Faculty of Electrical Engineering
University of West Bohemia
Pilsen, Czech Republic

Pavel Trnka

Electrical insulating liquids in dielectric systems

FACULTY OF ELECTRICAL ENGINEERING
UNIVERSITY OF WEST BOHEMIA

University of West Bohemia

City	Pilsen (CZ)
Founded in year	1991 (1950)
Number of employees	2132
Number of students	14 500
Annual sales	100 million €
Core business	University, Research institute

FACULTIES AT THE UNIVERSITY
Faculty of Applied Sciences
Faculty of Economics
Faculty of Electrical Engineering (FEE)
Faculty of Philosophy and Arts
Faculty of Education
Faculty of Law
Faculty of Mechanical Engineering
Faculty of Health Care Studies
Faculty of Art and Design

R&D center RICE

RESEARCH AND INNOVATION CENTRE FOR ELECTRICAL ENGINEERING - Basic Overview

- **RICE** is a trademark of the Faculty of Electrical Engineering in Pilsen, **Czech Republic** for the R&D area.
- **Close to 200 researchers.**
- **Whole research chain** from basic (theoretical) research up to development of functional samples and their complete testing.
- R&D projects with **total budget approaching 100 mil. EUR**.
- **Leader / coordinator of more than 70% of the projects.**

Competence Roadmap

MAIN RESEARCH TARGETS

Transport Systems
- Traction vehicles and systems
- Automotive (HEV/FEV)
- E-mobility and complex transport systems

Power Engineering
- Nuclear technology
- New technologies for the production of electricity and heat
- Smart grids and smart cities
- MV power electronics
- Renewable energy sources

Molecular electronics and sensors
- Organic electronics and semiconductors
- Printed and flexible electronics
- Mikrovia and Embedded technology
- Sensors and "smart" sensor systems
- Smart textiles

INDUSTRIAL PARTNERS

RICE

Mechanical Eng.	ICT
Natural Science	R & D Partners

CORE COMPETENCIES

- Power electronics & Drives
- Materials research
- Electronic, Embedded systems, ICT
- Control Theory Modeling and Computation
- Diagnostics, Testing and Validation

Organized Conference CDEE 2024

IEEE Czechoslovakia Section

2024 International Conference on Diagnostics in Electrical Engineering (Diagnostika)

Since 1993
Biennially

Last – September 2022
Next – **September 3-5, 2024**

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RICE – unique research infrastructure

Research infrastructure:

- A hall laboratory and testing room for medium-voltage power electronics and transportation systems for testing up to 31 kV_{AC} / 4MW.
- **Opened on June 15, 2016**

Hall laboratory, 31 kV_{AC} / 4MW

Hall laboratory in deeper details

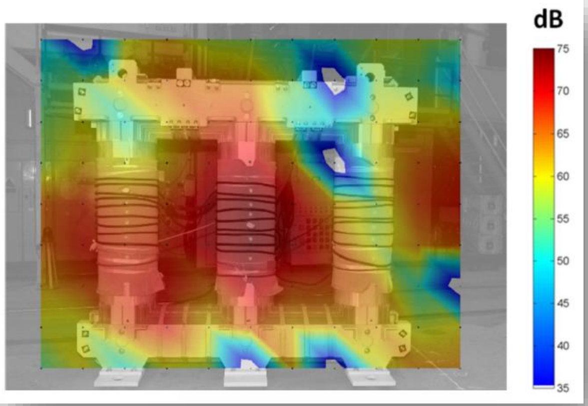
Testing of transportation and MV power electronics systems

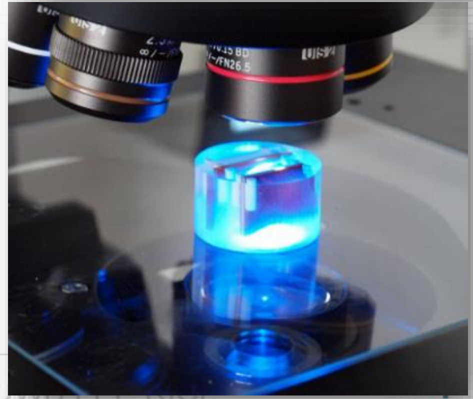
- Typical DUT power up to **4 MW**.
- Max. dissipated heat (power losses) of **500 kW**.
- Traction catenary:
  - AC **25 kV / 50 / 60 Hz** (max. 31.5 kV),
  - AC **15 kV / 16,7 Hz** (max. 19 kV),
  - DC **600 V, 750 V** with max. voltage up to 1 250 V,
  - DC **1.5 kV** and **3 kV** with max. voltage of 5.5 kV.
- 3-phase power supply systems:
  - Fixed voltage and frequency: 22 kV / 50 Hz, 10 kV / 50 Hz, 6 kV / 50 Hz, 3 kV / 50 Hz, 690 V / 50 Hz, 400 V / 50 Hz.
- Programmable power supplies:
  - AC 0 – 11.5 kV / 40 – 120 Hz, AC 0 – 690 V / 0 – 120 Hz.
  - DC 0 – 15 kV.
- 2 MV test beds, reconfigurable LV test area up to 4 test beds.
- MV and LV pits with loading motors (IM, PMSM).
- High-speed high-precision measurements (50 μs sampling rate).
- IR cameras with trigger event capability.
- Max crane load 12500 kg.

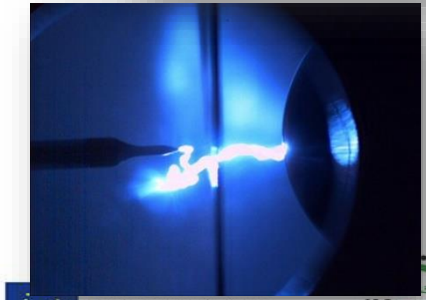
MINISTRY OF EDUCATION, YOUTH AND SPORTS
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
INVESTING IN YOUR FUTURE
OP Research and Development for Innovation

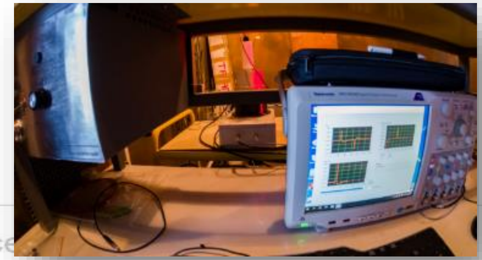
Diagnostics and testing

- **High Voltage Materials Diagnostics**
  - Electrical parameters of EIS and machinery, non-electrical parameters on HV machinery
- **X-Ray diagnostics and 3D tomography**
- **Diagnostics of materials and structural analysis**
  - electrical tests, dielectric spectroscopy, PEA space charge
  - structural analysis (thermal-mechanical analysis, dynamic-mechanical analysis, thermogravimetry, differential scanning calorimetry)
- **Environmental testing**
  - UV, Gases, Corrosive
- **Microscopy laboratories**
  - optical microscopes
  - laser confocal microscope with 3D and fluorescence microscope
  - Electron microscope









Diagnostics and testing

- **Acoustics**
  - electroacoustics
  - anechoic&echoic chamber
  - reverberation laboratory
  - the design of new measurement methods

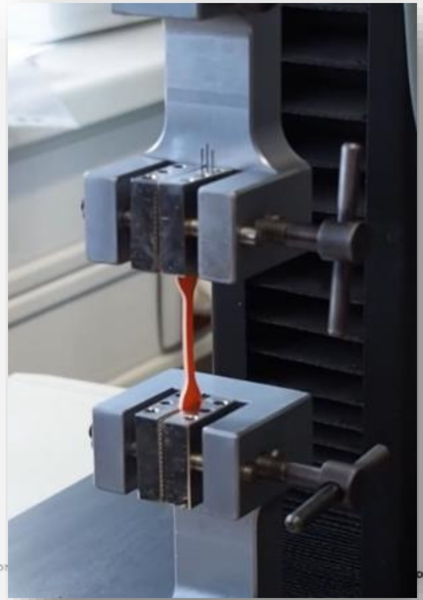
- **Electromagnetic compatibility (EMC)**
  - measure the electromagnetic interference.
  - the EMC anechoic chamber

- **Electrical laboratory (EL)**
  - an accredited testing laboratory (no. 1090)
  - tests in the field of electromagnetic compatibility and tests of environmental resistance.

