Visegrad Fund

Using the aging models for modern EIS lifetime prediction

Pavel Trnka
FEE, University of West Bohemia in Pilsen

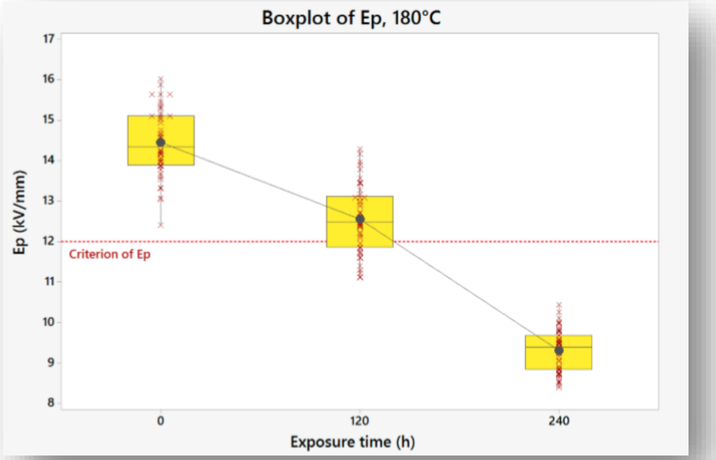
ViF- Engineering platform and cooperation for analysis of nanocomposites

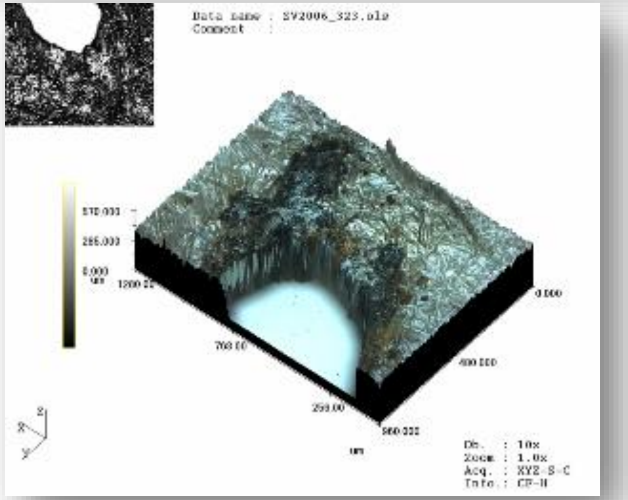
28.4.2021

Introduction

Aging description and life time estimation

- Along with the introduction of online diagnostic systems for the electrical equipment state examination, software solutions for the processing of acquired data are also gaining importance. One way to predict the future state of equipment is to use aging models for its components. The lecture will deal with ways of obtaining aging models, determining their parameters and endpoint criteria. Finally, the possibility of using models for emerging nanomaterials will be evaluated.





Materials and Diagnostics

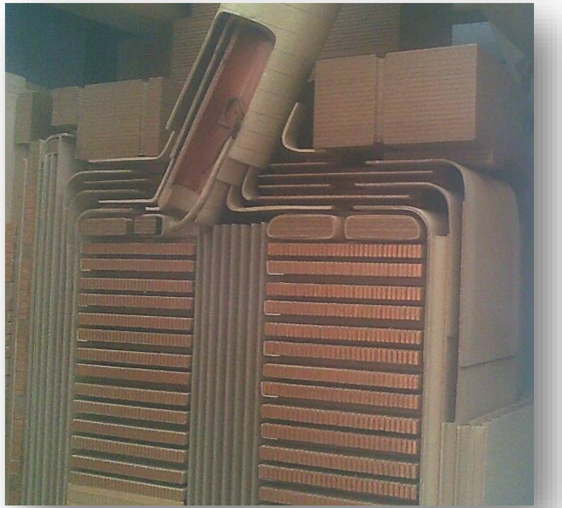
In high-voltage technology - EIS electrical insulation systems rather than EIM (materials) - many different properties requirements

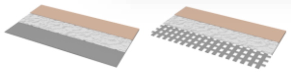
Multicomponent & composite materials

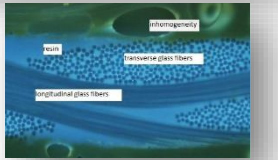
Liquid and gaseous EIS - with a structure for modeling the shape of the electric field intensity

- Properties / parameters

- Degradation factors and mechanisms



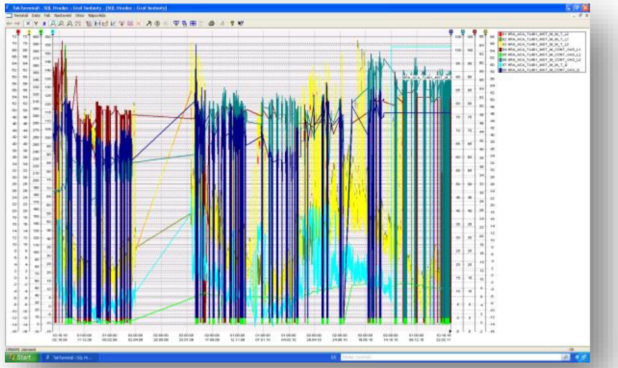


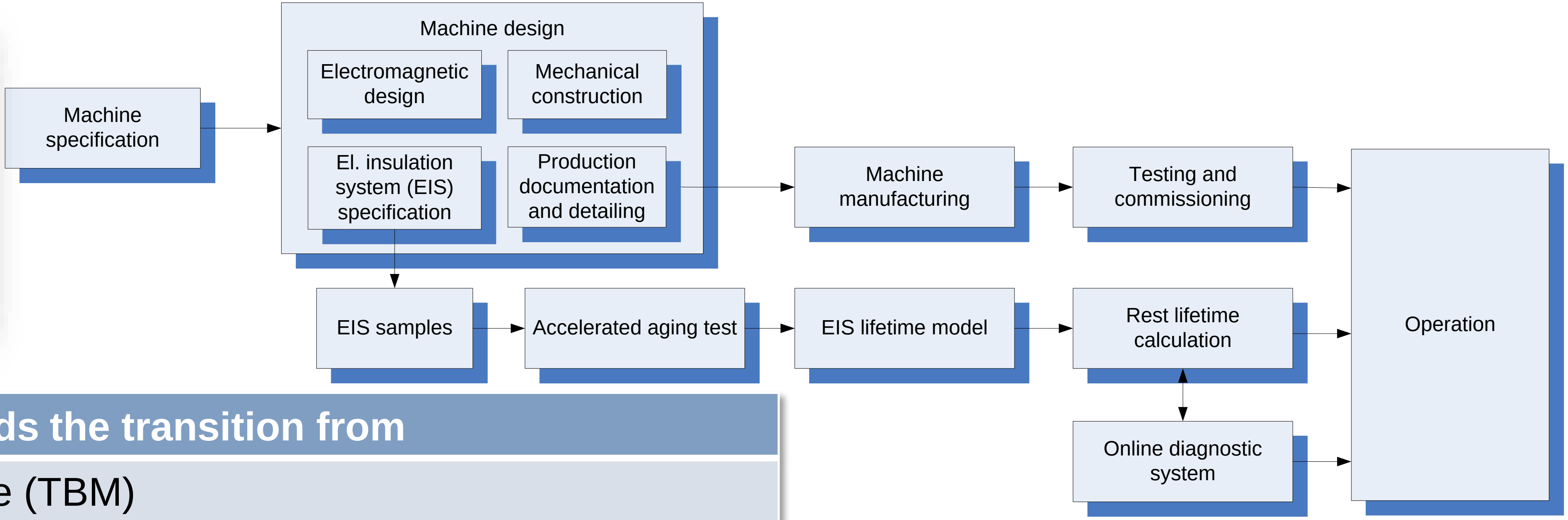


X_1	X_2	X_3	The most sensitive unit
$Q_1(t)$	$Q_2(t)$	$Q_3(t)$	$Q_4(t)$

$$Q_{ser} = 1 - \prod_{i=1}^{N} (1 - Q_i)$$

Diagnostics vs. long-term asset management





Nowadays, work towards the transition from

Time Based Maintenance (TBM)
to

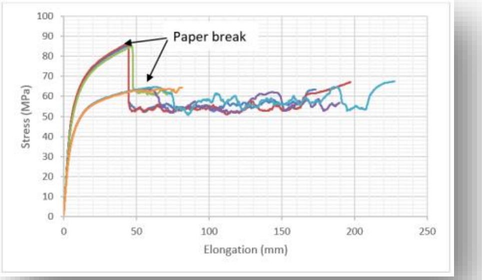
Condition Based Maintenance (CBM) and online diagnostics

Importance in the field of safety - human health, failures, outages, environmental protection, financial costs

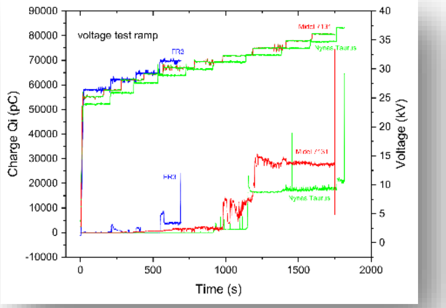
Cost optimization

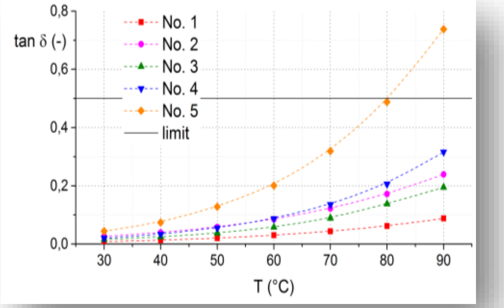
Modern EIS - Composites

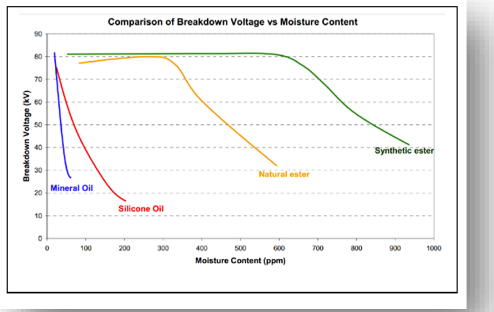
Dielectric properties
Mechanical properties
Thermal endurance
Chemical stability
Technological properties
etc.
✓ Price



= f(t, T, f, E, ppm,..)
or better
= f((T,f, E,…),t)







