

# COMPARATIVE EVALUATION OF BREAKDOWN STRENGTH OF NATURAL ESTERS AND MINERAL OIL

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**Abstract:** This paper presents results of experimental investigations on natural esters dielectric and coolant fluids regarding the breakdown strength. The breakdown voltage (BDV) for small and medium oil gaps (from 2 mm up to 40 mm) under AC and lightning impulse (LI), uniform and non-uniform electrical field is measured. Experiments involve new, aged and with mineral oil contaminated natural esters. The creep BDV over 5 mm long pressboard element impregnated with both mineral oil and natural ester is measured. The discharge development is investigated by means of partial discharge inception voltage and streamer velocity measurements. The application suitability of the Weibull and Gaussian distribution functions is discussed with reference to the estimated withstand voltage. Natural esters require additional handling care during the experiments regarding the conditioning of the fluid. Avoiding the contact with the atmosphere and by removing the breakdown products (gases, carbon particles) natural esters showed in the investigated arrangements same or better dielectric performance than mineral oil.

## 1. INTRODUCTION

Parallel with the worldwide constantly growing demand for the electrical energy an environmentally and safety aspect is raised. Power transformers being crucial elements in electric power transmission network also have to follow this trend, setting the challenge for power transformer manufacturers. For more than one century power transformers are filled with mineral oil serving as a heat transfer and insulating medium. Nowadays significant efforts are aimed in quest for environmentally friendlier replacement of this petroleum-based product.

Natural esters (vegetable oils) refined from plant materials are intruded as a solution. They are non-toxic, more biodegradable and less flammable than a mineral oil. For the last 10 years natural esters have been successfully used in more than 45,000 low and medium power installations [1]. Since natural esters possess weak oxidation stability they require to be used in hermetically sealed transformers [2]. Some other adverse characteristics like poor low temperature performance and higher viscosity are to be considered when handling natural esters [3]. Dissimilarities between natural esters and mineral oil in chemical and physical characteristics require further considerations before they can be widely used in power transformers.

The oil-cellulose insulation system is considered as unsurpassed standard insulation system in the high voltage technique for transformers, in particular to the high power range. The dielectric strength of the pressboard is approximately 3 to 4 times higher than the dielectric strength of the oil. The AC field stress in pressboard is further reduced because of its permittivity ( $\epsilon$ ) which is higher than permittivity of oil (approximately twice higher). This means that stresses in the oil are increased in the layered dielectric by the

ratio of  $\epsilon$  oil to pressboard. Therefore oil gaps form weak links being in series with barriers. All this emphasize dielectric strength as a primary characteristic of insulating fluids.

Taking breakdown voltage of the oil or pressboard as a numerical value without knowing details of test conditions can lead to the faults in insulation systems design. A number of factors like size, concentration and nature of soluble (water, hydrocarbon gases) as well as insoluble (metallic and non-metallic particles, fibers) impurities present within oil influence breakdown strength in many different ways. Besides the condition of insulation material itself, condition of test cell needs to be also considered. The material, shape and area of electrodes, their conditioning, gap spacing, electrode pretreatment, rate of applied voltage rise, effect of oil velocity and the settling time between two consecutive stresses also greatly influence dielectric strength of oil-pressboard insulation.

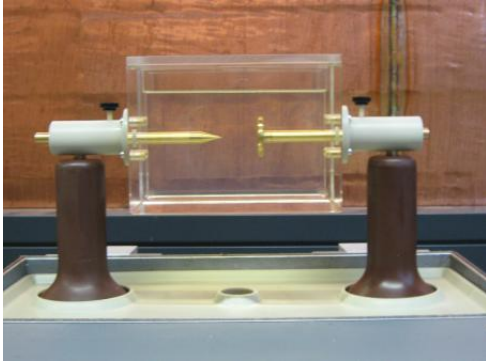
In this contribution results of breakdown strength measurements on two commercially available natural esters (NE1, NE2) and mineral oil Nynas Netro 3000X (NN3000X) as a reference fluid are presented.