- **Laboratory of Dielectrics - member of**

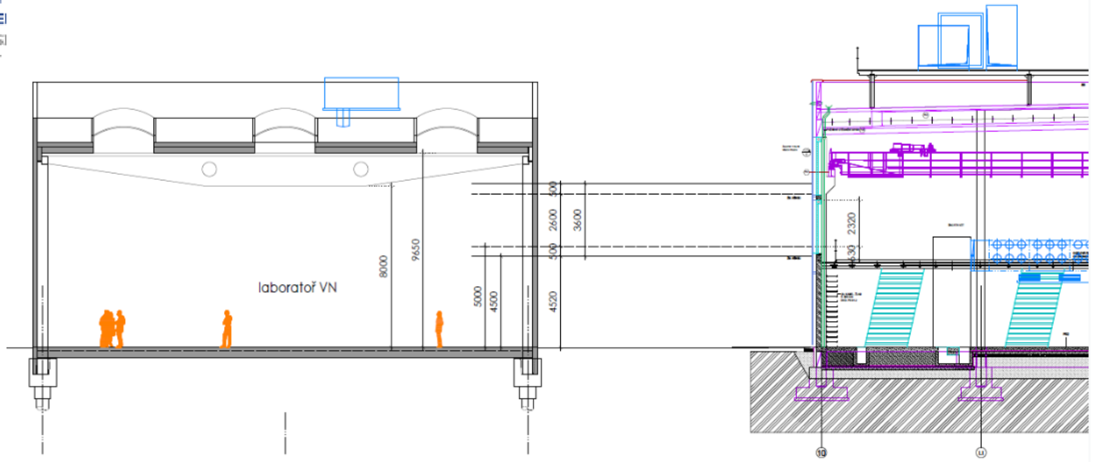
- **Mechanical Tests**

ZKUŠEBNA E-38

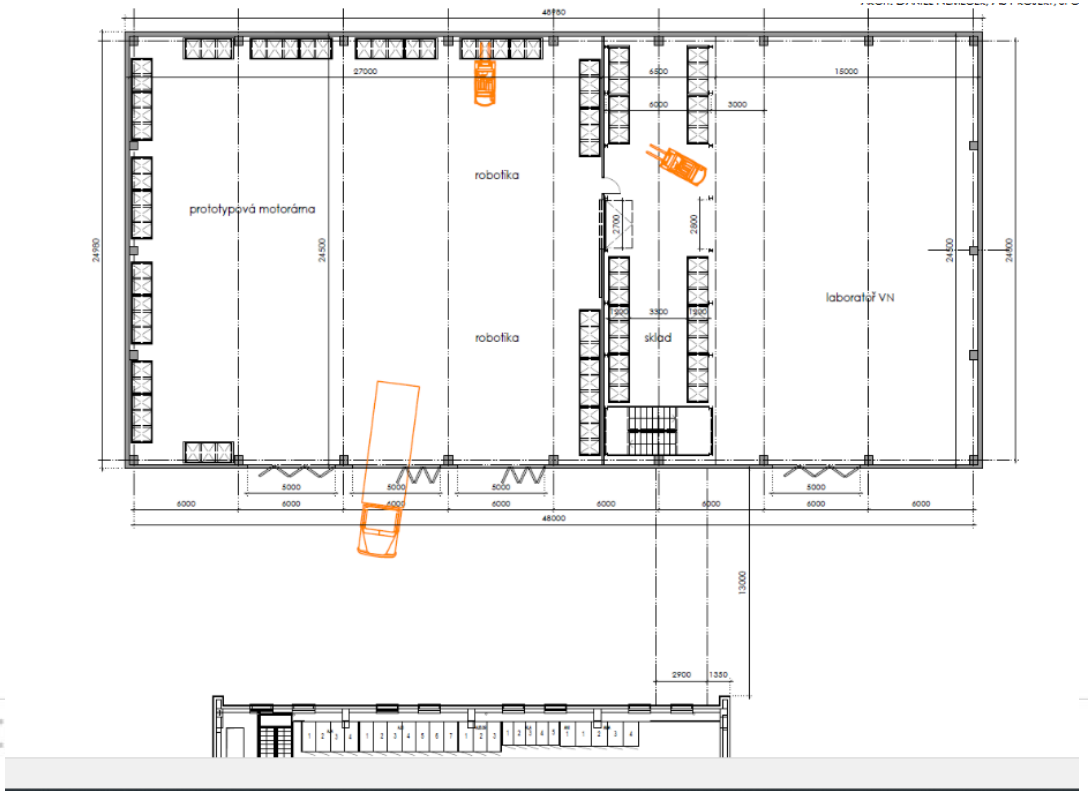


600 kV laboratory, Dielectric systems Lab 200 kV

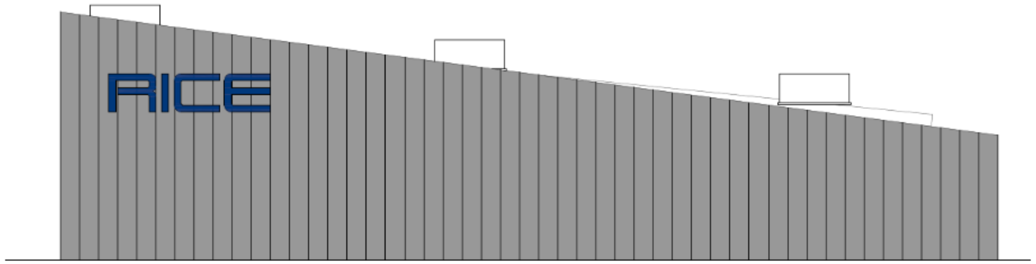
New HV Lab



PŘÍČNÝ ŘEZ



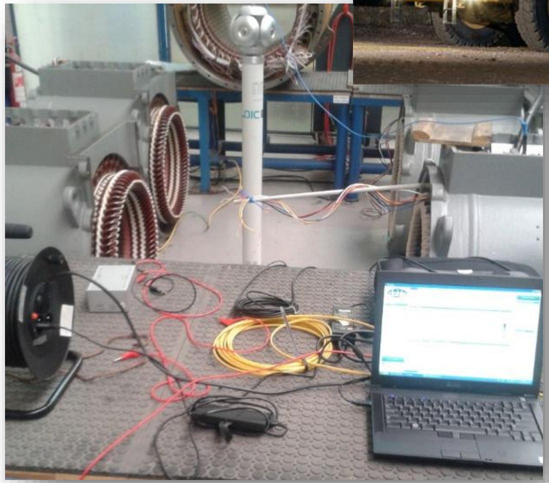
SEVERNÍ POHLED



ZÁPADNÍ POHLED

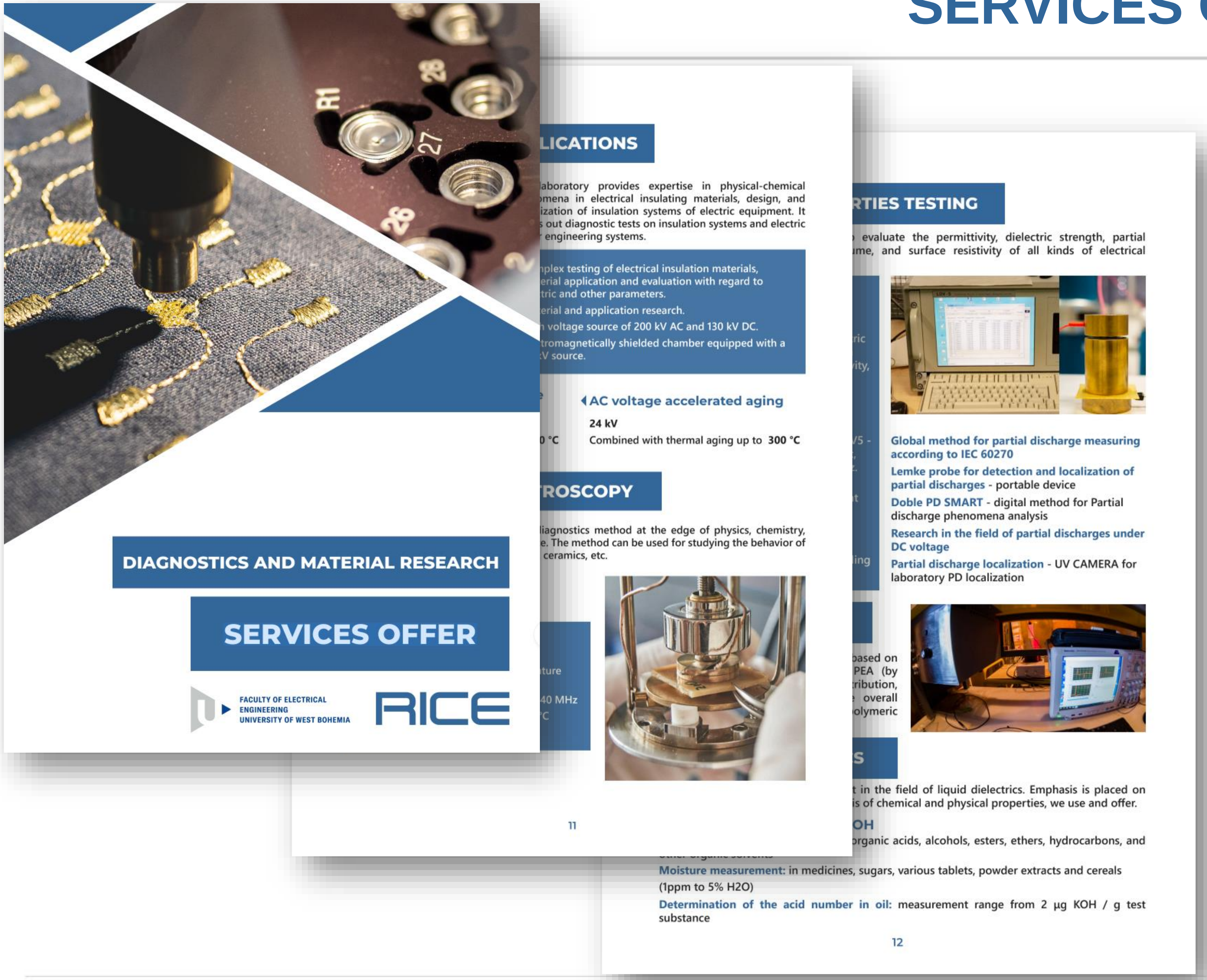
High voltage diagnostics group

MAIN RESEARCH TOPICS
Complex database system for expert prognostication of reliability of rotating machines
Low-noise rotary displacement machines
NanoDielectrics – nano insulating materials
Resin curing monitoring
Gaseous insulation with environmental friendly N_2/O_2 - mixtures
Environmentaly Friendly Insulating Liquids
Hybrid gaseous insulation
Transfomers
Partial discharge behaviour at DC voltage



MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
EVROPSKÁ UNIE EVROPSKÝ FOND PRO REGIONÁLNÍ ROZVOJ
OP Výzkum a vývoj pro inovace

SERVICES OFFER – Diagnostic Group



Finnished R&D projects – HV group

UMTRIS (Umweltvertraglichkeit von Transformatorenolen - alternative Isolierfluissigkeiten)	
Project objectives	• Aging and properties of alternative insulating liquids
Project duration	2017 - 2020
Funding provider	Bayerisch-Tschechische Hochschulagentur

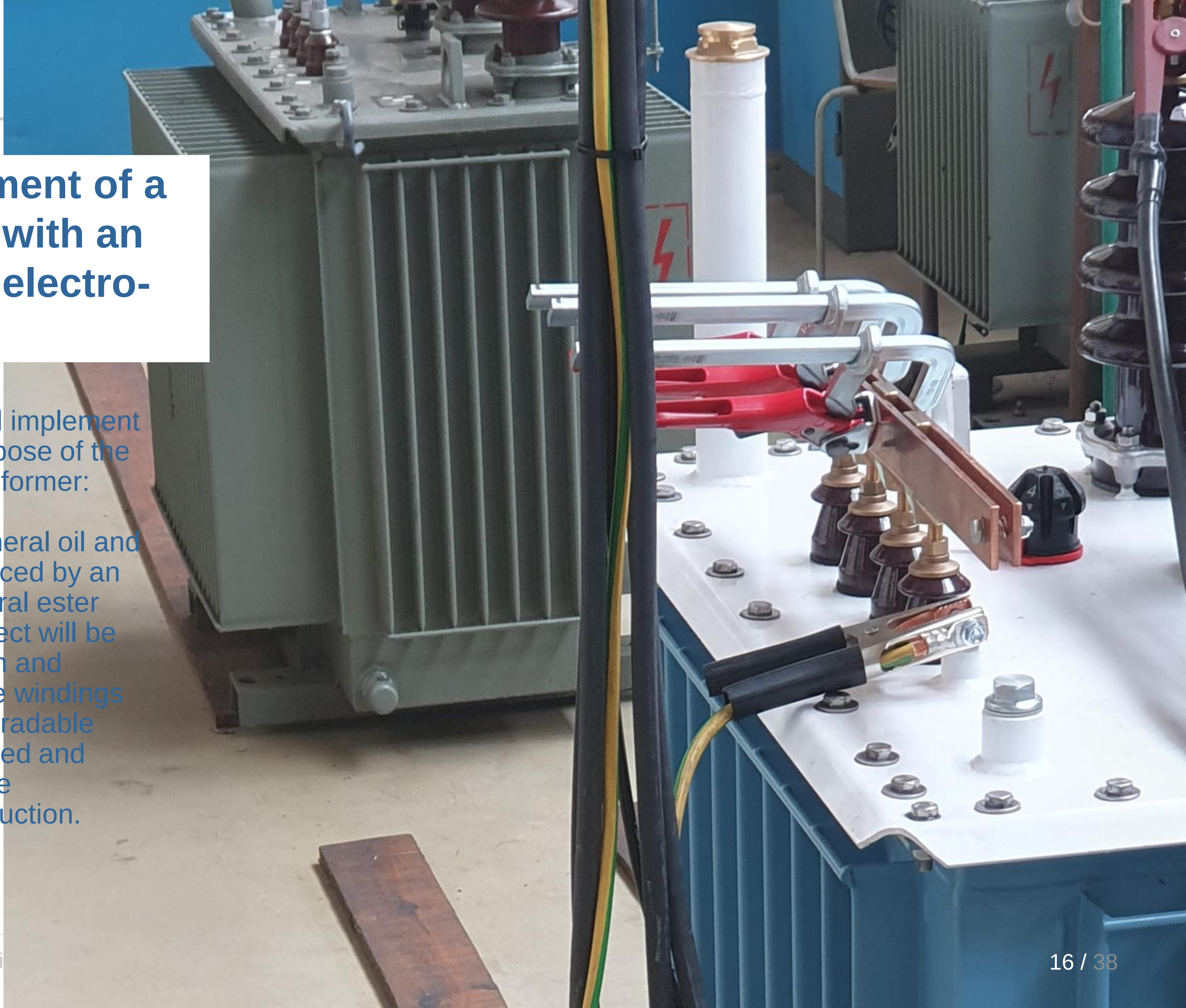
Past R&D projects – HV group

Environment – Friendly Insulating Liquids	
Description	• Nowadays used electro insulating fluids have some improper features in the terms of environmental protection and impact on human health. • Project proposes a solution to allow the development and manufacturing of new fluids from raw materials, which in their nature do not negatively affect the environment and in the same time are biodegradable. • Suggested fluids are produced from renewable sources therefore can reduce energy dependence of EUROPE.
Project duration	2013 -2016, 2017
State funding provider	Technology Agency of the CR, 2017 Internal

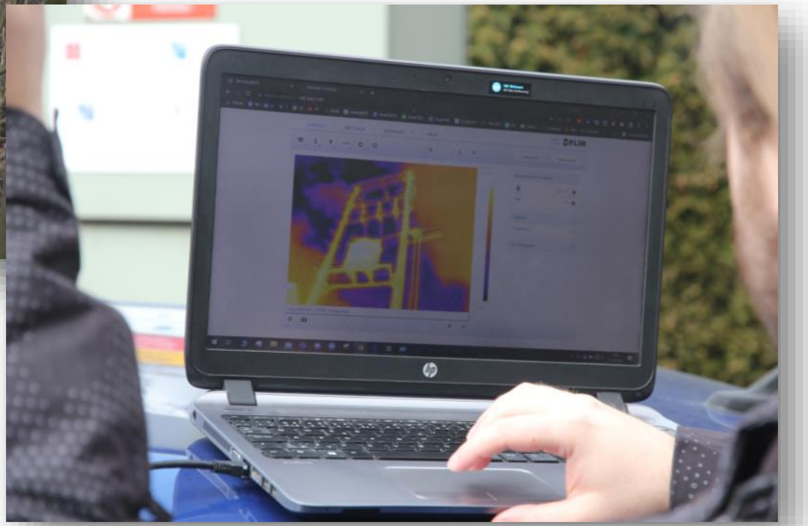

ENVITRAFOL
Biologicky odbouratelná elektroizolační kapalina
RICE
Charakteristické vlastnosti

Project – InBio - Development of a distribution transformer with an environmentally friendly electro-insulating liquid

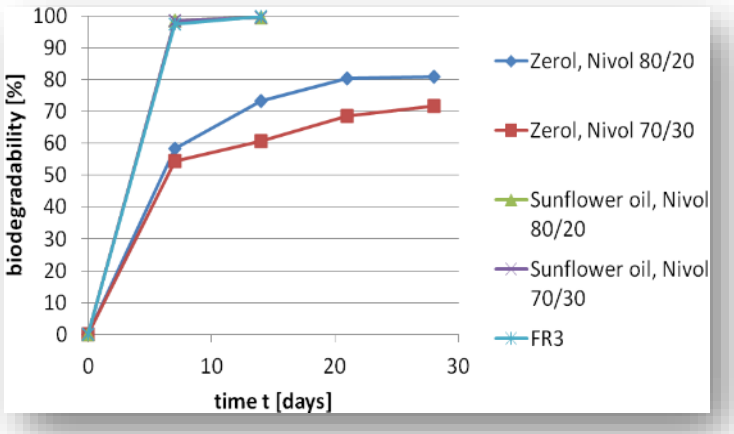
- The aim of the project is to develop and implement a new distribution transformer. The purpose of the project is to modify key part of the transformer: electroinsulation system. Currently is electroinsulating system created by mineral oil and cellulose paper. Mineral oil will be replaced by an electroinsulating liquid based on a natural ester from domestic sources. During the project will be designed the cooling, electrical isulation and hermetic system of the transformer. The windings will be redesigned for the use of biodegradable liquid. The prototype will be manufactured and tested. In the last year of the project, the transformer will be ready for serial production.



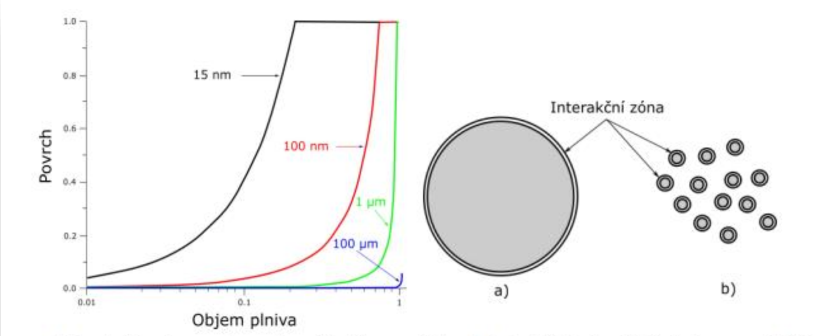
Transformer with Envitrafol



- Dielectric liquids are an inseparable part of various electrical appliances and machines. They are used in cables, switches, capacitors, and transformers. The further presentation covers a brief history of using dielectric liquids in transformers, diagnostic methods used for dielectric liquids, searching for new liquids proper for the environment, and **sustainable development**. Addressed will be the problems with material compatibility, different physical properties of new liquids, and new **nanofluids**.