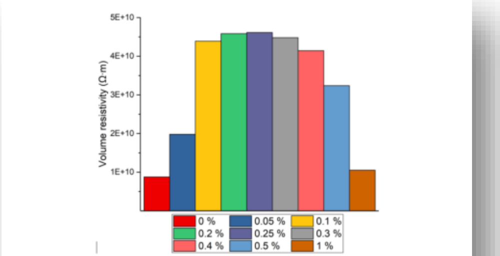
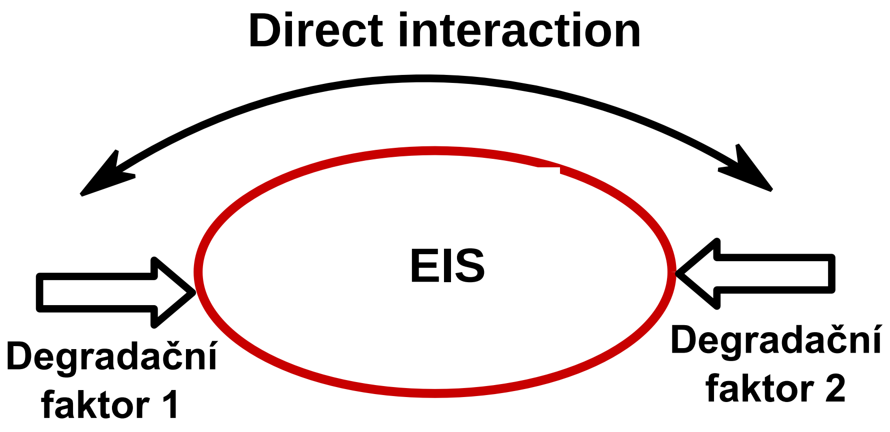
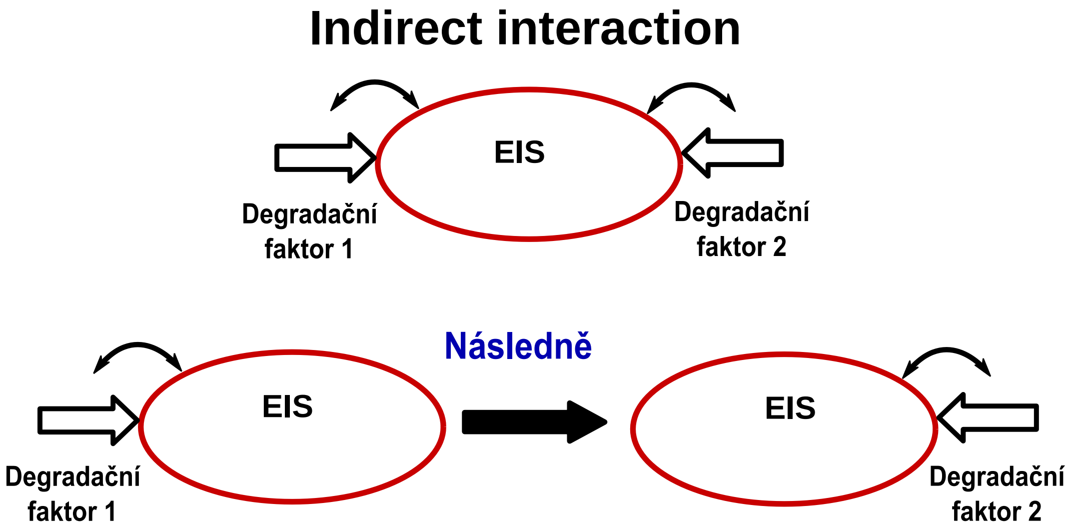


Figure 10. Dependence of volume resistivity of nanofluid with ST TiO_2 on nanoparticle concentration, 90 °C

Multi-factor point of view

Direct interaction is the simultaneous interaction of all degradative influences, which influence each other to such an extent that their individual action is significantly different from the state if these factors acted individually. An example of a direct interaction is, for example, oxidation at elevated temperatures.	**Indirect interaction is conditional influence e.g. mechanical stress → cracks → partial discharge**





Diagnostics methods and Access

Three Possible Accesses to Diagnostics

- After Failure - AF
- Time Based Management - TBM
- Predictive or Condition Based Management – CBM
- **Advantages:**

Increase of the Reliability

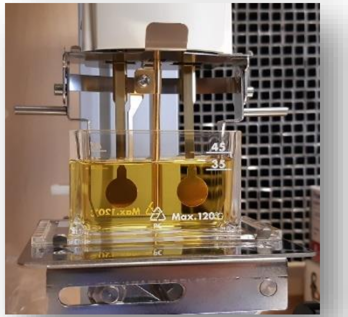
Better overview of the status of operated units

Increase the efficiency of maintenance planning

⇨ **Cost and time savings**

Diagnostic approaches - fundamental differences

Off - line	On-line
Some methods of better outcome - long-term data and experience	Continuous information about the current status
Possibility of visual inspection	Increased reliability and readiness
One universal equipment Laboratory or Mobile Lab	Better maintenance planning
	Possibility of monitoring of remote devices
Some offline parameters differs from online	SMART GRID a Industry 4.0
Problematic shutdowns	Financial requirements for widespread deployment
Necessary onsite presence of experts	Data infrastructure and storage (data safety)





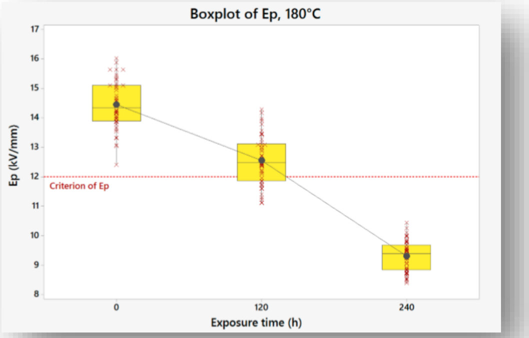

How determine the status

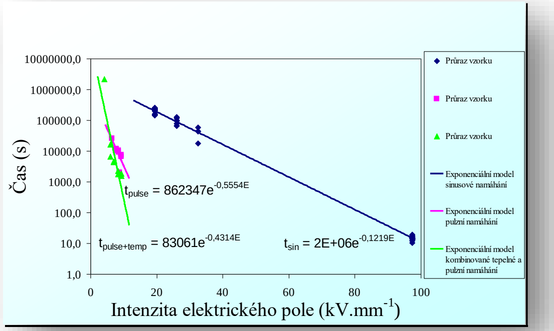
Main degradation factor indetification	
Main degradation factor	Temperature, humidity, radiation, physical phenomena, human factor, PDs, high voltage, chemical, biological impacts
Knowledge of equivalent relevant diagnostic parameter	Diagnostic signal
Method for its monitoring	Sensors, measuring devices, reliability
Monitoring of load, environmental influences	Sensors, measuring devices
Knowledge of the criterion, "increase / decrease" of the parameter	Experience, standards, physical limits
Model	Life time tests, study of mechanisms
Evaluation - expert system	Secure transmission, storage, real-time processing
Expert	Validation

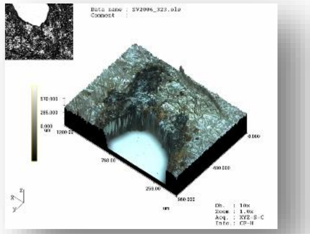
EIS aging monitoring & condition modeling

Empirical access

- Known degradation factor (s) / process (es)
- Corresponding diagnostic signal - time dependent
- Known endpoint criterion
- Known empirical model - It is not necessary to understand the mechanism - still can get good predictions
- Common problem: How to determine the endpoint criterion

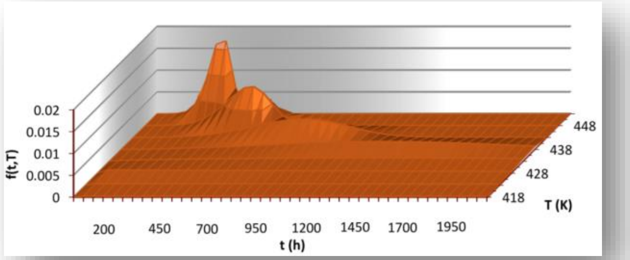


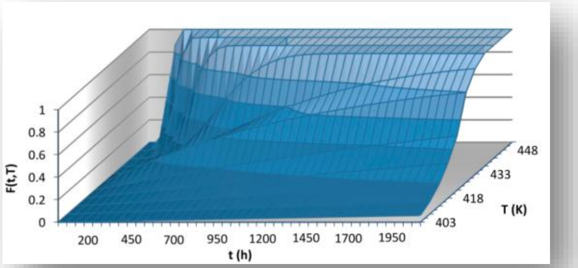




Statistical access

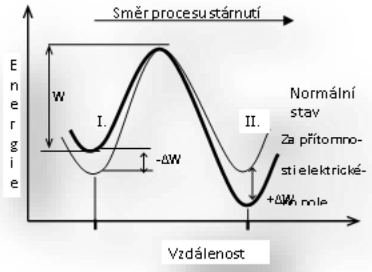
- A large number of the same devices
- "Online" measurement of statistical data
- Knowledge of statistical tools
- Probabilistic, statistical model - Common problem: Choice of appropriate approach / Merging / combining data, wronge assumption
- Prediction, but without specific information about the device



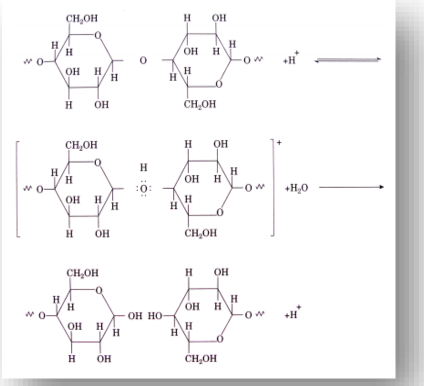


"Physical" approach

- Prerequisite knowledge of the degradation mechanism
- Corresponding diagnostic signal - time dependent
- Precise criterion (U_p (BDV), tensile strength σ_p, U_i (CIV)…)
- Physical model
- State prediction
- Common problems: Functional for one degradation mechanism, but unknown synergies of other degradation processes



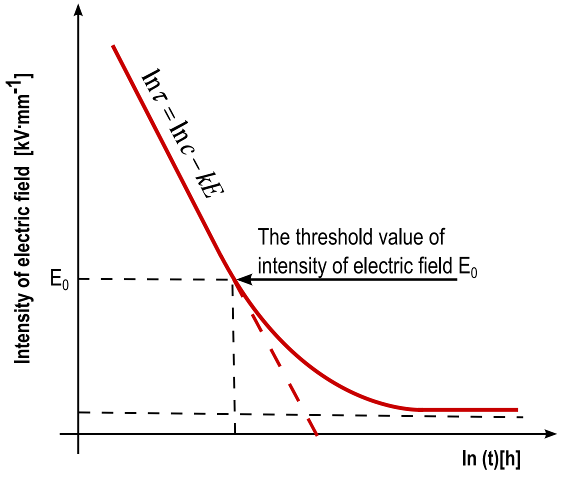
$$\tau_{ST} = \left(\frac{h}{2\,fk_BT}\right) e^{\left(\frac{\Delta W_0}{k_BT}\right)} \cosh\left(\frac{1}{2}\varepsilon_0\varepsilon' \frac{\Delta V_F E_{ST}{}^2}{k_BT}\right),$$



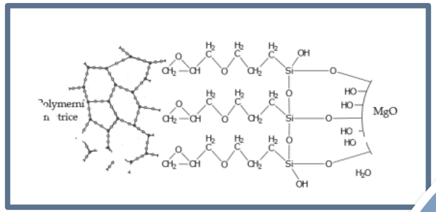
EIS aging monitoring & condition modeling

„Physical/statistical access

- Prerequisite knowledge of the degradation mechanisms
- Corresponding diagnostic signal - time dependent
- Set criterion
- Physical model
- Available statistical data
- Prediction with a certain probability
- Current issues:
  - Inclusion of multiple degradation factors
  - Reliable online diagnostic systems
  - Implementation of Condition Based Management
  - Constantly new materials & their combinations
  - **Nanocomposites** – not fully known processes...

