels of the matter.

Radiation : compilation of data





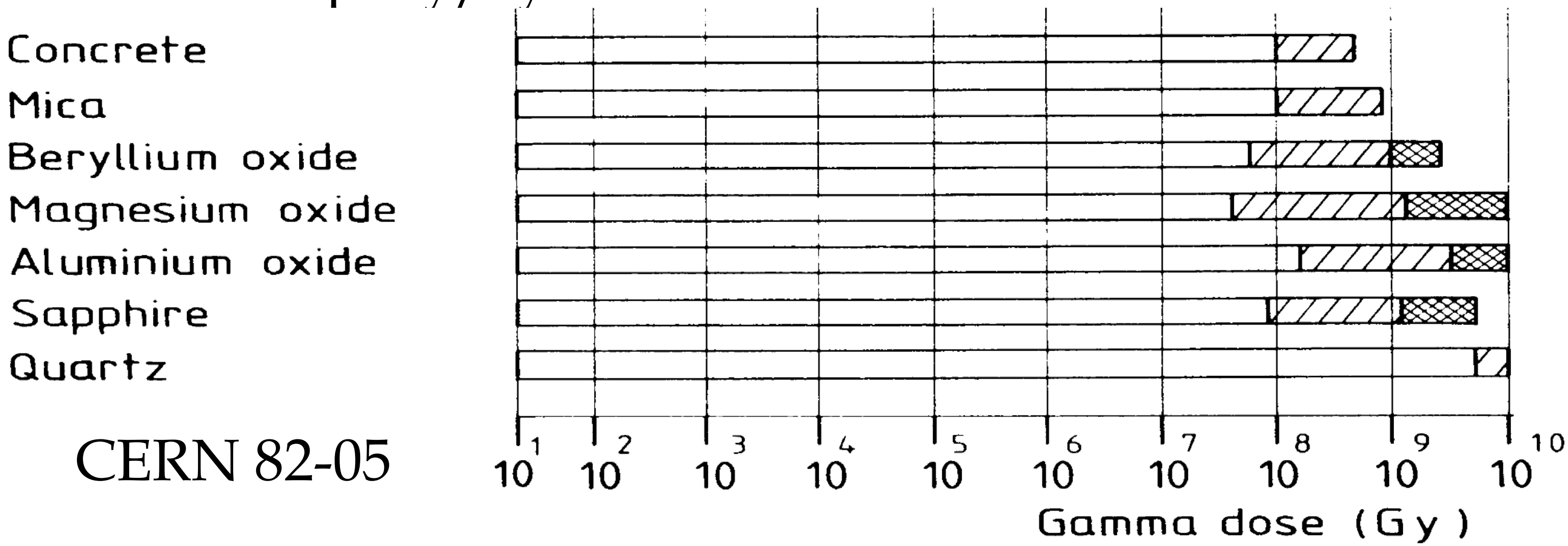




Very high radiation doses

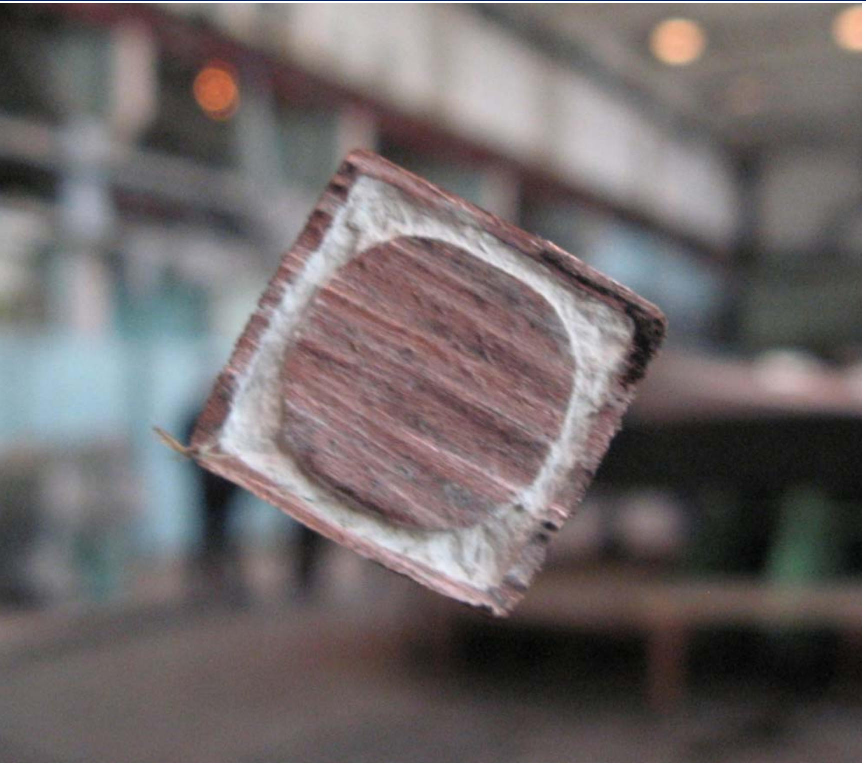
Above 10^8 Gy you need special techniques

