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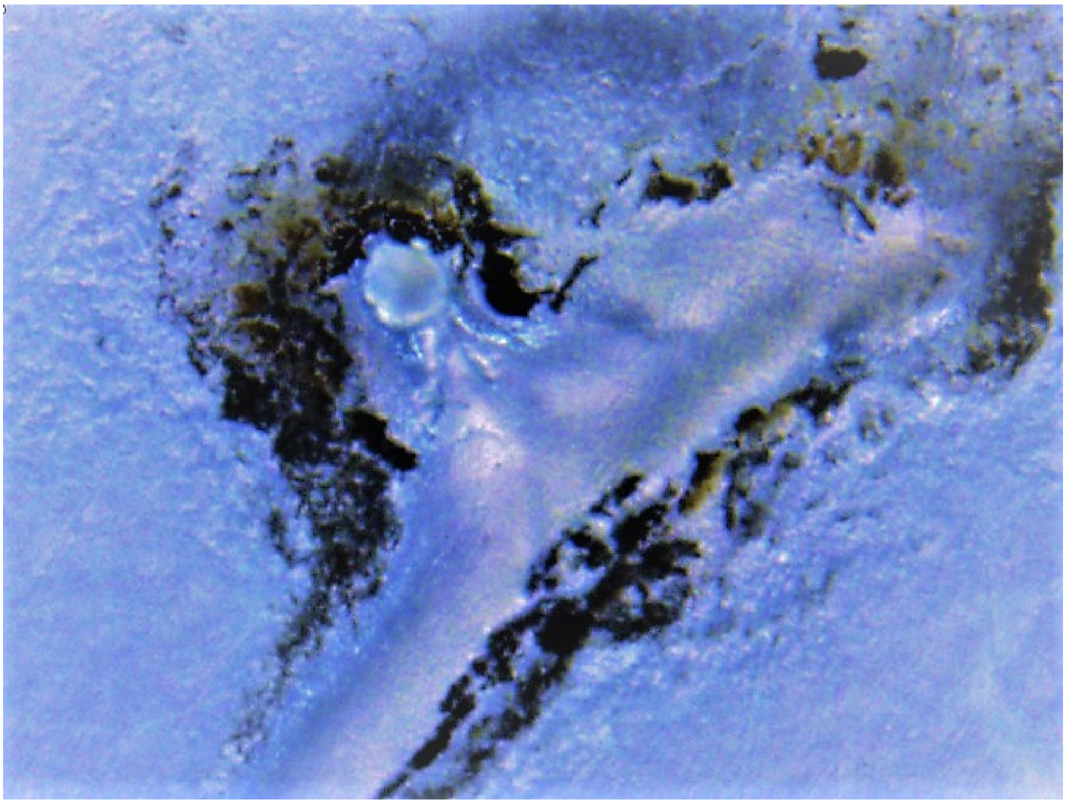

Method Development of Short Term AC Breakdown Testing

Testing intended for high voltage cable insulation materials

Bachelor's thesis in Chemical Engineering

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Gothenburg, Sweden 2018

Bachelor's thesis 2018: KBTX11

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Abstract

To transport electricity around the world, power cables with high quality is required. Our society depend on electricity and the demand is only increasing, which is why development and careful quality control of power cables are necessary. One important factor to consider when striving towards acquiring cables with a long life time is the insulation material of the cable. Insulation material is usually polymeric materials since they have excellent dielectric properties, which means they isolate an electrical flow good. The material tested in this diploma work is polyethylene.

To assure that the insulation material have a long life time and withstand high voltage, different tests are executed. This thesis will treat alternating current breakdown testing, which is a test to acquire the breakdown strength of a material. It is important to know how much voltage the material can withstand. To execute these tests, a method for high voltage testing needs to be developed further since electrical testing is complicated and requires reliable results. To test the insulation material, it is placed between two electrodes that applies the voltage in a rig. The rig is placed in a bath with oil inside a high voltage cabinet and the voltage is applied, this is when the measurement of breakdown strength starts.

The the method development of AC breakdown testing has included changing parameters in the test setup, to isolate the electrical field that is applied to the electrodes and the material so the breakdown occur in the material and not in the surrounding environment. These parameters have included: oil in the the bath, electrodes and silicone gums moulded around the electrodes. Furthermore, insulation materials with defects may decrease the overall quality. This is why polyethylene infused with a fiber particle is tested when the method development is concluded, to see if the infused fiber affect the breakdown strength of a material.

The best parameters for testing the material and reducing the problems with breakdowns in the surrounding material were the fluorosilicone oil called Wacker oil and spherical electrodes moulded in a field grading silicone gum with high permittivity named Powersil 415. They gave results with the highest applied voltage, longest test time and breakdowns with an even pattern. In addition, when testing materials infused with a fiber particle compared to reference samples without a particle, the results did not differ as much as it theoretically should, but it determined that the polyethylene films used in the method development was of high quality compared to materials that were prepared in the lab.

Keywords: Power cables, insulation material, breakdown testing, fiber particles, high voltage.

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Hedvig Pollak, Gothenburg, May 2018

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1
Introduction

The global transition towards a fossil free energy market requires innovative and sustainable solutions. Many of the renewable energy sources transform heat och mechanical power to electrical power. To use this power, we have to be able to both store and transport it in an effective and safe way. To transit useful electricity all over the world, power cables are used, and they need to be persistent to physical stress and heat, as well as having excellent electric properties and a long lifetime.

The first power cables were invented in the late 19th century, when the second industrial revolution thrived. The need for electricity has only increased since then and power cables like high voltage cables are now used both submarine and underground to transport electricity to our society[1].

One way to ensure that power cables have a long lifetime is to carefully test and accomplish great insulation material for the cables. The insulation material for power cables has to withstand and endure high voltage, heat and they need to be water resistant so that no electrical breakdown occurs and causes the cable to break. To ensure that the insulation material has the electrical properties that are needed, it is tested with different methods. One of them is called AC breakdown testing, where AC is short for Alternating Current, and is a test with the intent to measure the breakdown strength of the material using alternating current. It is important to know the breakdown strength of a material since that determines how much voltage you can apply before an electrical breakdown occur.

A problem that may occur in the cables is that the insulation material contains particles that affect the quality of the cable. Particles in the insulation material of the cable can cause electrical degradation which in the end can lead to an electric breakdown. Electric breakdowns can occur both short term and long term. Most tests in the literature are short terms tests, with the limitation that there is an uncertainty of what would happen over time when the cable age. It is difficult to measure the electrical properties in a material, since electrical testing itself is complicated and unexpected. However, one way to test a material properties is to do short term breakdown testing. Short term breakdowns are the ones studied in this diploma work and is a fast way to acquire information about the electrical properties of the material.

1.1 Aim

The prime aim of this thesis is to develop a method to do effective and accurate high voltage testing of insulation material intended for high voltage cables. The method is already used at Borelias, so the aim is to develop it. The testing is limited to alternating current high voltage. The second goal is to test the material with a fiber particle in it, to see if it affects the overall breakdown strength. The material tested is cross-linked polyethylene, which is a common insulation material.

1.2 Specification

To further clarify the way forward some questions are stated.

- Where will the breakdown occur? (In the middle of the electrodes? Outside the electrodes? At the edge of the electrodes?)
- How high voltage can be measured before the breakdown?
- Which parameters are the best to use for testing the material?
- Where will the breakdown occur when the material is infused with fiber compared to without fiber?
- Will the breakdown strength decrease when the material is infused with a fiber?

2

Theory

The theoretical background for high voltage, cables and challenges with will be presented in this chapter. Breakdown testing and analysis of data are explained to describe the methods and the results.

2.1 Introduction to high voltage testing

High voltage cables are used for transporting energy in form of electricity. To transport the huge amount of electrical effect that is required for society, the cables are designed to manage extremely high voltage. This is because electrical effect is dependent on current and voltage and, as can be seen in Equation 2.1 an increase of voltage (U) or current (I) will result in a higher effect (P). An increased current will result in a lot of heat development, which results in energy losses that is not desired. An increased current will push electrons into the material and the electrons are adhered, thus resulting in an increase of energy which is what causes the heat development. Therefore the cables are designed to transport high voltage instead of high current.

$$P = I * U \tag{2.1}$$

This is why high voltage testing of insulating materials intended for cables is so important. The high voltage requires an insulation material that has excellent dielectric properties, resulting in a long life time of the cables.

In power cables, both alternating current and direct current are used to transport electricity. The difference between AC and DC is that the electrical charge - current, only flows in one direction in DC, while AC changes direction periodically. In this thesis, high voltage testing with alternating current is executed and discussed. The testing of the materials measures the breakdown strength, which is a value in kV/mm, hence the amount of applied voltage in kilo volts per millimeter material [2].

2.2 Dielectric materials

Dielectric materials are materials that do not conduct electrical flow, they are therefore viable insulation materials. When an electrical field is applied to a dielectric material, the flow can not conduct through it as it does with for example metals. This is because the dielectric material has no free electrons that can move through the material due to chemical bonds. Instead, a polarization of the material is created, where the positive and negative charges affect the electrical field in the opposite directions, decreasing the applied electrical field in the material [3].

One example of a dielectric material used as insulating material in power cables is cross-linked polyethylene. Polyethylene is one of the most used polymers today, due to its wide field of application, and the crossed-linked version of the polymer has excellent electric properties because it has few dielectric losses and a high breakdown strength. This is connected to the strong chemical bonds in the cross-linking [1].

2.3 Electrical degradation mechanisms

Electrical degradation is the loss of electric properties over time. Polymeric materials are affected by age and are therefore studied using degradation mechanisms to be able to established what happens with a cable over time. Physical stresses can over time cause deformation of the material, while the ageing can cause chemical changes such as difference in chemical structure because of reactions freeing radicals. The ageing affects the overall electric properties of the material, resulting in decreased dielectric abilities and an increase of possibility for treeing [1][4].

2.3.1 Treeing

One type of degradation is so called treeing, it is a pre-breakdown pattern that take the form of a tree. It can occur as water treeing or electrical treeing, where water treeing occur in the existence of an electric field under wet conditions and electrical treeing occur due to electrical stress. Both of these mechanisms are long term pre-breakdown phenomenons that can lead to an actual breakdown in the material [1][4]. In Figure 2.1, the sharp edge has resulted in a field enhancement which in turn has emerged to an electrical tree.

