Evaluation of Transformer Solid Insulation

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Abstract

Liquid impregnated cellulose materials in the form of Insulation paper are used in power transformers as electrical insulation and as mechanical support for the windings and leads. The mechanical strength of these materials will reduce over time the thermal performances of these materials are of interest both for assuring a high quality of new units, and also for estimating remaining life for asset management.

Managing an ageing transformer population requires decisions regarding life extension activities, e.g., Transformer condition control, reclamation and drying, and life assessment for reinvestment. Knowledge of transformer ageing can either be based on diagnostic monitoring and ageing markers or by modelling of ageing kinetics.

Direct Evaluation

The mechanical properties of insulating paper can be established by direct measurement of its tensile strength or degree of polymerization (DP). These properties are used to evaluate the end of reliable life of paper insulation. It is generally suggested that DP values of 150-250 represent the lower limits for end-of-life criteria for paper insulation; for values below 150, the paper is without mechanical strength. Direct measurement of these properties is not practical for in-service transformers

Analysis of paper insulation for its DP value requires removal of a few strips of paper from suspect sites. This procedure can conveniently be carried out during transformer repairs. The results of these tests will be a deciding factor in rebuilding or scrapping a transformer.

Note: Since it is usually not practical (and often dangerous to the transformer) to obtain a paper sample from a de-energised, in-service transformer an alternative method has been found.

Furan Analysis

When a cellulose molecule de-polymerises (breaks into smaller lengths or ring structures), a chemical compound known as a furan is formed.

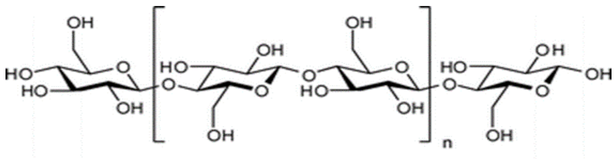


Figure 1: Cellulose molecule consisting of a chain of saccharide rings.

By measuring the quantity and types of furans present in a transformer oil sample, the paper insulation overall DP can be inferred with a high degree of confidence. The types and concentration of furans in an oil sample can also indicate abnormal stress in a transformer, whether intense, short duration overheating or prolonged, general overheating. Furan analysis can be used to confirm Dissolved Gas Analysis where carbon monoxide present indicates problems with solid insulation.

Table 1

5-Hydroxymethyl-2-furaldehyde	5H2F	Oxidation
Furfuryl alcohol	2FOL	High Moisture
2-Furaldehyde	2FAL	Overheating, old faults
2-Furyl methyl ketone	2ACF	Rare, lighting
5-Methyl-2-furaldehyde	5M2F	Local, severe overheating

It has been shown that the amount of 2-furaldehyde in oil (usually the most prominent component of paper decomposition) is directly related to the DP of the paper inside the transformer.

Paper in a transformer does not age uniformly and variations are expected with temperature, moisture distribution, oxygen levels and other operating conditions. The levels of 2-furaldehyde in oil relate to the average deterioration of the insulating paper. Consequently, the extent of paper deterioration resulting from a "hot spot" will be greater than indicated by levels of 2-furaldehyde in the oil.

For typical power transformer, with an oil to paper ratio of 20:1, the 2-furaldehyde levels have the following significance:

Table 2

Furan Content (ppm)	DP Value	Significance
0-0.1	1200-700	Healthy transformer
0.1-1.0	700-450	Moderate deterioration
1-10	450-250	Extensive deterioration
>10	<250	End of life criteria

Furan measurements have gained popularity in the past 20 years because they offer measurements of specific chemical compounds such as 2-FAL, which can be directly correlated with the aging of the transformer's paper insulation. Several equations describing a degree of polymerization (DP) as a function of log10 (2-FAL) for kraft paper have been developed, and it is shown that accurate DP estimation is not always possible. It is advisable not to apply any furan-DP correlation without proper analysis directly. Additionally, certain actions may affect the furan concentration in the oil, such as oil reclamation and oil treatment, among others.

Comparing Various Models in Predicting DP from 2FAL

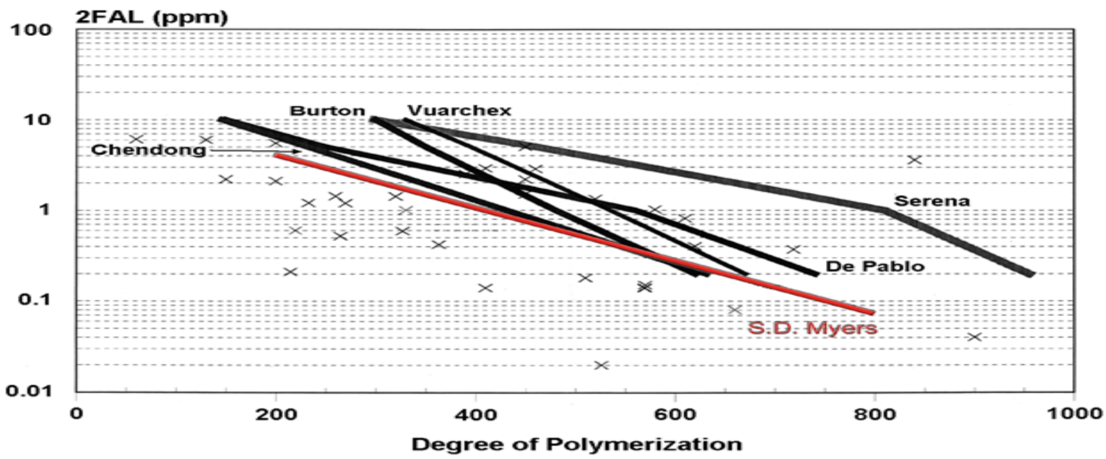


Table Comparing furan-DP models [Courtesy of SD Myers]

Ageing Rates of Insulation paper

There are three main processes of degradation: Hydrolysis–Oxidation–Pyrolysis

In a real transformer all these processes – hydrolysis, oxidation and pyrolysis act simultaneously, resulting in a non-linear Arrhenius plot

Temperature(Pyrolysis)

Ageing rates increase with operating temperature. The ageing of cellulose can be described by the equation:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = A \cdot e^{\frac{-E_A}{RT}} \cdot t \quad \rightarrow \quad \frac{1}{DP_0}\left(\frac{DP_0}{DP_t} - 1\right) = A \cdot e^{\frac{-E_A}{RT}} \cdot t$$

This equation describes how the DP-value decreases from the start value (DP0) to a value DPt after a time t by a so-called Arrhenius relation.

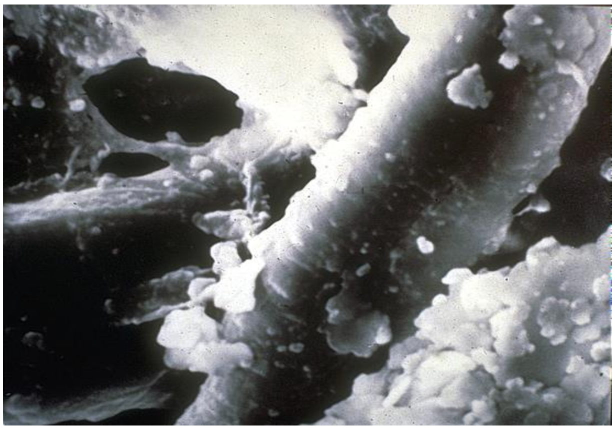
Oxidation

In a similar way to hydrolysis, oxygen is a highly reactive element which causes the breakage of cellulose bonds to form by-products such as water, carbon monoxide and carbon dioxide.

