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Influence of the normal and tangential components of electric field strength on the beginning of surface discharge at bounding surfaces between synthetic resin pressed wood/oil and Nomex/oil

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1 Motive and definition

Different insulating materials, like for ex. synthetic resin pressed wood, chipboard, Nomex or paper, are used for output transformers filled with oil. These materials are submitted to high electric field strengths.

The present examination assignment is to improve the understanding of the different influences, especially of the components of the electric field strength, on the beginning of surface discharge at the bounding surface between solid insulating materials and insulating oil. General statements about surface discharge processes are known from literature [1]. More specific examinations with synthetic resin pressed wood are described in [2, 3].

The research project is financially supported by **Röchling Stiftung in Mannheim** who merits our special thanks. The **Company Röchling Engineering Plastics** and the **Company Schweizer Isolierstoffe** have been so kind as to supply the test specimens.

2 Experimental set-up and test procedure

The tests are carried out in a plastic test container with a diameter of 700 mm and a height of 700 mm. The test container is filled with transformer oil Shell Diala D.

A pair of vertically installed electrodes with a diameter of 250 mm which produces a homogenous electric field is used as test equipment.

The following specimens are used:

1. Rectangular rods made of synthetic resin pressed wood quality LII/2-E3 with the dimensions 10 x 10 x 300 mm, manufacturer Röchling Engineering Plastics.
2. Rectangular rods made of Nomex with the dimensions 9.8 x 9.8 x 300 mm, manufacturer Dupont.
3. Round rods made of synthetic resin pressed wood quality LII/2-E3 with a diameter of 10 mm and a length of 300 mm, manufacturer Röchling Engineering Plastics.

The specimens are installed between the electrodes with an oil gap of 2 mm in between.

Fig. 2-1 left shows the electrodes and the high voltage connection. **Fig. 2-1 right** shows details of the installation of the specimens with the supporting structure. The specimen is thus situated exactly in the middle between the electrodes.

In order to examine the influence of the normal field strength component at the bounding surface between the insulating oil and the solid insulating materials, that is to say perpendicular to the surface of the insulating material, as well as the tangential field strength component at the bounding surface between the insulating oil and the solid insulating materials, that is to say parallel with the surface of the insulating material, the specimens are introduced between the plate electrodes so that they can be rotated.

The angle α between the rods and the electrodes and the distance between the electrodes s can be varied (**Fig. 2-2**).

Fig. 2-1 Test set-up without oil. Left: electrodes with high voltage connection Right: support structure with installed specimen exactly in the middle between the electrodes. Oil gap approx. 2 mm between the electrodes and the specimen.

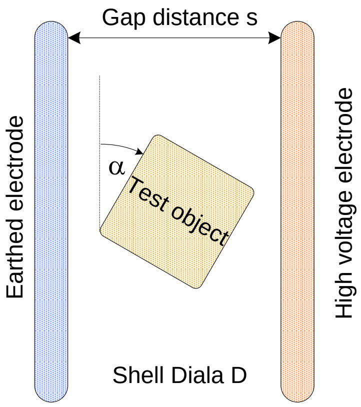


Fig. 2-2 Angle α to describe the position of the quadrangular specimens

The voltage increase is carried out with ac voltage AC 50 Hz linear with approx. 100 kV / min up the 0,6 times the expected disruptive voltage and from then on in 5 % steps of the original value with an exposure time of 60 s per voltage level.

3 Test of rectangular rods made of synthetic resin pressed wood

3.1 Test models and general descriptions

In order to facilitate analysis of the results the descriptions “rough side” and “smooth side” of the synthetic resin pressed wood which can be seen in **Fig. 3-1** will be used.

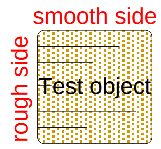


Fig. 3-1 Typical position and percentaged frequency of discharge channels in 0°-position of the rods

Fig. 3-2 schematically shows the chosen set-up of electrodes and the different angles of the specimens for the tests.

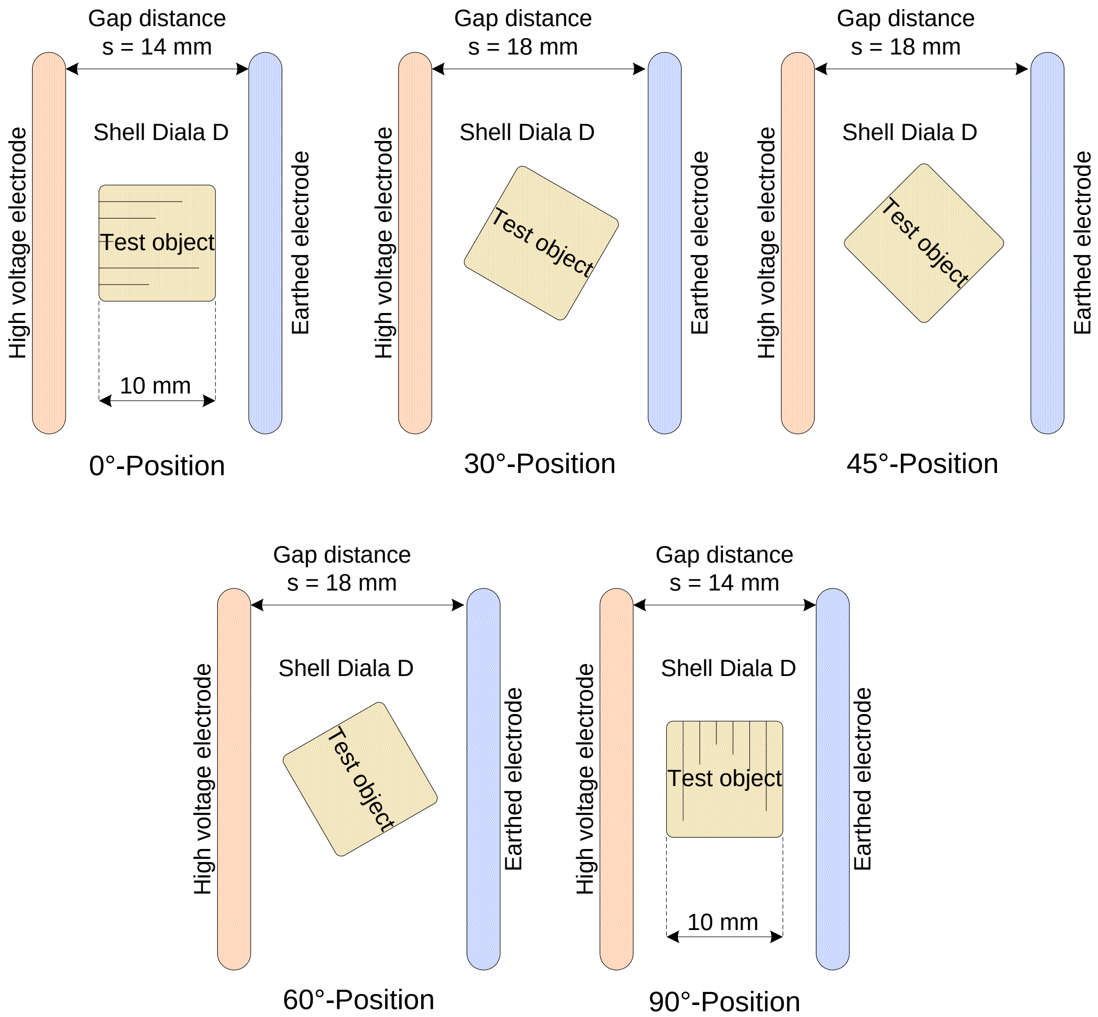


Fig. 3-2 View from above, electrodes with installed specimen for $\alpha = 0°$, $\alpha = 30°$, $\alpha = 45°$, $\alpha = 60°$ and $\alpha = 90°$

The distance s between the electrodes, that is to say the sparking distance, amounts to 14 mm (angles $\alpha = 0°$ and $\alpha = 90°$) or 18 mm (angles $\alpha = 30°$, $\alpha = 45°$ and $\alpha = 60°$).

3.2 Test analysis and test results

3.2.1 Determination of existing electric field strengths

In order to analyse the test results, first of all the average values and standard deviations for all test models must be determined. **Table 3-1** shows the results.

Table 3-1 Results of the disruption tests of synthetic resin pressed wood for the 5 different angle positions.