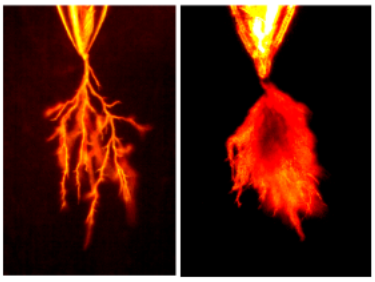

Figure 2.1: Electrical treeing from a sharp edge.

2.4 Electrical breakdowns

The definition of breakdown strength in a material can be described as the maximum voltage that can be applied until the material forms a leading pathway for the electrical field and the material disrupts. When the material disrupts and a conductive pathway is formed, it is called an electrical breakdown. Breakdowns occur due to different factors, these factors are usually divided into short time and long term breakdowns, depending on what time frame they occur when degrading a material. The source of breakdowns is usually some local imperfection or diversity in the material or its surrounding test environment. Thus, breakdowns occur at the weakest point in the surroundings[1].

2.4.1 Short time breakdown

Short time breakdowns can be categorized in the following groups:

- Intrinsic breakdown
- Thermal breakdown

where intrinsic breakdowns are the desired breakdowns for the method development in this thesis. Intrinsic breakdowns take place when the breakdown strength of the material is tested, without other surrounding factors influencing the breakdown. The breakdown happens when the applied electrical field to the material is greater than the electrical field within the material. An intrinsic breakdown can occur after 10 ns and up to 1000 kV/mm, which is far above levels where materials usually fail in practice. Thermal breakdowns are caused by dielectric losses in the insulation material. Dielectric losses develop increased temperature which emerges a breakdown[5][6].

2.4.2 Long term breakdown

Long term breakdowns are breakdowns that materialize over a long period of time. They can happen due to ageing, hence mechanical stresses resulting in deformation and chemical ageing resulting in dielectric losses. The long term breakdown mechanism can be divided in three categories:

- Breakdowns caused by partial discharge activity
- Breakdowns caused by inclusions of foreign particles
- Water treeing
- Electrical treeing

where electrical treeing is the most common one.[5] These breakdowns are hard to prevent since there is an uncertainty of what is going to happen over time. Different cables have various challenges over time since they are orientated in various environments - overhead lines, submarine lines and ground lines. The risk that the insulation material contains particles is equal for all types, while water treeing has a higher risk in the submarine lines.

Partial discharges are local electrical discharges that only partially overpass the insulation material between conductors in the cable. This can happen if there is a void in the material where the electrical field breaks through. During a partial discharge, the increased applied voltage reaches a point where the gas inside the void can not resist the electrical field and an electrical discharge occurs in the void. Partial discharges are not a full breakdown but contributes to a degradation of the insulating material which can later lead to a breakdown [5][6].

2.5 Non homogeneous insulating materials

If an insulating material contains particles that do not add to the material bonding and structure, the overall breakdown strength of the material may decrease. If a particle - for example a fiber - happens to be infused in the material during the production, it can enhance the degradation mechanism by causing treeing in the material. Figure 2.2 shows defects that may occur in cables[7].

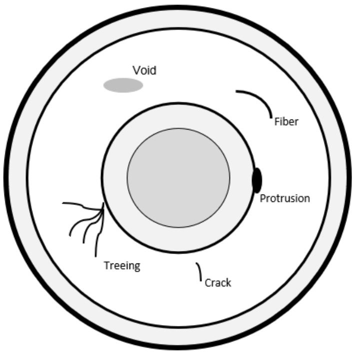

Figure 2.2: Schematic view of defects that may occur in a cable.

Defects in the cables create an increase in the electrical field at the non adding particle in the insulation material, the increase in electric field can intensify the partial discharges and greatly push the degradation forward. Hence, any particles that do not add to the original polyethylene insulation material are undesired. This requires caution within the production process and carefulness when installing the cables so no unnecessary mechanical stress is applied [5]. Depending on defect, the field enhancement is different. For example, a void give field enhancement in the cavity, when partial discharges increases over time. While defects such as fibers and metals give field enhancements in the edges around the defect. Eventually these defects will result in partial discharges that may lead to a electrical breakdown[8].

2.6 Breakdown testing

One of the reason to do breakdown testing is to test the quality of a material. The challenges with this type of testing is that the breakdowns do not occur in the material, but rather in the weakest link between the three mediums - the oil, the material and the electrode edge - called a triple point. It it easier to test the voltage capacity of a thinner test sample - a thinner sample requires less applied voltage - than a thicker test sample. An increase in the electric field (voltage) risks that the breakdown occurs somewhere else in the surrounding environment than in the material. Hence it is more difficult to reach the same breakdown strength in a thicker material. Figure 2.3 shows an overview of the test rig used for the experiments in this thesis, where HVAC is short for High Voltage Alternating Current. When testing breakdowns in a material with infused particles, the hypothesis is that the breakdown strength is going to decrease when the material is infused with fiber particles compared to a clean material [2].

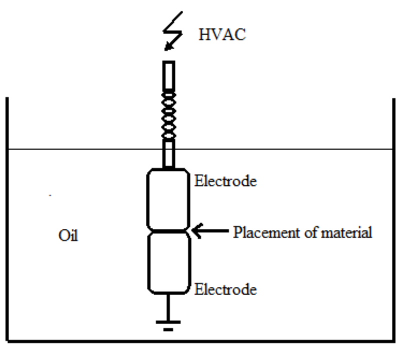

Figure 2.3: Schematic view of an example test rig for high voltage testing.

To control the electrical field, parameters with high permittivity are used. The permittivity is a material's ability to control an electric field, it can be referred to as a dielectric constant. Thus, a material with high permittivity is believed to improve the results in breakdown testing since that is a value of how good the dielectric properties are. In Equation 2.2, the left side shows the electric properties of the parameters used for the testing - in this Equation the oil, and the right side shows the electric properties of the material tested. E is the breakdown strength in kV/mm, epsilon is the dielectric constant (permittivity), and tangens delta is dielectric losses. This means that if the surrounding mediums (right side) have a higher value than material tested, it is less likely for the breakdown to occur there, which is the aim when changing parameters in the test rig [2].

$$\sqrt{tan\delta^2 + 1} \times E_{oil} \times \varepsilon_{oil} > E_{material} \times \varepsilon_{material} \times \sqrt{tan\delta^2 + 1} \tag{2.2}$$

2.7 Weibull distribution

This distribution is a way to determine how the electrical breakdowns occur. It is frequently used for electrical breakdowns since these data are notoriously deviating from the normal distribution. The Weibull distribution analyze the data with the consideration that the entire systems fails if one value fails[1]. The graphs obtained when doing a Weibull analysis show a 90 % confidence interval with the data values connected to the x-axis.

When studying the Weibull distribution, a pattern of breakdowns may be detected. If the slope of the coefficient is very narrow - have a high "shape value" - the pattern of the breakdowns is most likely the same. For example - if all breakdowns would occur at the same voltage value and have the same orientation, the slope of the collected data would be very straight. The shape parameter in the graphs is the Beta value - the range of failures in the distribution. If the Beta value is equal to 1, no connection can be concluded between the distribution of the breakdowns. If the Beta value is higher than 1, it is an indication that the distribution is narrow and a pattern in the breakdowns can be detected. However, if the Beta value is much higher than 1, for example around 70, the breakdowns probably has not occurred in the material, but rather another phenomena, possibly breakdowns in the surrounding environment. The scale parameter in the graphs is the alpha value, in Weibull distributions, this is the probability that 63 % of the breakdowns occur before that value and this is a useful distribution for electrical breakdowns[1].

3

Method

The method for the practical testing will presented in the following section. The testing is iterative - each result determine the way forward. Discussions with the supervisor and the research group are being held continuously to make sure the project move in the right direction.

3.1 Method development

The method development for high voltage testing of insulation material is studied using a test rig placed inside a high voltage cabinet. The rig is placed in a bath with silicone oil that controls the electrical field, making it possible to apply voltage under controlled circumstances. The rig consists of two electrodes placed towards each other where the test sample is placed between them. The general construction of the test rig is used throughout the project, but parameters such as oil and electrodes are changed. Figure A.1 displays the general setup where the samples are tested. The insulation material tested is a thin film of polyethylene which is placed between the electrodes, and after the breakdown occurs, the orientation of the breakdown at the film is studied. The desired orientation of the breakdown on the films is in the middle of the electrodes, because the edge of the electrode has a high risk of creating a triple point where the breakdown occurs. Results are acquired after a so called ramping of voltage. The initial value of the applied voltage is 15 kV, and is then increased with 100 V/s. Each test consists of 10 samples of film being executed separately until breakdown. In Figure A.1 a picture of the test rig can be seen and a more detailed view with explanation of the setup can be viewed in Appendix 1.

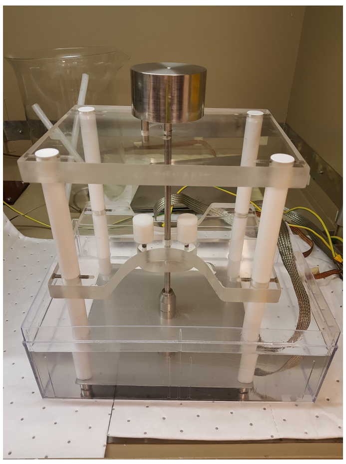

Figure 3.1: High voltage test rig with standard electrodes.

3.1.1 Test series

The same type of polymer films are tested but with different thickness, one type is 0.3 mm thick and the other 0.5 mm. When ten samples of both 0.5 mm and 0.3 mm films have been tested with the same oil and electrodes, they are referred to as a series. Hence, a series consists of 20 sample tests in total, with the notation that some deviation occur when samples are discarded for various reasons. All series are run with an initial value of 15 kV and an increase of applied voltage of 100 V/s.

3.1.2 Reference testing

Before starting the experiments with the initial value 15 kV, two reference tests were done. This was made to both learn the test setup and to test the polyethylene films to get a standard result. The polyethylene films have not been used before, which is why they are tested. The reference testing was done with 20 mm standard electrodes, silicone oil and an initial value of 0 volts with a raise of 2 kV/s, which is the standard reference test at Borealis.

3.1.3 Parameters

To optimize the method for high voltage testing, parameters are changed. An overview of series and what they are tested with can be seen in Table 3.1. The direct goals with each changing parameter is to get an increased voltage and time before the breakdown and to steer the orientation of the breakdown from the electrode edge to the middle of the electrodes. Table 3.1 shows the parameters that were changed during the method development and their properties.

