

POLYURETHANE FOAM APPLICATION FOR HIGH VOLTAGE INSULATION

by

Mehmet Argin

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by

Mehmet Argin

has been approved

November 2007

Graduate Supervisory Committee:

George Karady, Chair
Richard Farmer
Raja Ayyanar
Keith Holbert
Elbadawy Elsharawy

ACCEPTED BY THE GRADUATE COLLEGE

ABSTRACT

Polyurethane foams have been in use for decades by the industry. The use of polyurethane foams is common in low voltage switchgears, but few applications are reported in medium and high-voltage (HV) systems. At high voltages, sulfur hexafluoride (SF₆) and/or nitrogen (N₂) is applied in hollow insulation systems like Optical Instrument Transformers (OIT) to avoid internal flashover.

Firmly sealing these gases within the insulating system over a long period of time as well as over variable temperatures is difficult. As a result of this sealing problem, gas pressure drops, moisture may penetrate into the insulation medium, and the dielectric strength of the insulation system decreases. This work proposes the use of polyurethane foams to fill the hollow spaces in insulation systems.

Much of the research effort focused on the demonstration of the dielectric strength of three different foams which are investigated using alternating current (AC) and lightning impulse voltages under different humidity and temperature conditions. It is shown that polyurethane foams have 2-3 times better dielectric strength than air. The breakdown strength decreases with the thickness of the foam; temperature and humidity have negligible effects on the breakdown voltage. The foam breakdown stress depends on the void size and distribution. The high density foams, with smaller void diameters, have higher breakdown stress.

As the breakdown mechanism within polyurethane foam was explained, a hypothesis was developed to describe the mechanism that leads to electrical breakdown of polyurethane foams. Partial discharge measurements revealed that electrical breakdown of polyurethane foam is not the result of progress of discharges in time, as in other

polymeric materials; discharges are very low and increase immediately before breakdown, suddenly increasing the electric field and producing an avalanche. Therefore, the mechanism that leads to breakdown in polyurethane foam is an avalanche breakdown mechanism. A computer program is developed with COMSOL Multiphysics Program controlled by MATLAB script to simulate the avalanche breakdown. There is an agreement between the simulation and experiment results therefore simulation results proved the feasibility of the avalanche progress.

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CHAPTER 1

INTRODUCTION

I. STATEMENT OF THE PROBLEM AND MOTIVATION

The use of polymers, a type of solid insulation material, is now applied extensively. There are many new industrial activities which generate a demand for superior materials which have strict performance requirements, such as higher electrical breakdown strength, lower thermal expansion coefficient. Also cost reduction is important. These requirements often involve a combination of many difficult-to-attain properties and may state the use of a composite material whose constituents will act synergistically to solve the application needs. New utilization and applications of the existing polymers and new polymers and improvements in usual polymer groups go beyond the conventional performance limits. Therefore, it is in fact important to understand their properties, operation, cost, implementation and potential of the available composite materials.

One such polymer is polyurethane, which is finding its way into high voltage insulation applications. Polyurethanes have wide application in many fields of industry like automotive seating, casting, bedding, roof insulation and carpet mats for decades. Polyurethanes' acceptance is due to several factors, including their excellent mechanical strength, moisture resistance, excellent adhesion properties, solvent and chemical resistance, and ease of processing [1]. In electrical engineering, polyurethanes are usually formulated as casting compounds to pot and encapsulate electrical and electronic systems. Therefore, they are used to encapsulate sensors, magnets, circuit boards and semiconductor devices, transformers, solenoid coils and inductors [2, 3, and 4]. A typical

example is given in Fig. 1. Polyurethane foams are used extensively at low voltage switchgear installations [5]. However, it has had limited use in medium and high-voltage (HV) systems.

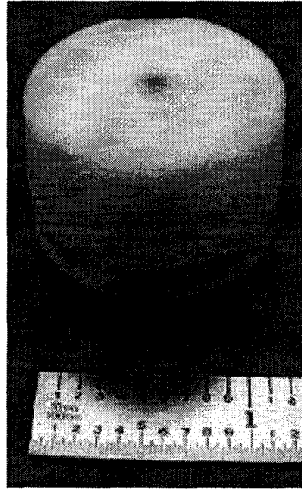


Fig. 1 14lb/ft³ polyurethane foam encapsulated transformer [4]

At high voltages, sulfur hexafluoride (SF₆) and/or nitrogen (N₂) is applied in hollow insulation systems like Optical Instrument Transformers (OIT) to avoid internal flashover. Firmly sealing these gases within the insulating system over a long period of time at variable temperatures is difficult. As a result of this sealing problem, gas pressure drops, moisture may penetrate into the insulation medium, and the dielectric strength of the insulation system decreases. Also, since SF₆ is a greenhouse gas (which is less than 1% by weight of all greenhouse gases combined) with a global warming potential that is 23,900 times greater than CO₂ over a 100-year time horizon, an atmospheric lifetime of 3,200 years [6], there is a growing concern about its application due to seal failures that have an environmental impact. In comparison with these gases, the polyurethane foam provides for a much easier seal and eliminates the potential risk of gas leakage. Also, the

water penetration and condensation effect can be minimized to a greater extent since the polymeric materials are noted for their better hydrophobic properties. Furthermore, the lightness of the polyurethane foam due to its porous structure encourages its application for high voltage insulation.

II. LITERATURE REVIEW

It is vital to predict the electrical breakdown strength of insulation materials used in the field before the applications. Knowing the limits of the insulation materials will ease their implementation, therefore it is significantly important to understand the breakdown mechanism of porous structure of polyurethane foams. The breakdown mechanism of gas and liquid types of insulation materials have been studied and well defined in the literature [7-10]. There are also studies which investigate the mechanisms in solid insulation materials [10-12]. The electric stresses in gaseous cavities in solid dielectrics have first been studied by B. Salvage and his colleagues in early sixties [13, 14]. Electric stresses in an elliptic cylindrical cavity with the minor axis of its elliptic cross-section parallel to the field and an oblate spheroidal cavity with its axis parallel to the field located in a solid dielectric contained between two infinite plane parallel electrodes were calculated. It is found that the shape of the cavity has an important effect on the electric stress and under direct voltages; appreciably higher stress can be produced in a cavity that has low permittivity. Then the electric stresses in elliptic cylindrical and oblate spheroidal gaseous cavities were investigated by means of an electrolytic tank to verify the theory. Agreement within 3% has been obtained between measurement and theory.

In 1985, D.Koenig and H.J.Heller studied the short time breakdown performance of polyurethane (PUR) foam under AC voltage stress [15]. The raw material of the PUR foam was polyol and isocyanat and the propellant medium was fluorcarbon CCl_2F_2 . A high-pressure foaming machine was used to manufacture polyurethane specimens. After the manufacturing, they observed via optical measurement that polyurethane (PUR) foam has microporous structure and fluorocarbon gas was found to be the main gaseous component of the single void in the foam.

Breakdown experiments and PD measurements were performed. PD measurements indicated that partial discharge in few pores would not be sufficient to cause breakdown of the whole polyurethane foam specimen in a short time. It is also proved that the breakdown voltage increases with the thickness of the material.

In 1986, electric stress distribution in cavities embedded within dielectric structures was investigated by D.Chang and his colleagues [16]. It was found that electric stress is enhanced in low permittivity areas like cavities. For an ideal disk-shaped void, the stress enhancement is a function of the orientation of the cavity with respect to the applied field. The cavity stress increases as the permittivity of the surrounding dielectric increases. And the stress in a cavity is decreased by an increase in the number of series cavities.

In 1989, D. Koenig, B.Bayer and H.J. Heller worked on the electrical behavior of self-skinning polyurethane (PUR) hard foam [17]. They mainly focused on the breakdown performance, impulse voltage strength and PD behavior of dielectric material. Meanwhile, the structure of the material and the form and size of pores were investigated.

The proposed polyurethane (PUR) hard foam was produced with a solid skin and the production had microporous structure.

Partial discharge measurements gave PD values of less than 5 pC that are within IEC standards. In most cases only a few PD impulses appeared before breakdown took place. As the result of this situation, it is concluded that if a sufficiently high stress in the pores of the foam is achieved, a 'few' starter breakdowns of single pores are sufficient to initiate the breakdown of the remaining microporous dielectric.

A breakdown model that finds the breakdown voltage of microporous structure was developed based on the partial pressures of the gaseous components in voids. In order to that, gas in the voids has been extracted by levigating the foam specimen in a vacuum cell. The specimen was pressed on a rotating grinding disc thus all voids were damaged and gas inside the voids were released. The composition of gas was then analyzed by a mass spectrograph and partial pressures of gaseous components were obtained. Next, the dielectric strength of a single void was calculated by using Paschen curves that gives breakdown voltage under different gas pressures and the breakdown model is developed based on this breakdown voltage. Therefore, the model depends on the knowledge of partial pressures of the gaseous components of the single void in the PUR hard foam. A difference was noticed between measured and calculated breakdown voltage.

These previous studies mainly focused on the characterization of electrical properties of only one type polyurethane foam and determination of the electrical stresses within voids. The effects of different temperature and humidity conditions on the

breakdown strength had never been investigated. There is also no single study that demonstrates its application under high voltages. In addition, only a single model was developed to estimate the breakdown voltage of polyurethane foam by Koenig and his colleagues. Their hypothesis was based on the determination of the partial pressures of the gaseous components in voids and then finding the breakdown voltage of the voids by using the Paschen curves. The main challenge in determining the breakdown voltage of the polyurethane foam was the difficulty of finding the correct gas composition in the voids; therefore inaccuracy was obtained between the calculated and measured results. Last, none of these studies do not explain the breakdown mechanism within polyurethane foams.

