Aalto-yliopisto
Sähkötekniikan korkeakoulu

High Voltage Engineering

Lecture 9: Condition Monitoring of Electrical Equipment

Mahdi Pourakbari Kasmaei, 2020

Introduction

Condition Management & Monitoring Fundamentals

Ageing & Stress

Theory & Application

- Insulation materials
- Onsite testing & diagnostics
- Partial discharge
- MV cable measurements
- Dielectric Response

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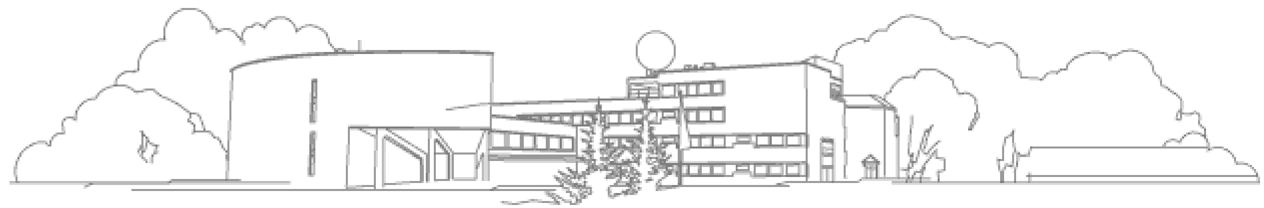
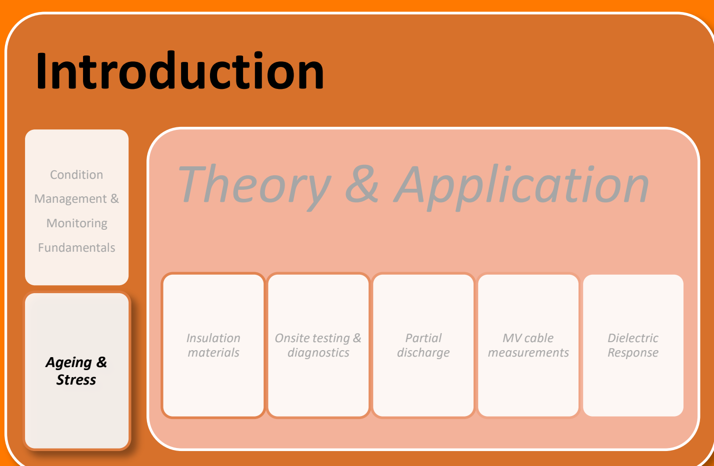


Condition Management and Monitoring Fundamentals



Condition monitoring
Maintenance strategies
Economic perspective
Monitoring methods

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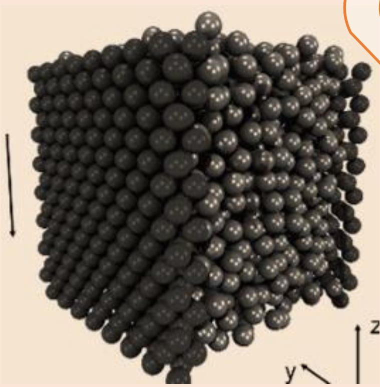


Materials may contain impurities and inhomogeneities

Operational stress can not be accurately predicted

Long-term behavior is unknown

Changing characteristics of aging device cannot be reliably predicted

CONDITION MONITORING IS REQUIRED

CONDITION MONITORING

Availability, Reliability, and Quality

Generation | *Transmission* | *Distribution* | *Utilization*

↓

Economical Efficiency

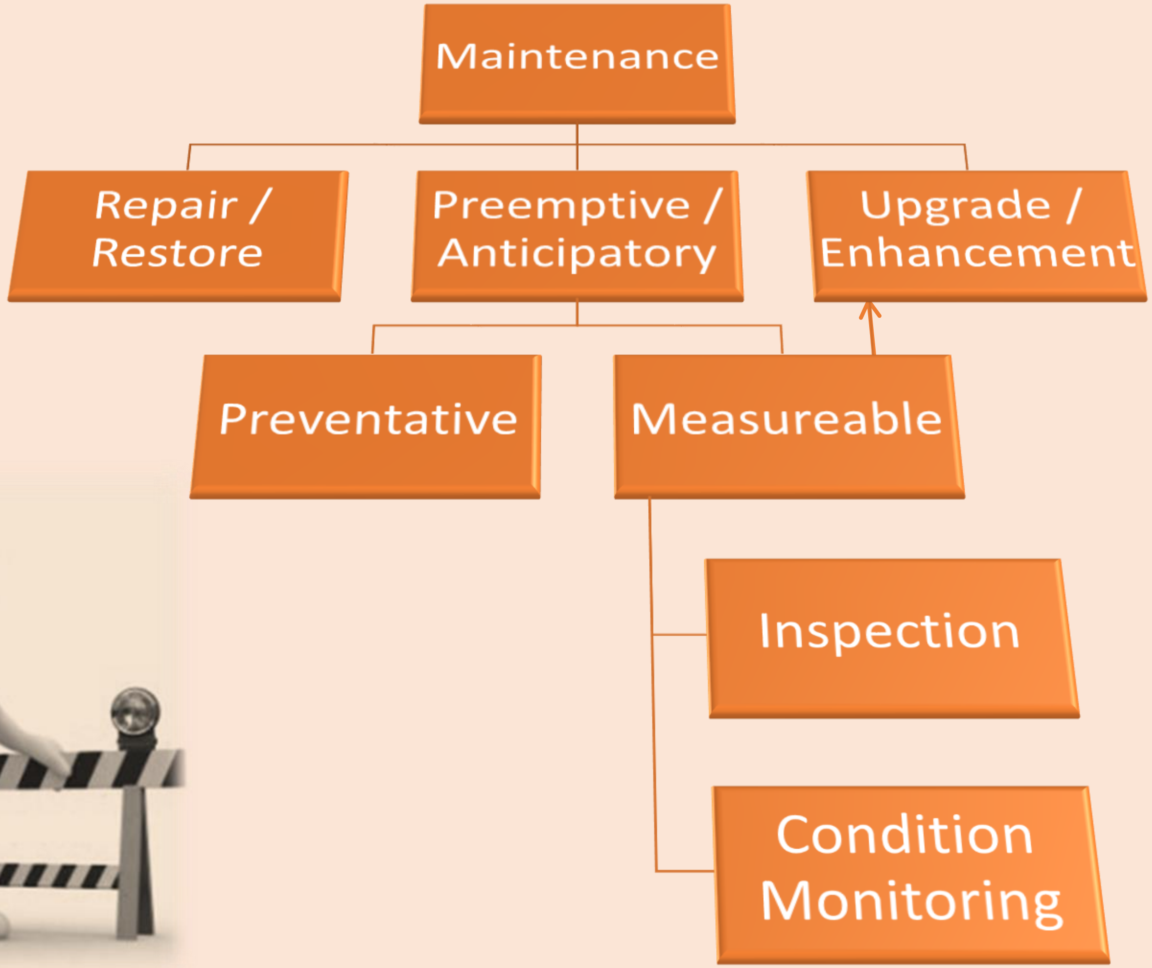
↓

Safety

↓

Environmental Protection

MAINTENANCE STRATEGIES



MAINTENANCE STRATEGIES

Run-to-failure RTF
- Faults are fixed when they occur
- Inefficient and expensive for large systems

Preventative maintenance PM
- Scheduled preemptive maintenance
- Equipment serviced at same regular intervals
- Weakness is determining most suitable and economical maintenance interval

Condition-based maintenance CBM
- Maintenance performed based on the condition of individual equipment

Reliability-centered maintenance RCM
- Considers impact of individual device failure
- Maintenance actions selected based on financial consequences of failure (priority)

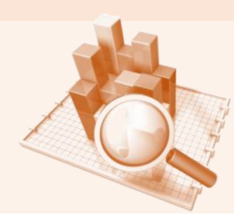
Corrective maintenance CM
- Repairs faults and returns device to original condition
- Repair, replace, restore

Predictive maintenance PDM
- Maintains operating characteristics
- Operating conditions are monitored and faults preemptively avoided
- Plans necessary maintenance activity

Improvement maintenance IM
- Repair actions aimed at improving operating characteristics and serviceability so that future maintenance is reduced
- upgrade

Difference between preventative (PM) and predictive (PDM) maintenance:

- PDM uses **monitoring** to determine required service interval
- PM is based on equipment life expectancy **statistics**



ECONOMIC PERSPECTIVE

Economic efficiency of condition monitoring assessed by comparing operating costs **with** and **without** monitoring

Cost = *device, installation, maintenance, fault, interruption, repair*

Profit = *reduced fault frequency, reduced need for maintenance*

100 % RELIABILITY NOT POSSIBLE

Specified by:

- **Customer** – willingness to pay for quality
- **Authorities** – standards, regulations

ECONOMIC PERSPECTIVE

Maintenance based on:

TIME

CONDITION

RELIABILITY-CENTERED MAINTENANCE RCM MODEL

standard minimum criteria to ensure assets continue to function as required in their present operating context

(remove *redundancy* but ensure adequate *reliability*)

Establish

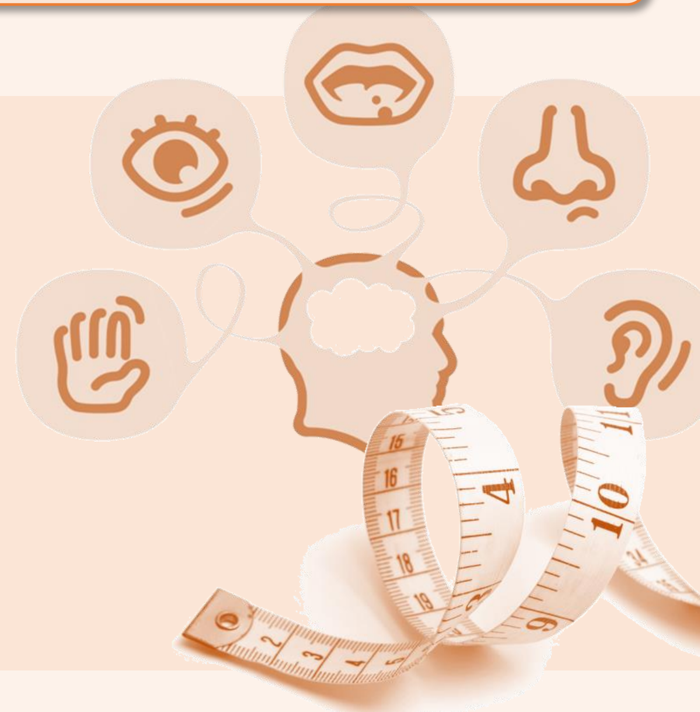
- Safe minimum level of maintenance
- Operating procedures and strategies
- Capital maintenance regimes and plans

→

Increase

- Cost effectiveness
- Machine uptime
- Understanding of risks

MONITORING METHODS

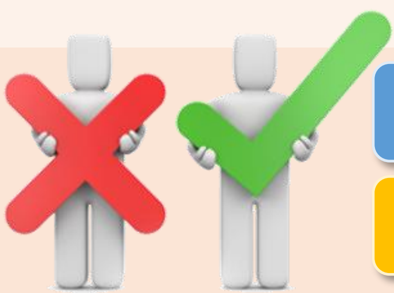


Subjective

Sensory indication – sight, audio, smell (not taste or touch)

Objective

Diagnostics based on measured values



Online – no service interruption (enables continuous monitoring)

Offline – requires service interruption (periodic monitoring)

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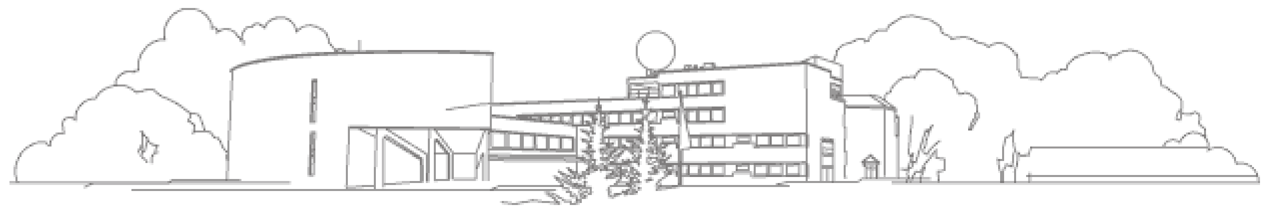
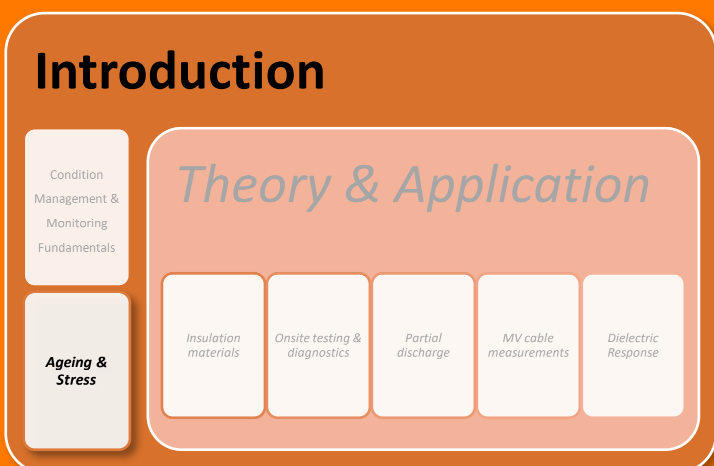


Ageing and Stress



Lifetime

Influential factors

Ageing & stress

LIFETIME

Anticipated lifespan of high voltage equipment depends on many factors:

- *Structure and dimensions of device*
- *Selected materials*
- *Manufacturing and testing procedures*
- *Type of operation*
- *Imposed stresses*
- *Implemented maintenance and repair procedures*

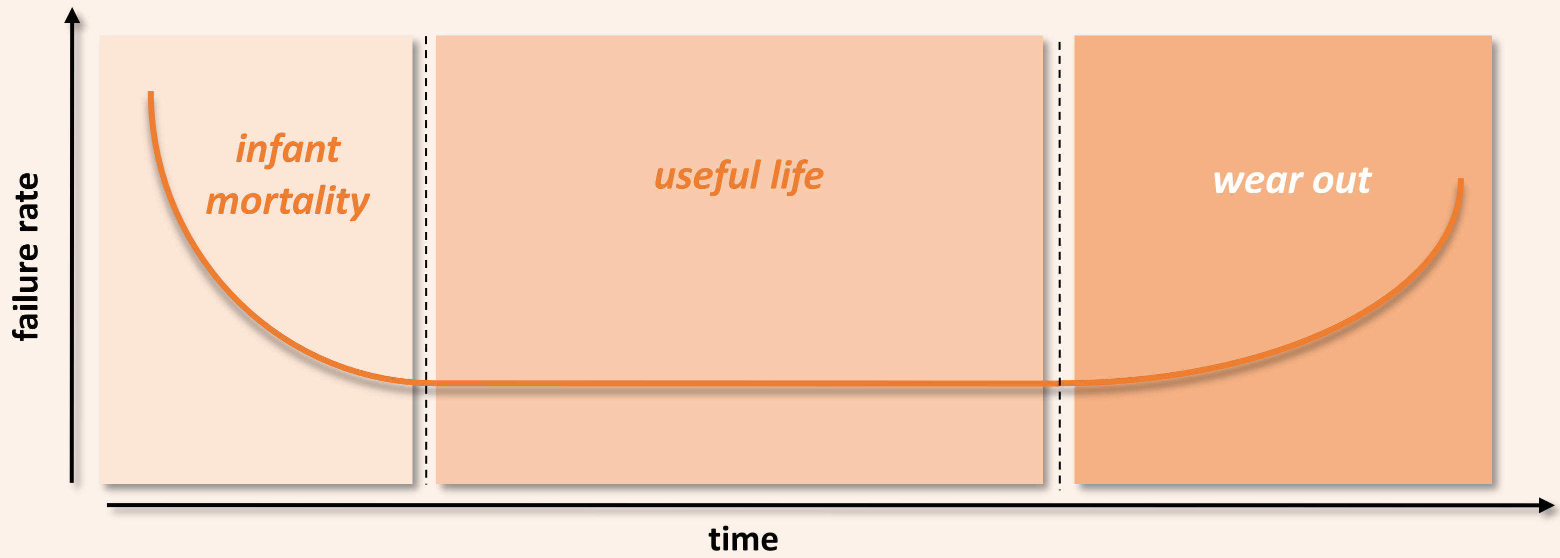
Most critical factors:

OPERATING CONDITION

ENVIRONMENTAL CONDITIONS

STRESS

LIFETIME



EARLY LIFE

High infant mortality rate – inadequate and faulty specimens fail when put into service

USEFUL LIFE

Constant failure rate – random failure resulting from individual abnormal stresses

LATE LIFE

Wear out – equipment approaches the end of their lifespan

LIFETIME

Technical Lifetime

total time period that equipment can technically **perform/function** before it must be replaced

Economical Lifetime

ends when the **cost of continued operation** of the existing device exceeds the **cost of a new investment** (e.g. total losses of the old device is too high)

Strategic Lifetime

Extended Lifetime

operation **beyond** the original design life of the components (without modifications)

AGEING & DETERIORATION

Ageing

Irreversible changes in one or more properties as a consequence of ***normal use*** *or as a result of electrical, thermal, mechanical, and environmental* ***stress*** *over time*

Ageing = *"normal change"*

Degradation = *"abnormal change"*

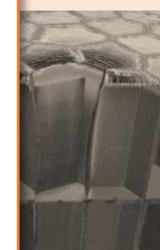
(equipment may deteriorate even when not in service)

ELECTRICAL STRESS

- Normal operational voltage
- Overvoltages (switching, lightning, earth fault)

MECHANICAL STRESS

- Vibration
- Bending
- Forces (tensile, compression)



THERMAL STRESS

- Heating

ENVIRONMENTAL STRESS

- Radiation (UV-light)
- Dirt, dust
- Animals

STRESS EXAMPLES

STRESS EXAMPLES

Damaged sheath (jacket) enabling corrosive ground water to enter the cable and cause severe corrosion of metallic shield

Composite support insulator (fiberglass core and polymer sheds)

Guess cause of damage!

STRESS EXAMPLES

Severe bird excrement contamination on glass insulator disk

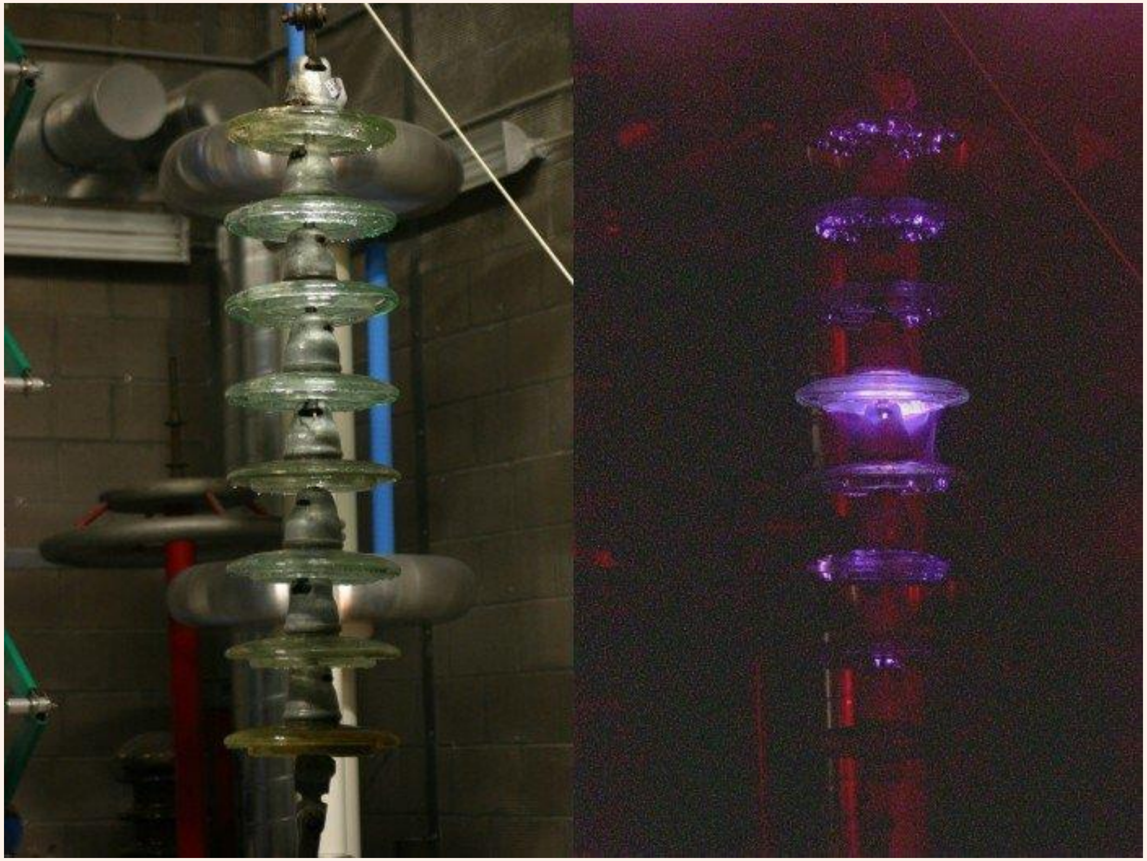
Left - arc damage caused by bird excrement on corona ring

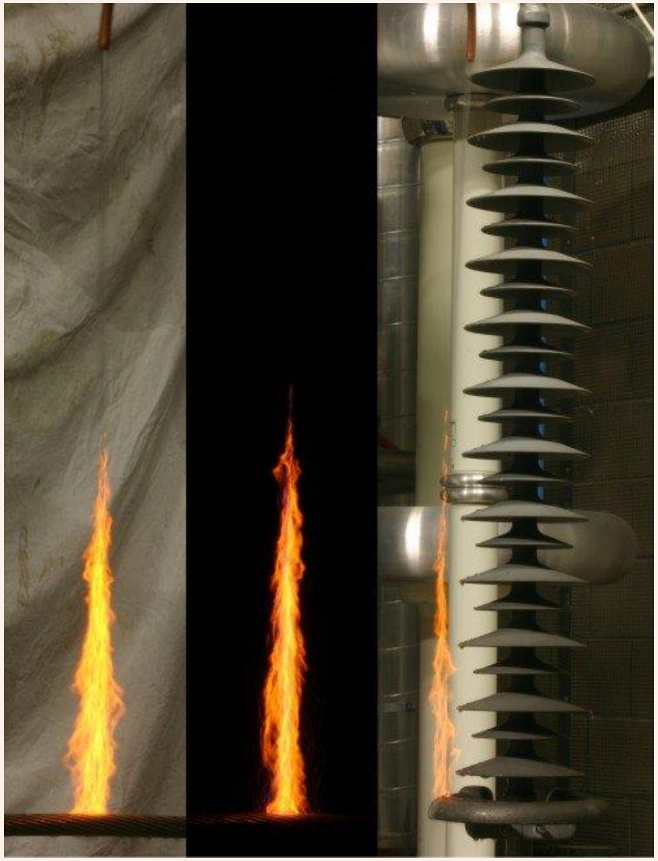
Right - loss of hydrophobic properties of composite insulator

- arc burned the insulator surface (blue color).
- Contaminated surface still retains hydrophobic properties.