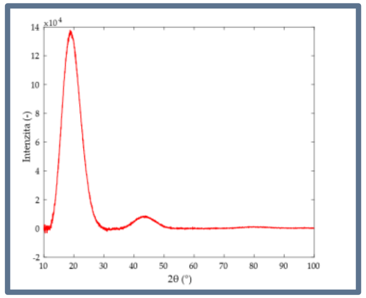


EIS aging monitoring & condition modeling



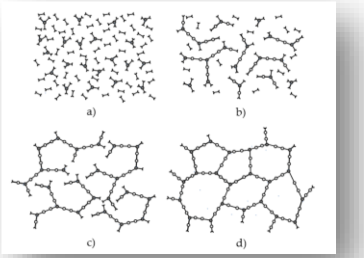
Technological step – a new material requirements

The synthesis of new material shifts its use to the distant future



Material selection based on historical experience

The need to move from empiricism to synthesis, explanation of internal bonds, structure

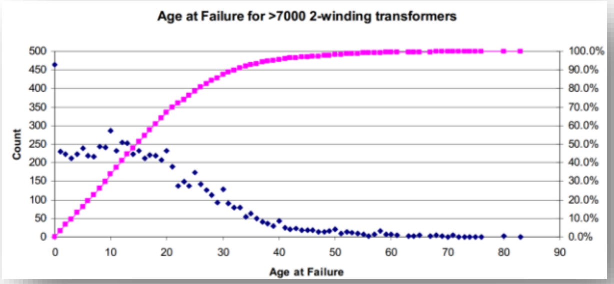


Current state

- Measuring systems exist
- The infrastructure for the transmission of large volumes of data has been created
- Industrial computers already have sufficient durability, reliability and performance
- Network storage exists
- Rapid development of online diagnostic systems
- Solve data processing and create a forecasting system

General / theoretical advantages of CBM

Revealing devices that are approaching the end of technical life (preparation for this fact)
Increasing the reliability of operation
Increasing of operational safety
Reducing maintenance costs because of targeting it to objects that really need maintenance
Reducing costs by not discarding unused objects (otherwise they would be discarded according to the schedule)
Reducing the impact on the environment by optimizing the use
Possibility of central object management and central administration, increasing the efficiency of a certain planned process - the way to industry 4.0 and SMART Grids



Implementation of CBM from the very design of the machine / equipment

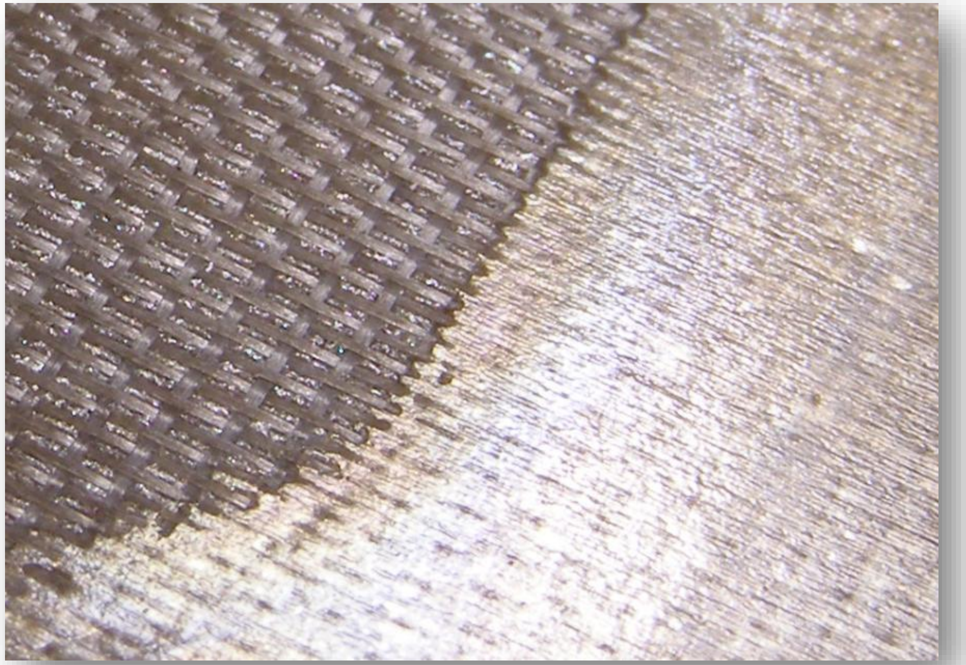
Machine specification

Design:
Electromagnetic design
Material Specification (EIS)
Mechanical construction
Production documentation...

Manufacturing proces

Tests before put to the operation

Operation



Material samples, eg samples of electrical insulation system (EIS)

Tests with increased degradation factor
eg temperature, mechanical stress

Aging models

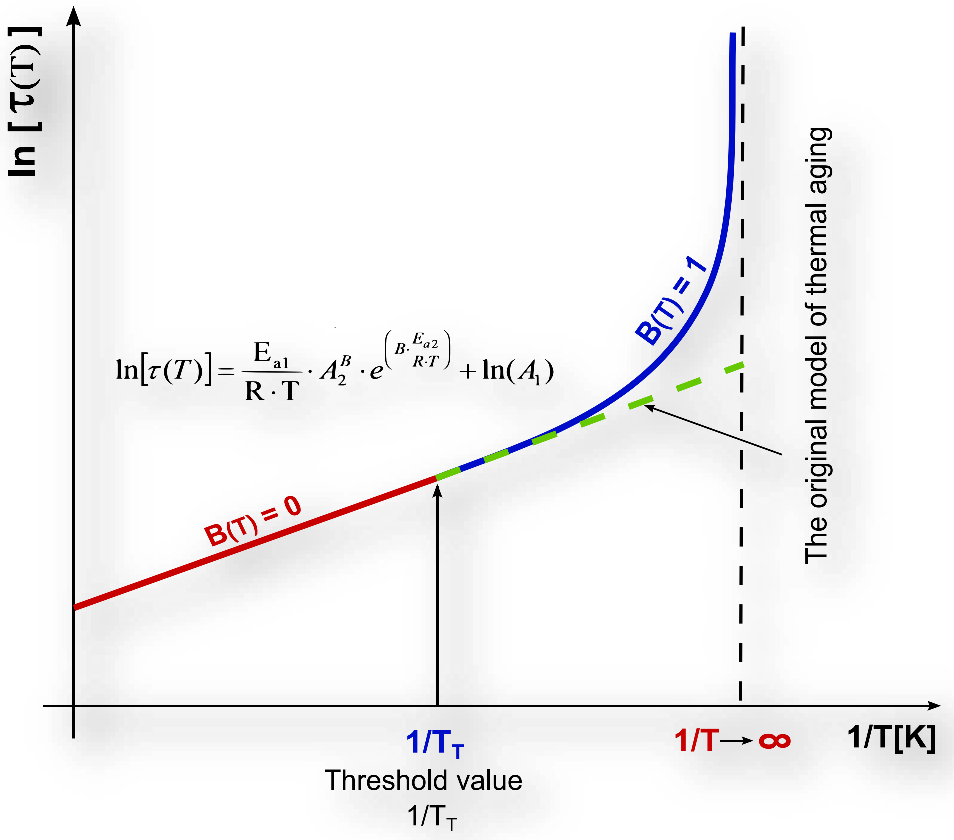
Online diagnostic system

Remaining life estimation

Ways to determine the state - model

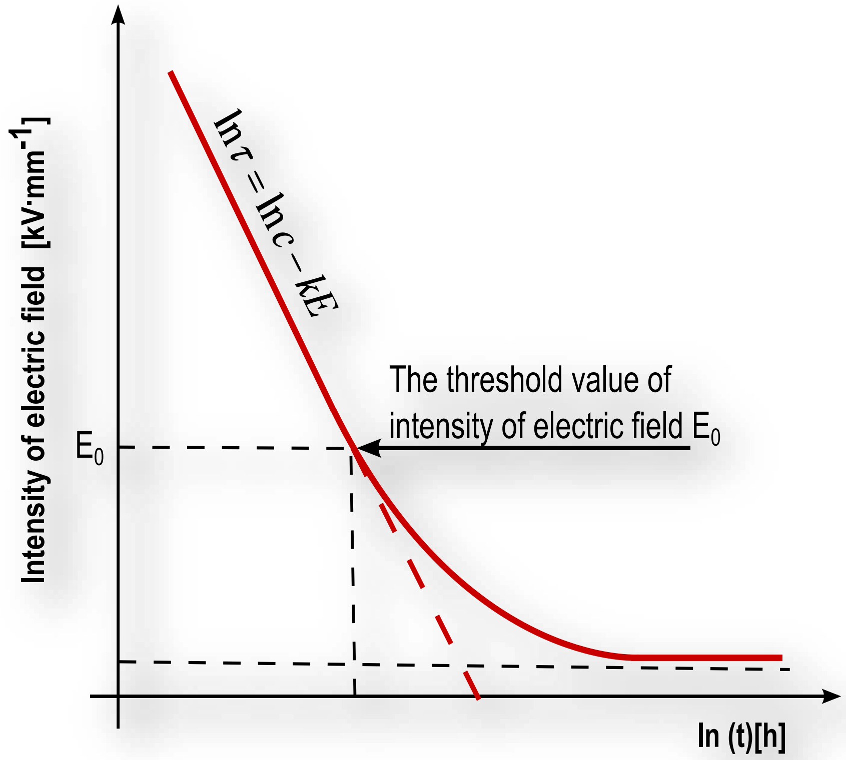
eg IEC 60216-1: "The application of this standard assumes that there is a practically linear relationship between the logarithm of the time required to change a selected property and the inverse of the corresponding absolute value…."

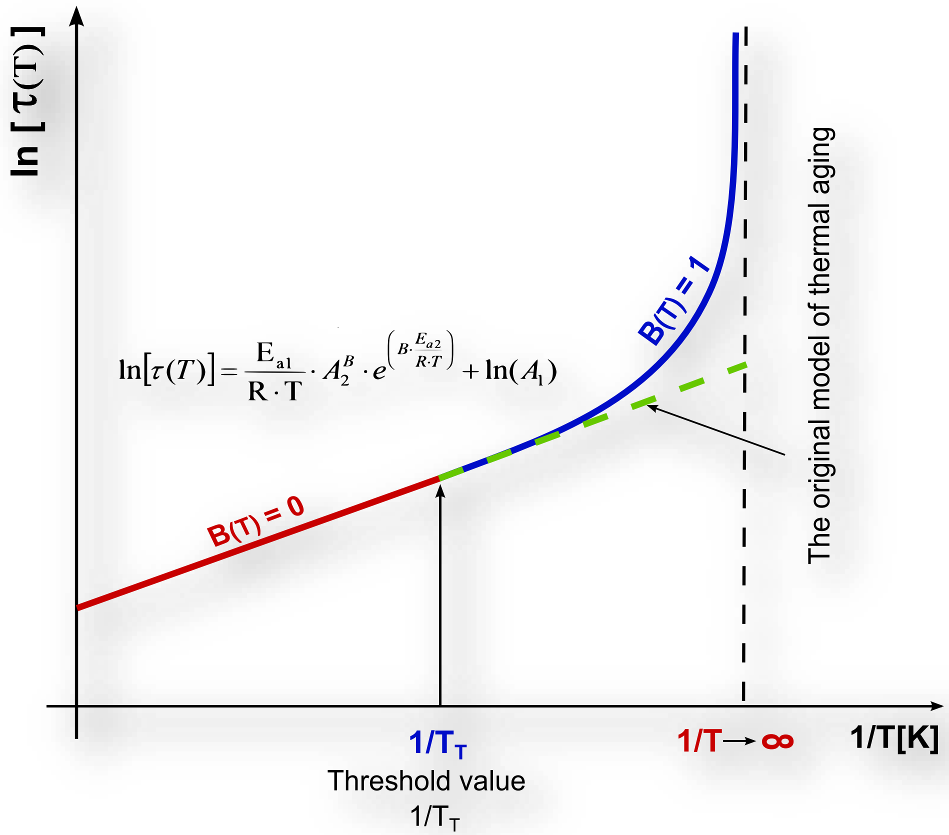
Statement: „Perform the accelerated degradation factor test so that no other degradation mechanism occurs…“



