

# AGEING OF THERMALLY UPGRADED KRAFT PAPER WITH SYNTHETIC ESTER AND NATURAL ESTER OILS UNDER DIFFERENT CONDITIONS

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## ABSTRACT

The paper has two parts: 1) Comparative Studies of accelerated ageing of TUK Paper using the synthetic ester oil (TRANSOL Synth 100) and Inhibited Mineral Oil and

2) Laboratory simulation of Retrofil conditions using the Natural Ester bioTRANSOL.

## PART 1

Accelerated Paper Ageing studies of TUK paper in Natural Ester Oil has been well documented in several laboratories across the world including at Savita Oil Technologies Ltd. However, there is virtually no published literature (according to our knowledge) on TUK paper ageing using Synthetic Ester Oil.

Our studies on the ageing of TUK paper, therefore, is perhaps first of its kind. We used IEEE C57 guidelines for the experimental design. The ageing studies were conducted at 160 °C for 34 days. The paper samples were removed from ageing apparatus at various intervals (6, 12, 18... days) and analyzed mainly for Degree of polymerization (DP). Oil samples were also withdrawn at the same time to analyze important oil parameters such as Acidity. The results clearly show that the Synthetic Ester Oil (TRANSOL Synth 100) performs much better than the inhibited mineral Oil in terms of Paper DP values at all the time intervals in which samples were withdrawn. While there was a sharp decrease in DP Values of paper aged in mineral oil, the decrease in DP of paper aged in Synthetic ester oil was not so sharp, showing that the synthetic ester oil preserves the paper quality better than the mineral oil. The research work discusses the results in terms of the protective mechanism of Synthetic Ester Oil on cellulose paper.

## PART 2

Retrofil of mineral Oil filled transformers with Natural ester has become widespread all over the world and it is catching up fast in India too. Two major objectives of such a retrofil have been: 1) Enhancing Fire safety of the transformer and 2) Ensuring biodegradability of the oil where the transformer is used in environmentally sensitive areas. The third major objective, namely, slowing down the ageing of paper insulation, may be in the minds of the end users, but not spelt out in clear terms. Even the oil manufacturers do not make aggressive claims on this because only time can tell whether a retrofilled transformer has lived up to its expectations on slowing ageing of insulation.

In the absence of real time field data on slowing down of ageing of insulation in retrofilled transformers, we, at Savita, wanted to simulate the retrofil conditions in the laboratory and see if slowing down of insulation ageing takes place. Towards this end, accelerated paper ageing studies were conducted at 160 °C, as per the conditions prescribed in IEEE C57 guidelines. The experimental design was as follows:

1. Ageing under pure mineral Oil
2. Ageing with pure bioTRANSOL
3. Ageing in pure bioTRANSOL after prior impregnation of paper with mineral oil for 48 Hours (After soaking the paper in mineral oil for 48 hours, mineral oil was completely removed and bioTRANSOL was introduced)
4. The above experiments were also carried out with and without copper wire in order to see the effect of copper wire on the ageing of paper.

The results showed that under retrofil simulation conditions employed in the laboratory, the Natural

ester, bioTRANSOL, indeed showed the effect of slowing down of paper ageing.

More work is planned to partially age a TUK paper in Mineral Oil and then transfer a part of the paper into a Natural Ester Oil and compare the ageing behavior.

## INTRODUCTION

Electricity is an integral part of human life. Efficiently maintaining electric power system has been an important aspect to cater growing power requirement for human comfort. Power transformer is one of the key components of electrical power system. Kraft paper and oil keep the windings insulated safely and can be monitored using different techniques to ensure overall working conditions of a transformer and thus the electrical system [1].