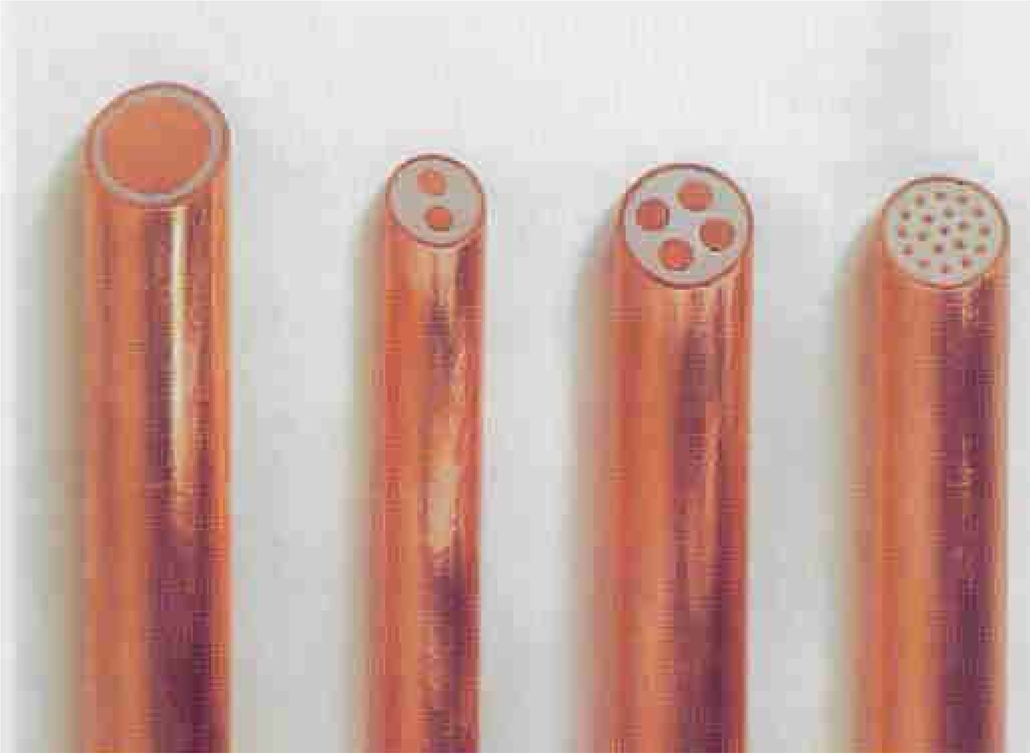
- inorganic insulations (issues : bonding and moisture absorption)
  - cements & minerals (concrete, mica, quartz)
  - glasses
  - ceramics (oxides of aluminum, magnesium, berillium)
- new compounds (issues : mechanical properties)
  - cyanathe esther
  - blends epoxy/cyanathe esther