These three mechanisms, oxidation, hydrolysis and pyrolysis normally do not act in isolation but rather as a group of reactions that reinforce each other.

Acids (Oxidation by Products)

Various organic acidic compounds are also released as by-products of Oxidation. These acids in turn also attack the cellulose. In particular, the degradation of insulation due to acidic reactions has the consequence of producing sludge. As this sludge is produced, it could be deposited in areas critical for the cooling processes of the coils, such as cooling ducts, that would block the free circulation of oil, which in turn increases the temperature and accelerates the whole ageing cycle once again. As we can see, there are a variety of mechanisms that cause degradation of the insulation system which effectively “ages” the transformer.



Electron Microscope picture of paper aged in oil (Acid value 0.15 mg/Kg)
Courtesy of SD Myers

Water (Hydrolysis)

The presence of water will increase the rate of cellulose degradation. At the beginning of a transformer’s life, the kraft insulation contains less than 0.5 % water, and the mineral oil is also dried. The water content levels within the transformer (in the paper insulation) may increase up to 5 % during its lifetime.
The rate of degradation of the paper starting from an initial water content value of 4 % was 20 times greater than that at 0.5 %. So, in principle as the transformer ages the rate at which the insulation deteriorates is expected to increase.

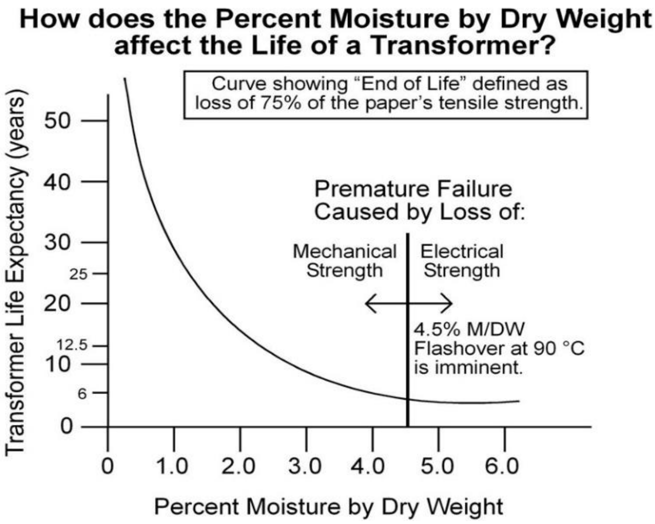


Figure: showing the influence of (Hydrolysis) water in oil on ageing of Kraft paper
Courtesy of SD Myers

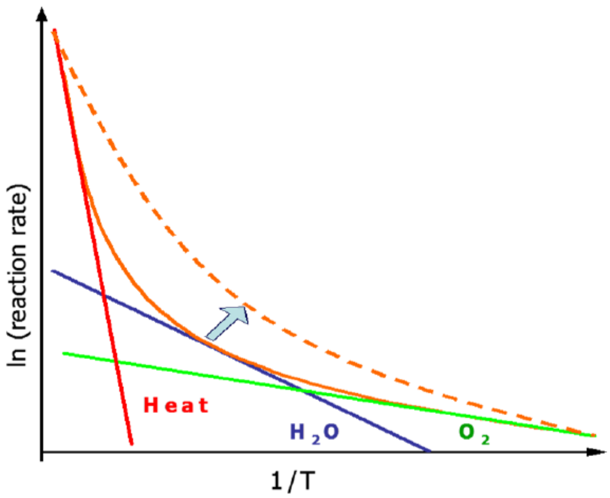


Figure: Sketch of ageing rates due to different ageing mechanisms documented in mineral oil. The arrow shows the effect of increased water content increasing the A-factor for Hydrolysis
Cigre Document 738

PAPER AGEING AND TRANSFORMER RISK ASSESSMENT

The “predicted” DP (degree of polymerisation) indicates an average paper condition over the whole transformer (subject to factors such as effective circulation). New Kraft paper has a DP in excess of 1200, and paper with a DP of 200 or less is considered to be unfit (subject to interpretation).
The values can be optimistic if the oil has been regenerated within the last two years.

This data should be valuated in conjunction with routine chemical analysis and transformer history.

The reduced strength of paper that results from abnormal ageing may be a direct or indirect cause of a failure. An understanding of the progression of cellulose ageing and the risks associated enables the Asset Manager to make an informative decision to the condition in a real transformer, the real situation is always more complex: temperature and water content varies along the winding, there are several different qualities of paper (e.g., thermally upgraded or normal Kraft paper), and the paper is present in many layers with temperature and water content gradients.

Also, cellulosic materials like pressboard and wood are used. Simple formulas may give insight in ageing mechanisms but are never sufficient for assessing the condition of a whole winding. Even so it is still believed that one should base the analysis on the weakest link, which will be the condition around the hotspot region in the transformer.

Ageing will be most pronounced in this region within the top end of the winding, and electro-mechanical forces will be strongest here. If the tensile strength in this region is insufficient to withstand these forces, this will be the most likely place for a failure to occur.

Furthermore, even if there was an agreed end-of-life criterion for the strength of the paper or the degree of polymerization of the cellulose, there remains the question of how large are the stresses? The risk of a failure is different for transformers operating in different circumstances. Lower, for those operating in grids where the transformer rarely experiences a short circuit or where the short-circuit currents are lower than what the transformer is designed for. Higher, for those exposed to frequent and high short circuit stresses from e.g. line to ground failures on power lines due to lightning, or when moved from one place to another.

Finally, in asset management an engineer will not only consider failure probability, but also on the consequence of that failure to get a more complete picture of the risk involved with a certain specific transformer or a larger fleet of transformers.

Other Diagnostic Compounds

The presence of phenols and cresols in concentrations greater than 1 ppm indicate that solid components containing phenolic resin (laminates, spacers, etc.) are involved in overheating.

Methanol (MeOH) and ethanol (EtOH).

It has been demonstrated over several years that the ageing of impregnated paper in insulating liquid, which results in cellulose degradation, produces molecules of light alcohols, methanol (MeOH) and ethanol (EtOH).
In laboratory experiments, a good correlation has been established between the increase of the methanol content in insulating liquid and the decrease of the degree of polymerisation of the cellulose, irrespective of the type of paper, standard Kraft or thermally upgraded. Further, at the early stages of paper ageing, i.e., of cellulose degradation, the methanol content is always higher than that of furanic compounds (mainly 2-furfural), so this behaviour suggests that methanol could be a relevant in-oil marker to detect early paper ageing in transformers and to assess its evolution.

CASE STUDY: INSULATION FAILURE.