## 2. EXPERIMENTAL TECHNIQUES

### 2.1. Test Set-up

The breakdown voltage is studied by using three different test vessels. As AC 50 Hz power source an automatic insulating oil tester Bauer DTA 100 E with maximal output voltage of 100 kV is used. 1.2/50  $\mu$ s lightning impulses are generated by means of 10 stage Marx impulse generator. First test vessel (TV-1) IEC156/1995-05 standardized with oil volume of 400 ml and VDE calotte electrodes is used for measurement of AC breakdown voltage. Second test vessel (TV-2) is also used for AC measurement with Bauer automatic

power supply. It is a Perspex vessel having a volume of 1500 ml (Figure 1). This test vessel allows for point-plane electrode system to be connected on automatic AC power supply. By exchanging the electrodes various electrical field conditions can be realized.



**Figure 1:** Perspex test vessel (TV-2) built for utilization on Bauer DTA 100 E AC power source

For generation of the non-uniform electrical field two different point electrodes (tip radius 3  $\mu\text{m}$  and 100  $\mu\text{m}$ ) were faced to the plane electrode with diameter of 50 mm. Partial discharges are also measured on this test vessel by connecting it to the HV laboratory transformer. Furthermore, in this vessel was possible to implement electrodes with the impregnated pressboard between them for generation of the creep breakdown stresses. A third test vessel (TV-3) used for application of higher lightning impulse voltages is made of a plastic cylinder sealed at both sides with metal covers. This test vessel has a diameter of 200 mm and volume of 15 liters.

Natural esters, possessing a higher viscosity than mineral oil require additional care while filling the test vessels. Air bubbles captured in natural ester need more time to dislocate from the fluid. For this reason a pause before stressing the fluid and pause between successive breakdowns are increased. In such a way influence of the impurities generated by breakdown, on the estimation of the breakdown strength is avoided. The viscosity of the natural ester can be increased even more by oxidation, which is much faster than by mineral oil. Therefore, exposure of natural esters to atmosphere during experiments is reduced to minimum.

Moisture, being the enemy number one for the dielectric strength of fluids, is measured and controlled during all experiments. A relative humidity (RH) is measured by means of Vaisala HMP228 capacitive moisture sensor. Humidity level was kept for all used fluids under 15 % (about 200 ppm for natural esters and about 10 ppm for mineral oil at room temperature).

## 2.2. Interpretation of measured data

All measured breakdown values are statistically evaluated. For each experiment the mean value ( $\mu$ ) and the standard deviation ( $\sigma$ ) are calculated. Furthermore in order to obtain the withstand voltage (low

breakdown probability) value, measured breakdown values are fitted to two commonly used probability functions. With evaluated function parameters ( $\alpha$ ,  $\beta$ ) a breakdown probability for given voltage value  $P_W(U)$ , for Weibull cumulative distribution function is calculated as follows:

$$P_W(U) = 1 - e^{-\left(\frac{U}{\alpha}\right)^\beta} \quad (1)$$

Where:  $\alpha$  = scale factor

$\beta$  = shape factor

Second used probability function is Normal (Gaussian) cumulative distribution function. With evaluated function parameters ( $\mu$ ,  $\sigma$ ) a breakdown probability for given voltage value  $P_N(U)$  is calculated as follows:

$$P_N(U) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^U e^{-\frac{(U-\mu)^2}{2\sigma^2}} dU = \frac{1}{2} \left[ 1 + \text{erf}\left(\frac{U-\mu}{\sigma\sqrt{2}}\right) \right] \quad (2)$$

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (3)$$

Where:  $\mu$  = mean breakdown voltage (kV)

$\sigma$  = standard breakdown deviation (kV)

$\text{erf}(x)$  = error function

Fitting and calculation are done with 95% confidence. Goodness of fitting for these two functions is evaluated through the three different criteria (normal log-likelihood, BIC and AICc).