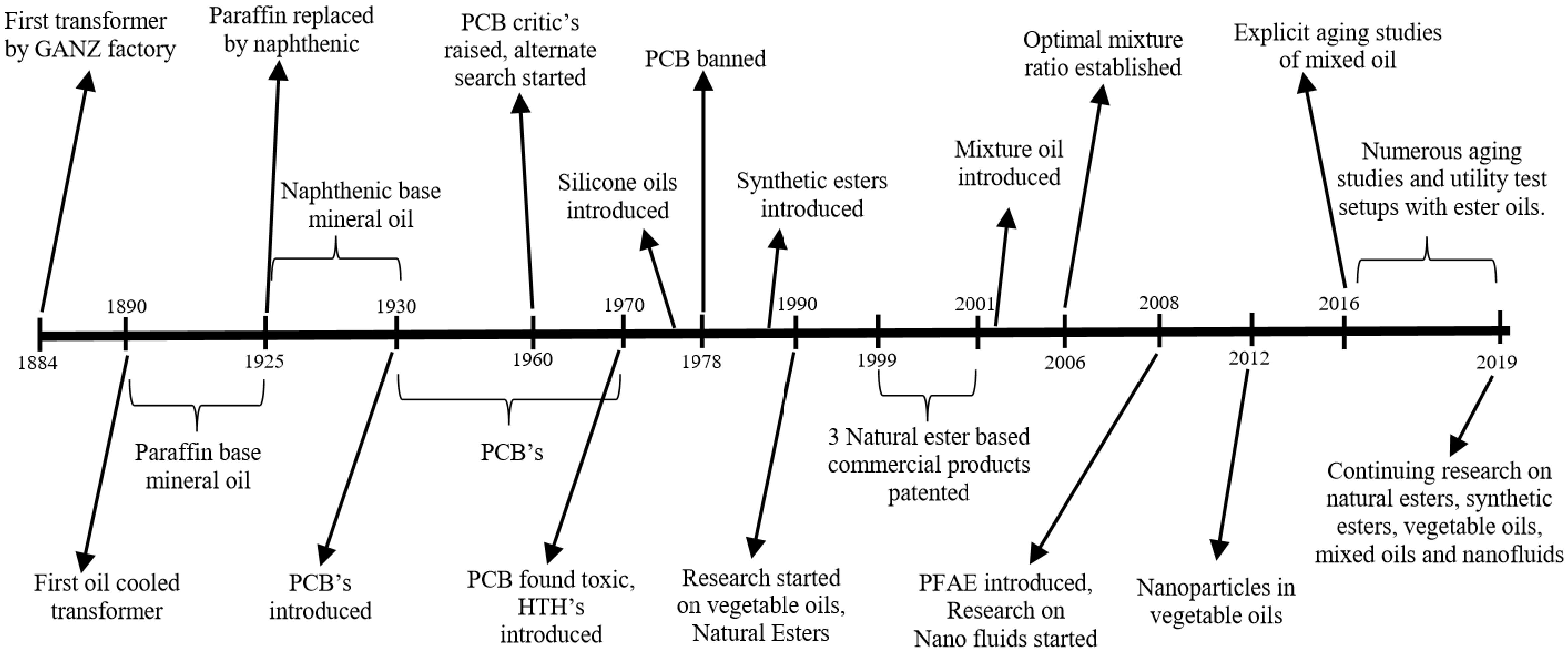
Biodegradability test OECD 301



Obr. 4: Poměr povrchu rozhraní / objemu plniva (*převzato z [14]*)
Obr. 5: Interakční zóna částic (*převzato z [13]*)

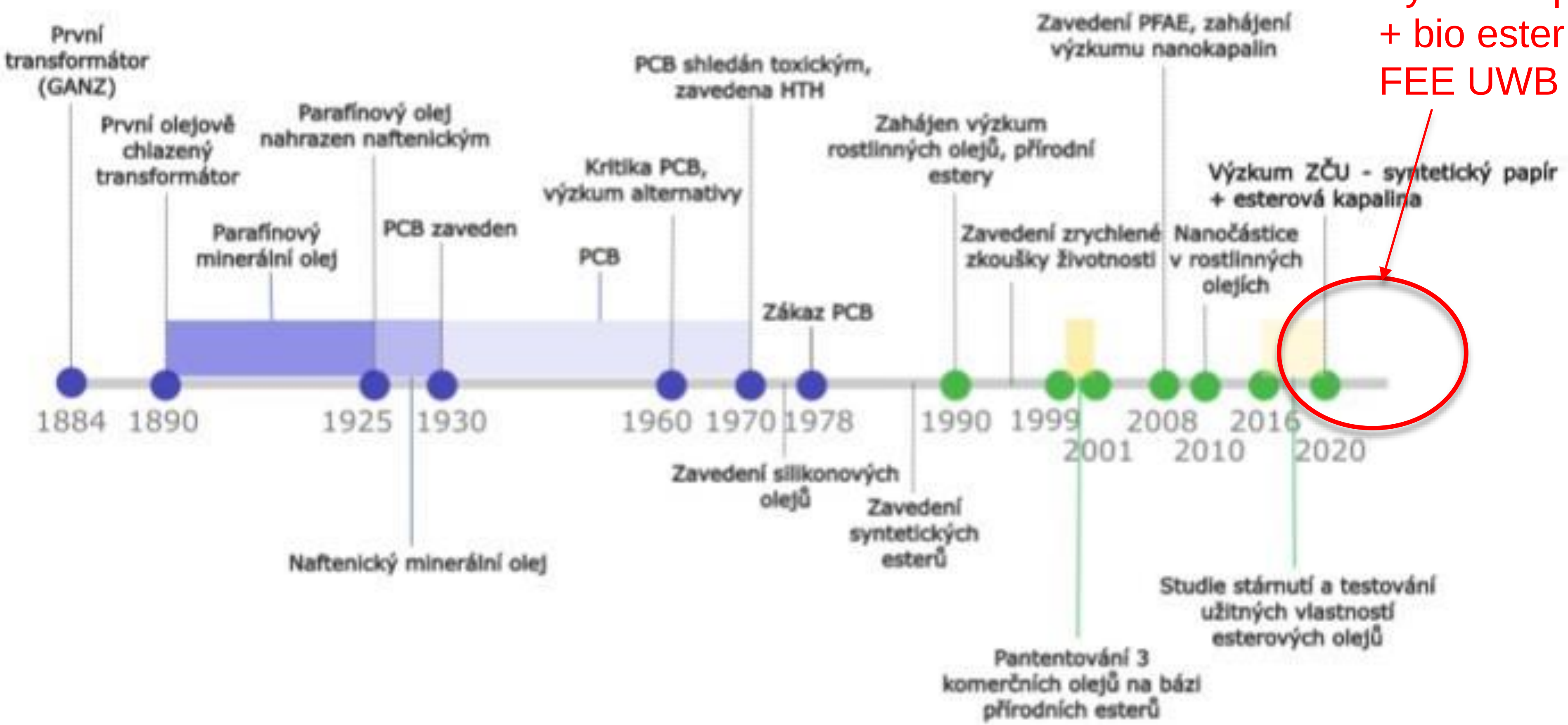
[13] KOCHETOV, R. Thermal and Electrical Properties of Nanocomposites, Including Material Processing. Finland, 2012. Disertační práce. Lappeenranta University of Technology.

Electroinsulating oils use – historical overview



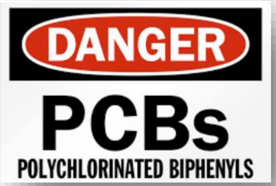
Electroinsulating oils use – historical overview

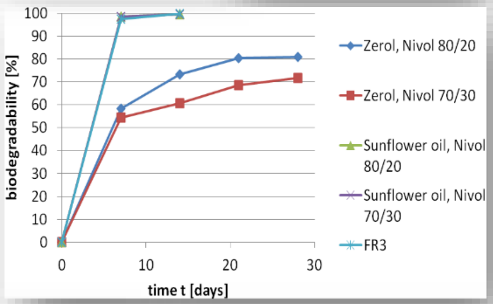
Synthetic paper + bio ester – FEE UWB

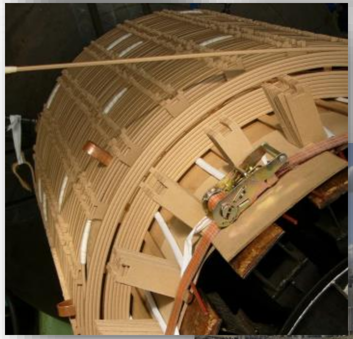


TRANSFORMER‘S INSULATION HISTORY		
EIS	**From**	**Observation**
Commercial Oil Extraction (Romania)	1857	Than Bulgaria and USA
GANZ Factory, Budapest, M. Dery, O.Blathy and K.Zipernovsky	1884	First closed core transformer
Petroleum based oil use in transformer	1887	For transformer cooling
Oil–insulated transformer (Brown). The oil cellulose two-phase insulation system	1890	**Way to high power and high voltage**
3 phase HV transformers with mineral oil (AEG)	1890, 1891	Evidence of the benefits of HV for energy transfer

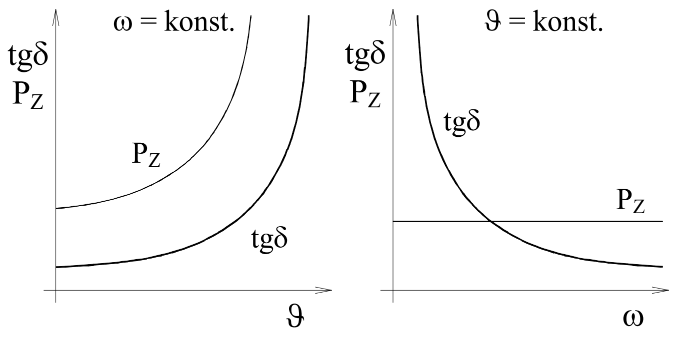
Paraffinic oils	1890 - 1925	Pour point
Naphthenic oils	1925-1930	Health issues
PCB (Ancolor, Delor), not flammable	1932 – 1978	CZE e.g. till 1986
Silicon/Kraft Paper later Silicon/Aramide Paper	1970	PCB replacement
Synthetic Esters, e.g. MIDEL 7131 – less flammable for lower voltage -rolling stock transformers	1980	Biodegradable
Natural esters	2004	Sustainable development, higher thermal class and fire point
Nanofluids with mineral, natural ester	2008/2012	BDV increase
GTL, NITRO BIO	2020	Shell Qatar 2011

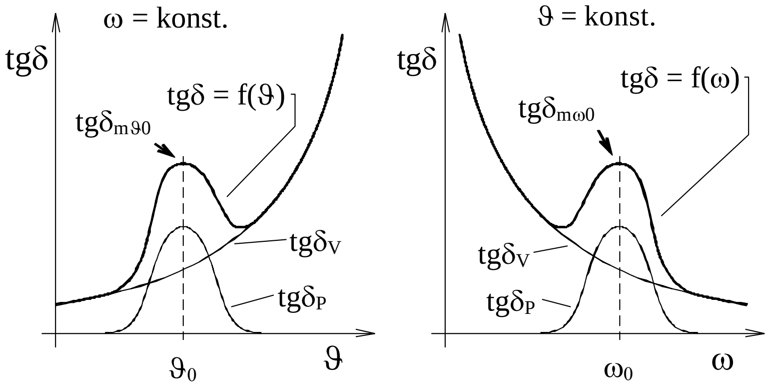


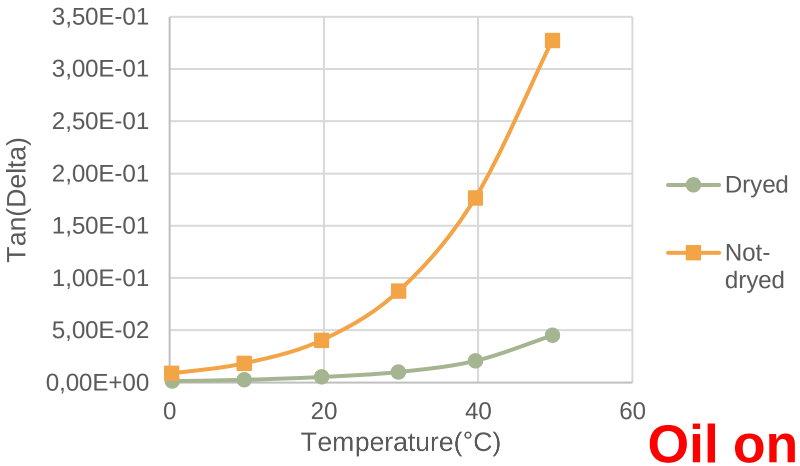




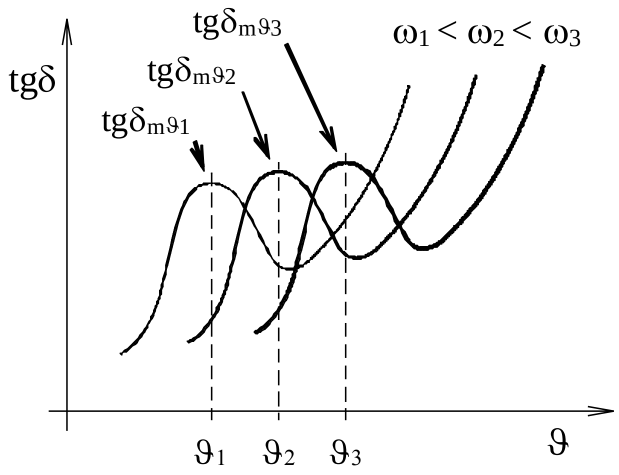
Theoretical dielectric response in AC Voltage