OVERIEW: The transformer failed in service while undergoing Power-On purification to remove moisture from the insulating oil.

TRANSFORMER DETAILS

Primary Voltage: 11 kV	Secondary Voltage: 500V	VA Rating: 500 KVA
Vector Group: Dyn11	Impedance: 4.1%	Tap Changer: Off Load
Make: CAWSE & MALCOLM	Year Manufactured: ?	Conservator: No
Breather Size: CHG2	Oil Volume Litres: 600	

Transformer Oil Analysis-Diagnosis

The Dissolved Gas analysis indicated a Partial discharge of low energy density (IEC 599) with the C02/C0 Ratio of 16. 5 indicating insulation paper degradation. (>3 and <11) Normal Ratio.

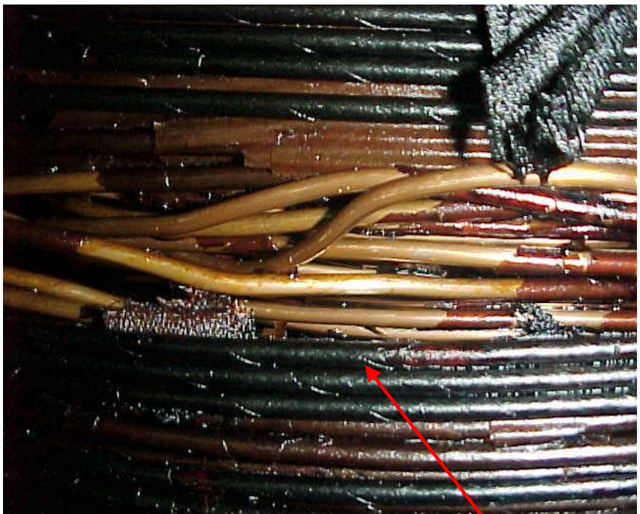
The Furan analysis of 8.97 ppm indicated Extensive paper deterioration. (Optimistic value as the oil purification process removes Furans compounds).

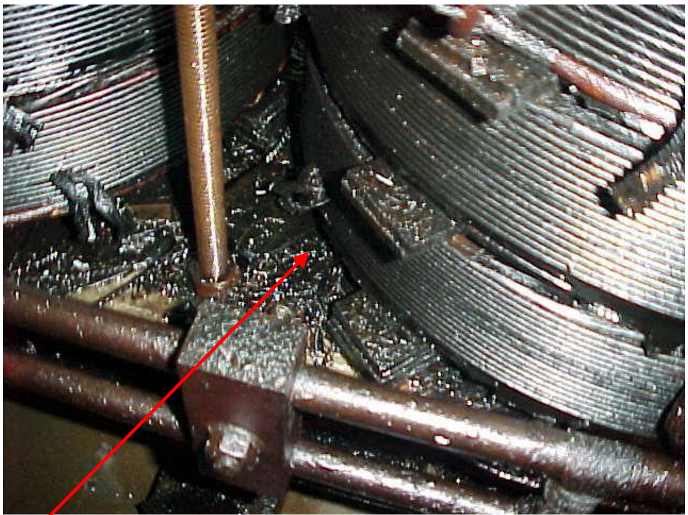
The maintenance history of the transformer revealed that oil replacement and purification took place on 12-03-2000. The Furan production rate was 160 ppb (parts per billion) per month (ppb/month). The Morgan Schafer Company reports that a furan production rate of 25 ppb/month is cause for concern.

The transformer oil analysis indicated a case of advanced paper insulation deterioration. (See Table 3)

Findings

The transformer was removed to a works facility and inspected. The paper insulation clearly was at End of life criteria.





End of Life Criteria (Degree Of Polymersiation DP <200) : 75 % Tensile strength Loss

Risk Assessment-To Plan remedial actions:

A transformer with a low DP can continue to operate normally providing it does not experience any external events.

In a situation where the load is suddenly changed, or the transformer is subject to mechanical shock or there is a through fault on the system this transformer has a higher risk of failing.

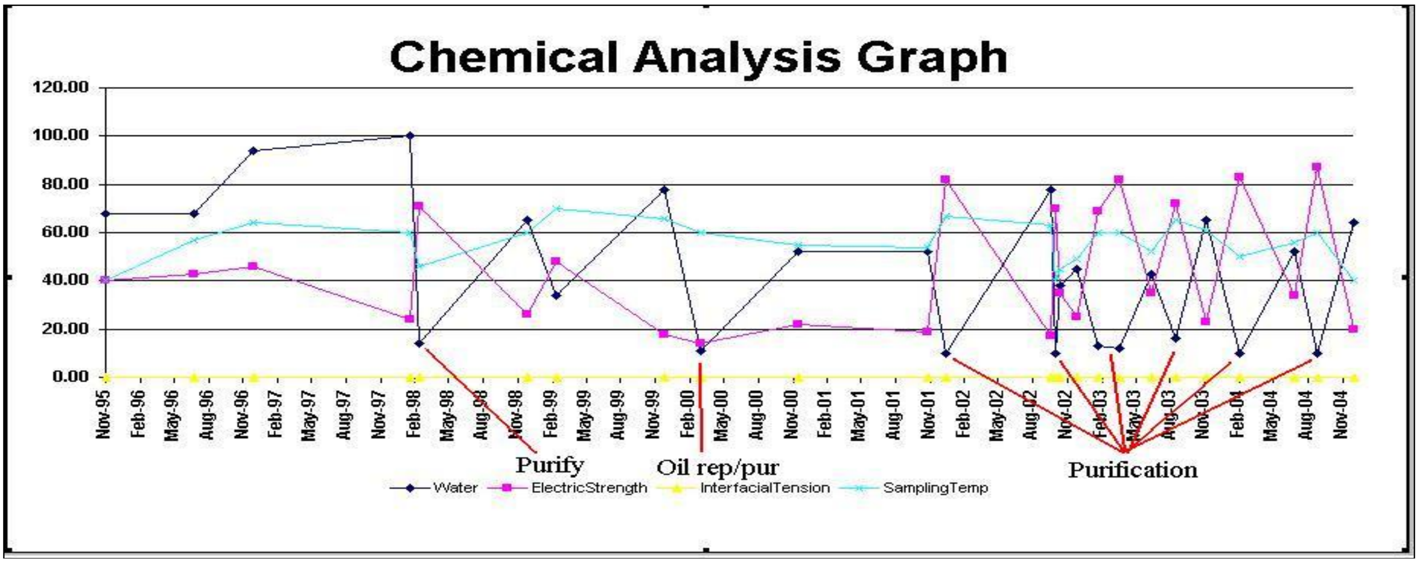
It should be noted that aggressive oil reconditioning when the mechanical strength of the paper is so low can do more harm than good.

It is strongly advised that exposure to fault risk should be managed carefully and plans for end of life developed.

Note: Oil reconditioning can remove the evidence of paper degradation but the degradation itself is irreversible.

Review of Maintenance History.

The transformer had undergone oil purification on ten occasions since 1995 in an attempt to remove moisture and improve the dielectric. With oil replacement on 12-03-2000. The oil purification had no effect in improving the oil condition.