Courtesy of Paul Taklaja, Tallinn University of Technology

STRESS EXAMPLES





Partial discharge on naturally contaminated glass insulator string (pre-wetted with tap water)

Highly conductive salt water stream induced flashover

Courtesy of Paul Taklaja, Tallinn University of Technology

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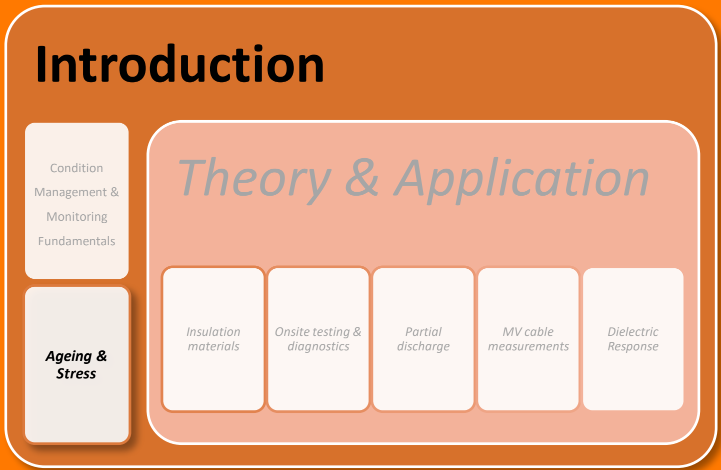
Insulation materials



Solid (and liquid) insulation

Gas insulation

Properties

Degradation

SOLID INSULATION

PURPOSE

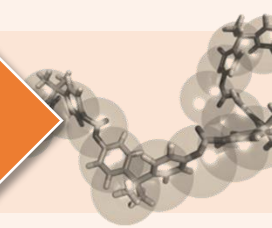
- **Electrical insulation** – *isolate live components from ground*
- **Mechanical support** – *maintain clearance distance*

REQUIREMENTS

- *High* **dielectric strength**
- *Good* **mechanical strength**
- *Adequate* **thermal resistance** (*heat tolerance*)

3 CATEGORIES:

Organic → *Inorganic* → *Synthetic*



<table>
<thead>
<tr><th></th><th>Insulation</th><th>Breakdown Field Strength E_b (kV/mm)</th><th>Temperature Index TI (°C)</th><th>Comments</th></tr>
</thead>
<tbody>
<tr><td rowspan="6">Organic</td><td>Paper (dry)</td><td>6</td><td>90</td><td rowspan="6">• easy to handle and machine
• typically good dielectric properties
• insulating properties change during service life
• temperatures above 100 °C deteriorates insulator
• Typically porous – absorb liquids, impregnation
• transformers, cables, capacitors</td></tr>
<tr><td>Paper (oil impregnated)</td><td>40 – 75</td><td>105</td></tr>
<tr><td>Rubber</td><td>20</td><td>75</td></tr>
<tr><td>Wood (dry)</td><td></td><td>90</td></tr>
<tr><td>Wood (oil impregnated)</td><td></td><td>105</td></tr>
<tr><td>Press wood (dry)</td><td>6</td><td>90 – 120</td></tr>
<tr><td rowspan="3">Inorganic</td><td>Porcelain</td><td>30</td><td>1000</td><td rowspan="3">• withstand high temperatures
• excellent dielectric and mechanical properties
• poor machinability, cannot absorb liquids
• overhead lines, bushings, rotating machines</td></tr>
<tr><td>Glass</td><td>16</td><td>400 – 1000</td></tr>
<tr><td>Mica</td><td>80</td><td>500 – 700</td></tr>
<tr><td rowspan="5">Synthetic Polymer</td><td>Polythene (PE)</td><td>20</td><td>105</td><td rowspan="5">• All industrially produced solid insulation
• Excellent electric properties, easy to machine
• thermoplastic / thermoset plastic
• wide range of applications depending on manufacturing process - moisture sealing, tensile strength, flexibility</td></tr>
<tr><td>Polystyrene (PS)</td><td>100</td><td>80 – 90</td></tr>
<tr><td>Phenolic plastic (bakelite)</td><td>5 – 16</td><td>120 – 155</td></tr>
<tr><td>Epoxy plastic</td><td>20 – 40</td><td>105 – 155</td></tr>
<tr><td>Melamine</td><td>13 – 14</td><td>120</td></tr>
</tbody>
</table>

(Temperature Index TI = withstand temperature of insulator over 20 000 h)

Organic material

Prone to change during operation

- **Oxidation** (combination with oxygen, e.g. rusting iron, yellow brittle paper)
- **Pyrolysis** (thermochemical decomposition at elevated temperatures, e.g. charring wood)
- **Hydrolysis** (polymer degradation caused by addition of water, e.g. aging of cellulose)

Large molecular chains split into smaller segments

Electrical, chemical, and mechanical properties are altered

Synthetic polymers

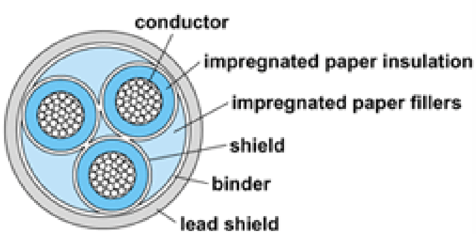
Long term stability

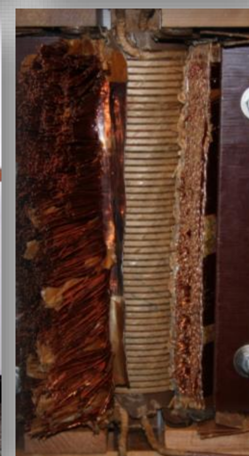
Gradual post-manufacturing **crystallization** (further polymerization) can lead to changes in molecular size and embrittlement

Chemical reactions producing acids

Electrical properties are not changed but mechanical strength can deteriorate

OIL IMPREGNATED PAPER INSULATION





OIL – electrical strength and cooling

PAPER – mechanical and electrical strength

DEGRADATION OF OIL INSULATION

Transformer oil is an **organic material** which **oxidizes** as it ages

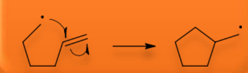
Hydrocarbon molecules in oil oxidize into hydrogen peroxide H_2O_2

H_2O_2 rapidly disintegrates into free radicals

(atom, molecule, or ion with unpaired valence electrons or open electron shell)

Radicals are highly reactive and quickly oxidize

New radicals are formed

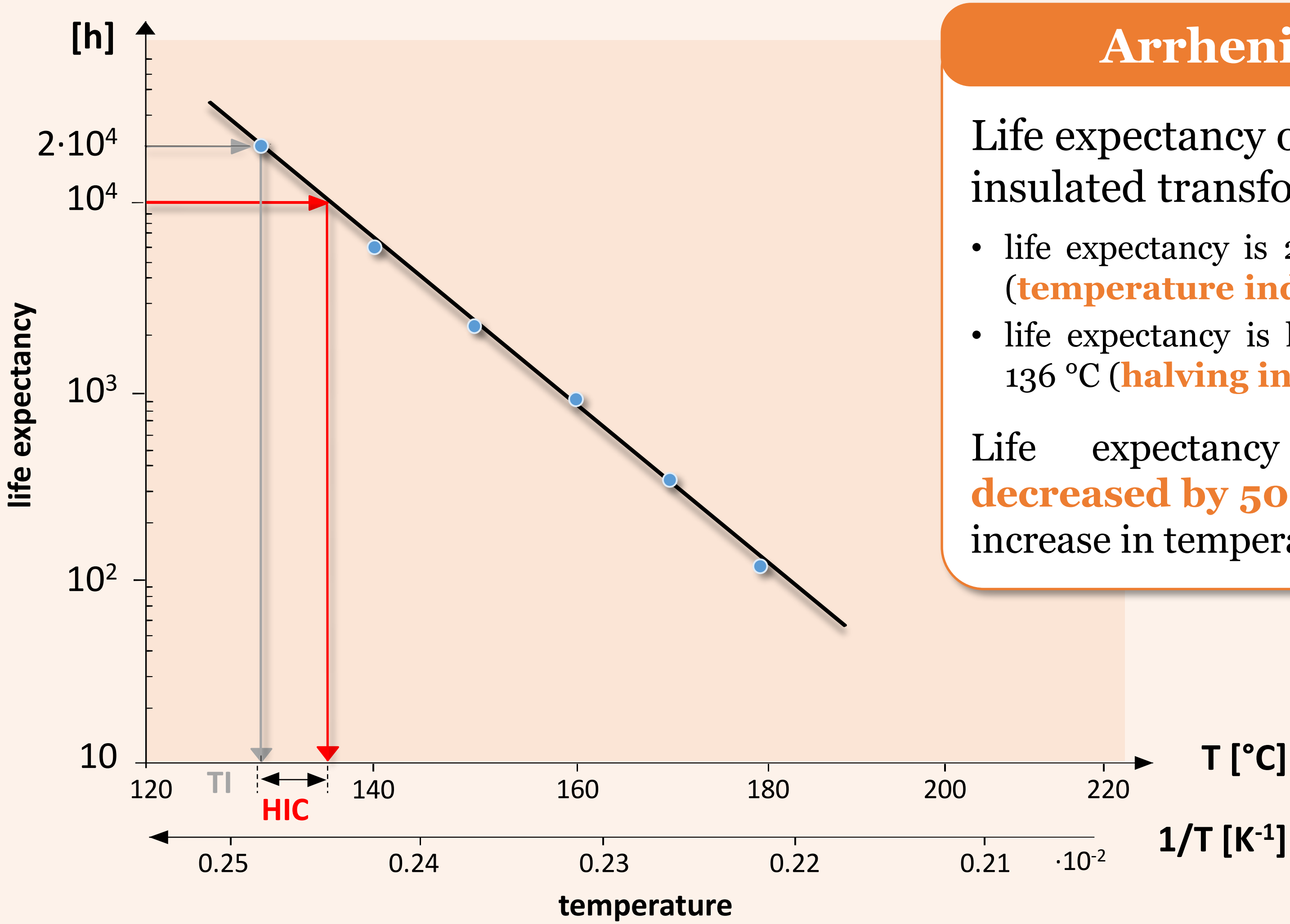


Chemical reactions

Form deposit (sludge), conducting impurities, water, and acid compounds in the oil