III. OBJECTIVE AND SCOPE OF THIS RESEARCH

In this research, electrical properties of polyurethane foam are investigated and polyurethane foam is considered as an insulation material to replace SF₆ and N₂ inside hollow insulation systems to prevent internal flashover. The insulation of hollow insulation systems was investigated by modeling it with foam filled tubes. All the previous studies had been performed with only one type of polyurethane foam. In this study, much of the research effort focused on the demonstration of the breakdown strength of three different foams which are investigated using AC and lightning impulse voltages under different humidity and temperature conditions.

Also, the critical parameters affecting the breakdown strength of polyurethane foam including void size, void distribution, void density, partial discharges, humidity and heat were studied. The effects of these parameters were discussed and a hypothesis that

explains the breakdown mechanism of polyurethane foam was developed and presented. A computer program that shows the breakdown mechanism was developed with COMSOL controlled by MATLAB. Computer program results were discussed and a correlation was made between the experiments and the COMSOL Multiphysics Program.

IV. OUTLINE OF THE THESIS

The outline of the thesis organized as follows:

- Chapter 1 provides the statement of the problem and motivation, literature review about the studies of polyurethane foam and the objective of the report.
- Chapter 2 concentrates on the classification of different types of polyurethane foam and presents polyurethane foam production.
- Chapter 3 discusses the experimental methods and description of the tests.
- Chapter 4 presents the experiments performed to determine the dielectric properties of the polyurethane foam. The results of the three major tests, the AC breakdown test for short term, lightning impulse breakdown test and partial discharge tests are discussed. Investigation of the effect of moisture in the foam and the effect of temperature at various levels are given. Test results for foam filled tubes under AC and lightning impulse voltages are presented.
- Chapter 5 presents the novel hypothesis and the computer simulation developed to describe the mechanism that leads to electrical breakdown of polyurethane foams.
- Chapter 6 concludes the report and provides suggestions for the future work.

CHAPTER 2

CHARACTERIZATION OF THE POLYURETHANE FOAM

I. CLASSIFICATION OF THE POLYURETHANE

Polyurethanes are the most well known polymers used to make foams. Polyurethanes are playing a vital role in many industries and they are used in a surprising array of commercial applications. Table 1 shows the application area of the polyurethanes.

TABLE 1
THE APPLICATION AREA OF POLYURETHANES

Two component formulations	Flexible slab	Flexible molded	Carpet	RIM	Solid	Rigid foam
Casting	Furniture bedding	Automotive setting	Attached cushion	Automotive	Elastomers	Insulation-board stock
Encapsulation	Automotive	Bedding	Unitary	Mechanical	Coatings	Appliances
Sealants	Carpet underlayment				Adhesives	Automotive
	Carrier media				Medical	

Polyurethanes provide significant advantages. These advantages can be briefly given as the following:

- Mechanical and physical resistance
- Easily shaped and transported
- Light weight
- Variable volume and density

- Good heat resistance
- Excellent adhesion to metal, wood, glass, and ceramics

Isocyanates and a range of polyols of different molecular weights are used to produce all types of polyurethane materials.

The polyols are reactive substances that contain at least two isocyanate-reacting groups attached to a single molecule. Polyols are manufactured based on either polyether or polyester and named as polyether-based and polyester-based. The polyols have been developed to have the required reactivity with isocyanates and to produce polyurethanes with specific properties. The choice of polyol is especially the size and flexibility of its molecular structure and its functionality. Isocyanates are mainly divided into two groups. These are toluene diisocyanate (TDI), and diisocyanate-diphenylmethane (MDI) and its derivatives. They are derived from petrochemical intermediates and are manufactured by well-understood and closely defined chemical processes. Most polyols and isocyanates used in the manufacture of polyurethanes are liquid at ambient temperatures and are easily handled.

The basic materials for polyurethane production apart from polyisocyanates and polyols include catalysts, cross-linking agents, chain-extending agents, blowing agents, surfactants, colouring materials, fillers and flame-retardants. All practical polyurethane systems include at least some of these auxiliary chemicals.

Foams are produced by gas bubbles formed during the polyurethane polymerization mixture. The process of bubble formation is called the blowing. The blowing reaction is one of several reactions that occur in the final polyurethane mixture

while it is foaming. Polyurethane foam reactions are exothermic. The generated heat may be used to vaporize a liquid blowing agent, which is a substance used in the polymerizing reaction mixture between an isocyanate and a polyol to form gas bubbles, when the chemicals polymerize and expand to produce a polyurethane foam. There are mainly two types of polyurethane foams that are manufactured by using polyurethanes. These are flexible and rigid polyurethane foams.

The American Society for Testing and Materials (ASTM) has given a basic definition of these two types of foams. A cellular plastic is considered flexible if a piece eight inches by one inch by one inch can be wrapped around a one-inch mandrel at room temperature. If the foam cannot be wrapped around the mandrel, it is considered as rigid [18].

A. Flexible polyurethane foams

Flexible polyurethane foams are open-celled materials and allow air to flow through when flexed [19]. They have a limited resistance to an applied load and are reversibly deformable. The Fig. 2 shows the open cells of flexible foam.

Flexible foams can be manufactured in different shapes by cutting or molding. The density of the low-density type of flexible foam varies between 10 to 80 kg/m³, and the density of the high-density type is over 100 kg/m³. Flexible foams are discolored rapidly when exposed to ultraviolet radiation. Their resistance to strong acids and alkalis is poor especially when hot. Working temperature variation is between 50 °C and 100 °C. Permanent deformation may occur because of the compressive deformation at high temperatures. They remain flexible down to -40 °F.

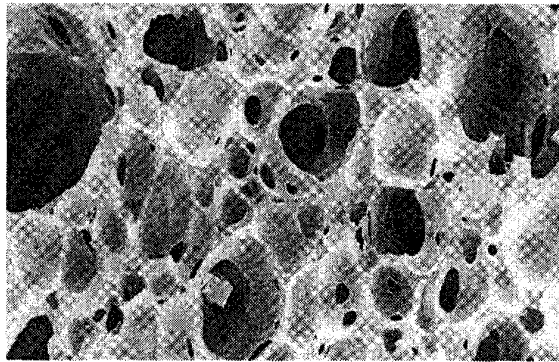


Fig. 2 Photomicrograph showing the open cells of flexible foam [19]

Flexible foams have different types of applications including toys, seating, headrests, shoe soles, spa pillows, upholstered furniture, mattresses, taxidermy forms and prosthetics. The cleanliness and economy of flexible polyurethane foams are important in upholstery. Different types of flexible polyurethane foams are produced for different purposes by changing the composition. Each of the following types of applications uses different types of flexible polyurethane foam product.

- Auto seat cushions, motorcycle, bicycle seats, prosthetics
- Auto dash pads, head', console and door liners
- Strong but soft toys, novelty items
- Archery targets, taxidermy forms

B. Rigid polyurethane foams

Rigid polyurethane foams are highly cross-linked polymers with a closed-cell structure. The bubbles inside the material has unbroken walls so that gas movement is impossible. The low-density type is a highly effective thermal insulant and the high-density types are very strong and rigid. The closed cell of rigid foam is shown in Fig. 3.

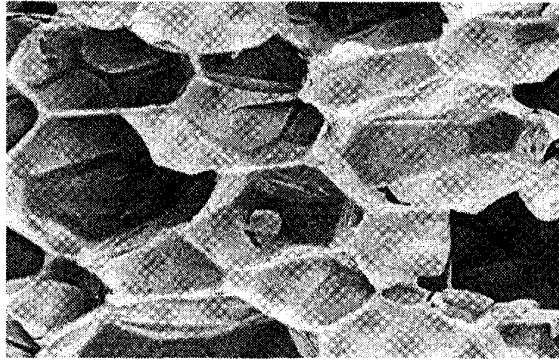


Fig. 3 Photomicrograph showing the closed cells of rigid foam [19]

Rigid polyurethane foams can be produced in a range of densities from less than 10 kg/m^3 to about 1100 kg/m^3 . Most rigid polyurethane foam production consists of lightweight foams for thermal insulation. Rigid polyurethane foam demonstrates versatility both through its physical strengths and mechanical properties, therefore enabling it to be used in a wide variety of applications including construction, packaging, refrigeration industry, plumbing, chemical plants and ships. The ability to be foamed in place by pouring or spraying, combination of high strength and lightweight, good heat resistance, excellent adhesion to metal, wood, glass, and ceramics are some of the properties for rigid polyurethane foams. Rigid polyurethane foams are usually used at lower thicknesses than other insulants, which means that their heat or fuel contribution to a fire is low compared to other, thicker insulating materials.

The equivalent weight of polyol in making the rigid foam affects some properties, such as [19].

- Higher closed-cell content
- Higher compressive strength
- Lower rate of water vapor permeability

- Higher heat resistance
- Lower water absorption

Rigid polyurethane foams are also produced in a variety of types for different purposes like the flexible polyurethane foams. These application area and different types are classified as follows:

- Flotation products, large void filling, decorative and molded parts, taxidermy forms, and insulation.
- Stricate, structural and decorative molded parts, simulated wood products and decorative artifacts.
- Insulated masonry wall systems, building panels, cold storage rooms, walk-in coolers, freezer panels, and refrigerators.
- Filling large voids in commercial vessels, pleasure craft, dock floats.
- Flotation applications, construction building panels, cold storage rooms.

II. PRODUCTION PROCEDURES OF POLYURETHANE FOAM

In the previous section, the main properties of polyurethane foams have been outlined. The production mechanism of foams is of great importance in determining their electrical properties, since proper production of polyurethane foams will increase the dielectric strength.

One of the main parameters affecting the breakdown strength of polyurethane foams is voids. The presence of voids causes discharges in the foam when exposed to the high voltages and these discharges may reduce the breakdown strength of polyurethane foam material, therefore it is important to eliminate voids in polyurethane foam

manufacturing. Voids can be minimized with careful production techniques, but it is not possible to avoid the existence of voids during foam production.