Table 3.1: Parameters and their properties.

Name	**Parameter**	**Permittivity**	**Theoretical**
Xiameter - silicone	Silicone oil	2.6	Good heat stability, low surface energy, various applications
Wacker fluid	Silicone oil	7	Field grading - Fluorosilicone give strong dielectric abilities
Powersil 415	Silicone gum	15	Field grading – Used for cable applications, terminations of cables
Powersil 600 A/B	Silicone gum	2.9	Anti-tracking - Terminates currents in materials
Sylgard 184 (DC gum)	Silicone gum	2,7	Good dielectric properties - Used for high voltage resistor packs
Semicosil 927	Silicone gum	8	Field grading – Fluorosilicone – Used for embedding of electronic components

Table 3.2: Overview of test series and parameters.

Series	Electrode	Oil	Silicone gum
1	Standard	Silicone	-
2	Standard	WACKER FLUID AF98/1000	-
2	Standard	WACKER FLUID AF98/1000 - degassed	-
3	Spherical	WACKER FLUID AF98/1000	-
4	Spherical	WACKER FLUID AF98/1000	Powersil 415 uncured
5	Spherical	WACKER FLUID AF98/1000	Powersil 600 A/B
6	Spherical	WACKER FLUID AF98/1000	Powersil 415 cured
7	Spherical	WACKER FLUID AF98/1000	DC gum
8	Spherical	Silicone	Powersil 415 cured

The reason to try these specific parameters shown in Table 3.1 and dividing them in series seen in Table 3.2, is that they have high permittivity, field controlling and field isolating properties. If the electrical field around the electrodes can be changed or isolated, the breakdown can be controlled and hopefully occur in the desired place - the material between the electrodes.

The Wacker oil has a higher permittivity than the standard silicone oil, hence the dielectric properties are believed to be better for the high voltage testing. They are both silicone oils but the Wacker oil is much more viscous. The different silicone gums are moulded on the spherical electrodes to try to isolate the edge between the flat part of the electrode and the spherically formed one. When the moulding of the gum is done, it is presumed that the mold stays in place around the electrodes.

3.1.4 Series 1&2

These two series were executed with standard electrodes, they are the most commonly used at Borelias when testing AC breakdowns. Figure 3.2 shows how they look in the rig for testing when the electrodes are placed upon each other. The difference between series 1 and 2 is that the oil is changed from silicone oil to Wacker oil to see the difference it makes.

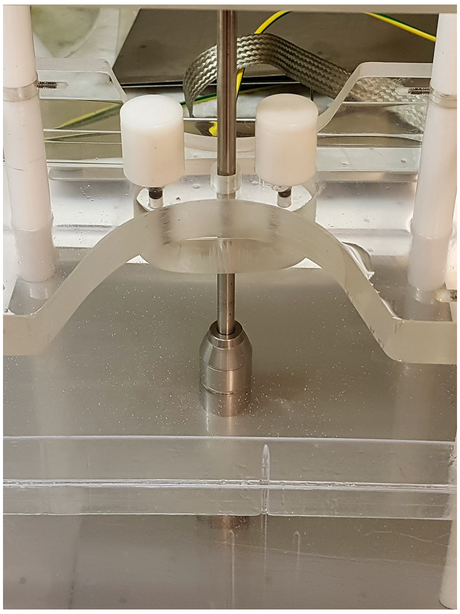

Figure 3.2: Standard electrodes for series 1 and 2.

3.1.5 Series 3

This series was the first time the spherical electrodes were used. One reason to try spherical electrodes is because the edge of the electrodes are round, hence they have a softer edge and the risk of getting a triple point there is decreased. In addition to spherical electrodes, Wacker oil and films of both 0.3 mm and 0.5 mm were tested.

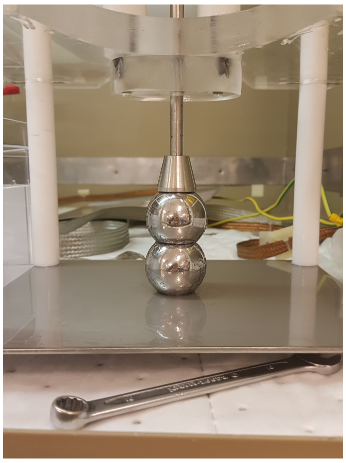

Figure 3.3: High voltage test rig with spherical electrodes for series 3.

3.1.6 Series 4

In this series, silicone gum around the spherical electrodes is introduced. This gum is called Powersil 415 and is a field grading silicone rubber with high permittivity, which means it has a great ability to control the electric field. At this first try, the mold was simply processed straight from the package and shaped around the electrodes, the result and setup can be viewed in Figure 3.4. The silicone gum was shaped around the electrodes with the goal to steer the breakdown away from the electrode edge towards the middle of the electrodes. Series 4 is executed in Wacker oil.

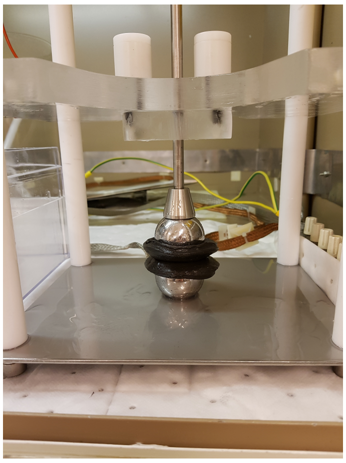

Figure 3.4: High voltage test rig with spherical electrodes moulded in uncured Powersil 415 for series 4.

3.1.7 Series 5

A new gum for spherical electrodes was tested in series 5, Wacker oil and these electrodes are used to study the testing and the breakdown pattern. Powersil 600

A/B is a silicone gum with two components, three parts of component A and one part B with strong dielectric properties. Figure 3.5 displays a picture of the setup with this mold. The two liquid components A and B were mixed and then degassed in a vacuum oven for about an hour before is was poured in a glass beaker around the electrodes and left to cure for 16 h.

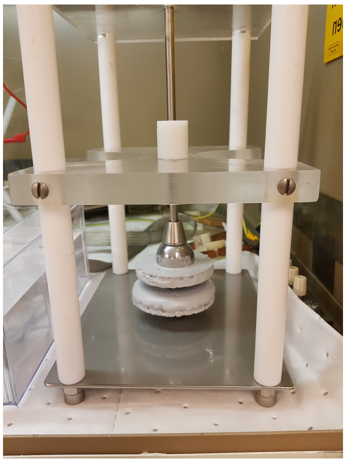

Figure 3.5: Spherical electrodes moulded in Powersil 600 A-B for series 5.

3.1.8 Series 6

For the 20 tests in series 6, the field grading silicone gum Powersil 415 was used again but this time it was cured. The mold was shaped around the electrodes and then cured in an oven for 2 hours to harden the gum so it remainrf at the same place around the electrodes, making it easier to handle. In addition to these electrodes, Wacker oil was used. Figure 3.6 shows how the moulded electrodes look in the test rig.

Figure 3.6: Spherical electrode s moulded in cured Powersil 415 for series 6.

3.1.9 Series 7

Series 7 was a short series with five 0.5 mm tests. This is because the execution of the moulding of electrodes did not proceed as expected. The spherical shape affected the gums ability to stay in the same place. This was a one component gum and was cured in an oven for three hours before using it. The series was done in Wacker fluid.

3.1.10 Series 8

In this final development test, the cured Powersil 415 spherical electrodes were used and the standard silicone oil (Xiameter) is used to see if the applied voltage can be as high as in the Wacker oil as well as affecting the breakdown orientation.

3.2 Fiber testing

The second goal with this diploma work was to test a material with and without a fiber particle infused in it. This was done in two different ways to see if there is any difference in the results. One method was to press polyethylene plaques to use as test samples and the other was to use tape, long stripes of polyethylene made at Borealis, that were cut evenly to test samples. Each method was executed without fiber particles in it to have a reference, and then proceeded with fiber particles. Table 3.3 consists of the parameters used for this testing.

Table 3.3: Overview of the parameters for fiber testing.

Series	Electrode	Oil	Mold	Sample	Type
9	Spherical	Silicone	Powersil 415 cured	Plaque	Reference
9	Spherical	Silicone	Powersil 415 cured	Plaque	Fiber particle
10	Spherical	Silicone	Powersil 415 cured	Tape	Reference
10	Spherical	Silicone	Powersil 415 cured	Tape	Fiber particle

4 Results

In this following section, the relevant and comparing results are presented. In total 218 tests were done, resulting in a great amount of data to analyze. The results are presented in Weibull distribution graphs, where each value is one test sample with a breakdown. The plotted values are breakdown strength, measured in kV/mm. All data can be viewed in Appendix 1.

4.1 Method development

The method development was successful and generated a lot of data. The results are presented with each parameter being compared to one another.

4.1.1 Effect of oil

The two oils gave different outcomes. The Wacker oil resulted in a higher voltage value, less amounts of small discharges and noise during the measurement period of the test samples. This is why the Wacker oil was used for the most part of the method development.

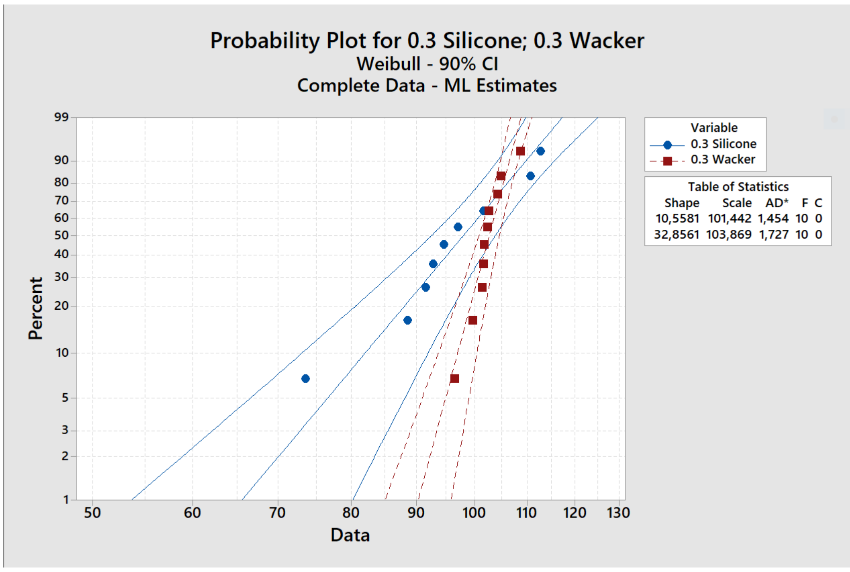

Figure 4.1: Weibull distribution of breakdowns in 0.3 mm polyethylene films in silicone and Wacker oil with standard electrodes.

