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Institut für
Hochspannungstechnik und
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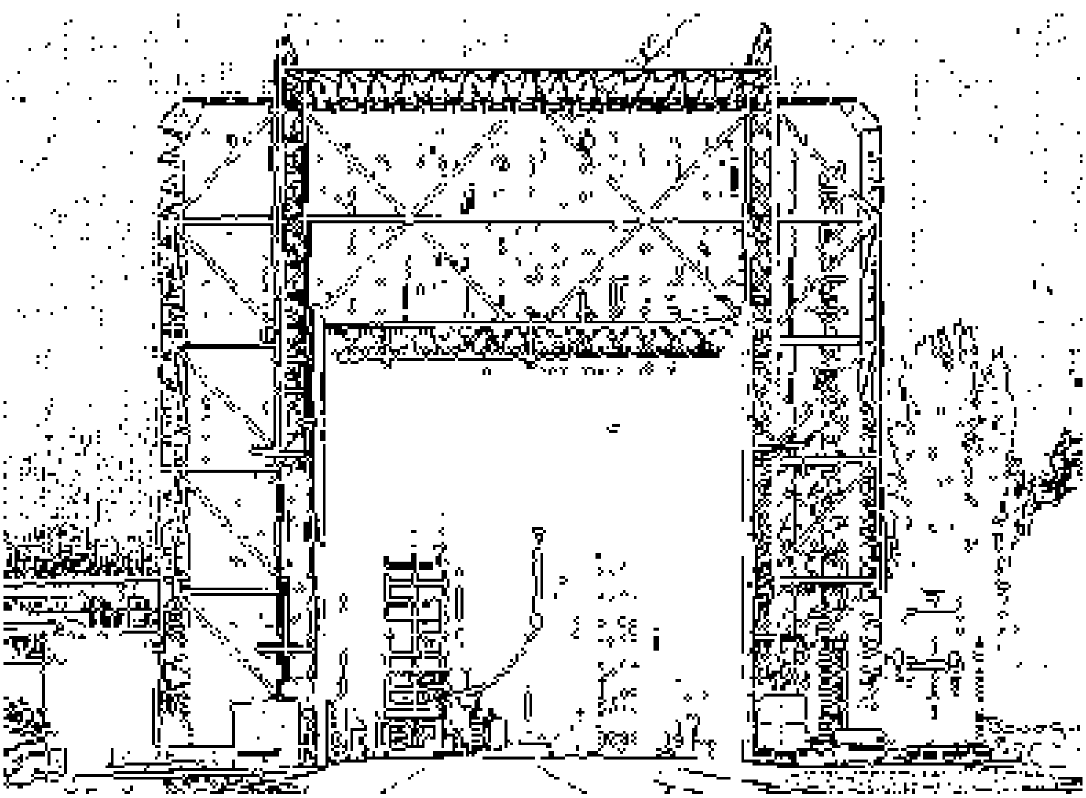
GRAZ UNIVERSITY OF TECHNOLOGY

DIPLOMA THESIS



INSTITUTE OF HIGH VOLTAGE AND SYSTEM MANAGEMENT

Analysis of electrical, thermal and mechanical characteristics of various Mica papers in high voltage insulation systems

Untersuchung elektrischer, thermischer und mechanischer Eigenschaften verschiedener Glimmerpapiere in Hochspannungsisolationssystemen

Diploma Thesis

From

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Graz University of Technology

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Kurzfassung

Diese Diplomarbeit präsentiert Resultate aus experimentellen Tests, durchgeführt an speziellem Hochspannungsglimmerpapier. Die Untersuchungen wurden vorgenommen um Unterschiede zwischen verschiedenen Produkten aus Glimmerpapier und dessen charakteristischen Eigenschaften festzustellen.

Untersuchte Produkte:

- Kalzinierte Mica (drei verschiedene Bänder)
- Unkalzinierte Mica (zwei verschiedene Bänder)

Die Untersuchung wurde an Produkten mit verschiedenen Materialstärken (unterschiedlichem Glimmeranteil pro m²) durchgeführt. Es wurden drei verschiedene Bänder aus kalziniertem Mica (0,12mm, 0,18mm und 0,21mm Stärke) und zwei verschiedene Bänder aus unkalziniertem Mica (0,18mm und 0,28mm Stärke) getestet.

Das Hauptziel dieser Diplomarbeit ist es, Informationen über die Eigenschaften von kalziniertem und unkalziniertem Glimmerpapier für Hochspannungsanwendungen zu erlangen. Bisherige Tests an Glimmerprodukten geben nicht genügend Information über Vor- und Nachteile von unterschiedlichen Glimmeranteilen in den Bändern, sowie wenig klare Aussagen über die Unterschiede zwischen kalzinierten und unkalzinierten Glimmerprodukten.

Im Rahmen dieser Diplomarbeit wurden verschiedene Tests durchgeführt um die Durchschlagspannung zu ermitteln, und um thermische und mechanische Eigenschaften zu untersuchen.

Für jede Materialprobe wurden so viele Bandstücke (Layers) zusammen gepresst damit eine Materialstärke von ca. 0.5 mm erreicht wurde. Zwei Probenhalter wurden speziell entwickelt um mehrere Proben in Transformatoröl gleichzeitig mit Spannung belasten zu können. Bei bisherigen Tests wurde die Durchschlagfestigkeit nur an ganzen Stäben

aus Metall oder Kupfer in Glimmerbänder eingewickelt, und unter Hochspannung getestet. Das Ziel war jetzt, Resultate aus Messungen ohne die Einwirkung andere Materialien wie Metall oder Kupfer zu erhalten.

Im Laufe der Untersuchungen hat sich herausgestellt, dass es mit den vorhandenen Ressourcen nicht möglich war, Proben herzustellen die mit ausreichender Genauigkeit die gleichen Materialstärken aufweisen. Durch die leicht unterschiedlichen Dicken der Proben waren sie unterschiedlichen elektrischen Feldstärken ausgesetzt, was einen deutlichen Einfluss auf die Messergebnisse hatte.

Durch den Vergleich von Proben die ähnlichen elektrischen Feldstärken ausgesetzt waren lassen sich folgende Aussagen treffen.

Unkalziniertes Mica scheint unter besagten Testbedingungen eine leicht höhere Durchschlagfestigkeit zu besitzen, solange es nicht thermisch belastet wird. Nach thermischer Belastung zeigte es ein wesentlich schlechteres Verhalten wo hingegen kalziniertes Mica kaum Unterschiede in der Durchschlagfestigkeit zeigte. Es konnte kein signifikanter Unterschied zwischen Materialen mit verschiedener Anzahl von Schichten festgestellt werden.

Die Resultate sind sehr abhängig von dem Herstellungsprozess, Bänderzustand sowie dem Probenpressprozess.

Abstract

This diploma thesis presents results of experimental tests performed on mica paper for high voltage equipment applications. The investigation was made to recognize differences between different mica products and their characteristics.

These are:

- Calcined mica band (three types)
- Uncalcined mica band (two types)

Investigation was specified on different thicknesses of the products, which means the quantity of mica parts per square metre differs. From the first product which is mica band based on calcined mica paper, three different thicknesses of material are taken (0,12mm; 0,18mm and 0,21mm). From the second product, which is mica band based on uncalcined mica paper, two different thicknesses were taken (0,18mm and 0,28mm).

The fundamental aim of this thesis is to provide information about the behaviour of calcined and uncalcined mica for high voltage equipment usage. Previous tests do not give enough information about advantages or disadvantages of thin or thick roles of mica products.

Within this diploma thesis a variety of tests were applied in order to clarify the point of breakdown voltage, thermal and mechanical behaviour.

In order to achieve 0.5 mm thickness of the samples, there were several layers of material pressed together at high temperatures in conditions near that of industrial ones. Two special sample holders were invented in order to test several samples simultaneously under even voltage in an oil environment. In previous tests this was made by testing a whole bar rolled in material and put under high voltage. The goal of the current procedure is to look at the results without considering additional presence of other material like copper or iron.

In the course of the investigation it became clear that to produce samples with the exact material thickness under the present conditions was not possible. Due to slight thickness differences, the samples were put into different electrical field strengths which significantly affected the results of the measurements.

Due to the comparison made between samples exposed to similar electrical field strengths, the following statements can be made:

Uncalcined mica tape seems to have higher dielectric strength under these test conditions and as long as there is no thermal load applied. Uncalcined mica tape in comparison to calcined mica has achieved worse results after a thermal load was applied. No significant difference between materials with different numbers of insulation layers could be stated.

The results are very dependent on the manufacturing conditions and process, mica roles condition, and pressing methods.

Content:

1. Introduction

For many years, micas have been used in the insulation systems of high-voltage rotating machines. The two forms of mica most commonly used are muscovite and phlogopite for the electrical industry. They differ mainly in colour, hardness, cleavability and calcination temperature Micas possess a combination of chemical, physical, electrical, thermal, and mechanical properties not found in any other product. This has made them an important component of high-voltage insulation systems. While micas are resilient and incompressible, they are also easily sliced into thin films, which can be colourless and transparent. This ability to be easily split into very thin sections while maintaining a robust strength through the other two axes gives mica its unique properties and makes it so easy to handle. These properties result from the structural arrangement of the atoms (1)

2. Insulation Systems

Insulating material plays a main role in the high voltage machinery. A more precise definition is given like this:

The dielectric strength of an insulating material can be defined as the maximum electric stress the dielectric material can withstand without breakdown. (2)

Insulation material has more than one parameter of importance for how the breakdown strength reacts. Those are for instance the pressure, surrounding condition like humidity, temperature, the test electrodes, etc. One of the most common reasons for insulation breakdown is the partial discharge either on the insulation surface or in between its layers. Another cause would be some thermal, mechanical or electro-thermal load.

In many types of electrical machines, there are separate parts which operate at different voltage stages at the same time. That is why solid dielectric materials are used in order to avoid shortcuts which lead to early aging of the system. Liquids and gasses normally have lower breakdown strength than a solid does. To be guaranteed that an insulation system would work failure free, it should be necessary to have high mechanical strength, small dielectric losses, be resistant to moisture and thermally stable.

When solid insulation gets damaged (ex. breakdown) it stays that way permanently. In liquids or gasses it recovers when the electric field is removed. There are few mechanisms for breakdown in a solid insulation system which can be determined:

- Electro-mechanical breakdown
- Breakdown due to treeing
- Thermal breakdown
- Electro-chemical breakdown
- Partial discharges (internal or on the surface)
- Intrinsic or ionic breakdown

2.1. Application in rotating machines

Electric rotating machines divide generally into two categories. High voltage machines are operating at voltages above 1000V and low voltages below that value. The greater the value of the applied voltage, the more difficult it gets to be electrically isolated. That is why machines that work with voltage above 22kV are rarely built.
There are some classifications about the insulation for rotating machines. The most common classes are:

- Class E (low voltage)

  Class E insulation consists of materials or combinations of materials, which by experience or tests can be shown to be capable of operation at Class E temperature (materials possessing a degree of thermal stability allowing them to be operated at a temperature 15 Centigrade degrees higher than Class A materials).
  Maximum allowed temperature: (IEC60034-1 only): 120C, 248F.

- Class F (high voltage), replaces even class B

  Class F insulation consists of materials or combinations of materials such as mica, glass fiber, asbestos, etc., with suitable bonding, impregnating or coating substances, as well as other materials or combinations of materials, not necessarily inorganic, which by experience or tests can be shown to be capable of operation at the Class F temperature (materials possessing a degree of thermal stability allowing them to be operated at a temperature 25 Centigrade degrees higher than Class B materials).
  Maximum allowed temperature: (IEC60034-1 & NEMA MG1-12.43): 155C, 311F.

- Class H (for special insulation from expensive materials)
  Class H insulation consists of materials such as silicone elastomer and combinations of materials such as mica, glass fibre, asbestos etc., with suitable bonding, impregnating or coating substances such as appropriate

silicone resins. Other materials or combinations of materials may be included in this class if by experience or tests they can be shown to be capable of operation at the Class H temperature.

Maximum allowed temperature: (IEC60034-1 & NEMA MG1-12.43): 180C, 356F. (3)

Class F is defined as the class of the future because of its wide application possibilities. Class H is mainly applied on small machines and under special conditions like heavy loads in big motors, because the costs for the materials like Teflon or Silicone are normally very high.

One of the top products for producing insulation is Mica. It has been used since ancient times and its excellent isolating abilities are known since the very beginning. At first it was applied in the form of thin splittings. Together with some carrying and binding materials, like glass cloth and resins, it turned to be the most common insulation for rotating machines. Thin sheets of those three components are called "*micanite".* Mica has transformed nowadays to products like mica paper and mica bands. Sizes of mica scales differ from big to small in many variations. Some new methods were developed to cultivate mica in a way that it could be applied to unreachable places and also to bring it to a form which allows more freedom of application. Of course mica alone would be difficult or impossible to manage. It has to be supported by carrying materials such as paper or glass, and together with some epoxy resins it builds up a completely new product. Resins as a binding agent is widely used in both, low and high voltage machines. In other systems it might be used instead of resins which additionally fill the air/gas gaps. This prevents the system from partial discharges, and seals it against moisture. This varnish film should stay flexible but still should cover the whole insulation. In addition the solvent, which is normally in the varnish, must not chemically react with the insulation.

Mica has very good ohmic resistance. Machines are often exposed to high voltages and therefore an electrical insulation needs to stay reliable for many cycles.

As mica is a natural product and it splits easily, it must be supported to stay stable and avoid delamination. That is why it is normally produced in the form of bands or tapes. Together with the carrier and binder it could be finally wound onto a conductive bar. Some changes into the structure of the adhesive could lead to either delamination or dry the varnish out, which causes air gaps to occur.

Picture 1: Natural Mica (4)

Mechanical and thermal stability are also very important for the reliability of an insulation system. Sometimes there are vibrations or other parameters that could disrupt the working conditions of the machine, so thermal and mechanical properties of the insulation are of great importance.

Nowadays the most reliable mica insulations consist of three main components where the binder is a resin. Bitumen-based adhesives have more substantial properties in the presence of high temperature and remain flexible. In addition to that, this type of resin binder allows application of Vacuum Pressure Impregnation, a method used for mica tapes to be impregnated directly on the conductive bars. Not all the resins are appropriate for VPI, because some build up gas gapes where partial discharge then takes place.

Mica tapes with lower content of resin are normally used for VPI process. They are wounded onto the windings and then placed in vacuum. After that VPI vessel is filled with resin and heated again so that the bars can be fully impregnated with resin.

Resin Rich (RR) method base on mica tapes, which consist of higher amounts of resin. They are then wound directly on the conductive parts/bars and after heating and pressing processes, the rest of the resin together with the air, are carried out and it cures.

With the passage of time mica tapes become more stable, build up a variety of different needs, and are specialized according to the areas that need to be isolated. Glass clothes and glass-fiber are playing the role of the carrier and it provides more stability at higher temperatures. It is also less chemically active so it matches better than paper. Glass fibers are very strong and they are hard to wear out so winding is now easier. Resin combined with polyester improves the electrical and thermal conductivity. Now insulation systems in big and powerful motors like wind motors and once in power plants will provide reliability for many years. This generation of mica tapes is the new age. They allow the producers of electrical machines the possibility to impregnate due to either VPI process or RR process.

The advantages of new technologies due to these two methods are reducing the sizes of the machines while increasing their capabilities. The more the materials and its properties are being studied, the more the total capability can be increased.

The conventional understanding of the breakdown of mica-based insulation systems has been that thermally induced mechanical stresses in the rotating machines cause the mica “sheets” to delaminate or results in separation of the mica and resin binder, and that thermal stresses cause degradation of the resin mica interface. These voids, or cracks, can then support electrical discharges, which produce more destructive defects, known as trees. Trees grow through the insulating materials at a rate dependent upon various stress factors but lead, eventually, to insulation system breakdown and plant failure (5)

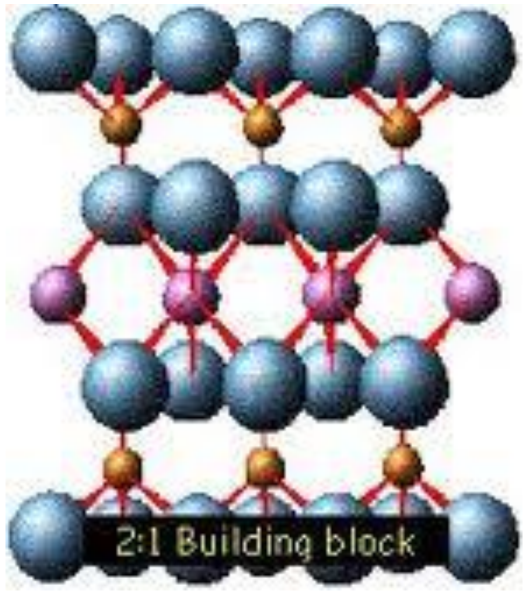
2.2. Mica

2.2.1. What is Mica

Mica has been used since the beginning of mankind. It was popular in the form of powder because of its sparkles and mainly used in cosmetics. This characteristic is even nowadays applied into different paintings and cosmetics. Also because of its ability to resist against heat, mica was widely used in forms of glasses for coal or wooden ovens. Some rare other application was implemented by the Russians as they made portholes for warships out of it. This type of mica was then called “muscovite” after the city of Moscow. (6)

Mica is a layer-type dielectric (mica films are obtained by splitting mica blocks). The extended two-dimensionally layered strata of mica prevent the formation of conductive pathways across the substance, resulting in a high dielectric strength. It has excellent thermal stability and, because of its inorganic nature, is highly resistant to partial discharges. It is used in sheet, plate, and tape forms in rotating machines and transformer coils. (7)

Mica is a sheet silicate which has very good cleavage. It consists of an octahedral layer between two tetrahedral layers. (6)



Picture 2: Tetrahedral mica structure (4)

2.2.2. Mica splittings

Mica has been won as chunks. After that it is cut and transformed so that it can be manually separated for the final shape.

Most mica comes from India, Brazil and Madagascar. There are sources of mica splittings also in the United States where it is used in the electrical industry. It has lots of applications such as electronic capacitors, microwave glasses, vacuum tubes, etc. Mica scraps combined with some additional bondage are used in the insulation of rotating machines. Mica is then transformed in thin sheets called mica paper.

Picture 3: Mica splittings (4)

2.2.3. Mica mineral

There 28 known species of the mica silicate group but for the production of mica paper only two types are relevant.

Muscovite is the most widespread mineral. The name comes from the city of Moscow. Large deposits were used nearby to make windows. It is considered the best mica for electrical devices. The mechanical properties are better than those of Phlogopite.

Muscovite: $KAl_2 (Si_3AlO_{10}) (OH)_2$

Picture 4: Muscovite (4)

Phlogopite: $KMg_3 (Si_3AlO_{10}) (OH)_2$

Phlogopite contains Magnesium and is dark in appearance. It is softer than muscovite and can withstand higher temperatures.

Picture 5: Phlogopite (4)

Muscovite starts to calcine at 550°C; whereas the calcination temperature of Phlogopite is 750°C.
There is also synthetic mica which is synthesized by melting blends of industrial chemicals and minerals at high temperature. It has excellent heat endurance (-1100 °C).

2.2.4. Manufacturing of mica paper

Mica paper looks like real paper and it consist only of mica scales with no binding component at all. A slowly running paper machine produces it from hydrous pulp.

By the usage of water, mica flakes can be disintegrated without destroying the surface force. The flakes are subjected to size gradation in vibrating screens.
Disintegrated, fine mica flakes, in bulk form (aqueous pulp) are fed at a definite consistency on a paper mill, where continuous sheets of mica paper are reeled.

2.2.4.1. Uncalcined mica pulping process

Hydro –mechanically processed mica paper

In this process pieces of natural mica are put into distilled water and exposed to a higher pressure water-jet and thereby split up into fine particles, which immediately are supplied to a machine. The bonding between the mica scales in this case are achieved by the electrostatic forces, which appear on fresh cut mica. Mica is fed into a kiln at 650 ˚C where organic contamination is eliminated. This mica paper is usually used in VPI tapes to aid with impregnation of resins.

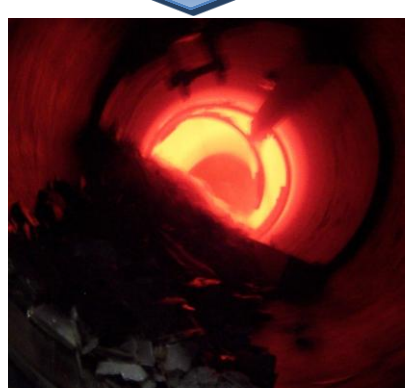
2.2.4.2. Calcined mica pulping process

Thermo-chemically processed mica paper

For manufacturing of calcined mica paper, it is put at a temperature of about 1600˚C so that the crystal water in the mineral structure is damped away.

Mica scales

Mica conveyor belt



Mica is heated at 550˚C -650˚C into a kiln

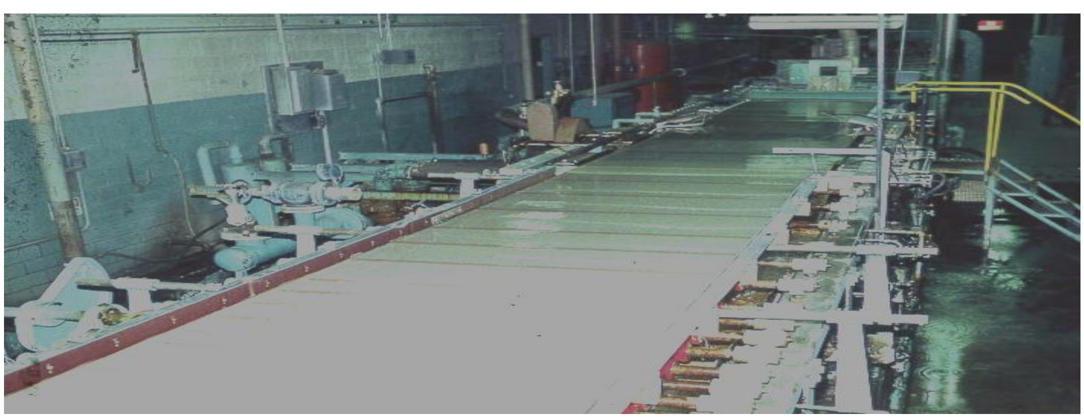
Picture 6: Mica Pulping Process a) (6)

After this calcination process the mica is soaked with diluted acids and colloid silicic acid is developed by dissolving alkali from the surface. This silicic acid is the binder for the production of mica paper. This process makes much smaller (up to 6 times smaller) and softer mica flakes which produce a tighter more flexible paper, usually used for resin rich tapes.

Mica slurry is disintegrated into smaller thinner flakes. One per cent solid slurry is formed into a flat sheet at the head box and then transferred to a screen belt called fourdriner to form the paper.