## 3. MEASUREMENTS AND RESULTS

### 3.1. Uniform electrical field

The characterization of natural ester dielectric strength in uniform AC electrical field is done by means of the small fluid volume (TV-1). Following the IEC 60156 voltage was continuously increased with the rate of 2 kV/s. The pause after breakdown for mineral oil was 2 min and for natural esters 5 min. The pause for natural esters is increased since they have higher viscosity, giving enough time for all breakdown products to be removed from the stress area by stirring. The settling time after filling the vessel and before applying the voltage was 40 min. Before filling the test vessel and electrodes were cleaned with heptane and refined with dry compressed air.

Since fluids used in this experiment were very dry (RH < 10 %) in some cases breakdown voltage was above 100 kV. Therefore, the distance between electrodes is reduced from 2.5 mm to 2 mm. In order to obtain sufficient measured values for accurate statistical evaluation fluids were tested in series of 40 to 50 breakdowns. Also some fluids showed increasing tendency of the breakdown voltage in first 5 breakdowns. Therefore the number of six breakdown values suggested by IEC 60156 had to be increased.

**Table 1:** Breakdown probability values for 2 mm AC uniform fluid gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	45.1	66.4	66.36	9.14
NE1	53.0	70.6	70.59	7.59
NE2	61.1	74.2	74.25	5.77
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	43.7	67.5	70.02	9.72
NE1	47.4	71.4	74.00	10.30
NE2	55.9	75.0	76.84	14.41

Used power supply device has a low breakdown current and short power circuit interrupting time. Therefore, the same fluid sample was used during one series of breakdowns.

After fitting the measured values to breakdown distribution functions, a 1 % breakdown probability (withstand) voltage  $U_{1\%}$  and 50 % breakdown probability (mean) voltage  $U_{50\%}$  were calculated (Table 1). Natural esters showed about 10 % higher mean breakdown voltages. The standard deviation of natural esters is smaller than for mineral oil. This leads even to higher difference between fluids for withstand voltage values. NE2 has about 35 % higher withstand voltage than mineral oil according to the Normal distribution.

### 3.2. Non-uniform electrical field

#### Fluids in New Condition

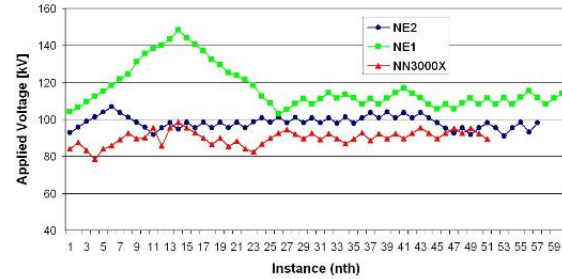
The test vessel TV-2 was equipped with brass point-plate electrodes and mounted on the Bauer automatic AC power supply. The point electrode was with tip radius of 100  $\mu\text{m}$  and the gap distance was 30 mm. The experiment was conducted on same way as the experiment for uniform electrical field. Fitted AC breakdown results of this experiment are given in Table 2.

**Table 2:** Breakdown probability values for 30 mm AC non-uniform (100  $\mu\text{m}$  tip radius) fluid gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	43.8	56.0	56.00	5.21
NE1	45.4	55.6	55.63	4.39
NE2	44.1	53.0	53.00	3.78
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	39.7	56.6	58.35	11.96
NE1	41.6	56.1	57.65	14.07
NE2	38.4	53.3	54.84	12.96

In this case, all three tested fluids showed similar mean breakdown voltages. Also, having similar standard deviations the withstand voltages are in the same relation.

The same test vessel was connected to the Marx generator in order to obtain the lighting impulse breakdown strength. Up and down test method according to the IEC 60060-1 class 2 was carried out. This method involves in steps increasing of the impulse voltage starting from about 80 % of expected withstand voltage. When the breakdown appears voltage is in steps decreased until the breakdown does not appear anymore. Then the voltage is again increased and so on (Figure 2).



**Figure 2:** Lighting impulse breakdown values for up and down test method on 40 mm point-plate gap

It can be seen on Figure 2 that for natural esters the breakdown values significantly drop after the first breakdown appeared. This suggests that high energy lighting impulse breakdowns produce impurities which have stronger impacted on natural ester breakdown strength. These measurements will be repeated with fluid exchange after each breakdown in order to obtain suitable breakdown strength value.