Measured surface discharge or disruptive voltage					
synthetic resin pressed wood angle position α	**0°**	**30°**	**45°**	**60°**	**90°**
average value [kV]	102.2	131.1	122.1	130.8	119.9
standard deviation [kV]	15.3	19.4	20.7	20.1	13.1

These voltage values may not be compared directly with one another due to the different distances between the electrodes. In order to be able to determine the electric field strength at different locations on the bounding surface between the oil and the rod made of synthetic resin pressed wood at the beginning of discharge and to compare between the different test models, all examined models are reproduced by means of a field calculation program [4]. The average voltage values shown in **Table 3-1** are used as voltage values between the plate electrodes.

Table 3-2 shows the calculated amount of the electric field as „Surface Plot“, that is to say a colour is attributed to every field strength value. In these pictures the maximum field strength is marked in the darkest red colour and can be found in the area of the edge for the positions $\alpha = 30°$, 45° and 60°. For the positions $\alpha = 0°$ and $\alpha = 90°$ there is a large volume with a high, relatively stable, field strength between the electrodes and the surface of the specimen which is parallel to them.

Table 3-2 Numeric calculation of the electric fields just before disruption

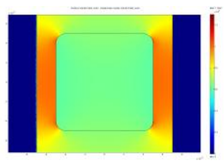
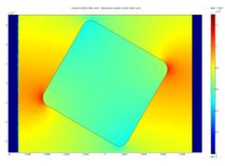
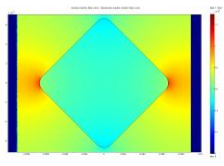
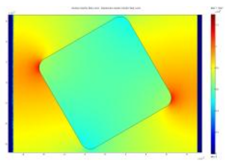
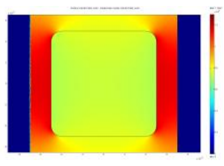
Amount of electric field strength, colour scale 0...13 kV / mm				
Position 0°	**Position 30°**	**Position 45°**	**Position 60°**	**Position 90°**
				
max: 10.4 kV/mm	max: 11.4 kV/mm	max: 10.8 kV/mm	max: 11.4 kV/mm	max: 12.2 kV/mm

Table 3-3 and **Table 3-4** show the field strength components parallel and perpendicular to the bounding surfaces between the oil and the rod made of synthetic resin pressed wood. In order to facilitate result analysis the electrodes are in rotated position for these field pictures, the specimen always stays in the same position.

In order to facilitate the denomination and to make it more clear the denomination x-component (horizontal direction) and y-component (vertical direction) are used in **Table 3-3** and **Table 3-4**, as these components are either the normal component or the tangential component depending on the part of the surface which is examined.

Table 3-3 Numeric calculation of the electric fields just before disruption

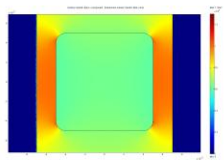
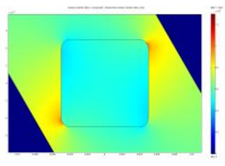
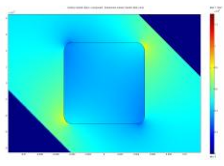
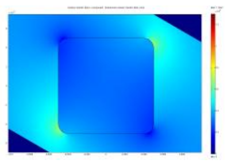
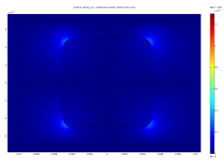
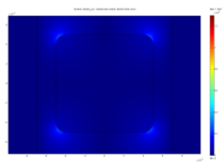
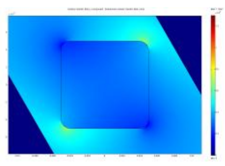
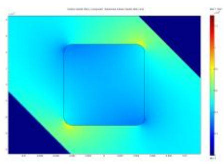
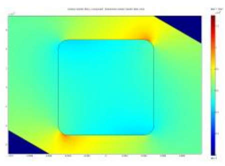
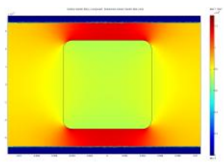
x-component of the electric field strength, colour scale 0...13 kV / mm				
Position 0°	**Position 30°**	**Position 45°**	**Position 60°**	**Position 90°**
				
max: 10.4 kV/mm	max: 10.0 kV/mm	max: 8.1 kV/mm	max: 7.1 kV/mm	max: 3.1 kV/mm

Table 3-4 Numeric calculation of the electric fields just before disruption

y-component of the electric field strength, colour scale 0...13 kV / mm				
Position 0°	**Position 30°**	**Position 45°**	**Position 60°**	**Position 90°**
				
max: 2.6 kV/mm	max: 7.6 kV/mm	max: 8.1 kV/mm	max: 9.6 kV/mm	max: 12.2 kV/mm

3.2.2 Results

3.2.2.1 Position of synthetic resin pressed wood $\alpha = 0°$

Fig. 3-3 shows typical discharge channels for this set-up.

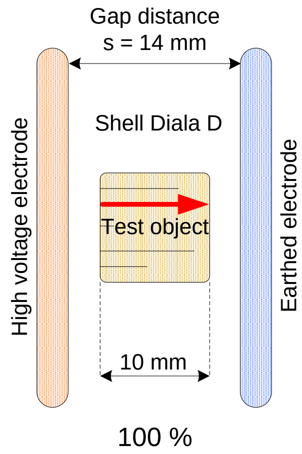


Fig. 3-3 Typical position and percentaged frequencies of discharge channels in 0°-position of the rods

Fig. 3-4 shows the calculated line diagrams of the electric field strength curves of the normal component and tangential component along the rough and the smooth side of the synthetic resin pressed wood rod.

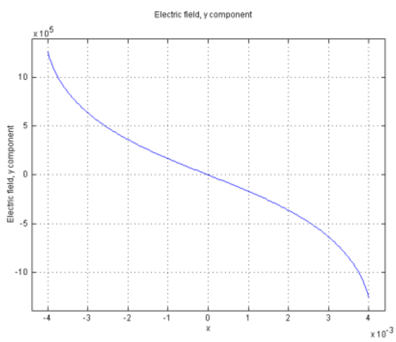
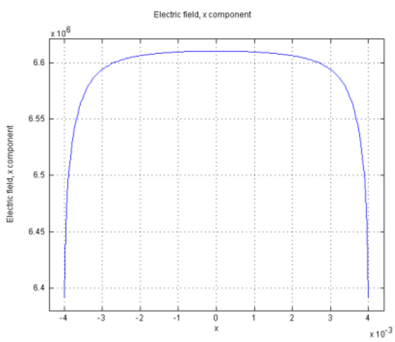
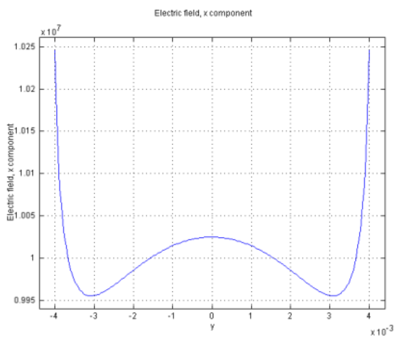
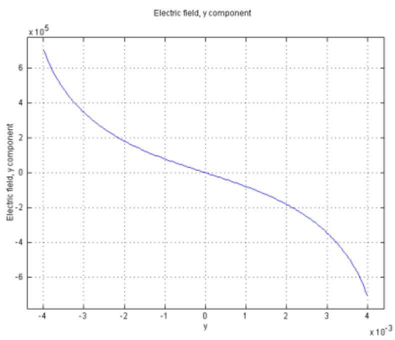
0°-position	normal component oil	tangential component oil
„smooth“ side		
„rough“ side		

Fig. 3-4 Curves of the normal and tangential components of the electric field strength along the smooth and the rough side of the synthetic resin pressed wood rod

The maximum field strength in oil (approx. 10.4 kV / mm) occurs on the rough side of the specimen. It leads to a first discharge.

The low strength of the tangential field on the rough surface (approx. 0.7 kV / mm, **Fig. 3-4**) does not provoke a slipping of the discharges towards the smooth surface, which has got a very high tangential field strength (approx. 6.4...6.6 kV / mm, **Fig. 3-4**). The discharge rather penetrates into the material due to the high normal component on the rough side (approx. 10.0...10.3 kV / mm, **Fig. 3-4**).

Within the synthetic resin pressed wood itself there are field strengths of 6.0...6.6 kV / mm. The electric strength within the synthetic resin pressed wood amounts to an average value of approx. 12 kV / mm parallel with the layers according to [5]. The disruption of the material must thus be caused by a discharge at the bounding surface of the material with the oil. After this actuation, field strengths of 6.0...6.6 kV / mm are sufficient to cause the disruption parallel with the layers of the synthetic resin pressed wood.