Kraft paper is a vital part of a transformer which keeps the winding insulation healthy. Integrity and stability of the insulation kraft paper under operating conditions is essential to decide the life and efficiency of a transformer. Monitoring of health and integrity of the TUK paper can be one of the tools to ensure safety and efficiency of a transformer. Cellulose and hemicellulose are the major constituents of TUK paper. Cellulose is biopolymer made up of polysaccharides consisting of d-glucose. TUK paper is widely used to insulate the windings in the transformer. The polymeric strength of the cellulose in the TUK paper is important in deciding integrity of paper insulation. The polymeric strength of this cellulose is generally termed as degree of polymerisation (DP value).

Thermal degradation of cellulose in oil has been well studied in literature [2-6]. Slow aging of insulation paper in ester-based fluids are discussed in the context of retrofilling conditions. It has been known that above 100 °C, the thermal degradation of cellulosic paper is predominant generating water in the system [6-8]. There is net generation of two molecules of water for thermal breakdown of each glucoside linkage. The water generated through thermal depolymerisation of paper further enhances oxidation of oil insulation. The generated acidity has further aggravated effect on degradation of paper through oxidative mechanisms. Thus, thermal effects if the power transformer have major impact on the health of a

power transformer. The thermal effects are minimised by replacing the mineral oils by either natural esters or synthetic ester oils [9]. It has been seen that using natural ester oils and synthetic ester oils, health of the transformer can be improved. Ester oils acts as a sump for generated water and acids in the system because of their potential of solubilizing the molecules of polar nature [1,9].

## MATERIALS

The insulating fluids used in the study were commercial grade synthetic ester (TRANSOL Synth 100), Inhibited mineral oil (TRANSOL) and natural ester oil (bioTRANSOL) all manufactured in the plant of Savita Oil Technologies Ltd. 0.09 mm thick thermally upgraded kraft (TUK) paper was obtained from Weidman 22 HCC Insuldur and used after treatment recommended in IEEE C57.100-2011.

## PART 1: COMPARATIVE STUDIES OF ACCELERATED AGEING OF TUK PAPER USING THE SYNTHETIC ESTER OIL (TRANSOL SYNTH 100) AND INHIBITED MINERAL OIL

### EXPERIMENTAL DESIGN AND PROCEDURE

A stainless steel-316 sealed tube reactor made as per IEEE C57.100-2011 was equipped with valves for nitrogen purging through dip pipe and venting cum vacuum application.



Fig. 1: Sealed tube reactor

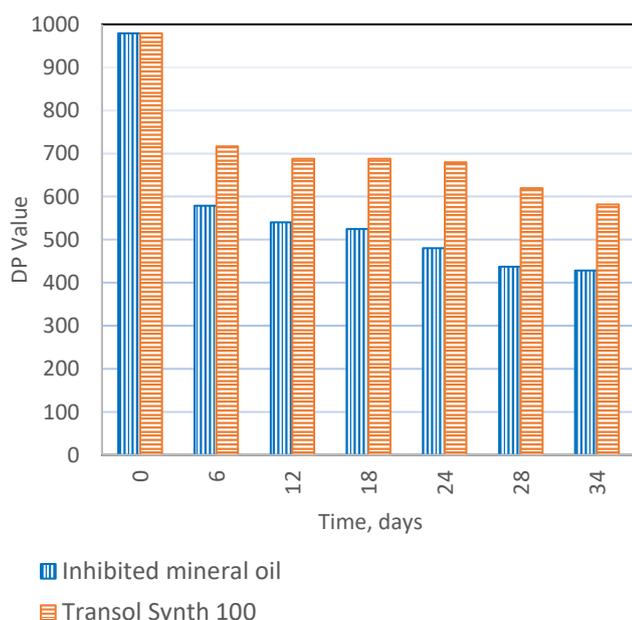
A pressure gauge was also provided to monitor the pressure in the reactor. The reactor assembly is shown in figure 1. Experiments were conducted as per the recommended procedure in IEEE C57.100-2011. Appropriate quantity of insulated oil was taken in the reactor. TUK paper of appropriate surface area was taken and folded in such a way that it is completely dipped in oil in the reactor. The reactor is then tightened and kept in electrically heated hot air oven for the pre-decided time. At the end of the experiment, the reactor was opened, the oil was taken out and analysed for its acid value. The TUK paper was also taken out, washed 4 to 5 times with n-hexane to decrease it and analysed for its DP value.