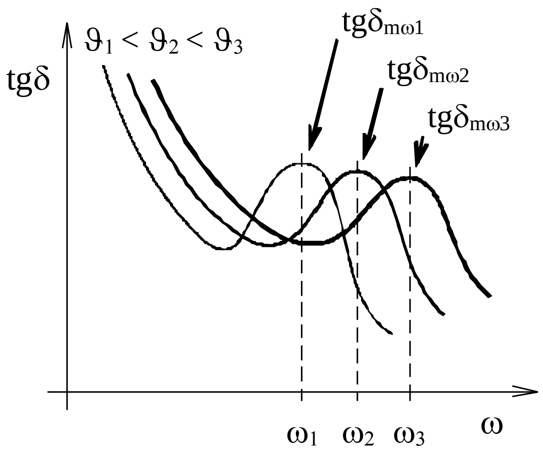


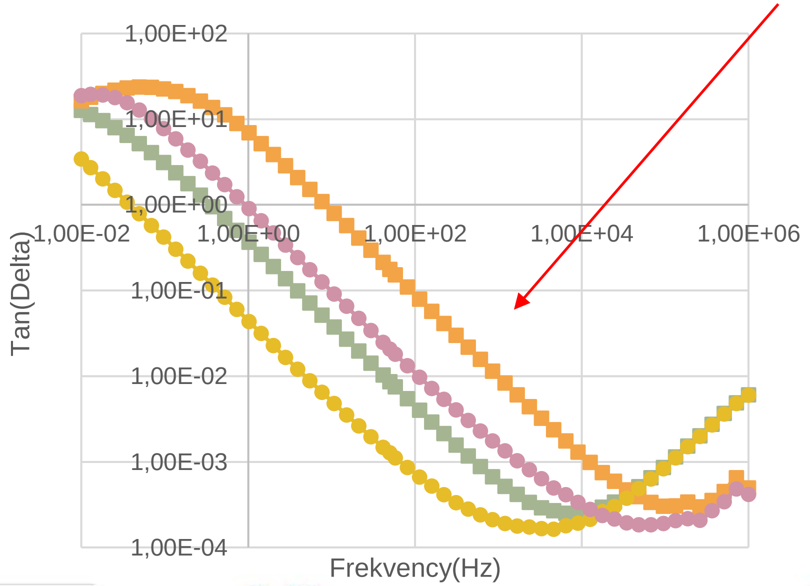




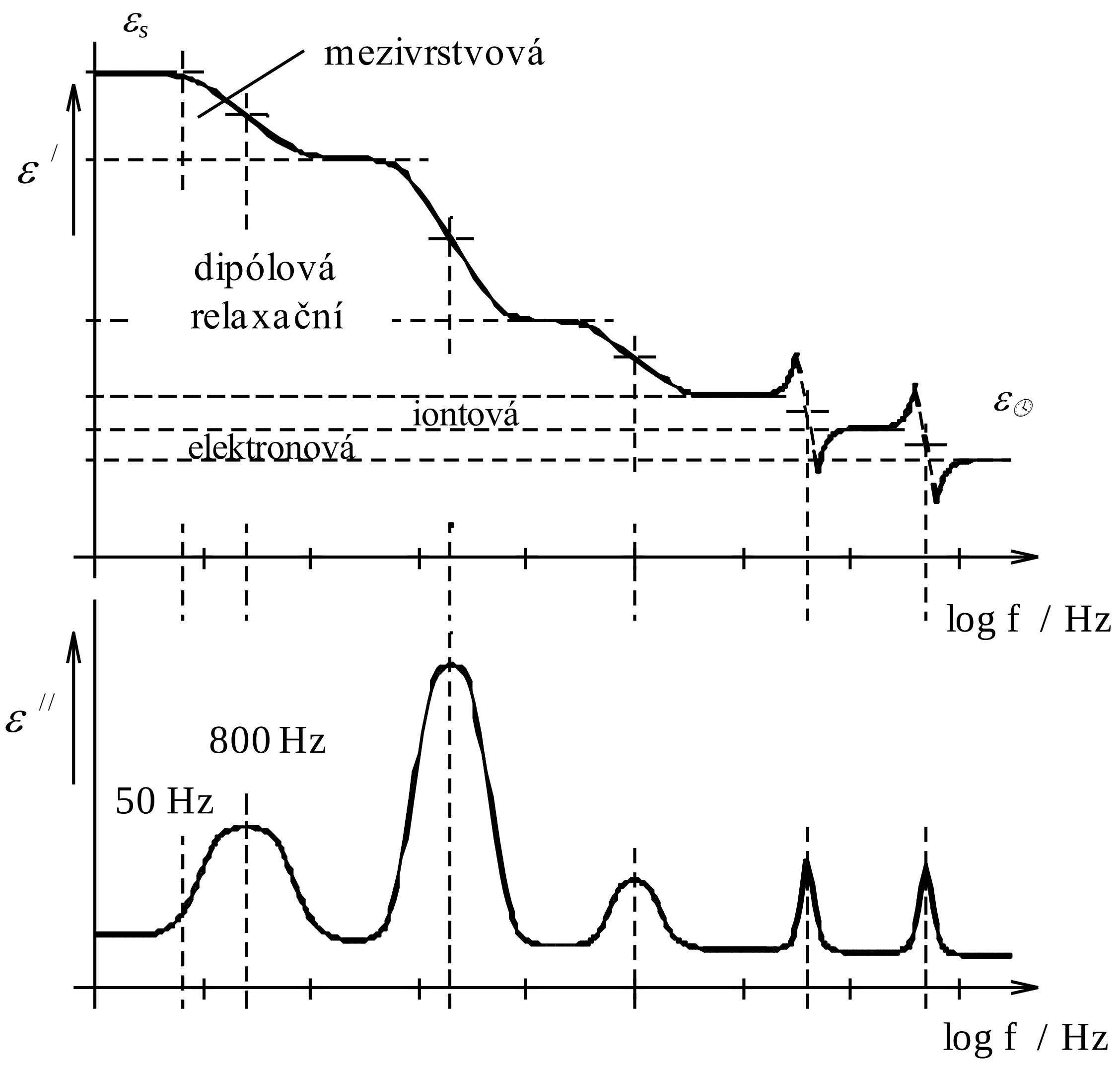
Oil only





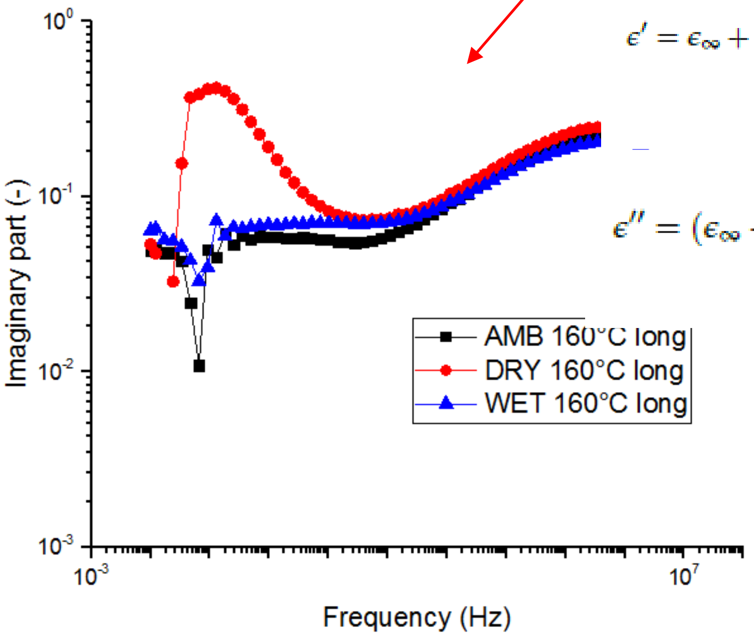


The Whole Dielectric Spectra



The whole system

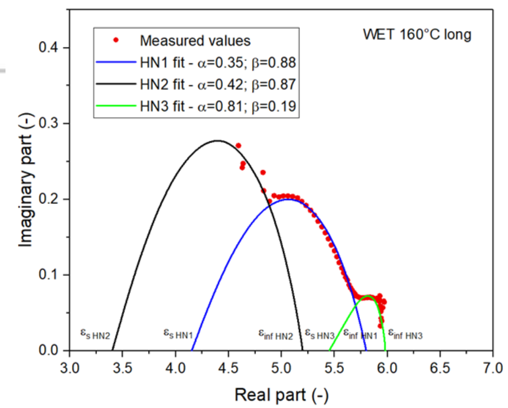
Experiment

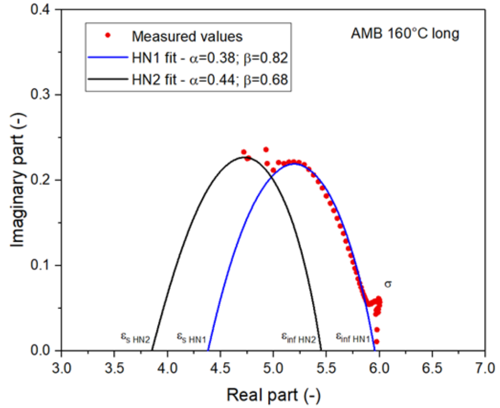


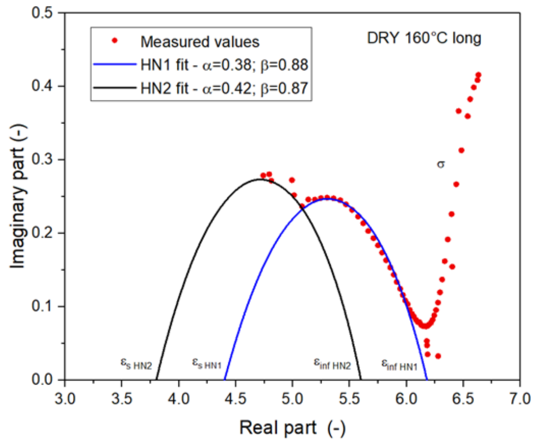
$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{(1+(j\cdot\omega\cdot\tau)^{1-\alpha})^{\beta'}}$$

$$\epsilon' = \epsilon_\infty + (\epsilon_s - \epsilon_\infty)\cdot\frac{\cos(\beta\cdot\varphi)}{\left[1+2\cdot\omega^\alpha\cdot\tau^\alpha\cdot\cos(\frac{\alpha\cdot\pi}{2})+\omega^{2\cdot\alpha}\cdot\tau^{2\cdot\alpha}\right]^{\frac{\beta}{2}}}$$

$$\epsilon'' = (\epsilon_\infty - \epsilon_s)\cdot\frac{\sin(\beta\cdot\varphi)}{\left[1+2\cdot\omega^\alpha\cdot\tau^\alpha\cdot\cos(\frac{\alpha\cdot\pi}{2})+\omega^{2\cdot\alpha}\cdot\tau^{2\cdot\alpha}\right]^{\frac{\beta}{2}}}$$

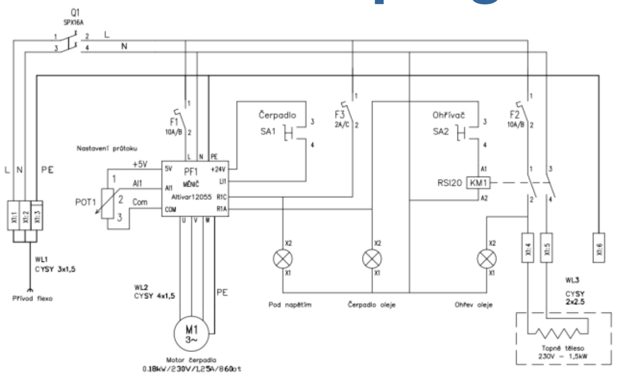






Bio ester + cellulose paper + copper
Aged by Temperature
Controlled moisture content

Developing of biodegradable fluid ENVITRAFOL – some notes

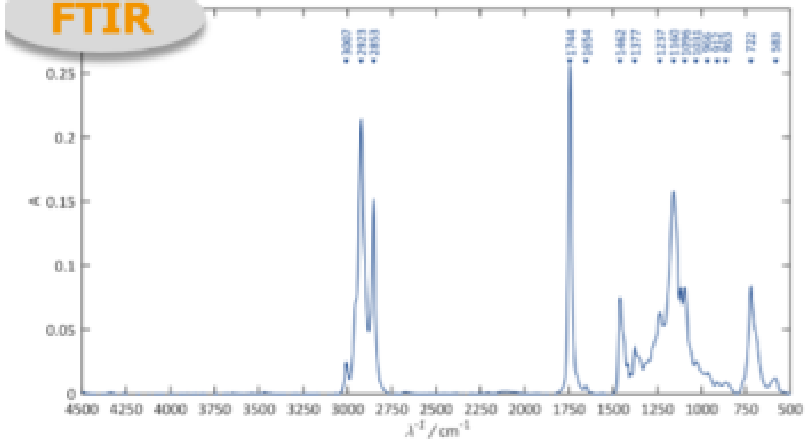


Parameter (Unit)	Limit Value from IEC 62770	ENVITRAFOL
Before Test of Oxidative Stability		
Appearance	Clear, free of sediment and suspension	Fulfill
Viscosity at 100 °C (mm^2/s)	max 15	8.26
Viscosity at 40 °C (mm^2/s)	max 50	35.84
Pour point (°C)	max -10	-24
Water content (mg/g)	max 200	45.8
Density at 20 °C (g/ml)	1.0	0.915
Breakdown voltage (kV/2.5 mm)	min 35	60
Dissipation factor at 90 °C (-)	max 0.05	0.00358
Acid number (mgKOH/g)	max 0.06	0.011
Corrosive sulfur / DBDS	absent / below the limit of determination	absent
Additives antioxidants DBCP (wt %)	max 5	0.53
Additives all (wt %)	max 5	DBPC only
After Test of Oxidative Stability		
Dissipation factor at 90 °C (-)	max 0.5	0.02157
Viscosity at 40 °C (mm^2/s)	maximum increase of previous of 30%	35.3
Acid number (mgKOH/g)	max 0.6	0.041

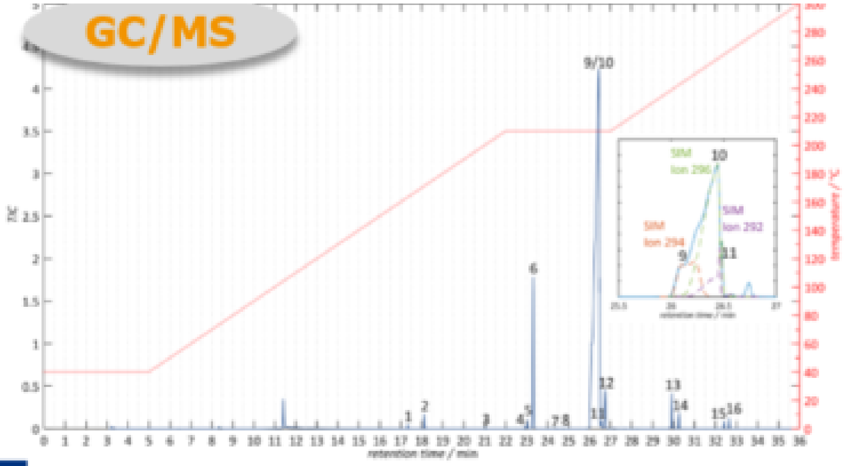
IV. ENVITRAFOL structural analysis

Constitution

FTIR



GC/MS

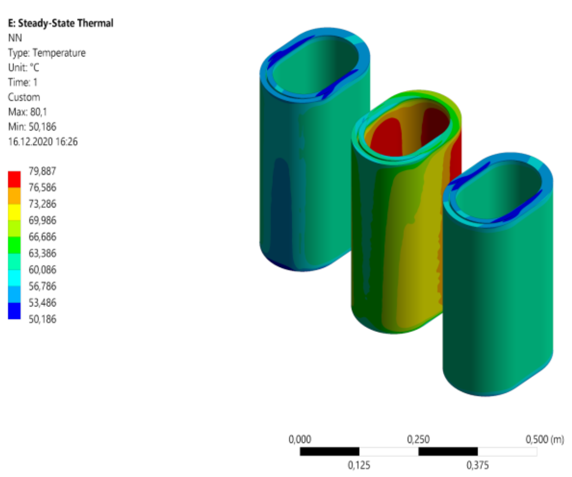


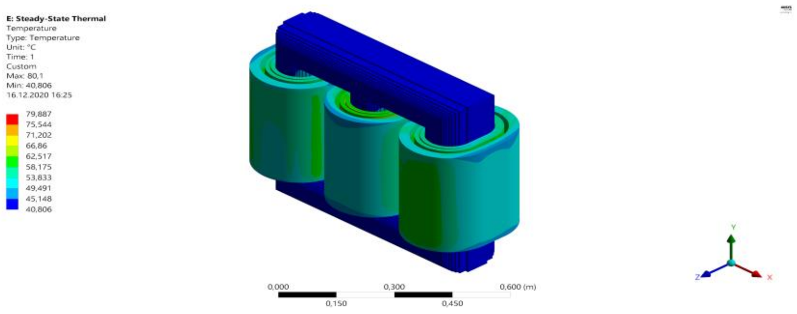
#	RT min	Peak-A %		Qual %
3	21.05	0.06	Tetradecanoic acid, methyl ester (Myristic acid, methyl ester)	99
4	22.92	0.05	7,10-Hexadecadienoic acid, methyl ester	99
5	23.04	045	9-Hexadecenoic acid, methyl ester,(Z)- (Palmitoleic acid, methyl ester)	99
6	23.30	6.03	Hexadecanoic acid, methyl ester (Palmitic acid, methyl ester)	99
7	24.40	0.08	cis-10-Heptadecenoic acid, methyl ester	99
8	24,76	0,05	Heptadecanoic acid, methyl ester (Margaric acid methyl ester)	98
9	26.22	19.2	9,12-Octadecadienoic acid (Z,Z)-, methyl ester (Linoleic acid, methyl ester)	
10	26.45	57.9	9-Octadecenoic acid (Z)-, methyl ester (Oleic acid, methyl ester)	
11	26.57	10.1	9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)- (Linolenic acid, methyl ester)	96
12	26.75	2.16	Octadecanoic acid, methyl ester (Stearic acid, methyl ester)	99
13	29.92	1.80	cis-11-Eicosenoic acid, methyl ester	99
14	30.27	0.68	Eicosanoic acid, methyl ester (Arachidic acid methyl ester)	99
15	32.41	0.36	13-Docosenoic acid, methyl ester,(Z)- (Erucic acid methyl ester)	98
16	32.37	0.37	Docosanoic acid, methyl ester (Behenic acid, methyl ester)	99