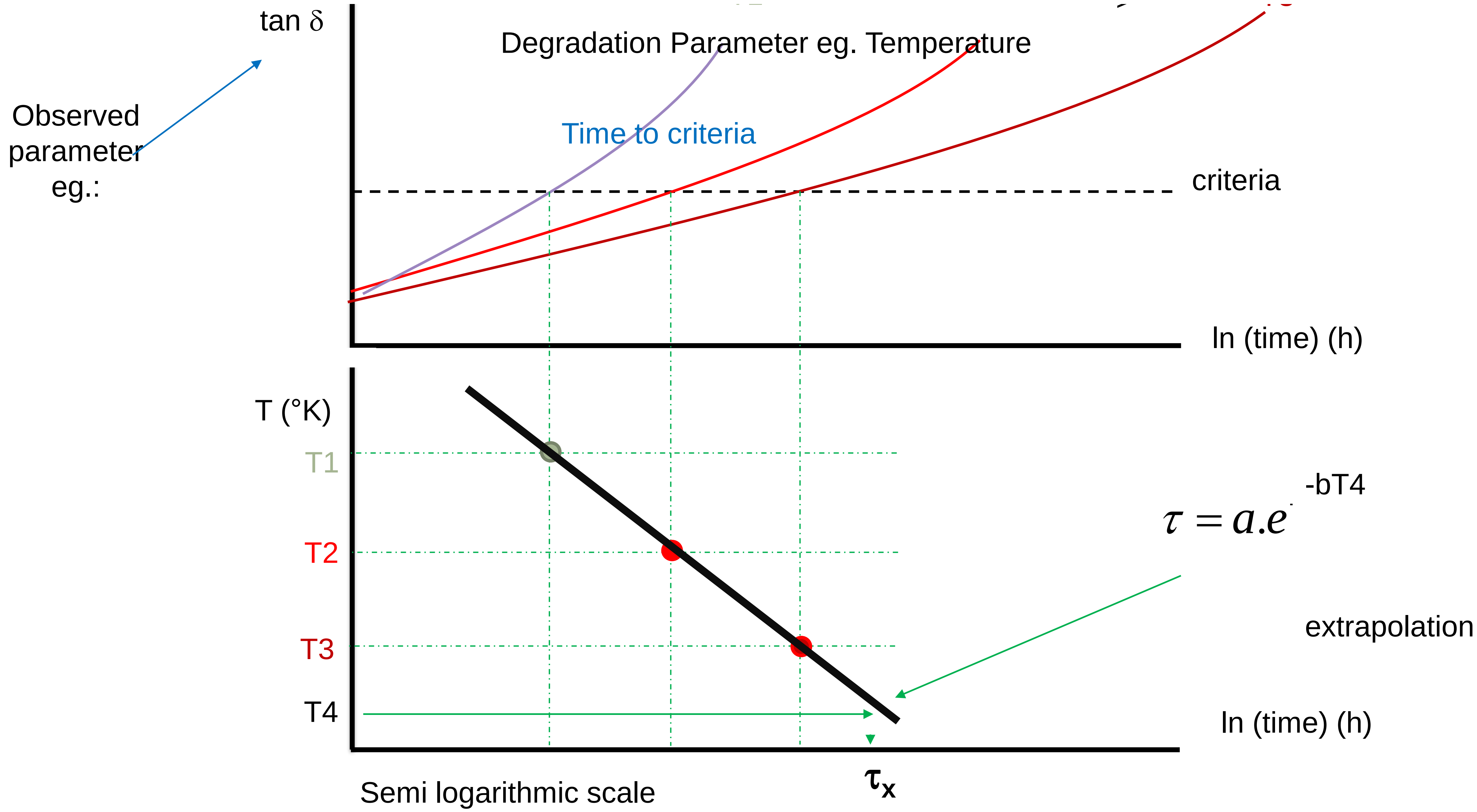
Criterion problem - end point and start point criteria

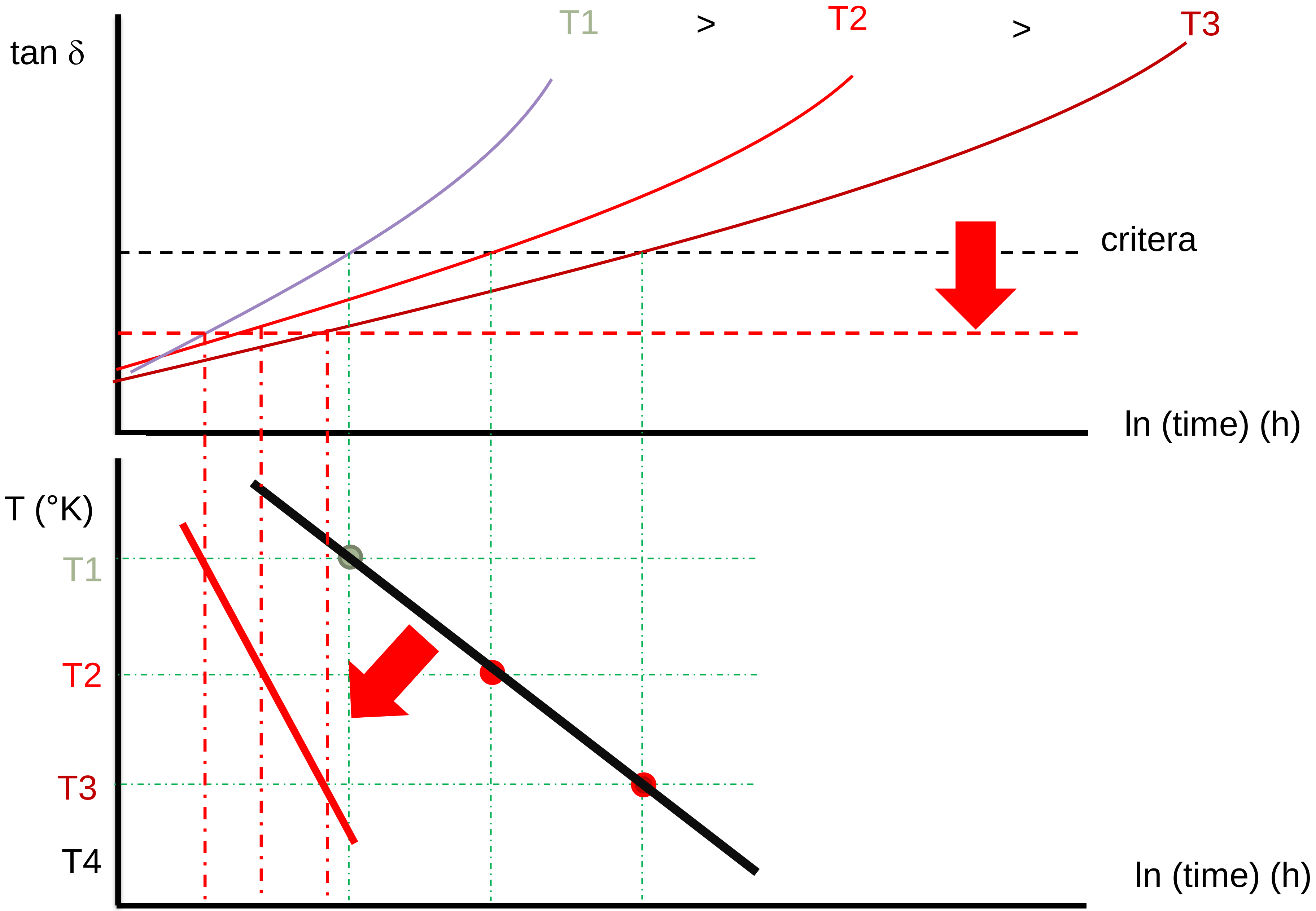
I.	Feedback approach
II.	Aging tests
III.	Synthesis of properties based on knowledge





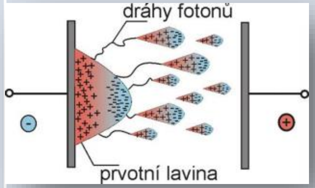
Principle of extrapolation of max operating time

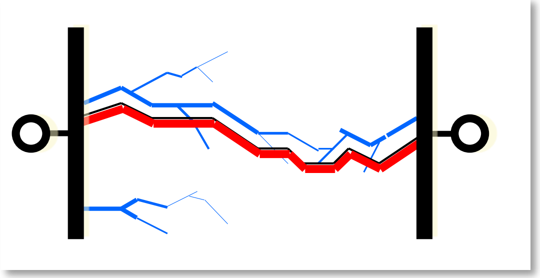




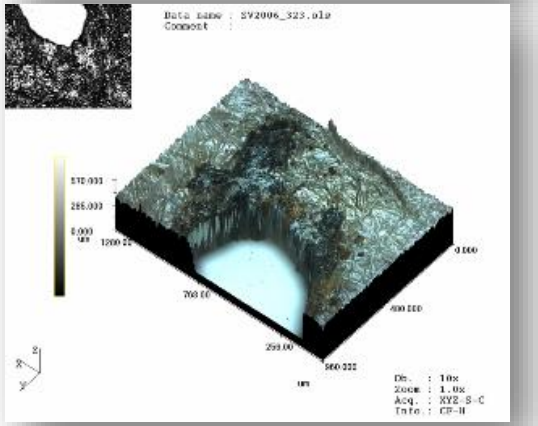
T1
>
T2
>
T3
tan δ
critera
ln (time) (h)
T (°K)
T1
T2
T3
T4
ln (time) (h)

„Precise endpoint criterion"

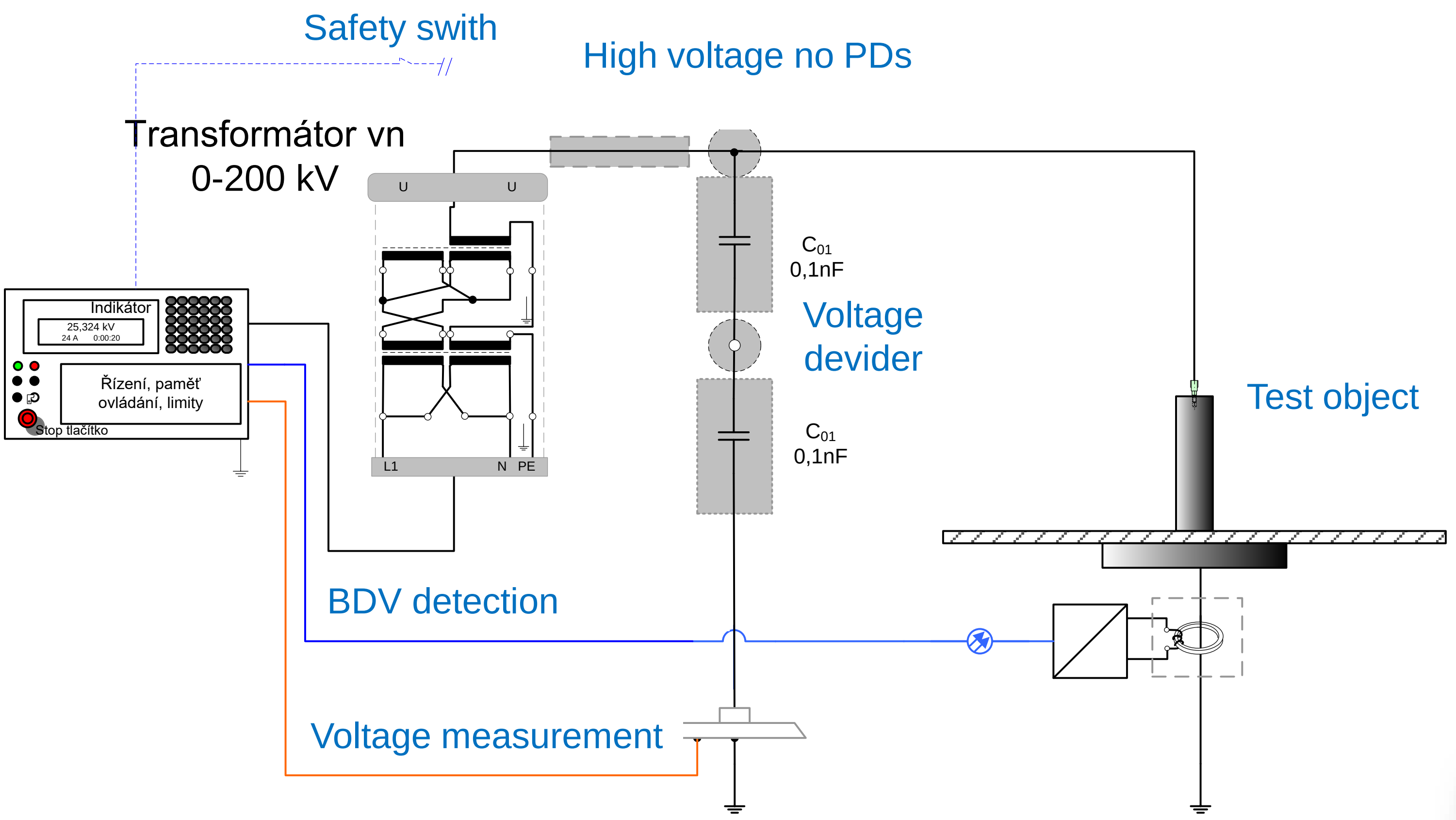
BDV		
Gaseous dielectric	Impact and photo ionization, streamer, space charge, avalanche-leader, spark, glow discharge, BDV	 
Liquid dielectric	Impurities Contained water Surface treatment of electrodes BDV hypotheses Restoration of electrical strength	Semispheric electrodes 2,5 mm, 2,54 mm, 2 mm, 1 mm  
Solid dielectric	The most complex processes of breakdown, smallest understanding of preces if BDV, Thermal, Electrical - ČSN EN 60243-1, Electrochemical, Electromechanical – electrostriction	