Figure 4.1 displays a distribution of Series 1 breakdowns in 0.3 mm polyethylene with the two different oils. The population for Wacker oil is more homogeneous since the confidence interval has less distribution and a higher slope value (labeled shape value in Figure 4.1), suggesting that the breakdown pattern is more alike when using this oil.

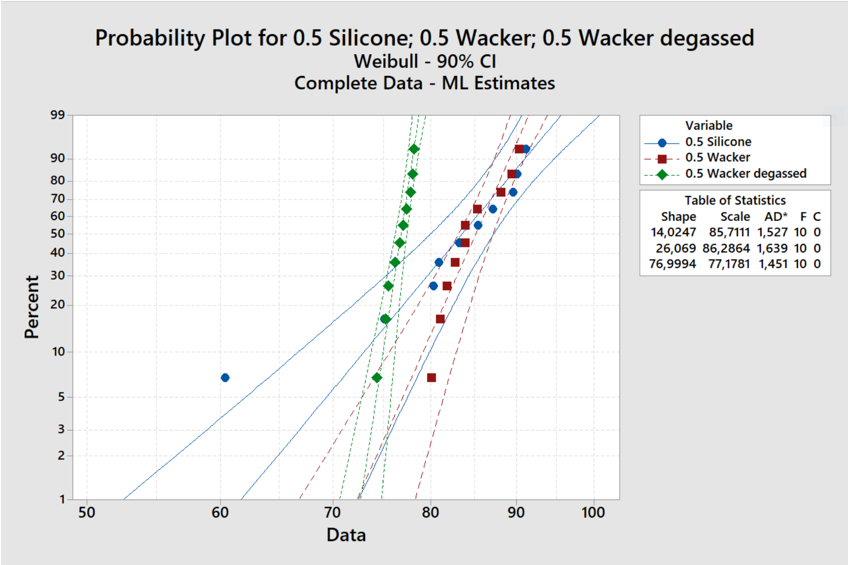

Figure 4.2: Weibull distribution of breakdowns in 0.5 mm polyethylene films in silicone and Wacker oil with standard electrodes.

The comparison between Wacker oil and silicone oil when testing 0.5 mm polyethylene films can be viewed in 4.2. The Wacker oil was extremely viscous and when poured into the bath, air bubbles were formed, which may decrease the electric properties like the high permittivity of the oil and affect the results negatively. Thus an attempt to degas the oil in an oven for 16 h at 60 degrees was done. The population of the degassed oil suggest the same sort of breakdown for all the test samples. As can be seen in Appendix 1, all the the breakdown seemed to occur out in the rig or oil, not in the material. This resulted in the homogeneous data with an extremely high coefficient of slope.

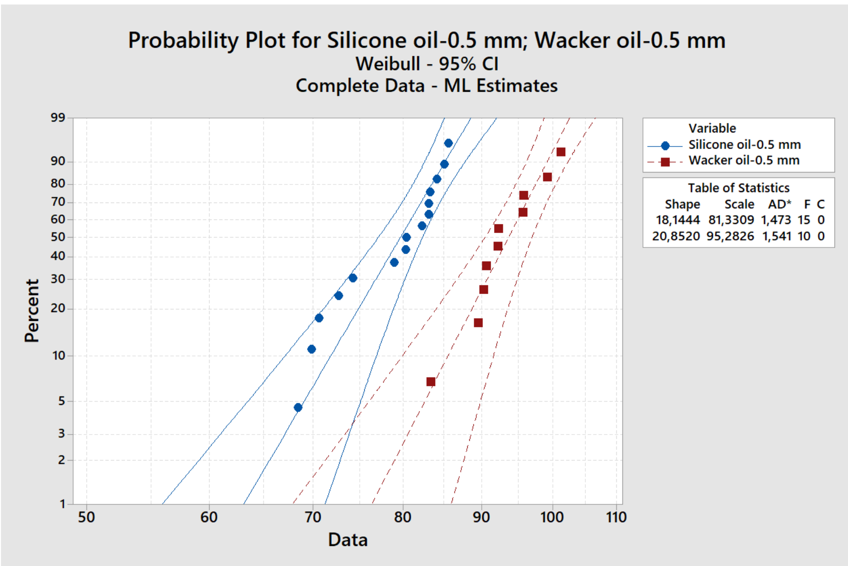

Figure 4.3: Weibull distribution of breakdowns in 0.5 mm polyethylene films in silicone and Wacker oil with Powersil 415 cured electrodes.

The effect of oil was also studied at the end of the method development, when the spherical electrodes was moulded with Powersil 415, to see how the combination of two field grading parameters (oil and mold) affects the breakdown results. The distribution of this can be seen in Figure 4.3, where the conclusion that the Wacker oil still has a higher voltage outcome can be established. The difference is that the silicone oil influences the orientation of the breakdowns towards the middle of the electrodes compared to the Wacker oil (see Apeendix 1).

4.1.2 Effect of moulding electrodes

A big part of the method development involved testing different silicone gums around the spherical electrodes to see how they affected the applied voltage and breakdown pattern. Three types of gums where tested, where cured Powersil 415 resulted in the highest voltage and longest time before a breakdown.

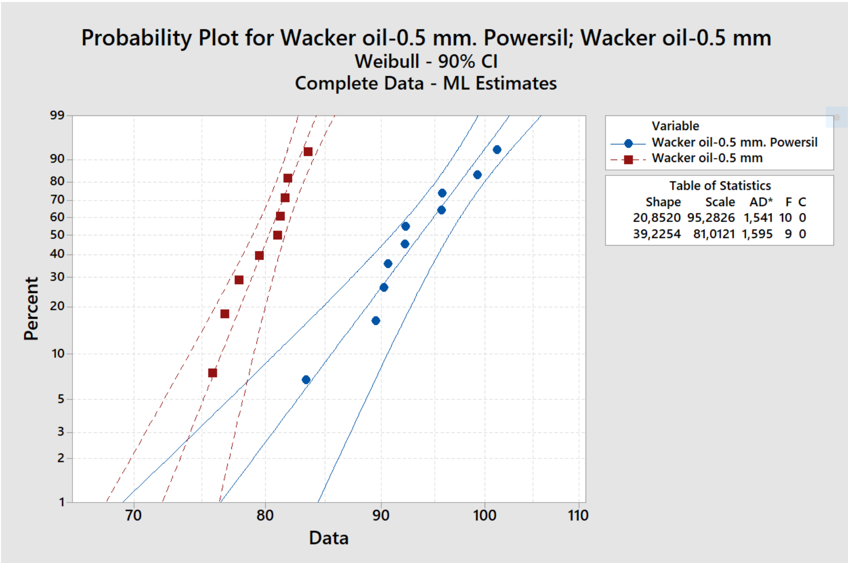

Figure 4.4: Weibull distribution of breakdowns in 0.5 mm polyethylene films in Wacker oil with Powersil 415 cured electrodes and spherical electrodes without mold.

As can be seen in Figure 4.4 the moulded electrodes gave a higher breakdown strength than the electrodes with no mold.

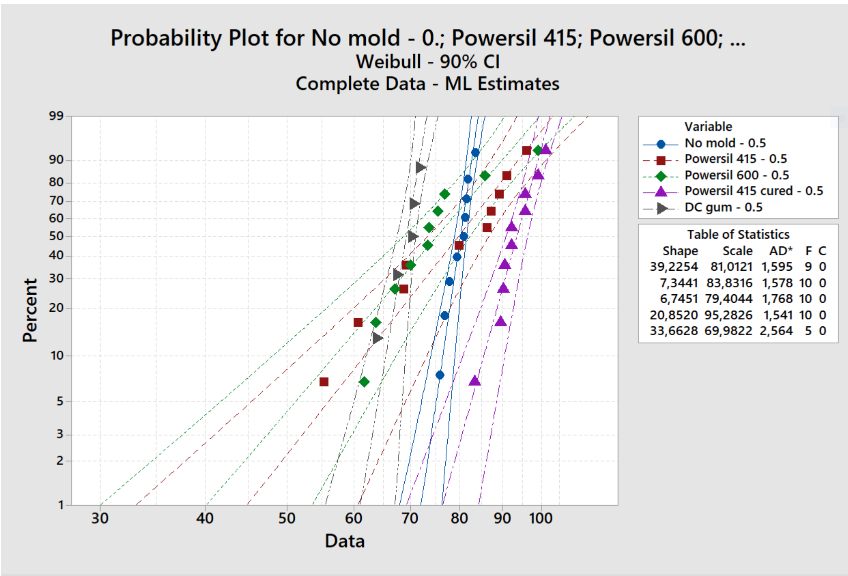

Figure 4.5: Weibull distribution of breakdowns in 0.5 mm polyethylene film with different mold around the spherical electrodes

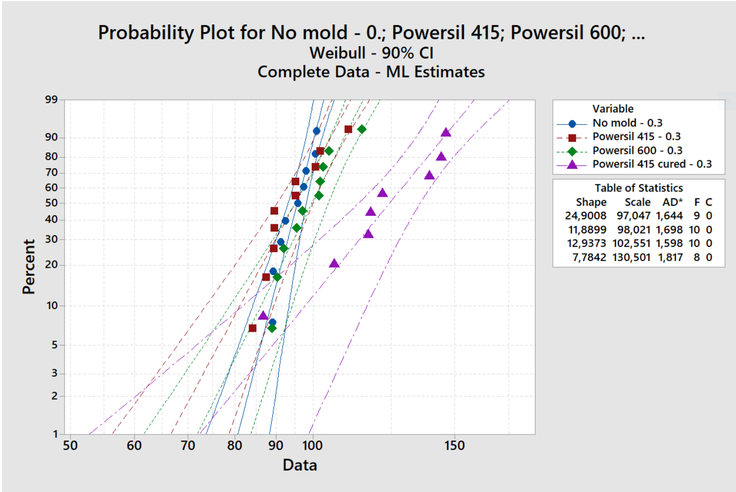

Figure 4.6: Weibull distribution of breakdowns in 0.3 mm polyethylene film with different mold of silicone gum around the electrodes.

