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Power Transformer Winding Insulation
: A Review of Material characteristics

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ABSTRACT
Transformers are one of the most important and cost-intensive components of electrical energy supply networks, thus it is of special interest to prolong their life duration while reducing their maintenance expenditures. The oil-paper insulation in power transformers is subjected to various stresses due to environmental conditions, voltage and fault stresses. Such stresses can cause deterioration of the oil-paper insulation in transformers. The condition of oil can be reversed back to some extent with the help of present technology such as on-line oil filtration by removing water and volatiles but not the acidic products of degradation. The degradation of paper insulation, however, is irreversible. Thus, the life of a transformer can be effectively determined by the life of its paper insulation. When paper degrades, it produces several by-products such as CO, CO2, and Furans and they migrate to the oil. There has been a growing trend throughout the world to study and estimate the deterioration of insulation strength of paper using such by-products as indicators. There are more direct approaches of degradation such as Tensile Strength (TS) and Degree of Polymerization (DP) measurements of paper. But these approaches require shutdown on the transformer and are considered intrusive.
It is felt that there is a need to review the insulation used in power transformer in terms of physical structure and degradation and various structural evaluation techniques available. This is being done to look for alternative materials which can substitute this natural material in terms of porosity, heat transfer, insulation and stability.

KEYWORDS
Transformer ageing, Oil Paper Insulation, moisture and ageing, paper insulation, aging, dielectric liquids, dielectric materials, insulation, insulation life.

INTRODUCTION
The most commonly used insulating materials in transformers are paper and mineral oil. Basically, apart from providing overall insulation to the transformer, the Mineral oil acts as coolant to the transformers, assisting in extinguishing arcs, and dissolves gases and moisture produced arising out of various phenomena within the transformer [1]. Whereas paper, it provides insulation to the conductor in the transformer windings. Presence of H_2O (water or moisture) in paper insulation has been linked to the decomposition of the paper fibers that is irreversible and eventually causes the paper to lose its mechanical and dielectric strength [2,3]. As for O_2 (oxygen), its presence causes oxidation on the mineral oil that leads to the deterioration on the oil insulation quality and the formation of acids. With acids present in the mineral oil, paper insulation is again exposed to deterioration and eventually ageing [3]. Ageing of paper insulation has been directly linked to its mechanical strength [2,4]. Studies have been done focusing on how long the paper can retain its mechanical strength as it ages before it loses its dielectric strength. Studies have also been done to estimate the life of transformers by studying the life of the paper insulation [4,5].

Cellulose Introduction: Cellulose is the most abundant biopolymer on Earth. About 33% of all plant matter is cellulose. Beta glucose is the monomer unit in cellulose. As a result of the bond angles in the beta acetal linkage, cellulose is a linear chain. Hydrogen bonding between the chains makes cellulose stiff and strong. There are different forms of cellulose. Porous cellulose fibers, Non-porous nano-crystalline cellulose particles, Regenerated cellulose films, Bacterial cellulose. Cellulose fibers are usually porous. This is refined cellulose with the amorphous region and impurities removed. The crystalline regions are several μm long and a few nm wide. Because of their high aspect ratio they can be regarded as nano-whiskers. These nano-crystals are further isolated in the form of independent particles. Cellulose nano-particles can be used as reinforcing phase

in thermoplastics and as novel paints because they can form liquid crystalline phases .

Regenerated cellulose film: Cellulose fibers are dissolved in alkali and carbon disulfide to make a solution called viscose, is then extruded through a slit into an acid bath to reconvert the viscose into regenerated cellulose film called cellophane. A similar process, using a hole (a spinneret) instead of a slit, is used to make a fiber called rayon.

Bacterial cellulose: It is also called microbial cellulose, a form of cellulose that is produced by bacteria. Bacteria from the genera Aerobacter, Acetobacter, Achromobacter, Agrobacterium, etc. synthesize cellulose. Only the Acetobacter xylinum produce enough cellulose to justify commercial interest.Acetobacter xylinum is reclassified as Gluconacetobacter xylinus (Yamada et al., 1997).

Bacterial cellulose has advantages over plant cellulose: Finer structure, Longer fiber length and much stronger, No hemicellulose or lignin need to be removed. But bacterial cellulose is about 100 times more expensive than plant cellulose. It is difficult to achieve large scale production capacity.