- Accelerated by **high temperature** and **moisture**
- Slowed down using **inhibiters**

DEGRADATION OF OIL-PAPER INSULATION



Arrhenius plot

Life expectancy of an oil-paper insulated transformer:

- life expectancy is 20 000 h at 130 °C (**temperature index, T1**)
- life expectancy is half of this value at 136 °C (**halving interval in °C, HIC**)

Life expectancy of insulation **decreased by 50%** with only a 6 K increase in temperature

DEGRADATION OF PAPER INSULATION

Moisture and chemical reaction in oil produce **acidic compounds** which weaken the paper insulation

This does not affect the electrical strength but **mechanical properties** deteriorate as fibers break and the paper becomes brittle

Paper is composed of long chains of **cellulose** molecules formed by glucose rings

↓

Reactions cause the cellulose chains to **break**

↓

Chain length (= **degree of polymerization**) decreases

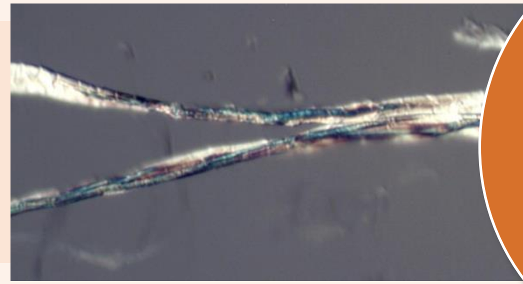
DEGRADATION OF PAPER INSULATION

Degree of Polymerization (DP)

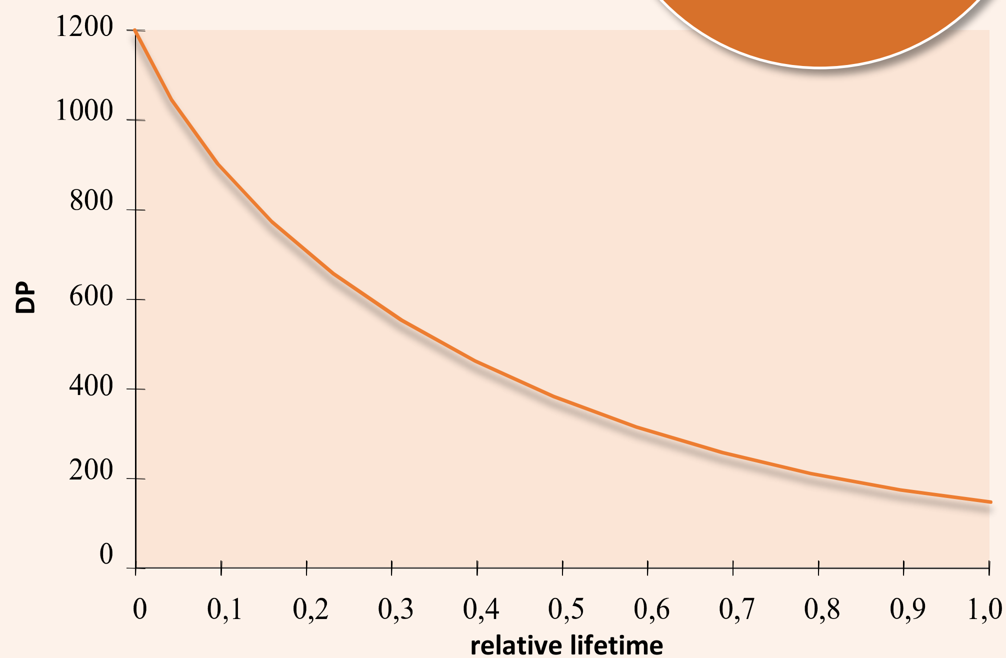
Defines the condition of paper insulation (mechanical strength)

- Average number of glucose rings per molecule
- **New paper** typically has DP of 1000 – 1300
- At **end of technical lifetime** DP is approximately 150 – 200

Generally, higher DP correlates with **higher melting temperature** and **mechanical strength** (harder material)



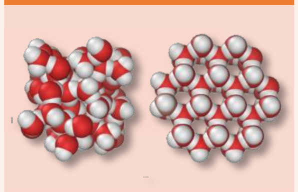
Determining DP value requires a **paper sample**



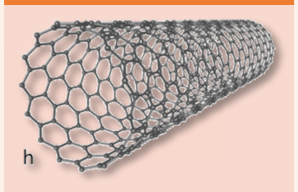
DEGRADATION OF PAPER INSULATION

Degradation of paper by ***chemical reactions***, ***overheating***, or ***electrical discharge*** forms byproducts that are mainly:

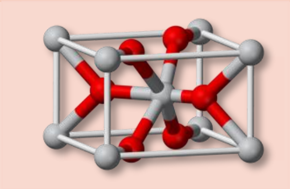
water



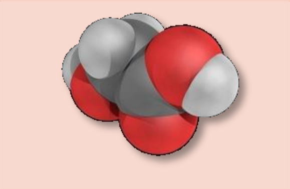
carbon



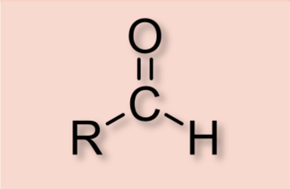
oxides



acids

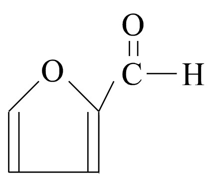


ALDEHYDES

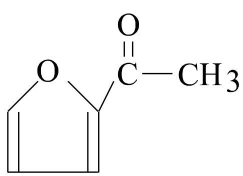


FURFURAL ANALYSIS: Aldehydes can be used for **furfural (furan) analysis** of oil-paper condition.

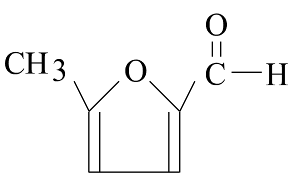
Furfuraldehydes formed during paper degradation:



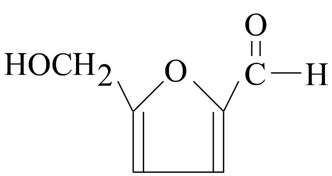
2-furfuraldehyde



2-acetylfuran



5-methyl-2-furfuraldehyde



5-hydroxymethyl-furfuraldehyde

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POLYMER INSULATION

Polymers used as practical insulation are grouped into:

Thermoset (*thermosetting plastics*)		**Thermoplastics** (*thermosoftening plastics*)	
Irreversibly cured	Insulators, instrument transformers	Can be re-melted and remolded	Cables, capacitors
Viscous or malleable prior to curing and irreversibly molded into final form	Epoxy resin, Bakelite, vulcanized rubber	Liquid when heated and freezes when cooled	Acrylics, nylon, PET, PE, PC, PI, PP

AGEING OF PLASTICS

Over time the mechanical, chemical, and electrical properties of polymers deteriorate

Mechanical stress – changes shape and size of insulator

Formation of small microscopic voids that can trigger PD

Chemical reactions – creates free radicals

Break molecular chains or form new bridges between chains

Environmental stress – UV radiation

Makes the polymer brittle (breaking of chains)

Physical
- Continuous gradual crystallization
- High temperatures
- Temperature fluctuations