CERN 82-05

Mineral Insulated (MI) MgO Cable





Used in Fire Protection, Nuclear Plants, Thermocouples, Magnets

Hygroscopic, shall be sealed in the ends

Not suitable for voltages > 1000 V

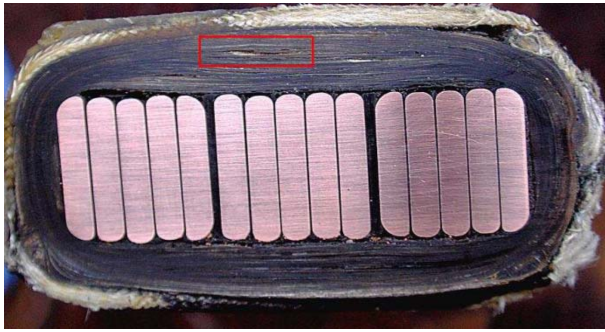
Composites : adhesion is critical issue

Fatigue on fiber-glass/resin composites
G.Liberti, D.Tommasini, Int Conf on Composite materials, Milano, May 1988

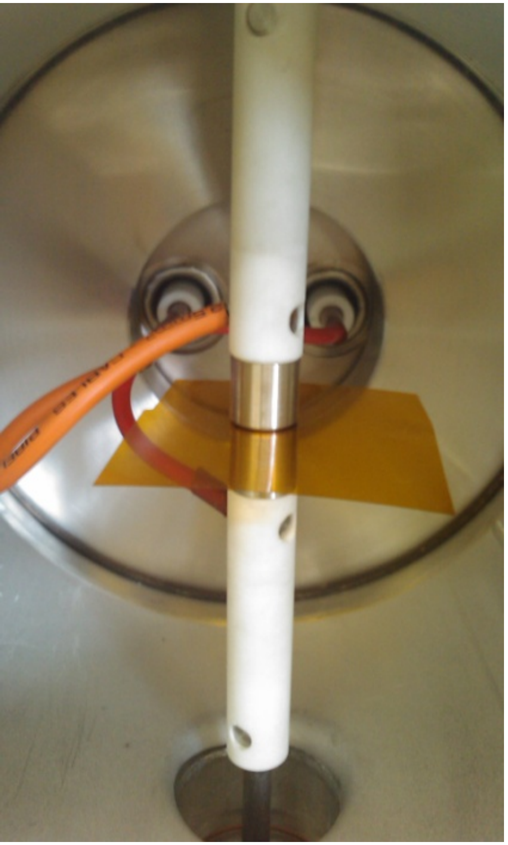
Generator bar after 40 years of service

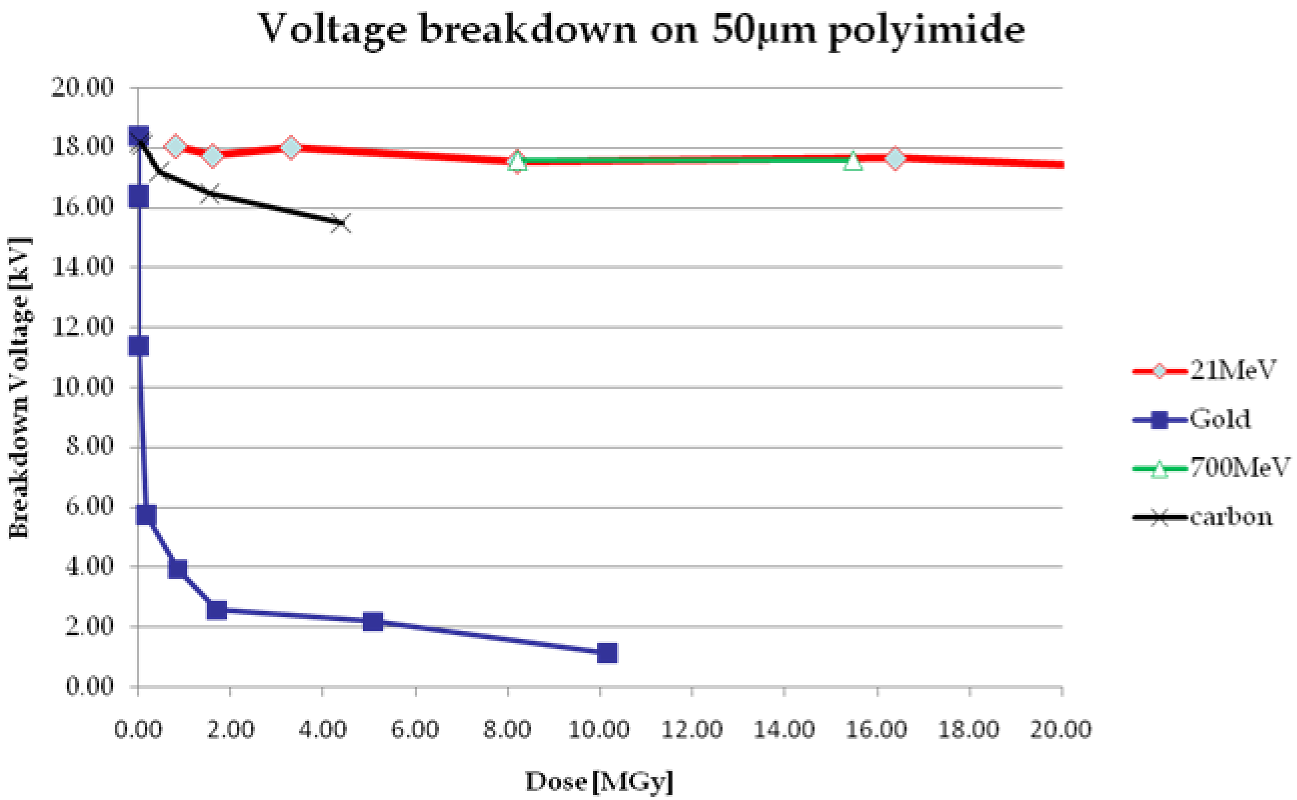