Cellulose Topology: Topology of polymers refers to the surface texture of polymers (J. Gooch, Encyclopedic Dictionary of Polymers, Springer,2007).The term surface texture designates the entirety of departures from the ideally smooth surface, inclusive of occasional flaws or other types of locally limited irregularities(M. Curtis, Dimensional Measurement, Indus. Press, 2007). Most surfaces are not smooth at atomic scale. A useful descriptor is the specific surface area (m2/g).Powders have a high specific surface area (10 to 500 m2/g). Surface texture means digression from the ideal smooth surface. It includes Topographical deviations generally associated with more of less regular waveforms, or waviness. On waveforms are the closely spaced random irregularities, called roughness, Waviness and roughness appear superimposed.
Maximum height of the profile (Rt) = Maximum peak height(Rp) -Maximum valley depth (Rv)

Techniques for examining cellulose surface topology: Surface profilometers are used to measures surface profiles, roughness, waviness and other finish parameters. Two basic surface profilometer technologies are used.Non-contact,Measure the surface texture by optically scanning a surface with a light or laser. Non-contact optical interferometer, is the technique of diagnosing the properties of two or more waves by studying the pattern of interference created by their superposition.

Linnik interferometer: A Linnik interferometer is a two-beam interferometer used in microscopy and surface contour measurements or topography.

Techniques for examining cellulose surface topology: Contact, Atomic Force Microscopy (AFM), also known as Scanning Force Microscopy (SFM), measures the height of surface features by touching the surface with an extremely sharp probe. Contact or stylus based surface profilometers use the technique to measure the surface topology.

AFM: The AFM consists of a micro-scale cantilever with a sharp tip (probe) at its end that is used to scan the specimen surface. The cantilever is typically silicon or silicon nitride with a tip with a radius of curvature on the order of nanometers. The probe is placed at the end of a cantilever with known mechanical properties. The instrument is also capable of imaging the surface while tapping the surface to minimize tip wear and sample damage. Another imaging technique involves hovering the tip above the surface. Hovering the probe tip very close to the sample causes atoms at the tip to interact with the atoms on the surface, and these interactions can deflect the cantilever. Measuring these interaction resulting tip deflection allows image analysis without ever touching the surface.

Advantages of AFM over the scanning electron microscope (SEM): AFM provides a true three-dimensional surface profile, Samples viewed by AFM do not require any special treatments (such as metal/carbon coatings) that would irreversibly change or damage the sample, SEM needs an expensive vacuum environment for proper operation, while most AFM modes can work perfectly well in ambient air or even a liquid environment, AFM can provide higher resolution. It has been shown to give true atomic resolution. Lateral resolution: 15-50 nm . Vertical resolution: 0.1 nm.

AFM Disadvantages: The SEM can image an area on the order of millimetres by millimetres with a depth of field on the order of millimeters, can only image a maximum height on the order of micrometres and a maximum scanning area of around 150 by 150 micrometres, An incorrect choice of tip for the required resolution can lead to image artifacts, Signals may require software enhancement and filtering. Such filtering could "flatten" out real topographical features.

Cellulose Porosity: Porosity refers to the ratio of the volume of voids contains within a sample of material to

the total volume, solid matter plus voids, expressed as a fraction, void fraction or percentage of voids according to Encyclopedic Dictionary of Polymers (J. Gooch, Springer,2007) Porosity(%)= (1-TrueVolume/BulkVolume)*100%

• Note that the pores collapse irreversibly when cellulose sample dries.

Techniques for examining cellulose porosity:

Mercury Porosimeter Principle:

In the porosimeter, mercury is forced into solid material. The pressure required to fill the pores completely is inversely proportional to the size of the pores

.D= -(1/P)4γ cosθ

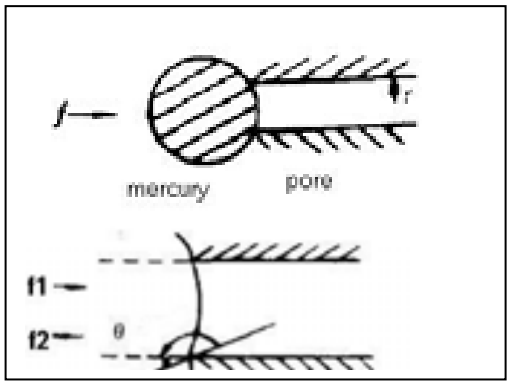
D- pore diameter P- applied pressure

γ -the surface tension θ -the contact angle

– The previous equation comes from capillary rise equation: P= -2γ cosθ/r

P-applied pressure r -radius of smallest capillary

γ- surface tension= 484 mN/m;θ-contact angle= 140deg



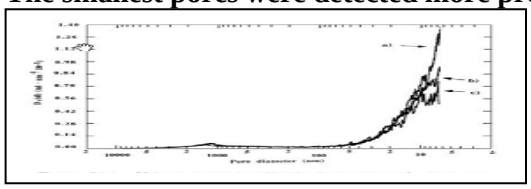
force in: f1=πr2P force out: f'= 2πr γ, f2=-2πrγ cos(180-θ) = -2πrγ cos θ