A. Polyurethane foam production

Four different types of production techniques for Foam I were studied in order to minimize the size of voids. Foam 1 is a low viscosity, high yield, low pressure, rigid, closed-cell, two component flotation foam ideal for use in filling large voids. Foam I consists of two components, namely parts A and B. The chemical name of the A part is isocyanic acid polymethylene polyphenyle ester. It is a dark brown liquid with boiling and melting point of 98°C and -18°C respectively. It is not soluble, but reacts slowly with water to liberate CO₂ gas. The flash point is 198.8°C. The chemical family of the B part is polyurethane resin. It is a light brown viscous liquid. Its boiling point is 89.6°C and it is slightly soluble in water. The flash point is 121°C [20].

A and B components of the foam are poured into a beaker and mixed for 45 seconds. The mixing ratio by weight is 75 gr from A and 75 gr from B. The mixture is then poured into the cylindrical molds with diameter and height of 10 cm and approximately one quarter of each mold is filled with foam. In the first technique, the foam is completely covered with a plate under 125.7-kg/m² pressure. The applied pressure prevents the foam from rising. In the second technique, the mold is covered with a plate that has no pressure on it. The only difference in the third production technique is that the plate used to cover the mold has holes to release air between the foam and the plate. These two configurations cause the foam to rise approximately up to one third of the mold's height. The fourth technique is similar to the first. The foam is

covered with a plate with holes in it to release air and 125.7-kg/m^2 pressure is applied. The pressure also prevents the rise of foam. Foam productions took place at room temperature ($24\text{ }^{\circ}\text{C}$) and room relative humidity (RH) (30-36%).

This process is completed in 30 second, but the foam is removed from the molds after 2 hours. Products are then investigated with SEM (Scanning Electron Microscopy). The cross section investigation of the products shows that the first and the fourth samples are denser than the second and the third samples. In the first and fourth sample the diameter of voids vary in the range of $100\text{ }\mu\text{m}$ and $150\text{ }\mu\text{m}$, but it varies between $100\text{ }\mu\text{m}$ and $300\text{ }\mu\text{m}$ in the second and third samples. The first and the fourth production techniques are found to be the best of all in terms of reducing the size of the voids.

Smooth and rigid skin is formed on the surface of polyurethane foam. The skin of the foam is cut and removed in order to observe the structure of the foam that has no skin. Then investigations are conducted with SEM. Fig. 4 shows two samples: one that has skin and another that has no skin.

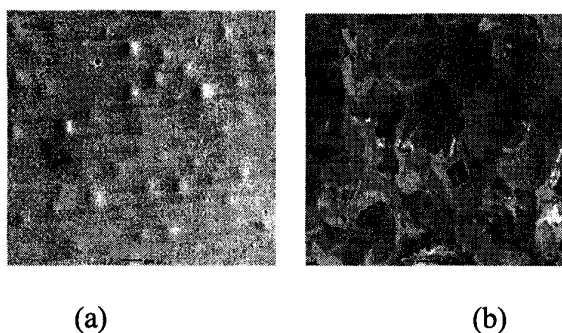


Fig. 4 (a) top view of Foam I with skin (b) top view of Foam I without skin

It is obvious from Fig. 4 that the top of the polyurethane foam sample with skin has denser and more rigid structure than the sample with skin removed. Water

penetration test was performed on these samples. After the production, samples are weighted, and submerged in a container filled with water and kept there for 24 hours and then removed from the container. Samples are weighted again and it is observed that foam samples with skin do not absorb any noticeable amount of water. It is concluded that the skin of the rigid pour polyurethane foam has a significant effect on preventing water entering the foam.

B. Polyurethane Foam selection

The comparison of the chemical properties of the different foams resulted in the selection of three different foams. Foam 1, Foam 2 and Foam 3 are selected.

Foam 1 is a low viscosity, high yield, low pressure, rigid, closed-cell, two component flotation foam ideal for use in filling large voids. Foam 2 is a two-part polyurethane backfill product designed to straighten utility poles. Foam 3 is a low viscosity, high density, rigid, closed-cell, two component molding foam. Table 2 lists the physical properties of these foams [20, 21 and 22]. The first foam production technique was used in order to manufacture all three types of Foams for electrical tests.

TABLE 2
PROPERTIES OF POLYURETHANE FOAMS

	Chemical Family	Chemical Name	PH level	Boiling point	
Type	Part A	Part A	Part B	Part A	Part B
Foam 1	Aromatic Isocyanate	Isocyanic acid	7.5-8.5	207.7 °C	14 lbs boils at 32°C
Foam 2	NA	Polymeric Diisocyanate	NA	210°C	Above 204.4°C
Foam 3	Aromatic Isocyanate	isocyanic acid	8	207.7 °C	Above 204.4°C

CHAPTER 3

EXPERIMENTAL STUDIES OF POLYURETHANE FOAM FOR INSULATION

PURPOSES

I. EXPERIMENTAL METHODS

Polyurethane foam is considered as an insulation material to replace SF₆ and N₂ inside hollow insulation systems to prevent internal flashover. Thus, polyurethane foam insulation should withstand the high voltages under operation both instantaneously and in the long term. Mainly, the behavior of the polyurethane foam under AC voltages, lightning impulse voltages and partial discharges is of great concern in characterizing the material.

A. AC voltage withstand tests

The dielectric strength of the insulation materials is determined with AC voltage withstand tests. An AC voltage is defined by its r.m.s value and/or its peak value. The ratio between r.m.s and peak value is given by the square root of 2 [23]. The tests with AC voltage require that the voltage should have a frequency in the range of 45-65 Hz, normally referred to as power-frequency voltage [24]. The frequency value may be considerably below or above this range when some special tests are of concern. The voltage waveform should approximate a sinusoid with both half cycles closely alike, and the ratio of peak to rms values should be equal to the square root of 2 within $\pm 5\%$. Greater deviations from the ratio of peak to rms values may have to be accepted especially if some test circuits or test objects have nonlinear impedance characteristics or very high capacitance.

The voltage shall be applied to the test object starting at a sufficiently low value to prevent any effect of overvoltage due to switching transients. It should be raised slowly to permit accurate reading of the instruments, but not so slowly as to cause unnecessarily prolonged stress on the test object at the test voltage. These requirements are generally met if the rate of rise above 75% of the withstand voltage is about 2% of the withstand voltage per second. The voltage shall be maintained for the specified time and the test requirements are generally satisfied if no disruptive discharge occurs on the test object [24]. If a breakdown value is required then the voltage is raised until a disruptive discharge occurs on the test object. This procedure is repeated several times and the mean of the measured values is taken as the breakdown voltage of the test object [25].

B. Lightning Impulse voltage withstand tests

Impulse tests are designed to prove that the insulation of electrical equipment does not breakdown on voltage surges of high magnitude and short duration mainly caused by lightning and switching. Lightning and switching impulses represent transients occurring naturally in high voltage system under operation. A single, unipolar voltage pulse is termed an impulse voltage in high voltage technology.

Definition of an impulse voltage is done by its peak value and time parameters. The time required to reach the peak value is of the order of $1\mu\text{s}$ for overvoltages following lightning strokes. Therefore, voltages generated in a laboratory to simulate these are called lightning impulse voltages. But the situation is different for internal overvoltages due to switching operations in high voltage networks. The time taken to reach the peak value is at least about $100\mu\text{s}$. Their reproduction in the laboratory is

called switching impulse voltages which are of approximately the same shape as lightning impulse voltages, but last considerably longer [23]. Fig. 5 shows the full lightning impulse. A full lightning impulse is defined as a lightning impulse not interrupted by any type of discharges [24].

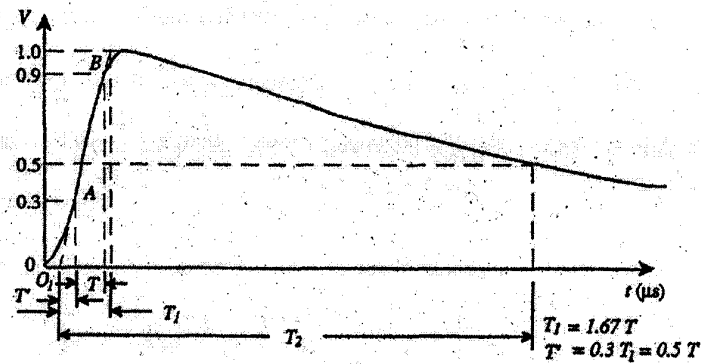


Fig. 5 Full lightning impulse without oscillations or overshots [24]

There are some definitions regarding the full lightning impulse. These are given as follow:

Virtual front time (T_1): The virtual front time (T_1) of a lightning impulse is 1.67 times T , where T is the measured time difference between the 30% and 90% voltage level corresponding to points A and B in Fig. 5.

Virtual origin (O_1): The virtual origin of a lightning impulse is the instant preceding corresponds to point A by a time $0.3 T_1$. This is the intersection with the time axis of a straight line drawn through reference points A and B on the front.

Virtual time to half-value (T_2): The virtual time to half-value (T_2) of a lightning impulse is the time difference between the virtual origin and the 50% of the peak voltage level in the tail.

Standard lightning impulse is defined as a full lightning impulse having a virtual front time of $1.2 \mu\text{s}$ and virtual time to half-value of $50 \mu\text{s}$. It is described as a 1.2/50 impulse. If the input voltage is increased too much, lightning impulse is chopped and therefore collapsed due to the discharges. The collapse of the voltage may occur on either the front, tail or at the peak. As an example, lightning impulse chopped on the tail is given in Fig. 6.