3.2.2.2 Position of synthetic resin pressed wood $\alpha = 30°$

Fig. 3-5 shows the registered discharge values and their percentaged frequencies.

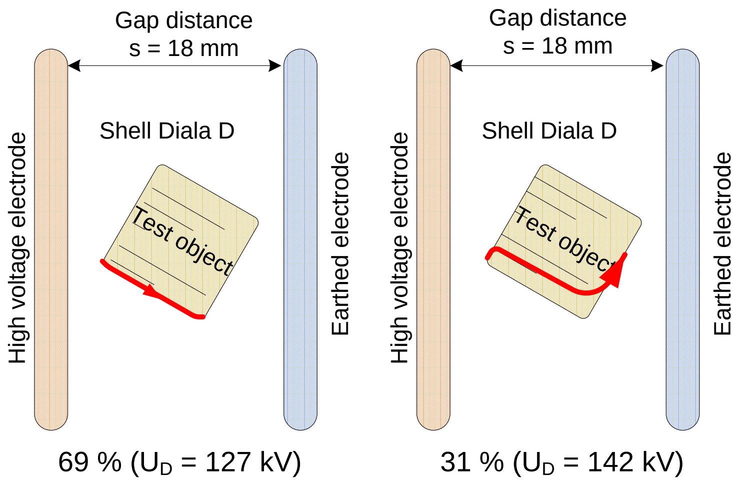


Fig. 3-5 Typical position and percentaged frequencies of discharge channels in 30°-position of the rods

The maximum field strength of 11,4 kV / mm according to **Table 3-2** occurs at the edge of the specimen and leads to the beginning of discharge.

In 69% of all cases there is a surface discharges on the „smooth“ side of the specimen, while in 31 % of the cases the discharge penetrates into the synthetic resin pressed wood on the „rough“ side and then passes through the specimen within one layer of wood and on to the opposite electrode.

For better understanding the tangential and normal field strength curves along the „smooth“ and the „rough“ side of the specimen are examined.

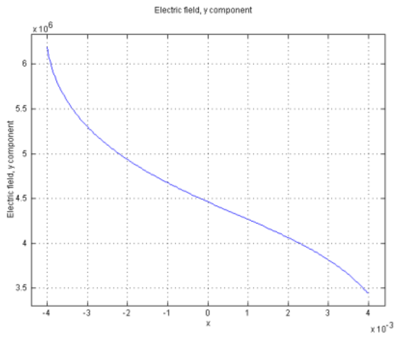
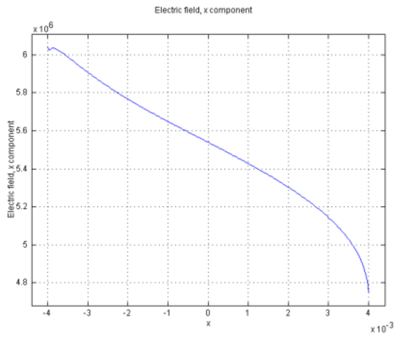
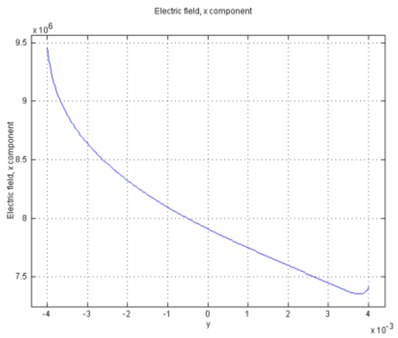
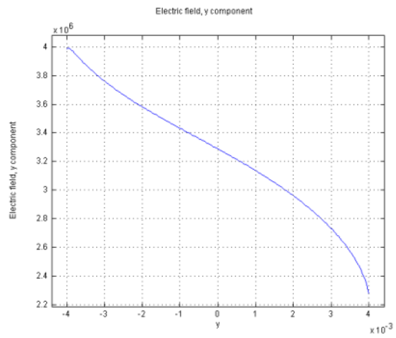
30°-position	normal component oil	tangential component oil
„smooth“ side		
„rough“ side		

Fig. 3-6 Curves of the normal and tangential components of the electric field strength along the smooth and the rough side of the synthetic resin pressed wood rod

The tangential component on the smooth side (approx. 6.0 kV / mm, **Fig. 3-6**) is considerably higher than the tangential field strength on the rough side (approx. 4.0 kV / mm, **Fig. 3-6**). This increases the probability that the discharge will spread on the smooth side.

Only when the beginning of surface discharge on the smooth side is very high for statistic reasons, there will be surface discharge along the rough side with penetration into the synthetic resin pressed wood. The normal component of the electric field strength on the rough side (approx. 9.5 kV / mm, **Fig. 3-6**) causes the penetration into the wood.

The normal component on the smooth side (approx. 6.2 kV / mm, **Fig. 3-6**) is too low to cause a penetration of the discharge that is perpendicular to the layers of the wood.

3.2.2.3 Position of synthetic resin pressed wood α = 45°

Fig. 3-5 shows the registered discharge channels and their percentaged frequencies.

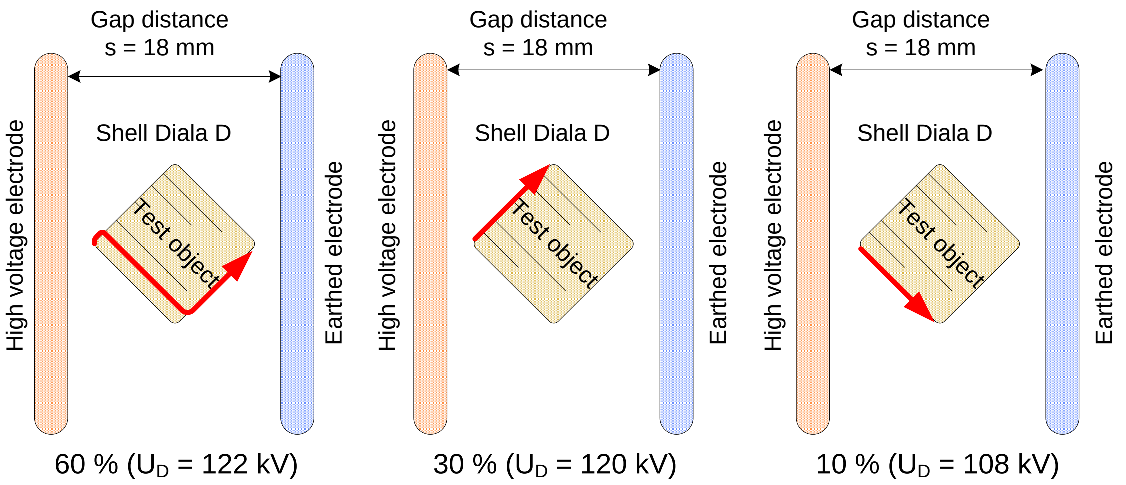


Fig. 3-7 Typical position and percentaged frequencies of discharge channels in 45°-position of the rods

Fig. 3-8 shows the electric field strength curves of the normal and tangential components along the rough and the smooth side of the synthetic resin pressed wood rod.

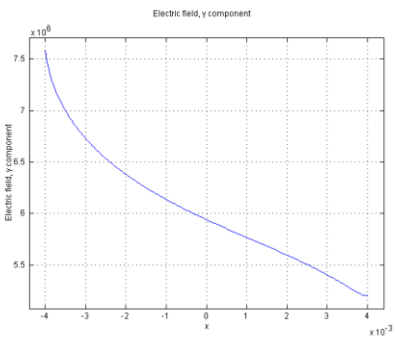
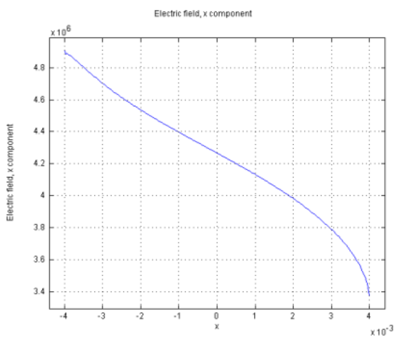
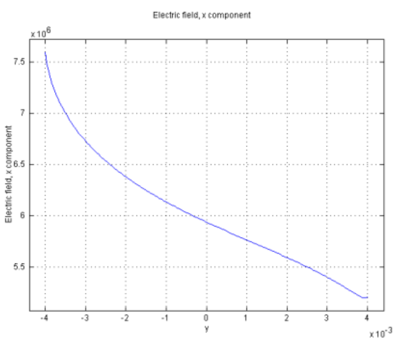
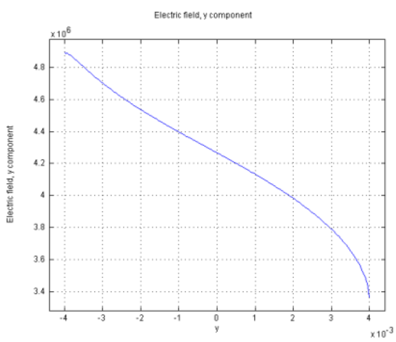
45°-position	normal component oil	tangential component oil
„smooth“ side		
„rough“ side		

Fig. 3-8 Curves of the normal and tangential components of electrical field strength along the smooth and rough side of a synthetic resin pressed wood rod

The maximum field strength of 10.8 kV / mm according to **Table 3-2** occurs at the edge of the specimen and leads to the beginning of discharge.