A Long Way to Industrial Use

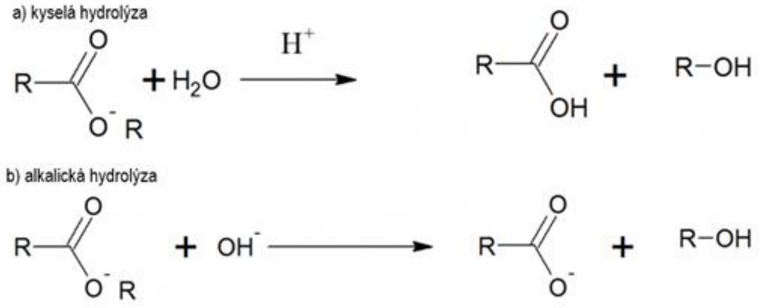
Biodegradable electrical insulating fluid ENVITRAFOL	UM CZ 29 982 U1 Biodegradable electrical insulating liquidTK02020017 - INBIO TA 03020251 Insulating liquids
Compliance with the normative requirements	BDV, Acid Number, tan δ, ρ_v, oxidation stability, water content
Parameters of EIS	Temperature stability, oxidative stability, E_p, ρ_v, tan δ, Low temperature properties
Compatibility test	All components of the transformer
Setting the diagnostic values	For diagnostics in operation
Parameter improvement, nanofluids	Reduction of water content, E_p, ρ_v, viscosity, 0.25 wt% TiO_2, inhibitors
Research in the field of Partial Discharges	Different electron mobility, different streamer length
EU Ecodesign II requirements	Regulation (EU) 2019/1783 , P_{0max} < 189 W

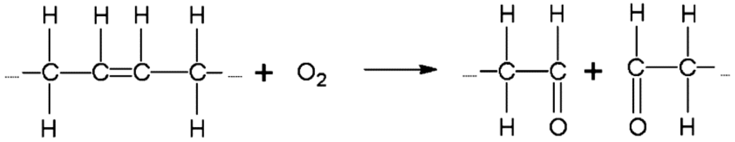
Design of the Transformer for ENVITRAFOL

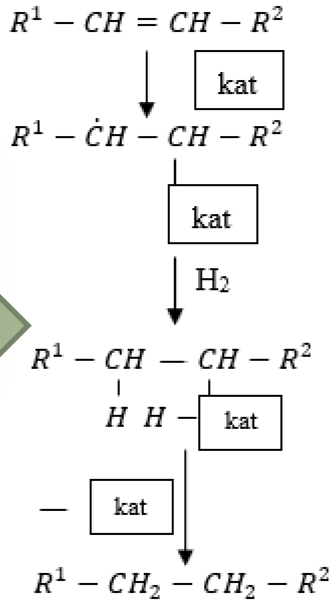




Hydrolysis
Oxidation Of Natural Esters (unsaturated and > 100°C saturated as well
Polymerization The degree of oxidation depends on the content of carbon double bonds C = C - weak points
Hydrogenation







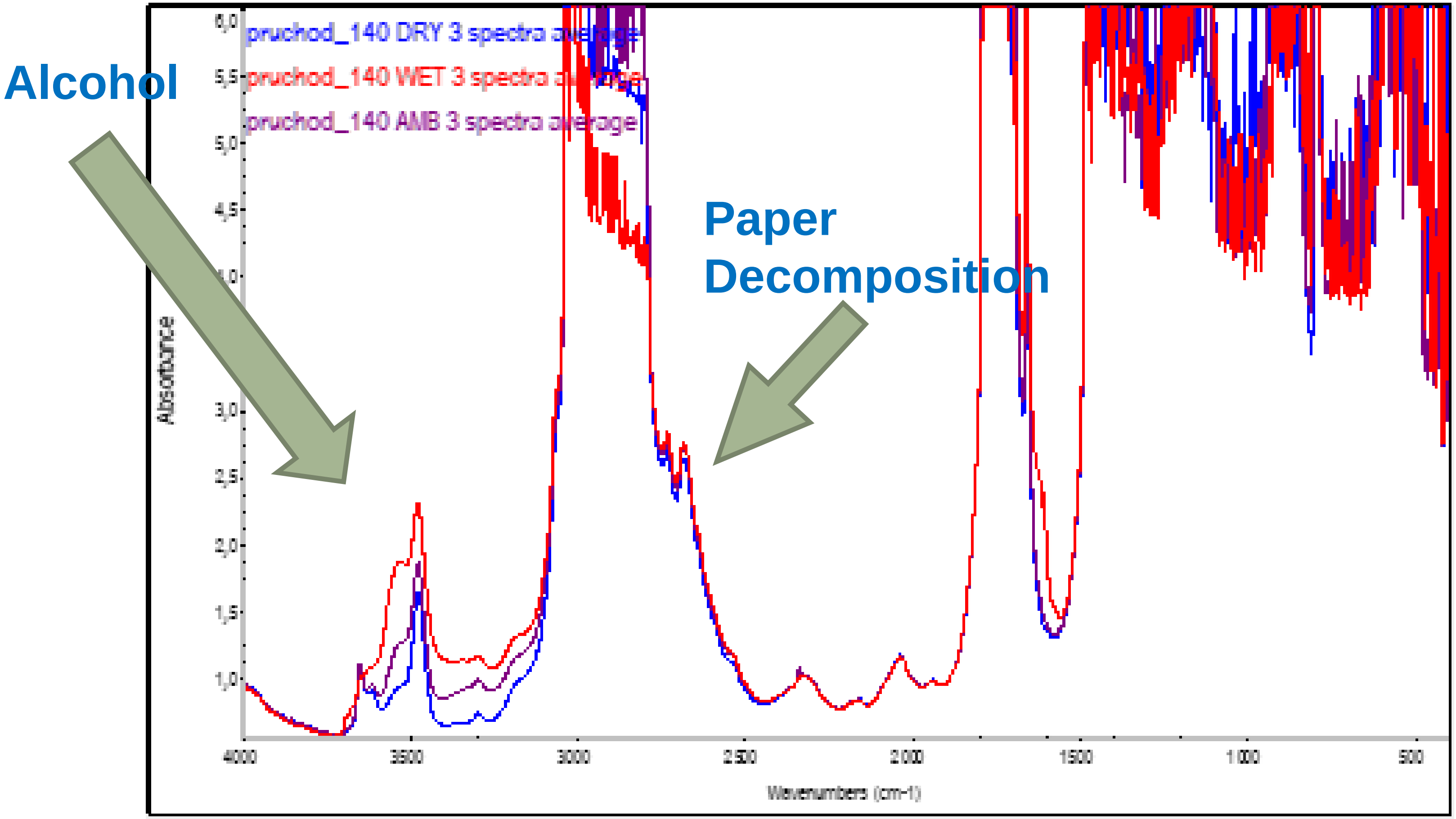
Saturated f.a = better oxidation stability **X** higher viscosity
Unsaturated m. = worse oxidative stability **X** lower viscosity

Conflicting properties - Pour point

TRNKA P., HORNAK J., PROSR P., MICHAL O., and WANG F., "Various Aging Processes in a Paper-Natural Ester Insulation System in the Presence of Copper and Moisture," in IEEE Access, vol. 8, pp. 61989-61998, 2020. IF=4,098, Q1, Top 20

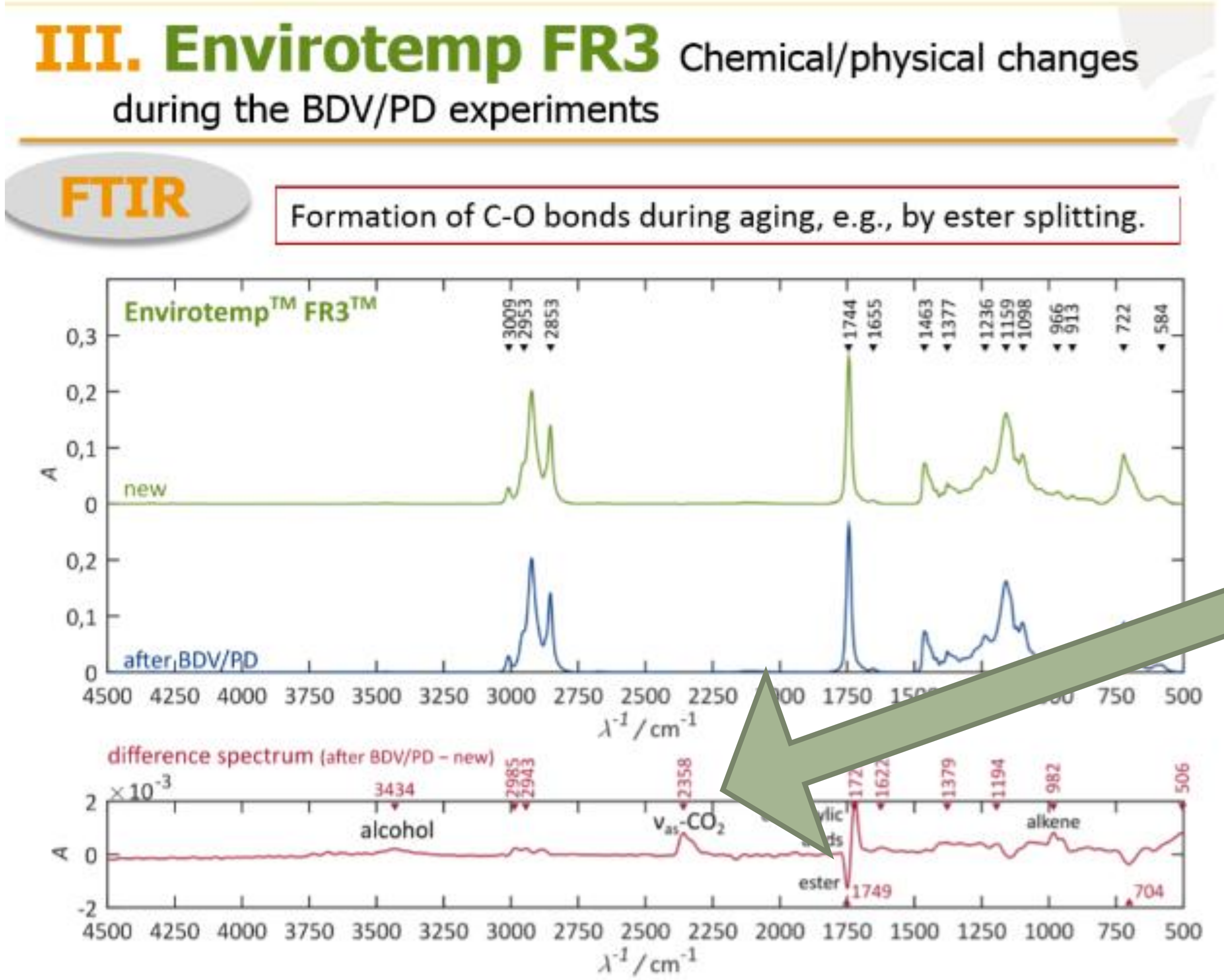
FTIR Example

- Natural ester aged by Temperature (with paper, moisture and Copper)