The distribution in Figure 4.5 and Figure 4.6 shows the affect of different molds of silicone gum on the spherical electrodes in Wacker oil, using both 0.3 mm and 0.5 mm films. The cured Powersil 415 got the best breakdown strength in the two films and was additionally the mold that fitted the electrodes best. These series (3-7) were executed with Wacker oil, hence the results are affected of both field grading oil and gum.

4.1.3 Effect of volume

As mentioned before, all series have been tested with 0.3 mm and 0.5 mm polyethylene films. In the previous two sections, the distribution of breakdowns has been compared with different oil and different electrodes. In this section, some examples where the actual polyethylene films are plotted against each other are shown. This is done to determine the volume effect of the breakdowns, hence how the thickness affects the result.

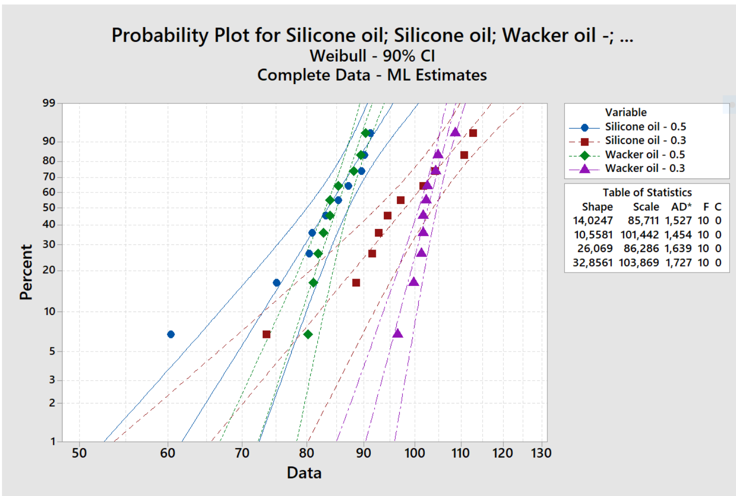

Figure 4.7: Weibull distribution of breakdowns in 0.5 mm and 0.3 mm polyethylene films with standard electrodes in both Silicone oil and Wacker oil.

The volume effect can be studied in Figure 4.7 where breakdowns in 0.3 have a higher breakdown strength than 0.5 in both silicone oil and Wacker oil, but the Wacker oil gives a better distribution in both cases.

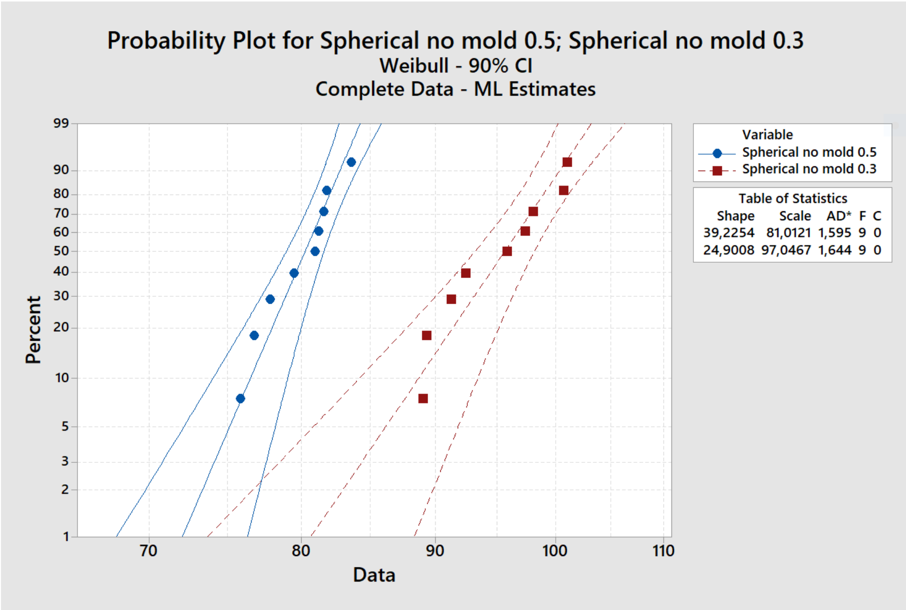

Figure 4.8: Weibull distribution of breakdowns in 0.5 mm and 0.3 mm polyethylene films with spherical electrodes and Wacker oil.

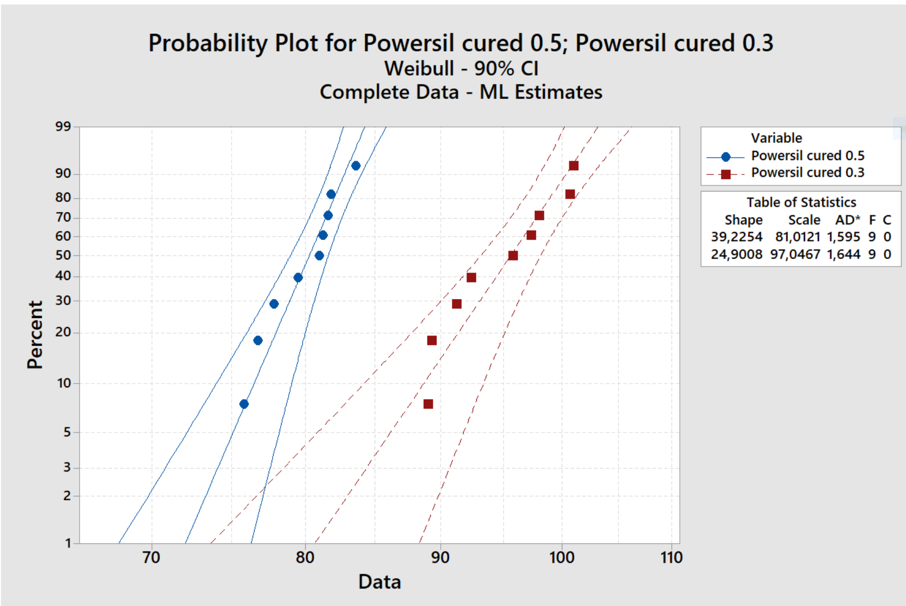

Figure 4.9: Weibull distribution of breakdowns in 0.5 mm and 0.3 mm polyethylene films with cured Powersil 415 electrodes and Wacker oil

In both Figure 4.8 and Figure 4.9 the 0.3 mm films are plotted against the 0.5 mm films in Wacker oil but with no moulded electrodes and Powersil 415 gum. 0.3 mm clearly has a higher breakdown strength than 0.5, but the distribution is more homogeneous in the 0.5 mm, establishing a more similar breakdown pattern.

4.2 Fiber testing

The fiber testing was executed using silicone oil and cured Powersil 415 electrodes in each of the methods. The results are presented in both tables and Weibull graphs.

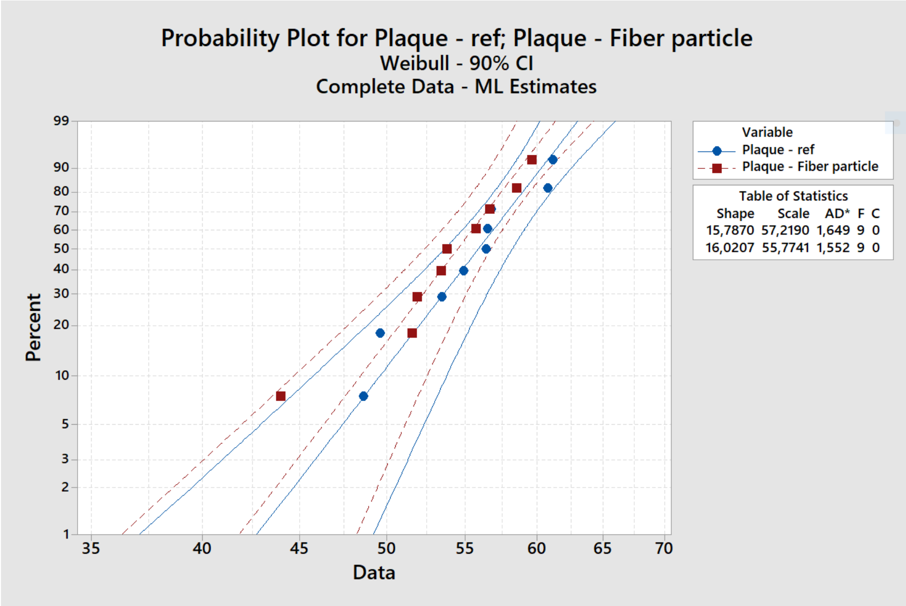

Figure 4.10: Weibull distribution of breakdowns in plaques with and without fiber particles in it.

The result of both fiber testing methods can be viewed in Figure 4.10 and Figure 4.11. The breakdown strength in the materials infused with a fiber particle is not much lower than the strength of the clean material in both methods. However, the breakdown distribution between the reference and fiber particle is similar in the plaques while they differ in the tape.

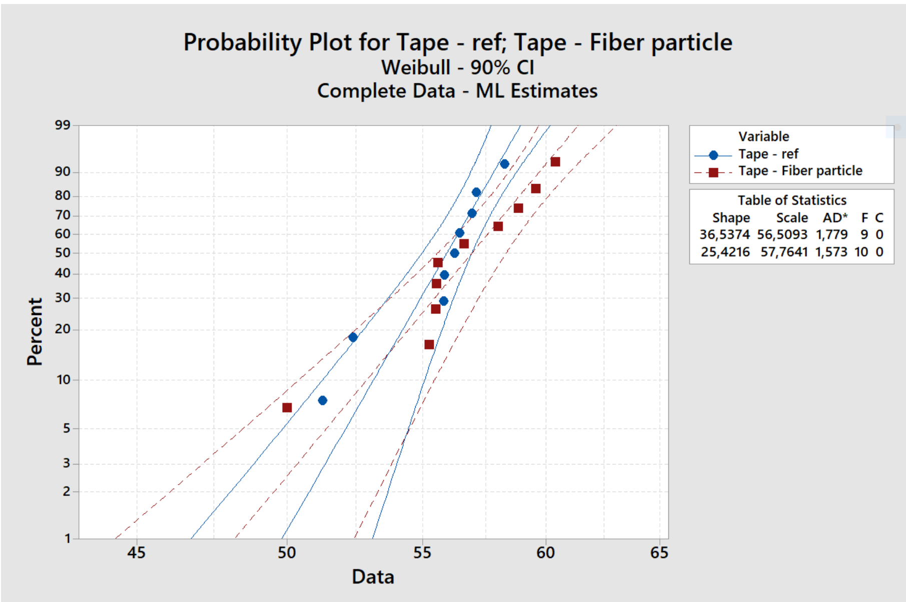

Figure 4.11: Weibull distribution of breakdowns in tape with and without fiber particles in it