Spreadsheet of Transformer oil analysis and Maintenance History

SampleDate	H_2	0_2	N_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2	%Gas	H_20	kV	Acidity	Temp	Furan	SampleType
13-Dec-2004	434	2340	64873	16	355	5863	15	0	0	8.63	64	20	0.10	40	8.97	
7-Sep-2004	0	0	0	0	0	0	0	0	0	0	10	87	0.09	60		Purification
9-Jul-2004	167	2500	55983	15	324	6322	0	0	0	8.01	52	34	0.09	56		
15-Feb-2004	0	0	0	0	0	0	0	0	0	0	10	83	0.09	50		Purification
19-Nov-2003	40	8547	70970	9	351	4259	17	19	0	8.38	65	23	0.09	61		
28-Aug-2003	0	0	0	0	0	0	0	0	0	0	16	72	0.07	65		Purification
23-Jun-2003	21	19370	65345	5	114	2116	0	0	0	8.53	43	35	0.07	52		
31-Mar-2003	0	0	0	0	0	0	0	0	0	0	12	82	0.08	60		Purification
3-Feb-2003	0	0	0	0	0	0	0	0	0	0	13	69	0.08	60		Purification
9-Dec-2002	120	21162	73130	7	124	2601	0	10	0	8.63	45	25	0.08	49		
23-Oct-2002	23	20525	56656	0	55	1189	0	0	0	8.01	38	35	0.09	45		
11-Oct-2002	24	5878	46760	1	63	4297	0	0	0	6.22	10	70	0.09	40		Purification
2-Oct-2002	45	9531	61661	11	237	4833	15	17	0	8.74	78	17	0.08	63		Suspect Fault
27-Dec-2001	0	0	0	0	0	0	0	0	0	0	10	82	0.07	67		Purification
6-Nov-2001	102	11165	53340	10	236	3729	11	11	0	7.03	52	19	0.07	54		
28-Nov-2000	0	24042	59971	9	207	2281	19	0	0	8.58	52	22	0.05	55		
12-Mar-2000	0	0	0	0	0	0	0	0	0	0	11	14	0.05	60		Oil rep/pur
9-Dec-1999	53	13284	59226	7	159	3754	18	19	0	8.8	78	18	0.05	66		
23-Feb-1999	0	0	0	0	0	0	0	0	0	0	34	48	0.18	70		Purification
8-Dec-1998	50	8079	69484	5	429	4872	10	0	0	8.49	65	26	0.18	60		
26-Feb-1998	0	0	0	0	0	0	0	0	0	0	14	71	0.17	46		Purification
30-Jan-1998	19	18445	68637	7	359	6250	9	0	0	10.97	100	24	0.17	60		
9-Dec-1996	58	15222	72938	17	425	9269	18	15	0	9.71	94	46	0.15	64		
4-Jul-1996	19	19031	67861	10	244	6588	5	0	0	9.5	68	43	0.13	57		
14-Nov-1995	16	4377	44646	6	351	6777	8	2	0	5.99	68	40	0.13	40		

Economic Consideration.

Accessing the state of the paper insulation is vitally important when considering a maintenance plan for a transformer. In this case a more cost-effective maintenance plan would be to remove the transformer to a works facility for Refurbishment.

The assumed average maintenance cost for this transformer was R 25 000 since 1995 with no benefits i.e., there had been no improvement in fluid insulation condition with a deterioration in solid (paper) condition.

The end result being in service failure amounting to significant Production losses.

Case Study: Predicted Insulation Failure

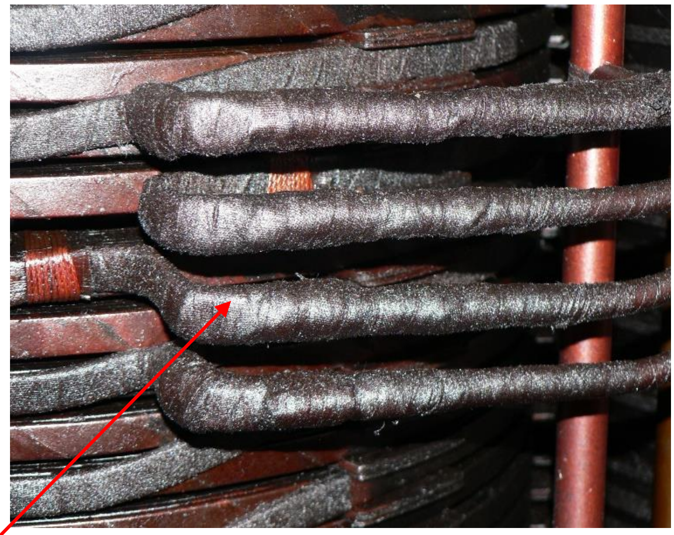
Substation:	POWER STATION NO.2	Transformer No:	TE 43	Serial No:	5292
Sample Point:	MAIN TANK	Sample Date:	14/01/2006	Analyses Date:	24/01/2006
Primary Voltage:	6.6 kV	Secondary Voltage:	550 V	VA Rating:	1500 KVA
Vector Group:	Dyn11	Impedance:	5.41%	Tap Changer:	On Load
Make:	JOHNSON & PHILLIPS	Year Manufactured:	1965	Conservator:	Yes
Breather Size:	None	Oil Volume Liters:	1967	Report Number:	MONDI-105651

TRANSFORMER INSULATING PAPER CONDITION

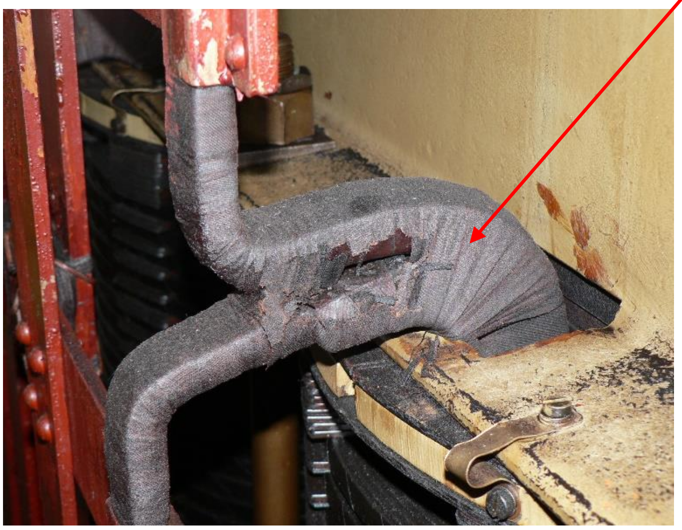
Furan ppm (mg/L)	**9.90**	>10 End of life criteria
Predicted Degree of polymersation	**218**	< 250 End of life criteria
Water in paper: % Dry Weight	**3.08**	2.0 (max)
Water in paper: Total Litres	7.87	

