Fabio Scatiggio

Trasmissione Elettricità Rete Nazionale S.p.A

Fabio Scatiggio was born in Venezia, Italy, in 1957. He is with Terna Rete Italia where he is in charge as Chemical Laboratory Manager.

He is the Italian representative in many IEC TC 10 and CIGRE A2&D1 working groups. Mr. Scatiggio has published many papers on transformers diagnosis by DGA and on problems related with presence of corrosive sulphur in oil.

Mr. Scatiggio received the “IEC Award 1906” in 2008 and was awarded as “CIGRE Distinguished Member” in 2012.

Electrical Insulation

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SOLID INSULATION

Electrical insulation is operated by:
Cellulosic Solid Insulation (**paper**, pressboard, wood, etc.)
Liquid Insulation (mineral **oil** or others).

Individual dielectric properties of oil and paper change when used together.

INSULATION	BDV (kV/mm)
Oil	12
Paper	40
Oil Impregnated Paper	64

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Electrical Insulation

Paper was discovered in ancient China in the firsts centuries A.C.

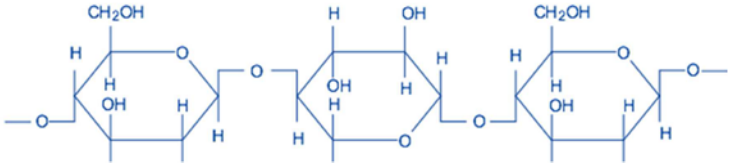
Then in middle age it was extensively produced in Fabriano (Italy) by the local handicrafts.

Solid insulation can be divided into:

Kraft Paper and Creep Paper, thickness < 0.2 mm.

Pressboard, Formable Pressboard and Transformer-board, thickness > 0.2 mm.

Cellulose is the organic main component of vegetable fibers (~ 50% of dried).



Cellulose is a polar linear polymer of glucose (polysaccharide) $(C_6H_{10}O_5)_n$

The repeating unit n is in range 1000÷1500 (typically 1200)

n = Degree of Polymerization.

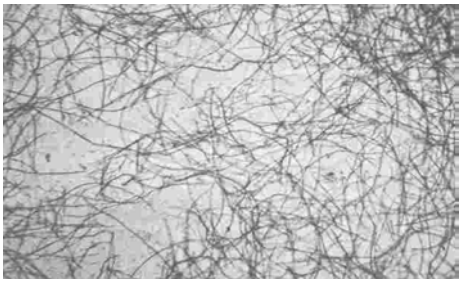
Electrical Insulation

Paper preparation:

1. Vegetable fibers fragmentation (conifers, beech wood, straw, cotton, cascade, etc.).
2. Pulp treatment in autoclave at 150-170°C with NaOH, Na_2S, or $NaHSO_3$.
3. Mechanical treatment for improving flexibility.
4. Addition of fillers, glues and colorants.
5. Dehydration.
6. Micro-creeping (eventually).
7. Calendering for defining thickness.

The morphologic structure of paper is a mixture of crystalline zones at high density and order, alternated with amorphous zones at low density without regular order.

As higher the crystallinity % is, as better the hygroscopicity and the chemical stability is.



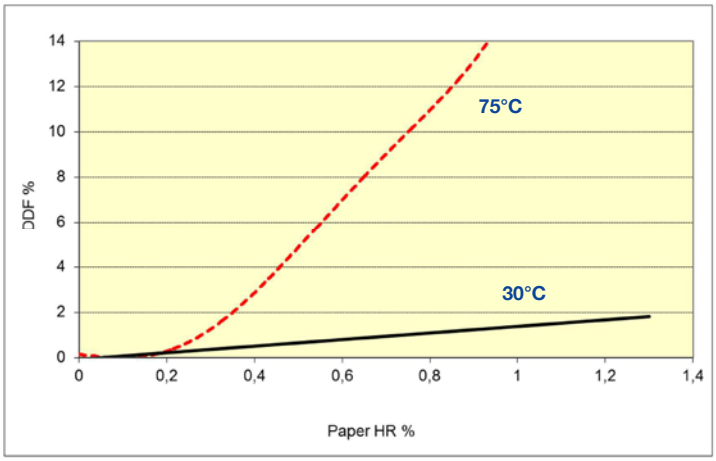
Electrical Insulation

The dielectric constant ε (permittivity) of paper is quite high (~ 7) due to the presence of carboxylic group (–OH) and is influenced by density.
It is always higher than any liquid (oil ~ 2.2).