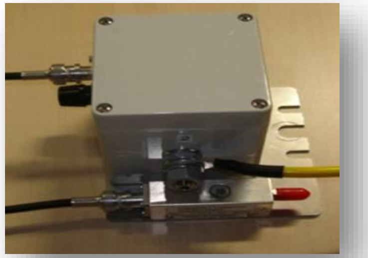


Setkání leaderů a vznik výboje



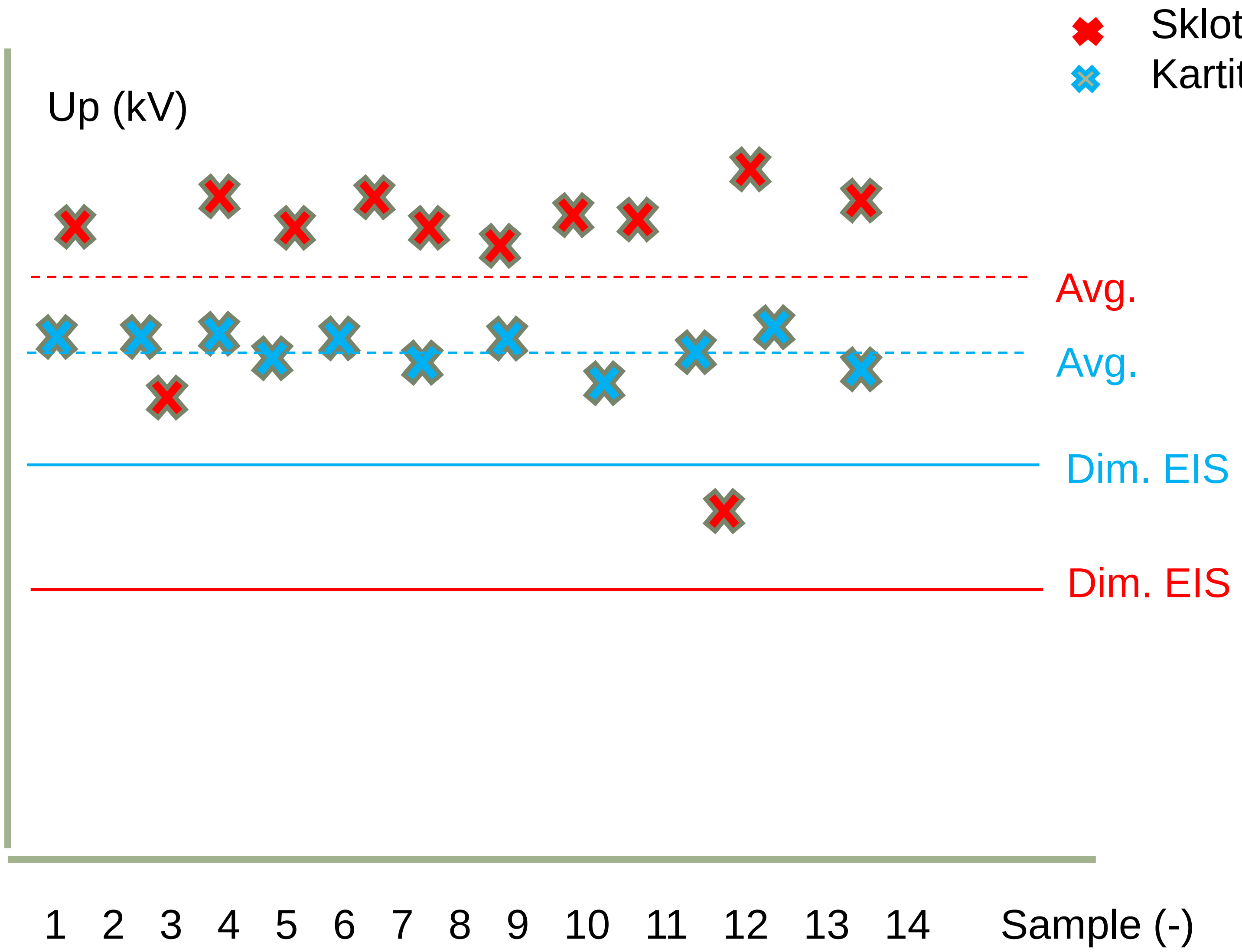
Measurement of the BDV

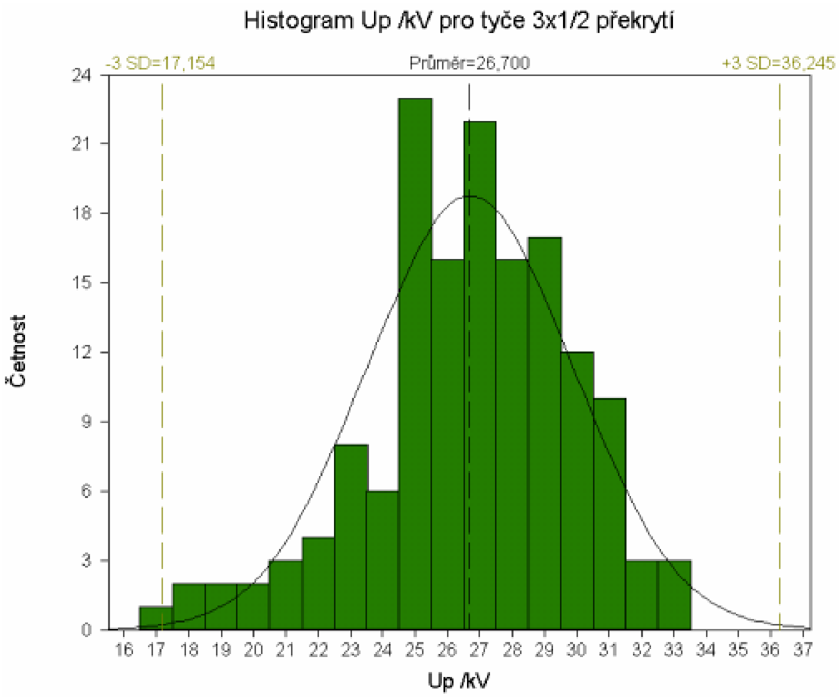




BDV detection

BDV Solid Materials



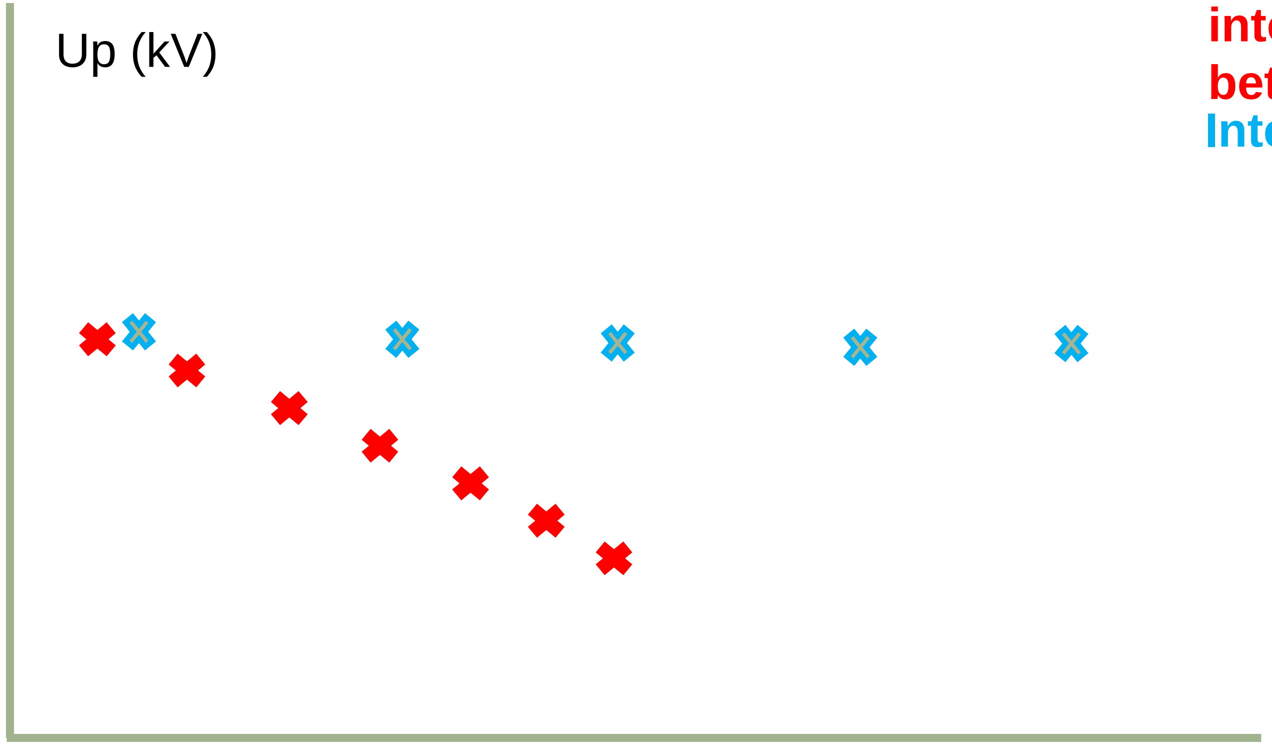


Obr. 10: Histogram Up /kV pro tyče se způsobem izolování 3 x 1/2 překrytí

BDV Liquids Dielectrics

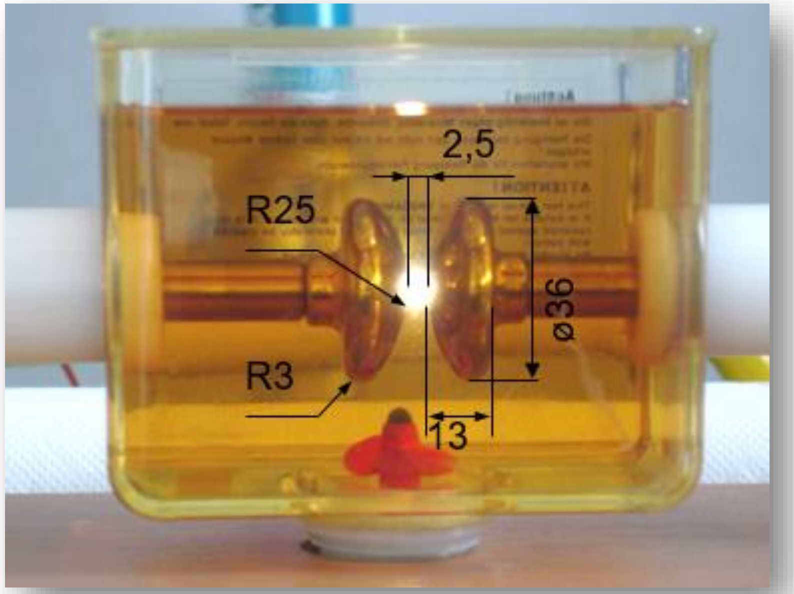
Too short intervals between BDV

Intervals OK



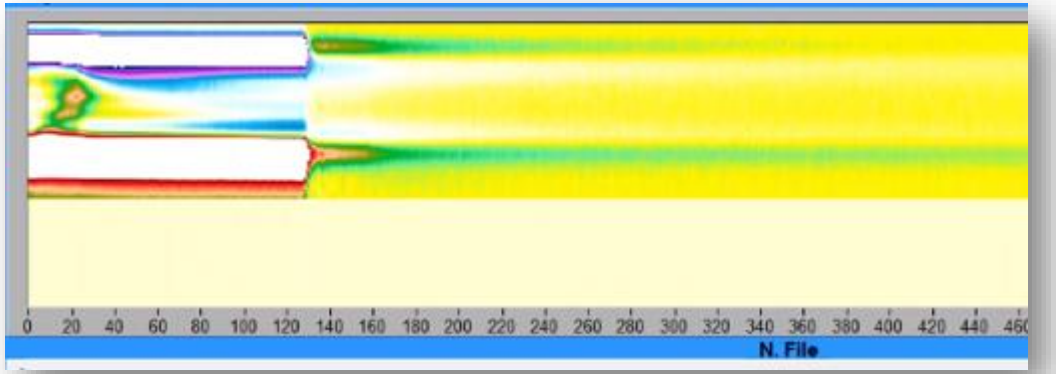
1 2 3 4 5 6 7 8 9 10 11 12 13 14 Number (-), time (min)

1 2 3 4 5 number (-), time (min)



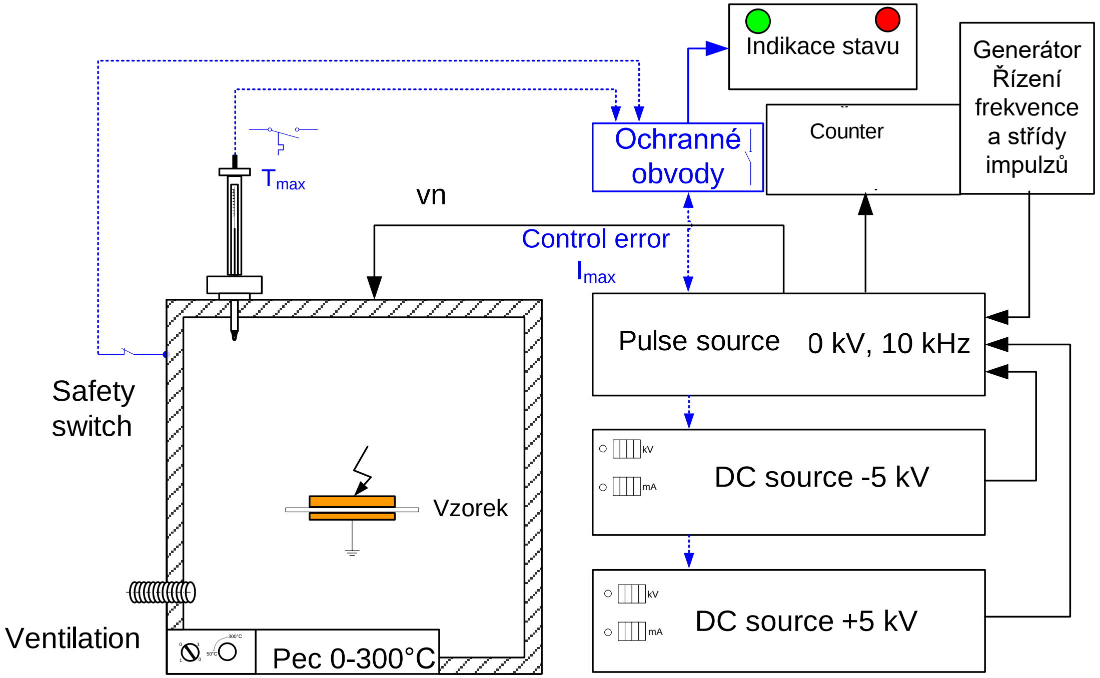
„BDV!?“....!

- Gradual phenomena of polarization, space charge, ionization, acceleration of ions and electrons, tree, thermal electrochemical, electric breakdown
- Agreed value
- Electrodes, spatial arrangement
- Thickness, distance
- Voltage rise rate
- Ambient Condition
- Partial discharges
- Influence of technology

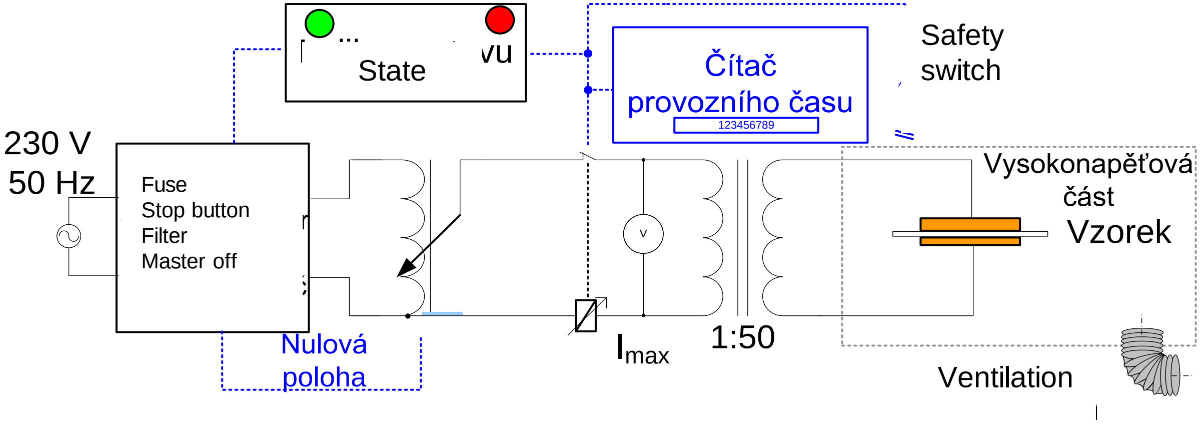


ASTM D1816	ASTM D 877		IEC 60156
	Procedure A	Procedure B	
USA	USA	USA	Europe

Time to BDV



Indikace stavu
Generátor
Řízení frekvence a střídy impulzů
Ochranné obvody
Counter
T_{max}
vn
Control error
I_{max}
Pulse source
0 kV, 10 kHz
DC source -5 kV
DC source +5 kV
kV
mA
Safety switch
Vzorek
Ventilation
Pec 0-300°C

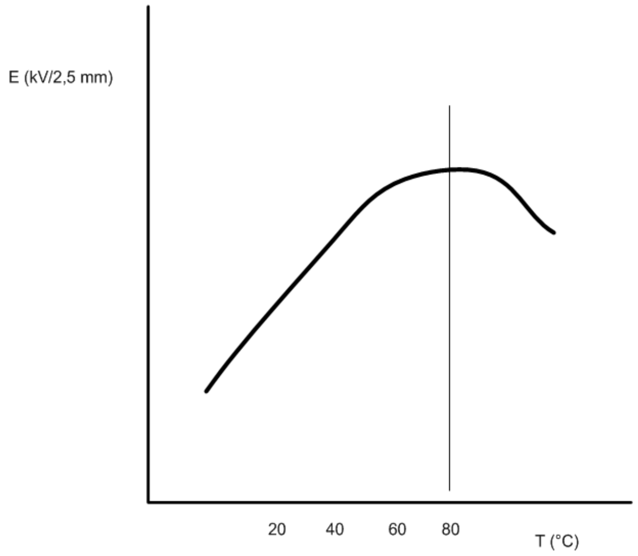


State
Čítač provozního času
123456789
Safety switch
230 V
50 Hz
Fuse
Stop button
Filter
Master off
V
Vysokonapěťová část
Vzorek
Nulová poloha
I_{max}
1:50
Ventilation

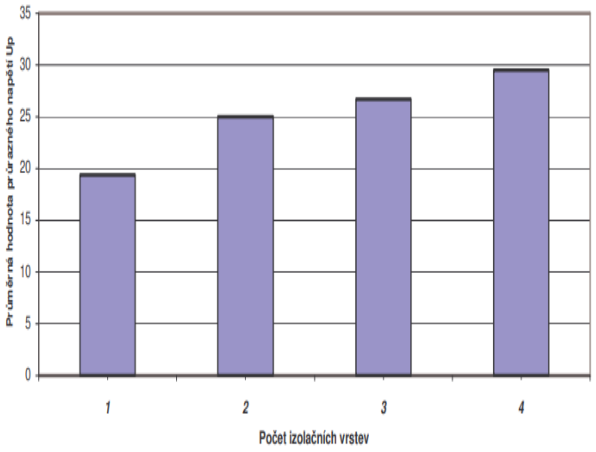
POZOR VN !