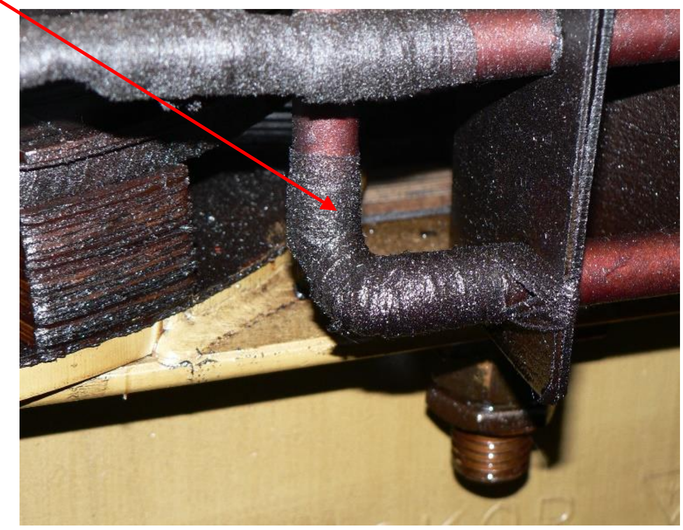
Paper insulation: Extensive deterioration-Serious production rate-316 ppb/month (see Furan). > 25 ppb/month (cause for concern)

RECOMMENDED: Remove from service for Inspection/Repairs to paper insulation.



FINDINGS: Extensive solid (paper) insulation deterioration



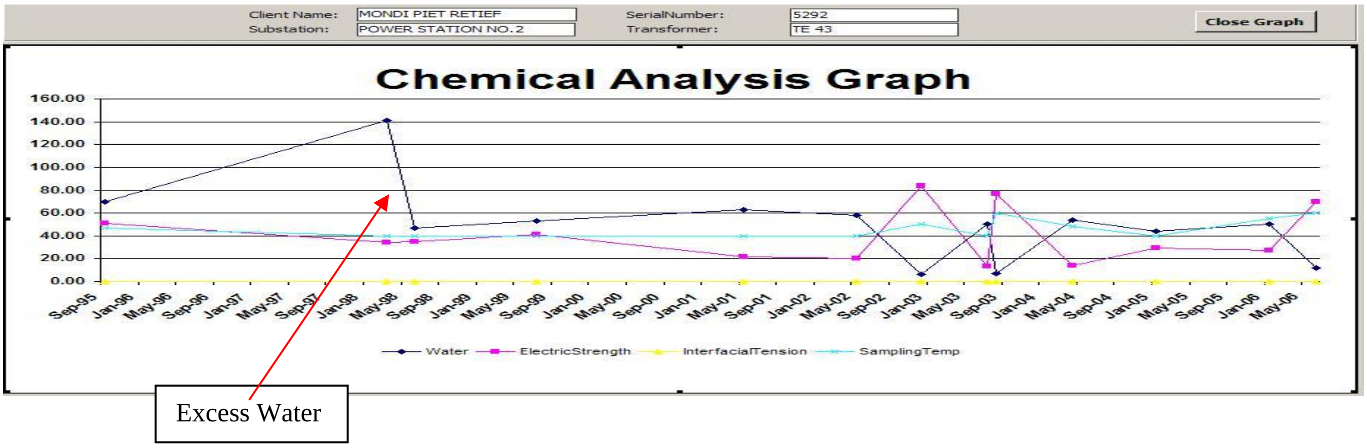


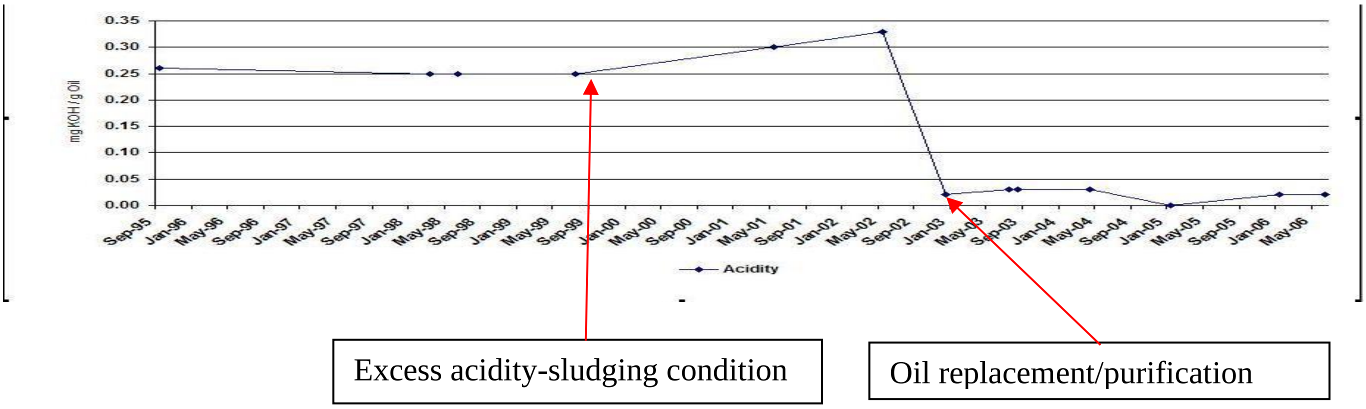
CONCLUSION:

The transformer was rewound/remanufactured at a works facility and then returned to service under planed conditions avoiding costly in-service failure.

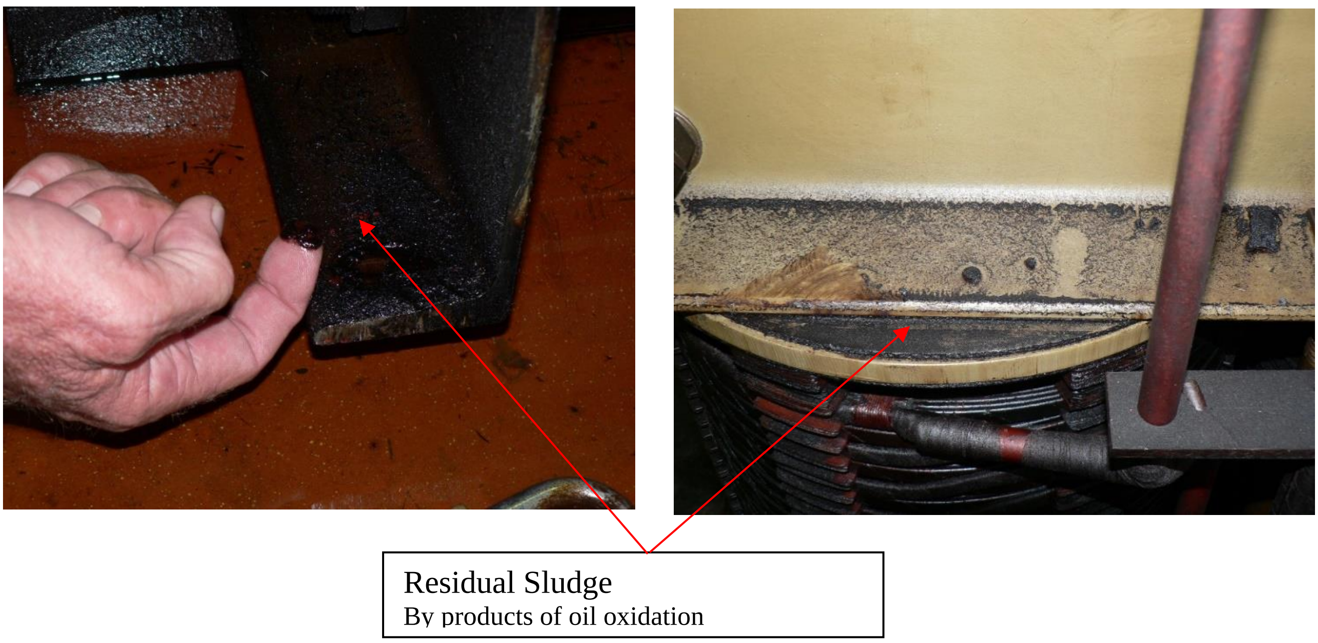
Cause of Insulation paper deterioration.