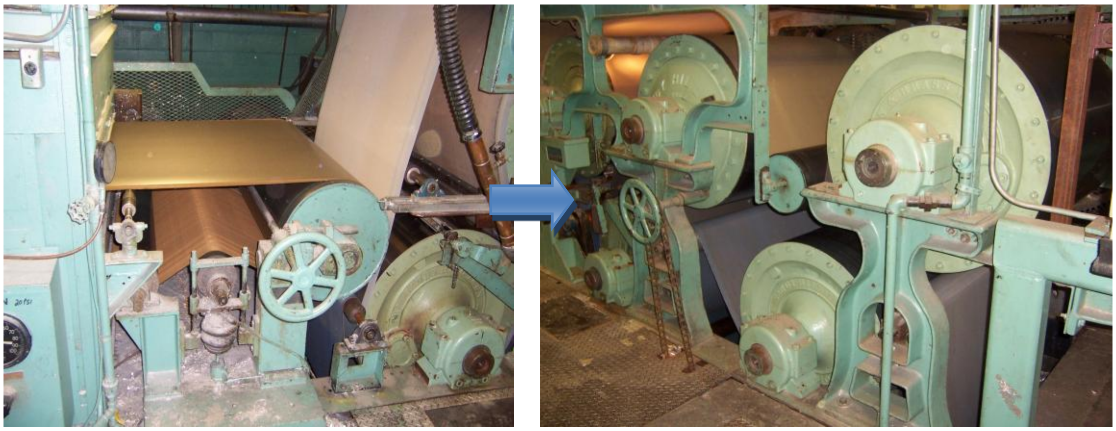
Picture 7: Mica Pulping Process b) (6)

Water is removed by vacuums pulling the water through the screen leaving a wet paper mat on top.



Picture 8: Mica Pulping Process c) (6)

The wet sheet is too weak to support its own weight and must be carried by belts through an infrared oven to start drying. The paper is then transferred over steam filled drums to completely dry the paper.



Picture 9: Mica paper process (6)

Paper weight and profile is continuously monitored with an inline basis weight meter. Mica paper is wound on cores. Mica paper is laminated to glass fabric and film to create flexible insulating materials.

Picture 10: Mica roles process (6)

2.2.4.3. Features of calcined and uncalcined mica paper:

The two types of mica differ mainly in the optical appearance, in the mechanical properties and porosity. Uncalcined mica paper is very shiny and the splittings character is visible, while the calcined mica paper is duller. Concerning mechanical properties calcined mica paper has a better bonding between the mica scales and therefore shows higher tensile strength but lower porosity. Uncalcined mica paper has a lower tensile strength and tends to lose more mica dust but has a high porosity.

2.2.4.4. Applications of calcined and uncalcined mica paper for high voltage insulating materials:

In the development and production of insulating materials the different physical properties of calcined mica paper are used to produce tailor made insulating tapes with distinctive working features. The uncalcined mica paper is largely used for VPI insulating materials, it is important that the resin does not drain out of the mica tapes during storage and handling. In this respect calcined mica paper is more advantageous. Of course both mica paper types can also be used for either application method with advantages and disadvantages.

2.2.5. Mica products

Block mica: Blocks of mica with an area 1-14 square inches or higher.

Mica scrap: Irregular lumps of mica with an area 1, 25 - 3, 81 square centimetres mostly used for production of mica paper.

Mica thins: Mica blocks with a thickness of 2-7 mm.

Mica splitting: Mica splittings consist of thin layers split from mica block. Thickness /10 sheets ≤ 12mm.

Mica splittings are generally produced manually with sharp knives to the required thickness. (6)

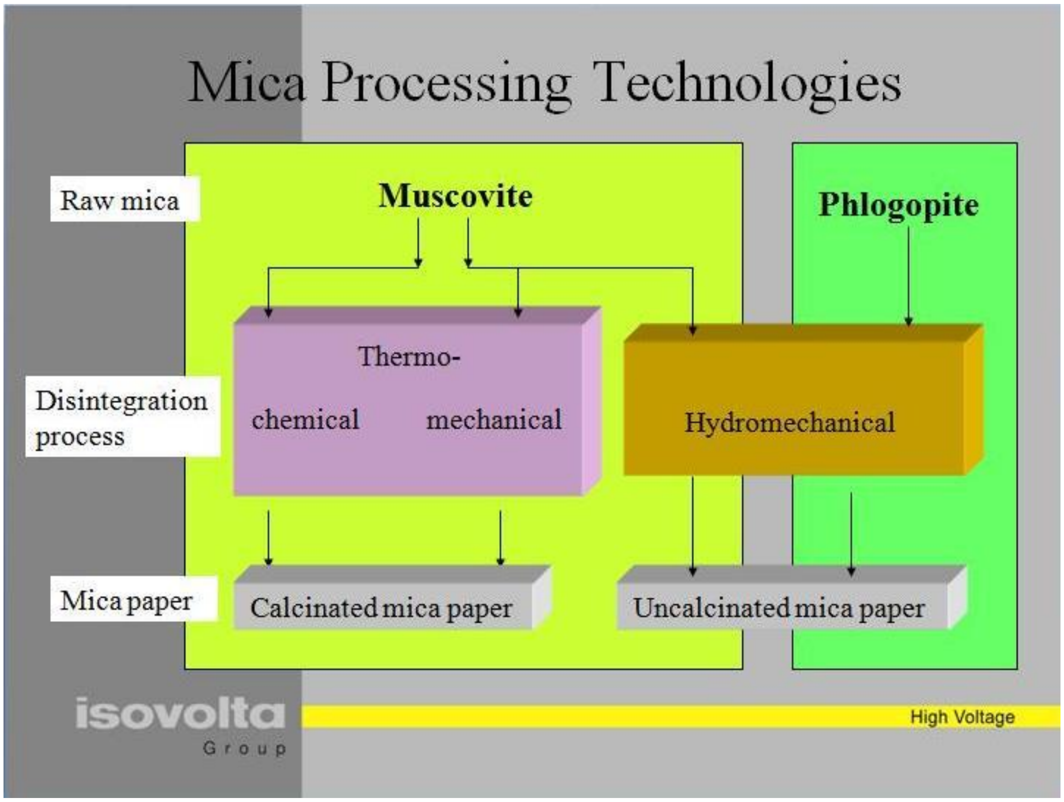


Figure 1: Mica process technology (6)

Mica paper has excellent electrical characteristics. Some of them are:

- High dielectric strength
- High mechanical strength
- Corona resistant
- Chemically inert
- High temperature stability
- Reasonable thermal conductivity (0,3-0,7 $Wm^{-1}K^{-1}$)

(6)

3. Requirements for insulation systems

Each insulation system is exposed to different stresses during its operating time. Some can affect its functionality and lead to early aging or even to serious damages and breakdown. The four main stresses are thermal, electrical, mechanical and ambient. A short description is given below.

3.1. TEAM-stresses

- **T**hermal stress – should provide good heat dissipation. Leads to degradation/aging of insulating materials
- **E**lectrical stress partial discharges, inverter-fed-drives
- **A**mbient stress moisture, oil, particles, radiation
- **M**echanical stress short-circuits forces, magnetic forces, centrifugal forces, transient forces

3.1.1. Aging stresses

Aging stresses show how the lifetime of the insulation can be calculated. Therefore it can be roughly divided to two main types:

- Constant stresses
- Transient stresses

Constant stresses show how failure that occurs with the time can be calculated. There is a coherency between the time to failure and the number of the operating hours. It is proportional to one another. (8)

Transient stresses on the other hand show the coherency between the time to failure and number of the transients of the machine experiences. It is proportional to one another. (6)

3.1.2. Thermal Stress

Delamination of the insulation is normally an effect that results after a thermal load has been applied. When a higher temperature is constantly applied to isolated parts of the machine it provides a variety of chemical reactions into the insulation. Due to oxidation of the layers of the insulation it easily gets breakable and mechanically unstable. Hence layers separate from each other or from the ground walls and the material will lose its strength.

3.1.3. Electrical stress

To calculate the insulation thickness which will be needed to insulate the windings it is necessary to know the applied voltage. If a high electrical field is constantly applied to a material that could lead to aging and also phenomenon called partial discharges could appear. Partial discharge (PD) is dielectric breakdown which can occur within the material layers of the insulation system (in gaseous, liquid or solid systems). It can be either on the surface or inside the material, but it does not bridge the space between two conductors. If the PD is protracted it could erode and eventually lead to breakdown of the insulation system. (2)

Binding materials like resins are normally organic and therefore weak. They can be destroyed after a certain time of being under high voltage. And so, they could chemically “fall apart”- delaminate. After more time has passed a tiny canal will be “dug” through the layers and so it causes an electrical breakdown.

3.1.4. Ambient stress

Ambient stress comes with factors from the environment which can affect the motor or the generator and lead to insulation failure. Some of these factors are:

- Moisture condensed on the windings
- Oil from the bearings or oil seal system in hydrogen-cooled machines
- High humidity
- Aggressive chemicals
- Abrasive particles in the cooling air or hydrogen
- Particles from brake shoe wear (if fitted) or carbon brush wear (if fitted) within the machine
- Dirt and debris brought into the machine from the environment
- Radiation

(8)

Of course it should not be a combination of all environmental factors, but together with some of the other stresses it could lead to machine failure or aging.

3.1.5. Mechanical stress

Unlike thermal and electrical stresses, there are no well-accepted models to describe the relationship between vibration amplitude and life. Although models do describe the amount of abrasion that may occur, they are not practical and none have become the basis for standard accelerating aging tests under vibration.

No model exists to relate the transient level to the number of the transients that can be withstood. Instead, manufacturers calculate the forces that could occur under various transient current situations, and determine if a single transient can be withstood. Aging is usually not considered. (8)

Other criteria for mechanical stress are bending, pressure and tension. Normally insulation is guaranteed by the producers up to 20-30 years (for big high voltage motors or generators). It is therefore very difficult for the manufacturers to test such a long time and wait for products. Accelerating aging tests provide the possibility to predict failures in a much shorter time. They speed up the aging process when test stresses are higher than the normal, such as higher temperature, higher voltage or combinations of them.

4. VPI Technology

At the moment there are two methods for the manufacturing of insulation for high voltage rotating machines - Vacuum Pressure Impregnation (VPI) and Resin Rich (RR).

4.1. Main characteristics of Vacuum Pressure Impregnation (VPI)

The impregnation of the winding insulation can be subdivided into two different methods, either the single bars are impregnated separately (individual VPI) or the bars are first assembled in the machine and the stator or rotor is impregnated as a whole (global VPI). Mica tapes used for the VPI-process have a resin content of 5 – 15 %. Prior to the impregnation for both VPI types, the material is dried. In this procedure, the bar (or machine) is placed into a vessel as shown in Figure 2-6 and heated for 6 – 12 hours at 80 –120 °C. Next, the insulation is set under the vacuum at < 1 mbar for 1 – 2 hours to remove the air from the cavities of the insulation. Afterwards resin flows from a storage tank into the vessel and impregnates the winding insulation. After a soak time of 1 – 3 hours, the vessel is pressurized for 1 – 4 hours at 4 bar. Finally, the residual resin is removed from the vessel, put back into a storage tank, and the insulation is cured for 8 – 12 hours at 140 – 170 °C. The whole VPI process takes between 17 and 33 hours. (9)

VPI bars have a resin content of about 30 % after processing. When the bars are impregnated individually, they can be pressed after impregnation in order to have a rectangular form so that the bars fit into the slot of the iron core. The advantages of VPI insulation are that the mica tapes are not sharply bent during the impregnation process. When applying the global VPI, the whole machine is impregnated and cavities between the insulation bars and the slot of the machine are also filled with resin. Both VPI-processes are very suitable to impregnate bars with a complex form. As the resin impregnates the insulation layer by layer, the impregnation of windings with a large thickness can be imperfect and the resin may not impregnate all parts of the insulation homogeneously. A further disadvantage of the global VPI-process is its requirements for large and expensive equipment. The global VPI bars do not have such a precise rectangular shape since they are not pressed. Furthermore at global VPI, the machine can only be tested after it was impregnated as a whole. Any failure in the insulation means a failure of the whole machine. (10) (11)

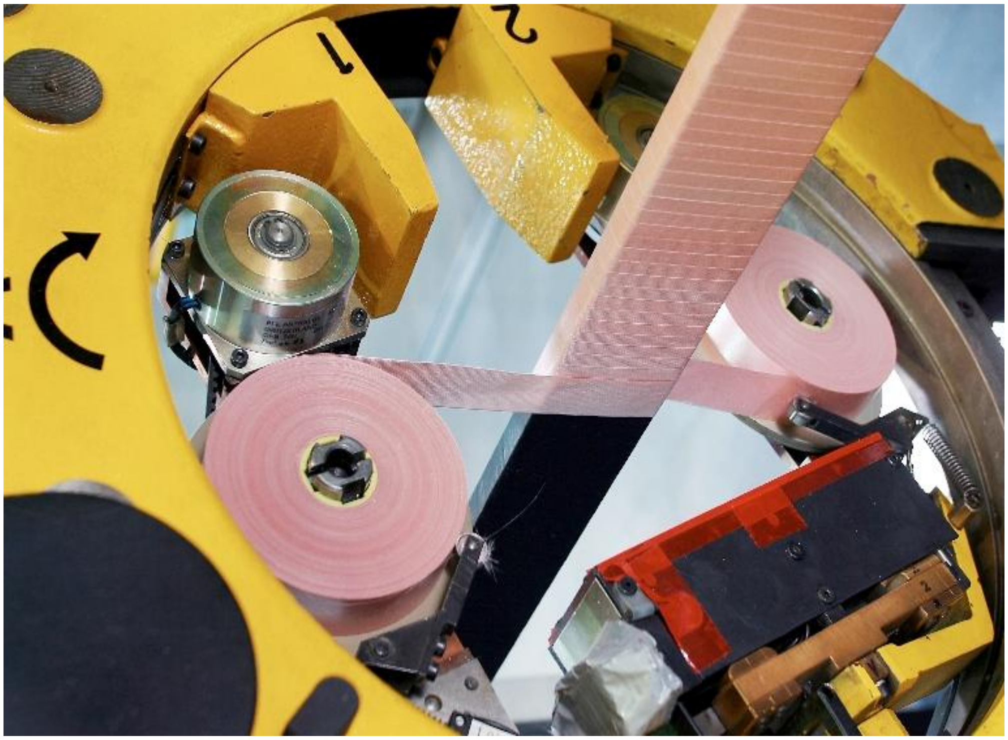
Picture 11: VPI- vessel (12)

Advantages:

- Easy assembling
- Parallel impregnation of all Roebel bars into the vessel
- High operating field-strength possible

Insulating Tape Composition for High Voltage Machines

- Mica
- Carrier (glass, film, fleece)
- Binding resin



Picture 12: Winding machines (Isovolta AG) – automatic (6)

4.2. Porous tapes for VPI – processes

For the manufacturing of insulation systems of rotating machines there are some different tapes which are used in order to insulate separate different parts of the stator for the exposition on variety of influence parameters of the machine and its surroundings.

Composition of Porous Tapes

- Uncalcined Mica paper
- Carrier
    - Glass cloth
    - PET - film
    - Kapton

- Binder (resin)
    - For the mica paper
    - For the bonding of carrier and mica (13)

4.3. Supportive Materials by VPI Tapes

Mica paper itself is very unstable and therefore it should be supported by a carrier. This carrier allows the insulation to be easily rolled.

4.3.1. Glass- cloth

As mica flakes are not very flexible and can easily lose their isolating function if not placed properly, there is a need of a carrier that will support mica on difficult and complex places.

Glass fibers perfectly match the requirements for a carrier of mica. Its characteristics are given below:

- conventional (twisted)
- optimum thermo-mechanical stability: very good bonding allows thermal overstress up to 200°C without delaminating
- fast impregnation
- up to 21 kV in global VPI systems, high mica content
- problematic in high humidity (water absorption)

(13)

4.3.2. PET- film

PET – films are also used in the VPI mica tapes as carriers. Some of their characteristics are:

- highly economic, cheap
- high breakdown voltage
- prolonged impregnation 2-3 times
- up to 10 kV

  (13)

4.4. VPI Comparison

In the high voltage machines it could be differed between two impregnating processes:

- Single Bar VPI
- Global VPI

Some of the advantages and disadvantages are given in the table below:

Single Bar VPI	Global VPI
Advantages • High operating field strength • Single bar testing possible	*Advantages* • High operating field strength • Hermetic sealing of stator • Good thermal contact
Disadvantages • Economic only for high volumes	*Disadvantages* • No single bar testing possible • Difficult removal of defective coils • Large amount of resin used

Table 1: Comparison Single Bar VPI and Global VPI (6)

4.5. Impregnating Resins

The main purpose of the binder resin is to fill voids within the insulation that occur during manufacturing of the bars. In addition, it is used to provide mechanical strength, improve heat transfer, and provide electrical, thermal and environmental resistance of the mica paper. (10)

During manufacture, from the single components to the final winding insulation, binder resin is applied at three stages. First, it is used to keep the mica flakes together when applied to mica paper. Secondly, it is used to hold the mica paper and the support material together when manufactured to mica tapes and finally, it is used for impregnation of the whole insulation. (9)

For mica paper and mica tapes, binders of epoxy resin are used. (11)

Epoxy is a thermosetting plastic. It will therefore not melt, but burn and degrade when heated past its melting temperature. The binders are used in combination with catalysts that reduce the curing time of the epoxy after application of the tape. Various factors of the insulation are determined by the binder resin, such as thermal stability, fabrication process, fabrication time, electrical strength and price. (10)

Resins are binding components which play a significant role for the mica tapes. They can be of different types according to the needs of the insulation system.

- Epoxy-resins without accelerator (Bisphenol-A Resin/Hardener system)
- Epoxy-resins with accelerator
- Polyester-modified epoxy-resins
- Polyesterimide-resins
- Silicone-resins
  (13)

4.6. Additional Materials

To guarantee a good insulation for the entire system, additional materials were implemented. They have special functionality and provide good corona protection.

Winding insulations in machines with voltage levels > 3 kV must be protected from corona discharges. (10)

Corona discharges may occur in the slot of the machine or at the end windings. Discharges in the slot occur in small air filled gaps between uneven surfaces of the winding insulation and the laminated core. These discharges are very harmful for the material since they have a high energy and may destroy the surface of the insulation material .Corona protection in the slot is made of conductive tape and/or paint. (10) (11)

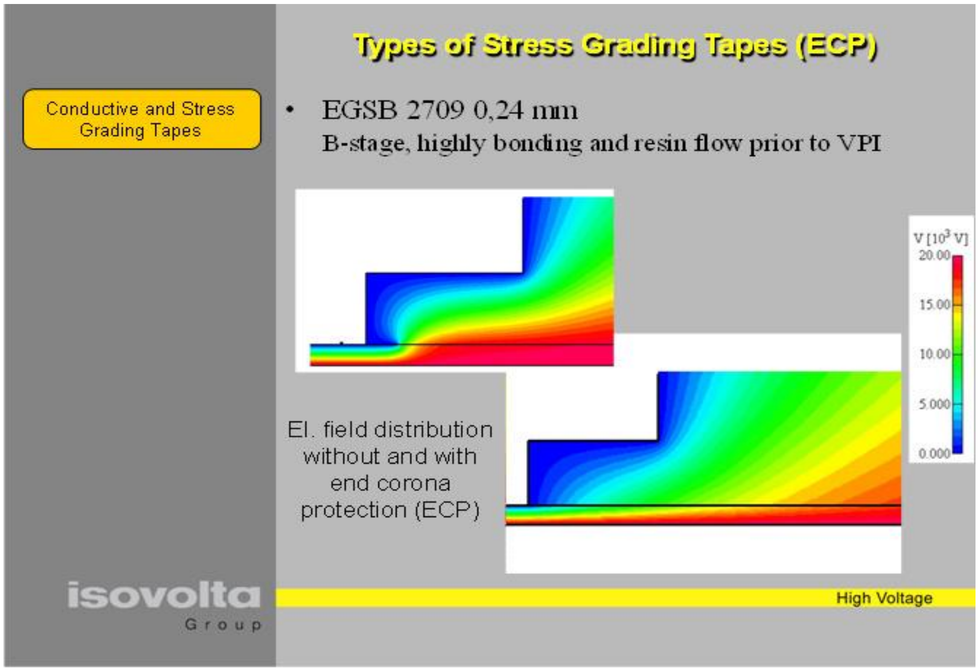


Figure 2: Conductive and Stress Grading Tapes – Isovolta AG; (13)

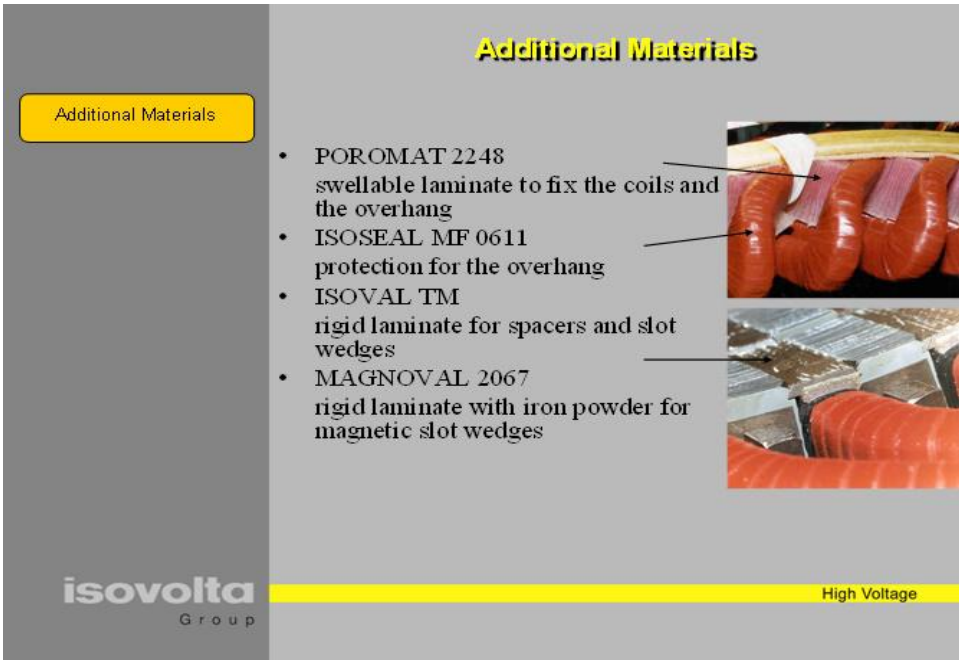


Figure 3: Additional Materials (13) **(13)**

5. Resin Rich Technologies

By applying the resin-rich method, the insulation bar of the high-voltage electrical machine is wrapped in a material which has high resin content (about 40-45% of the total band weight). The insulation is then put under pressure and high temperatures in a special press-machine. A special oven which is heated to 160°C is prepared. The bar is put into the oven under some light pressure so that the desired temperature is achieved. After heated to a certain point, the resin becomes liquid and then a pressure of around 100 Bars is applied on the bar. The pressure is normally applied from the middle to the ends of the bar. (9)

Right after that curing process follows. During pressing a certain amount of resin comes out, carrying out the air. The bar is taken out of the oven after one hour. The curing process takes around 4 hours in a 160 °C heated oven. Each insulation bar is pressed separately. (6).