Paper is not soluble in water but large amounts of water can be absorbed into (hygroscopicity).
Water affects:

- reducing BDV
- increasing DDF (tan δ)
- reducing resistivity
- increasing permittivity

dielectric losses ➽ ε · tan δ



Electrical Insulation

Max working temperature of Kraft paper is 105°C (thermal class A), but paper starts to loose his mechanical properties at 70°C.

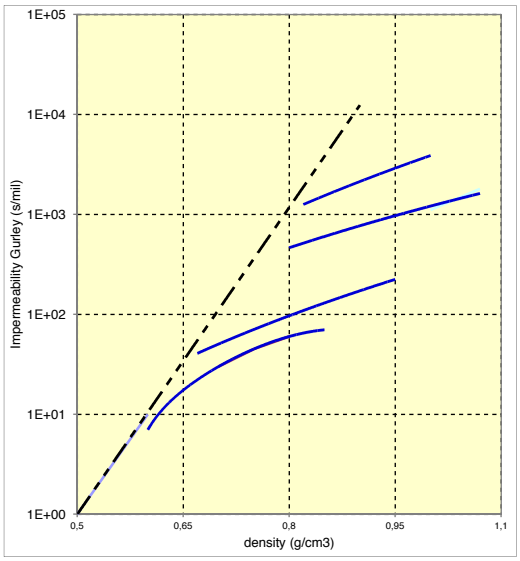
Water and oxygen speed up the paper degradation by hydrolysis and oxidation.

Westinghause patented Insuldur®: a thermally up-graded paper composed by Kraft paper + dicyanamide, which can work at higher temperatures (up to 115°C).

Electrical Kraft paper is today prepared almost exclusively with conifer wood

Composition	%
Cellulose	95 - 97
Pentosane (max)	4
Lignine (max)	3
Ashes (max)	1
Iron (max)	0.01
Copper (max)	0.003

Electrical Insulation



Dotted black line:
untreated paper

Continuos blue lines:
paper after calendering

Paper for electrical purposes:

1. Winding insulation: thickness 60-80 µm and density 0.75
2. Main insulation and Continuously Transposed Conductor (CTC) : thickness 120-150 µm and density 0.75
3. Oil fluid cables (electrical field 8-10 volt/µm): thickness and density are function of electric field intensity, with small thickness and high density near the conductor.
4. Power factor correction capacitors (electrical field up to 15 volt/ µm): many layers with thickness 15 µm and density 1.1-1.2 and high purity.

Specification for kraft paper

Property	Unit	Min	Nominal	Max
Weight	g/m^2	41	45	47
Thickness	µm	57	60	63
Density	Kg/dm^3		750	
Humidity	%	4	5	6
Tensil resistance, longitudinal	KN/m	5		
Tensil resistance, traversal	KN/m		1.8	
Elongation, longitudinal	%		2.2	
Elongation, traversal	%		4.5	
Burst resistance	KPa	200		
Ashes	%			0.7
pH of water extraction		7.5	8.3	9.0
Conductivity of water extraction	mS/m			4.5
BDV	KV/mm	8		
DP		1200		1400

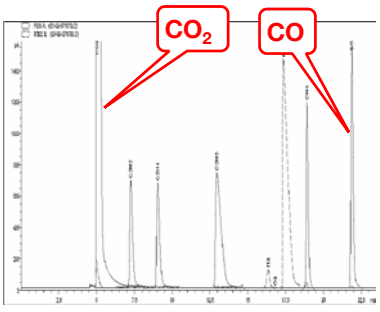
Cellulose decomposition

The rate of production of water, CO_2 and CO increases exponentially with the temperature, and until 130°C the molar ratio is 40/10/1 (until 130°C).

$$Q_{(mg/g\cdot ora)} = 5{,}4\cdot 10^{13}\cdot e^{-\frac{15300}{T}}\cdot t_{(ore)} \quad H_2O$$

$$Q_{(\mu l/g\cdot ora)} = 20\cdot 10^{15}\cdot e^{-\frac{15300}{T}}\cdot t_{(ore)} \quad CO_2$$

$$Q_{(\mu l/g\cdot ora)} = 3\cdot 10^{15}\cdot e^{-\frac{15300}{T}}\cdot t_{(ore)} \quad CO$$