BDV

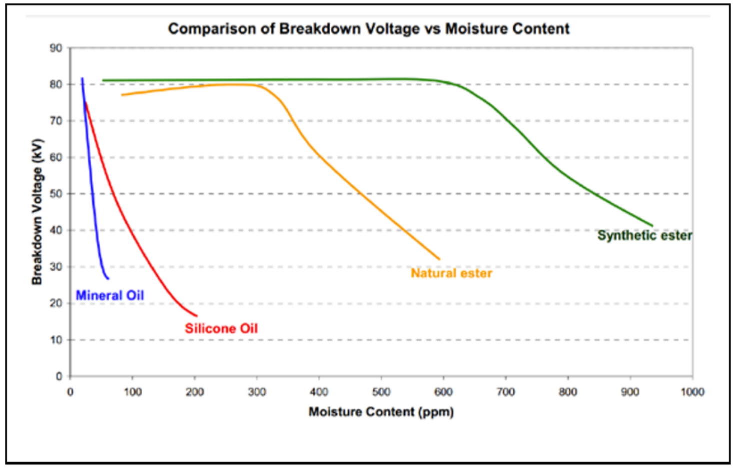
Temperature



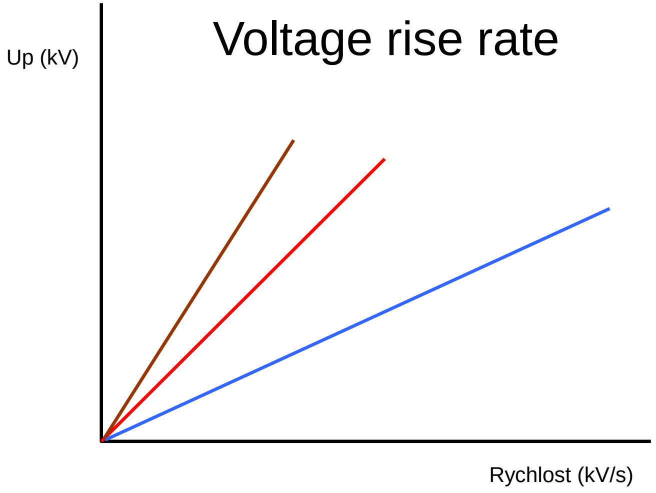
Number of layers, thickness



Moisture content



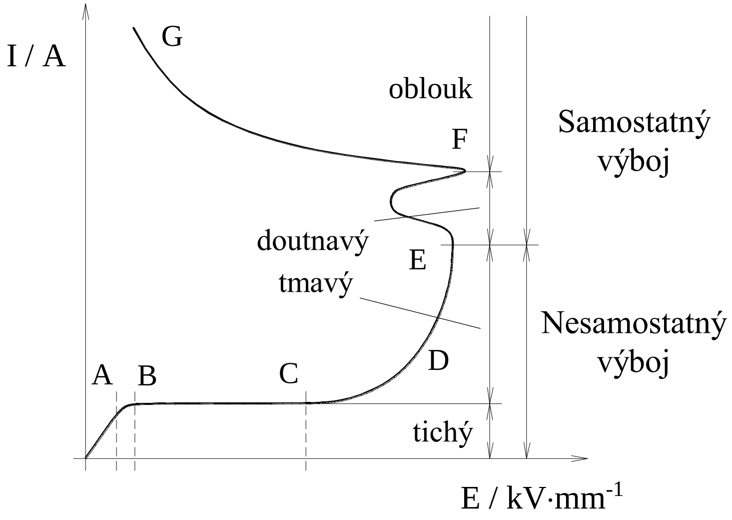
Voltage rise rate



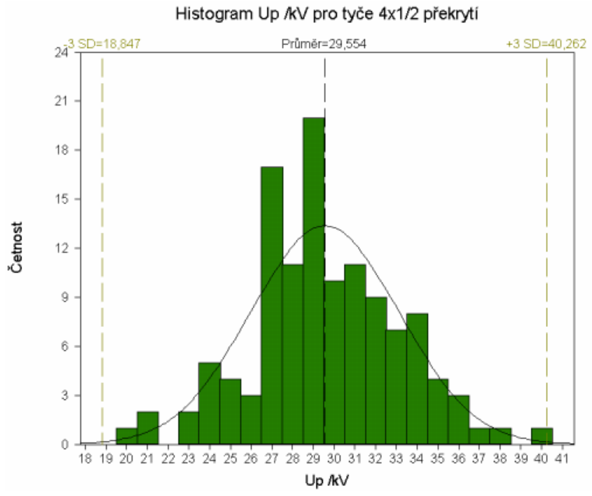
ASTM D1816	ASTM D 877	ASTM D 877	IEC 60156
USA	USA, Procedure A	USA, Procedure B	EU
0,5 kV/s	3 kV/s	3 kV/s	2 kV/s