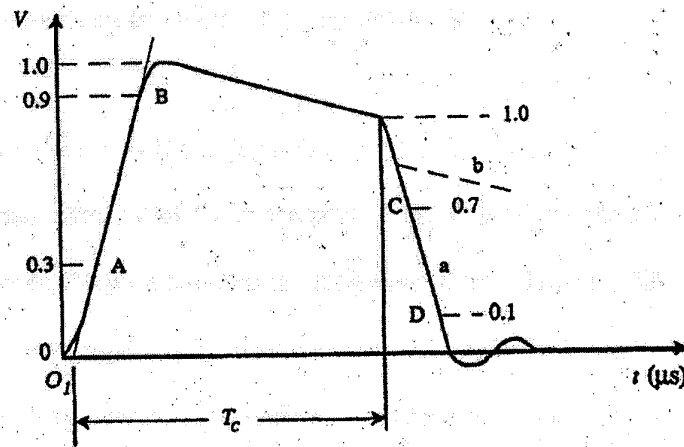


Fig. 6 Lightning impulse chopped on the tail [25].

Impulse voltages are generated in either of the two basic circuits denoted "circuit a" and "circuit b" shown in Fig. 7.

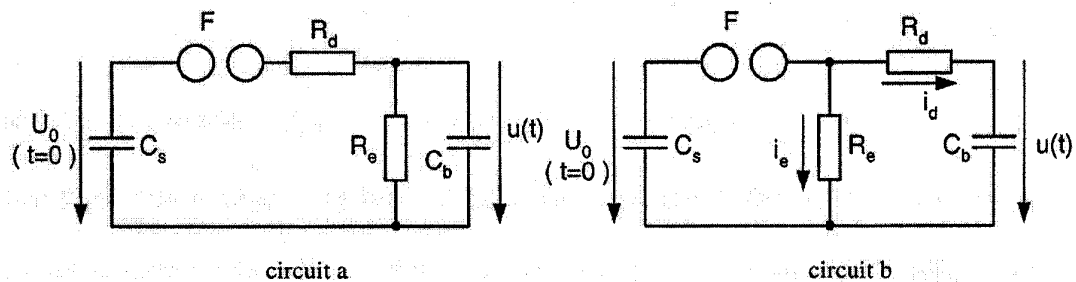


Fig. 7 Basic diagrams of impulse voltage circuits [25]

The impulse capacitor C_S is charged via a high charging resistance to the direct voltage U_0 and then discharged by ignition of the switching gap F . The output voltage $u(t)$ appears across the load capacitor C_b . The only difference between circuit a and circuit b is the position of the discharge resistor R_e . In the first case, it is connected in front of, and in the other, behind the damping resistor R_d .

The curve shape of the impulse voltage is determined by the value of the circuit elements. Rapid charging of C_b to the peak value U provides the short time to front whilst the slow discharging provides the long time to tail. This is achieved by $R_e \gg R_d$. The full charging voltage U_0 appears across the series combination of R_d and C_b in both circuits immediately after ignition of F at $t=0$. The smaller the value of the expression $R_d C_b$, the faster is the rate at which the output voltage $u(t)$ reaches its peak value. There is a relation between the peak value U and U_0 and is given in Equation 1.

$$\frac{U}{U_0} \leq \frac{C_s}{C_s + C_b} \quad (1)$$

The impulse capacitor C_S is chosen much greater than the load capacitor C_b to provide a given charging voltage U as high as possible. Therefore, the exponential decay of the impulse voltage on the tail would then occur with the time constant $C_S (R_d + R_e)$ in circuit a and with the time constant $C_S R_e$ in circuit b.

C. Partial discharge test

Partial discharge refers to a discharge that does not completely bridge the space between the electrodes. The term corona has also been used frequently, but such usage is imprecise and is gradually being discontinued. The magnitude of such discharges is usually small; therefore they cause progressive deterioration and may lead to ultimate

failure [26]. Partial discharges are distinguished into four types and these are: internal discharges, surface discharges, corona discharges and discharges in electrical trees. The following Fig. 8 through Fig. 11 illustrates these partial discharges.

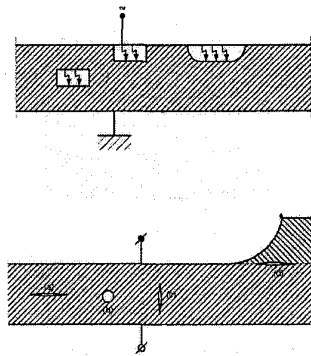


Fig. 8 Internal discharges [26]

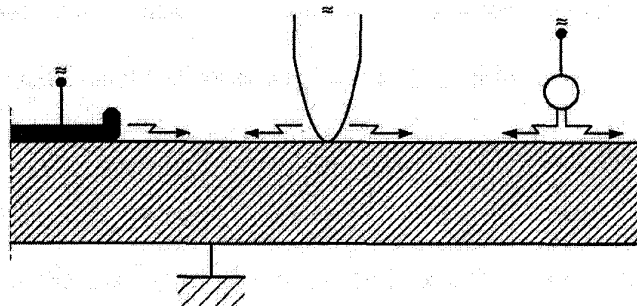


Fig. 9 Surface discharges [26]



Fig. 10 Corona discharges [26]

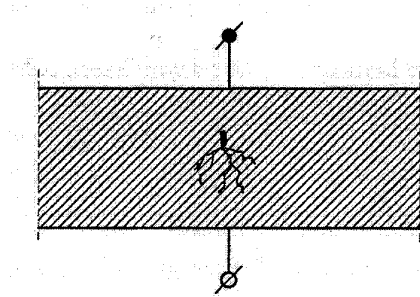


Fig. 11 Discharges in electrical trees [26]

Internal discharges occur in inclusions of low dielectric strength. These are usually gas-filled cavities, but oil-filled cavities also can breakdown and cause gaseous discharges. The discharge starting voltage depends on the stress in the cavity and the breakdown strength of the cavity if gas-filled cavity is considered. Oil-filled cavities are considerable in oil-impregnated paper insulation such as in transformer windings and in cables.

Surface discharges may occur if there is a stress component parallel to a dielectric surface. These discharges exist in bushings, ends of cables, the overhang of generator windings and where a discharge from outside touches the surface. The discharge affects the electric field so that, in general, the discharges extend beyond the region where the original surface component of the electric field was high enough to cause discharges.

Corona discharges are observed in gases at sharp points in the electrical field. They occur usually at the high voltage side. The location of the corona discharges is either at sharp edges at earth potential or at half-way between the electrodes. Although the distance between the electrodes may be large, the field concentration at a sharp edge causes a partial breakdown of the surrounding air.

Discharges by electrical treeing start from defects in the insulation. After the progression of trees for some time, the stem and the larger branches grow hollow causing considerable discharges. These discharges are very stable and no detectable discharges are seen for a long time, but when the treeing sets in, discharges become visible and grow rapidly that they may cause breakdown in an extremely short period.

The ultimate goal of the partial discharge detection is to determine if an insulation design is promising. Therefore, detection of whether discharges are present or not is very important. The existence of the discharges and where they are located will determine the voltage life of the insulation [26]. There are some definitions regarding the partial discharge. These are given as follows.

The apparent charge: The apparent charge (q) of a partial discharge is that charge which, if it could be injected instantaneously between the terminals of the test object, would momentarily change the voltage between its terminals by the same amount as the partial discharge itself [27]. The apparent charge is expressed in terms of coulombs (C).

Inception voltage: The AC voltage across the sample at which discharges start to occur when the voltage is increased is called the inception voltage, and the corresponding stress in the surrounding dielectric is the inception stress.

Extinction voltage: If the voltages are decreased after discharges have been started, the voltage at which the discharges extinguish is called the extinction voltage and the corresponding stress is the extinction stress.

To understand the behavior of the discharges, Fig. 12 shows the behavior of internal discharges at AC voltage using the a-b-c circuit. The capacity of the cavity is

represented by a capacitance that is shunted by a breakdown path. The capacity of the dielectric in series with the cavity is represented by a capacitance b and the rest of the dielectric is represented by a . A recurrent discharge occurs if the circuit is energized with AC voltage: c is capacitively charged and reaches the breakdown voltage of the cavity, is charged again, and breaks down.

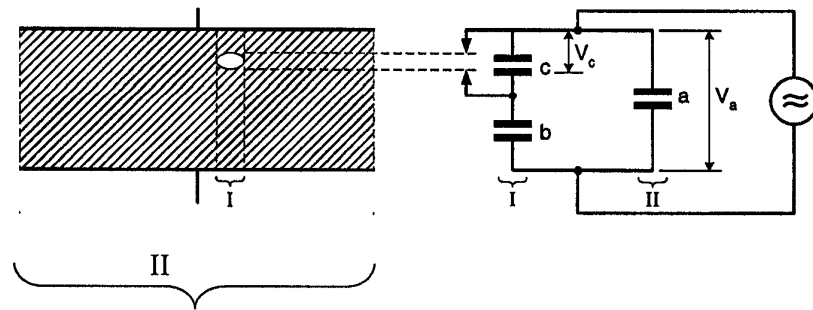


Fig. 12. A dielectric circuit

Discharges cause patterns of current impulses in the leads of a sample. These samples are detected by many circuits, but they all can be reduced to one basic diagram as shown in Fig. 13.

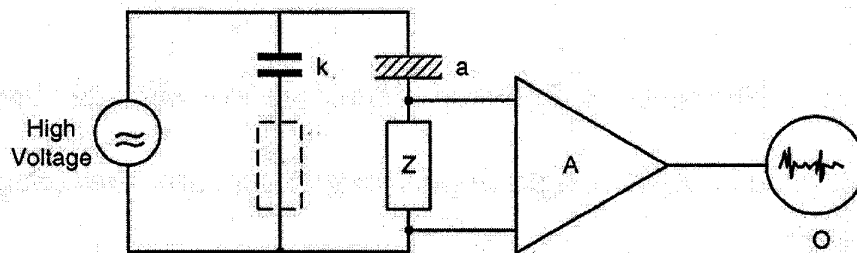


Fig. 13. Basic diagram for electrical discharge detection

The elements used in this diagram are as follows.