Chemical
- De-polymerization
- Bridge formation

Electrical
- Partial discharge
- Electrical treeing
- Water treeing

Most important properties of polymers are **MECHANICAL** and **DIELECTRIC** strength

both are influenced by temperature

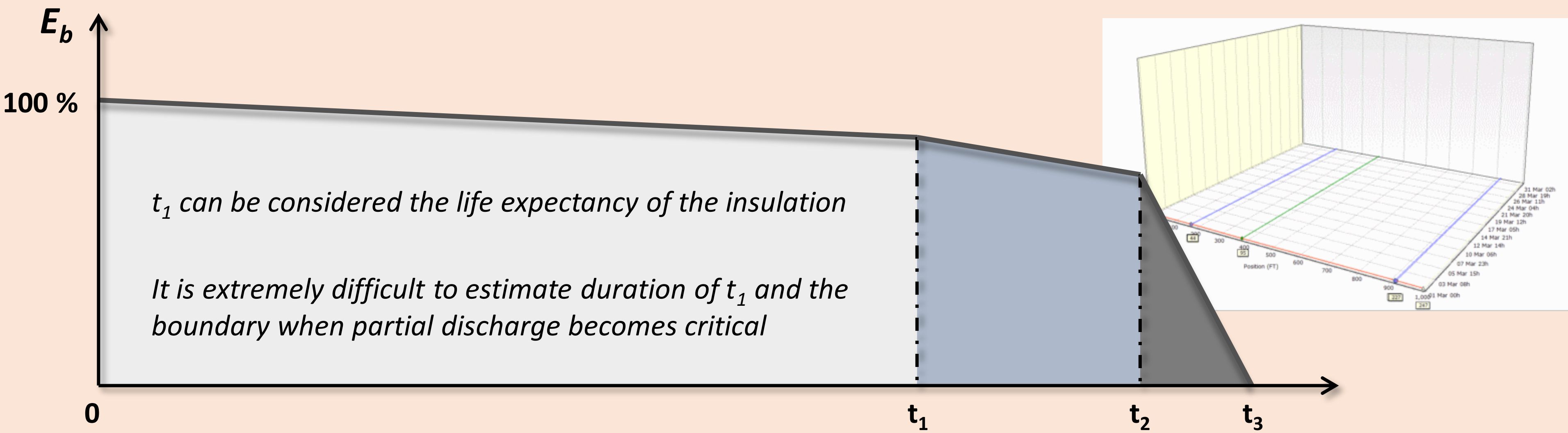
- Components have different **thermal expansion coefficients**
- Non-uniform expansion results in **fractures**

The most important breakdown mechanism for thermoset and thermoplastics is related to **partial discharge**

$0 \rightarrow t_1$ Initially, PD causes **gradual erosion** and **homogeneous deterioration** of the cavity wall

$t_1 \rightarrow t_2$ Discharge concentrates on a specific region of the cavity forming **deeper recesses** in the wall

$t_2 \rightarrow t_3$ Conductive channels form from the now highly inhomogeneous cavity and develop in a branching pattern (**electrical treeing**) until complete breakdown occurs



t_1 can be considered the life expectancy of the insulation

It is extremely difficult to estimate duration of t_1 and the boundary when partial discharge becomes critical

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Partial discharge

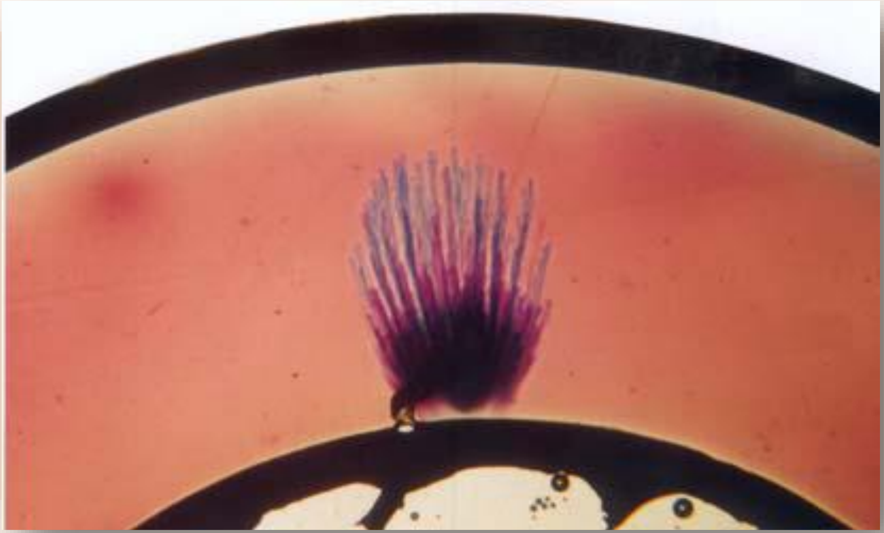
- local accumulation of electric field and depreciation of electrical withstand strength.
- cause erosion and can eventually lead to breakdown

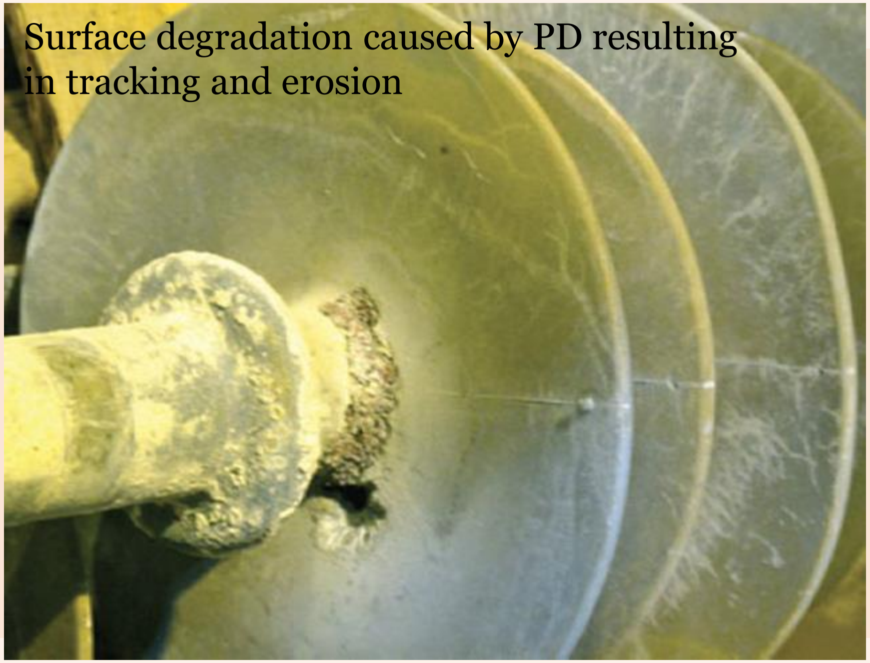
Electrical treeing

- weakly conducting branching tree-like formation
- does not lead to immediate breakdown

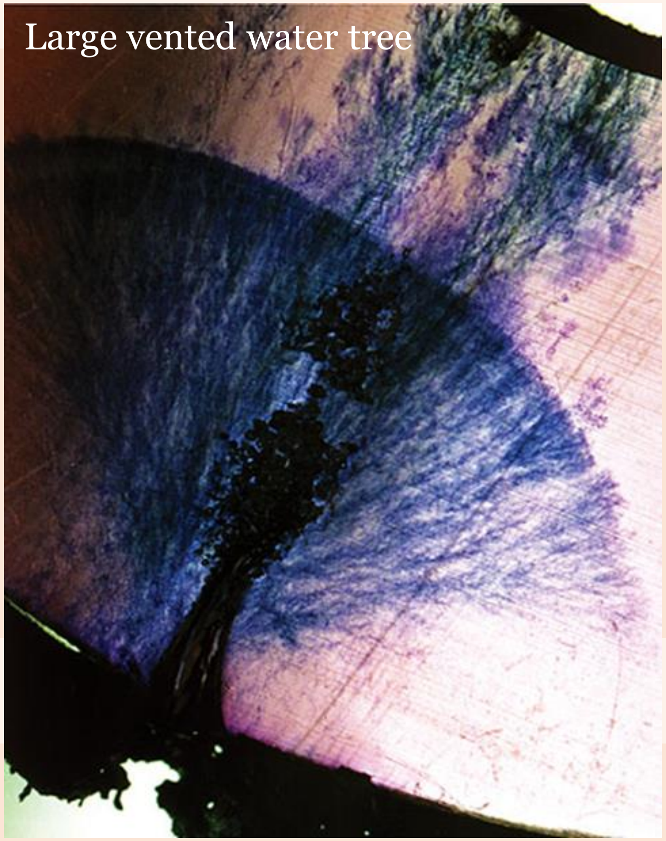
Water treeing

- propagation of moisture within the insulator
- a water tree can lead to electrical treeing