In 90 % of all cases the discharge will move in parallel direction with the „rough“ side. 30 % do not penetrate into the material, 60 % pass through the wood in parallel direction with the layers and then pass on the other „rough“ side in parallel direction.

The tangential field strengths on the rough and on the smooth sides are the same in 45°-position (approx. 4.9 kV / mm, **Fig. 3-8**). But as 90 % of the discharge moves to the rough side, one must conclude that the surface discharge resistance of the rough side is lower than the resistance of the smooth side.

The normal component on the rough surface (approx. 7.6 kV / mm, **Fig. 3-8**) in most of the cases leads to a penetration of the discharge into the synthetic resin pressed wood.

In 10 % of the cases the discharge runs along the „smooth“ side of the synthetic resin pressed wood.

3.2.2.4 Position of synthetic resin pressed wood $\alpha = 60°$

Fig. 3-11 shows typical discharge channels marked in red for this test set-up.

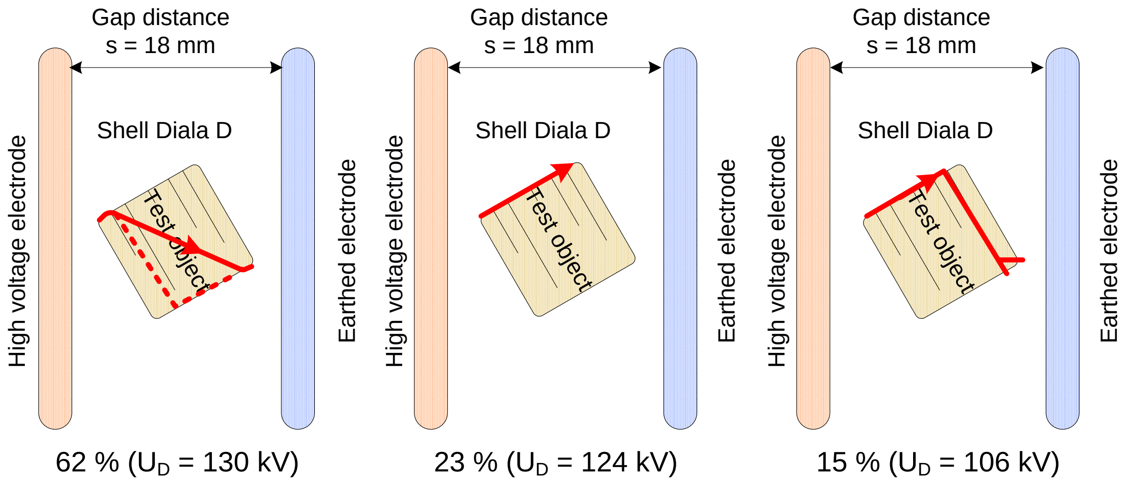


Fig. 3-9 Typical position and percentaged frequencies of discharge channels in 60°-position of the rods

Fig. 3-10 shows the electric field strength curves of the normal and tangential components along the rough and the smooth side of the synthetic resin pressed wood rod.

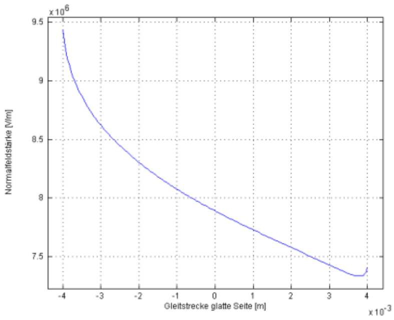
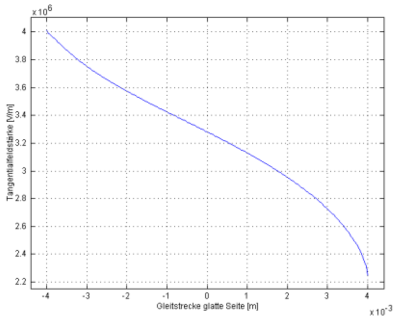
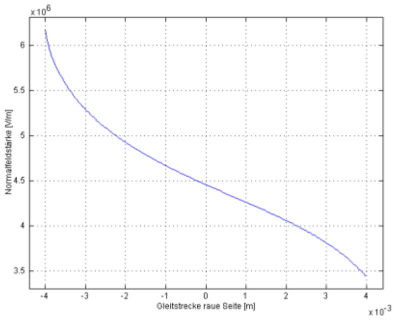
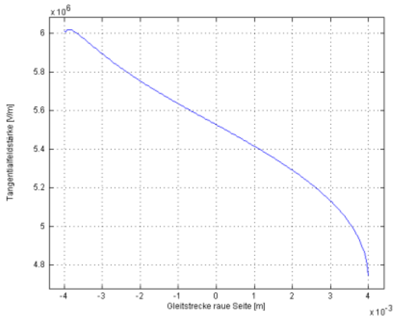
60°-position	normal component oil	tangential component oil
„smooth“ side		
„rough“ side		

Fig. 3-10 Curves of the normal and tangential components of electrical field strength along the smooth and the rough side of a synthetic resin pressed wood rod

The maximum field strength of 11.4 kV / mm according to **Table 3-2** occurs at the edge of the specimen and leads to the beginning of discharge.

In 100 % of the cases the discharge moves in parallel direction with the „rough“ side. 23 % do not penetrate into the material, 62 % move through the wood in parallel direction with the layers and then run in parallel direction on the other „rough” side or run through the wood diagonally.

The tangential field strength on the rough side (approx. 6.0 kV / mm, **Fig. 3-10**) is much higher than on the smooth side (approx. 4.0 kV / mm, **Fig. 3-10**). The normal component on the rough side (approx. 6.3 kV / mm, **Fig. 3-10**) makes the discharge penetrate into the wood in 62 % of the cases.

3.2.2.5 Position of synthetic resin pressed wood $\alpha = 90°$

Fig. 3-11 shows typical discharge channels marked in red for this test set-up.

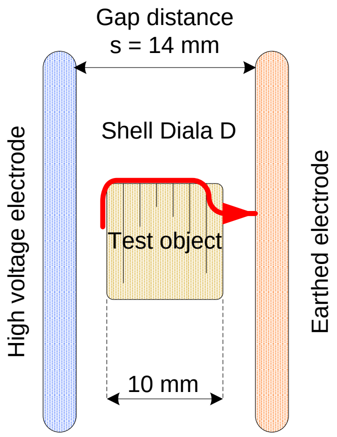


Fig. 3-11 Typical position of discharge channels in 90°-position of the rods

Fig. 3-12 shows the electric field strength curves of the normal and tangential components along the rough and the smooth side of the synthetic resin pressed wood rod.