- A high voltage source that is free from charges.
- a is the sample affected by the discharges.

- An impedance Z , across which voltage impulses are caused by the discharge impulses in the sample.
- A coupling capacitance k that facilitates the passage of the high-frequency current impulses.
- An amplifier A .
- An observation unit o .

Detection and evaluation of partial discharges are a difficult problem of measuring technology. The background noise picked up by the observation units prevents the determination of the measurement of the quantity that is to be detected. The measured result is therefore influenced by a background noise level that has high and also time-variant values. The interference sources are divided into two categories [28].

- Disturbances independent of the voltage supplied to the sample caused, for example, by switching operations, commutating machines, high voltage tests in the vicinity, radio transmission, etc.
- Disturbances associated with the test voltage, but that does not occur in the sample, such as partial discharges in the testing transformer, on the high voltage conductors or by the sparking of imperfectly grounded objects in the vicinity.

Disturbances independent of the voltage supplied to the sample may be reduced by shielding the test circuit or by conducting the test in a shielded room. Interference by conduction may be suppressed by means of a low-pass filter in the voltage supply circuit. Partial discharges on the connecting leads between the test voltage source and the sample

may be avoided if the leads are smooth surfaced and of sufficient diameter, with spherical terminals [28].

The partial discharges are evaluated in terms of the specified quantities at a specified test voltage that may be well above the expected partial discharge inception voltage. The voltage is gradually increased from a low value to the specified value and maintained there for the specified time interval. Measurements are made at the end of this time interval or made while the voltage is being increased or decreased or throughout the entire test period [28].

II. DESCRIPTION OF THE TESTS

As it is discussed in the previous section, three kinds of tests have been presented to determine the dielectric characteristics of three type of polyurethane foam in this study. These are: AC voltage withstand tests, lightning impulse voltage withstand tests and partial discharge tests. The tests were conducted at three different temperature and humidity conditions. After selecting the best foam of all, the insulation of an OIT was modeled by foam filled tube and the same tests were conducted with this tube.

A. *Temperature and Humidity Conditions*

In order to see the effects of various humidity and temperature levels on the strength, foam samples were tested under the following conditions.

The temperature tests were conducted with samples exposed to different heat conditions (24 °C, 40 °C, and 60 °C) to observe the effect of heat on the foam's electrical properties. The samples tested at 40 °C and 60 °C were heated for an hour in an oven.

Immediately following the samples' removal from the oven, electrical tests were completed.

The samples were also tested at ambient humidity 36RH (Relative Humidity), 45RH and 80RH. Humidity conditions were generated according to the ASTM Standard 104-02 [18]. 200 gr Sodium Chloride and 200 gr water was mixed in a plastic beaker and then put into small humidity chamber.

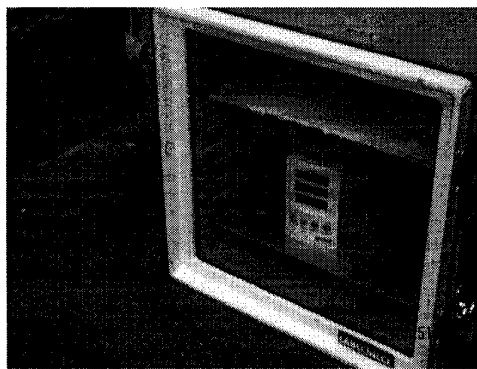


Fig. 14. Humidity Chamber

The mixture increases the ambient humidity to 80% RH in a very short time and remains almost constant. The samples were kept under 80% RH for the duration of 48 hours, and then high voltage tests were performed. Water absorption was not apparent at these three different levels of humidity; thus, measurements show less than 1% water absorption under all three conditions. Each sample was manufactured using the same method; this assures the uniformity of the samples. Fig. 14 shows the humidity chamber.

B. AC voltage withstand tests

Polyurethane foam samples were exposed to AC voltages under different humidity and temperature conditions. The foam samples were tested in a vessel filled with transformer oil in order to prevent discharges. Before starting the tests, it was

investigated to see if transformer oil penetrates into the foam samples or not. Foam sample weight is measured before putting it into the test vessel which is filled with transformer oil. The sample was kept there for 24 hours and its weight is measured after removing it from the test vessel. There was not noticeable amount of change in sample's weight. Thus, the test result indicates that transformer oil does not penetrate into the foam sample. Fig. 15 shows the test vessel.



Fig. 15. Test vessel

The AC breakdown test was conducted according to the IEEE Standard 4-1995 [24]. The test was performed with 60 Hz AC voltages. The test sample was energized to various voltage levels. The voltage was applied to the foam sample starting at a sufficiently low value then raised slowly with 0.8 kV/sec to permit accurate readings until breakdown. The thickness of the samples was measured and the breakdown strength was calculated by dividing the breakdown voltage to the thickness of the sample. This procedure was repeated for each breakdown.

Special electrode system made of steel was used for the tests. One of the electrodes, manufactured according to the ASTM Standard, has opposing cylinders 51

mm in diameter, 25 mm thick with edges rounded to 6.4 mm radius and the other electrode was in plane shape.

The tests were conducted in the High Voltage Laboratory at the 5th floor of ERC. The high voltage transformer rating is 100 kV and 5kVA. The Fig. 16 shows the set-up for AC voltage withstand test.

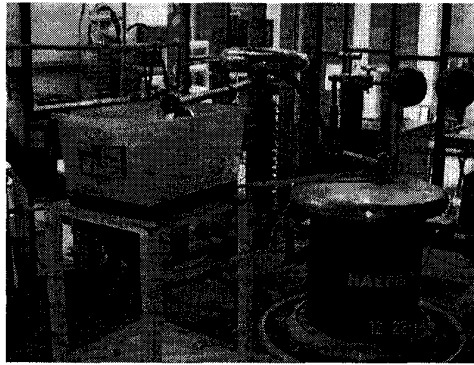


Fig. 16. Test set-up for AC voltage withstand test

C. Lightning impulse voltage withstand tests

Polyurethane foam samples were tested with lightning impulse voltages under different humidity and temperature levels. The foam samples were tested in a vessel filled with transformer oil in order to prevent discharges.

The waveshape of the applied lightning impulse voltage was 1.2/50. Impulses have positive polarity. The breakdown voltage was determined by stepwise increasing the impulse voltage, applying 5 impulses per step with 10 seconds time interval between two impulses.

The thickness of the samples was measured and the breakdown strength was calculated by dividing the breakdown voltage to the thickness of the sample. This procedure was repeated for each breakdown. The electrode system used for the AC

withstand test was also used for the lightning impulse voltage withstand test. The tests were conducted in the High Voltage Laboratory at the 5th floor of ERC.

D. Preparation of the foam filled tubes and the test methods.

After being selected the best foam of all, special tubes with electrodes were designed to model OITs to investigate the performance of polyurethane foam.

Paper tubes of 61.0 cm (24") long and 20.3 cm (8") diameter were prepared. Two covers one for bottom and one for top of the tube attached with electrode length of 22.8 cm (9") and electrode radius 1.27 cm (0.5") were also designed. The gap between the electrodes was 15.2 cm (6"). Fig. 17 shows the diagram of the proposed foam filled tube.

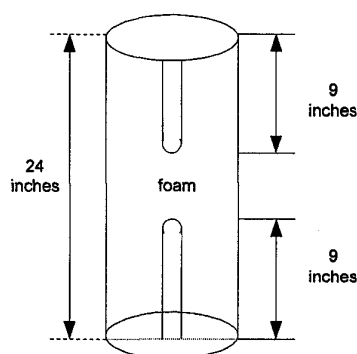


Fig. 17. Foam filled tube

A and B components of Foam I are poured into a beaker and mixed about 45 seconds. The mixing ratio by weight is 400 gr from A and 400 gr from B. Two holes were drilled on sides of the tube to provide a path for the excessive amount of foam to exit the tube. The top cover of the tube was removed and then the mixture was poured into the tube. The cover was later closed tightly while the foam rises and the tube was kept under this condition for four hours before the electrical tests.

The AC and lightning impulse breakdown voltages of these samples were determined by a large number of tests. The waveshape of the applied lightning impulse voltage was 1.2/50. The test was performed with both positive and negative polarities. At each voltage level, fifteen full impulses of each polarity were applied.

The Partial discharge was measured at each voltage level while the voltage was maintained for three minutes. Measurements were conducted according to IEEE Recommended practice 454-1973 [28]. These tests were performed at Nxtphase Corporation, Vancouver, BC, Canada.



Fig. 18. Lightning impulse test set-up

The effect of repeated lightning impulse voltage on a foam sample was determined by using 600 impulses with a peak voltage of 120 kV. The foam filled tube and the lightning impulse test set-up used for the repeated lightning impulse test is shown in Fig. 18.

CHAPTER 4

EVALUATION OF THE TEST RESULTS

The high voltage tests were performed to determine the dielectric strength of polyurethane foam insulation exposed to different humidity and temperature conditions. The AC and lightning impulse tests were conducted with samples that were exposed to 36% RH, 45% RH, 85% RH and (24 °C), 40 °C, and 60 °C. The results were evaluated and discussed comprehensively then the best foam of all three types was determined.

The insulation of hollow insulation system was modeled by foam filled tubes and the performance of the foam filled tube was investigated with AC voltage withstand, lightning impulse withstand and partial discharge tests to determine the quality and limit of the insulation. Table 3 illustrates the number of tests conducted with each foam type under different conditions.