**COMPARATIVE AGING OF TUK PAPER IN INHIBITED MINERAL OIL AND SYNTHETIC ESTER, TRANSOL SYNTH 100**

TUK paper was tested for 34 days in inhibited mineral oil and the synthetic ester, TRANSOL Synth 100 separately at temperature of 160 °C as recommended by IEEE C57 guidelines. Untreated TUK paper gave the degree of polymerisation value as 979 and it got depolymerised in the inhibited mineral oil as well as in TRANSOL Synth 100.

Table 1: TUK paper accelerated stability test in mineral oil (TRANSOL) and TRANSOL Synth100.

No. of days	TRANSOL		TRANSOL Synth 100	
	DP value of TUK paper	Acid value of oil, mgKOH/g	DP value of TUK paper	Acid value of oil, mgKOH/g
0	979	0.006	979	0.013
6	579	0.022	717	0.92
12	540	0.023	688	2
18	525	0.026	688	2.34
24	480	0.03	680	2.72
28	437	0.031	620	2.78
34	428	0.031	582	2.79



Trend analysis of degradation or depolymerisation of the TUK paper is presented the figure 3. Initial sharp degradation to 40% over the zero-day value in mineral oil and 27% in TRANSOL Synth 100 was clearly seen. This is the first phase of paper degradation saturation at the testing conditions, and it happened in around 150 hours. Comparatively lower degradation of paper was noted in TRANSOL Synth 100. After this phase, a slow degradation was seen. The paper degradation was found more severe in mineral oil than in TRANSOL Synth 100. It was 56% in 820 hours in case of inhibited mineral oil, whereas it was only 40% in case of TRANSOL Synth 100. Thus, in the initial phase 32.5 % and in the later phase 23.1 % more degradation of the TUK paper was seen in inhibited mineral oil compared to the synthetic ester, TRANSOL Synth 100.

Fig. 2: Ageing of TUK paper in inhibited mineral oil and TRANSOL Synth 100.

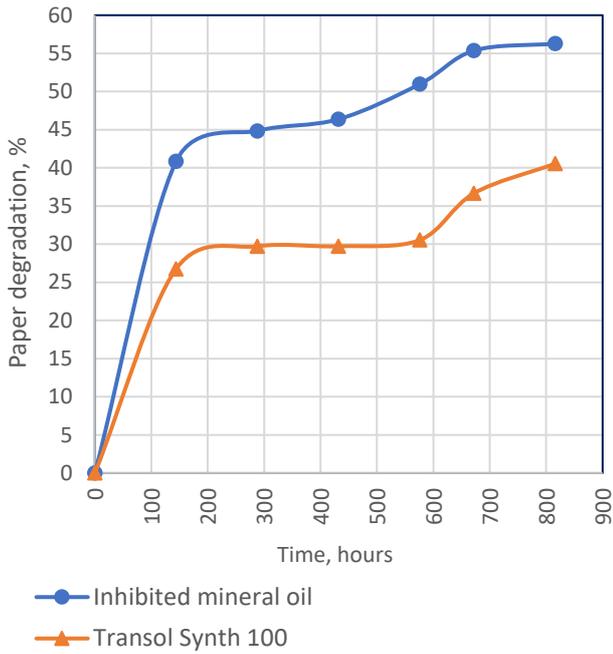


Fig. 3: Trend of TUK paper degradation in inhibited mineral oil and TRANSOL Synth 100.