#### Inhomogeneity Effect

For insulation system design the influence of the electrical field distribution and intensity on the breakdown strength of natural esters is essential. In order to obtain different electrical field intensities on the tip of point electrode a gap distance and point electrode tip radius were altered. Results of measurement with point tip radius of 3  $\mu\text{m}$  and 100  $\mu\text{m}$  and electrodes gap of 30 mm and 40 mm are given in Tables 2-5.

**Table 3:** Breakdown probability values for 30 mm AC non-uniform (3  $\mu\text{m}$  tip radius) fluid gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	44.2	55.5	55.48	4.88
NE1	43.0	48.4	48.35	2.32
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	40.2	56.05	57.65	12.72
NE1	40.1	48.6	49.47	21.81

By reducing the tip radius (increased electrical field intensity) mineral oil keeps similar breakdown values and NE1 obtained about 10 % lower mean breakdown value and unaltered withstand voltage (Table 2, 3). Reiteratively decrease of electrical field by increasing

the gap distance result in similar effect on both fluids. Mineral oil kept slightly higher mean breakdown voltage but withstand voltages are in the same range.

**Table 4:** Breakdown probability values for 40 mm AC non-uniform (3  $\mu\text{m}$  tip radius) fluid gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	56.1	63.0	63.00	3.21
NE1	53.3	57.0	56.96	1.57
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	51.2	63.9	65.17	19.07
NE1	51.0	57.2	57.74	36.85

### *Aged Fluids*

Since the natural esters are very new products in power transformers there are no available records of the dielectric behavior over longer period. Therefore an ageing experiment is conducted. It involves both, natural ester (NE1) and mineral oil. Metal vessels were filled with the same proportional mass ratio of fluid and materials that can be found in real power transformers (cooper, aluminum, iron, zinc and cellulose). The vessels were sealed preventing the contact of heated fluids with the atmosphere and put in an oven under temperature of 150  $^{\circ}\text{C}$  for 63 days.

The AC breakdown voltages were measured using TV-2 mounted on Bauer automatic power supply device. Used electrodes were point-plate, were the point electrode was an Ogura fine needle with the tip radius of 3  $\mu\text{m}$ . The oil gap was adjusted to 40 mm. Fitted AC breakdown results of this experiment are given in Table 5.

**Table 5:** Breakdown probability values for 40 mm AC non-uniform (3  $\mu\text{m}$  tip radius) aged fluid gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	53.0	56.5	56.54	1.53
NE1	52.8	55.5	55.55	1.18
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	51.1	56.8	57.29	40.23
NE1	51.8	55.7	56.09	57.67

It can be seen that aging does not effects breakdown strength of natural ester and for mineral oil there is only a slight decrease of breakdown strength (Table 4 and 5).

### *Breakdown Strength of Fluid Mixtures*

For retro fill of power transformers previously filled with mineral oil another aspect to be considered is the breakdown strength of natural ester contaminated with mineral oil. TV-2 was filled with a ratio of 90 %

natural ester and 10 % of mineral oil. Fitted AC breakdown results of this experiment are given in Table 6.

**Table 6:** Breakdown probability values for natural ester contaminated with 10 % of mineral oil in 40 mm AC non-uniform (3  $\mu\text{m}$  tip radius) gap

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
Cont. NE1	54.2	55.8	55.77	1.18
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
Cont. NE1	51.4	55.9	56.36	49.35

Results show that contamination of natural ester with mineral oil does not influence the breakdown strength of natural ester (Table 4 and 6).

### *Breakdown initiation and propagation*

In order to qualify the breakdown process in natural esters pre-breakdown partial discharges (PDs) are recorded. It is observed that PDs in natural ester initiate at slightly lower voltage as in mineral oil (Table 7).