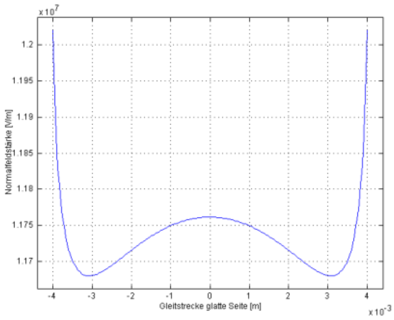
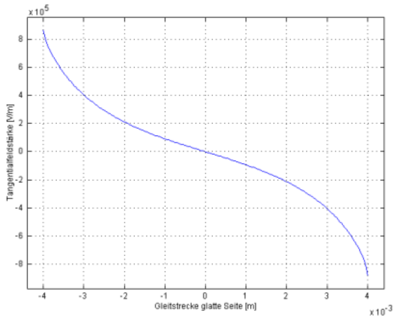
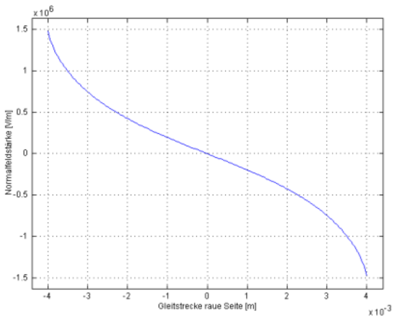
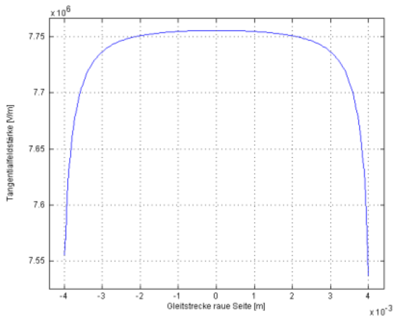
90°-position	normal component oil	tangential component oil
„smooth“ side		
„rough“ side		

Fig. 3-12 Curves of the normal and tangential components of electric field strength along the smooth and the rough side of a synthetic resin pressed wood rod

The maximum field strength of 12.2 kV / mm according to **Table 3-2** occurs close to the edge of the specimen and leads to the beginning of discharge.

This field strength, for which the normal component is by far the strongest, is not sufficient to disrupt the synthetic resin pressed wood in perpendicular direction to the layers. According to [5] an average value for the field strength of approx. 18 kV / mm would be necessary to achieve this.

Due to the low tangential component (approx. 0.8 kV / mm, **Fig. 3-12**) the discharge passes on the smooth side around the edge and reaches the area of the high tangential field strength on the rough side (approx. 7.6...7.8 kV / mm, **Fig. 3-12**).

3.2.3 Comparison of results

For all specimens the beginning point of discharge is the edge of the specimen which is submitted to the highest stress. The average oil field strengths for all test set-ups are between 10.4...12.2 kV / mm.

Summary 1: From approx. 10 kV / mm there may be discharge at the bounding surface between synthetic resin pressed wood and oil. This is the average field strength determined during the tests. Statistic analysis of the tests according to Weibull [6] gives a corresponding 1 % probability of 5.6 kV / mm, a 0.1 % probability of 4.1 kV / mm and a 0.01 % probability of 3.0 kV / mm.

The further curve of discharge depends on the test set-up. After the condition for the beginning of discharge of approx. 10 kV / mm has been fulfilled, tangential field strengths of 0.8 kV / mm are sufficient to cause surface discharge. Normal components of the field strength from approx. 3...4 kV / mm make the discharge penetrate into the wood on the „rough“ side in approx. 60 % of the cases. In approx. 40 % of the cases the discharge slides along the bounding surface.

Summary 2: When the field strength for the beginning of discharge according to summary 1 is exceeded, a tangential field strength of approx. 0.8 kV / mm along the discharge channel is necessary, in order to make the discharge proceed. Statistic analysis of the tests according to Weibull [6] gives a corresponding 1 % probability of 0.55 kV / mm, a 0.1 % probability of 0.45 kV / mm and a 0.01 % probability of 0.35 kV / mm.

Summary 3: Discharge can penetrate into the synthetic resin pressed wood in parallel direction with the layers, if there is a normal component of the field strength of approx. 3...4 kV / mm in arithmetic average. Statistic analysis of the tests according to Weibull [6] gives a corresponding 1 % probability of 1.7...2.2 kV / mm, a 0.1 % probability of 1.2...1.6 kV / mm and a 0.01 % probability of 0.9...1.2 kV / mm.

For angle position $\alpha = 0°$ the beginning of discharge occurs at 10.4 kV/mm, while for angle position $\alpha = 90°$ this beginning of discharge occurs at 12.2 kV/mm. Local elevations of the field on the rough side are obviously responsible for this phenomenon. The reasons for this elevation of the field are not yet explained.

For angle positions $\alpha = 30$, 45 and 60° there is a lower volume of high stress compared to angle positions $\alpha = 0$ und 90°, so that the disruptive field strengths are somewhat higher for statistic reasons.

Summary 4: The local field elevations are higher on the rough side than on the smooth side.

The highly stressed volume is a factor of influence.

4 Test of round rods made of synthetic resin pressed wood

4.1 Test models

Fig. 2 schematically shows the chosen set-up of electrodes and the two angle positions α = 0° and 90°of the specimens for the tests. The distance s between the electrodes, that is to say the sparking distance amounts to 18 mm.

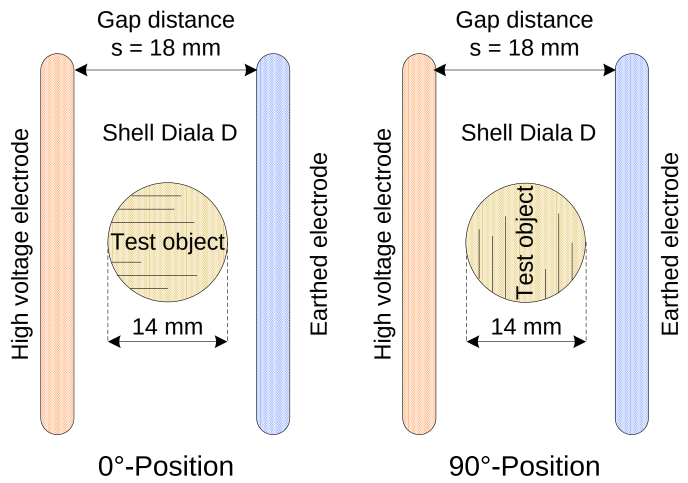


Fig. 4-1 View from above onto the electrodes with installed specimen

4.2 Test analysis and test results

4.2.1 Determination of existing electric field strengths

In order to analyse the test results, first of all the average values and standard deviations for the two test models must be determined. **Table 4-1** shows the results.

Table 4-1 Results of the disruption tests of synthetic resin pressed wood rods for 2 different angle positions.

Measured surface discharge or disruptive voltage		
specimens of synthetic resin pressed wood	**position 0°**	**position 90°**
average value [kV]	97.2	115.0
standard deviation [kV]	10.5	11.7

In order to be able to determine the electric field strength at different locations on the bounding surface between the oil and the rod made of synthetic resin pressed wood at the beginning of discharge and to compare between the different test models, all examined models are reproduced by means of a field calculation program [4]. The average voltage values shown in **Table 4-1** are used as voltage values between the plate electrodes.

Table 4-2 shows the calculated amount of the electric field as „Surface Plot", that is to say that a colour is attributed to every field strength value. In these pictures the maximum field strength is marked in yellow or orange and it occurs in the narrowest gap between the wooden rod and the electrodes.

Table 4-2 Numeric calculation of electric fields just before disruption

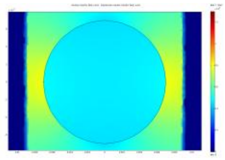
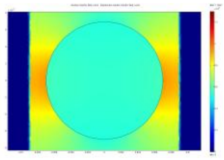
Amount of electric field strength, colour scale 0...13 kV / mm	
Position 0°	**Position 90°**
	
max: 8.0 kV/mm	max: 9.5 kV/mm

Table 4-3 and **Table 4-4** show the field strength components in parallel and perpendicular direction with the bounding surfaces between the oil and the synthetic resin pressed wood rod.

Table 4-3 Numeric calculation of electric fields just before disruption

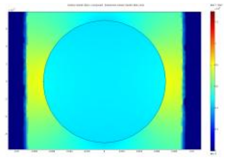
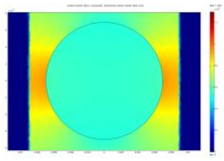
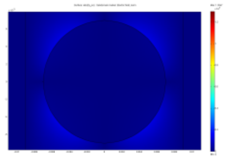
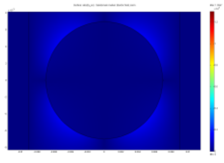
x-component of electric field strength, colour scale 0...13 kV / mm	
Position 0°	**Position 90°**
	
max: 8.0 kV/mm	max: 9.5 kV/mm

Table 4-4 Numeric calculation of electric fields just before disruption

y-component of electric field strength, colour scale 0...13 kV / mm	
Position 0°	**Position 90°**
	
max: 1.3 kV/mm	max: 1.5 kV/mm

4.2.2 Results

4.2.2.1 Position of synthetic resin pressed wood rod α = 0°

On part of the specimens no signs of burning could be found. The discharge obviously moves around the specimen through the oil and the emergency shut-down that is used for the tests prevents a burning of the specimen. **Fig. 4-2** shows the curve of typical signs of burning and their frequencies.