R. Bruetsch and all :"Insulation Failure Mechanisms of power generators"

New bar with defects



Importance of radiation type : an example





Ion beam induced degradation of polyimide is not only depending on the absorbed dose : the ion type plays a major role. The analysis of pre-discharge current patterns suggests different forms of damage depending on the irradiation type. Investigations of these effects on polyimide and on other materials are under way.

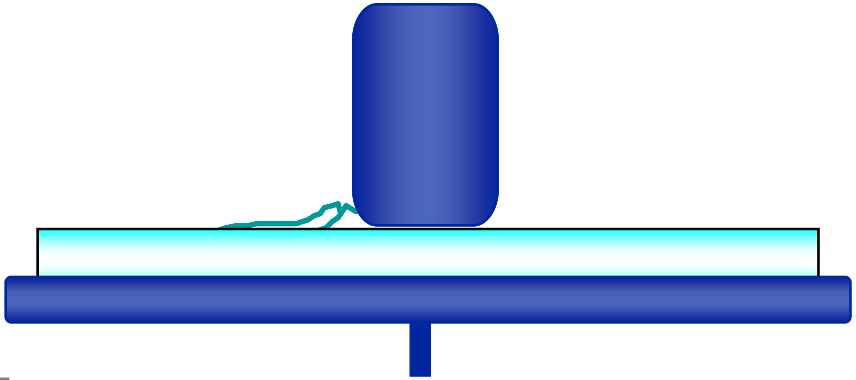
Courtesy Roberto Lopez, CERN, and Tim Seidl, GSI