Breakdown Voltage

U-A characteristic

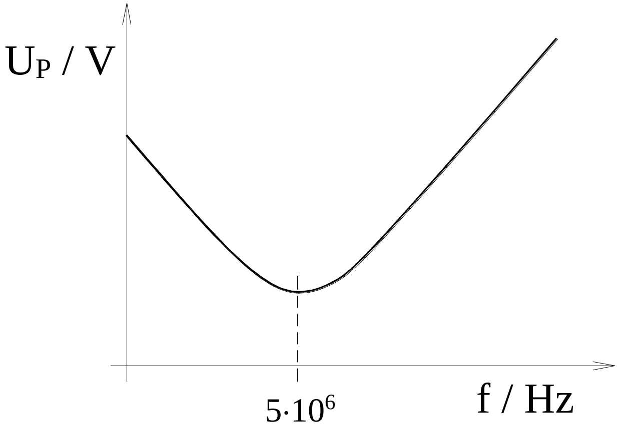


Technology

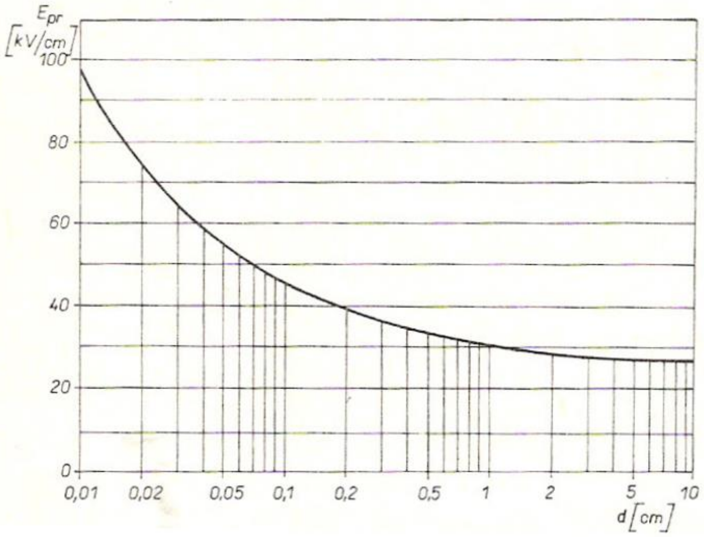


Obr. 11: Histogram Up /kV pro tyče se způsobem izolování 4 x 1/2 překrytí

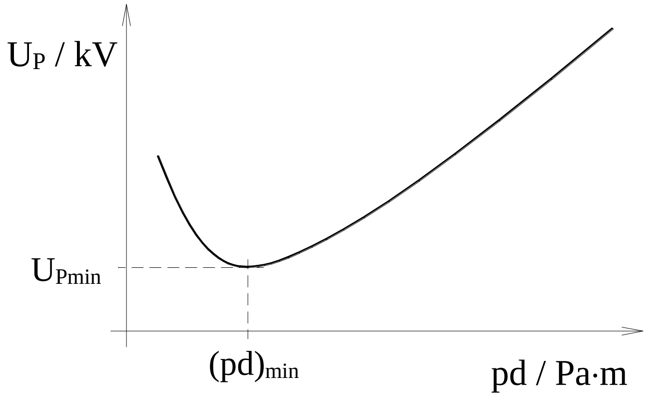
Frequency



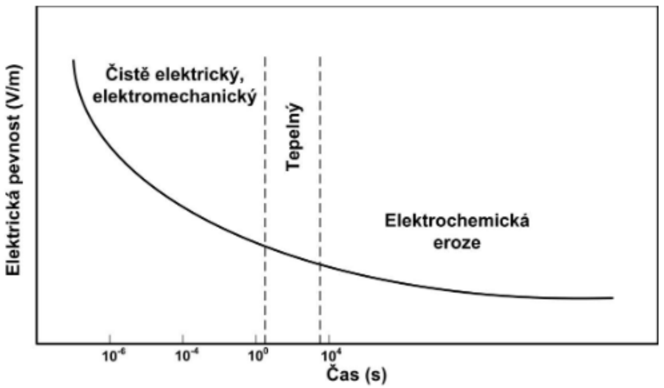
Thickness



Pressure and distance

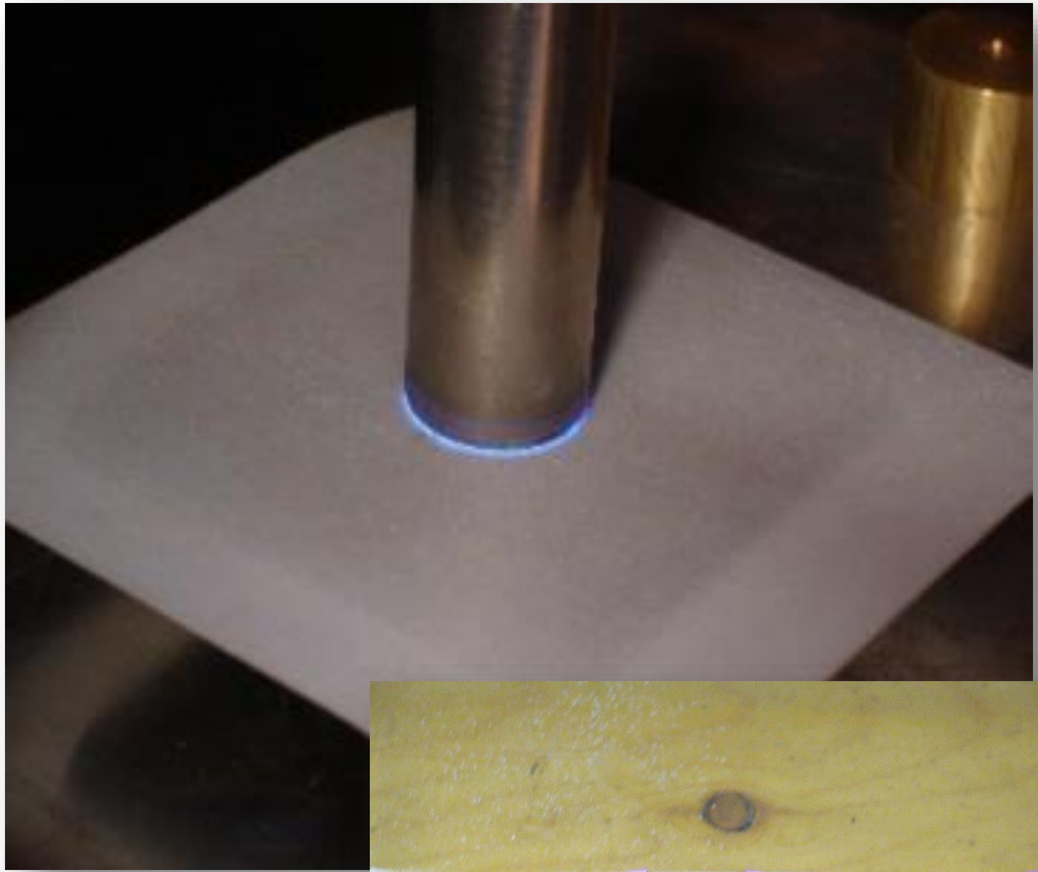


Time

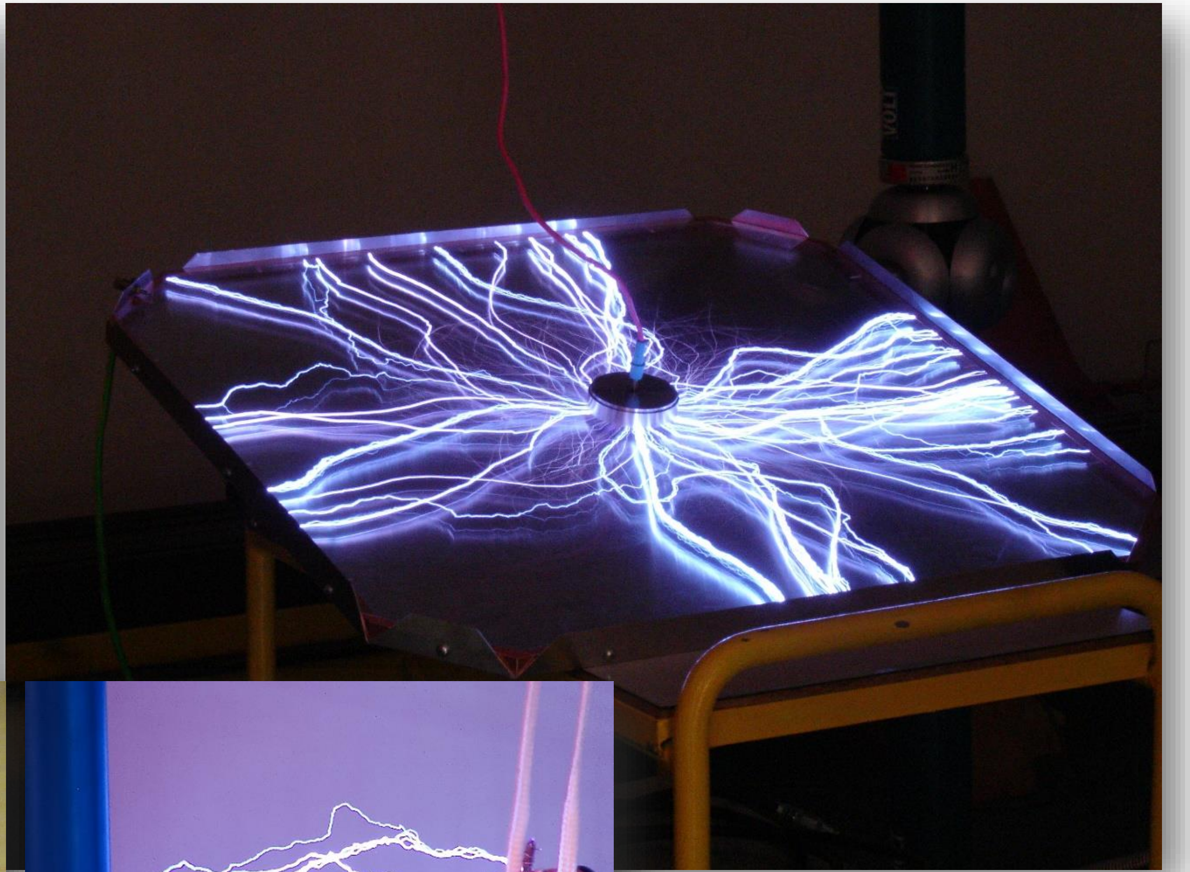


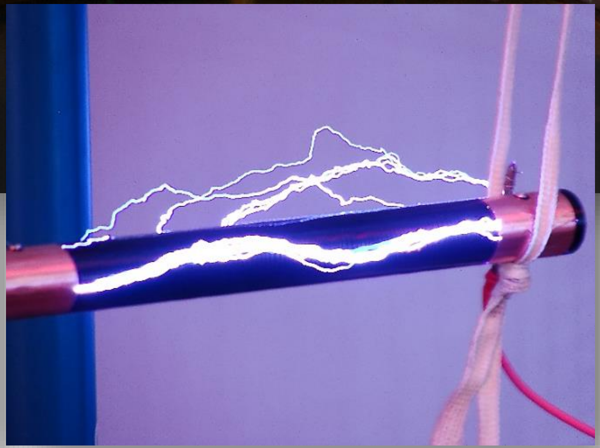
Source: Mentlík,V. BEN, Štyrcová DP, FEL

High frequency corona



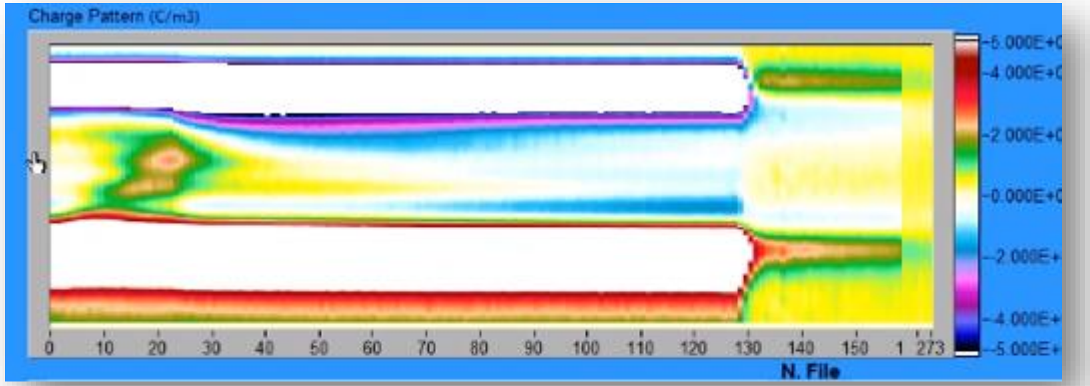
50 Hz sinus corona

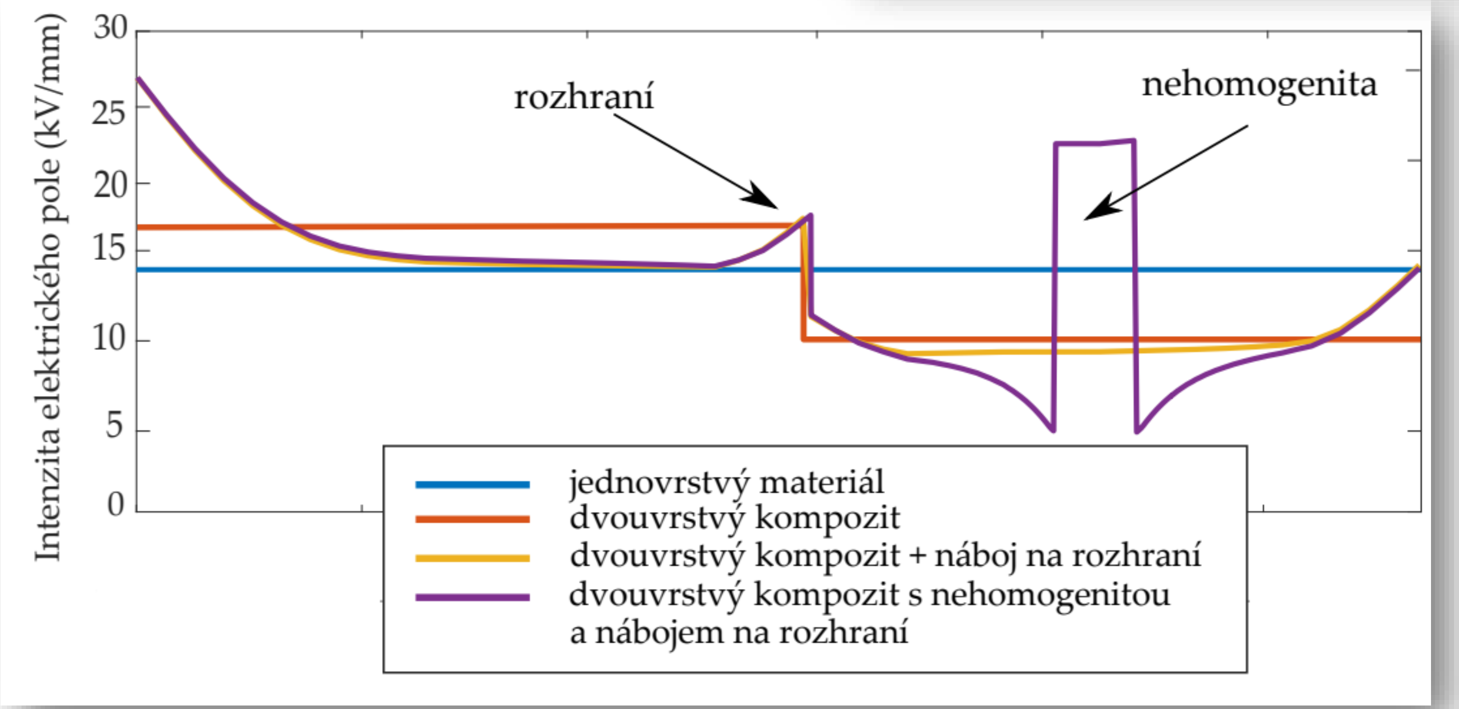




Local electric field deformation

Electric field distribution within EIS is not "linear"
Modification of materials - nanoparticles
Space charge research, HV DC! PEA





Sample	Ri [Ω]	pi1 [-]	pi10 [-]	ρ_v [Ω·m]	tg δ [-]	ε_r [-]	Ep [kV/mm]
DGEBA - Laromin® C260	**3.21E+15**	**3.41**	**5.46**	**5.37E+15**	**7.70E-03**	**3.59**	**37.74**
	2.59E+15	*1.11*	*3.35*	*4.06E+15*	*1.36E-03*	*0.54*	*0.85*
DGEBA - Laromin® C260 - SiO_2 hydrofobní	**2.71E+16**	**3.99**	**7.82**	**4.95E+16**	**7.36E-03**	**3.85**	**38.30**
	2.22E+16	*0.15*	*1.08*	*3.83E+16*	*1.52E-04*	*0.07*	*0.56*