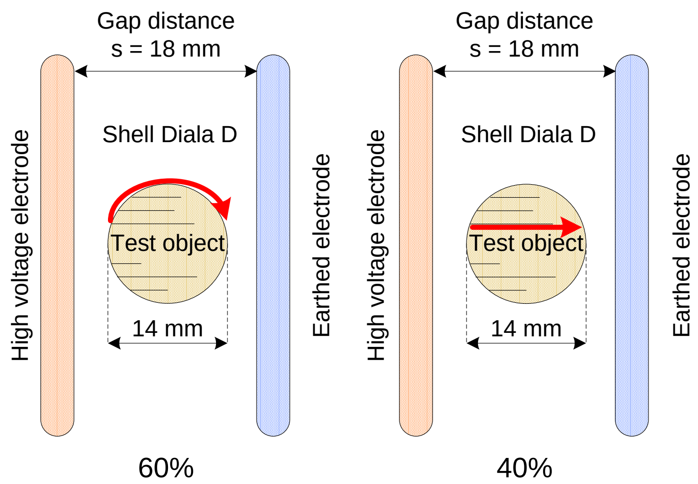


Fig. 4-2 Typical position of discharge channels in 0°-position of the round rods

The location with the maximum field strength is situated within the oil between the electrodes and the synthetic resin pressed wood in the 2 mm gap and amounts to 8.0 kV / mm according to **Table 4-2**. This field strength is sufficient for a beginning of discharge, which is then lead around the specimen due to the tangential field strength which rises up to approx. 8.0 kV / mm (**Table 4-4**).

Within the synthetic resin pressed wood there are field strengths of 4.6...4.8 kV/mm. The electric resistance within the synthetic resin pressed wood parallel with the layers according to [5] amounts to an average value of approx. 12 kV / mm.

4.2.2.2 Position of synthetic resin pressed wood α = 90°

On part of the specimens no signs of burning could be found. The discharge obviously moves around the specimen through the oil and the emergency shut-down that is used for the tests prevents a burning of the specimen. **Fig. 4-2** shows the curve of typical signs of burning and their frequencies.

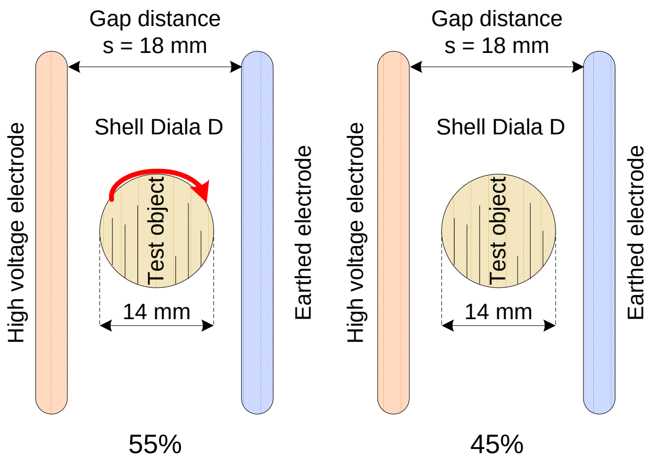


Fig. 4-3 Typical positions of discharge channels in 90°-position of the rods

The location with the maximum field strength is situated within the oil between the electrodes and the synthetic resin pressed wood in the 2 mm gap and amounts to 9.5 kV / mm according to **Table 4-2**. This field strength is sufficient for a beginning of discharge which is then lead around the specimen due to the tangential field strength which rises up to approx. 9.5 kV / mm (**Table 4-4**).

Within the synthetic resin pressed wood there are field strengths of 5.5...5.8 kV / mm. The electric resistance within the synthetic resin pressed wood in perpendicular direction with the layers according to [5] amounts to an average value of 18 kV / mm.

4.2.3 Comparison of results

For all specimens with signs of burning the point of the beginning of discharge is the side subject to the highest stress. The average beginning field strengths in the oil are between 8.0...9.5 kV/mm for both test set-ups. For these field strengths there obviously is a beginning of discharge at the bounding surface between synthetic resin pressed wood and oil, and the discharge moves around the specimen.

Summary 1: From approx. 8.0...9.5 kV/mm there may be discharge at the bounding surface between synthetic resin pressed wood and oil. This is the average field strength determined during the tests. Statistic analysis of the tests according to Weibull [6] gives a corresponding 1 % probability of 5.0...6.0 kV / mm, a 0.1 % probability of 3.9...4.6 kV / mm and a 0.01 % probability of 3.1...3.6 kV / mm.

The further curve of discharge depends on the test set-up. After the condition for the beginning of discharge of approx. ca. 8.0...9.5 kV/mm has been fulfilled, already low tangential field strengths are sufficient to cause surface discharge.

Summary 2: When the field strength for the beginning of discharge according to summary 1 is exceeded, only a low tangential field strength is necessary along the discharge channel, in order to make the discharge proceed.

For angle position $\alpha = 0°$ the beginning of discharge occurs at 8.0 kV/mm, while for angle position $\alpha = 90°$ it occurs at 9.5 kV/mm. Local field elevations on the rough side are obviously responsible for this phenomenon. The reason for this field elevation is not yet explained.

Summary 3: The local field elevations on the rough side are stronger than on the smooth side.

5 Test of rectangular rods made of Nomex

5.1 Test models

Fig. 5-1 schematically shows the chosen installation of electrodes and the different angle positions of the specimens for the tests. The distance s between the electrodes, that is to say the sparking distance, amounts to 14 mm (angle α = 0°) or 18 mm (angle α = 30° and 45°).

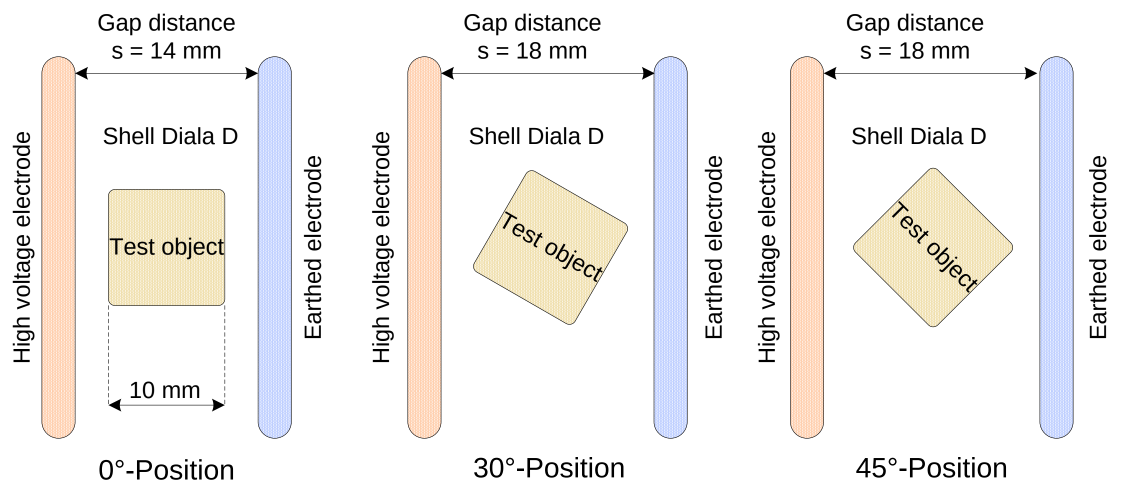


Fig. 5-1 View from above onto the electrodes with installed specimen

5.2 Test analysis and test results

5.2.1 Determination of existing electric field strengths

In order to analyse the test results, first of all the average values and standard deviations for all test models must be determined. **Table 5-1** shows the results.

Table 5-1 Results of disruption tests of NOMEX for the 3 different angle positions.

Beginning of surface discharge or disruptive voltage			
specimens NOMEX	**0°**	**30°**	**45°**
Average value [kV]	91.7	109.3	113.0
standard deviation [kV]	19.7	20.2	17.1

The voltage values may not be compared directly due to the different distances between the electrodes. In order to be able to determine the electric field strength at different locations on the bounding surface between the oil and the Nomex rod at the beginning of discharge and to compare between the different test models, all examined models are reproduced by means of a field calculation program [4]. The average voltage values shown in **Table 5-1** are used as voltage values between the plate electrodes.