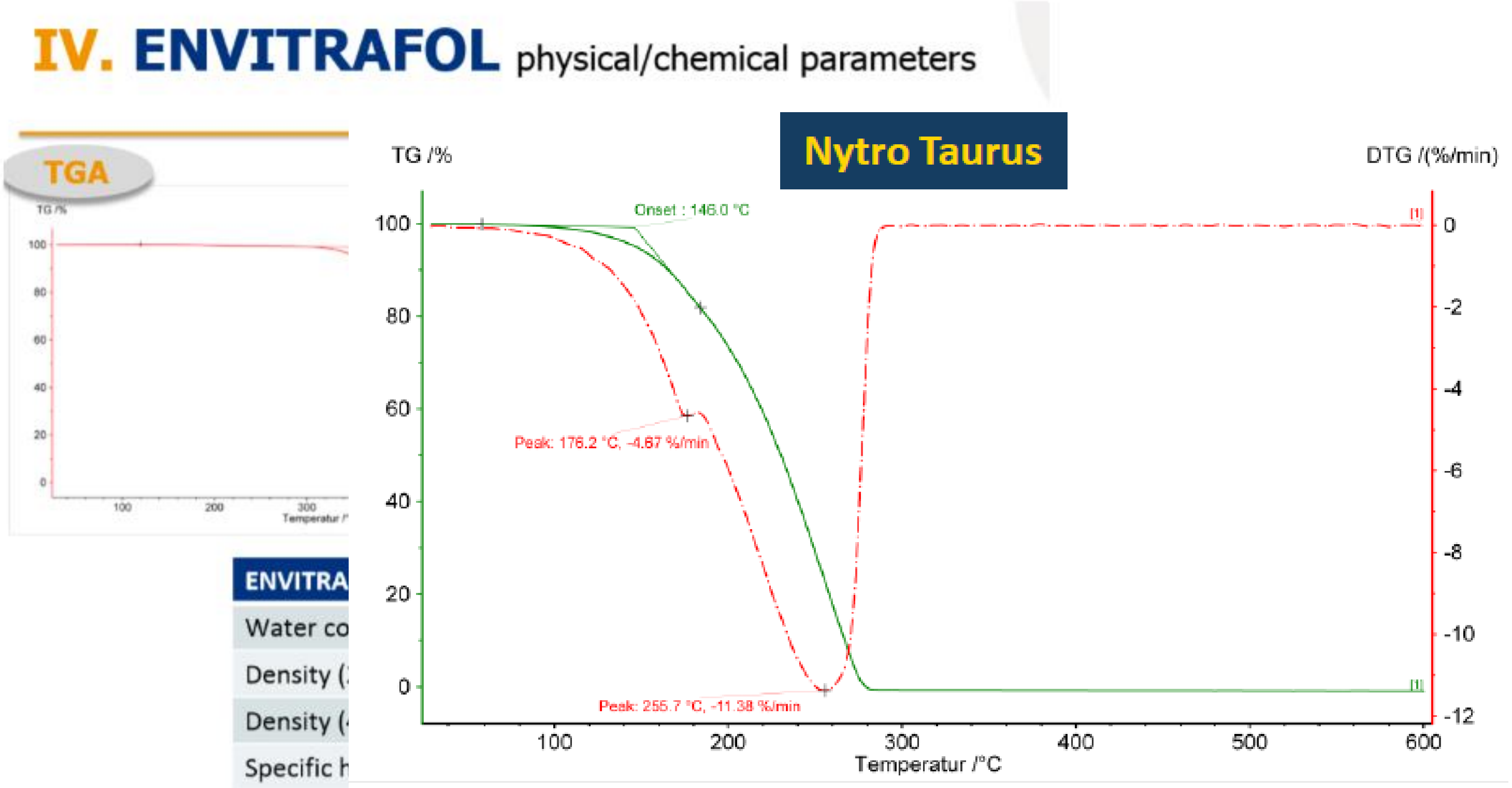
FTIR Example

- Natural Ester Aged by Impulses



Impulses and BDV

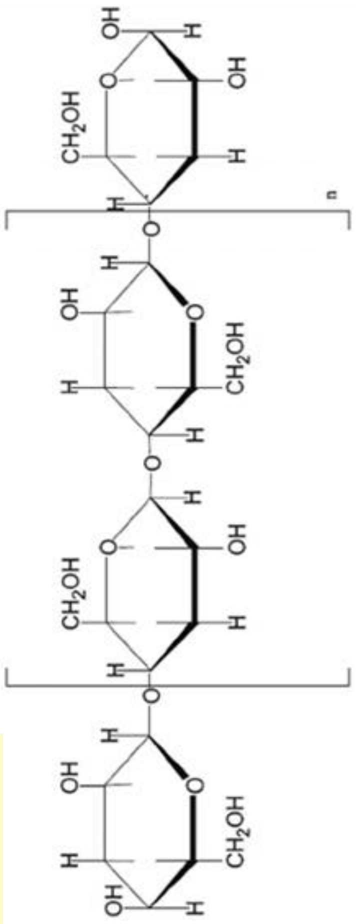
Non Flammable Fluids, Flash Point > 150°C



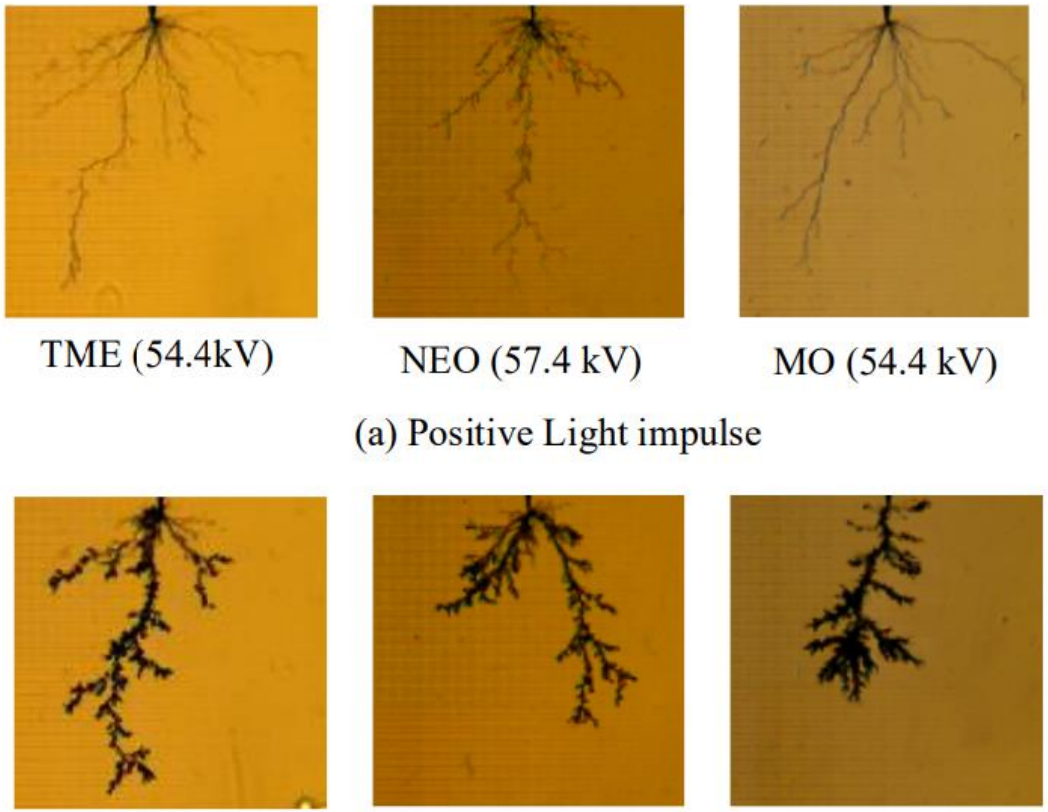
Relative premittivity (20°C; 1kHz)	ε_r	3.031	
Dissipation factor (80°C; 1kHz)	tan δ	0.009	
Decomposition temperature	T	386.4	°C

Poss. Cellulose Type Degradation

Type of chemical reaction	Reactants	Products
Thermal hydrolysis	cellulose + H_2O	D-glucose
Acid hydrolysis	cellulose + H_3O^+	D-glucose
Alkaline hydrolysis	celulose + base	low molecular weight products
Fotooxidation	cellulose + O_2 (UV, Visible)	Aldehyds, ketons
Enzymatic hydrolysis	cellulose + cellulase	low molecular weight products
Oxidation	cellulose + O_2 (T, hv)	partially oxidized and depolymerized cellulose

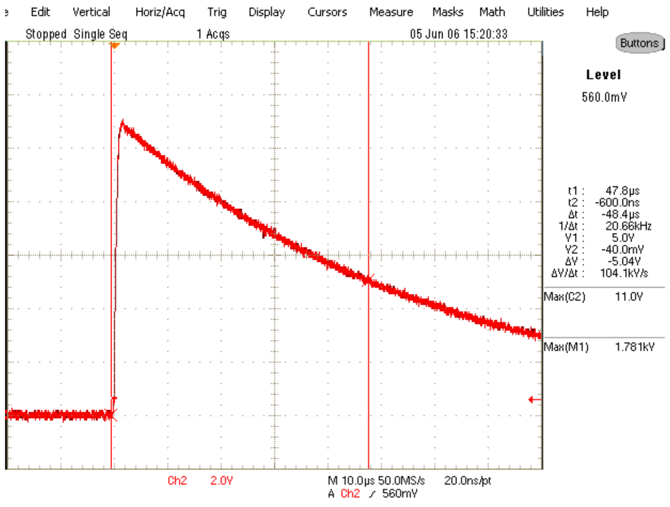


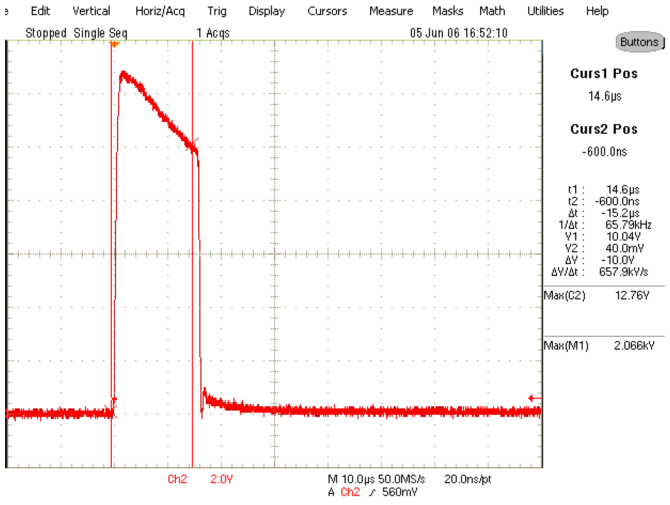
LI streamers in various oils



(a) Positive Light impulse

(b) Negative Light impulse





WANG, K., WANG, F., SHEN, Z., LOU, Z., HAN, Q., LI, J., TRNKA , P., ROZGA, P., Breakdown and streamer behavior in homogeneous synthetic trimethylolpropane triesters insulation oil, *IEEE Transactions on dielectrics and electrical insulation,* 2020, ISSN: 1070-9878, IF=2,324

Nanofluid with Envitrafol

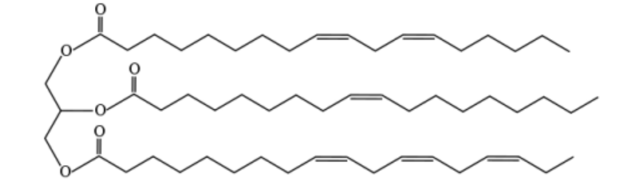
The pros and cons

- **Pros:**
- Improving of the selected properties
- Thermal conductivity, Resistivity, BDV

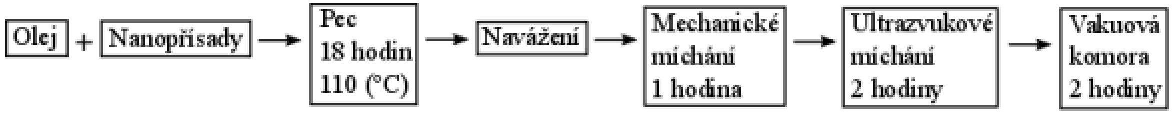
- **Cons:**
- Sedimentation and agglomeration
- Compatibility

- Homogeneously dispersed nanoparticles are a prerequisite for stable nanofluid
- Nanoparticles will remain dispersed if the Van der Waals forces are compensated by repulsive forces (respectively forces acting against attractive forces) such as electrostatic steric or electro-steric forces.

Obr. 5.3 Míchadlo s dvojitou šroubovicí



Obr. 4.5 Strukturální vzorec řepkového oleje



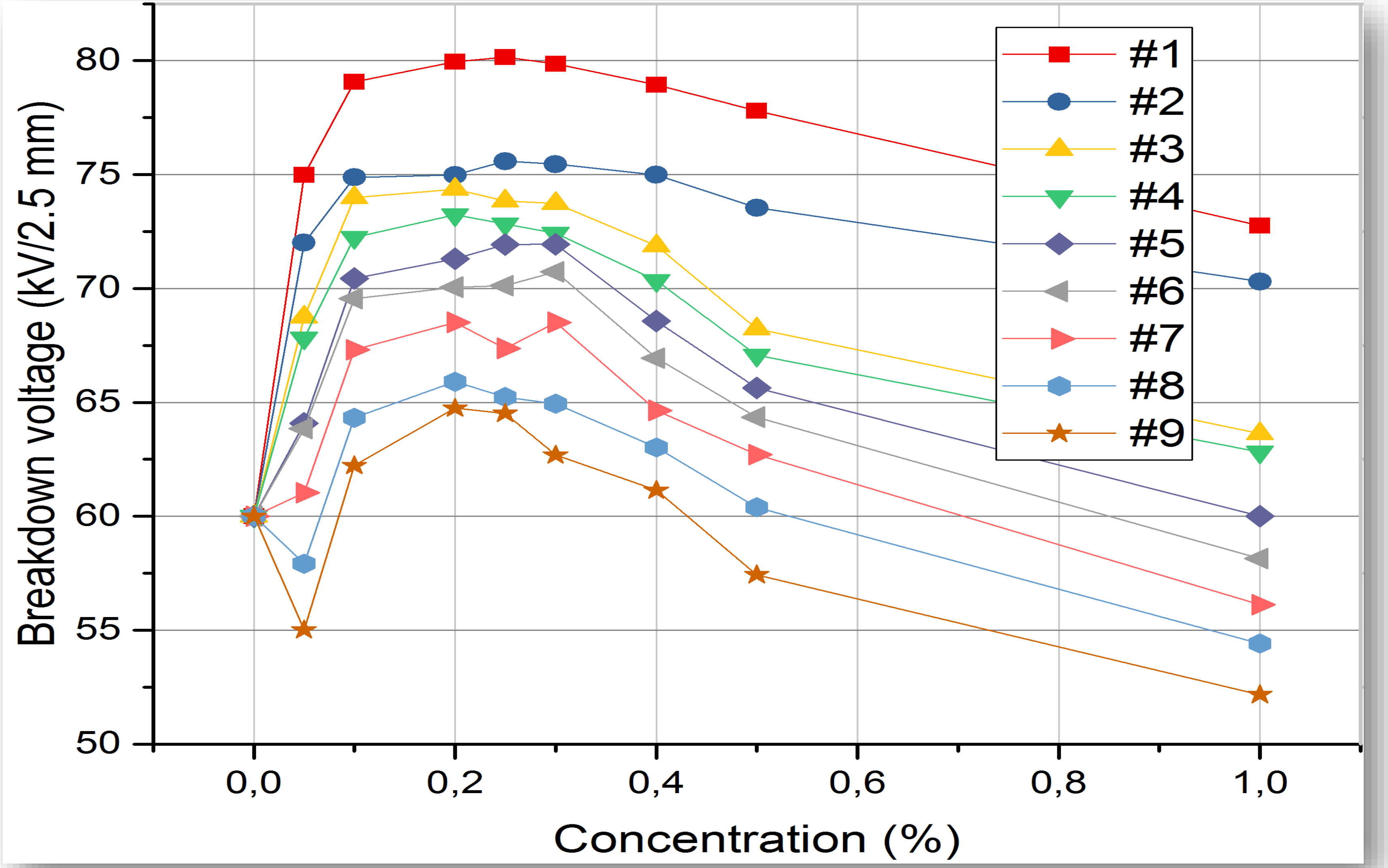
Obr. 5.7 Schematický postup výroby fluidního systému s nanopřísadami

- These forces are important for the stability because they form a barrier that the particle must overcome to interact and create agglomerates with other particles. If the energy of this barrier is greater than the kinetic energy of the particle, the solution remains stable and homogeneously dispersed.
- In practice, to improve the stability of the nanoparticle, surfactants are used, i.e. surface treatments that reduce the surface tension in the liquid acting at the interface between the particles and the liquid. This interface determines the forces (mainly steric) acting on the formation of bonds between the particles. When using a surface treatment, it is necessary to select the proper type based on the application (not all surfactants interact suitability with the liquid) and then the proper amount, because too large amount of surfactant leads to "bubble creation" around the particle that easily captures the surrounding parts, which again leads to the formation of agglomerates.