### Acidity and Paper Degradation

During this study it was noted that the acidity of TRANSOL synth 100 increased more than that of TRANSOL. A sharp and continuous decrease in DP value was noted with marginal increase in acid value in case of TRANSOL indicating fast aging of TUK paper with acidity in mineral oil. On the contrary, Synthetic ester- aged TUK paper did not show such sharp decrease in DP in spite of a sharp increase in acidity. Thus, the TUK paper is highly tolerant to acidity in the synthetic ester oil, TRANSOL Synth 100. This may be clearly seen from the trends shown in figure 4. It was noted that the paper obtains a steady state for its DP value as the acidity increased from 1 to 2.7 mgKOH/g of oil. This behaviour indicates that TRANSOL Synth 100 protects the paper from its degradation over a wide range of acidity in the system. The comparative trends of effects of acidity on paper degradation for mineral oil and synthetic ester may be explained as follows: Mineral oil oxidation produces more aggressive lower molecular weight acids (C2 to C8 acids) while synthetic ester, on oxidation produces less aggressive fatty acids (C7 to C10). The tolerance of paper to acidity in the case of synthetic ester is a clear advantage over mineral oil.

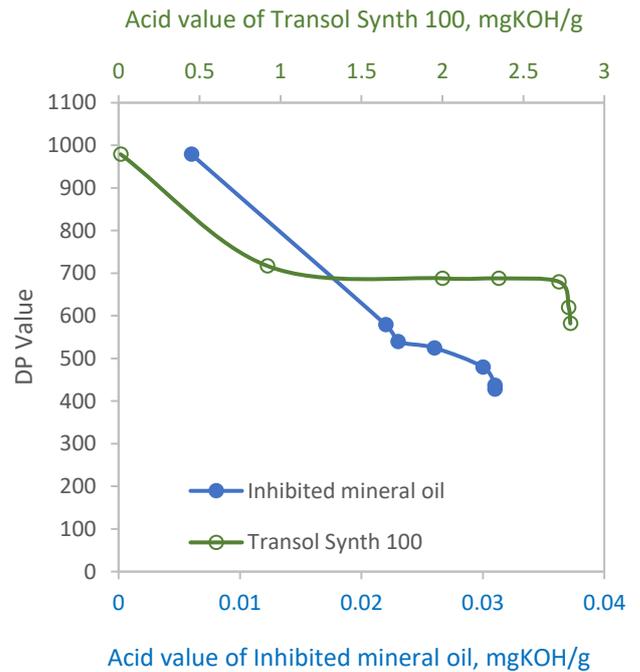


Fig. 4: Effect of acidity of oil on TUK paper degradation in inhibited mineral oil and TRANSOL Synth 100.

Cellulose from the TUK paper is known to generate water and simultaneously acidity. When the studies were conducted in the mineral oil, during thermal degradation of the paper, generated water and acidity are hold by the paper itself experiencing an aggravated degradation. However, in case of the synthetic ester, TRANSOL Synth 100, water and acidity generated by the paper is dissipated in the oil media arresting the further degradation of the paper. Thus, TRANSOL synth 100 not only absorbs moisture and acidity but also retards paper degradation and provides longer life to the paper and thus to the transformer.

## PART 2: LABORATORY SIMULATION OF RETROFIL CONDITIONS USING THE NATURAL ESTER, BIOTRANSOL

### EXPERIMENTAL DESIGN AND PROCEDURE:

The experiments were carried out in the sealed tube reactor as shown in figure 1. In the experiments simulating retrofil conditions, TUK paper was first dipped in inhibited mineral oil for 48 hours at room temperature and then was used for further stability tests.

**COMPARATIVE STUDY OF TUK PAPER UNDER RETROFIL CONDITIONS**

paper in bio TRANSOL with copper were studied separately for evaluating the stability of the TUK paper.

TRANSOL, bio TRANSOL, Mineral oil-soaked paper in bioTRANSOL and the mineral oil-soaked

Table 2: TUK paper depolymerisation with time in inhibited mineral oil (TRANSOL) and bioTRANSOL (ageing in bioTRANSOL carried out after initial soaking of paper in TRANSOL).