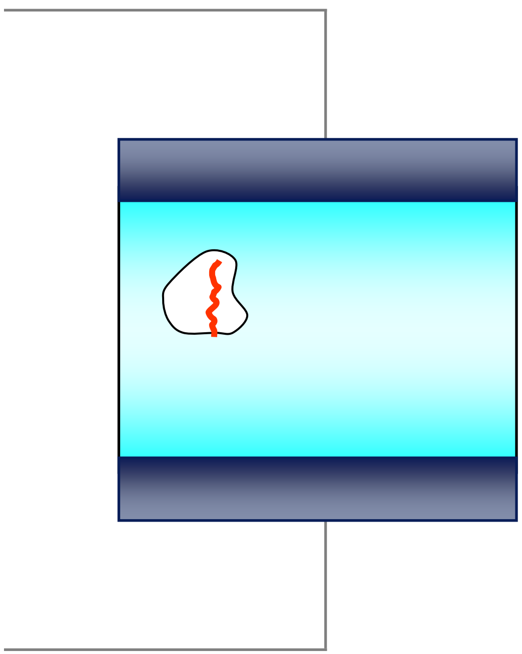
Partial discharges

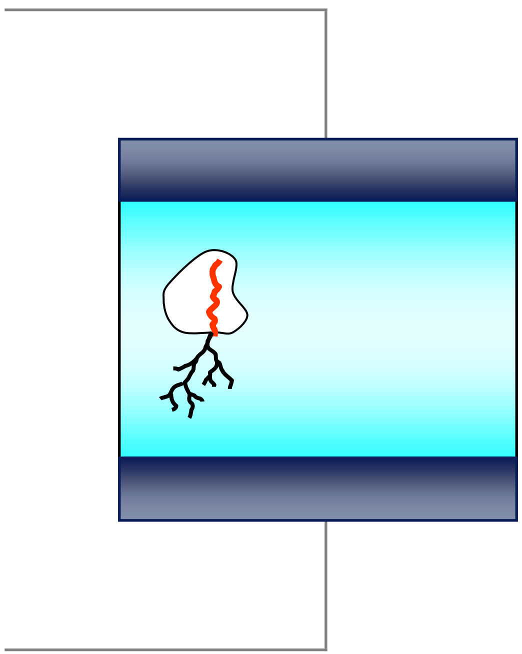
They constitute one of the main mechanisms of ageing of an electrical insulation in continuous operation.

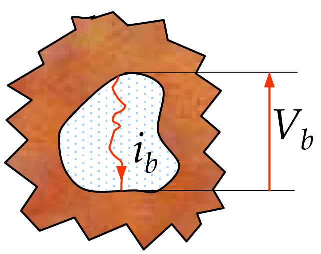
Interfaces air/dielectric such as air bubbles and de-laminations, represent volumes with :

- lower dielectric strength
- concentration of electric field









Corona

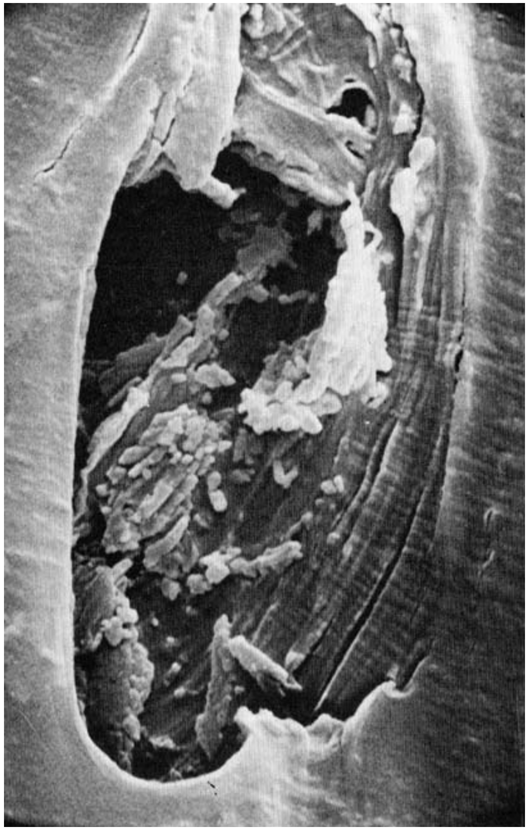
In a gas and non uniform electric fields, when the breakdown field is exceeded we can have local ionization and discharges. The compounds formed during the discharges and the bombardment of ions can degrade nearby insulating materials.