f1=f2

πr2P= - 2πr γ cos θ

P= -2γ cosθ/r

The smallest pores were detected more precisely:



Effect of scanning speed on porosimetry accuracy: The phenomenon is in agreement with Moscou and Lub's assumption* that there is no time for mercury to intrude into the sample and cover the inner surface when fast scanning speeds are used in the measurement.

Latest development in mercury intrusion porosimetry technique:

1. Poremaster series prosimeter from Quantachrome
2. Traditionally, N2 absorption method is used for pore size < 10 nm.
3. Now, Pore size ranges from about 900 μm to less than 3.5 nm in the 60,000 psi units can be detected.

Limitations: The material must not react with mercury, The porosimeter measures only those pores which open to the outside surface, The values of large openings within the sample, connected to the surface by narrow pores will be indicated as diameters of narrow pores, The limit of pore measurement is 0.003 to 360 micrometers. A maximum pressure of 60,000 is available.

Size exclusion chromatography:

SEC principle: A molecule is more or less able to enter the pores of a porous material depending on the molecule's size. When a column is packed with a porous material and an eluent is forced through, injected molecules that are too large to enter the pores will be eluted in the 'void volume' of the column. Tiny tracer molecules penetrate into almost all the pores of the material. Ve= Vo+ KVp

Ve- elution volume of the tracer, Vo- void volume of the column,K- distribution coefficient of the tracer, decided by the size and shape of the tracer and the size distribution and shape of the pores, Vp- total volume of the pores in the column

SEC conditions:

In order to characterize a porous structure reliably, these conditions should satisfied no adsorption interaction btw tracer molecules and porous material, distribution function.

$$f_p(R_p) = (1/V_p)\{dV/dR_p\}$$

where V is the volume of pores with a radius between R_p and $R_p + d R_p$

and V_p is the total pore volume of the membrane

Nuclear magnetic resonance (NMR):

NMR porosity:

The amplitude of a proton NMR measurement is directly proportional to the amount of hydrogen in the material investigated. The transverse relaxation time T2 is short in solids, of the order of 10 μs. The signal from those protons can be eliminated from the measurement by ignoring very fast component of the signal. The relaxation times of protons in pore fluids are greater than 1 ms. These protons are visible in the signal. The

relaxation times of water trapped in very small pores have intermediate values. By collecting these signal, the porosity and pore distribution can be determined:

- The H spin-spin(T2) relaxation profiles can be translated to pore size by the relationship btw T2 and surface-to volume (S/V) ratio of the pore.
  1/T2= ρ(S/V)
  ρ- surface reflexivity

NMR advantages:. Mercury Intrusion and Size Exclusion Chromatography technique may damage the delicate pore structure, means of non-destructive testing, without affecting the material structure. Mercury Intrusion and Size Exclusion Chromatography technique can test only the pores that are open to the outside surface. It can penetrate into the inner structure of the material, including the pores that are not exposed to the outside surface.

Cellulose: Electrical Properties:

Structure of Cellulose is β(1→4) linked D- glucose units. It is Crystalline and straight-chained .Cellulose is made of interwoven fibres. Mainly obtained from wood pulp and cotton. Cellulose being a natural material will have polar contaminants like lignin and other phenolics within the cellulose matrix. Further it has tendency to absorb moisture and is naturally degradable because of the weak glycosidic linkages. In order to minimize the contaminants the paper has been specially selected and impregnated to get the electrical grade papers for use in power transformer insulation applications.

Conductivity: It does not conduct as dry entity, used as an insulator, used as scaffolding for conductible materials.