To understand the cause, the maintenance history of this unit was reviewed. The graph trends show typical high moisture in oil and acid contents, which cause the paper insulation deterioration. (See table 3)





The oil replacement/purification(maintenance) at January 2003 was not performed with Internal flushing.
Note: A small extra quantity of oil is needed to rinse the interior of the tank and the immersed parts.
It is essential that the tank and the surfaces of conductors and insulators be cleaned effectively.
A final pressure flush with clean oil of known quality has proved beneficial in the removal of fibres and other extraneous material.
It should be noted that possibly up to 10% of the original oil might remain adsorbed in the solid insulation and its contaminants may take some time to migrate into the new oil.



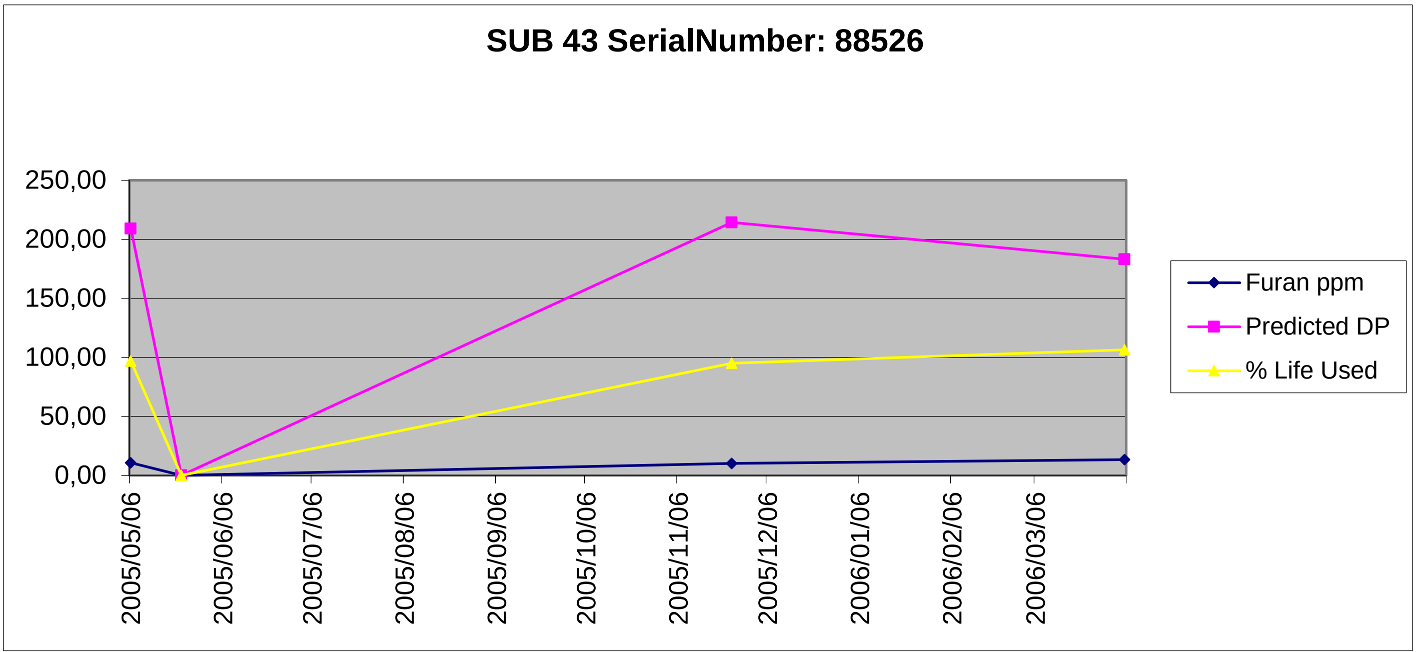
Case Study: Predicted Insulation Failure

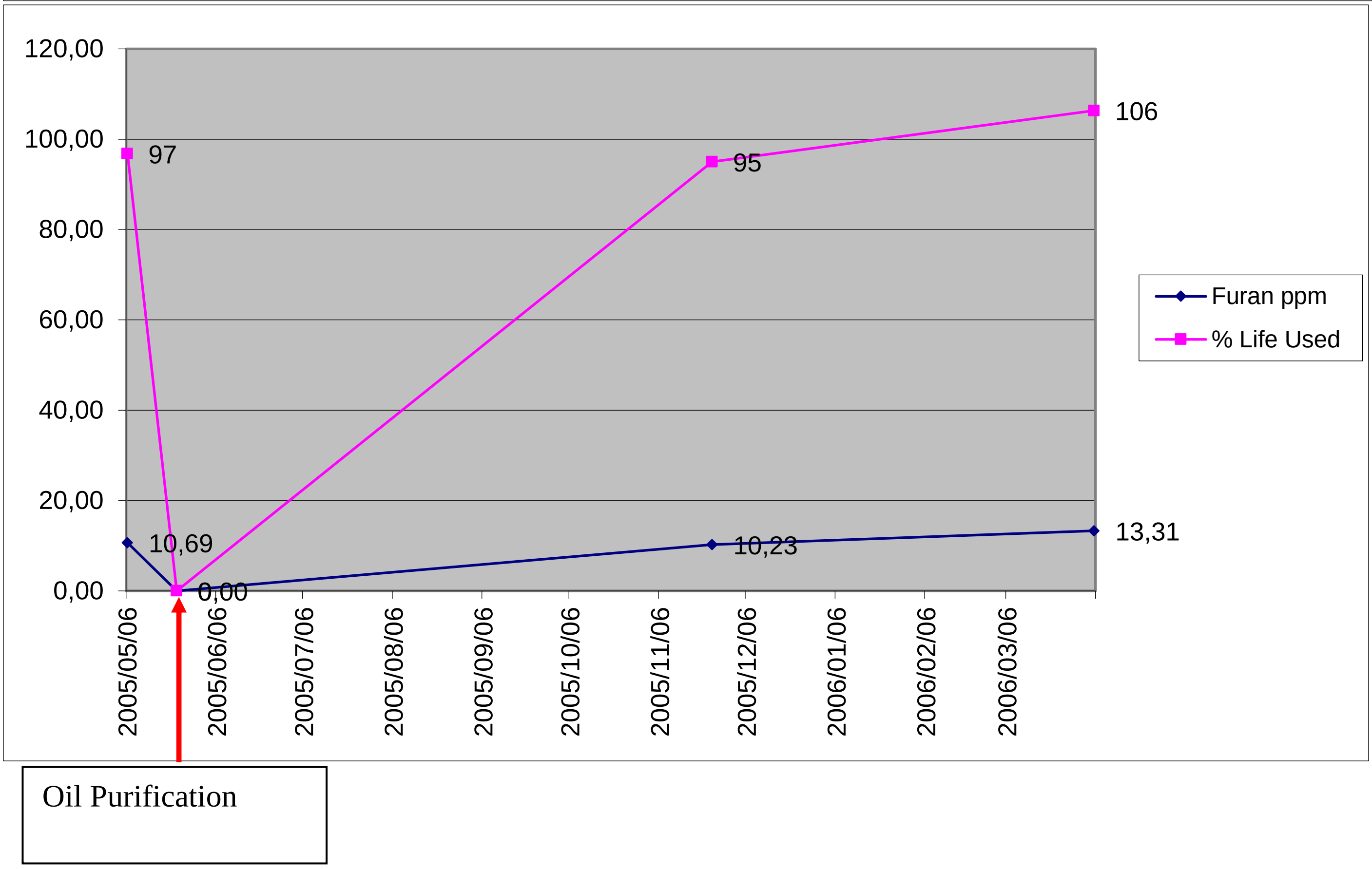
Substation: SUB 43	Transformer No: 43004	Serial No: 88526
Sample Point: MAIN TANK	Sample Date: 05/04/2006	Analyses Date:12/04/2006
Primary Voltage: 11 kV	Secondary Voltage: 6.6 kV	VA Rating: 10 MVA
Vector Group: Dyn11	Impedance: 11.4%	Tap Changer: OFF LOAD
Make: B.B.T	Year Manufactured: 1991	Conservator: Yes
Breather Size: SA3	Oil Volume Litres: 4882	Report Number:SAPPI-107919