DGEBA - Laromin® C260 - SiO_2 hydrofobní - FGE	**6.28E+15**	**3.47**	**6.64**	**1.03E+16**	**4.48E-03**	**2.99**	**35.80**
	1.23E+15	*0.32*	*1.48*	*1.48E+15*	*2.72E-04*	*0.24*	*0.82*
DGEBA - Laromin® C260 - SiO_2 hydrofobní - FGE - NPA	**1.69E+16**	**3.33**	**8.13**	**2.64E+16**	**5.55E-03**	**3.73**	**36.16**
	1.69E+16	*0.19*	*3.35*	*2.76E+16*	*4.48E-04*	*0.13*	*0.63*
DGEBA - Laromin® C260 - SiO_2 hydrofobní - NPA	**2.80E+16**	**3.59**	**7.50**	**3.32E+16**	**4.70E-03**	**3.66**	**38.38**
	1.95E+16	*0.76*	*1.66*	*2.18E+16*	*1.32E-03*	*0.19*	*0.86*

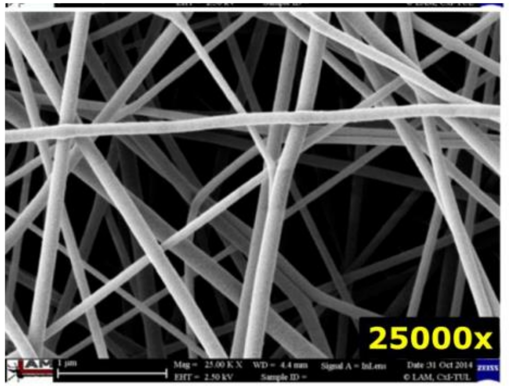
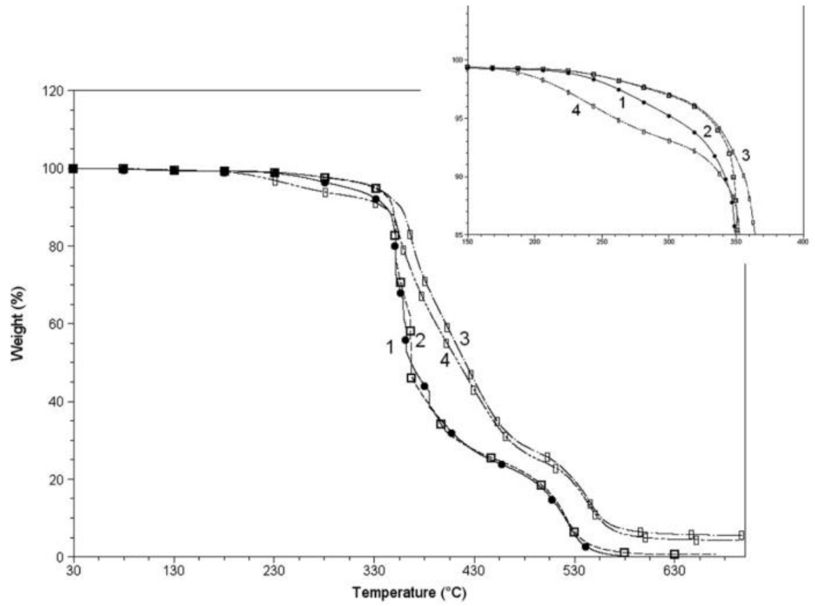


Table 2

Nanocomposite thermal stability – 3% mass loss (electrotechnology criteria).

System	T_3, °C
DGEBA-Laromin	271
DGEBA-Laromin-POSS,E8	
DLE8(1,1)-T150	299
DLE8(1,1)-T190	298
DLE8(3.2)-T150	299
DLE8(10)-T150	307
DLE8(14)-T150	301
DGEBA-Laromin-POSS,E_{Ph}1	
DLE1(4)-T150	263
DLE1(4)-T190	263
DLE1(8)-T150	229
DLE1(8)-T190	256

Heating rate 5 °C/min. T150 – curing at 150 °C, T190 – curing at 190 °C.



Faculty of electrical engineering

University of West Bohemia, Czech Republic

Thank you for your attention!

Doc. Ing. Pavel Trnka, Ph.D.

+420 377 634 518
+420 377 634 002

pavel@fel.zcu.cz

Univerzitni 26
306 14 Plzen
Czech Republic

www.fel.zcu.cz