Potentiometric Titration: It can be used to find the number of acid groups in a solution, used to find the dissociation constants of acidic groups. NaOH is added to acid solution, with a pH graph being created from the potential measurements. Concentrations are calculated as follows:

- **$[H^+]$ = (Vekv –Vt)COH / (Vo + Vt)**
- **$[OH^-]$ = - $[H^+]$**

Influence of Porosity in the Surface of cellulose has believed to have pores, allows for ions to flow in and out of cellulose substructure and also allows for more surface area that can be accessed for reactions. Overall effect of pores is minimal compared to surface potential. Because of Influence of Water/Drying, Conductivity increases with water content. Drying of cellulose fibers can lead to closure of pores.

Charge Density: It is nothing but Amount of electric charge on the surface area of cellulose, is very important regarding stability of colloid. It gives insight into interactions with other colloids in solution. Charge Density of Cellulose which decreases with acid groups on the cellulose surface. Raw cotton has a surface charge of 18.5mmol/kg. Regenerate Fibers have 4.7 mmol/kg,

Electrophoretic Mobility: It is the Proportionality between particle speed and electric field strength. Ions in solution can be moved with the application of an electric field. It can be calculated with various methods, namely electrophoresis. Mobility = Particle Velocity / Electric Field Strength.

Zeta Potential: Zeta potential is the potential difference between the dispersed medium and the stationary layer of fluid attached to the particle. There is a Correlation between zeta potential and mobility. It is used to describe the stability of a colloid.1.from 0 to ±5,Rapid coagulation or flocculation,2.from ±10 to ±30 Incipient instability,3. from ±30 to ±40Moderate stability,4.from ±40 to ±60Good stability,5.more than ±61Excellent stability

Zeta Potential Measurement Methods: Electrophoresis is Used for particulates (colloids). Laser Doppler Velocimetry is Used for particulates (colloids). It Uses laser refraction to measure mobility. Streaming Current is Used for flat surfaces and porous objects (films, membranes, fibers).Steaming Current Measurements measures the movement of charge between nodes. It is the measurement of mobility.

$$\zeta = \frac{\eta\{\lambda_0 + 2\lambda s\}\Delta E}{\varepsilon_r \varepsilon_0 \quad \Delta P}$$

Steaming potential high impedance

Smoluchowski Equation is the relation between mobility and zeta potential.

λ 0 -specific conductivity of solution

λ s=-specific conductivity of solution

r-capillary radius

l= capillary length

$$\mu = \varepsilon \zeta / \eta$$

remember $\varepsilon = \varepsilon_r \varepsilon_0$

Henry Equation with Ohshima is To account for double layer as well as inner electrokinetics. It is Used for materials that are not solid.

$$\mu_e = \frac{2 \varepsilon_v \varepsilon_0 \zeta f(ka)}{3 \eta}$$

$$f(ka) = 1 + \frac{1}{2\{1+\frac{2.5(1+\exp(-ka))}{Ka}\}^3}$$

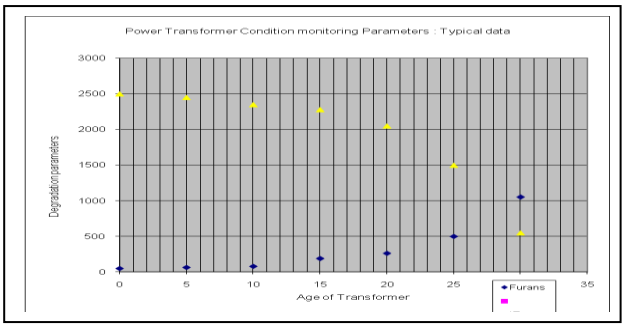


Figure.2 Graph of Degradation v/s Age of transformer

Zeta Potential of Cellulose is of Low negative values and -10 to -20 mV in water is as shown in figure 1.

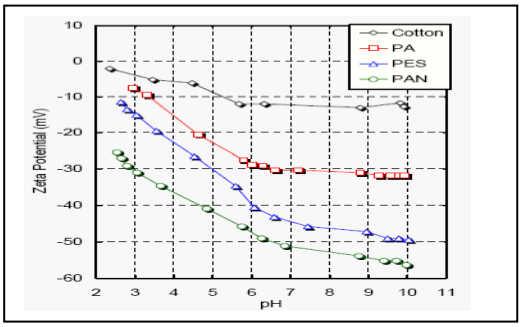


Figure 1. Zeta Potential of Cellulose

Power Transformer Condition Monitoring Parameters: Typical data

Transformer Age (Yrs)	Total Furan Content	Moisture content	Insulation Resistance Ohms	Moisture in solid insulation	Moisture in winding (Estimated)	Ambient temperature summer average	Average Load %
0	50	8	2500	--	0.05	39	60
2	65	12	1800	--	0.09	39	74
4	80	17	1745	--	1.02	40	76
6	190	19	1609	--	1.17	40	75
8	263	21	1589	--	1.61	39	75
10	500	26	1400	--	1.9	39	75
12	1053	26	1350	2.2	2.2	39	75