Electrical Insulation

LIQUID INSULATION

In 1887 first use of oil for transformer insulation by Westinghouse, as alternative to air and bitumen impregnated paper

Insulating fluids serve 3 main function:

- To remove the heat generated by load and no-load losses
- To insulate electrically, also in combination with solid materials
- To lubricate moving parts

Ideal performances of insulating liquids:

- High BDV
- Low DDF
- Good permittivity
- Arcing quenching power
- Electrical and chemical stability
- High specific heat and thermal conductivity
- Low viscosity
- Good performance at low temperature
- Low vapor tension
- Compatibility with others materials (Metals, varnishes, gaskets, paper, etc.)
- Non-toxicity, environmental friendly, low flammability
- Easy to use and to reclaim
- Easy to dispose
- LOW COST and EASY FINDING

Fluids

Type	Application	Performance
Mineral oil	All	All
Aromatics hydrocarbons	Cables, capacitances, bushings	Electrical stability Low DDF
Silicons	Transformers, capacitances	Low flammability Electrical and chemical stability
Vegetable and synthetic esters	Trasformers	Low flammability, eco-friendly, good permittivity
PCB (now banishes)	Transformers, capacitances	Low flammability, good permittivity
Perfluoroethers	Transformers	Low flammability, high BDV also as vapor.

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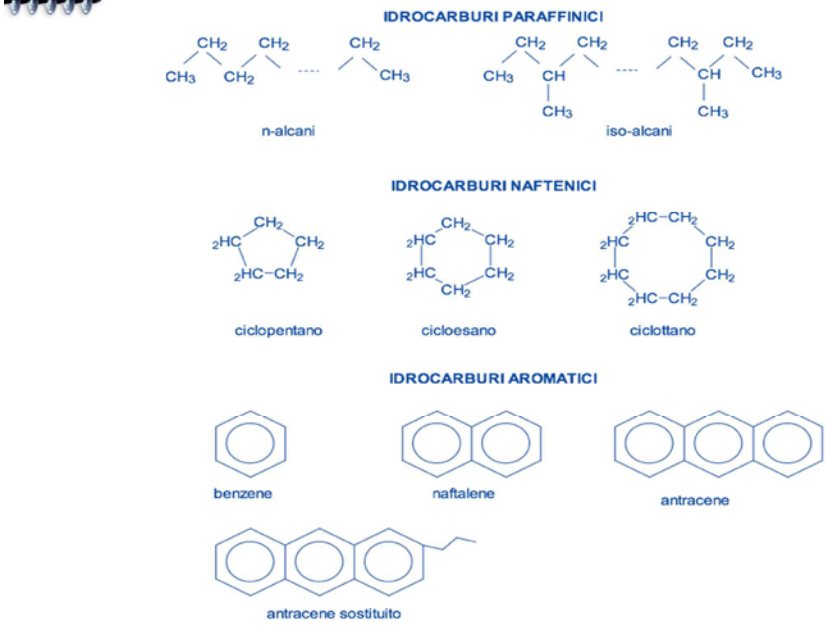

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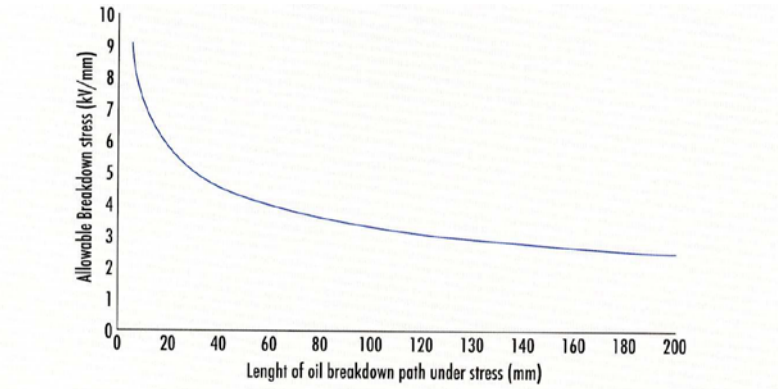
IEC 60296