No. of days	DP value of paper		
	Aged in TRANSOL	Aged in bioTRANSOL	Aged in bioTRANSOL after initial soaking in TRANSOL
0	950	950	950
11	568	747	681
20	318	568	636
28	306	562	562
83	248	417	428
101	224	391	416
150	209	378	364
200	184	341	351
250	184	329	284
275	140	294	260

The DP values of the TUK paper were monitored with respect to time at 160 °C so that the stability of TUK paper can be judged. Retrofiling of mineral oil transformer with bioTRANSOL can be imagined as the TUK paper contaminated/soaked with mineral oil which may impact the stability of the paper during after retrofil. Stability of TUK paper only in inhibited mineral oil and in bioTRANSOL after soaking the paper in mineral oil were also studied for comparing their DP values. The latter experiment mimics retrofil conditions. The study was conducted at 160 °C for 275 days and presented in Table 2.

Unused fresh TUK paper showed a DP value of 950. DP value decreased very fast to 318 when the paper was aged in TRANSOL. However, when the paper was aged in bioTRANSOL (after soaking in mineral oil), the decrease in DP was comparatively slower even in this initial fast degradation phase, indicating superiority of the natural ester over mineral oil. Presence of copper in the ageing experiments did not show any significant effect on the results. Decrease in DP values with time are presented in figure 5.

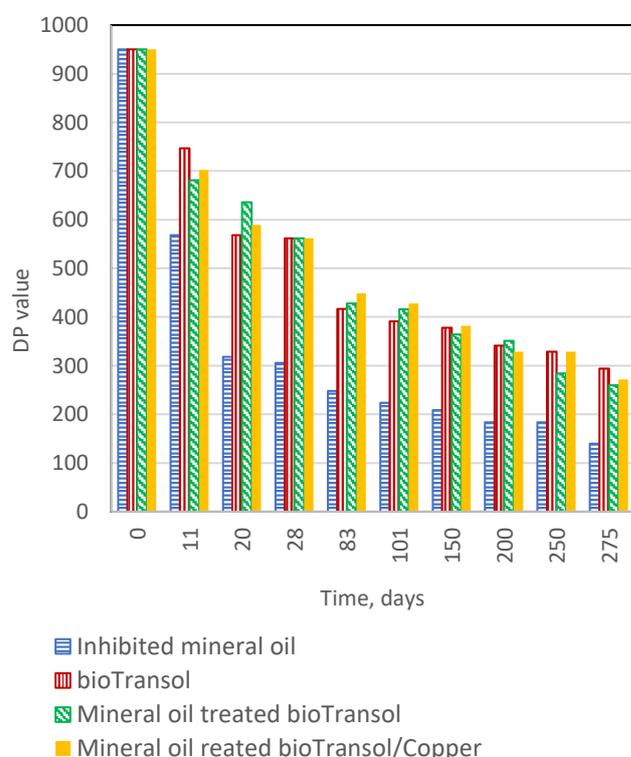


Fig. 5: Comparative stability of TUK paper under retrofil (with bioTRANSOL) conditions.

After 275 days the DP values decreased to 140 and 294 in TRANSOL and bioTRANSOL respectively. bio TRANSOL- aged paper showed less degradation under conditions of mimicking retrofil.

**Trend of Paper Degradation at Retrofil Conditions:**

The above results mentioned in the previous paragraph are captured graphically in figure 6. It may be seen from the figure that TUK paper degrades faster in mineral oil as compared to bioTRANSOL. In the initial fast degradation phase, mineral oil showed 66% degradation (0.142% per hour) whereas the corresponding degradation in bioTRANSOL was only 40.2% (0.083% per hour) in initial 480 hours. After 480 hours, the slower degradation was experienced by the TUK paper both in mineral oil and bioTRANSOL. The rate of was 0.0024% and 0.003% per hour in mineral oil and bio TRANSOL respectively. (There was no impact of Mineral oil soaking on the TUK paper when studied in bio TRANSOL as retrofil conditions with and without copper). At the end of the study after 6600 hours, the paper in mineral was found to be 85.2% degraded whereas in bioTRANSOL

it was 69.0% degraded. Thus, bioTRANSOL was found to be more robust both in initial phase and at the later stage of degradation. Mineral oil-soaked paper with and without copper showed 72.6 and 71.4% degradation after 6600 hours in bio TRANSOL at testing conditions.