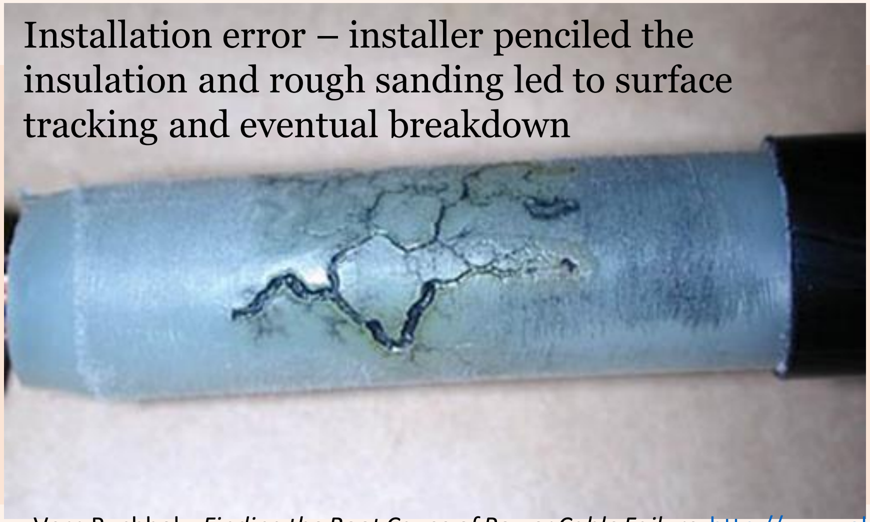




Surface degradation caused by PD resulting in tracking and erosion



Large vented water tree

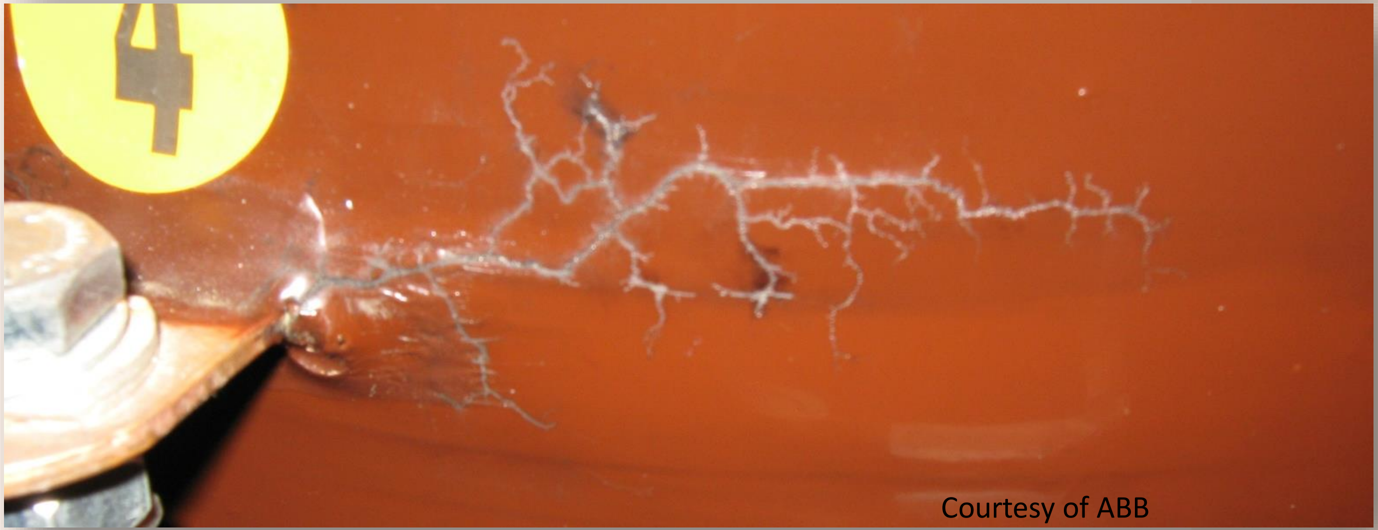


Installation error – installer penciled the insulation and rough sanding led to surface tracking and eventual breakdown

XLPE cable with multiple externally visible water trees

Vern Buchholz, *Finding the Root Cause of Power Cable Failure* http://www.electricenergyonline.com/show_article.php?mag=&article=186

Surface tracking on cast resin dry-type transformer



Courtesy of ABB

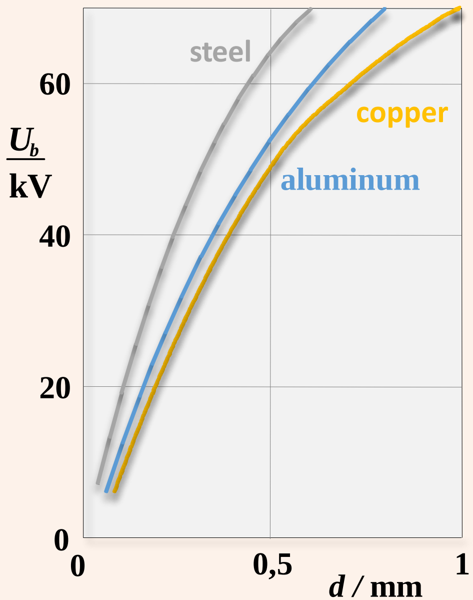
GAS INSULATION

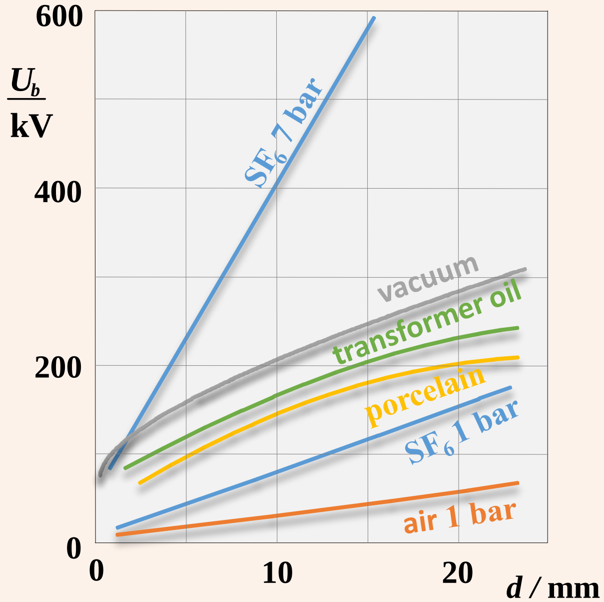
Vacuum – *high frequency capacitors, vacuum switches and breakers*

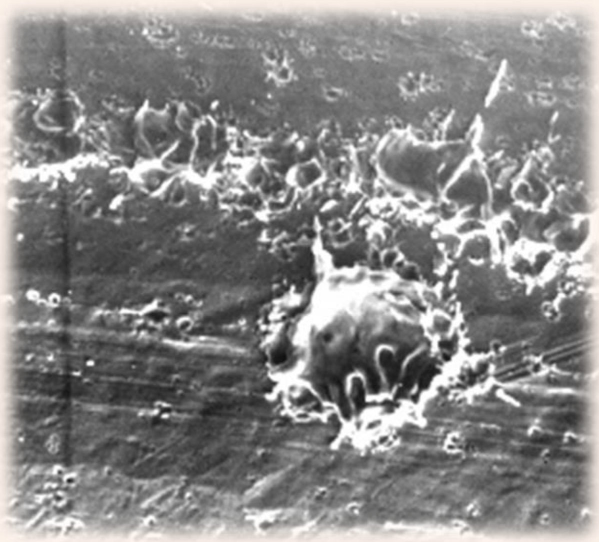
Ideal insulation in theory – no free charge carriers

⇨ In practice, gas insulation at **very low pressure**

⇨ Charge carriers provided by electrode material (and impurities)