**Table 7:** Partial discharge inception voltage

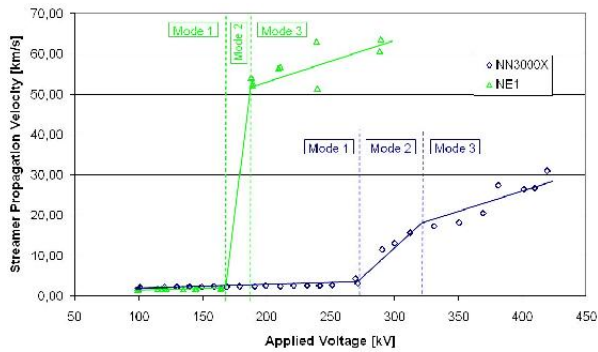
PD Inception Voltage		3 $\mu\text{m}$	100 $\mu\text{m}$
30 mm	NE1	18.8	22.4
	NN3000X	20.6	23.2
40 mm	NE1	21.7	23.9
	NN3000X	22.5	24.7

Also, by putting a 1 mm thick pressboard barrier in parallel with the plate electrode it was possible to generate strong PDs (up to 2 nC) without breakdowns between the electrodes. The electrode distance was 30 mm and distance from plate electrode to the barrier was 10 mm. In this case it was observed that PDs generated in natural ester have about 30 % higher intensity than in mineral oil for same applied voltage.

The point-plate electrode system with gap distance of 40 mm was mounted in TV-3 in order to measure the time to breakdown for lightning impulse voltages. Starting under expected withstand voltage value applied impulse voltage was continuously increased all over the breakdown voltage. In this manner shifting of the time to breakdown to the front of the lightning impulse is achieved. Assuming that the streamers are initiated directly after applying the voltage impulse, with known gap distance and measured time to breakdown, the streamer propagation velocity over lightning impulse was calculated as follows:

$$v_s = \frac{d_{gap}}{t_{BD}} \quad (4)$$

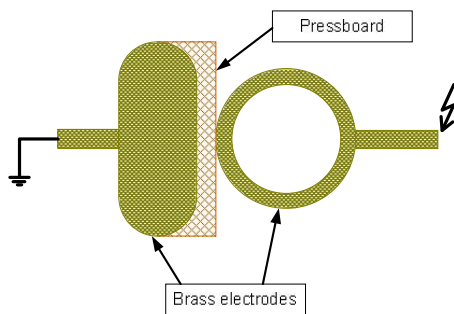
Where:  $v_S$  = Streamer velocity (km/s)  
 $d_{gap}$  = Gap distance (mm)  
 $t_{BD}$  = Time to breakdown ( $\mu$ s)



**Figure 3:** Streamer propagation velocity over 40 mm point-plate gap under lighting impulse

As in some previously done investigation on mineral oil [5] three different propagation modes are identified in both fluid (Figure 3). Mode 1 is related to the voltages directly above breakdown value and involves slight increase of streamer propagation velocity in the range from 2 to 3 km/s. In mode 2, streamer velocity increases strongly with slight increase of applied voltage. Mode 3 involves again slight increase of streamer velocity over applied voltage in range of 10 km/s. Natural esters reached fast Mode 3 of streamer propagation velocity at lower voltages than mineral oil. Also natural ester Mode 3 is on higher velocities than Mode 3 of mineral oil. This indicates that streamers propagate faster in natural ester than in mineral oil, having more potential to bridge larger gaps and to create a breakdown.

### 3.3. Creep breakdown strength



**Figure 4:** Electrode configuration for generation of creep breakdown on impregnated pressboard

Pressboard elements 50 mm wide, 15 mm long and 1 mm thick were impregnated with mineral oil and natural ester (for each fluid ten pieces). The impregnation process involves a procedure with drying and impregnation under vacuum. Drying temperature was 110 °C and applied vacuum was 100 Pa. The pressboard element was inserted for 10 mm into the

channel along diameter of disk-like electrode. The diameter of the disk-like electrode was 50 mm. The second ring-like electrode was placed in contact with the pressboard. The ring-like electrode had an outer diameter of 35 mm and a thickness of 8mm (Figure 4). This configuration generates a strong tangential component of the electrical field over the pressboard surface, initiating the creep breakdown. The configuration was realized in TV-2 and connected to the impulse generator. The lightning impulse voltage was applied in steps. On each step a set of three impulses was applied until the breakdown occurs. After each breakdown fluid and pressboard were exchanged. Fitted LI breakdown results of this experiment are given in Table 8.