Table 5-2 shows the calculated amount of the electric field as „Surface Plot“, that is to say that a colour is attributed to every field strength value. In these pictures the maximum field strength is marked in orange and is situated in the area of the edge for angle positions 30° and 45°. For angle position 0° there is a large volume with a high, relatively stable, field strength between the electrodes and the surface of the specimen which is parallel to the electrodes.

Table 5-2 Numeric calculation of electric fields just before disruption

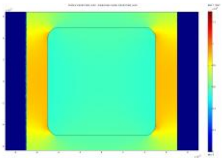
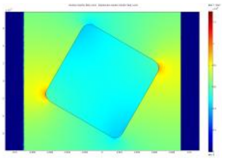
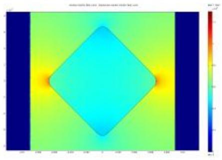
Amount of electric field strength, colour scale 0...13 kV / mm		
Position 0°	**Position 30°**	**Position 45°**
		
max: 9.1 kV/mm	max: 9.3 kV/mm	max: 10.0 kV/mm

Table 5-3 and **Table 5-4** show the field strength components in parallel and perpendicular direction with the bounding surfaces between oil and the Nomex rod. In order to facilitate analysis of the results, the electrodes have been rotated for these pictures, the specimen stays in the same position.

Table 5-3 Numeric calculation of electric fields just before disruption

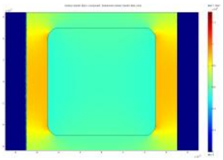
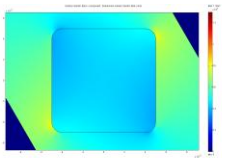
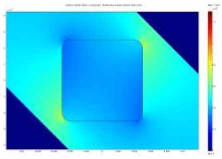
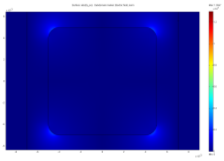
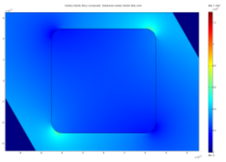
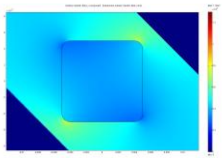
x-component of electric field strength, colour scale 0...13 kV / mm		
Position 0°	**Position 30°**	**Position 45°**
		
max: 9.1 kV/mm	max: 7.7 kV/mm	max: 6.6 kV/mm

Table 5-4 Numeric calculation of electric fields just before disruption

y-component of electric field strength, colour scale 0...13 kV / mm		
Position 0°	**Position 30°**	**Position 45°**
		
max: 2.3 kV/mm	max: 5.6 kV/mm	max: 7.1 kV/mm

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Dipl.-Ing. M. Kröger

5.2.2 Results

5.2.2.1 Position of Nomex α = 0°

Fig. 5-2 shows typical discharge channels for this test set-up.

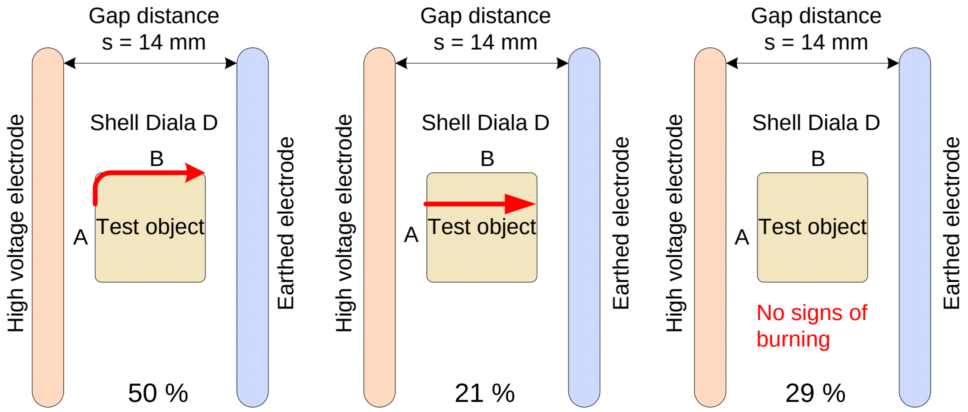


Fig. 5-2 Typical position and percentaged frequencies of discharge channels for 0°-position of the rods

Fig. 5-3 shows the calculated line diagrams of electric field curves of the normal and tangential components along the sides A and B according to **Fig. 5-2** .

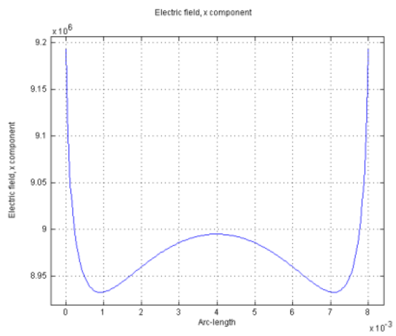
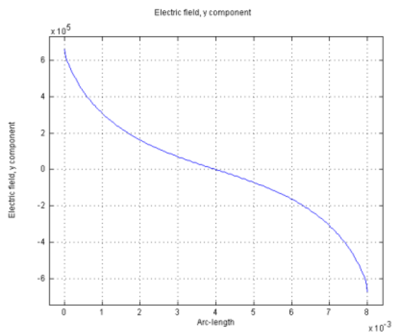
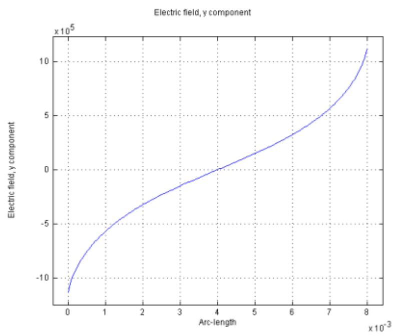
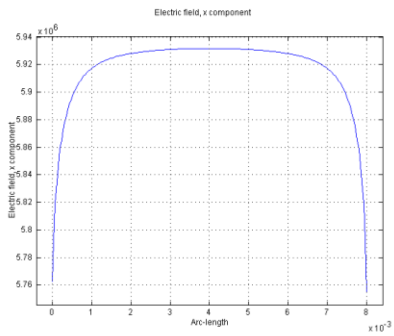
0°-position	**normal component oil**	**tangential component oil**
side A	 a.	 b.
side B	 c.	 d.

Fig. 5-3 Curves of normal and tangential components of electric field strengths along the sides A and B (according to **Fig. 5-2**) of a Nomex rod

The location with the highest field strength is situated within the oil between the electrodes and the Nomex rod in the 2 mm gap and according to **Table 5-2** amounts to 9.1 kV/mm.

When comparing the three models of disruption according to **Fig. 5-2** surface discharge around the specimen is the most frequent. The tangential field strength on side A amounts to a maximum of 0.65 kV/mm. It is sufficient to cause surface discharge.

5.2.2.2 Position of Nomex α = 30°

Fig. 3-5 shows the registered discharge channels and their percentaged frequencies.

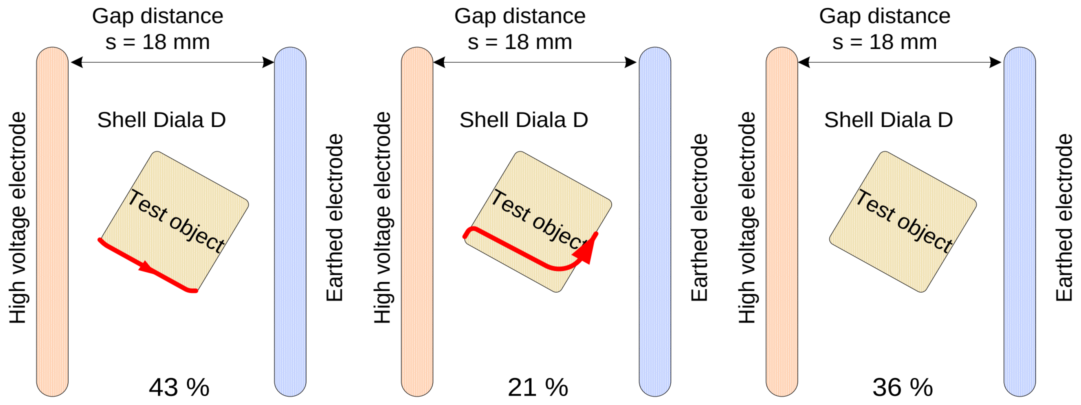


Fig. 5-4 Typical position and percentaged frequencies of discharge channels for 30°-position of the rods

The most frequent case with 43 % is a surface discharge on the surface of the specimen. The maximum field strength at the edge of the specimen according to **Table 5-2** amounts to 9.3 kV / mm. This field strength leads to a beginning of discharge and during further course the tangential component of approx. 7.7 kV / mm causes a surface discharge on the surface of the specimen.