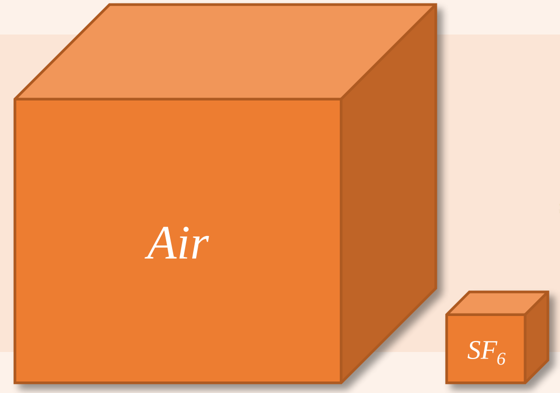


DC voltage withstand strength of a vacuum is approximately **8 times greater** than air at 1 bar

GAS INSULATION

Sulfur Hexafluoride SF_6

- Stable, non-toxic, inflammable, poorly reactive with other materials
- 5.1 times **heavier** than air (risk of oxygen displacement)
- 3 times better dielectric strength compared to air (8.9 kV/mm)
- 24000 times more **potent** greenhouse gas compared to CO_2
- Breakdown by-products potentially **hazardous**



100 %

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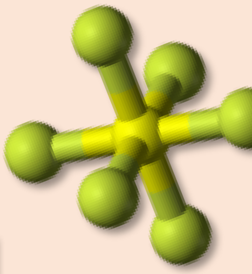
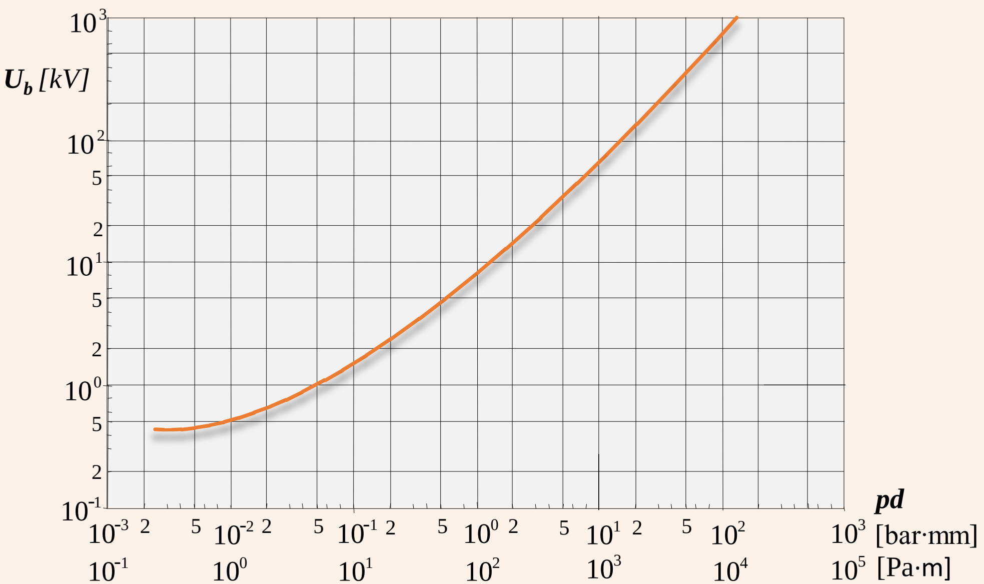




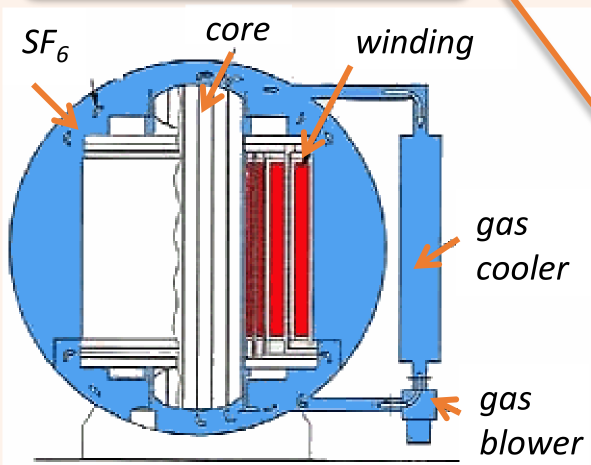
GAS INSULATION

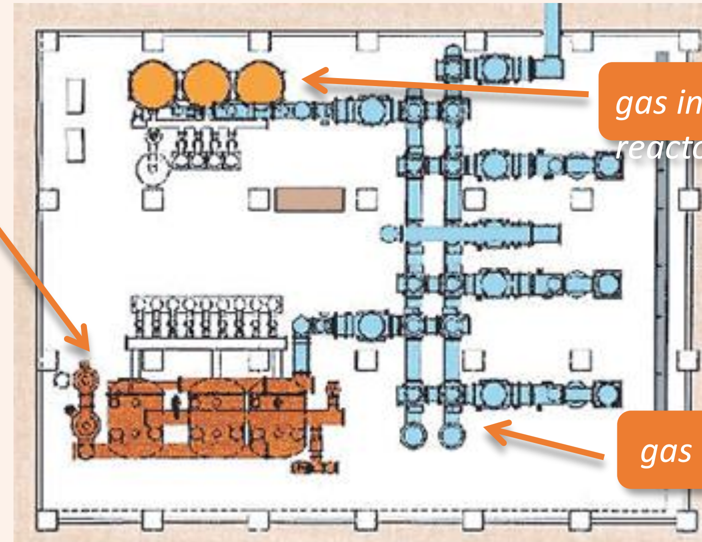
Properties of gases at 20° C, 1 atm

	Density [g/dm³]	**Ionization Voltage U_i** [V]	**Breakdown Field Strength E_d** [kV/mm]
H_2	0.08	15.40	1.90
He	0.17	24.60	1.00
Ne	0.84	21.60	0.29
N_2	1.17	15.80	3.30
Air	1.21	-	3.20
O_2	1.33	12.80	2.90
Ar	1.66	15.80	0.65
CO_2	1.84	13.70	2.90
Kr	3.48	14.00	0.80
Xe	5.50	12.00	-
SF_6	**6.15**	**15.90**	**8.90**

Gas Insulated Substation GIS

gas insulated transformer





gas insulated shunt reactor

gas insulated switchgear

GAS INSULATION

Challenges:

- **Gas leakage** — *reduced **dielectric strength***
  __environmental__ issues
- **Gas transformation** — *chemical **reactions** with impurities*
  *breakdown **byproducts***
- **Free particles** — *inhomogeneous **electric fields***
  partial discharge

OVERVIEW

Stressing of insulation				
Thermal	*Electrical*	*Mechanical*	*Chemical*	*Environmental*

In practice all stresses apply **simultaneously**

- *Synergy (collective interaction) is not an arithmetic sum*
- *Entity is difficult to model*

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On-site Testing & Diagnostics

Introduction

Condition Management & Monitoring Fundamentals

Ageing & Stress

Theory & Application

Insulation materials

Onsite testing & diagnostics

Partial discharge

MV cable measurements

Dielectric Response

Testing

Equipment

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TESTING

Factory testing – laboratory conditions

Type testing	*assurance of correct **design***
Routine testing	*assurance of correct **fabrication***
Sample testing	***extended** routine testing*

Designing	**Prototype**	**Mass Production**	**Finished Product**
Design Testing	***Type Testing***	***Routine Testing***	***Sample Testing***
	Extensive ensemble of testing to ensure suitability of equipment type. Testing repeated every 3 – 5 years to give customer updated results.	Small scale testing for every produced device. Find defective specimen.	Random testing of small portion of manufacture batch.

TESTING

On-site testing

Commissioning test	*assurance of proper* ***transportation*** *and* ***installation***
After repair	*assurance of* ***service*** *validity*
Diagnostics	*determination of present* ***condition***



TESTING

Quality of Testing

- Suitability and condition of ***equipment***
- ***Standards*** and regulations (rules)
- Testing ***methods***
- Consistency, diligence, flow of information
- Qualification of ***personnel***
- ***Traceability*** of measurements

DOCUMENTATION!

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TESTING versus DIAGNOSTICS

Testing

- Standards
- High voltage
- Can be destructive
- Easy to interpret
- Time consuming
- Standard equipment
- Can include diagnostics

Diagnostics

- Recommendation or instructions
- Smaller voltage
- Cannot be destructive
- Difficult to interpret
- Has to be time-efficient (service interruption)
- Special equipment
- Can include testing