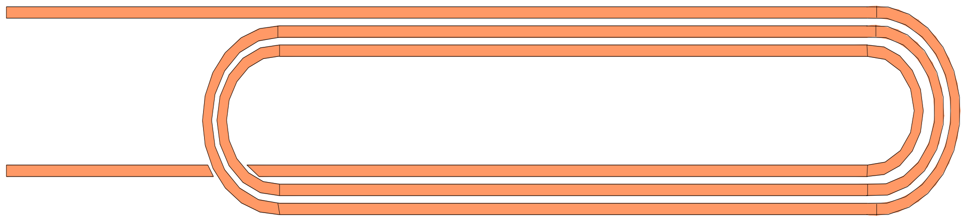
The advantages of resin rich bars are an almost rectangular shape, a tight arrangement of the mica tapes, and that the whole cross section of the insulation is impregnated with similar quality that comes due to the pressing process. Since every insulation bar is produced separately, the electrical tests can be taken separately before the bars are assembled in the machine, which is a further advantage. (10) (11)

Picture 13: Resin Rich Press (12)

5.1. Conventional RR Process

Underneath are given step by step the conventional RR process.

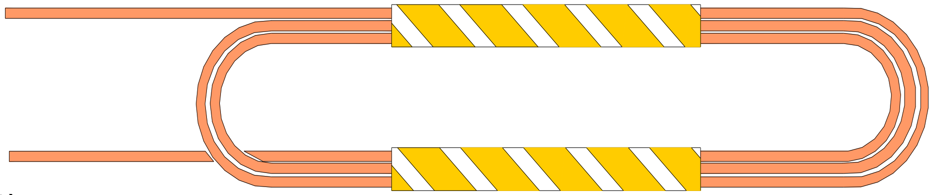
1) Loop of wire – copper is put into a loop shape



(6)

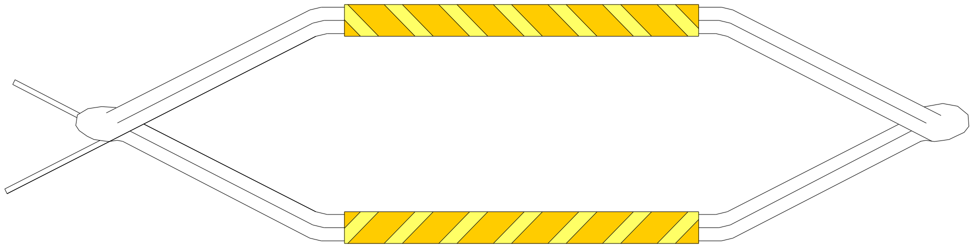
2) Pre-consolidation

   Material VOTAFIX E 2102; 15 – 20 min. / 160°C is applied.



(6)

3) Pull into diamond shape (shape needed for the end placement in the stator).



(6)

4) Overhang Insulation Feinmicaglas; Calmicaflex

5) Straight part Calmicaglass

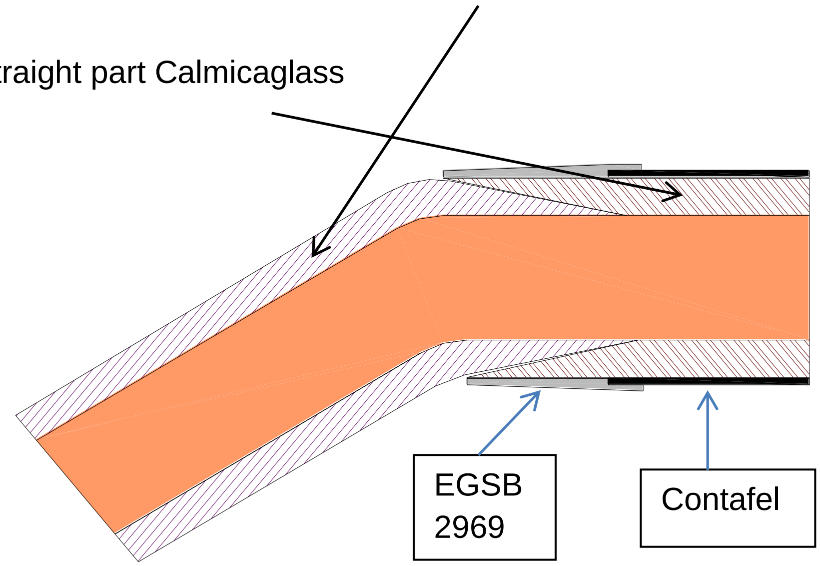


Figure 4 (6)

6) Corona Protection

7) Pressing 1 hour / 160° C in a special RR press

8) Voltage test

9) Sealing

10) Isoseal P 0713 – Material needed to seal all the insulation layers and for humidity protection.

11) Assembling into stator

12) Post-curing > 3 hours / 160° C – to obtain final form.

(6)

6. Test procedure and choice of mica bands

Two Resin-Rich bands were selected for the experiment.

Calmicaglass®0409, which consist of mica paper based on **calcined** muscovite, a glass cloth carrier and thermosetting epoxy Novolac.

Also Calmicaglass®0893, which consists of mica paper based on **uncalcined** muscovite, glass cloth and thermosetting epoxy Novolac.

Both materials are set in the insulation of coils and bars for high voltage electrical machines.

Calmicaglass®0409 is used for the insulation of bars and coils of motors and generators up to highest output and nominal voltage. Calmicaglass®0409 is a very flexible glass mica paper combination, which can be easily wrapped in full width by hand or taped on automatic taping machines. After curing in a hot press, insulation with excellent dielectric, thermal, mechanical, and chemical properties is obtained.

Calmicaglass®0893 can be used for manufacturing of moulded parts such as commutation caps or wound tubes and cylinders. Calmicaglass®0893 is supplied interleaved to prevent sticking of layers. Calmicaglass®0893 is a very flexible glass mica paper combination, which can be taped even on tight bends. Excellent dielectric, thermal, mechanical, and chemical properties are obtained after pressing. (14)

6.1. Test samples preparation

For testing the quality characteristics of the materials, samples with initial size and thickness were prepared. For this matter and in order to achieve the nominal thickness of 1mm and 8 layers as it is applied on the electrical machines, samples of material are cut and laid down over each other.

The transformer in the high voltage cell could achieve a maximum voltage of 30 kV. During the preparation for the voltage endurance test with samples of 1mm thickness, it was clear that it would take a very long time to have a breakdown. For more efficiency of the aging tests it was preferred a preparation of samples with nominal thickness of 0,5mm which is just half of the original size of 1mm. In this way the time to breakdown will be shorter but the conditions will stay very near to the reality.

The number of the applied layers varies depending on the nominal thickness of the mica band.

From each one of the materials an appropriate number of layers is taken and pressed together in a press machine under the even conditions.

6.2. Pressing conditions

Test samples are made of large sheets (1 square meter) of mica rolls because the pressing conditions were not suitable for manufacturing of small samples. Afterwards, final test samples (8,5cm x 8,5cm) were cut out manually. Conditions in the press machine:

155 °C and ~110 Bars pressure for 70 minutes.

Depending on the nominal thickness of the mica tape, a different number of layers (2, 3, 4 or 6) were taken for producing the test samples. The goal was, after the pressing process, to achieve the thickness of 0,5mm samples.

Calmicaglass®0409 – Band thickness 0,12mm -> 6 layers;

Calmicaglass®0409 – Band thickness 0,18mm -> 4 layers;

Calmicaglass®0409 – Band thickness 0,21mm -> 3 layers;

Calmicaglass®0893 – Band thickness 0,18mm -> 4 layers;

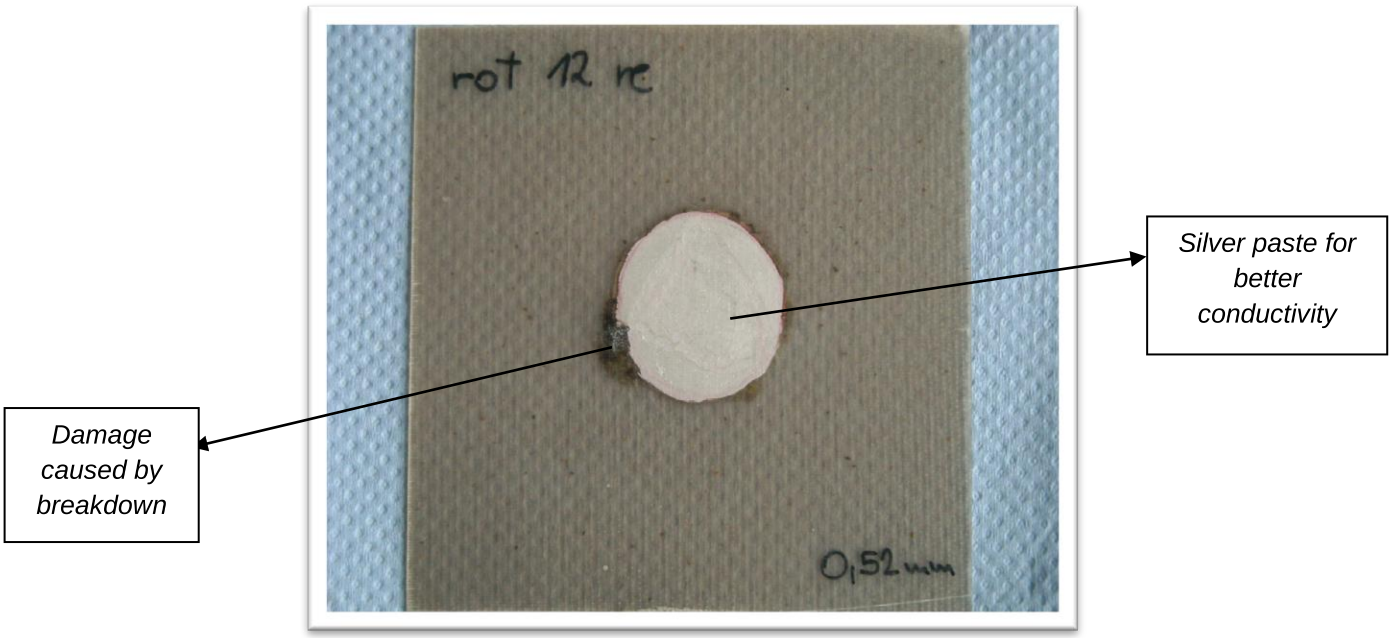
Calmicaglass®0893 – Band thickness 0,28mm -> 2 layers;

After pressing, the sheets are led into the press machine to cool down to room temperature. The thickness of the prepared samples varies between 0,35mm to 0,65mm. In the middle of the big sheet ($1m^2$), the applied pressure is higher and therefore the sheet thickness there is below 0,5mm. The applied pressure at the edges of the sheet is lower than in the middle, therefore the sheet thickness in this area is higher. Thickness in the middle of each sample is measured again more accurately and was written down on each test sample.

This kind of pressing cannot be applied directly on Roebel bars because the thickness of the test samples varies, while during the more precise pressing phase of Resin Rich method, insulation thickness remains constant all over the bar.

6.3. High Voltage Endurance Tests

To examine the dielectric strength of different materials a voltage endurance test has been made. Materials were put under constant voltage load until a breakdown occurred.



Picture 14: Calmicaglass®0409 after breakdown and a couple of hours under 45kV.

Samples of both the materials Calmicaglass®0409 with nominal thickness of 0,12mm; 0,18mm and 0,21mm and Calmicaglass®0893 with nominal thickness of 0,18mm and 0,28mm are tested under two different voltages to compare the lifetime of the samples.

6.3.1. Test setup

The samples were put in plastic vans filled with transformer oil. The samples were placed between a pair of two electrodes and connected to high-voltage in a special high voltage cell.

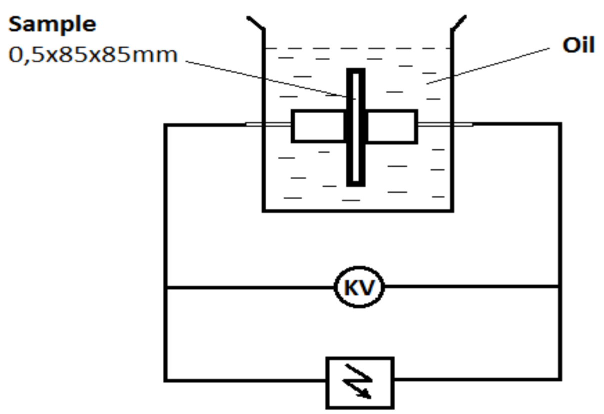


Figure 5: Test Constellation

Picture 15: High voltage cell for sample test

When such tests are held into insulating liquids, like mineral transformer oil, they should equate and respond to the Standard IEC 60296 (fig.6). It is necessary to ensure adequate dielectric strength of the liquid to avoid flashovers. Contamination, which reduces the electric strength of the oil or other liquid, may increase the measured electric strength of the test sample.

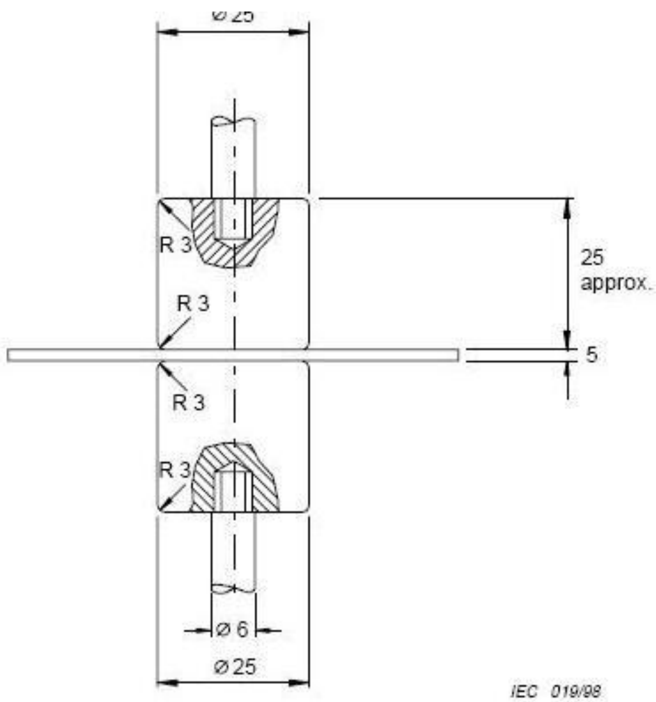
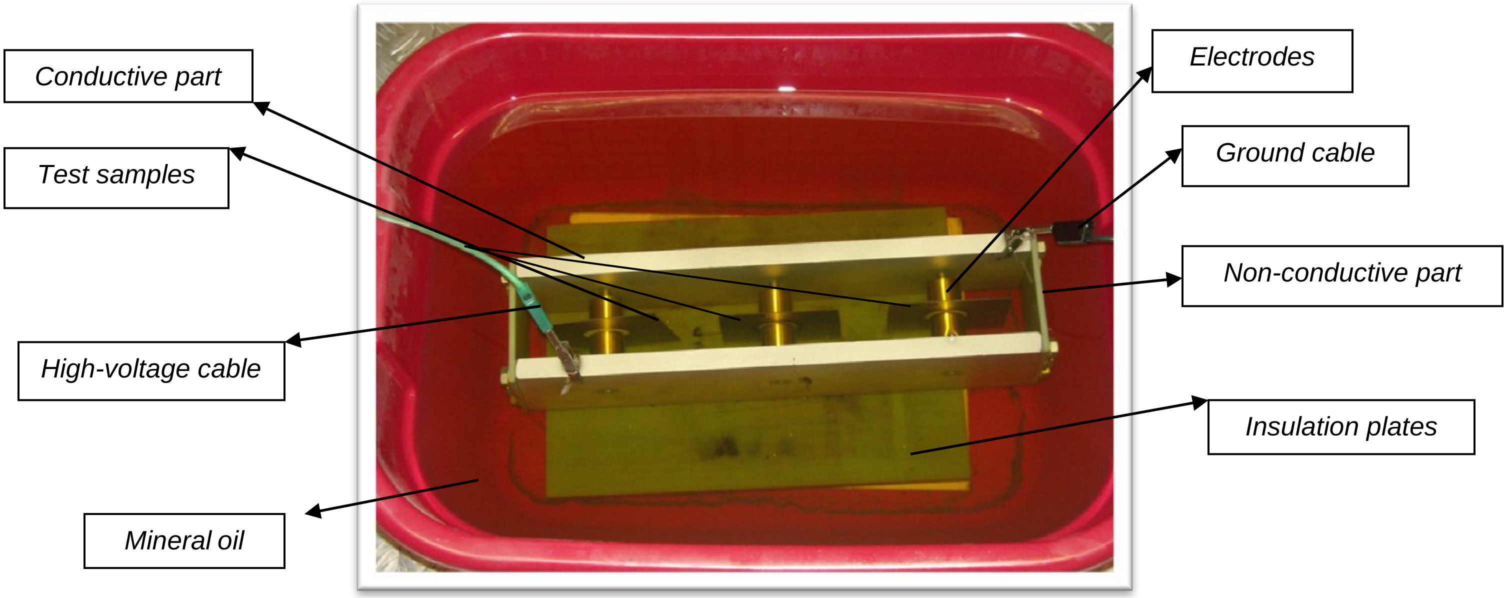


Figure 1b – Equal diameter electrodes

Dimensions in millimetres

Figure 6: Electrode arrangements

Test samples are put in oil because of its great insulating characteristics. The electrodes have cylindrical form which is the common form of electrodes for tests over solid bodies in transformer oil (Standard IEC 60263-1). In figure 6, the geometry of the electrodes could be seen according to the IEC Standard.



Picture 16: Van with mineral oil and test samples between electrodes

The conductor part of the experimental device, which holds the electrodes is put additionally over two insulating plates, so that the plastic bucket is completely isolated from the metal floor in the high voltage cell. Parallel sides of the electrode-holders are made of aluminium which is very conductive. Two non-conductive plates connect the aluminium sides. At one of the conductive sides a high voltage cable is switched on, and on the other conductive side a ground cable is connected. High-voltage is taken from a transformer with 30kV capacity. Test samples are stuck manually between two electrodes. The sample size is big enough, so that no flashovers can occur, only breakdowns. In order to load exactly this field between the electrodes, a conductive silver paste is put on both side of the sample where the electrodes are placed. In this way the silver area is under direct contact with the applied voltage on the electrodes. The way that the current will have to make is defined. It has no other options but to try to get through the layers of the material, destroying the insulation.

6.3.2. Test results

The time to breakdown has been taken for every single sample. (see attachment)