Property	TR	Swithgears
1- Function		
Viscosity at 40°C	< 12	< 3,5
Viscosity at-30°C	< 1800	
Viscosity at -40°C		< 400
Pour Point (°C)	< -40	< -60
H_2O (ppm)	< 30	< 40
BDV (KV)	< 30	< 70
Density at 20°C	< 0895	
DDF 90°C	< 0,005	
2-Safety		
Flash-point (°C)	< 135	< 100
PCB (ppm)	< 2	
PCA (%)	< 3	

Property	TR	Switchgears
3-Stability		
Appearance	clear	
Acidity (mg/Kg)	< 0,01	
IFT	- - -	
Corrosive and potentially corrosive sulfur	non corrosive	
Antioxidants additives	U uninhibited T trace I inhibited	
2-FAL (ppm)	< 0,1	
4-Performance		
Oxidation stability - acidity	< 1,2	
Oxidation stability -sludge	< 0,8	
Gassing	- - -	

BDV (mineral oil) and gap



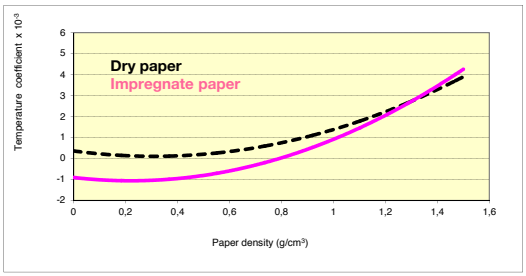
Electrical Insulation

Even if not included in IEC 60296 some others performances are requested

Performance	Unit	Typical
Thermal volumetric expansion		$6 – 8 \cdot 10^{-4}$
Vapor tension @ 80°C	Torr	< 1
Specific heat	KJ/Kg °K	1.6 – 1.8
Thermal conductivity	W/m °K	0.14

COMBINED INSULATION

The liquid insulation is used coupled with solid insulation in order to fill the cellulose's fiber inter-spaces. This avoids the presence of air and moisture for improving the dielectric behavior.

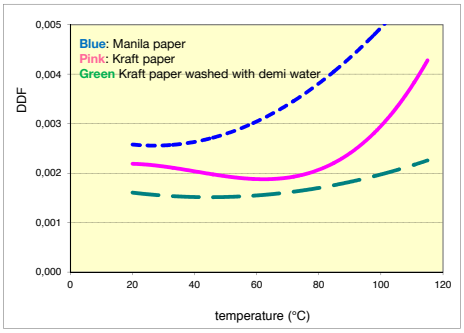


Temperature coefficient of dry paper is positive
Temperature coefficient of insulating liquids is always negative
Coupling paper with density=0,72 and mineral oil the temperature coefficient is null. So capacitance is constant even when temperature changes.

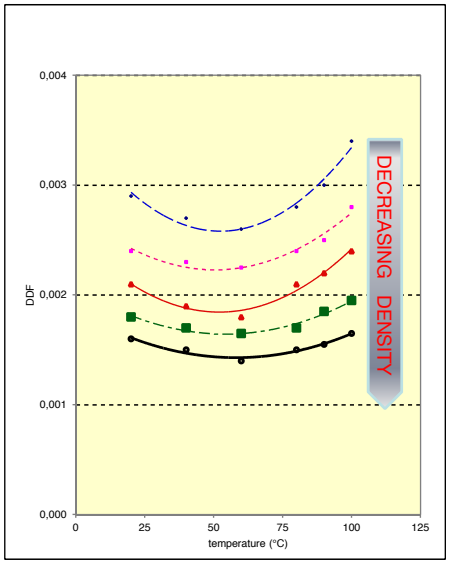
Electrical Insulation

Dielectric losses (tan δ) are due to:

- Dipolar polarization (–OH), acts at low T
- Ionic conductivity (others ions), acts at high T



Depending by type of paper and temperature (min in range 50-80°C)



Dielectric losses of paper-oil are function of paper's apparent density. Low density paper has reduced dielectric losses than high density paper, since impregnating liquid exhibits always low dielectric losses.

On the contrary BDV is better for high density paper.

So a compromise must be found between the risk of thermal runaway and the risk of electric breakdown.

Thanks for attention

fabio.scatiggio@terna.it