Envitrafol Based Nanofluids #1

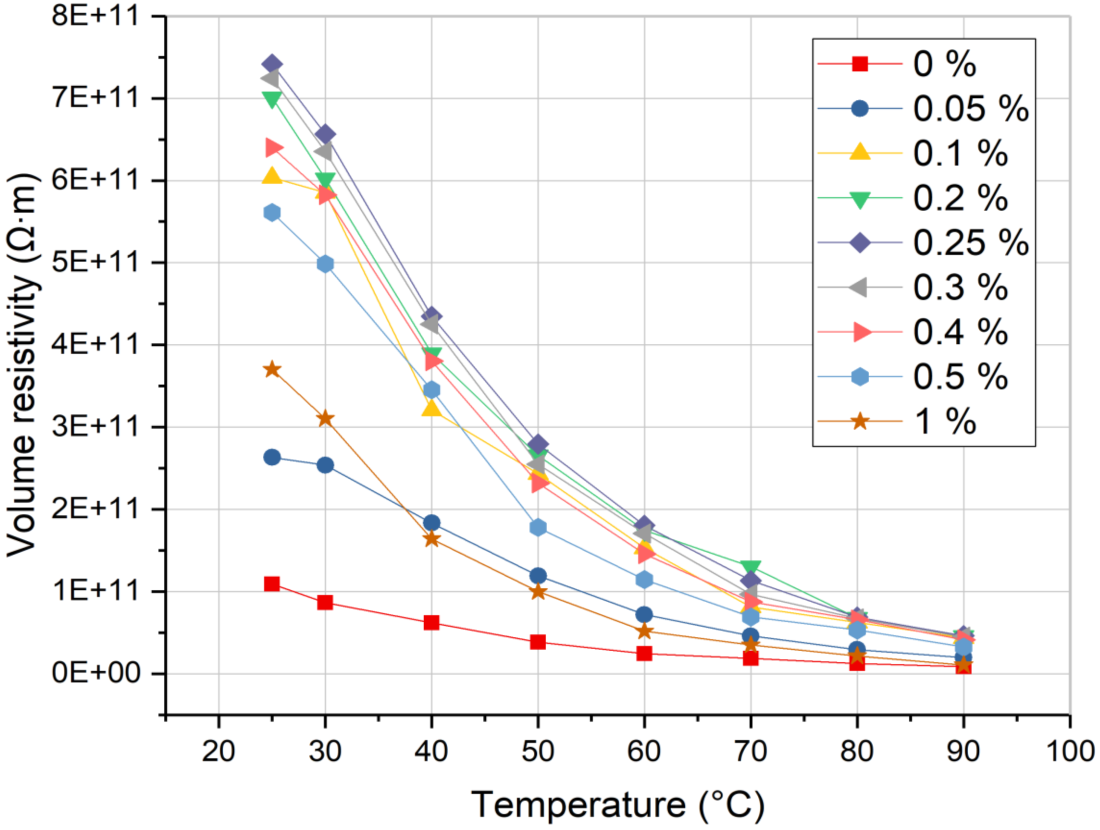
#	Nanofiller	Surface Treatment	Primary Particle Size (nm)	Max. Breakdown Voltage BDV (kV/2,5 mm)	Weight Content at max. BDV (%)
1	TiO_2	SiO_2	20	80,1	0,25
2	TiO_2	-	20	75,6	0,25
3	Al_2O_3 - γ	-	10	74,3	0,2
4	Al_2O_3 - γ	-	20 – 30	73,2	0,2
5	ZnO	-	20	72	0,3
6	ZnO	(3-Aminopropyl) triethoxysilan	30	70,8	0,3
7	ZnO	-	30	68,5	0,2
8	SiO_2	(3-Aminopropyl) triethoxysilan	20	65,9	0,2
9	SiO_2	-	30	64,5	0,2

Nanofluid with Envitrafol - BDV



#	Nanofiller
1	$TiO_{2\ 20\ ST}$
2	$TiO_{2\ 20}$
3	$Al_2O_3 - \gamma$ 10
4	$Al_2O_3 - \gamma$ 20-30
5	ZnO 20
6	ZnO 30 ST
7	ZnO 30
8	$SiO_{2\ 20ST}$
9	$SiO_{2\ 30}$

Volume resistivity of Nanofluid ST TiO2 #1



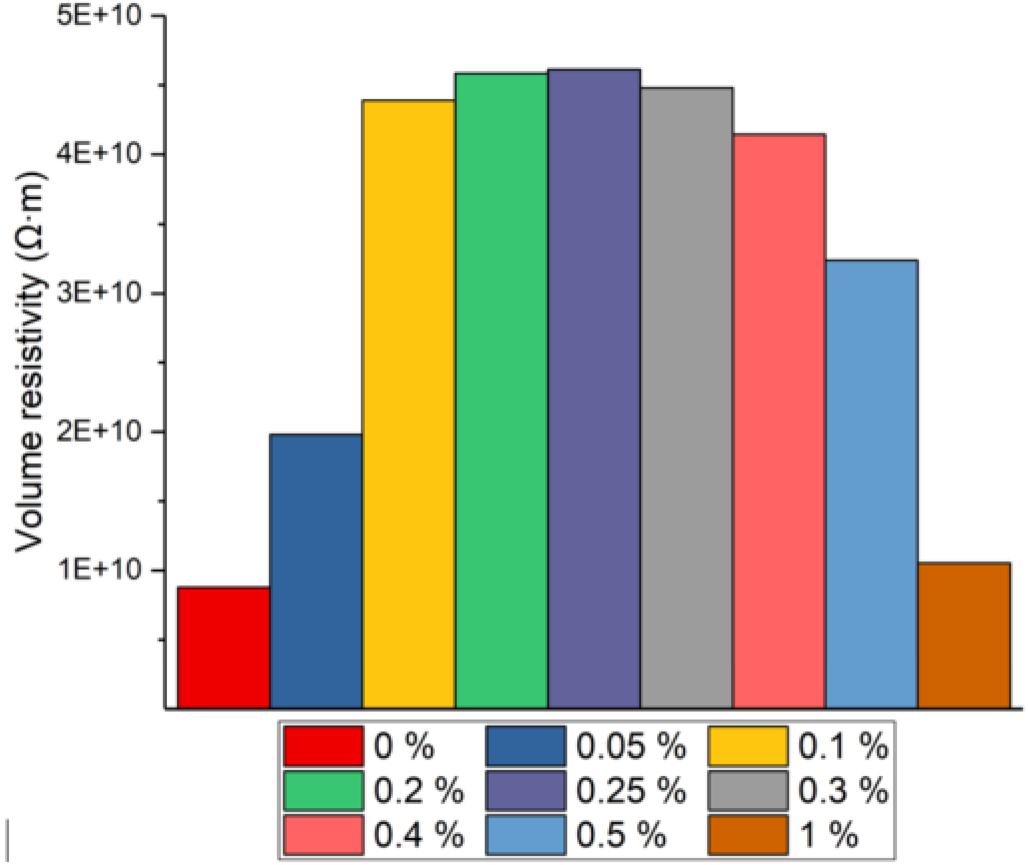
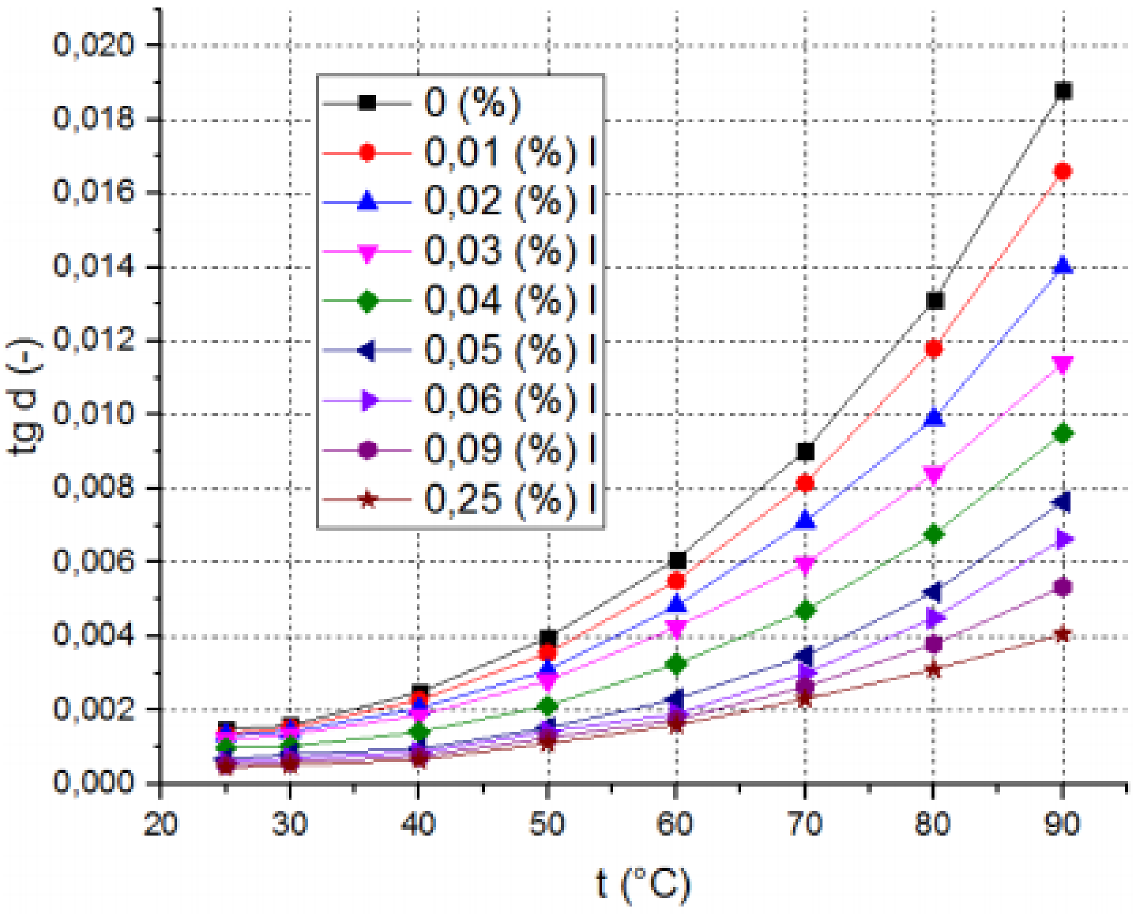
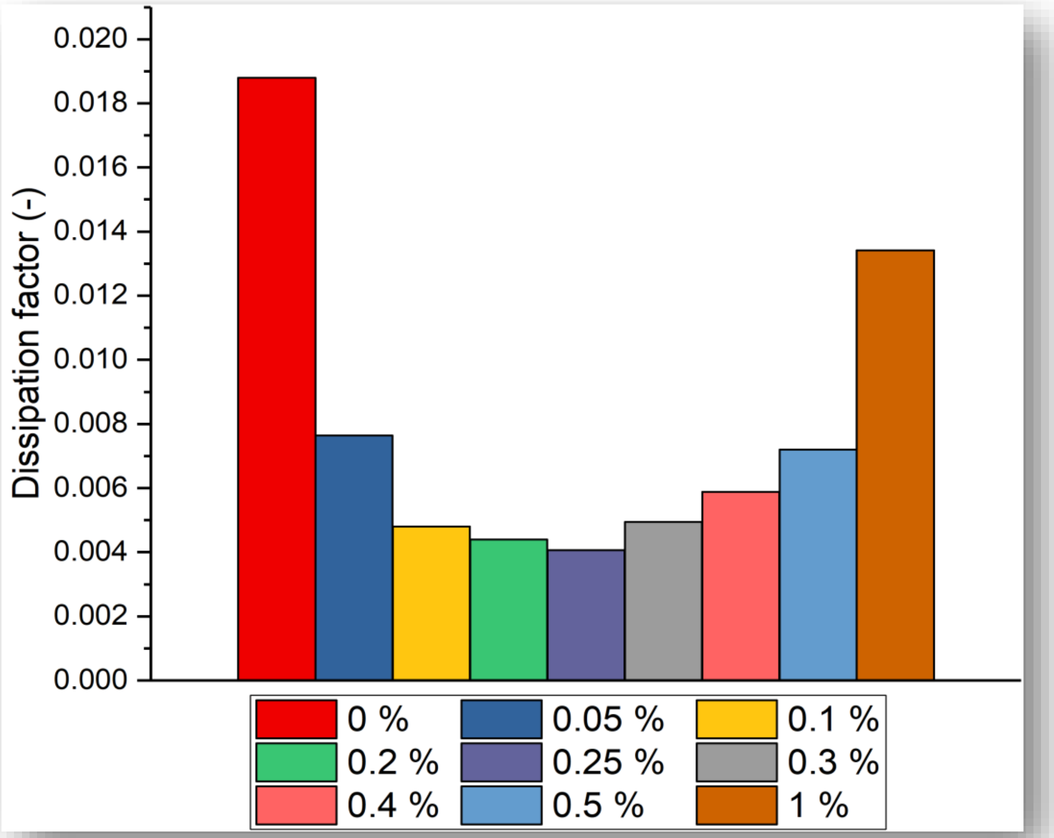


Figure 10. Dependence of volume resistivity of nanofluid with ST TiO_2 on nanoparticle concentration, 90 °C