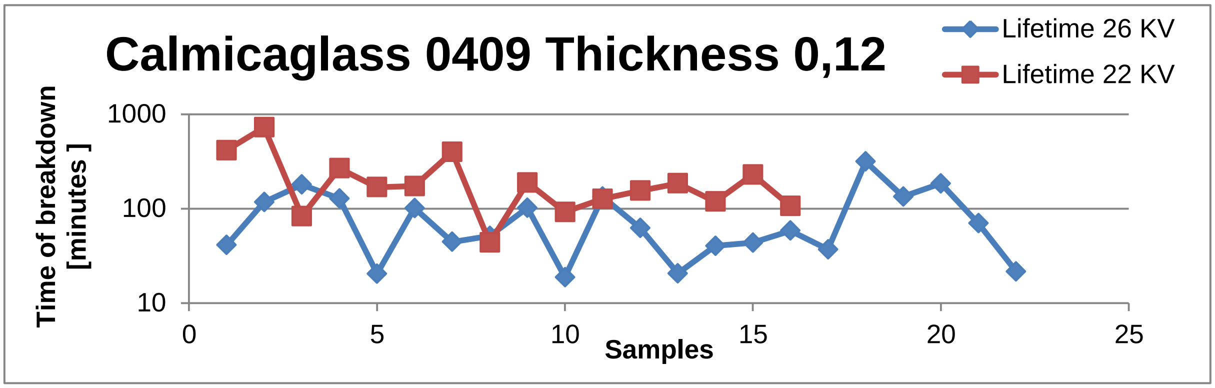


Figure 7: Calmicaglass®0409 thickness 0,12mm

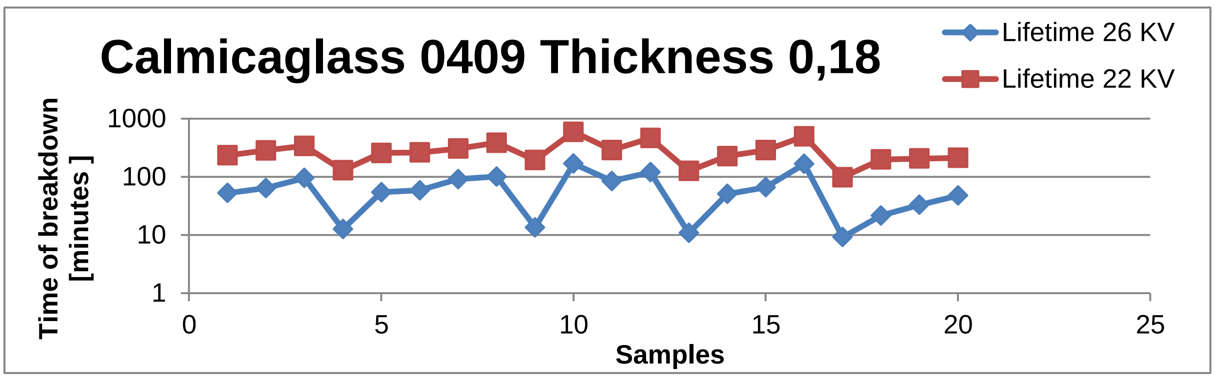


Figure 8: Calmicaglass®0409 thickness 0,18mm

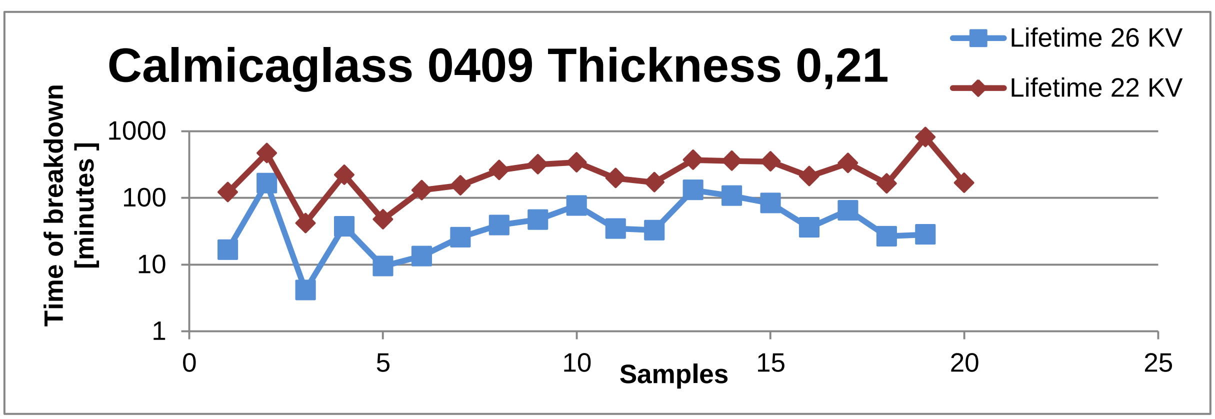


Figure 9: Calmicaglass®0409 thickness 0,21mm

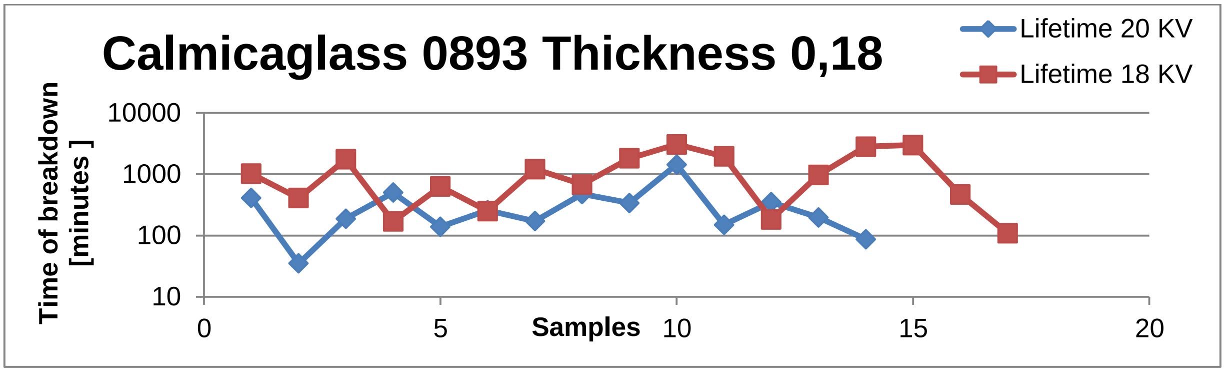


Figure 10: Calmicaglass®0893 thickness 0,18mm

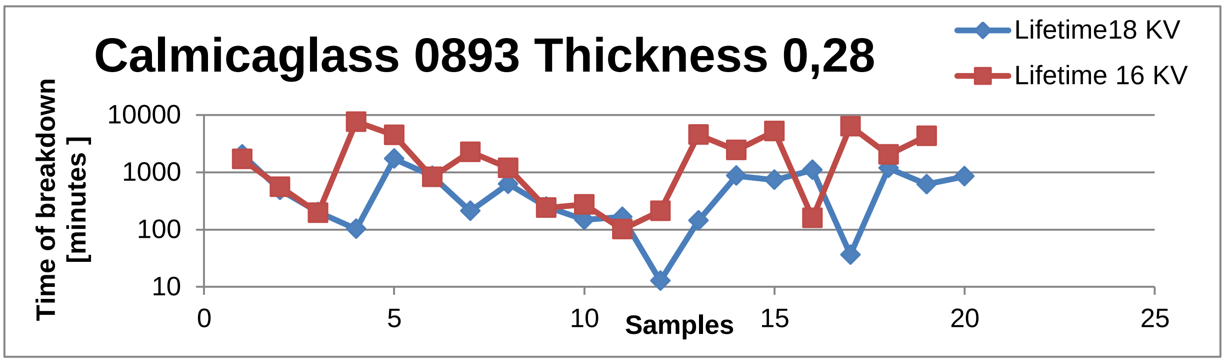


Figure 11: Calmicaglass®0893 thickness 0,28mm

As predicted all materials have shown same behaviour: Lower voltage – longer lifetime and higher voltage – shorter lifetime.

Because of the two different test voltages and the slight difference of the thickness of the samples, the applied electrical field strength E [kV/mm] for each sample differs.

The thicknesses of the samples have been noted down separately (see attachment) therefore it was possible to calculate the electrical field strength E for each probe.

For further investigations of the connection between E and time to breakdown all data for all materials was put into a diagram (Figure 12).

Due to the fact that showing all samples led to confusing curves, average values for field strength ranges of 1 kV/mm where taken. This reduces the number of shown points to a descriptive form.

Calmicaglass®0409 0,12mm		
E [kV/mm]	Average time [min]	Number of Samples
38	44	1
39	189	1
40	276	4
41	239	4
42	133	5
43	208	5
44	123	4
45	122	4
46	63	3
47	51	2
48	64	3
49	20	2
50	41	1

Calmicaglass®0409 0,18mm		
E [kV/mm]	Average time [min]	Number of Samples
37	329	7
38	213	4
39	226	3
40	352	4
41	133	6
42	80	3
43	55	2
44	167	1
46	52	2
49	11	1
50	31	6
52	64	1

Calmicaglass®0409 0,21mm		
E [kV/mm]	Average time [min]	Number of Samples
41	154	1
42	340	5
43	389	4
44	222	4
45	132	4
46	221	1
47	171	1
48	131	1
49	92	2
50	82	4
52	21	3
53	29	7

Calmicaglass®0893 0,18mm		
E [kV/mm]	Average time [min]	Number of Samples
35	3069	1
36	1594	4
37	970	1
38	866	4
39	630	1
40	908	7
41	332	2
42	409	4
43	466	1
44	248	2
45	276	4
46	35	1

Calmicaglass®0893 0,28mm		
E [kV/mm]	Average time [min]	Number of Samples
33	4468	1
34	3467	2
35	4795	3
36	6357	1
37	1209	2
38	2546	3
39	1695	1
40	1109	5
41	867	1
42	829	3
43	371	4
44	217	2
45	363	2
47	304	3
48	177	2
50	157	2
51	36	1
52	13	1

Table 2

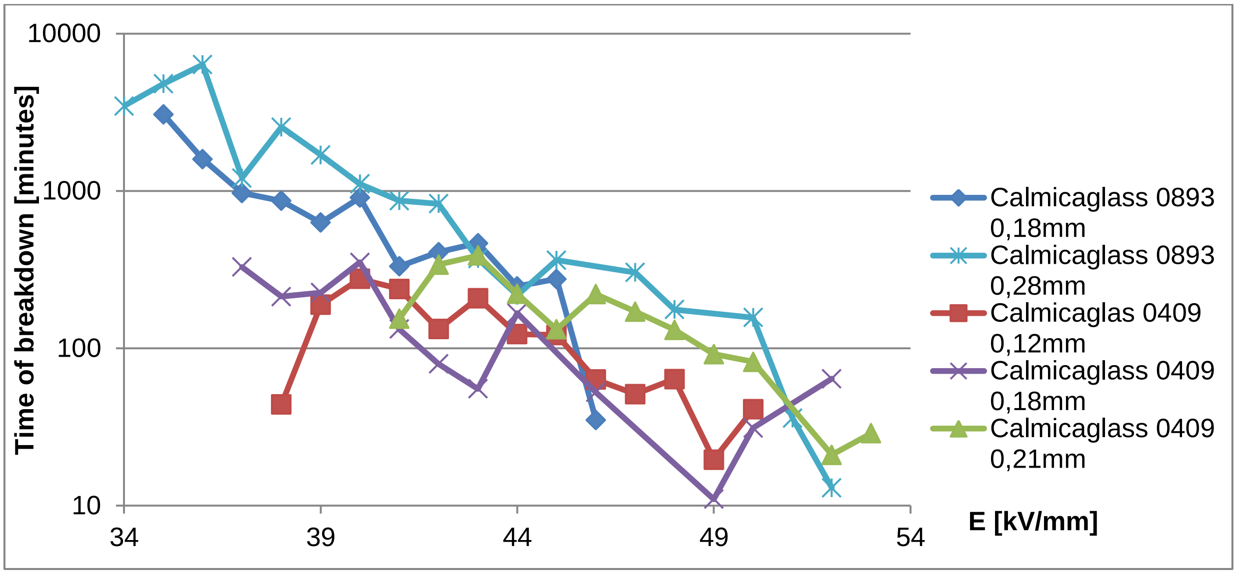


Figure 12: Time of breakdown / E [kV/mm]

Figure 12: Time of breakdown / E [kV/mm] shows a strong dependency of breakdown time on electrical field strength for all materials. Higher electrical field strength leads to a dramatic reduction of time to breakdown.

Because of different sample thicknesses it is difficult to compare different materials regarding time to breakdown.

A correct comparison of materials would only be valid for the same field strengths for all samples. Different sample thicknesses make this impossible.

To have the chance to compare the materials one has to choose a small range of field strength.

For all further investigations the electrical field strength range from 41kV/mm to 47kV/mm was taken. In this range all materials provide data. Samples out of this range stay unconsidered.

6.3.3. Weibull distribution

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. In probability, theory and statistics, the **Weibull distribution** is a continuous probability distribution. It is named after Waloddi Weibull who described it in detail in 1951, although it was first identified by Fréchet (1927) and first applied by Rosin & Rammler (1933) to describe the size distribution of particles. (2)

The software program Visual XSel 12.0 was used for the following graphics. The graphics below show the Weibull distribution of breakdown probability at 63.2%.