In 21 % of the cases the discharge occurs and the discharge penetrates into the Nomex rod and exits on the other side of the rod.

5.2.2.3 Position of Nomex α = 45°

Fig. 3-5 shows the registered discharge channels and their percentaged frequencies.

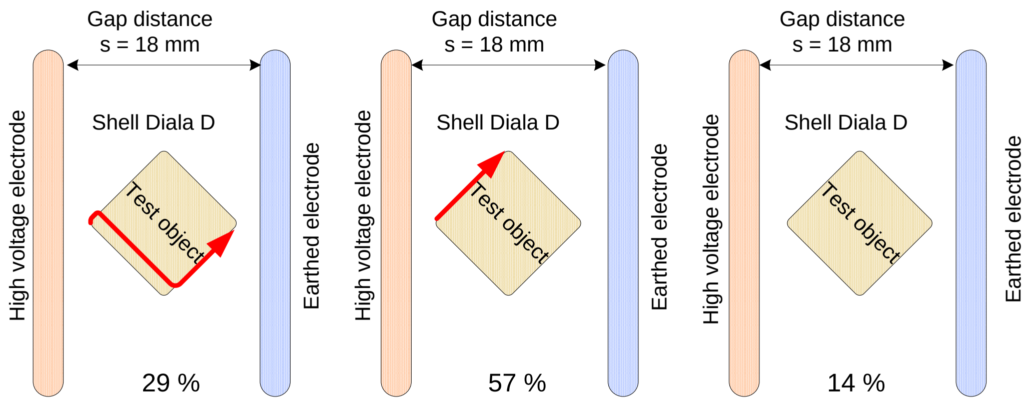


Fig. 5-5 Typical position and percentaged frequencies of discharge channels in 45°-position of the rods

The beginning of discharge occurs at the location with the highest amount of field strength of 10.0 kV / mm and in 57 % of the cases the discharge moves in parallel direction with the surface and does not penetrate into the material, 29 % pass trough the Nomex.

5.2.3 Comparison of results

For all specimens the beginning of discharge occurs at the corner of the specimen which is subject to the highest stress. The average field strengths for the beginning of discharge in the oil are between 9.1...10.0 kV / mm for all test set-ups. For these field strengths a beginning of discharge obviously occurs at the corners of the bounding surfaces between Nomex and oil.

Summary 1: From approx. 9.1 kV / mm there may be surface discharge at the bounding surface between the Nomex rod and oil. This is the average field strength determined during the tests. Statistic analysis of the tests (according to Weibull [6]) gives a corresponding 1 % probability of 4.0 kV / mm, a 0.1 % probability of 2.5 kV / mm and a 0.01 % probability of 1.7 kV / mm.

The further course of discharge depends on the set-up. After the condition for the beginning of discharge of approx. 9.1...10.0 kV / mm has been fulfilled, tangential field strengths of 0.65 kV / mm (**Fig. 5-3 b**) are sufficient to cause surface discharge.

Normal components of field strength from 5.6 kV / mm (**Table 5-4**) make the discharge penetrate into the Nomex in approx. 21 % (α = 30°, **Fig. 5-4**) of the cases.

Normal components of field strength from 7.1 kV / mm (**Table 5-4**) make the discharge penetrate into the Nomex in approx. 29 % (α = 45°, **Fig. 5-5**) of the cases.

Summary 2: When the field strength for the beginning of discharge according to summary 1 has been exceeded, a tangential field strength of approx. 0.65 kV / mm along the discharge channel is necessary to make the discharge proceed. Statistic analysis of the tests (according to Weibull [6]) gives a corresponding 1 % probability of 0.28 kV / mm, a 0.1 % probability of 0.18 kV / mm and a 0.01 % probability of 0.12 kV / mm.

Summary 3: The discharge can penetrate into the Nomex, if there is an average normal component of field strength from approx. 5.6 kV / mm. Statistic analysis of the tests (according to Weibull [6]) gives a corresponding 1 % probability of 2.7 kV / mm, a 0.1 % probability of 1.9 kV / mm and a 0.01 % probability of 1.23 kV / mm.

Summary 4: For angle position α = 0° the beginning of discharge occurs at 9.1 kV/mm, while for angle position α = 45° it occurs at 10.0 kV/mm. The reason for this is probably the larger highly stressed volume for angle position α = 0°

6 Further work

The obtained results must be verified using rods with larger dimensions, for ex. 20 x 20 x 300 mm or 30 x 30 x 300 mm. A further important test set-up is shown in **Fig. 6-1**.

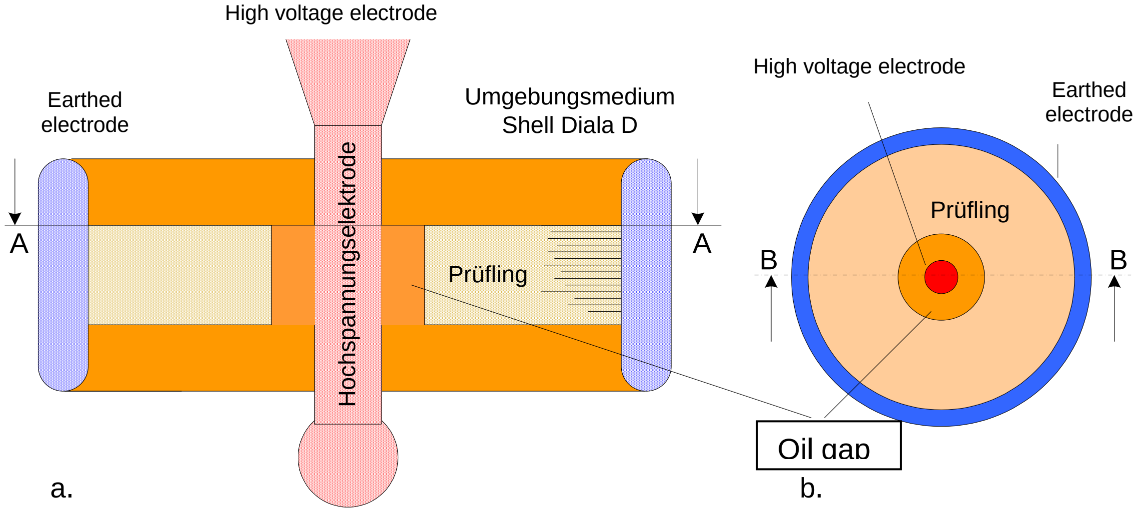


Fig. 6-1 **a.** Section B-B through a possible test set-up
b. Section A-A through a possible test set-up

In this test set-up factors of influence at the edge of the synthetic resin pressed wood rod can be examined in realistic conditions.

Further examinations must be carried out concerning the reasons of field strength elevations on the rough side of the synthetic resin pressed wood (**chapter 3.2.3**).

7 Literature and auxiliaries

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[2] Buckow, E. Havekost, M. Investigation of Creeping Discharges on the Surface of Laminated Compressed Wood Used in Power Transformers. Technical Report 1999, Laboratory for High Voltage Technology, University of Applied Sciences Osnabrück http://www.et.fh-osnabrueck.de/energie/HochspannungstechnikEMV/index.html

[3] Buckow, E. Havekost, M. Einfluss des Materials und der Oberflächenbeschaffenheit auf den Gleitentladungseinsatz an Grenzflächen mit Transformatorenöl. Technical Report 2004, Laboratory for High Voltage Technologie, University of Applied Sciences Osnabrück http://www.et.fh-osnabrueck.de/energie/HochspannungstechnikEMV/index.html

[4] Fa. Comsol Feldsimulator FEMLAB 3.0, www.femlab.de

[5] Buckow, E. Havekost, M. Teilentladungseinsatz von Kunstharzpressholz bei einer Beanspruchung parallel zur Schichtung Technical Report 2002, Laboratory for High Voltage Technologie, University of Applied Sciences Osnabrück http://www.et.fh-osnabrueck.de/energie/HochspannungstechnikEMV/index.html

[6] Fa. CRGRAPH Statistiksoftware Visual XSEL 2000, Handbücher, www.crgraph.de

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