TABLE 3

NUMBER OF TESTS CONDUCTED WITH EACH FOAM TYPE UNDER DIFFERENT CONDITIONS

	Room temperature 24 °C			Room RH 30-36%		
	36% RH	45% RH	80% RH	24 °C	40 °C	60 °C
Foam 1	15	15	16	15	15	17
Foam 2	16	26	17	16	15	13
Foam 3	11	NA	14	11	10	NA

I. AC VOLTAGE WITHSTAND TEST RESULTS OF FOAM I

A. Tests results under 36%RH, 45%RH and 80%RH

The result of the tests performed with Foam I under 36%RH, 45%RH and 80%RH are illustrated in the following Tables and Figures:

TABLE 4
AC WITHSTAND TEST RESULTS OF FOAM I AT 36%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.7	26	37.1
0.9	29	32.2
0.9	44	48.9
1	42	42
1	30	30
1.1	34	30.9
1.2	34	28.3
1.2	48	40
1.4	58	41.4
1.4	46	32.9
1.45	56	38.6

Average AC breakdown strength at 36%RH is calculated as 36.5 ± 6.3 kV/cm.

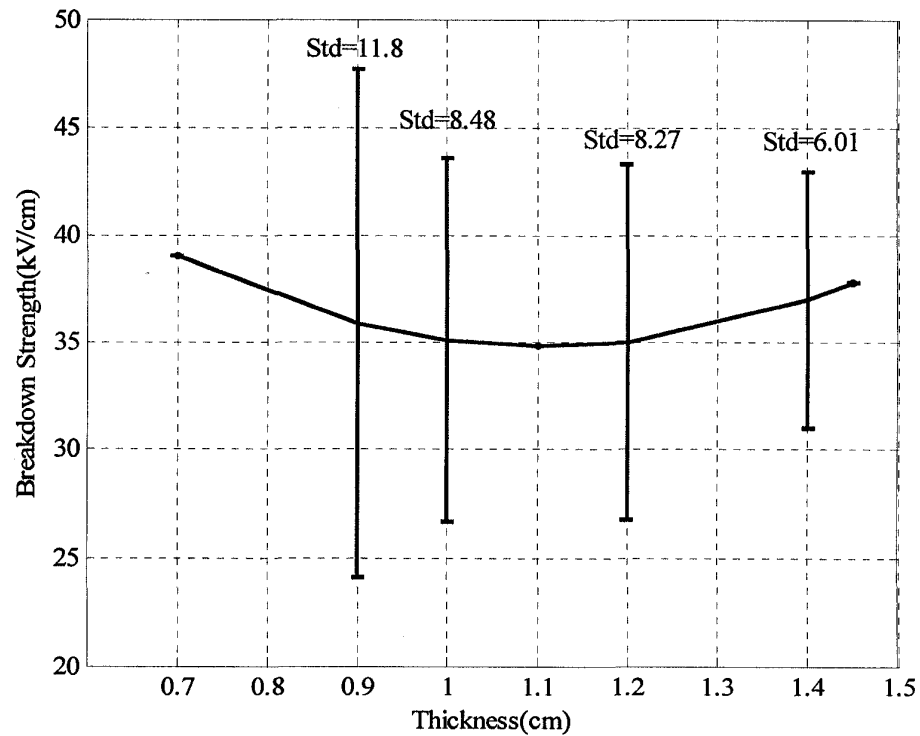


Fig. 19. AC Breakdown Strength versus Thickness of Foam I at 36%RH

TABLE 5
AC WITHSTAND TEST RESULTS OF FOAM I AT 45%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
1	50	50
1.15	60	52.1
1.15	62	53.9
1.15	65	56.5
1.16	60	51.7
1.18	60	50.8
1.18	62	52.5
1.2	70	58.3

Average AC breakdown strength at 45%RH is calculated as 53.2 ± 2.9 kV/cm.

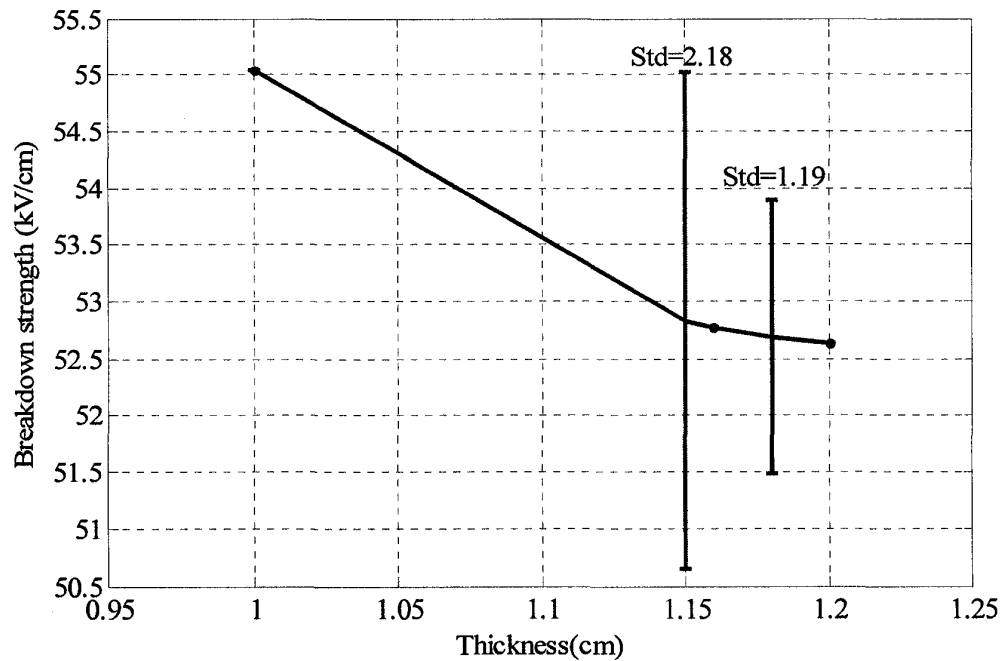


Fig. 20. AC Breakdown Strength versus Thickness of Foam I at 45%RH

TABLE 6
AC WITHSTAND TEST RESULTS OF FOAM I AT 80%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
1.02	51	50
1.02	58	56.8
1.02	55	53.9
1.1	50	45.5
1.2	51	42.5
1.2	60	50
1.2	66	55
1.2	66	55
1.2	77	64.1
1.3	76	58.5
1.3	78	60
1.3	78	60
1.3	83	63.8
1.3	88	67.6

Average AC breakdown strength at 80%RH is calculated as 55.9 ± 7.2 kV/cm.

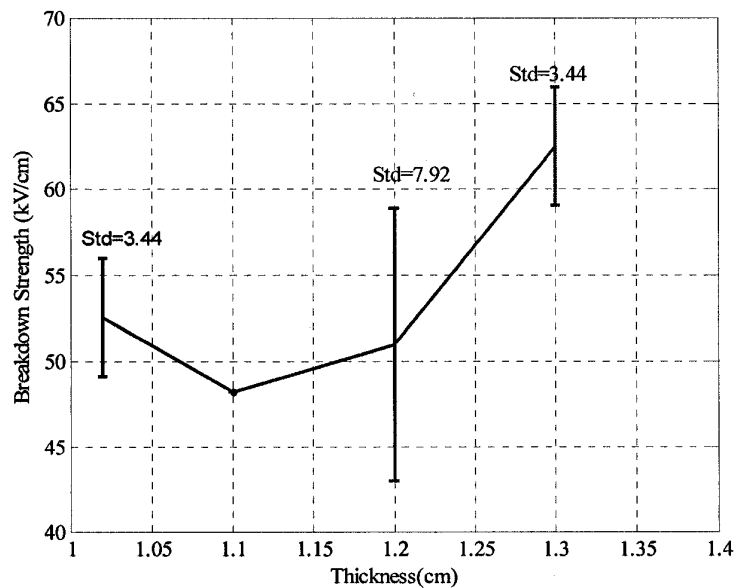


Fig. 21. AC Breakdown Strength versus Thickness of Foam I at 80%RH

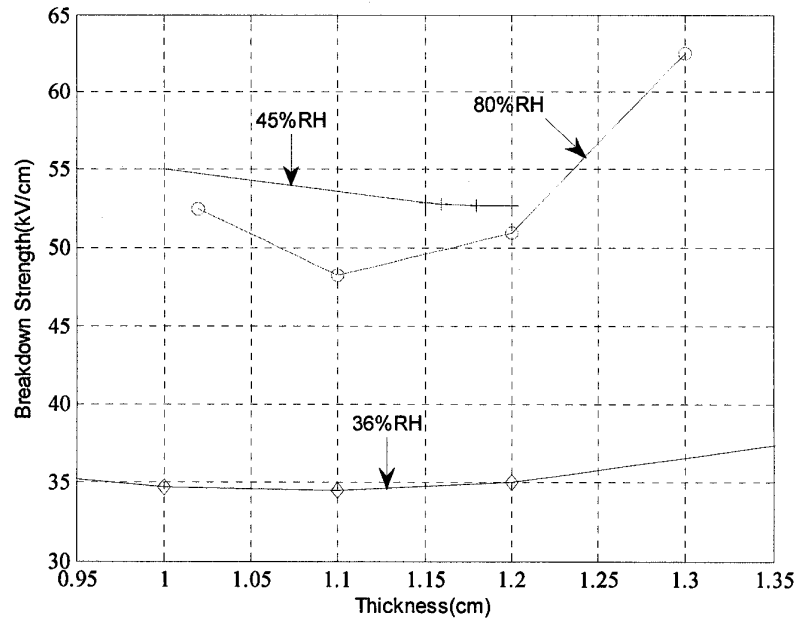


Fig. 22. The comparison of AC Breakdown Strength versus Thickness of Foam I at 36%RH, 45%RH & 80%RH

It is obvious from the above tables and figures that there is not always a linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes within the foam. Results show that the breakdown strength is independent of the relative humidity seeing as the strength is lowest for the minimum humidity level and highest for the medium humidity level for the thickness range of 1cm through 1.2 cm and highest for the maximum humidity level for the thickness range of 1.2 cm through 1.3 cm. The result conforms to the study explained in Chapter 2 conducted to see the water penetration into the polyurethane foam samples. The average AC breakdown strength of Foam I under three different humidity level is calculated as 48.8 ± 10.6 kV/cm.