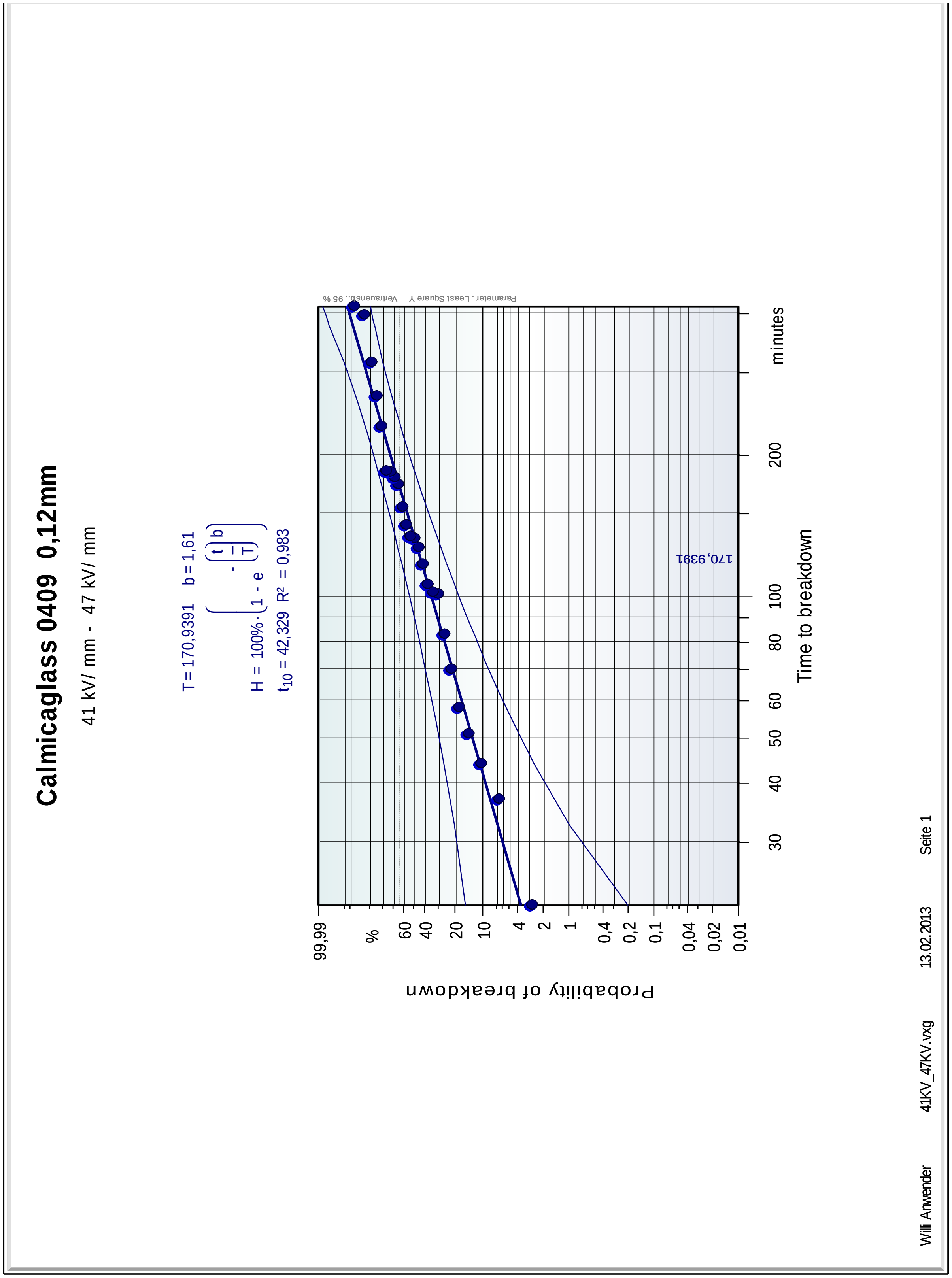


Figure 13: Weibull Calmicaglass®0409 0,12mm

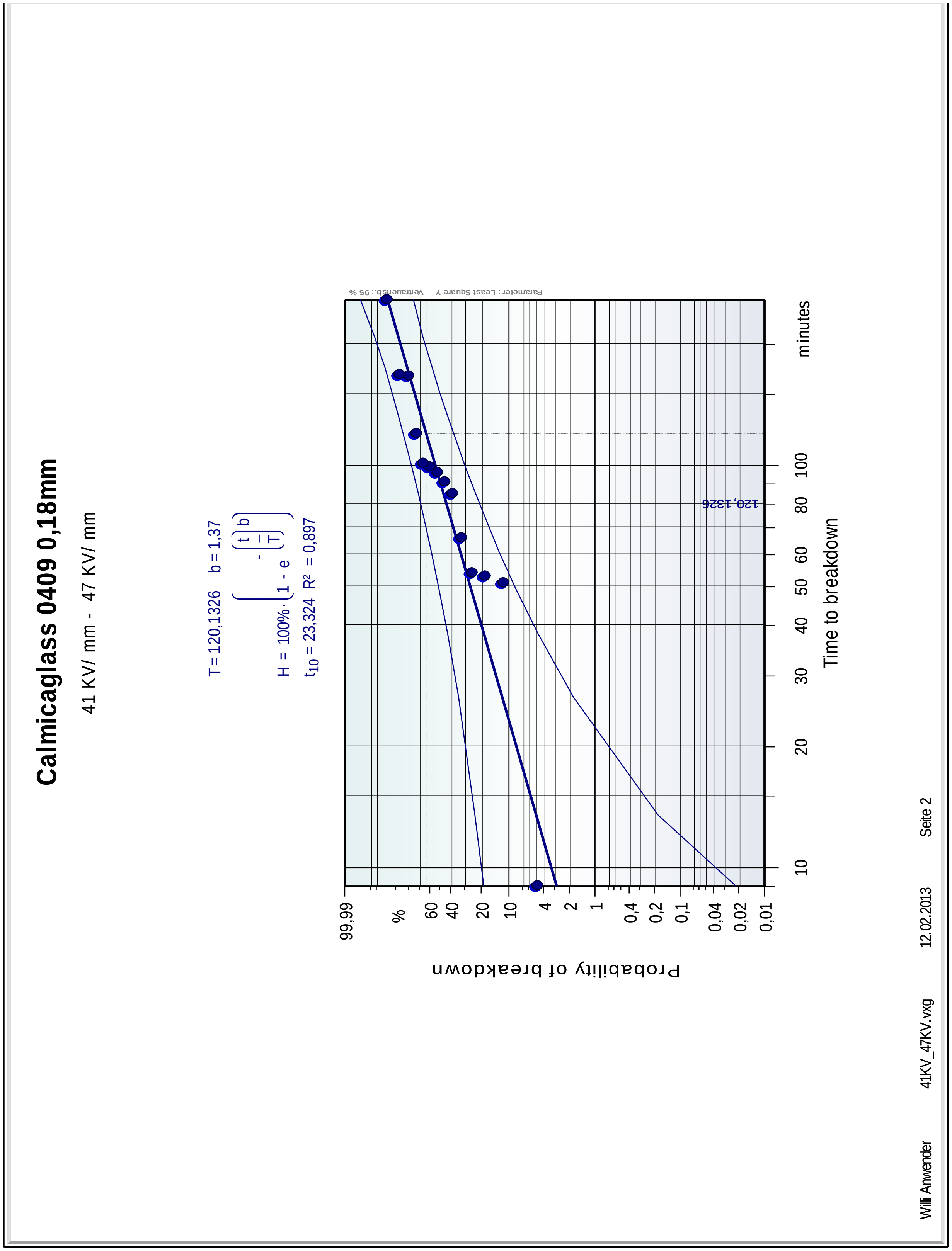


Figure 14: Weibull Calmicaglass®0409 0,18mm

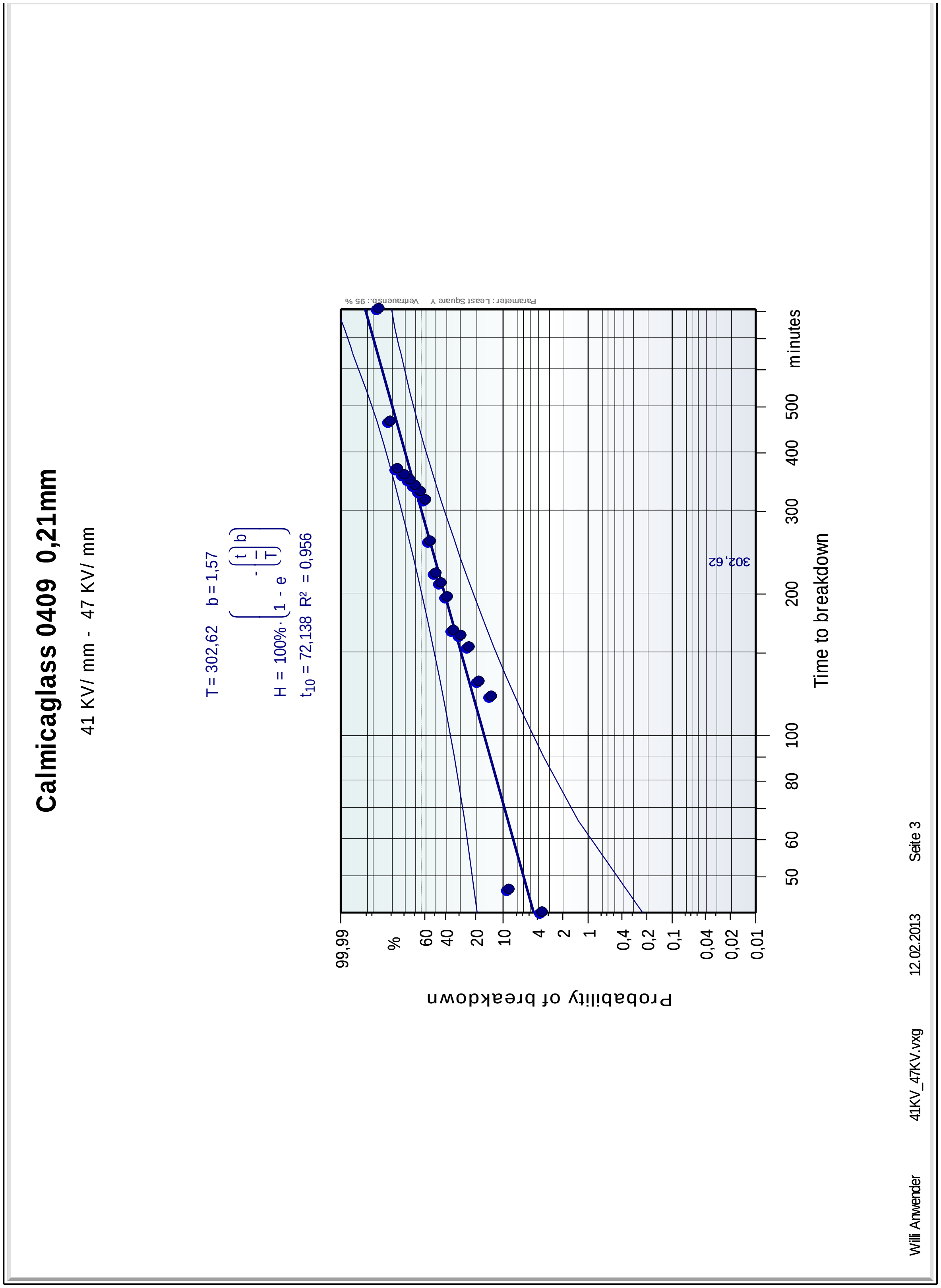


Figure 15: Weibull Calmicaglass®0409 0,21mm

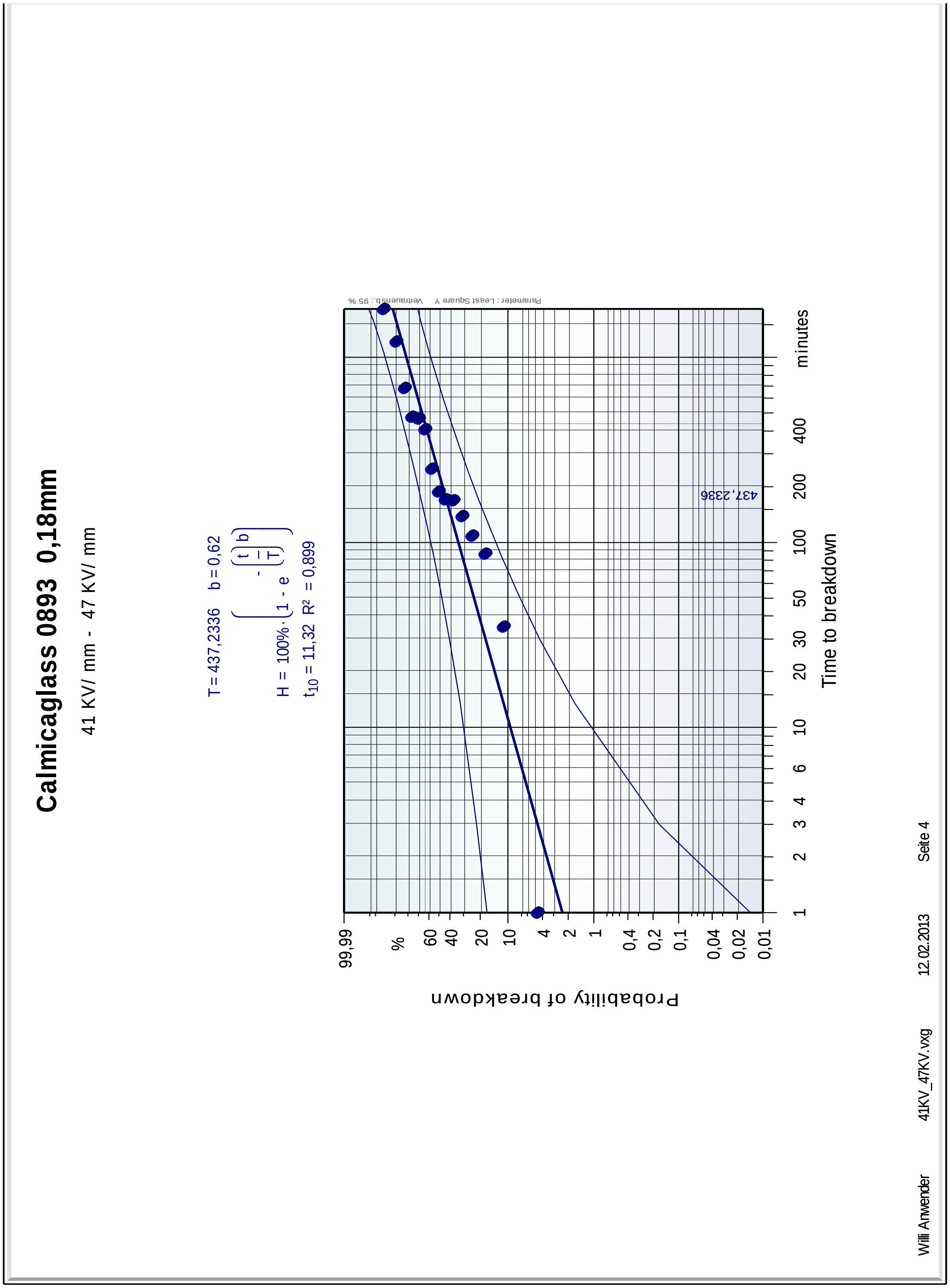


Figure 16: Weibull Calmicaglass®0893 0,18mm

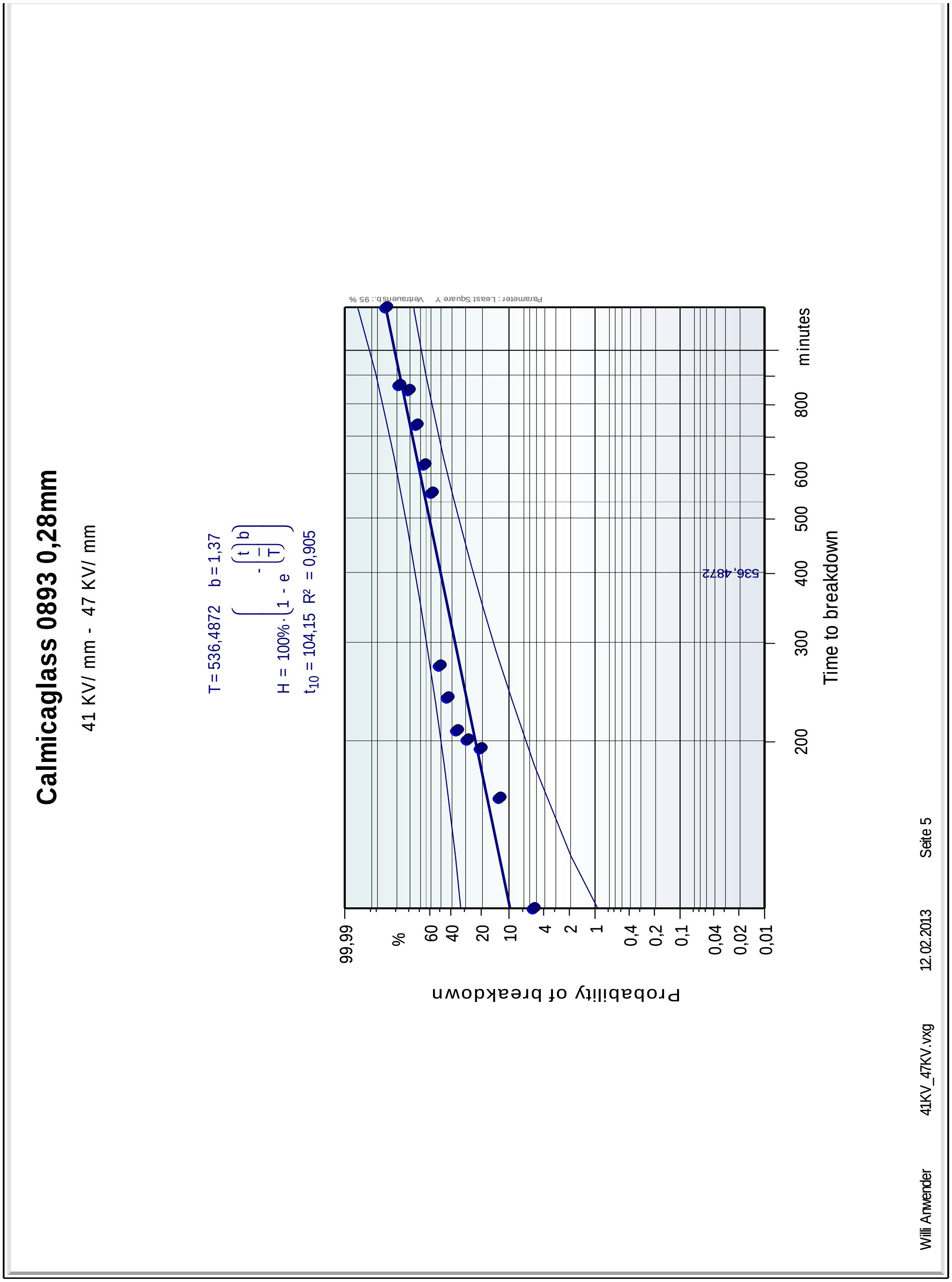


Figure 17: Weibull Calmicaglass®0893 0,28mm

6.3.4. Test Analysis

Besides the time to breakdown at 63,2% (received by Weibull Distribution), the amount of mica of each sample, could also be a matter of interest.

The amount of mica for each one of the 5 materials was calculated in order to find a possible dependency between time to breakdown and mica content.

Mica paper :

Material	Mica content [g/m²]	Material	Mica content [g/m²]
Calmicaglass®0409 0,12mm	75	Calmicaglass®0893 0,18mm	120
Calmicaglass®0409 0,18mm	120	Calmicaglass®0893 0,28mm	250
Calmicaglass®0409 0,21mm	150		

Table 3: Mica content

(13)

A sample has a size of 8,5 cm x 8,5 cm. That makes area of 0,0072 m^2.

One layer of the sample from Calmicaglass®0409 with 0,12mm thickness has then:

$75 g/m^2 \times 0{,}0072\ m^2 = 0{,}54 g$ Mica

The samples from this material consist of totally 6 layers total

$0{,}54 g \times 6 = 3{,}24 g$ Mica.

All data can be seen in the following diagram:

Material Band-thickness	**Number of layers**	**Mica content**	**Load range**	**Time to breakdown at 63,2% (Weibull)**
Calmicaglass®0409 0,12mm	6	3,25 g	41-47 kV/mm	170,94 minutes
Calmicaglass®0409 0,18mm	4	3,46 g	41-47 kV/mm	120,13 minutes
Calmicaglass®0409 0,21mm	3	3,24 g	41-47 kV/mm	302,62 minutes
Calmicaglass®0893 0,18mm	4	3,46 g	41-47 kV/mm	437,23 minutes
Calmicaglass®0893 0,28mm	2	3,60 g	41-47 kV/mm	536,49 minutes

Table 4: Calmicaglass®0893, Calmicaglass® 0409 Time of breakdown

Against the expectations, materials with more layers have shown no advantage in comparison to those with few layers. Just the opposite, material which has few layers (Calmicaglass®0409 0,21mm and Calmicaglass®0893 0,28mm) shows better results. This tendency remains not true for all the cases. Calmicaglass®0409 with 0,18mm and 4 layers shows worse results than Calmicaglass®0409 with 0,12mm and 6 layers. Also, a connection between time to breakdown and amount of mica within the sample could not be clearly stated.

What could be clearly seen from the tests is that the dielectric strength by Calmicaglass®0893 is higher than the one from Calmicaglass®0409.

6.4. Resin content

To get more information about the organic part in the samples after pressing the mica sheets, some resin content tests are additionally made. Five test samples, with thickness around 0,5mm, are taken from each material. They were weighted two times: before and after burning into an oven at 700 °C for 90 minutes. At this temperature all organic components are burnt out, so that only inorganic components like glass and mica stay. In this way it is possible to find out how much resin was left in the sample.

Picture 17: Oven for burning out the organic parts

The table below shows the weight of the samples before and after the burning test using the example of Calmicaglass0409 0,18mm.

Sample	1	2	3	4	5	Average value [g]
Weight before [g]	6,835	6,895	6,887	6,229	7,074	**6,784**
Weight after [g]	4,260	4,300	4,289	4,260	4,371	**4,296**
Difference [g]	2,575	2,595	2,598	1,969	2,703	**2,488**
Sample thickness [mm]	0,54	0,54	0,54	0,51	0,54	
Calmicaglass 0409; Band Thickness- 0,18mm; Number of Layers pressed – 4;						

The average weight before burned for this example: 6,784g

The average reduction of weight (resin burned): 2,488g.

Using formula one, percentage amount of resin for the samples after pressing can be calculated:

$$\frac{\text{resin (burned)}}{\text{total probe weight before burned}} \times 100\%$$

Formula 1

$$\frac{2{,}488\text{g}}{6{,}784\text{g}} \times 100\% = 36{,}67\%$$

This calculation was made for all the materials and can be seen in table 5.

Material	Resin in the sample after pressing [%] (Calculation)
Calmicaglass®0409 0,12mm	39,2
Calmicaglass®0409 0,18mm	36,67
Calmicaglass®0409 0,21mm	40,7
Calmicaglass®0893 0,18mm	36,09
Calmicaglass®0893 0,28mm	38,08

Table 5: Resin content after pressing process and after burning out at high temperature

The calculated values differ not too much from the datasheet values for resin content. This is because the amount of lost resin during pressing is not very high.

If these values were compared with the results of the voltage endurance test, it can be observed that within the material more resin in the sample means longer operating hours. It should be considered that because of the small number of samples this dependency happens by chance.

6.5. Dynamic-Mechanical Analysis

With **D**ynamic **M**echanical **A**nalysis (**DMA**) it is possible to make a quantitative determination of the mechanical properties of sample under an oscillating load and as a function of temperature, time and frequency. (15)

Most materials are both elastic (stiff) and viscous (damping behavior), i.e. they are **viscoelastic**. Thus they yield to an applied load, partially through viscous flow, with a permanent deformation. At the same time, the mechanical behavior is a function of temperature, time, degree and type of load. Structural transformations (e.g. glass transitions, secondary relaxations, cross-linking) are seen in considerable changes in the thermal and mechanical properties, which are demonstrated with the DMA. Dynamic-mechanical analysis provides the user with extensive, practical information: (15)

- Operable temperature ranges for application and processing (glass transition temperature, onset of softening and brittleness)
- Design data concerning stiffness and damping properties (modulus values, damping factor)
- Data on the composition and structure of polymers and polymer blends (compatibility)
- Curing, Vulcanization
- Ageing

DMA is significant and dependable information for:

- Research and development
- Quality control
- Quality assurance
- Failure analysis

Tests run in the temperature range from **-170°C** to **600°C** provide an important data on the material. Dynamic, isothermal and stepwise temperature control makes it possible to design flexible temperature programs suited to a particular problem. The sample is subjected to a **defined, forced oscillation**. A sinusoidal force (input signal) affects a deformation of the viscoelastic sample (output signal). This also produces sinusoidal, but phase shifted, oscillation which is then recorded. These oscillations are reduced to a signal of extremely low noise level in the DMA controller by means of **FOURIER-Analysis**.

The frequency range of **0.01 Hz to 100 Hz** includes up to 25 fixed frequencies, which can be selected individually or in any combination (multiple frequency). The deformation amplitude (**approx. 0.1 µm to 240 µm**) as well as the sample position is controlled independently from one another. Thereby, constant contact between the push rod and the sample is guaranteed, even when the material softens greatly. (15)

Thermal:

The rectangular cross section of the furnace is fit to the sample geometry, such that the sample is **heated** constantly and **homogeneously**. The temperature gradient is minimized to + 1°C over a sample length of 60 mm. The sample temperature is registered by a sample thermocouple and precisely controlled via the STC function (Sample Temperature Control). (15)

Mechanical:

In three-point bending the dynamic force is superimposed by a static preliminary force. Thus, even with great changes in the modulus, secure positioning of the sample is guaranteed. (15)

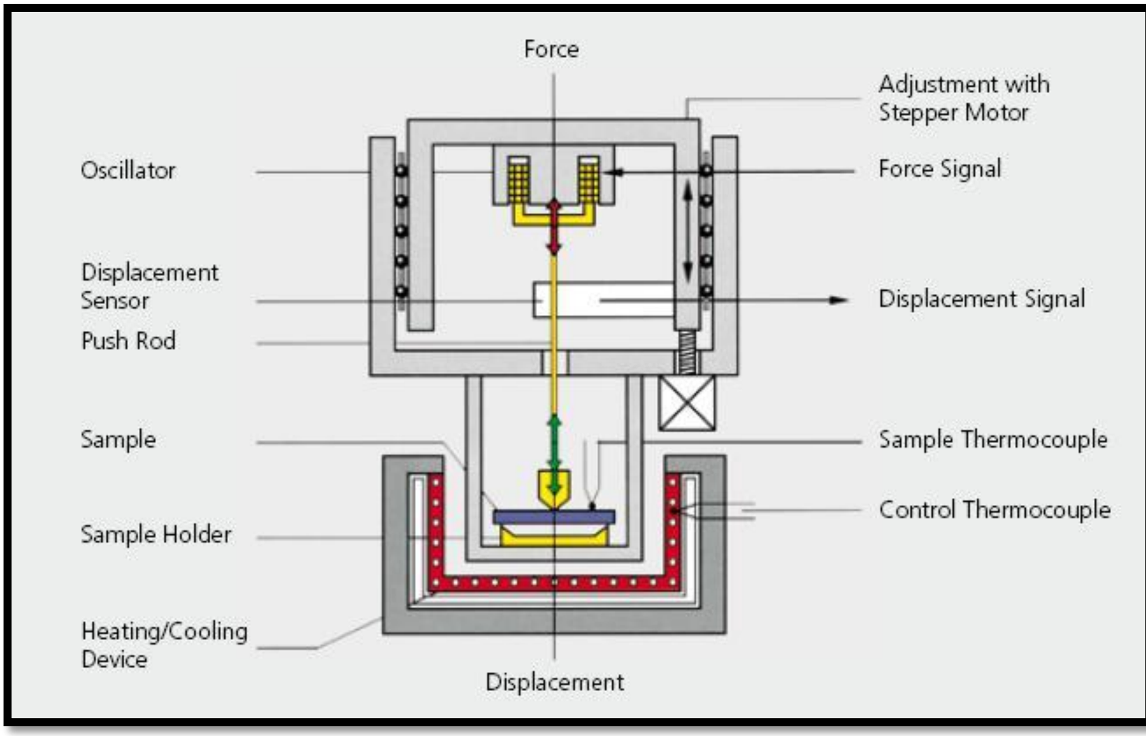


Figure 18: DMA device – construction (15)

6.5.1. Measurements

On the graphics below is shown that both of the materials have similar value of the loss factor tan δ and elasticity module curves.

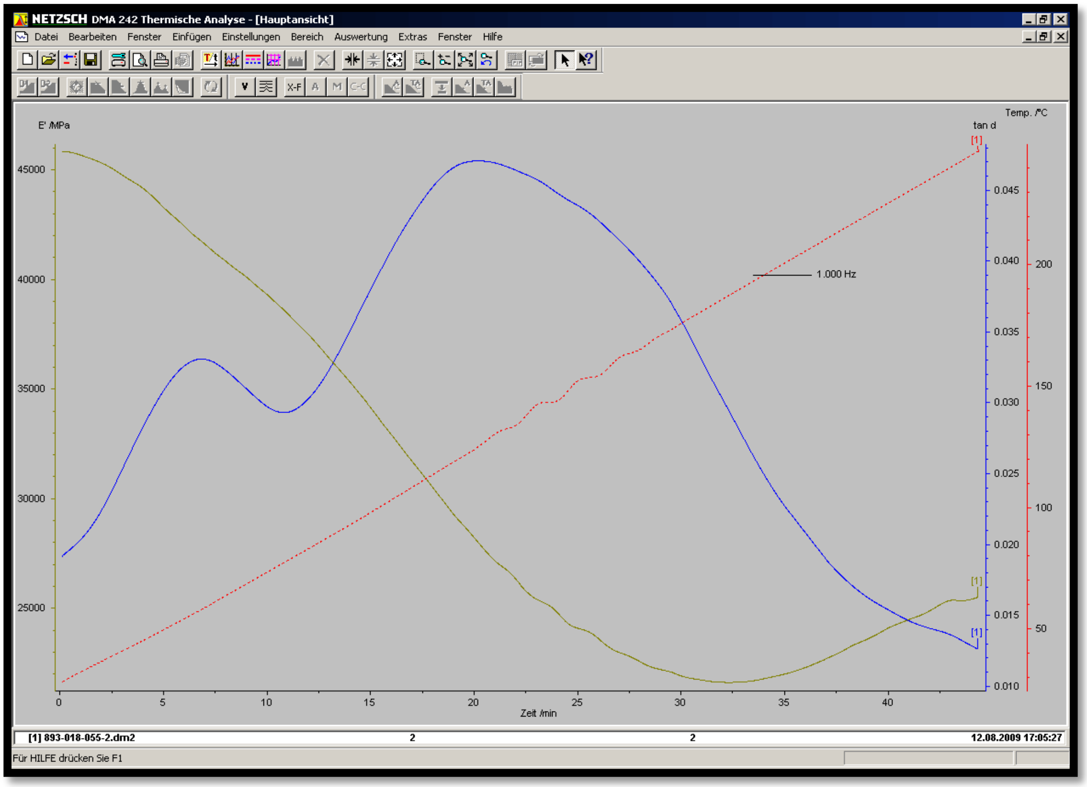


Figure 19: Calmicaglass®0893 (up) and Calmicaglass®0409 (down)

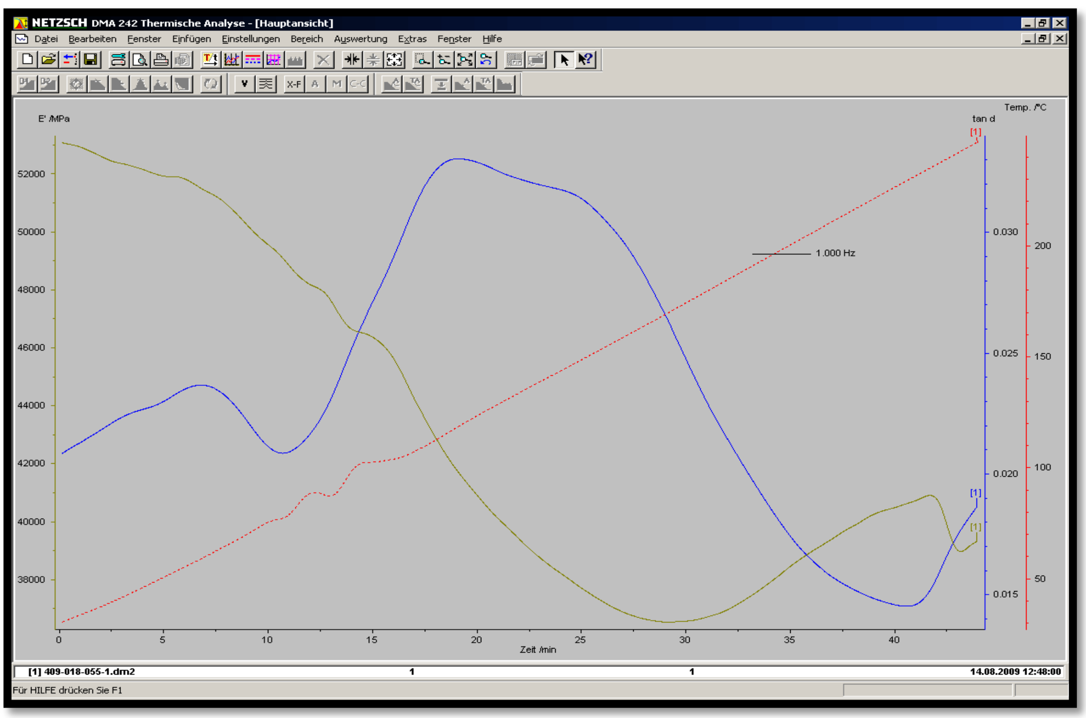


Figure 20

Both samples have 4 layers of material with nominal band thickness 0,18mm.

The test shows that by Calmicaglass®0893 the characteristic curve of loss factor tan δ has a bit higher peak than the one from Calmicaglass®0409. That means this material is a little bit "softer" in mechanical meaning than the other one. After both the materials are made with the same resin (Novolac) and the difference is only in the amount of quantity in the band a big difference with this device could not be detected. Conditions like oven temperature, oscillating frequency, force and duration have been kept the same.

6.6. Thermal-load tests:

Additional thermo-cycling test are made in order to determine the lifetime of the material after being heated.

Samples from Calmicaglass®0893 and Calmicaglass®0409 with nominal band thickness 0,18mm and 4 layers are chosen for this test. The thickness of the sample is about 0,5mm – 0,6mm. 15 test samples from each one of the material are put in an oven at 200 °C for a time as follows:

- 5 Sample Calmicaglass®0893 and 5 Sample Calmicaglass®0409 for 50 hours.
- 5 Sample Calmicaglass®0893 and 5 Sample Calmicaglass®0409 for 100 hours.
- 5 Sample Calmicaglass®0893 and 5 Sample Calmicaglass®0409 for 150 hours.

While rising the voltage to 18kV some of the first samples from Calmicaglass® 0893 tested after thermal load, had an immidiate breakdown. These are:

- 2 samples Calmicaglass®0893 with 50 hours thermal load
- 2 samples Calmicaglass®0893 with 100 hours thermal load
- 1 sample Calmicaglass®0893 with 150 hours thermal load

That is why a voltage of 16kV was taken for Calmicaglass® 0893 and the samples with breakdown stay unconsidered.

Test conditions were as follows:

Calmicaglass®0409 samples are tested under nominal voltage of 22kV, and Calmicaglass®0893 samples under nominal voltage of 16kV. That means there is a load between 35 and 37 kV/mm on each sample of Calmicaglass®0409 and respectively between 29 and 37 kV/mm for Calmicaglass®0893 samples.

The samples are then tested under high voltage under same conditions as before, in transformer oil.