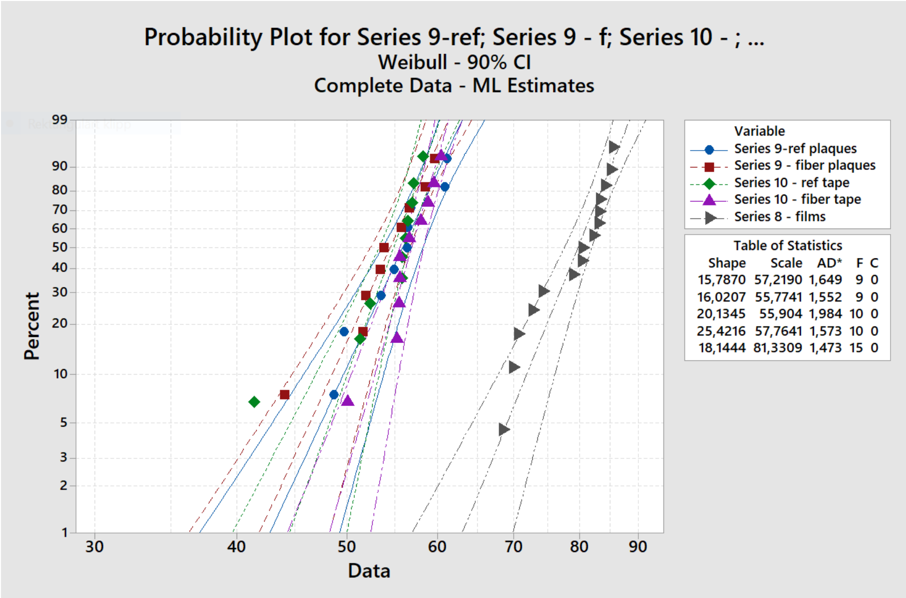

Figure 4.12: Weibull distribution of breakdowns in plaques and tape vs breakdowns in polyehtylene films.

As can be viewed in Figure 4.12, all the polyethylene films have a higher breakdown strength than the pressed plaques and the tape.

5

Discussion

In the following section, the results of both the method development and the fiber testing will be discussed.

5.1 Method development

Since the testing of different parameters was iterative, each new decision about the way forward required discussion about the results. The results acquired after each series were applied voltage and breakdown time, as well as physical observations such as lightning, small discharges, buzzing sounds and breakdowns in the rig instead of between the electrodes. If a test series did not have any of the mentioned physical observations and the breakdown occurred smoothly with no sound between the electrodes it was successful.

5.1.1 Effect of oil

The Wacker oil reduced the sound and lightning while increasing the voltage before breakdown. It was therefore used during the entire testing of molded electrodes. The coefficient slope studied in Figure 4.1 and Figure 4.2 can also establish that the breakdown pattern is more similiar in the Wacker oil than in the silicone oil, suggesting that the breakdowns occur in the same place or in the same way each time. The effect of the oil was also studied using cured Powersil 415 electrodes, the distribution of this can be seen in Figure 4.3 where the Wacker oil results in a higher voltage value, but the distribution between the two oils does not show a big difference in pattern. This can be connected to the breakdown results in Appendix 1, where it is clear that the majority of the breakdowns occur at the electrode edge, although the silicone oil gave more results where the breakdown took place towards the centre of the electrodes.

When the oil was degassed and dried in an oven, the general moisture content was increased, something that was not expected. Some physical trait of the oil has been changed during the drying which resulted in breakdowns out in the rig and in the oil, therefore no real breakdown was detected. The extreme high coefficient of slope is typical for series where the breakdown occur due to other mechanisms than the ones occurring in the material breakdowns.

One important factor that was considered when using the standard silicone oil for the last tests, the fiber testing, was that the silicone oil had resulted in more breakdowns in the centre of the electrodes compared to the Wacker oil. Thus, the orientation of the breakdowns had a better result using the silicone oil. Since this is a desired factor when testing any insulation material, it was thought to be best to go back to the standard oil when doing the actual fiber particle testing. This to make sure that the acquired results reflected the breakdowns in the infused material, and not breakdowns in the rig or oil.

5.1.2 Effect of moulding electrodes

All of the gums around the spherical electrodes resulted in less noise, lightning and undesired breakdowns, in addition to an increased voltage compared to the clean spherical electrodes. The moulding of electrodes was therefore an effective way to get a breakdown in the polyethylene films and not in the rig or oil, thus making them a successful tribute to the method development. When cured, the Powersil 415 silicone gum was the best alternative for continuous use. It stayed in place around the electrodes despite the movement when placing new films between them and the oil surrounding them. It was also the gum that resulted in the highest applied voltage before a breakdown, results than can be seen in Figure 4.4, Figure 4.5 and Figure 4.6, where the breakdown strength (kV/mm) of the polyethylene film is considerably increased when using cured Powersil 415.

The general complication with the moulding of the silicone gums was the disability to stick to the electrodes. The spherical shape was not optimal to get the gum to stay put. Together with the movement of placing new films between the electrodes, the oil in the bath enhanced this problems and the gums eventually came off, except the cured Powersil 415.

It was difficult to mould the gums around the electrodes so the edge between the flat part and the spherically part of the electrode was isolated. This made it hard to determine if the gum entirely isolated the area where a triple point can occur - at an edge. Since this was the intention with the gums, the cured Powersil 415 electrodes - that stayed in place and isolated the edge fairly good, was determined the best mold for the material testing.

5.1.3 Effect of volume

All series were tested with both 0.3 mm and 0.5 mm, so the effect of the thickness is tested in each series. It is therefore interesting to compare the films with different thickness with each other. The reason why the 0.3 mm film has a higher breakdown strength can be explained with two factors. One factor is that the thicker the material, the higher voltage needs to be applied to get a breakdown. When the applied voltage is increased more and more, the risk of the breakdown occurring somewhere else than in the material is enlarged. The risk of getting a triple point somewhere in the surrounding environment is therefore increased. The other factor is more applicable on cables - the thicker the material the higher risk of a defect in the material, which affect the breakdown strength negatively. This factor is the actual concept of volume effect compared with the factor of breakdowns occurring, for example, in the rig. In the experiments in this thesis, the results reflect the first factor, when the voltage is increased - the breakdowns occur at a triple point rather than in the material.

5.2 Fiber testing

The results from the series where the materials were tested with and without a particle in it was not equal to the hypothesis. The results showed no significant difference in breakdown strength between the tests with and without a particle in it, not in the plaques nor in the tape. However, something that could be established after these series was that the polyethylene films used in the method development was of much better quality than the plaques and the tape.

Why the breakdown strength was not affected of the fiber particle could depend on a few factors and error sources in the experiments, such as the preparation of the material. The tape contained many particles besides the fibers, resulting in poor quality of the material. This is believed to affect the breakdown strength so the infused fiber has less of an impact on the overall strength. The breakdown strength in both the plaques and the tape was much weaker than the polyethylene films - the general quality of the material affected the breakdowns, hence making it hard to conclude the actual effect of the fiber.

5.3 Films versus plaques and tape

The breakdown strength is much higher in the tested polyethylene films than in the pressed plaques and tape from Borealis. This implied that the polyethylene films are of high quality with few disruptions in the material.

6
Conclusion

In general, the method development was successful. Increased applied voltage and time was obtained when trying different oil and silicone gums around the electrodes. The breakdowns occurred more evenly in the material and the noise, lightning and small discharges disappeared when using the silicone gums around the electrodes. The Wacker oil gave more homogeneous data compared to the standard Xiameter silicone oil, which is desired when studying the breakdown pattern. The best parameters to use for the testing was the cured Powersil 415 with the Wacker oil.

The polyethylene films have a high quality and high breakdown strength compared to the other material samples that were tested in this diploma work. No difference in breakdown strength could be detected from the testing of fiber infused material, so the conclusion that it affects the breakdowns strength and the orientation of the breakdown could not be drawn.

For future testing - the polyethylene films could be prepared with particles in it. This would give an accurate testing with a high quality material, hence reducing the problem with sample preparation where the material is affected by human factors and errors. This could take the material and defect testing further and really develop the breakdown testing at Borealis.