B. Tests results under room temperature (24°C), 40°C and 60°C

The result of the tests performed with Foam I under room temperature (24°C), 40°C and 60°C are illustrated in the following Tables and Figures.

TABLE 7
AC WITHSTAND TEST RESULTS OF FOAM I AT ROOM TEMPERATURE (24°C)

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.7	26	37.1
0.9	30	33.3
0.9	44	48.9
1	43	43
1	30	30
1.1	34	30.9
1.2	34	28.3
1.2	48	40
1.4	58	41.4
1.4	48	34.3
1.45	56	38.6

Average AC breakdown strength at 24°C is calculated as 37 ± 1.2 kV/cm.

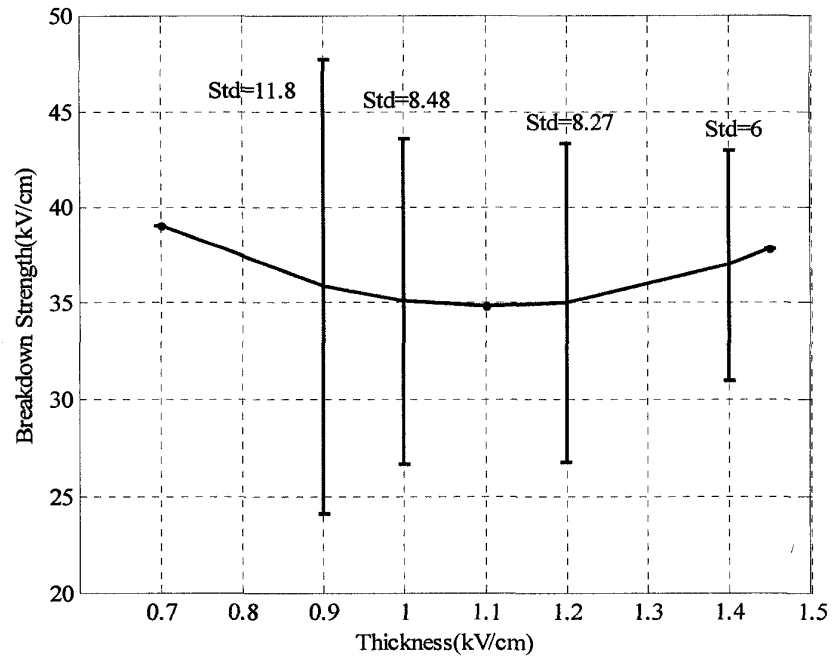


Fig. 23. Breakdown Strength versus Thickness of Foam I at room temperature (24°C)

TABLE 8

AC WITHSTAND TEST RESULTS OF FOAM I AT 40°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.7	32	45.7
0.8	38	47.5
0.85	41	48.2
0.85	43	50.6
0.85	48	56.5
0.85	49	57.6
1	50	50
1	51	51
1	51	51
1.4	80.7	57.7
1.5	91	60.7
1.5	93.1	62.1
1.5	97	64.6
1.6	99	61.8

Average AC breakdown strength at 40°C is calculated as 54.6 ± 6.2 kV/cm

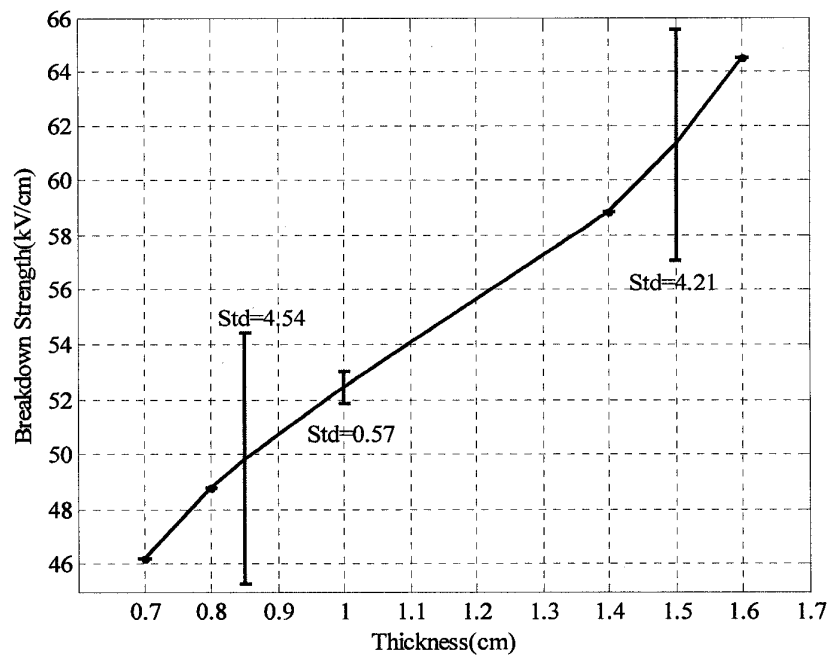


Fig. 24. AC Breakdown Strength versus Thickness of Foam I at 40°C

TABLE 9

AC WITHSTAND TEST RESULTS OF FOAM I AT 60°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
1.05	48	45.7
1.05	48	45.7
1.1	52	47.3
1.2	64	53.3
1.5	52	34.7
1.5	52	34.7
1.5	60	40
1.5	70	46.7
1.6	72	45
1.6	85	53.1

Average AC breakdown strength at 60°C is calculated as 44.6 ± 6.5 kV/cm

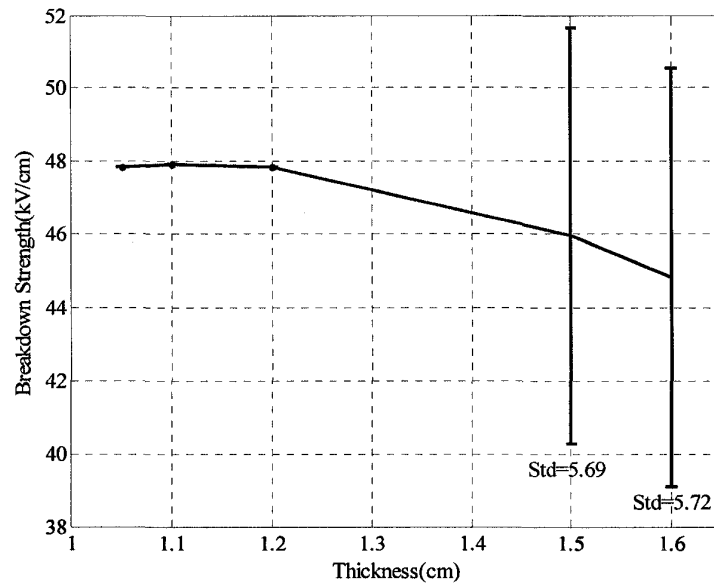


Fig. 25. AC Breakdown Strength versus Thickness of Foam I at 60°C

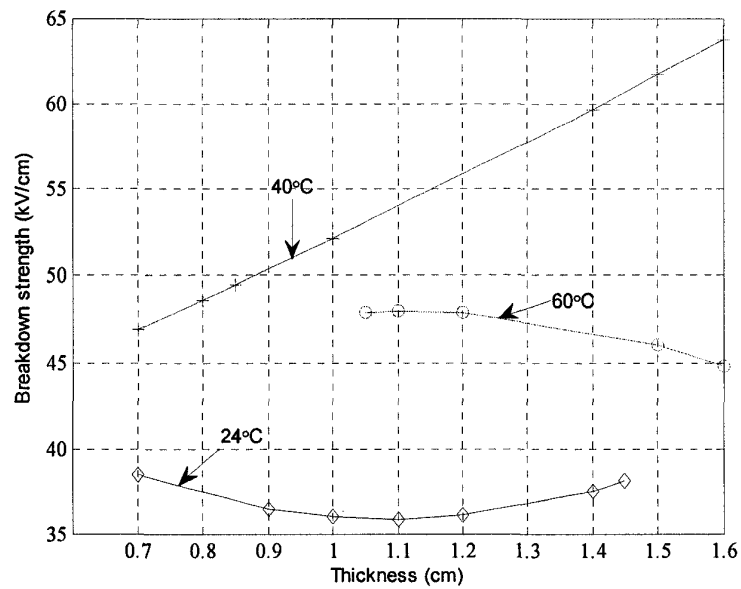


Fig. 26. The comparison of AC Breakdown Strength versus Thickness of Foam I at 24°C, 40°C and 60°C

The above tables and figures show that there is not a constant linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes inside the foam. Results show that the breakdown strength is also independent of the temperature as relative humidity given that the strength is lowest for the minimum temperature and highest for the medium temperature for the thickness range of 0.7 cm through 1.5 cm. The average AC breakdown strength of Foam I under three different temperature level is calculated as 46.1 ± 9.9 kV/cm.