6.6.1. Weibull Distribution results

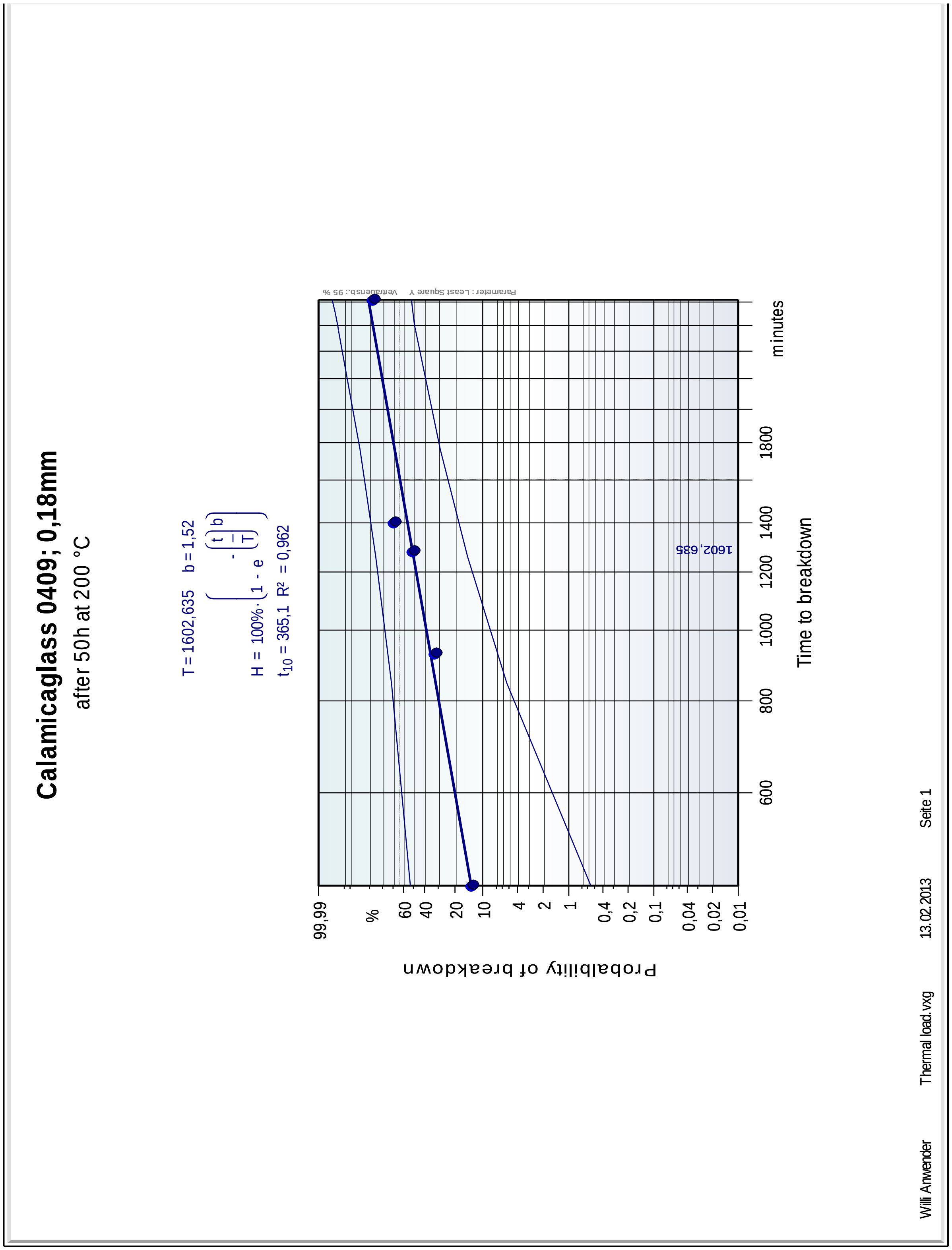


Figure 21: Weibull Calmicaglass®0409 0,18mm 50h thermal load

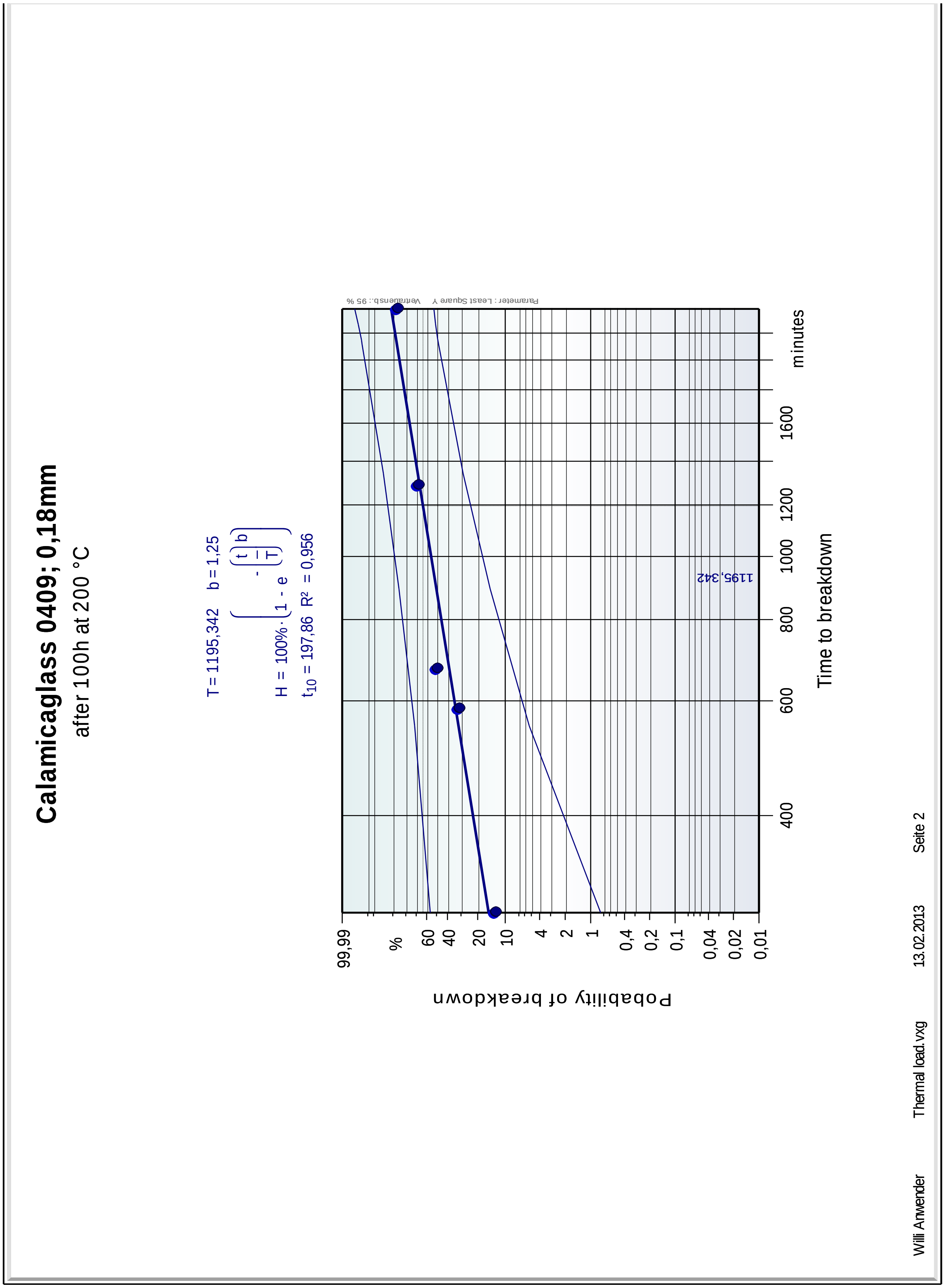


Figure 22: Weibull Calmicaglass®0409 0,18mm 100h thermal load

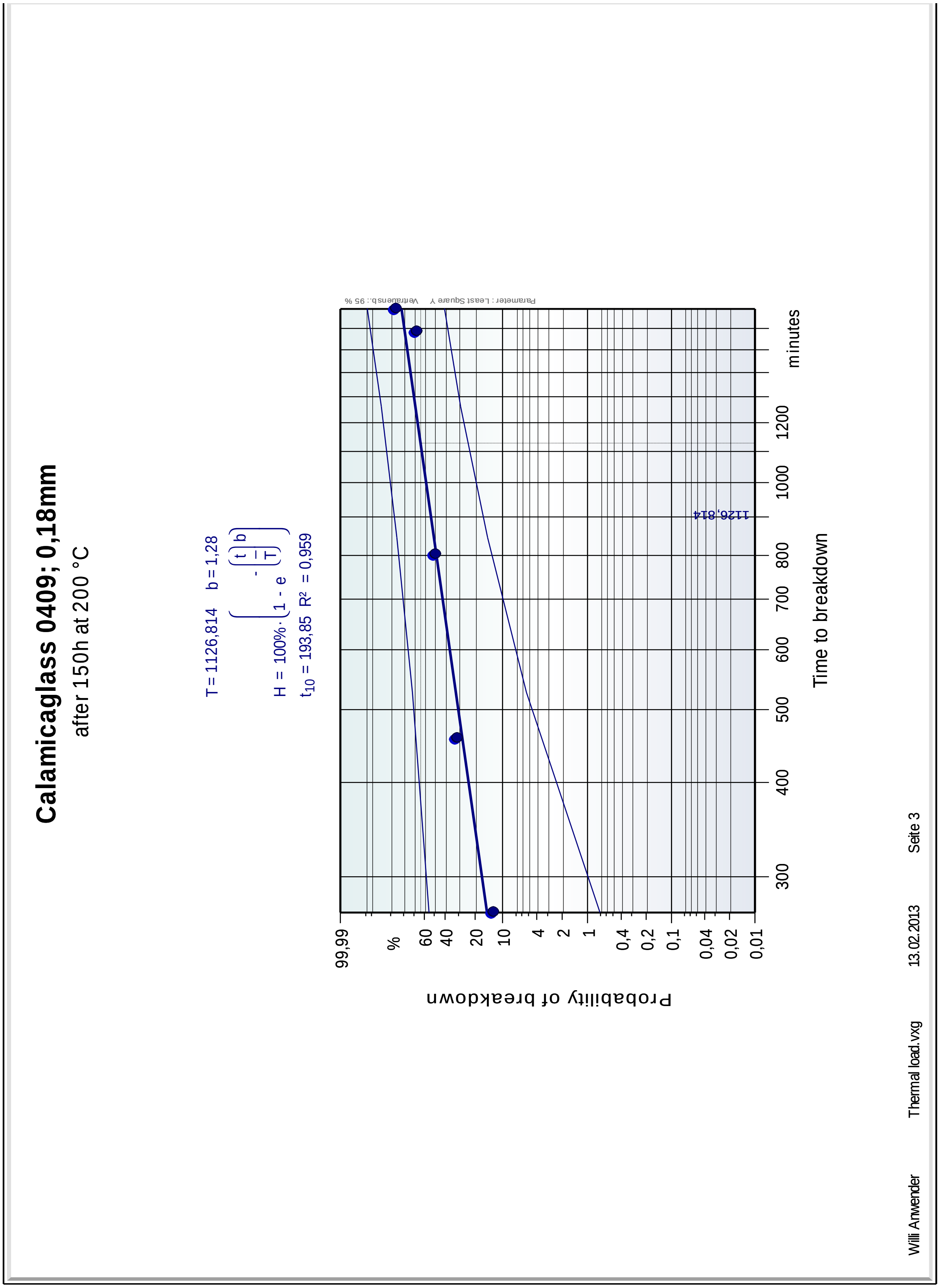


Figure 23: Weibull Calmicaglass®0409 0,18mm 150h thermal load

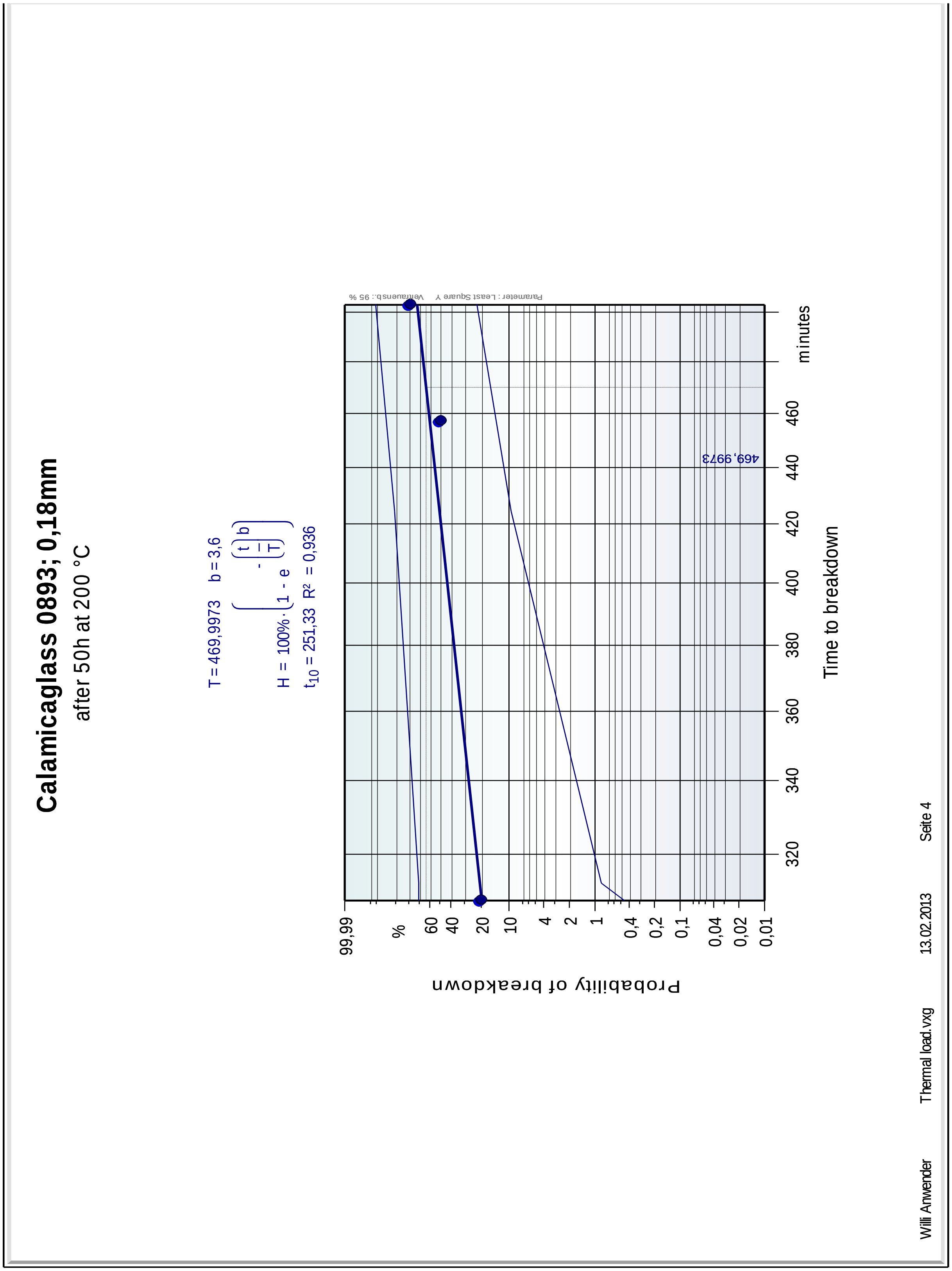


Figure 24: Weibull Calmicaglass®0893 0,18mm 50h thermal load

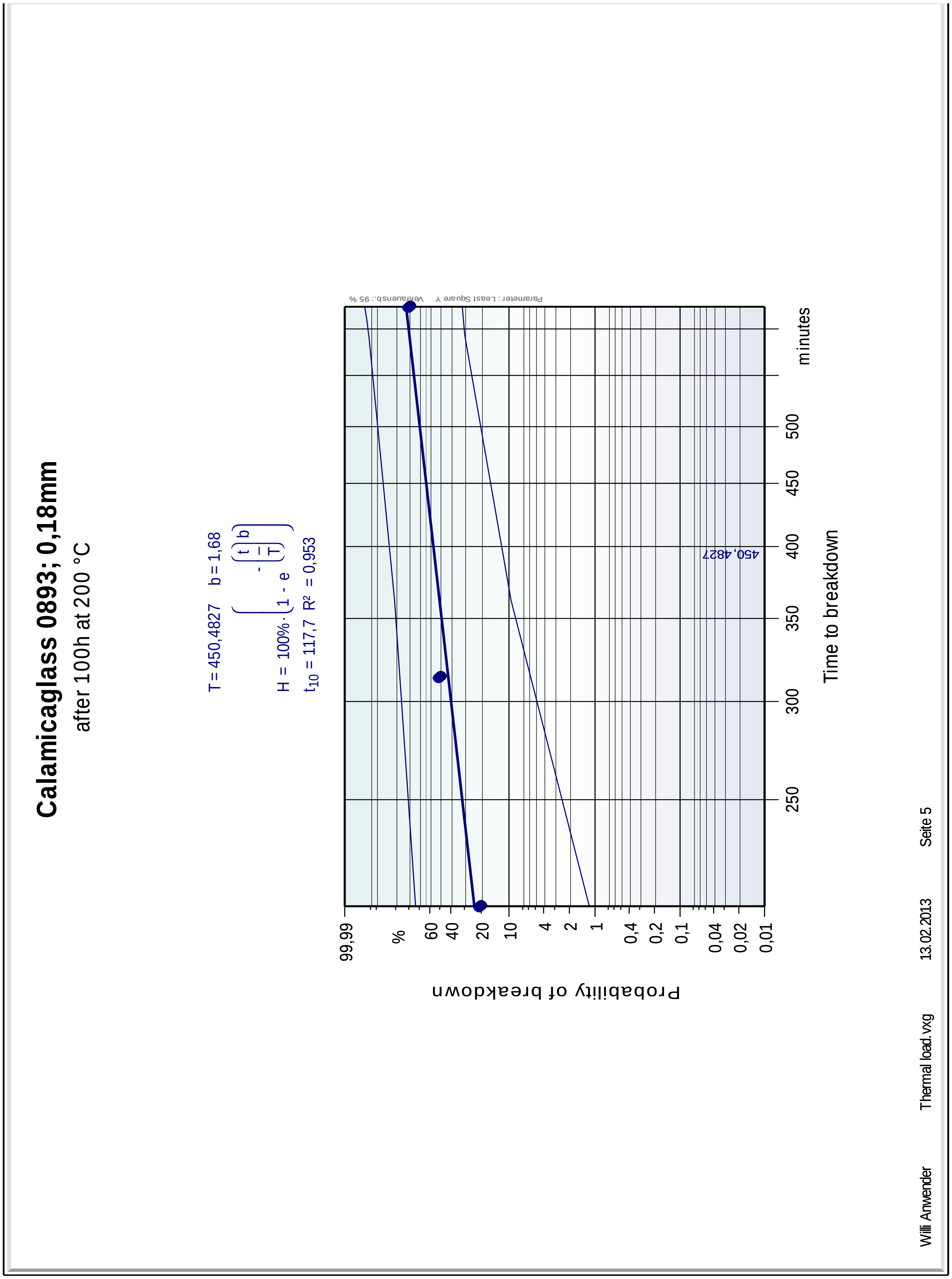


Figure 25: Weibull Calmicaglass®0893 0,18mm 100h thermal load

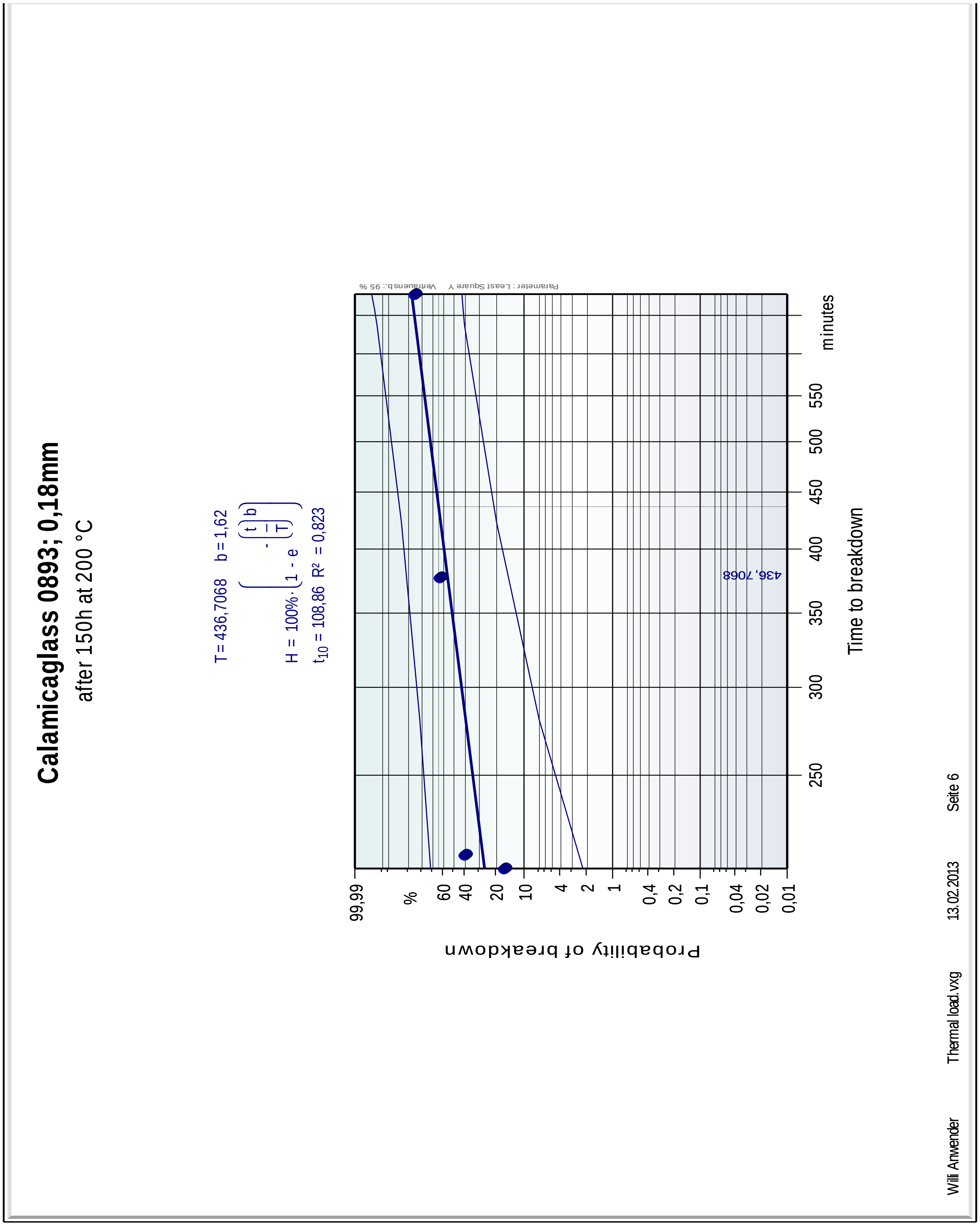


Figure 26: Weibull Calmicaglass®0893 0,18mm 150h thermal load

All data originals can be found in the attachments.

6.6.2. Data Analysis

For the precise analysis of the times to breakdown, with and without thermal load, samples with simular electric field strength should be compared. That condition was heavy for realization because the sampes from Calmicaglass®0409 used for thermal load test were thicker and therefore the electric field strength was lower. Additionally the samples from Calmicaglass®0893were tested under lower nominal voltage.So finally an adequate test data for thermally unloaded samples was chosen.