In this case natural ester impregnated pressboard obtained about 10 % higher mean breakdown value and about 35 % higher withstand voltage. This can be attributed to the higher permittivity of the natural ester. Thus, the electrical stress is more homogeneously distributed along dielectrics boundary surface as in case of mineral oil.

**Table 8:** LI creep breakdown probability values for 5 mm long impregnated pressboard

Fluid	Normal Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\mu$	$\sigma$
NN3000X	61.1	121.4	121.37	25.90
NE1	82.6	132.5	132.46	21.45
	Weibull Distribution			
	$U_{1\%}$ [kV]	$U_{50\%}$ [kV]	$\alpha$	$\beta$
NN3000X	56.3	123.3	131.95	5.38
NE1	79.6	134.9	141.31	8.01

## 4. CONCLUSION

Natural esters require distinct operating conditions involving cleaner and sealed apparatuses. In these conditions natural ester showed same or better dielectric properties than mineral oil. While estimating withstand voltage of natural esters Weibull distribution always led to the lower value than Normal distribution, being on the safety side of design calculation.

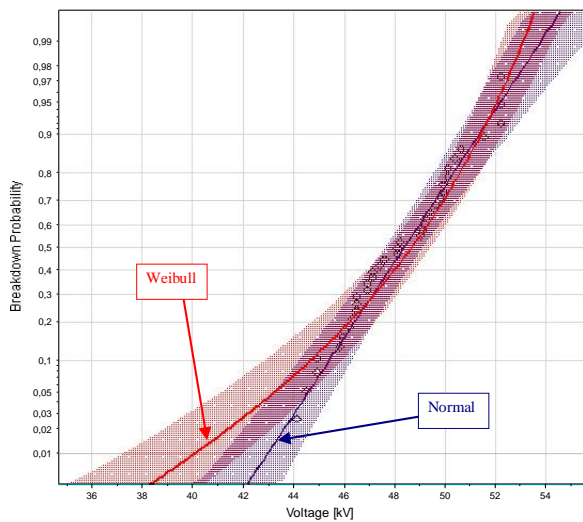
It is found that natural esters have compared to mineral oil a smaller standard deviation of measured breakdown values (Table 1-8). It means that although natural ester and mineral oil can have similar mean breakdown values, a low breakdown probability (withstand) voltage can significantly differ.

The breakdown probability functions plotted in Figure 5 correspondent to Table 3. For each of the breakdown distribution tables (Table 1-8, except Table 7) matching graphs are plotted and considered. It can be seen that the measured breakdown data follow better Normal than Weibull distribution, especially in the low breakdown probability region. This phenomenon is confirmed for all conducted experiments by

determination of the goodness of fitting by means of three different criteria (normal-log likelihood, BIC and AICc).

Ageing of the natural ester does not influence the breakdown strength (Table 4, 5). However, during the long exploitation of power transformers different impurity particles can be created. Stronger influence of the impurities (Figure 2) on the natural ester breakdown strength calls for further investigation of this phenomenon.

The lower PD inception voltage and higher streamer propagation velocity indicate that natural esters in complex non-uniform electrical field stress conditions can manifest poorer breakdown strength properties than mineral oil. This is going to be investigated in conditions involving higher voltages and larger oil gaps.



**Figure 5:** Fitted Weibull and Normal breakdown probability functions with 95 % confidence limits for NE1 in 30 mm AC non-uniform gap

The relative permittivity of natural esters (about 3.2) is closer to the permittivity of pressboard (about 5). It means that there is a slighter stresses on the oil in the layered dielectric arrangement. Particularly a creep stress over the pressboard impregnated with natural ester can be reduced (Table 8).

The contamination of natural ester with mineral oil does not influence the natural ester breakdown strength. Higher creep breakdown strength of pressboard impregnated with natural ester can save space of insulation system by reducing the gap distances for same voltage.

Different initiation and propagation characteristics of breakdown in natural esters call for further investigations before they can be employed in complex non-uniform electrical field configuration, involving large oil gaps as can be found in real power transformers.

## 5. REFERENCES

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