Corona can be of different forms :
• positive voltage: uniformly distributed bluish-white cloud
• negative voltage : reddish spots of current pulses

In air corona inception voltage depends on humidity and on contaminants. As an example, for a wire/plane configuration

Electrical treeing

In case of diverging electrical fields (like in HV cables or geometries with sharp edges, point-like electrodes …) we may observe a progressive evolution of a conducting path.



10 μm

Electrical treeing : branch

Courtesy Prof Francesco Guastavino, CMTEST lab, University of Genova

Electrical treeing : bush

Courtesy Prof Francesco Guastavino, CMTEST lab, University of Genova

Surface discharges

Courtesy Prof Francesco Guastavino, CMTEST lab, University of Genova

Electrical tracking

Progressive creation of a conductive path along a surface, due to un-sufficient distance between electrodes with respect to material properties of the surface and to environmental conditions.




Ageing

It consists in the degradation with time of one or several properties

It can be of non-electrical nature, possible leading
as a consequence
to the degradation of electrical properties

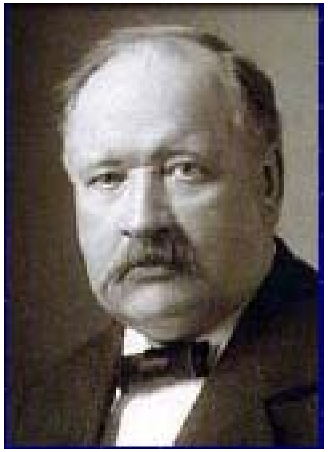



We have already seen some examples of progressive degradation of an insulation system (treeing, tracking, radiation).

Thermal ageing

Temperature governs the speed of a chemical reaction V_R according to the **Arrhenius** law :

$$V_R = A_R e^{-\frac{E}{KT}}$$



where :

E = activation energy

T = temperature in Kelvin

k = Boltzman constant

A_R = constant

If ageing is due to a chemical reaction, we then obtain :

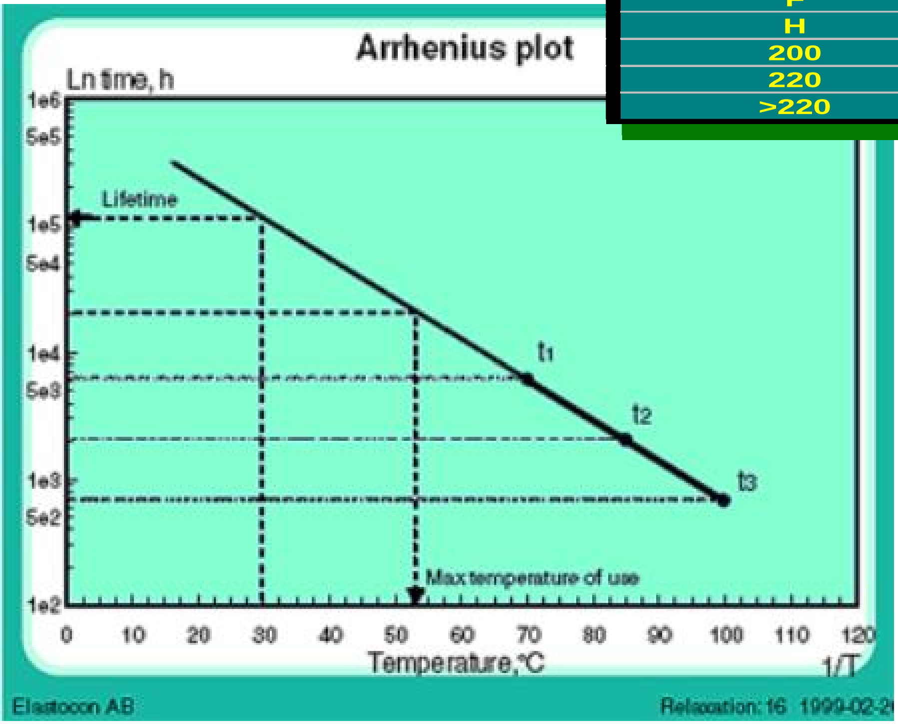
$$D = Ae^{\frac{E}{KT}}$$

In a logarithmic scale, provided the degradation mechanism does not change, is possible to draw the “Arrhenius line” with accelerated tests and obtain the temperature index (D>20000 h)