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A

Appendix 1

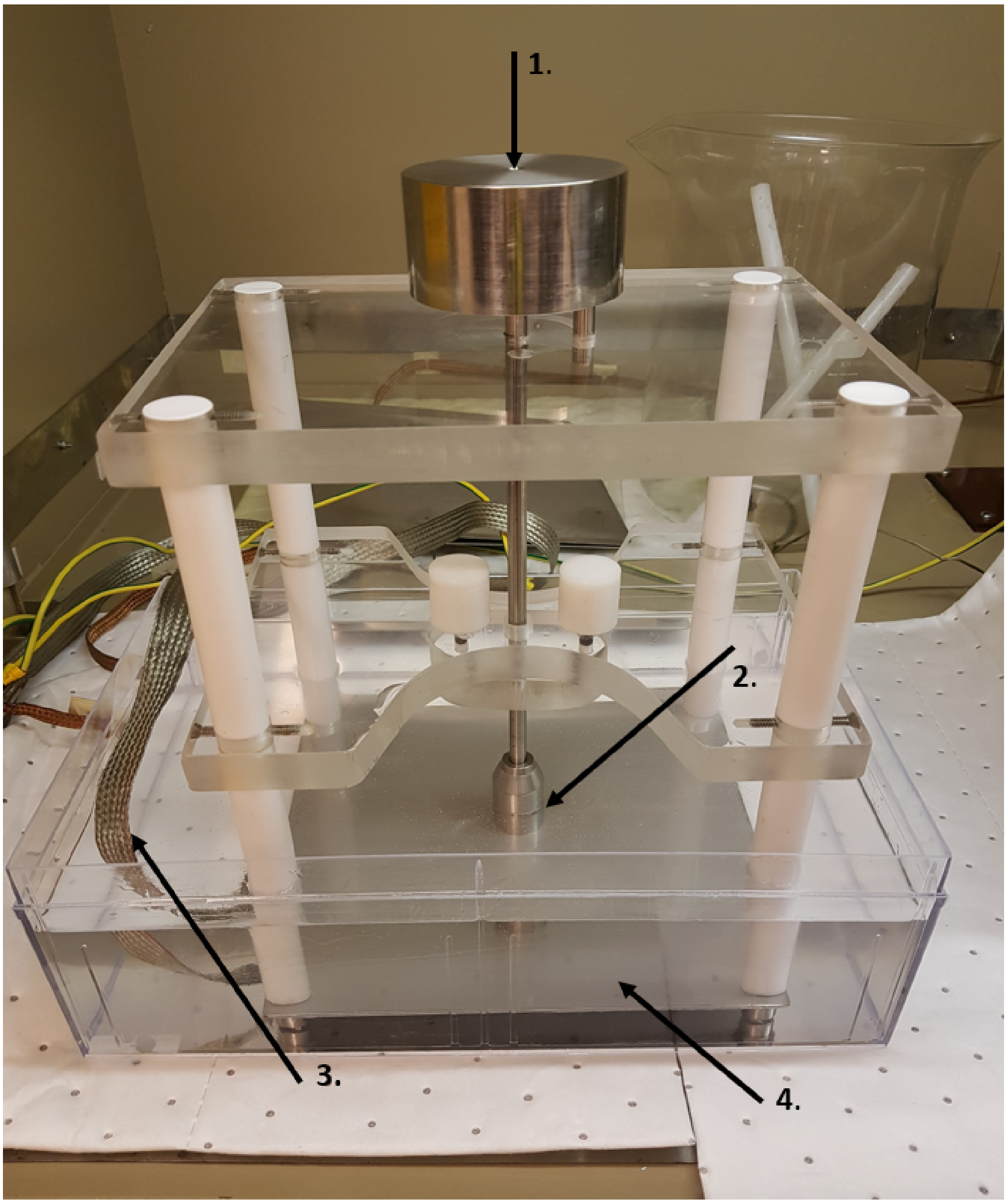

Figure A.1: High voltage test rig with standard electrodes, with explaining numbers - 1. Is where the voltage cable is connected. 2. Placement of material. 3. Grounding cable. 4. Silicone oi.

Table A.1: Reference testing - 2 kV/s, 0.3 mm, standard electrodes, silicone oil.

Nr	**Thick-ness (mm)**	**Time (s)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,283	23-27	37,9	133,92	BD at elctrd edge
2	0,301	18	38,8	128,90	BD in the centre, crackling sound
3	0,304	18	37,9	124,67	BD in the centre, crackling sound
4	0,311	20	40,3	129,58	BD outside the electrodes
5	0,302	18	37,9	125,50	Cracking sound, no visible BD
6	0,303	14	29,5	97,36	BD at elctrd edge
7	0,304	16	34,2	112,50	BD at elctrd edge, crackling sound
8	0,304	17	36,5	120,07	BD at elctrd edge, crackling sound
9	0,309	18	30,1	97,41	BD at elctrd edge, high crackling sound
10	0,305	18	39	127,87	BD in the centre, high crackling sound
			Average	**118,21**	
			Standard dev	**12,92**	

Table A.2: Reference testing - 2 kV/s, 0.5 mm, standard electrodes, silicone oil.

Nr	**Thick-ness (mm)**	**Time (s)**	**Voltage (kV)**	**kV/mm**	**Note**
1	0,51	22	45,6	89,41	Lightning, high crackling sound
2	0,494	23	48,7	98,58	Loud sound, BD in the bath
3	0,5	20	42,5	85,00	Loud sound, BD in oil, crater around elctrd
4	0,493	21	43,8	88,84	Lightning at the bath, crater
5	0,504	22	46,2	91,67	Loud sound, lightning, crater
6	0,505	22	47,5	94,06	Loud sound, lightning in the bath
7	0,491	21	45,4	92,46	Loud sound, lightning
8	0,502	23	48,2	96,02	BD at elctrd edge, crater, lightning
9	0,497	22	45,7	91,95	Crackling sound, lightning, crater
10	0,496	23	48,3	97,38	BD in the rig, crater, lightning
			Average	**92,54**	
			Standard dev	**4,16**	

Table A.3: Series 1 - 0.5 mm.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,506	04:49	46,1	91,11	Noise and elec.field, BD outside elctrd
2	0,501	2:...	37,6	75,05	BD outside electrode
3	0,51	04:31	44,4	87,06	Noise, BD at elctr edge
4	0,499	04:32	44,9	89,98	Loud noise, lightning, BD outside elctrd edge
5	0,512	-	30,9	60,35	BD at elecrd edge
6	0,504	04:16	43	85,32	Noise, BD at elecrd edge
7	0,511	04:09	42,5	83,17	Noise, BD at electrd edge
8	0,504	04:33	45,1	89,48	Loud noise, no visible BD
9	0,506	03:52	40,9	80,83	Noise, BD at electr edge
10	0,502	03:47	40,3	80,28	Noise, BD at electr edge
			Average	**82,26**	
			Standard dev	**9,20**	

Table A.4: Series 1 - 0.3 mm.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,303	02:22	30,8	101,65	BD in the centre, noise, crater
2	0,304	01:55	28,2	92,76	Noise, BD at electr edge
3	0,306	02:32	31,9	104,25	Noise, BD at electr edge
4	0,307	01:56	28,1	91,53	BD in the centre
5	0,307	02:58	34,6	112,70	Noise, BD in the centre
6	0,309	02:58	34,2	110,68	Noise, BD in the centre
7	0,305	02:53	27	88,52	BD in the centre
8	0,309	01:45	29,2	94,50	BD at electrd edge
9	0,306	02:38	22,5	73,53	BD in the centre
10	0,302	02:09	29,3	97,02	BD between the centre and the edge
			Average	**96,71**	
			Standard dev	**11,47**	

Table A.5: Series 2 - 0.5 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,502	03:44	40,2	80,08	Lightning, BD at electr edge
2	0,506	03:51	41	81,03	Noise, BD putside the elecr
3	0,51	04:08	41,7	81,76	Noise, BD inside the elecr edge
4	0,501	04:10	42	83,83	Noise, lightning, BD at electr edge
5	0,508	04:15	42,6	83,86	Noise, lightning, BD at electr edge
6	0,502	04:17	42,8	85,26	Noise, BD at eletr edge
7	0,509	04:32	44,8	88,02	Lightning, noise,BD at elecr edge
8	0,508	04:41	45,4	89,37	Noise, BD at elecr edge
9	0,503	04:41	45,4	90,26	Noise, BD outside elecr
10	0,503	04:05	41,6	82,70	Lightning, noise, BD outside elecr
			Average	**84,62**	
			Standard dev	**3,54**	

Table A.6: Series 2 - 0.3 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,299	02:31	32,5	108,70	BD in the centre, white clouds
2	0,294	02:07	29,9	101,70	BD at the elecr edge, white clouds
3	0,301	02:23	30,8	102,33	BD at the elecr edge, white clouds
4	0,31	02:34	32,5	104,84	Lightning,white clouds,BD at the elecr edge
5	0,303	02:25	31,6	104,29	Lightning, white clouds, BD at the elecr edge
6	0,309	02:27	31,7	102,59	Lightning, white clouds, BD at the elecr edge
7	0,307	02:15	30,6	99,67	Lightning, BD in the centre
8	0,305	02:19	31	101,64	Lightning, BD at the elecr edge
9	0,308	02:07	29,7	96,43	BD at the elecr edge
10	0,303	02:18	30,7	101,32	BD between the elecr edge and the centre
			Average	**102,35**	
			Standard dev	**3,24**	

Table A.7: Series 2 - 0.5, degassed Wacker oil.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,508	03:35	39,3	77,36	Lightning, no BD in film
2	0,504	03:43	38,8	76,98	Lightning, no BD in film
3	0,509	03:39	38,4	75,44	Lightning, no BD in film
4	0,504	03:46	39,3	77,98	Lightning, no BD in film
5	0,509	03:37	37,8	74,26	Lightning, no BD in film
6	0,496	03:38	38,6	77,82	Lightning, no BD in film
7	0,504	03:36	38,4	76,19	Lightning, loud noise, no BD in film
8	0,507	03:33	38,1	75,15	Lightning, loud noise, no BD in film
9	0,503	03:44	39,3	78,13	Lightning, no BD in film
10	0,509	03:41	39	76,62	Lightning, loud noise, no BD in film
			Average	**76,59**	
			Standard dev	**1,31**	

Table A.8: Series 3 - 0.5 mm.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,504	04:10	42,1	83,53	BD at the elecr edge, white clouds
2	0,505	03:44	39,3	77,82	BD at the elecr edge, white clouds
3	0,504	04:01	41,1	81,55	BD at the elecr edge, white clouds
4	0,503	3:...	38,6	76,74	Noise, BD at the elecr edge
5	0,500	03:56	40,6	81,20	Lightning, noise, BD at the elecr edge, white clouds
6	0,506	03:54	40,2	79,45	BD at the elecr edge
7	0,505	04:03	41,3	81,78	White clouds, BD at the elecr edge
8	0,508	03:36	38,5	75,79	Lightning, BD at the electr edge
9	0,504	03:58	40,8	80,95	Noise, small lightning, BD at the elecr edge
10	0,507	-	-	-	-
			Average	**79,87**	
			Standard dev	**2,59**	

Table A.9: Series 3- 0.3 mm.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,301	Standard	45	149,50	2 kV/s ramping
2	0,307	01:58	28	91,21	BD at the elecr edge
3	0,303	02:19	30,5	100,66	Lightning, white clouds, BD at the elecr edge
4	0,308	01:52	27,4	88,96	Lightning, white clouds, BD at the elecr edge
5	0,303	02:11	29,5	97,36	White clouds, no visible BD
6	0,308	02:10	29,5	95,78	White clouds, no visible BD
7	0,302	02:07	29,6	98,01	White clouds, no visible BD
8	0,309	02:32	31,2	100,97	Lightning, white clouds, BD at the elecr edge
9	0,307	01:52	27,4	89,25	Lightning, BD at the elecr edge
10	0,303	01:58	28	92,41	Lightning, BD at the elecr edge
			Average	**94,96**	
			Standard dev	**4,66**	