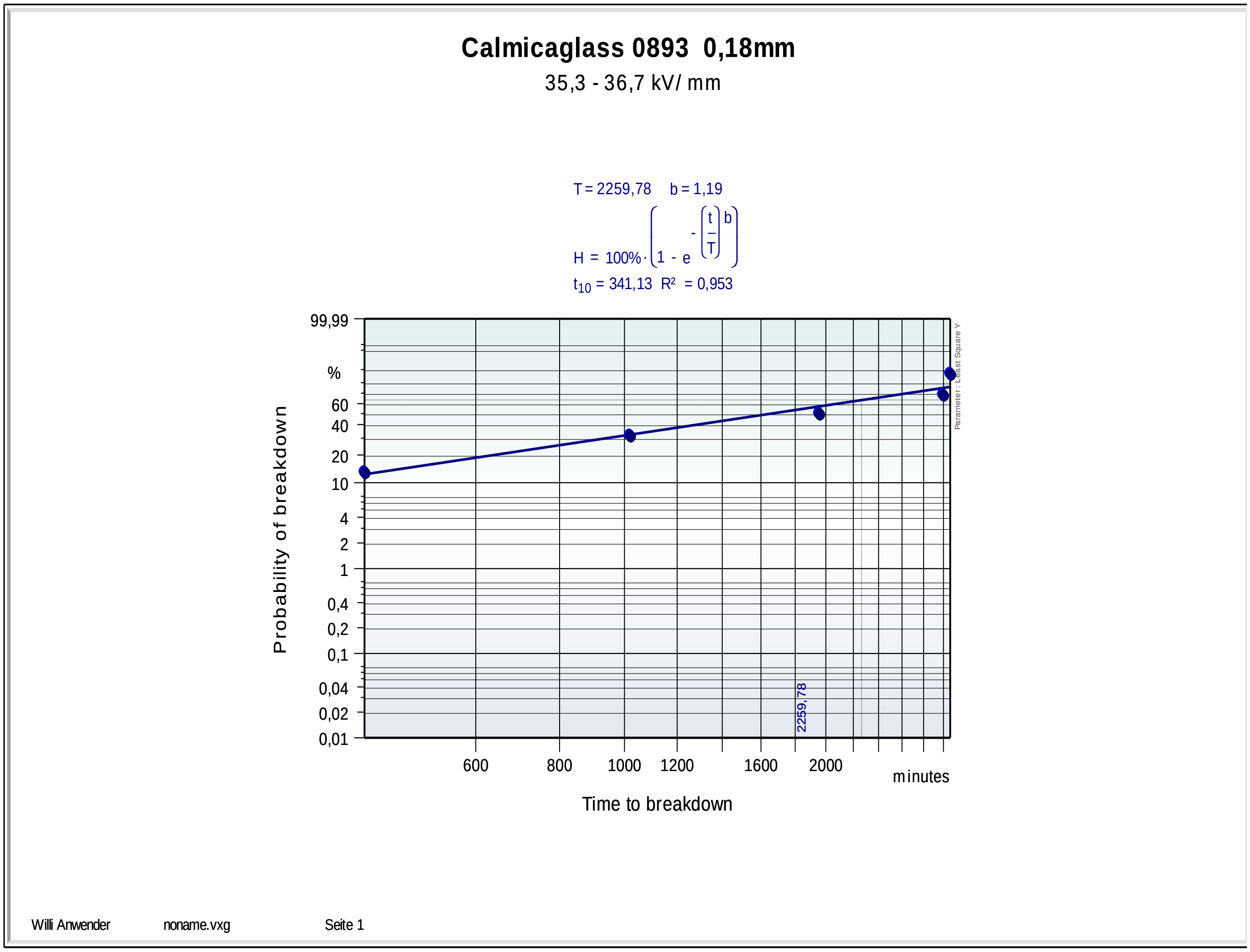


Figure 27: Calmicaglass®0893 0,18mm 35,3kV/mm - 36,7 kV/mm

The tables below present the dependancy between the time to breakdown and the thermal load they were exposed to.

Calmicaglass®0409 0,18mm	Breakdown time with thermal load (Weibull)	Breakdown time without thermal load
50h at 200 °C	1602,6 minutes 36,1 - 37,3 kV/mm	no data
100h at 200 °C	1195,3 minutes 36,1 - 37,3 kV/mm	no data
150h at 200 °C	1126,8 minutes 35,5 - 37,3 kV/mm	no data

Table 6 Calmicaglass®0409 0,18mm breakdown time

Calmicaglass®0893 0,18mm	Breakdown time with thermal load (Weibull)	Breakdown time without thermal load
50h at 200 °C	470 minutes 34,8 - 37,2 kV/mm	2259 minutes 35,3 - 36,7 kV/mm
100h at 200 °C	450,5 minutes 29,6 - 34,8 KV/mm	no data
150h at 200 °C	436,7 minutes 30,7 - 35,6 KV/mm	3069 minutes bei 35,29 kV/mm

Table 7 Calmicaglass®0893 0,18mm breakdown time

It is very good shown that both the Calmica tapes with the same number of layers and amount of mica in it, have shorter lifetimes after being exposed to such thermal conditions.

Lifetime of the samples is shorter this may be because of layer delamination after thermal load. Some air gaps occur between the separate layers so that partial discharge process takes place and leads to a faster breakdown.

Picture 18: A sample after temperature loading test.

Lighter spots can be observed on the picture above. Mica layers delaminate and "age". Increasing the hours under temperature load, the lifetime of the sample sinks.

6.6.2.1. Calmicaglass®0893

The comparison that was made with samples with no exposure to thermal load (Table 7) shows that Calmicaglass®0893 is much more stressed and age faster. It could be possibly explained by the fact that uncalcined mica tapes are normally used in VPI process because of its physical characteristics. It has lower tensile strength but higher porosity.

6.6.2.2. Calmicaglass®0409

In comparison to that, Calmicaglass®0409 shows better results when put under thermal load. Data for samples in this electric field strength is unfortunately absent so a direct comparison with and without thermal load, was barely possible. There were only 2 samples put under thermal load conditions that have similar low electric field strength like the one without thermal load. The table below shows a comparison of those two samples of Calmicaglass®0409 in the area of 37,29kV/mm.

<table>
<tr><th>Calmicaglass®0409
0,18mm</th><th>Breakdown time with thermal load
at 37,29 kV/mm</th><th>Breakdown time without thermal load
at 37,29 kV/mm</th></tr>
<tr><td>50h at 200 °C</td><td>448 minutes,
1402 minutes</td><td rowspan="3">464 minutes,
498 minutes</td></tr>
<tr><td>100h at 200 °C</td><td>672 minutes,
1285 minutes</td></tr>
<tr><td>150h at 200 °C</td><td>269 minutes</td></tr>
</table>

Table 8: Calmicaglass®0409 0,18mm breakdown time

This data is not sufficient to make a clear statement whether this product was better or not, but it could be seen that on those 2 samples the time to breakdown has not changed significantly. This shows that this material has better characteristics when exposed to high thermal conditions and ages slowly. Calcined mica tapes are commonly used in the Resin Rich method. They have the advantage of higher tensile strength and the bonding between the mica scales is better. Their mechanical properties are also better. (13)

6.7. Specific resistance

Specific electrical resistance or **volume resistivity** is a measurement of how strongly a material opposes the flow of electrical current. A low resistivity indicates a material that readily allows the movement of electrical charge.

Electrical resistivity ρ is defined by:

$$\rho = \frac{\mathbf{E}}{\mathbf{J}}$$

, where ρ is the static resistivity (measured in volt-metres per ampere, V m/A);

$\mathbf{E}$ is the magnitude of the electric field (measured in volts per metre, V/m);

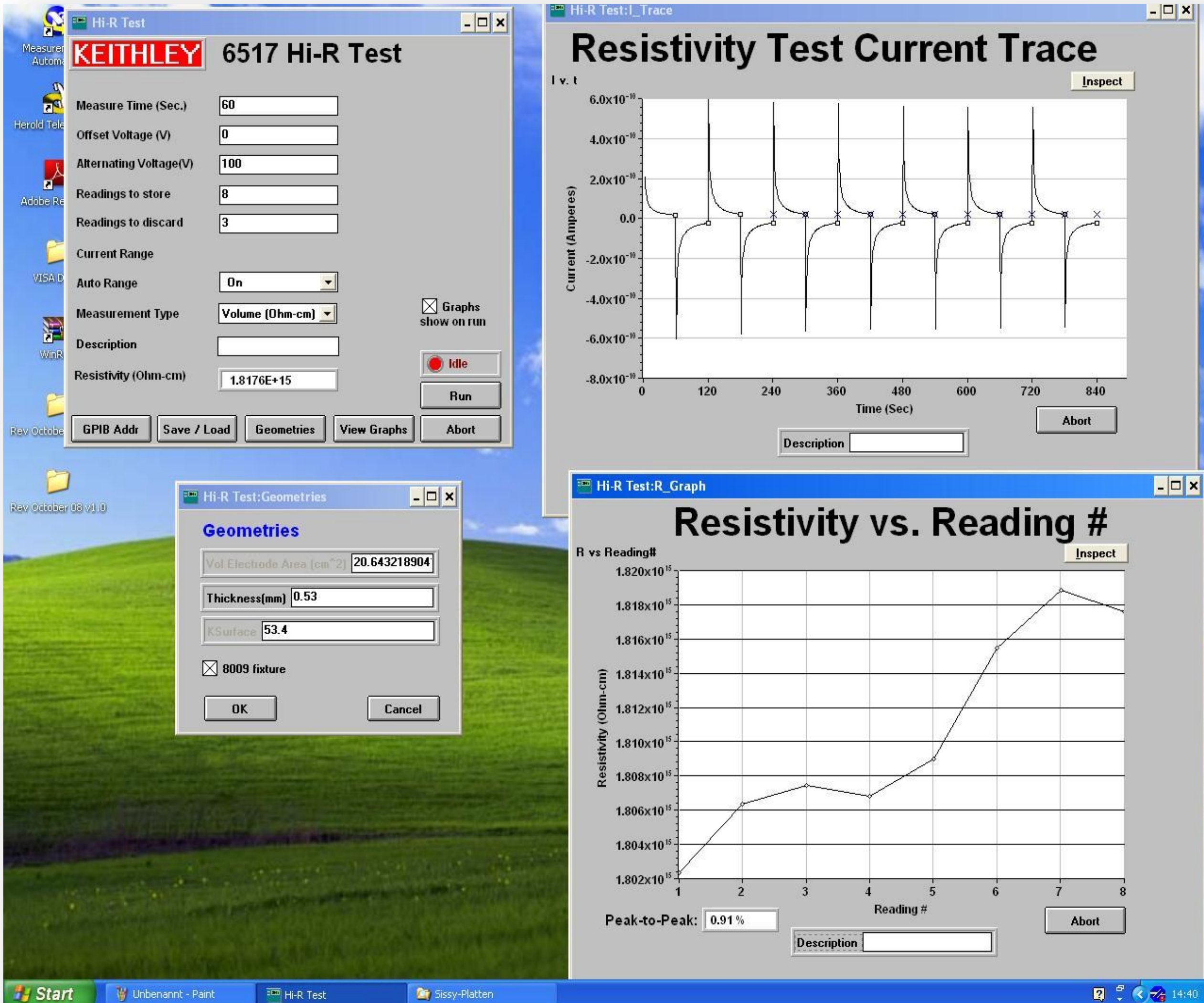
$\mathbf{J}$ is the magnitude of the current density (measured in amperes per square metre, A/m^2).

A test for volume resistivity has been made to check out if there are differences between the materials. On the table below the results and the values for Calmicaglass®0409 and Calmicaglass®0893 can be seen.

Calmicaglass®0409	**Sample-thickness**	**100V**	**200V**	**400V**	**800V**
ρ [V m/A]	**0,62-0,64 mm**	**$2,932 \times 10^{15}$**	**$2,882 \times 10^{15}$**	**$2,720 \times 10^{15}$**	**$2,388 \times 10^{15}$**
Calmicaglass®0893	**Sample-thickness**	**100V**	**200V**	**400V**	**800V**
ρ [V m/A]	**0,48-0,58 mm**	**$2,616 \times 10^{15}$**	**$2,586 \times 10^{15}$**	**$2,480 \times 10^{15}$**	**$2,293 \times 10^{15}$**

Table 9: Specific Resistance

This test was realized by Keithley Resistivity Test Fixture 8009 device, a laptop and Keithley Electrometer. Special software was applied via the laptop on the device and a sample with size 8,5cm x 8,5cm was put inside. Parameters such as measurement time, iterations of the measurement and voltage can be given. On the picture below a typical measurement of a sample can be seen.



Picture 19: Measurement of a Volume resistivity

Differences between Calmicaglass®0409 and Calmicaglass®0893 cannot be really observed. Both materials show very good isolating qualities. With increasing the voltage from 100V to 800V some polarization effects take place and the values of the resistivity sinks are minimal. Both products behave similarly in this test. Probes and conditions were kept the same.

7. Summary

The aim of this thesis was to compare the results from an aging, thermal, and mechanical test realised on mica-resin-glass insulation systems in cooperation with Isovolta AG Company. Mica bands were selected and given to make an investigation which shows whether calcined or uncalcined mica tape has better isolating characteristics and also if the number of insulation layers plays a main role in its abilities.

For this purpose, it was a new method invented to test only insulation material without the influence of the conductive part such as metal or copper bars.

The difficult part of the task was to prepare samples out of mica tape which are going to give trustful results. For the test, there were two tapes selected which are both used in the Resin Rich method for insulation of windings of high voltage machines. Additionally, those two tapes have separated to different band thickness, which means they have a different amount of mica. Respectively, from the first material there are 2 different thicknesses picked out and from the second material there are 3 different thicknesses picked out. Finally there are 5 separate materials which were put under a series of tests. All samples were put under even pressing conditions. Since the press was not meant for such purposes and for that delicate and precise pressing, there are still some differences like resin flow and thickness.

The original idea was to have samples prepared with a thickness of 1mm like for real machines. After some pre-tests, it was clear that it would have taken too long time until a failure occurs. So it was decided that samples be prepared with half of the original thickness (0,5 mm) and results to be measured in a much shorter period of time.

The number of sample layers varies between 2 and 6 dependant on the nominal thickness of the mica tape.

By the voltage endurance test, the dielectric strength of the materials was evaluated by the time to breakdown of the sample, which was noted down for each sample. A comparison between the materials was made that is based on the test results. To make a conclusion is very difficult because of the slight differences of the sample thicknesses which have influence for the number of operating hours (lifetime). That is why the data was gathered according to the applied electric field and then only samples with even or similar electric load were compared.

Because of the limited number of samples that was possible to be compared it should be taken into consideration that there is an element of uncertainty about the measured results.

By the evaluation of the results with Weibull distribution (which is normally applied for lifetime investigations), it seems that Calmicaglass®0893 has a bit higher dielectric strength than Calmicaglass®0409. Although, the materials with the fewest layers Calmicaglass®0893 with 0,28mm (2 Layers) und Calmicaglass®0409 with 0,21mm (3 Layers) gave the best results, a direct correlation between the number of layers and operating hours cannot be made.

In the thermal load test the same experiment was repeated but additionally the samples were exposed to high temperature (200 °C) for 50, 100 and 150 hours. Because of the even smaller number of samples during this test it is almost impossible to make any trustful conclusions out of the measurements. The results out of this experiment were plausible, as the samples with thermal load have shown lower number of operating hours than the ones which were not exposed to thermal load. Calmicaglass®0409 has shown barely a degradation of its isolating performance while Calmicaglass®0893 had a significant degradation shown.

A mechanical test in form of a test procedure with the Dynamical Mechanical Analysis device was applied on samples from Calmicaglass®0409 and Calmicaglass®0893 with 0,18mm thickness and 4 layers of material. The test shows the value of loss factor *tan delta* at rising temperatures and applied mechanical voltage. According to this test, the samples of both the materials show similar value for *tan delta* which means that, mechanically speaking, both the materials act the same.

8. Conclusion and Outlook

The usage of mica paper for insulation of high voltage machines is necessary because of its good electrical and thermal characteristics. The investigated mica tapes cover the need in all areas from low to high voltage machines. They can be both manually and automatically applied and also available for the different needs of the client. Both methods of application of wound coils and bars (resin rich or VPI method) are possible and the materials have the specifications required for each one. According to its application, the tapes vary in thickness, mica, resin, and glass cloth amount. Even difficult and complex areas and shapes are reachable thanks to very good tape flexibility.

The method described in this thesis gives a possibility for testing very delicate differences. For more precise results, it is necessary that all the conditions such as preparing the samples, pressing, and curing be more accurate and possibly remain the same for all samples. A larger number of samples with exact thickness is also necessary so that results can be compared and give a failure distribution in a better defined range.

Before choosing the press conditions, there were many trials on different presses and it should be noticed that the results were different. The pressure must remain constant during the press time and also calculated so that only the amount of resin which is normally pressed out by the manufacturing process flows away. Other pressing methods are required in order to obtain the process of getting samples which are going to give trustful results for continuous tests.

The high voltage cell, where the tests took place, is especially made for testing bars with insulation and their lifetime under working and extreme conditions. It covers all standards and requirements for realising such measurements. All measurement devices were approved and present exact data.

The test electrodes of the oil van are also built following the norm IEC 60296. Disadvantages and possible loss may come from the manual turning of the electrodes. After the samples were with 0.5 mm thickness, it was not possible to be sure that after putting the sample between the electrodes, they were fully contacting the sample face and also differ each time from one another. This could be obtained if electrodes are connected to springs which will guarantee the exact pressure against the sample walls.

Observing the pressing conditions and trying to remain same for all the prepared samples, there were some difficulties achieving the thickness of 0.5 mm. That is why samples with few layers became thinner than ones with many layers. That plays a main role later when nominal voltage was applied. In reality, by the process of manufacturing of insulated bars, this is easier to prevent because pressing conditions are different (RR presses or VPI barrels).

To make a clear view which mica paper (calcined or uncalcined) has better electrical characteristics and also at which thickness the best results can be reached, specific methods should be developed for the accurate preparing of the test samples.

9. References

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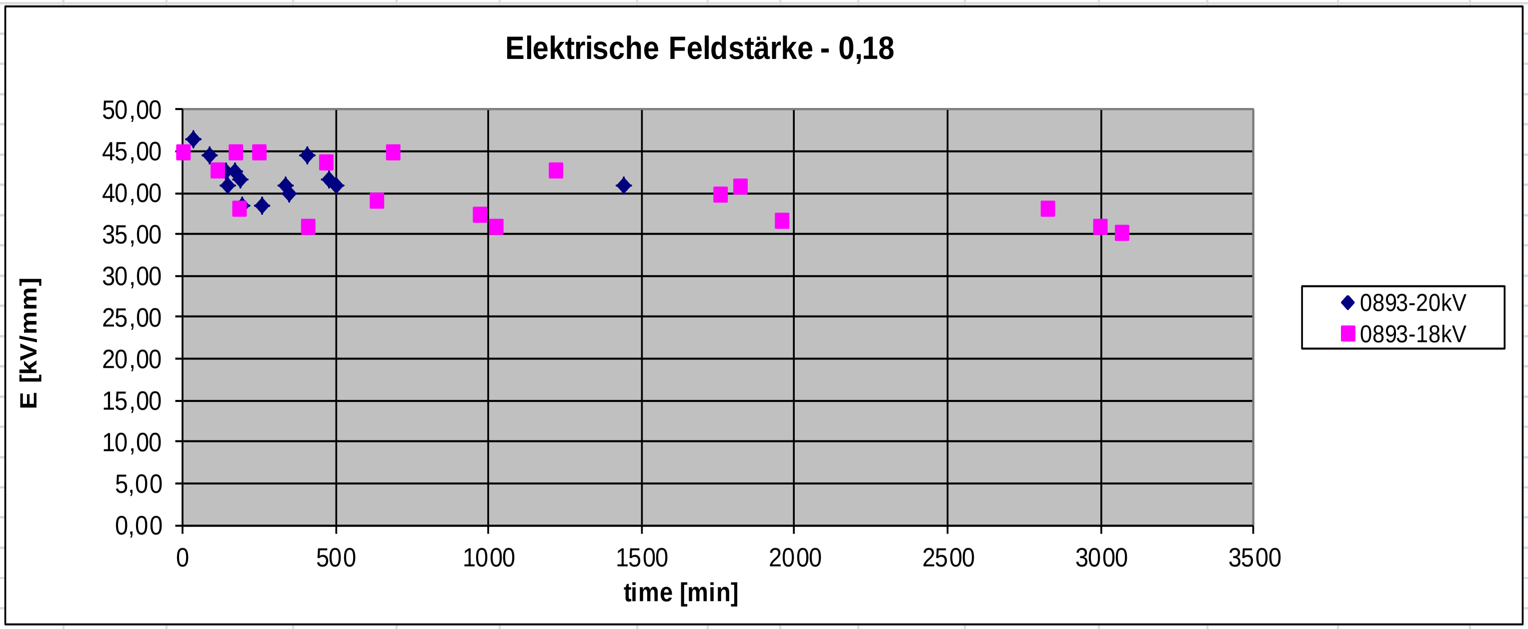
15. *NETZSCH- Datasheet.*