Our investigations reported here clearly confirm that retrofilling a transformer with bioTRANSOL would offer superior protection to TUK paper from ageing. This benefit is in addition the advantages of additional fire-safety and biodegradability conferred by bioTRANSOL.

**SUMMARY AND CONCLUSIONS**

Stability of TUK paper in inhibited mineral oil and synthetic ester was compared under accelerated ageing conditions. The TUK paper experienced degradation in two phases at 160°C - first severe degradation in initial 150 hours and second slow and steady degradation beyond 150 hours. The TUK paper showed relatively more severe degradation in inhibited mineral oil compared to that in the synthetic ester. Predominantly in the first phase 32.5 % and in the second phase 23.1 % more degradation of the TUK paper was observed in mineral oil compared to the synthetic ester.

During the stability study presented in this paper it was noted that the TUK paper is highly tolerant to acidity in synthetic ester, whereas a very small increase in the acidity of mineral oil degraded the TUK paper very fast. Synthetic ester could act as the sump for the acidity safeguarding the TUK paper in a very broad range of acidity from 0.9 to 2.7 mgKOH/g. Thus, the synthetic ester was found to be superior to mineral oil to protect the TUK paper at high temperature conditions and at higher acidity. Yet another reason for the protective effect on paper by synthetic ester could be that it forms less aggressive fatty acids (C7 to C10), compared to more aggressive acids (C2 to C8) formed in the case of the mineral oil.

TUK paper was also studied for its stability at retrofil conditions (replacing mineral oil in an old transformer with a Natural ester Oil). Soaking of TUK paper with mineral oil to mimic the retrofil conditions showed no effect on its degradation. The TUK paper showed 66% degradation at 0.142% per hour in mineral oil and 40.2% degradation at 0.083% per hour in the natural

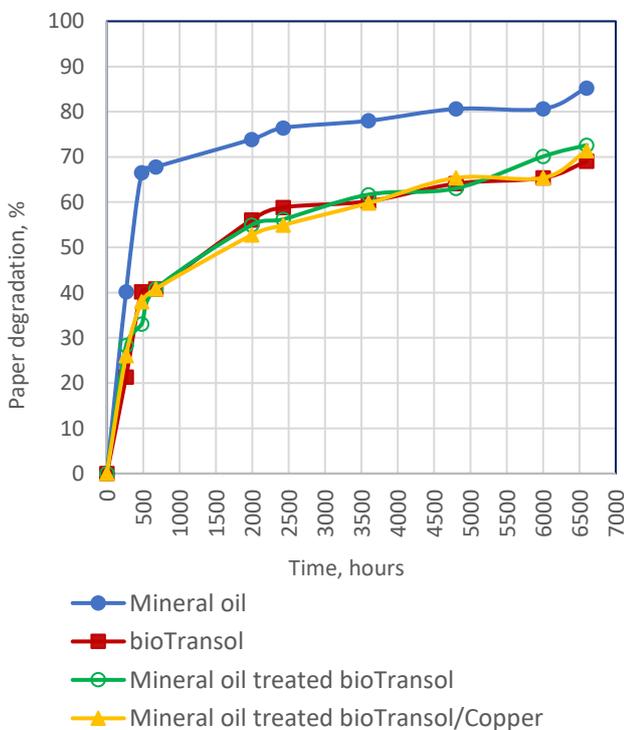


Fig. 6: Trend of TUK paper degradation under retrofil conditions

ester. Natural ester was observed to be more robust to TUK paper compared to mineral oil. In the second phase, degradation rate was slower 0.0024 and 0.003% per hour in mineral oil and natural ester respectively.

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