Figure 3. typical data of Power Transformer Condition monitoring Parameters

Transformer Age in no. of years	Furan Content	Insulation Resistance Ohms		
Age	Furans	IR	Moisture	Age
0	50	2500	0.05	0
5	65	2450	0.09	5
10	80	2350	1.02	10
15	190	2280	1.17	15
20	263	2050	1.61	20
25	500	1500	1.9	25
30	1053	550	2.2	30

Figure 4. typical data of Power Transformer Condition monitoring Parameters Age in no. of years, Furan Content, Insulation Resistance, Moisture, Age

Role of Double Layer is Zeta potential decreases with salt concentration and increases with double layer.

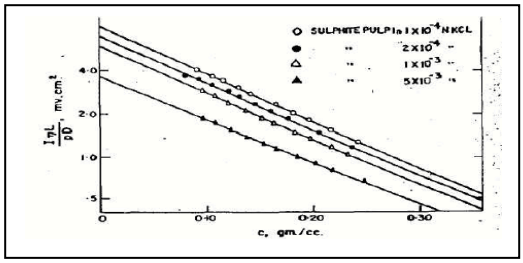
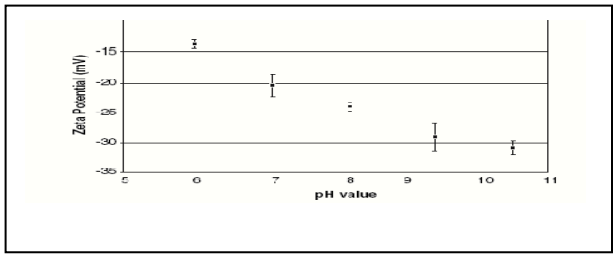


Figure 5. Zeta potential

Creating Stable Cellulose, Modification of cellulose is needed to create a larger zeta potential. Such mixtures include: Polyvinyl amine + CMC, Polyacrylonitrile + cellulose acetate, Acid treated cellulose. Cellulose Research Requiring Zeta Potential: Drug Delivery, Paper Processing, Textile Finishing, Nanocomposites



Three most common degradation factors of cellulose have been identified as thermal, oxidative, hydrolytic[3].Thermal Degradation[3],Oxidative Degradation[9],Hydrolytic Degradation[3], Degradation By-Products[3] ,Using the by-products as indicators to paper insulation condition [3,7],CO and CO2 [1],Furans [5] ,Non-Linear Relationship between Age and Degradation By-Products Concentration.

Weightages of the Degradation by-products : Typical degradation pattern on a 20 MVA trans former :It has been widely accepted that degradation is depending up the following aspects.

1. Loading of transformer : higher the load higher will be the electrical stresses and accompanied thermal stresses
2. Operating temperatures: It has been widely accepted that every 10^{o}C rise in temperature will almost double the rate of degradation. Hence, effective use of cooling accessories and maintaining the operating temperature will always of help in controlling the degradation rates.
3. Water levels in the oil and in the paper insulation has been found to be a critical factor in deciding the degradation rates.

Present demands on insulation: Our country is planning to go for 400 kV and 800 HV AC and DC transmissions. The power equipments needed will demand for good insulation will be far higher. This coupled with high ambient in the country it is felt that there is a need for looking alternative materials which can substitute cellulosic insulation.

Porous polymer preparation / Monoliths :

Porous polymers have been used in the area of chromatography wherein nano porous polymers can be prepared and used for separation of similar chemicals.
Monolithic separation media, made in one piece, contain only flow-through pores, which significantly augment the mass transfer based on convection. This enables use of high mobile phase velocities along with low back pressures and therefore fast separations without decrease of resolution. Glycidyl methacrylate stearylmethacryate-ethylenedimethacrylate and styrene-divinylbenzene monoliths have been parepared and have been characterized. Such materials can be investigated in place of cellulose insulation.

CONCLUSION

Degradation of cellulosic insulation depends up on loading, operating temperatures, water level in oil and in insulation.
Skilful maintenance of insulation under dry conditions will help preserving the insulation in dry conditions.
It has been widely accepted factors like operating temperature, moisture in winding and loading patters will have important weightages in degradation of insulation.

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