Table A.10: Series 4 - 0.5 mm.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,501	04:43	45,6	91,02	Lightning, cluds, BD at the electr edge
2	0,507	03:47	28	55,23	Lightning, BD at the electr edge
3	0,503	05:01	30,5	60,64	Noise, BD between the centre and the electr edge
4	0,507	04:26	43,7	86,19	BD at the electr edge
5	0,501	05:12	48,1	96,01	Clouds, BD at the electr edge
6	0,511	04:46	45,6	89,24	Clouds, BD at the electr edge
7	0,501	04:01	40	79,84	BD at the electr edge
8	0,51	02:32	44,5	87,25	Clouds, BD at the electr edge
9	0,5	03:16	34,6	69,20	BD at electr edge
10	0,51	03.20	35	68,63	Gensomslag strax utanför elektrod
			Average	**79,40**	
			Standard dev	**13,99**	

Table A.11: Series 4 - 0.3 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,301	01:59	26,9	89,37	Lightning, noise BD at the elecr edge
2	0,307	01:48	25,8	84,04	Lightning, BD at the elecr edge
3	0,306	02:30	31,2	101,96	Noise, BD between the elecr edge and the centre
4	0,302	02:00	27	89,40	BD at the elecr edge
5	0,307	02:09	29,2	95,11	Noise, clouds, BD at the elecr edge
6	0,3	02:15	28,5	95,00	Clouds, BD at the elecr edge
7	0,309	01:48	27	87,38	BD at the elecr edge
8	0,303	02:01	27,1	89,44	Clouds, BD at the elecr edge
9	0,31	02:57	34,3	110,65	BD at the elecr edge
10	0,303	02:20	30,5	100,66	BD at the elecr edge
			Average	**94,30**	
			Standard dev	**8,11**	

Table A.12: Series 5 - 0.5 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,51	-	50,6	99,22	BD at the electr edge
2	0,504	03:50	38	75,40	BD at the electr edge
3	0,507	03:43	37,3	73,57	BD at the electr edge
4	0,504	04:20	43,2	85,71	BD at the electr edge
5	0,508	02:53	32,3	63,58	BD at the electr edge
6	0,506	03:24	35,4	69,96	BD at the electr edge
7	0,507	03:10	34	67,06	BD between the centre and the electr edge
8	0,509	02:44	31,4	61,69	BD between the centre and the electr edge
9	0,509	03:43	37,3	73,28	No visible BD
10	0,508	04:00	39	76,77	BD between the centre and the electr edge
			Average	**74,62**	
			Standard dev	**11,08**	

Table A.13: Series 5 - 0.3 mm.

Nr	Thickness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,301	03:00	34,6	114,95	BD between the centre and the electr edge
2	0,301	02:37	30,7	101,99	BD between the centre and the electr edge
3	0,3	02:16	28,6	95,33	BD at the electr edge
4	0,309	02:14	28,4	91,91	BD at the electr edge
5	0,301	02:22	29,2	97,01	BD at the electr edge
6	0,314	02:09	27,9	88,85	BD at the electr edge
7	0,308	02:08	27,8	90,26	BD at the electr edge
8	0,309	02:46	31,4	101,62	BD at the electr edge
9	0,306	02:50	32	104,58	BD at the electr edge
10	0,309	02:48	31,8	102,91	BD at the electr edge
			Average	**98,94**	
			Standard dev	**7,91**	

Table A.14: Series 6 - 0.5 mm.

Nr	Thickness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,501	04:51	45,2	90,22	Lightning , noise, BD at the elctr edge
2	0,503	04:55	46,4	92,25	Lightning , noise, BD at the electr edge
3	0,512	05:21	49	95,70	Oil moving, no visible BD
4	0,508	05:10	46	90,55	BD in the centre
5	0,506	05:32	51,2	101,19	Lightning, noise, no visible BD
6	0,501	05:14	49,7	99,20	Lightning, noise, BD at the elctr edge
7	0,51	04:35	42,5	83,33	Lightning, noise, no visible BD
8	0,511	04:33	45,7	89,43	Lightning, noise, BD at the elctr edge
9	0,51	04:43	47	92,16	Lightning, noise, BD at the elctr edge
10	0,505	05:05	48,3	95,64	Lightning, noise, BD at the elctr edge
			Average	**92,97**	Contaminated oil
			Standard dev	**5,17**	

Table A.15: Series 6 - 0.3 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,305	04:34	44	144,26	BD at electrode edge
2	0,31	03:33	36,3	117,10	BD at electrode edge
3	0,301	04:50	44	146,18	Lightning, loud sound, no BD*
4	0,311	03:20	37,9	121,86	BD at electrode edge
5	0,306	03:31	36,1	117,97	BD at electrode edge
6	0,308	00:07	15,7		BD at electrode edge
7	0,306	01:55	26,5	86,60	BD at electrode edge
8	0,305	02:54	32,4	106,23	BD at electrode edge
9	0,301	04:09	42	139,53	BD at electrode edge
10	0,307	00:45	19,5	63,52	BD at electrode edge
			Average	**115,92**	*Electrodes did not fit properly
			Standard dev	**27,42**	

Table A.16: Series 7 - 0.5 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,507	03:03	34,2	67,46	Lightning, BD at the electrode edge
2	0,505	03:17	36,2	71,68	Lightning, BD at the electrode edge
3	0,51	03:28	35,8	70,20	Lightning, BD at the electrode edge
4	0,506	03:14	35,7	70,55	Lightning, BD at the electrode edge
5	0,510	02:55	32,5	63,73	BD at the electrode edge

Table A.17: Series 8 - 0.5 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,505	04:38	43,2	85,54	BD at the electrode edge
2	0,514		42,7	83,07	BD at the electrode edge, some noise
3	0,503	03:40	39,7	78,93	BD at the electrode edge
4	0,51	04:16	42,9	84,12	BD at the electrode edge, some noise
5	0,497		41,3	83,10	Lightning, BD at the electrode edge
6	0,503	04:14	42,8	85,09	BD at the electrode edge
7	0,503	04:05	41,9	83,30	BD in the centre
8	0,504	03:43	40,5	80,36	BD at the electrode edge
9	0,502	03:41	40,3	80,28	BD in the centre
10	0,501	03:52	41,2	82,24	BD at the electrode edge
11	0,497	02:55	34,7	69,82	BD at the electrode edge
12	0,505	03:11	36,7	72,67	BD at the electrode edge
13	0,496	02:58	35	70,56	BD at the electrode edge
14	0,51	02:57	34,9	68,43	BD at the electrode edge
15	0,5	03:22	37,1	74,20	BD at the electrode edge
			Average	**78,78**	
			Standard dev	**5,98**	

Table A.18: Series 8 - 0.3 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,299	01:21	24,5	81,94	BD at the electrode edge
2	0,31	01:49	27,2	87,74	BD at the electrode edge
3	0,302	01:19	24,3	80,46	BD at the electrode edge
4	0,311	01:36	26,3	84,57	BD between the centre and the electr edge
5	0,309	01:47	27,4	88,67	BD at the electrode edge
6	0,308	01:23	24,7	80,19	BD at the electrode edge
7	0,304	01:17	27,8	91,45	BD at the electrode edge
8	0,312	01:40	26,7	85,58	BD at the electrode edge
9	0,304	01:34	26,1	85,86	BD at the electrode edge
10	0,309	01:25	24,9	80,58	BD at the electrode edge
			Average	**84,70**	
			Standard dev	**3,88**	

Table A.19: Series 9 - reference plaques 0.5 mm.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,508	01:20	24,7	48,6	BD in the centre of the electrodes
2	0,51	01:26	25,3	49,6	BD between electrode edge and centre
3	0,493	01:49	27,8	56,4	BD between electrode edge and centre
4	0,509	02:02	28,9	56,8	BD at the electrode edge
5	0,501	01:57	28,3	56,5	BD in the middle of the electrodes
6	0,507	01:44	27,1	53,5	BD between electrode edge and centre
7	0,501	01:49	27,5	54,9	BD in the centre of the electrodes
8	0,495	02:12	30,1	60,8	BD between electrode edge and centre
9	0,507	02:21	31	61,1	BD between electrode edge and centre
			Average	**55,35**	
			Standard dev	**4,3**	

Table A.20: Series 9 - fiber particles plaques.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,508	02:00	28,3	55,7	BD in the centre of the electrodes
2	0,503	01:53	28,5	56,7	BD at the electrode edge
3	0,499	02:08	29,2	58,5	BD between electrode edge and centre
4	0,507	01:04	22,3	44,0	BD between electrode edge and centre
5	0,5	01:45	26,9	53,8	BD between electrode edge and centre
6	0,5	02:12	29,8	59,6	BD in the centre of the electrodes
7	0,5	01:41	26,7	53,4	BD between electrode edge and centre
8	0,505	01:37	26,2	51,9	BD between electrode edge and centre
9	0,516	01:40	26,6	51,6	BD between electrode edge and centre
			Average	**53,90**	
			Standard dev	**4,65**	

Table A.21: Series 10 - reference tape.

Nr	Thick-ness (mm)	Time (m)	Voltage (kV)	kV/mm	Notes
1	0,583	02:45	33,2	56,9	BD at the electrode edge
2	0,56	01:59	28,7	51,3	BD at the electrode edge
3	0,581	02:39	32,8	56,5	BD at the electrode edge
4	0,587	02:53	34,2	58,3	BD at the electrode edge
5	0,594	02:46	33,4	56,2	BD at the electrode edge
6	0,586	02:39	32,7	55,8	BD at the electrode edge
7	0,561	01:06	23,2	41,4	BD at the electrode edge
8	0,573	02:12	30	52,4	BD at the electrode edge
9	0,592	02:52	33,8	57,1	BD at the electrode edge
10	0,6	02:45	33,5	55,8	BD at the electrode edge
			Average	**54,2**	
			Standard dev	**5,0**	

Table A.22: Series 10 - fiber particle tape.

Nr	**Thick-ness (mm)**	**Time (m)**	**Voltage (kV)**	**kV/mm**	**Notes**
1	0,568	02:56	34,3	60,4	BD at the edge of the tape
2	0,601	02:51	33,4	55,6	BD at the electrode edge
3	0,574	02:36	32,5	56,6	BD at the electrode edge
4	0,596	02:41	33,1	55,5	BD at the electrode edge
5	0,583	02:49	33,8	58,0	BD at the electrode edge
6	0,573	02:36	31,8	55,5	BD at the electrode edge
7	0,591	03:09	35,2	59,6	BD at the electrode edge
8	0,58	02:04	29	50,0	BD between the electr edge and the centre
9	0,563	02:30	31,1	55,2	BD at the edge of the tape
10	0,573	02:48	33,7	58,8	BD at the electrode edge
			Average	**56,5**	
			Standard dev	**3,0**	