Dissipation Factor of Nanofluid ST TiO_2 #1

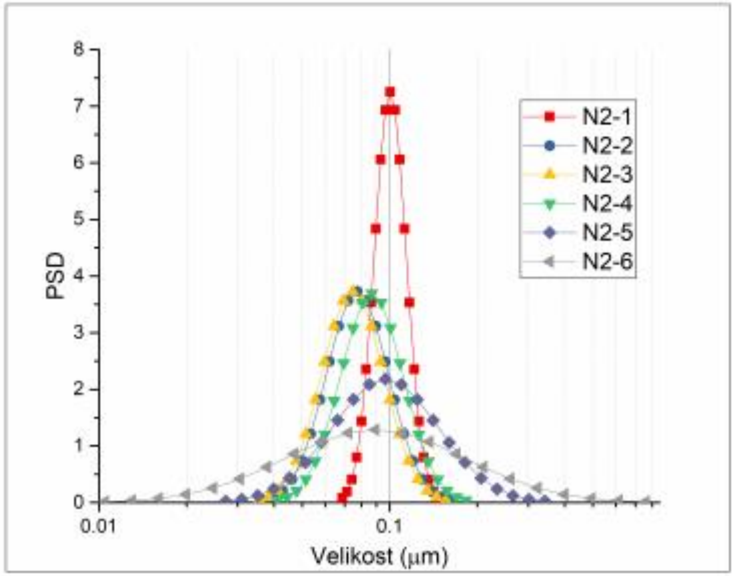




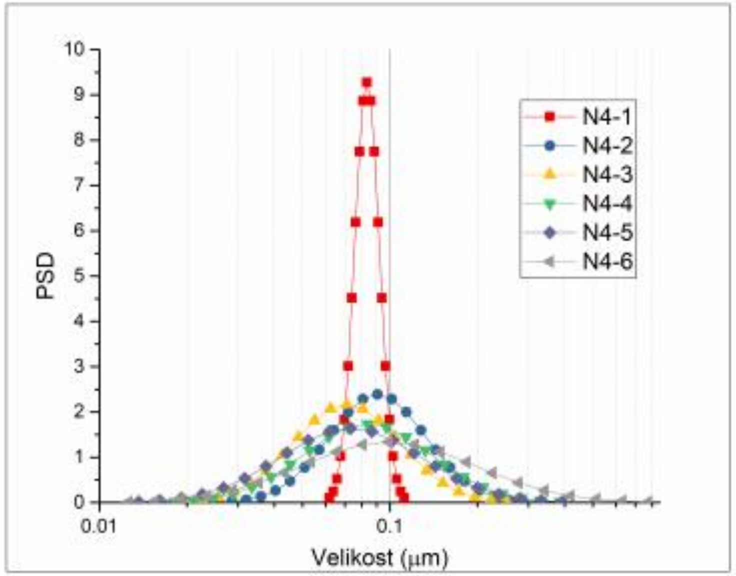
90°C

UNIZA Coop:Rapeseed MgO nanofluid #2

Agglomeration in 20 Days, using DT-1200 Spectrometre



Obr. 39: Disperze vzorku N2 v čase



Obr. 40: Disperze vzorku N4 v čase

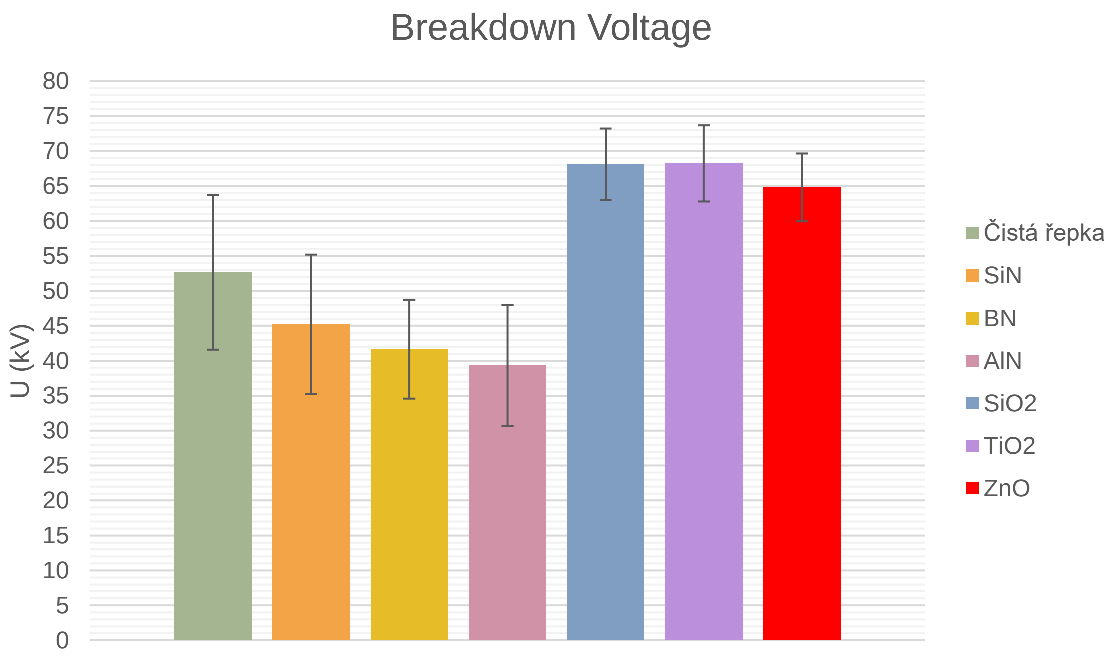
Tab. 17: Přehled označení experimentálních vzorků

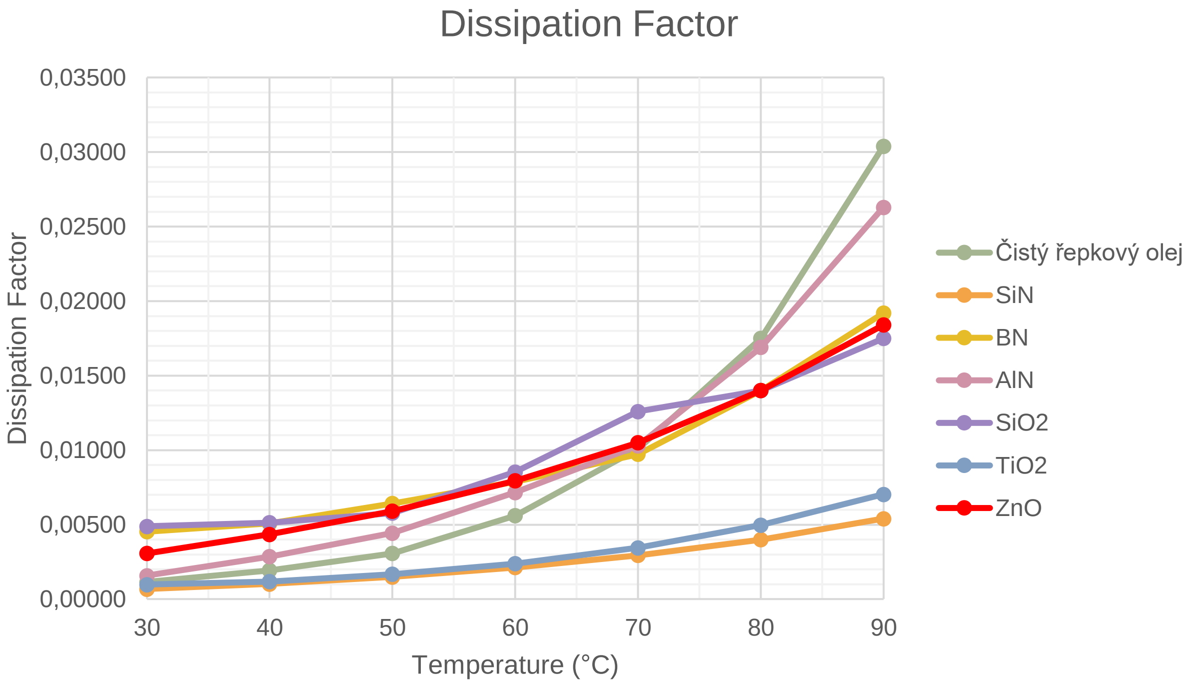
Koncentrace \ Surfaktant	S1	S2	S3	žádný
1.0 g/l	N1	N2	N3	N4
1.5 g/l	N5	N6	N7	N8
2.0 g/l	N9	N10	N11	N12

Source: Totzauer: DDP, Aspekty používání biodegradabilních elektroizolačních kapalin, ZČU, 2019

New Results

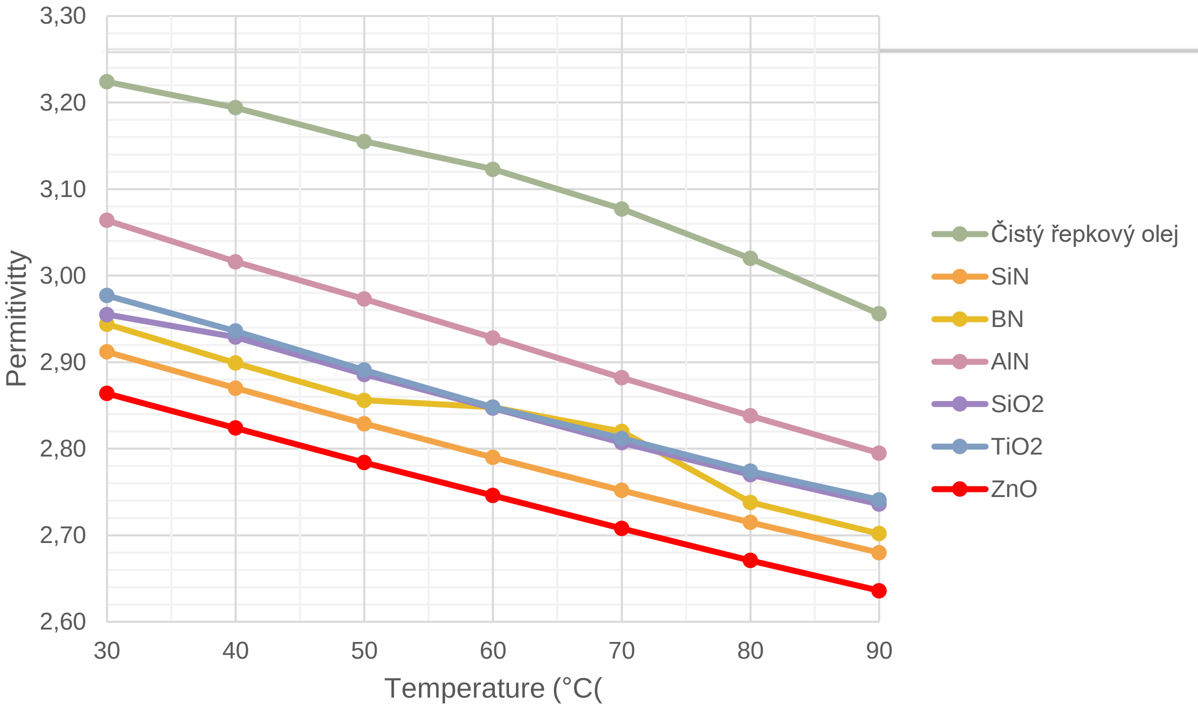
Nanofluids with SiN, BN, AlN, SiO_2, TiO2, ZnO





Source: Mokra, Z. Diploma thesis, 2023

New results

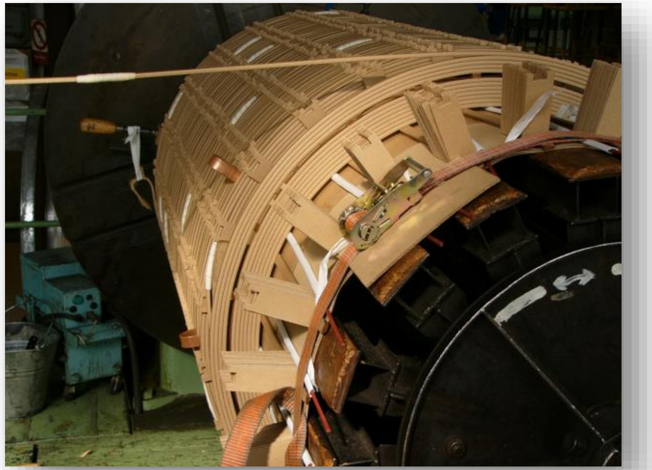


	Bio Ester	SiN	BN	AlN	SiO_2	TiO_2	ZnO
Riz (60 s) (GΩ.m)	4,35	50,84	16,62	9,99	55,59	59,18	9,91

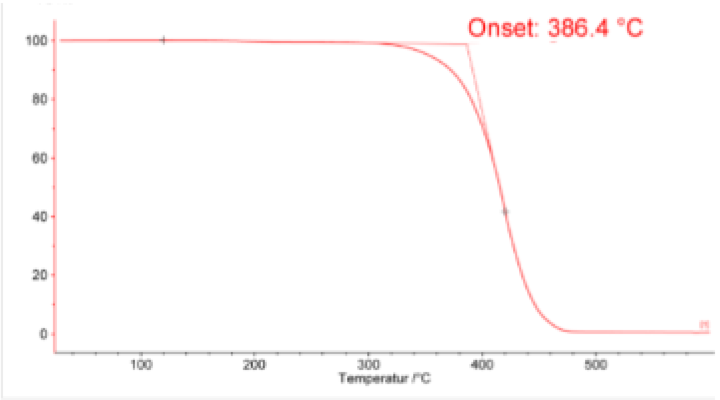
Source: Mokra, Z. Diploma thesis, 2023

New Electro insulating system?

- Kraf Paper thermal class A



Envitrafol



Nomex Termal class H

„Green Technology“

Cellulose paper

Same Technology

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Conclusions - Oils

- Nanofluids

- Further improving of the dielectric properties is achievable
- Nanoscale dielectric phenomena explanation
- Compensation of the higher space charge in natural esters
- The open question for use in electrical machinery is the issue of sedimentation and „filtering“ on the particles
- New high temperature EIS?
- Context of energy transition.

- TiO_2 ε_r =100 (Rutile)
- BDV of nanometric layer TiO_2 = 270 kV/mm
- E_L=30.E
- $BDV_{ENVITRAFOL}$ = 24 kV/mm

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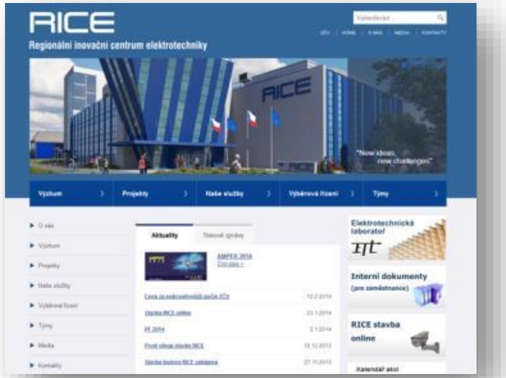

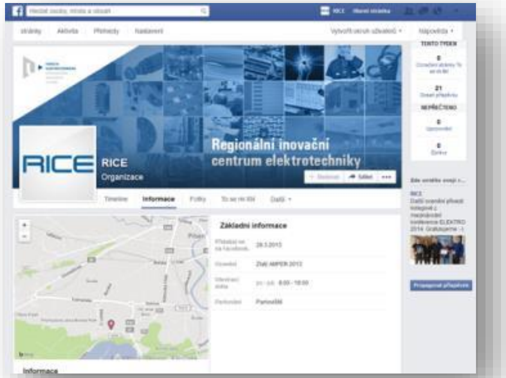

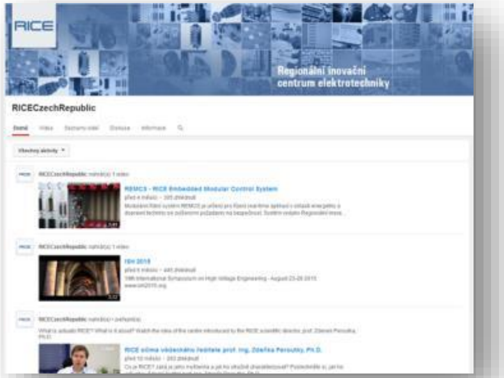

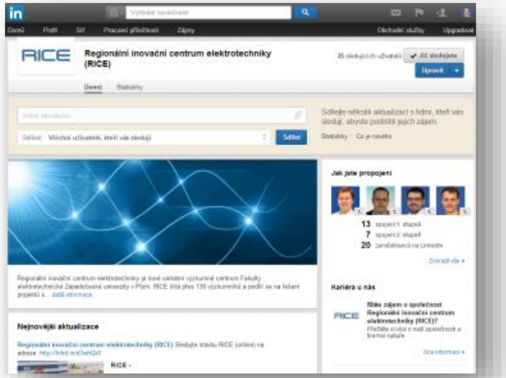

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