TRANSFORMER INSULATING PAPER CONDITION

Furan ppm (mg/L)	**13.31**	>10	End of life criteria
Predicted Degree of polymersation	**183**	< 250	End of life criteria
Water in paper:% Dry Weight	0.69	2.0 (max)	
Water in paper: Total Litres	11.72		

Paper insulation: Extensive deterioration-Serious production rate-770 ppb/month (see Furan). > 25 ppb/month(cause for concern- Morgan-Schaffer)

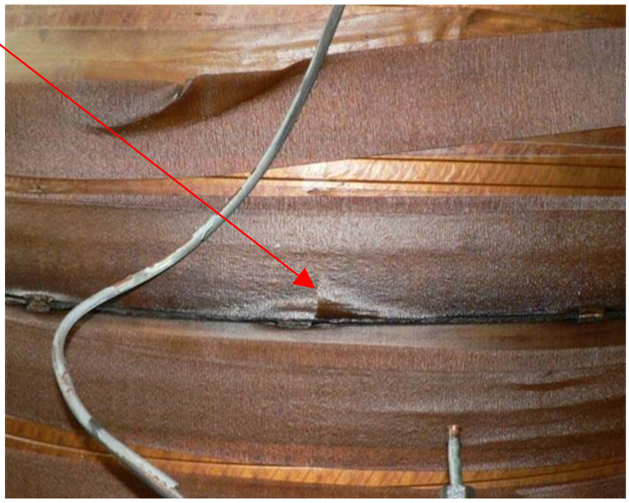




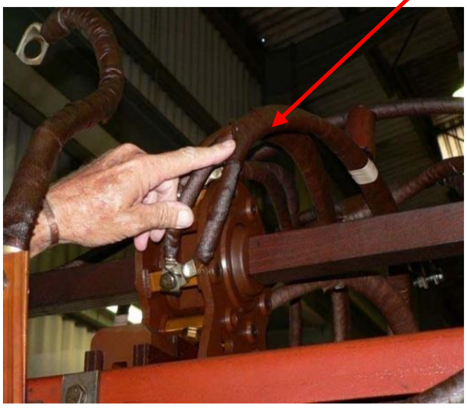
RECOMMENDED: Remove from service for Inspection/Repairs to paper insulation.

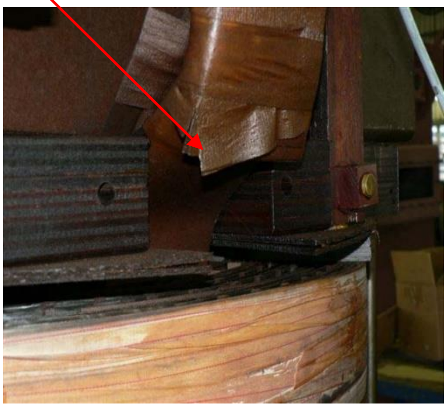
FINDINGS: Extensive solid (paper) insulation deterioration with Delaminating.

There was deformation of the windings coupled with overheating



Extensive deterioration of the LV and Tap changer Leads





CONCLUSION:

This transformer was one of four Main Incomer sister units and was ranked with the highest risk of failure.
Based on the above findings a refurbishment program was implemented for the remaining units.
Investigations on power transformer components have an important role in improving reliability and managing the risk of transformer failure.
The identification of the primary cause of failure and the subsequent analysis enables recommendations for corrective action to be made that hopefully will prevent similar failures from occurring in the future.
Most unexpected power transformer failures happen because of maintenance oversights and over loadings.
When design error and/or weaknesses developing over time are uncovered, enhanced monitoring/investigation on sister units built by same manufacturer will help in preventing future failures and therefore aid in managing the risk of unexpected failure.

The use of furan in oil analysis has a significant cost benefit in planning a maintenance program. This data needs to be viewed in conjunction with Dissolved Gas Analysis, fluid insulation tests and the maintenance history.

When the transformer reaches the end of its reliable, cost effective life, the solid insulation is longer strong enough to continue to keep it in service. One of the things that can be done with the transformer as it is taken out of service is to rewind or remanufacture it. This involves reusing the core steel, the case, and other structural components while rewinding with new insulation wrapped conductor and new solid insulation.

Case Study: Predicted Insulation Failure

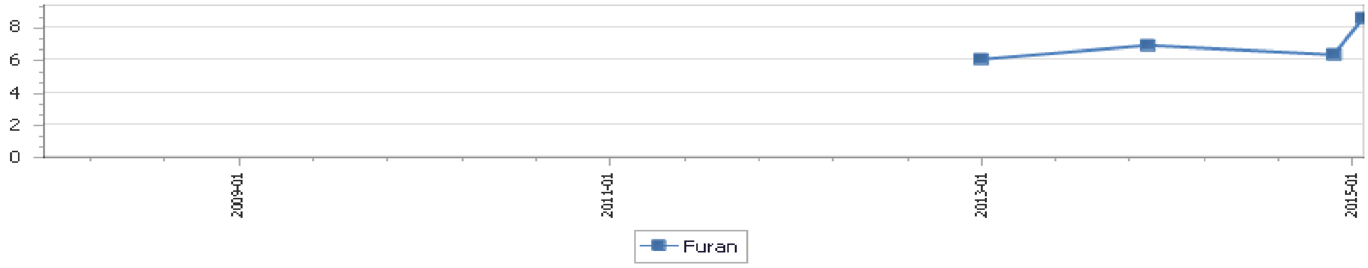
Sasol Synfuels: OEM: JEUMONT SCHNEIDER: 132 kV 54 MVA Serial No 91153

Paper insulation (Predicted DP): Extensive/Significant deterioration

(Furan trend-active degradation>**100ppb/month).**

The paper is near or at the critical condition: Plan to remove from service for Inspection.