10. List of figures

11. Attachment

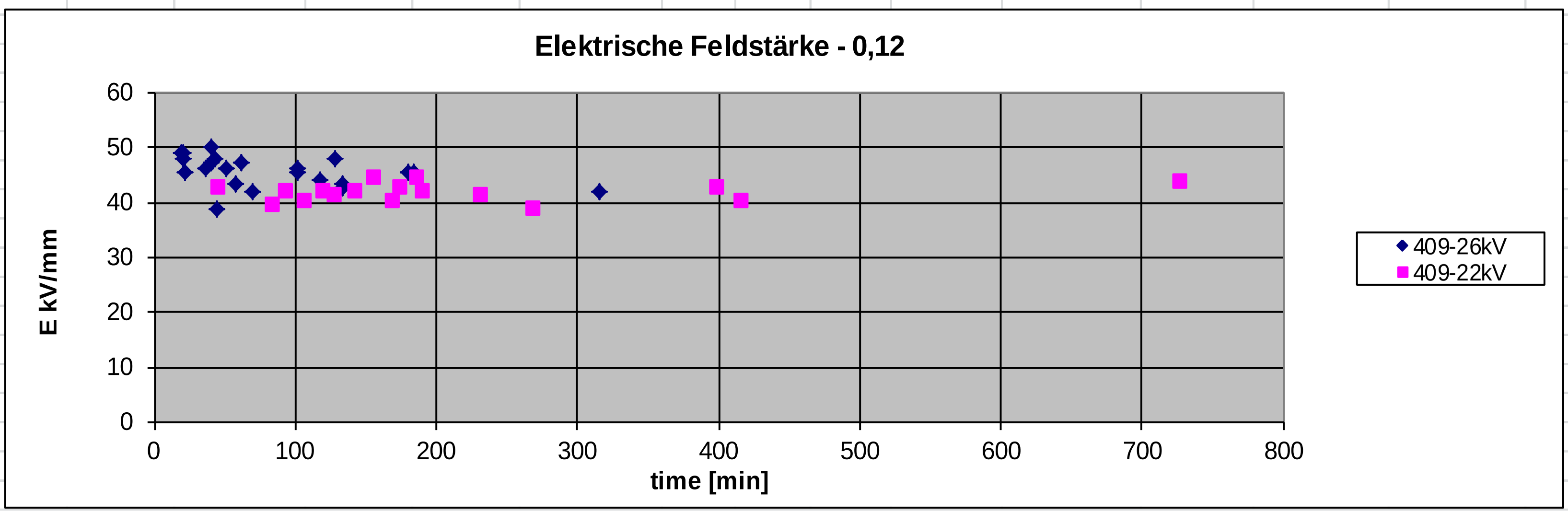
Calmicaglass 0893 Thickness 0,18						
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time to breakdown	Time [min]
B33re	893	0,43	20	46,51	0:35:04	35
B30li	893	0,45	20	44,44	1:26:53	87
R31re	893	0,47	20	42,55	2:18:53	139
R25re	893	0,49	20	40,82	2:29:20	149
B29re	893	0,47	20	42,55	2:51:27	171
B28re	893	0,48	20	41,67	3:08:22	188
B21re	893	0,52	20	38,46	3:16:45	197
R22mi	893	0,52	20	38,46	4:18:57	259
R27re	893	0,49	20	40,82	5:38:45	339
B23re	893	0,5	20	40,00	5:49:56	350
B32li	893	0,45	20	44,44	6:48:21	408
R20re	893	0,48	20	41,67	7:55:41	476
B24 li	893	0,49	20	40,82	8:20:15	500
R26mi	893	0,49	20	40,82	23:59:38	1440

Calmicaglass 0893 Thickness 0,18						
ID	Material	Thickness [mm]	Voltage [kV]	E[kV/mm]	Time to breakdown	Time [min]
R36re	893	0,4	18	45,00	0:01:21	1
R39re	893	0,42	18	42,86	1:49:20	109
B37li	893	0,4	18	45,00	2:49:23	169
R44li	893	0,47	18	38,30	3:03:19	183
R35mi	893	0,4	18	45,00	4:10:17	250
B50li	893	0,5	18	36,00	6:48:37	409
B38re	893	0,41	18	43,90	7:46:18	466
R42mi	893	0,46	18	39,13	10:29:43	630
R34li	893	0,4	18	45,00	11:22:49	683
R46mi	893	0,48	18	37,50	16:10:09	970
B48li	893	0,5	18	36,00	17:00:06	1020
R40re	893	0,42	18	42,86	20:15:36	1216
B43li	893	0,45	18	40,00	29:14:58	1755
B41li	893	0,44	18	40,91	30:22:23	1822
R47re	893	0,49	18	36,73	32:34:32	1955
R45re	893	0,47	18	38,30	47:03:04	2823
B49re	893	0,5	18	36,00	49:54:27	2994
B51mi	893	0,51	18	35,29	51:09:02	3069



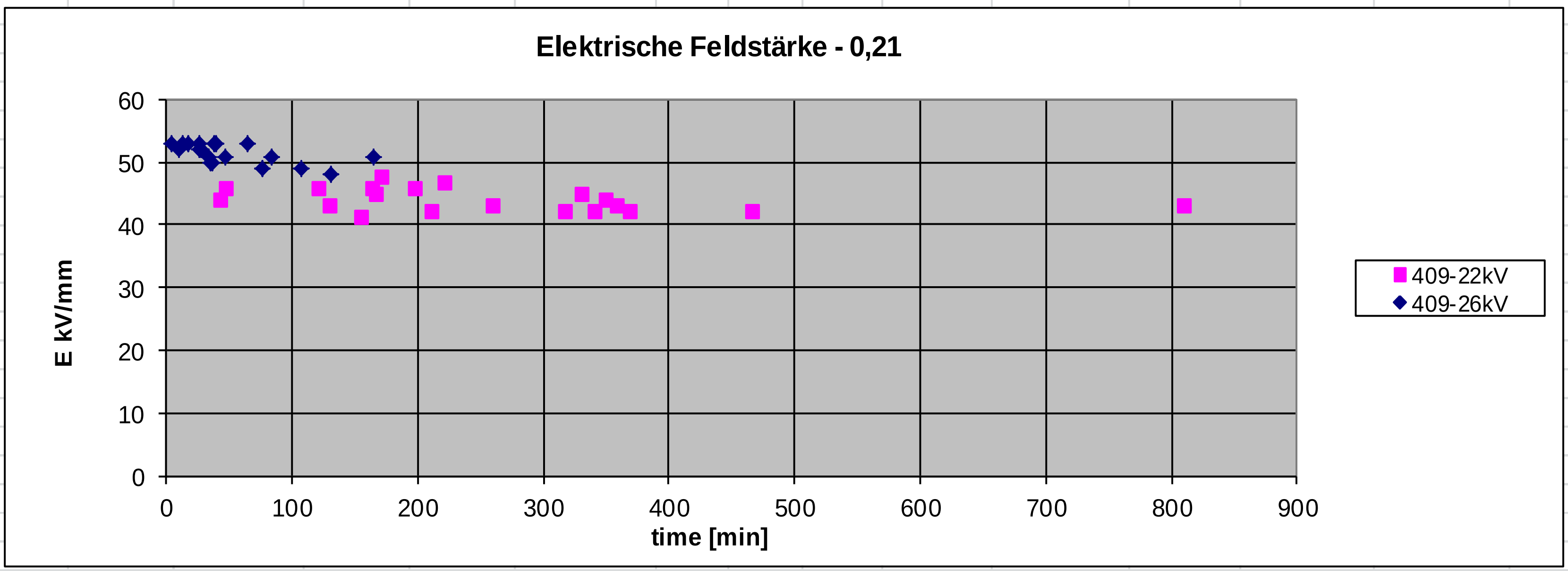
Calmicaglas 0409 Thickness 0,12						
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time to breakdown	Time [min]
B14re	409	0,53	26	49,06	0:18:42	19
R13li	409	0,54	26	48,15	0:20:25	20
R15li	409	0,53	26	49,06	0:20:34	21
R21mi	409	0,57	26	45,61	0:21:33	22
R1li	409	0,56	26	46,43	0:36:57	37
B4li	409	0,55	26	47,27	0:40:12	40
B16li	409	0,52	26	50	0:41:03	41
B7li	409	0,54	26	48,15	0:43:33	44
B12li	409	0,67	26	38,81	0:44:18	44
R3re	409	0,56	26	46,43	0:51:09	51
B10li	409	0,6	26	43,33	0:58:10	58
B5re	409	0,55	26	47,27	1:02:15	62
B19li	409	0,62	26	41,94	1:09:47	70
R20re	409	0,57	26	45,61	1:41:03	101
R2mi	409	0,56	26	46,43	1:41:45	102
B9re	409	0,59	26	44,07	1:57:20	117
R6li	409	0,54	26	48,15	2:07:30	128
R11mi	409	0,6	26	43,33	2:13:14	133
B17re	409	0,61	26	42,62	2:13:47	134
R8re	409	0,57	26	45,61	2:59:20	179
R22mi	409	0,57	26	45,61	3:04:20	184
R18li	409	0,62	26	41,94	5:15:00	315

Calmicaglass 0409 Thickness 0,12						
ID	Material	Thickness [mm]	Voltage [kV]	E[kV/mm]	Time to breakdown	Time [min]
R15mi	409	0,52	22	42,31	0:43:43	44
B17re	409	0,52	22	42,31	1:23:12	83
R1li	409	0,54	22	40,74	1:32:06	92
R9li	409	0,49	22	44,9	1:46:23	106
R2mi	409	0,54	22	40,74	1:58:36	119
B8li	409	0,49	22	44,9	2:06:32	127
B10re	409	0,5	22	44	2:22:08	142
B4li	409	0,53	22	41,51	2:34:37	155
R3re	409	0,54	22	40,74	2:48:16	168
B14re	409	0,52	22	42,31	2:52:48	173
B13re	409	0,51	22	43,14	3:04:47	185
R6li	409	0,56	22	39,29	3:08:34	189
R16mi	409	0,52	22	42,31	3:49:33	230
R12mi	409	0,51	22	43,14	4:27:00	267
B11re	409	0,51	22	43,14	6:37:37	398
B5re	409	0,53	22	41,51	6:54:53	415
R7mi	409	0,55	22	40	12:05:32	726



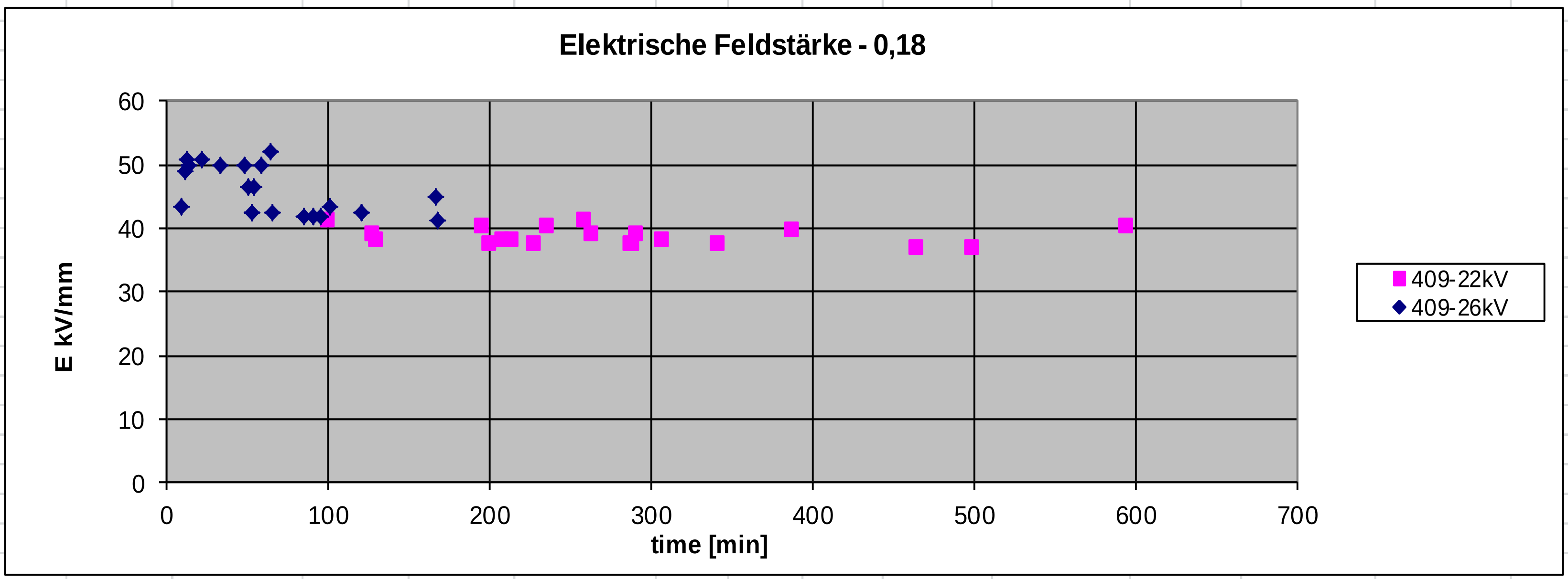
Calmicaglass 0409 Thickness 0,21						
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time to breakdown	Time [min]
8	409	0,5	22	44	0:41:44	42
7	409	0,48	22	45,83	0:47:20	47
2	409	0,51	22	43,14	2:09:55	130
11	409	0,48	22	45,83	2:00:55	121
14	409	0,53	22	41,51	2:33:43	154
18	409	0,48	22	45,83	2:42:52	163
20	409	0,49	22	44,9	2:46:46	167
3	409	0,46	22	47,83	2:50:42	171
5	409	0,48	22	45,83	3:16:50	197
16	409	0,52	22	42,31	3:30:43	211
4	409	0,47	22	46,81	3:40:36	221
1	409	0,51	22	43,14	4:19:11	259
10	409	0,52	22	42,31	5:17:07	317
19	409	0,49	22	44,9	5:30:17	330
15	409	0,52	22	42,31	5:40:02	340
6	409	0,5	22	44	5:49:25	349
12	409	0,51	22	43,14	5:58:07	358
9	409	0,52	22	42,31	6:08:31	369
17	409	0,52	22	42,31	7:45:28	465
13	409	0,51	22	43,14	13:29:15	809

Calmicaglass 0409 Thickness 0,21						
ID	Material	Thickness [mm]	Voltage [kV]	E[kV/mm]	Time to breakdown	Time [min]
17	409	0,49	26	53,06	0:04:08	4
10	409	0,5	26	52	0:09:26	9
3	409	0,49	26	53,06	0:13:23	13
13	409	0,49	26	53,06	0:16:40	17
9	409	0,5	26	52	0:25:36	26
14	409	0,49	26	53,06	0:26:32	27
11	409	0,5	26	52	0:28:07	28
8	409	0,51	26	50,98	0:32:47	33
5	409	0,52	26	50	0:34:36	35
4	409	0,52	26	50	0:35:55	36
18	409	0,49	26	53,06	0:37:17	37
16	409	0,49	26	53,06	0:39:05	39
12	409	0,51	26	50,98	0:47:00	47
15	409	0,49	26	53,06	1:05:00	65
6	409	0,53	26	49,06	1:16:24	76
19	409	0,51	26	50,98	1:23:00	83
1	409	0,53	26	49,06	1:47:19	107
2	409	0,54	26	48,15	2:11:04	131
7	409	0,51	26	50,98	2:45:23	165



Calmicaglass 409 Thickness 0,18						
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time to breakdown	Time [min]
20	409	0,6	26	43,3	0:09:09	9
4	409	0,53	26	49,06	0:10:51	11
1	409	0,51	26	50,98	0:12:36	13
2	409	0,52	26	50	0:13:29	13
3	409	0,51	26	50,98	0:21:35	22
7	409	0,52	26	50	0:32:56	33
6	409	0,52	26	50	0:47:39	48
9	409	0,56	26	46,43	0:50:39	51
15	409	0,61	26	42,62	0:52:42	53
10	409	0,56	26	46,43	0:54:19	54
11	409	0,52	26	50	0:58:42	59
5	409	0,5	26	52	1:04:00	64
16	409	0,61	26	42,62	1:05:54	66
13	409	0,62	26	41,94	1:24:36	85
19	409	0,62	26	41,94	1:31:10	91
12	409	0,62	26	41,94	1:35:36	96
14	409	0,6	26	43,3	1:41:20	101
17	409	0,61	26	42,62	2:00:03	120
8	409	0,58	26	44,83	2:47:01	167
18	409	0,63	26	41,27	2:48:09	168

Calmicaglass 409 Thickness 0,18						
ID	Material	Thickness [mm]	Voltage [kV]	E[kV/mm]	Time to breakdown	Time [min]
4	409	0,53	22	41,51	1:38:38	99
6	409	0,56	22	39,29	2:05:51	126
18	409	0,57	22	38,6	2:09:10	129
19	409	0,54	22	40,74	3:13:58	194
9	409	0,58	22	37,93	3:18:56	199
8	409	0,57	22	38,6	3:26:26	206
7	409	0,57	22	38,6	3:32:12	212
15	409	0,58	22	37,93	3:46:26	226
3	409	0,54	22	40,74	3:54:41	235
1	409	0,53	22	41,51	4:17:30	258
17	409	0,56	22	39,29	4:22:33	263
12	409	0,58	22	37,93	4:46:00	286
10	409	0,58	22	37,93	4:47:32	288
20	409	0,56	22	39,29	4:49:16	289
16	409	0,57	22	38,6	5:05:49	306
11	409	0,58	22	37,93	5:40:52	341
5	409	0,55	22	40	6:26:00	386
14	409	0,59	22	37,29	7:43:40	464
13	409	0,59	22	37,29	8:17:39	498
2	409	0,54	22	40,74	9:53:15	593

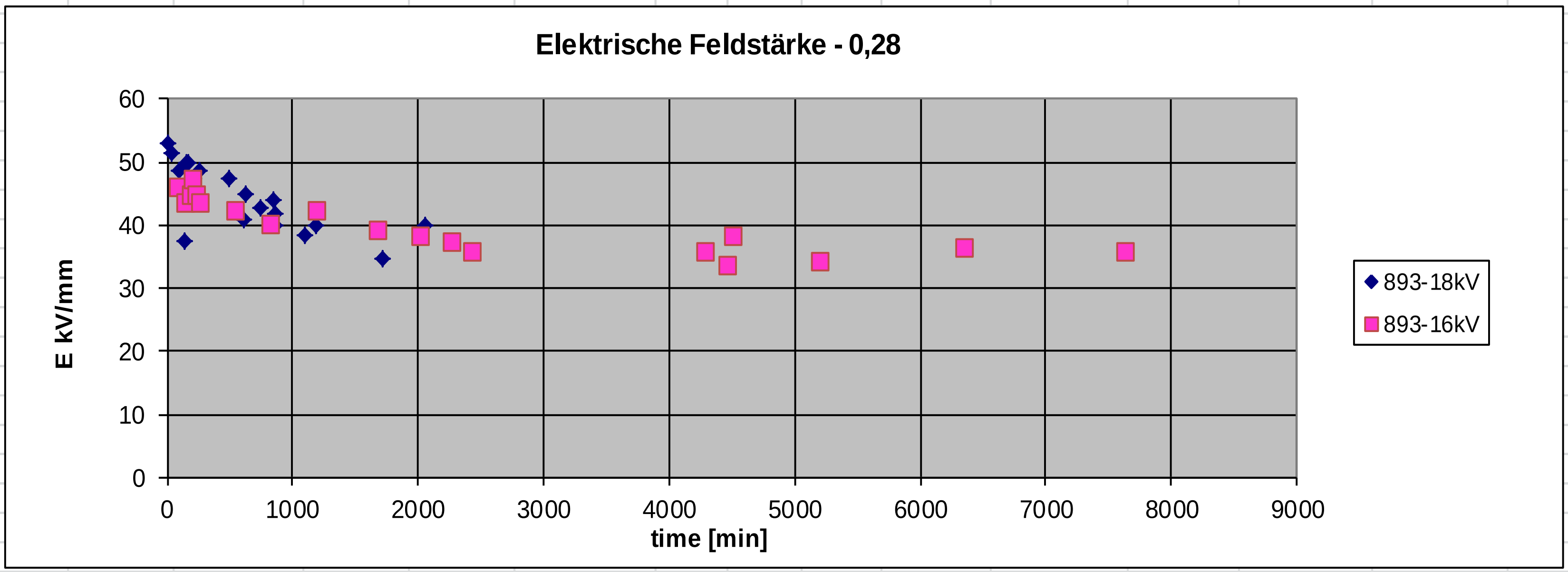


Calmicaglass 0893 Thickness 0,28

ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time to breakdown	Time [min]
1	893	0,34	18	52,94	0:12:40	13
2	893	0,35	18	51,43	0:36:19	36
6	893	0,37	18	48,65	1:42:14	102
19	893	0,48	18	37,5	2:23:18	143
4	893	0,36	18	50	2:28:04	148
3	893	0,36	18	50	2:45:48	166
11	893	0,41	18	43,9	3:21:49	202
7	893	0,38	18	47,37	3:31:20	211
5	893	0,37	18	48,65	4:10:52	251
8	893	0,38	18	47,37	8:09:15	489
14	893	0,44	18	40,91	10:16:04	616
9	893	0,4	18	45	10:25:52	626
12	893	0,42	18	42,86	12:17:19	737
10	893	0,41	18	43,9	14:09:16	849
16	893	0,45	18	40	14:23:59	864
13	893	0,43	18	41,86	14:26:58	867
18	893	0,47	18	38,3	18:13:46	1094
17	893	0,45	18	40	19:45:49	1186
20	893	0,52	18	34,62	28:38:17	1718
15	893	0,45	18	40	34:13:47	2054

Calmicaglass 0893 Thickness 0,28

ID	Material	Thickness [mm]	Voltage [kV]	E[kV/mm]	Time to breakdown	Time [min]
17	893	0,35	16	45,71	1:40:52	101
13	893	0,37	16	43,24	2:39:06	159
16	893	0,36	16	44,44	3:14:41	195
18	893	0,34	16	47,06	3:30:15	210
15	893	0,36	16	44,44	3:59:38	240
14	893	0,37	16	43,24	4:33:47	274
12	893	0,38	16	42,11	9:17:04	557
10	893	0,4	16	40,00	13:46:19	826
11	893	0,38	16	42,11	19:54:05	1194
9	893	0,41	16	39,02	28:14:43	1695
8	893	0,42	16	38,10	33:49:10	2029
7	893	0,43	16	37,21	37:54:17	2274
5	893	0,45	16	35,56	40:37:20	2437
3	893	0,45	16	35,56	71:41:30	4302
1	893	0,48	16	33,33	74:27:44	4468
19	893	0,42	16	38,10	75:14:22	4514
2	893	0,47	16	34,04	86:55:44	5216
6	893	0,44	16	36,36	105:57:07	6357
4	893	0,45	16	35,56	127:25:54	7646



Thermal Load

Calamicaglas 409; 0,18mm after 50h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
1	409	0,59	22	37,29	7:28
2	409	0,59	22	37,29	23:22
3	409	0,6	22	36,67	21:20
4	409	0,6	22	36,67	15:29
5	409	0,61	22	36,07	47:00

Calamicaglas 409; 0,18mm after 100h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
6	409	0,59	22	37,29	11:12
7	409	0,59	22	37,29	21:25
8	409	0,6	22	36,67	4:44
9	409	0,6	22	36,67	9:44
10	409	0,61	22	36,07	39:56

Calamicaglas 409; 0,18mm after 150h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
11	409	0,59	22	37,29	4:29
12	409	0,6	22	36,67	26:25
13	409	0,61	22	36,07	7:38
14	409	0,62	22	35,48	28:19
15	409	0,62	22	35,48	13:23

Calamicaglas 893; 0,18mm after 50h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
1	893	0,43	16	37,21	8:23
2	893	0,43	16	37,21	7:37
3	893	0,46	16	34,78	5:08
4	893	0,54	18	29,63	0:00
5	893	0,5	18	32	0:00

Calamicaglas 893; 0,18mm after 100h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
6	893	0,43	18	37,21	0:00
7	893	0,43	18	37,21	0:00
8	893	0,46	16	34,78	3:25
9	893	0,54	16	29,63	10:25
10	893	0,5	16	32	5:14

Calamicaglas 893; 0,18mm after 150h at 200 °C					
ID	Material	Thickness [mm]	Voltage [kV]	E [kV/mm]	Time [h:m]
11	893	0,43	18	37,21	0:00
12	893	0,45	16	35,56	3:26
13	893	0,47	16	34,04	6:17
14	893	0,52	16	30,77	3:32
15	893	0,5	16	32	11:19