Lifetime curve : thermal

In a logarithmic scale, provided the degradation mechanism does not change, is possible to draw the "Arrhenius line" with accelerated tests and obtain the temperature index.
According to IEC 60216-1, for windings, D>20000 h

Thermal classes (old)	TEMPERATURE °C	REFERENCE MATERIALS
Y	90	Paper, polyamide fibers
A	105	Oli impregnated paper
E	120	Polyesther resins
B	130	Mica-asphalts composites
F	155	Mica-thermoseeting composites
H	180	Silicon based
200	200	Thermosetting resins
220	220	Teflon, Kapton, Kevlar, Nomex
>220	>220	Inorganic systems



Montsinger's rule

A temperature rise of 10 K halves the expected life-time of an insulation system

Testing an electrical insulation

An electrical insulation shall be tested to ensure its aptitude to provide the required insulation levels over specified operation and faulty conditions and during a specified time.

In particular electrical tests are an excellent mean to verify if the manufacture has been done according to the required quality.

Tests shall put in evidence manufacturing defects

In most cases, this means specifying test levels much beyond the real operational conditions.

Overview of dielectric tests

Properties

Resistivity (step voltage or leakage current vs voltage)
Dielectric constant and loss factor over a range of frequencies
Partial discharge (in particular inception voltage)
Hipot
Breakdown voltage

Type

Type tests (qualification of design & manufacturing)
Routine tests (quality of the individual object)
Special tests (including for diagnostics)

Objects

Materials
Individual components
Assemblies (in factory and at reception)
After installation
In operation

Example : test of active conductor to ground/1

Let's consider a magnet operated at 100 V in dc, possibly undergoing 200 V under fault conditions.
The ground insulation scheme is designed with a minimum thickness of 2.0 mm.
By applying the rule :

$$V_{test} = 2 \cdot V_{\max} + 1 \ \ \text{kV}$$

we obtain Vtest = 1.4 kV

If the insulation is broken somewhere (direct hole to ground) you need about 5 kV in ambient air to create a discharge. 1.4 kV is not enough to intercept a bad manufacture !

Example : test of active conductor to ground/2

You have now to check a coil impregnation is humidity tight. The coil is operated at 100 V in dc, possibly undergoing 200 V under fault conditions. The insulation thickness is 1.0 mm.
You immerge the coil in tap water and check for leakage currents. What it the test voltage to apply?

The one which ensures there are no defects you judge harmful !

In case of our test in water, if we have a .1 μm hole, 1 mm deep, with tap water : $R \sim 10^8\ \Omega$

Type of water	Electrical conductivity (Siemens/meter)
Pure water	$5 \cdot 10^{-6}$
Tap water	0.005-0.05
Sea water (35g/kg)	5

If we do not have a full hole, but just a thinner (damaged) insulation, we need at least the breakdown strength of the insulation.

Assuming a good insulation keeps 10 kV/mm if we want 0.5 mm at any place we have to test at 5 kV.

Partial Discharge Measurements (Tests)

Partial discharges may be representative of defects or degradation of the insulation system.
They can be studied with respect to :

- voltage triggering a flow of charges (PD inception voltage)
- voltage stopping a flow of charges (PD extinction voltage)
- amount of charge involved in a single discharge
- energy dissipated in a single discharge
- time needed to produce inception or discharge at a given voltage
- characteristics of charge flow (in particular in a.c.)

In practice, for complex systems like magnet insulation, irrelevant defects may give noise covering a correct analysis.
On the other hand many defects (for example due to mechanical fatigue) are silent until shortly before a failure.

Important for cables (repetitive) and for large numbers (statistics)

In Conclusion

Failure of dielectric insulation is often determined :

- by a mechanical failure (direct or indirect)
- by unsafe dielectric design to environment/operation

a good designer ensures

- the design correctly considers operation & fault conditions
- the test conditions are such to identify defective manufacture