Paper samples taken for direct DP testing.



OIL QUALITY INDEX-OQIN(IFT/NN)
Class-Bad Oil 100% Sludgeing condition-Insulation damage and reduced cooling efficiency)

Date	H2	CH4	CO	CO2	C2H4	C2H6	C2H2	H2O	Temp	OQIN	Furan	Pred DP	% LU	Prod Rate ppb/m	Type
2015-01-22	22	19	620	4,565	8	13	0	34	58	62	8.59	235	88	1222	
2014-11-28	15	21	474	3,967	9	15	1	32	40	61	6.34	271	78	-49	
2013-11-25	13	31	413	4,814	10	19	0	41	38	68	6.94	260	81	80	
2013-01-03	17	40	688	5,870	14	28	1	28	61	64	6.07	276	77	-	
2012-01-11	0	35	489	9,656	0	0	2	50	25			0	0	-	
2011-01-11								34	34			0	0	-	
2010-12-02								52	80			0	0	-	
2008-12-11	23	37	726	4,351	8	13	0		65			0	0	-	
2008-12-03								43	45			0	0	-	
2007-12-18								50	50			0	0	-	

Sample	Sampling Position	DP Result 1	DP Result 2	**Average DP**
Sasol 54 MVA	Top Lead - Outer layer	372	390	**381**
Sasol 54 MVA	Top Lead - Inner layers	616	590	603
Sasol 54 MVA	Bottom Lead - Outer layer	407	431	**419**
Sasol 54 MVA	Bottom Lead - Inner layers	615	631	623

Both the Top and Bottom outer layer samples had similar and low DP values.
At this low level of Polymerisation index, the transformer has practically lost all its mechanical strength. The paper windings will also be too weak to withstand through faults and they will distort and buckle due to the forces set up by the high fault currents.

At this low DP value, a rewind would be recommended.

A furan test should be included with yearly maintenance and trends developed to monitor the condition of the paper.

TABLE 3

The progression towards insulation failure.

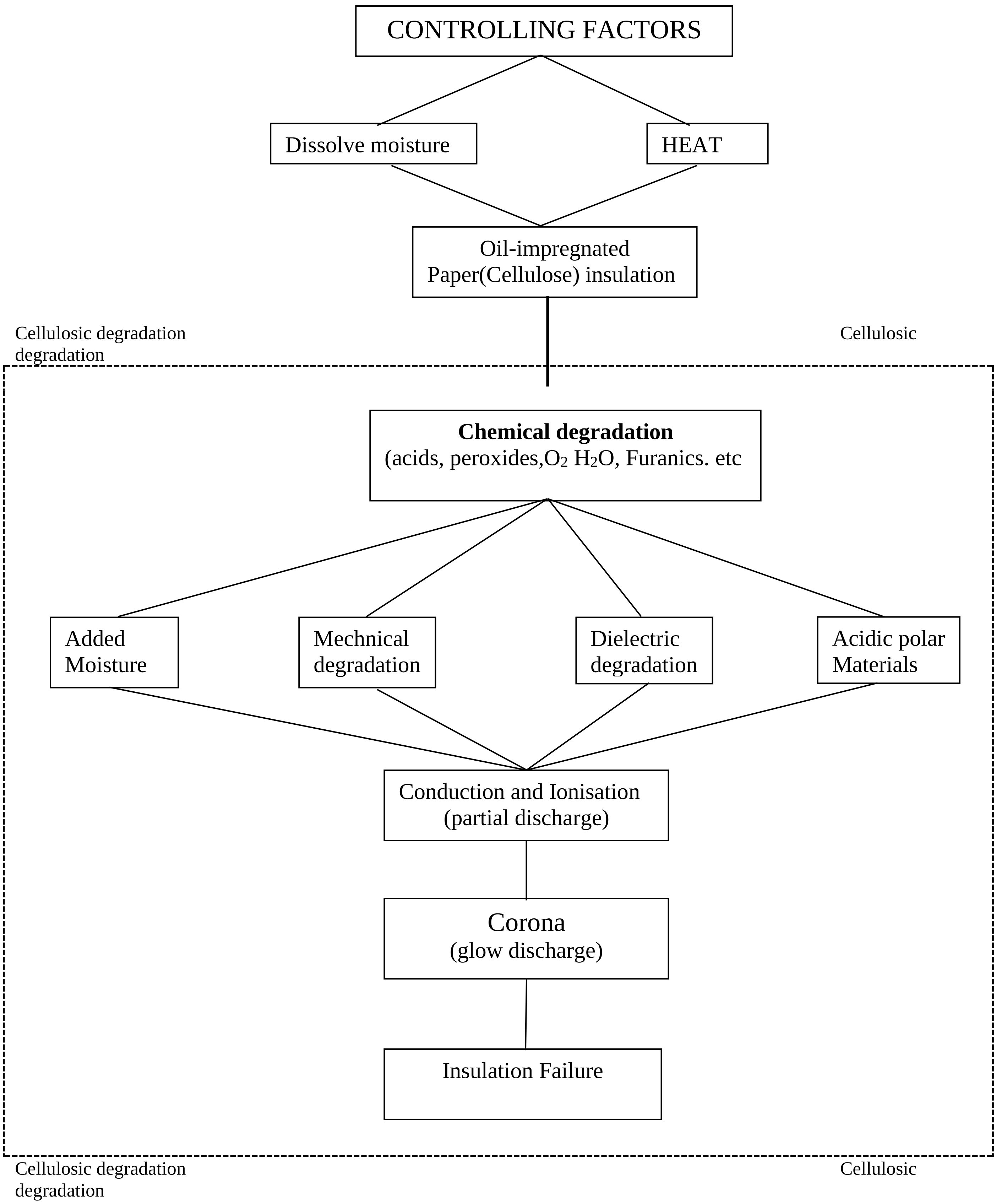


Table 4

DP Range	Remark
<200	Test indicates extensive paper degradation exceeding the critical point. Strongly recommend that the transformer be taken out of service immediately and visually inspected.
200-250	The paper is near or at the critical condition. Recommend that the transformer be taken out of service as soon as possible and thoroughly inspected. Paper samples can be taken for direct DP testing.
260-350	The paper is approaching the critical condition. Suggest inspection be scheduled and/or re-sample within 1 year to reassess condition.
360-450	The paper is starting to approach the critical condition. Suggest a re-sample in 1-2 years time.
460-600	Significant paper deterioration but still well away from the critical point.
610-900	Mild to minimal paper ageing.
>900	No detectable paper degradation

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