II. AC VOLTAGE WITHSTAND TEST RESULTS OF FOAM II

A. Tests results under 36%RH, 45%RH and 80%RH

The result of the tests performed with Foam II under 36%RH, 45%RH and 80%RH are illustrated in the following Tables and Figures:

TABLE 10
AC WITHSTAND TEST RESULTS OF FOAM II AT 36%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.8	26	32.5
0.8	41	51.3
0.8	39	48.8
0.85	32	37.6
0.85	38	44.7
0.9	43	47.8
0.9	25	27.8
0.95	38	40
0.95	38	40
1	30.5	30.5
1	42.5	42.5
1	42	42
1	30	30
1	37	37
1.2	42	35

Average AC breakdown strength at 36%RH is calculated as 39.2 ± 7.2 kV/cm

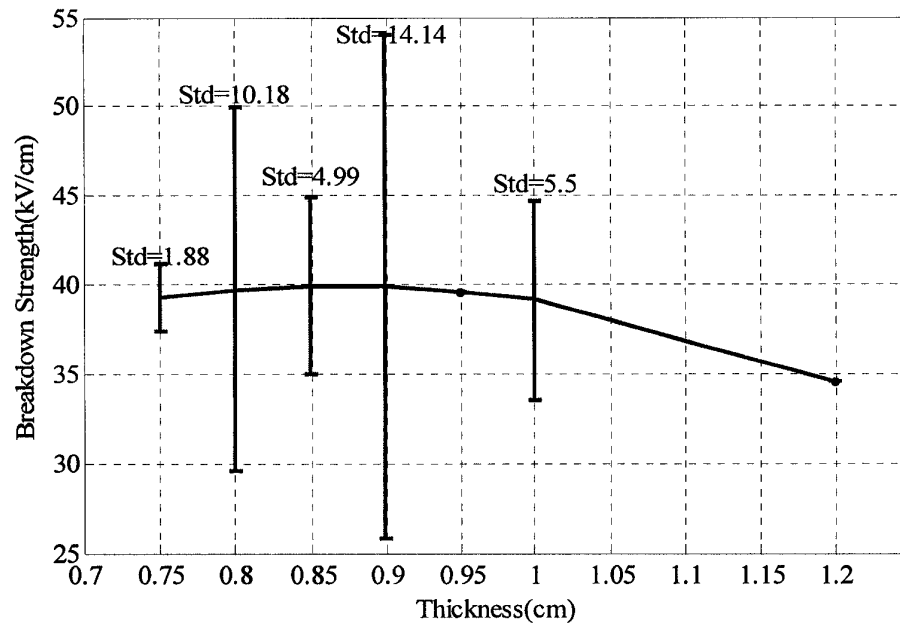


Fig. 27. AC Breakdown Strength versus Thickness of Foam II at 36%RH

TABLE 11

AC WITHSTAND TEST RESULTS OF FOAM II AT 45 %RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
1.1	44	40
1.1	45	40.9
1.1	50	45.4
1.1	50	45.4
1.1	51	46.3
1.1	52	47.2
1.1	53	48.1
1.1	53	48.1
1.1	53	48.1

The AC withstand test at 45%RH is conducted with samples having 1.1 cm thickness and the average AC breakdown strength at 45%RH is calculated as 45.5 ± 3.0 kV/cm.

TABLE 12
AC WITHSTAND TEST RESULTS OF FOAM II AT 80 %RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
21	0.75	28
30	0.75	40
37	0.8	46.3
27	0.82	32.9
27	0.9	30.0
33	0.9	36.7
34	0.9	37.8
40	0.9	44.4
58	1.2	48.3
40	1.22	32.8
46	1.23	37.4
55.5	1.23	45.1
46.5	1.28	36.3
50	1.28	39.1
40	1.29	31.0
42	1.3	32.3
55	1.35	40.7
49	1.5	32.7
54	1.55	34.8
51	1.58	32.3
57	1.6	35.6
48	1.6	30.0
41	1.6	25.6
58	1.61	36.0
42	1.62	25.9
56	1.64	34.1
50	1.8	27.8

Average AC breakdown strength at 80%RH is calculated as 35.3 ± 6 kV/cm.

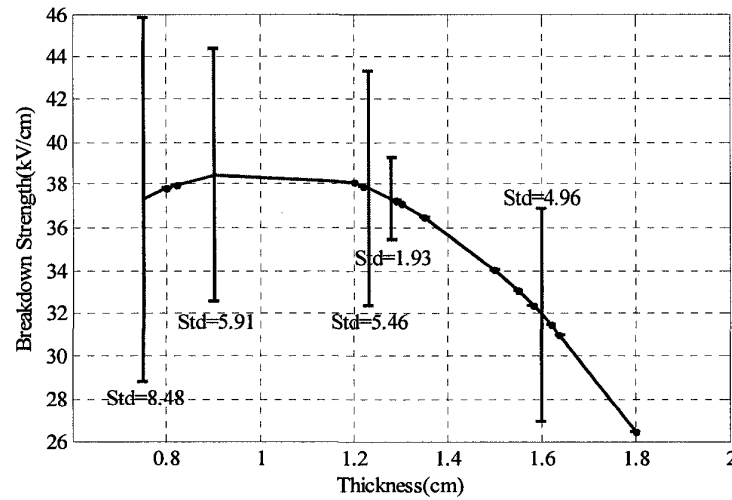


Fig. 28. AC Breakdown Strength versus Thickness of Foam II at 80%RH

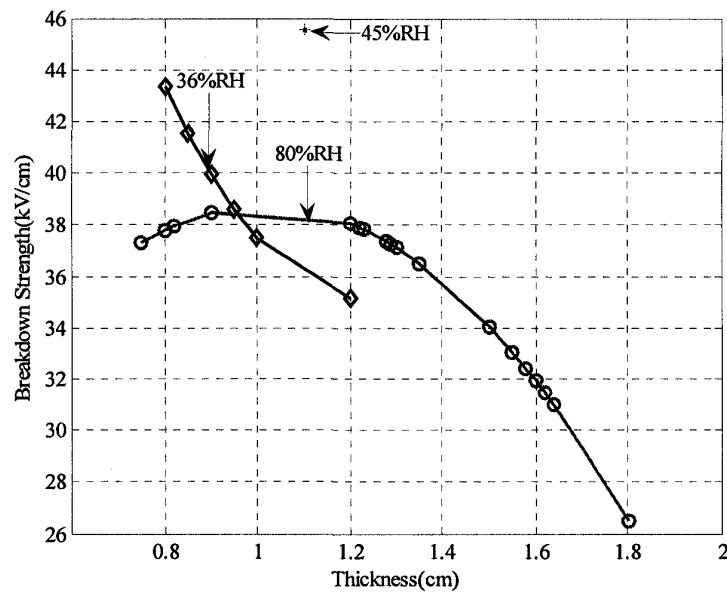


Fig. 29. The comparison of AC Breakdown Strength versus Thickness of Foam II at 36%RH & 80%RH

There is a non-linear relationship between the thickness of the samples and the breakdown voltage as seen in the above tables and figures, due to non-uniform

distribution of voids of different sizes within the foam. Results obtained for Foam II also show that the breakdown strength is independent of the relative humidity seeing as the strength is highest for the medium humidity level and lowest for the minimum humidity level for the thickness range of 1 cm through 1.2 cm. The average AC breakdown strength of Foam II is calculated as 39.1 ± 6.6 kV/cm.

B. Tests results under room temperature (24°C), 40°C and 60°C

The result of the tests performed with Foam II under room temperature (24°C), 40°C and 60°C are given in the following Tables and Figures:

TABLE 13
AC WITHSTAND TEST RESULTS OF FOAM II AT ROOM TEMPERATURE (24°C)

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.8	28	35
0.8	41	51.3
0.8	39	48.8
0.85	32	37.6
0.85	38	44.7
0.9	43	47.8
0.9	27	30.0
0.95	38	40
0.95	38	40
1	30.5	30.5
1	42.5	42.5
1	42	42
1	30	30
1	36	36
1.2	42	35

Average AC breakdown strength at 24°C is calculated as 39.2 ± 7.2 kV/cm

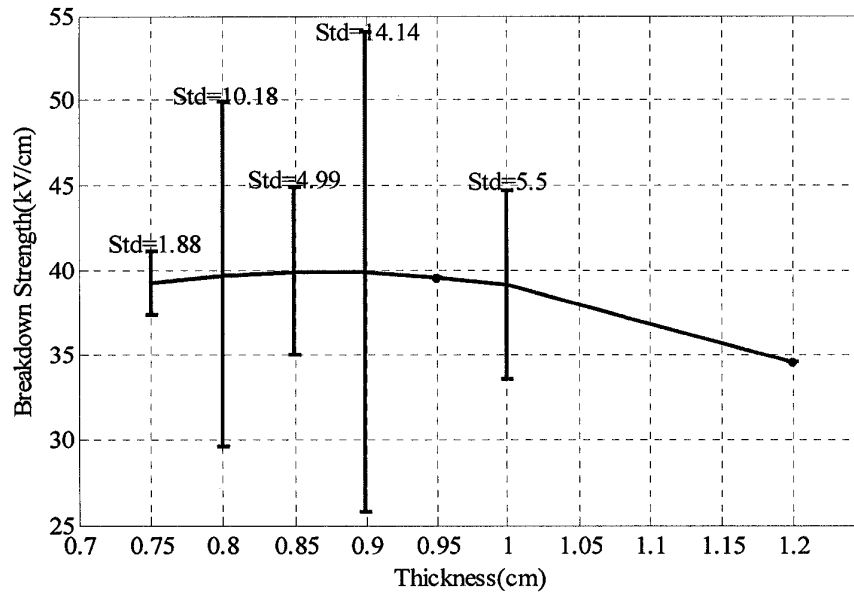


Fig. 30. AC Breakdown Strength versus Thickness of Foam II at 24°C

TABLE 14

AC WITHSTAND TEST RESULTS OF FOAM II AT 40°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.88	40	45.5
0.88	46	52.3
0.9	28	31.1
0.91	28	30.8
0.92	50	54.3
0.93	40	43.0
0.98	46	46.9
1	40	40
1.2	42	35
1.22	68	55.7
1.28	60	46.9
1.3	44	33.8
1.3	50	38.5
1.32	52	39.4
1.4	40	28.6
1.4	44	31.4
1.4	44	31.4
1.4	60	42.9
1.45	56	38.6

Average AC breakdown strength at 40°C is calculated as 40.3 ± 8.3 kV/cm

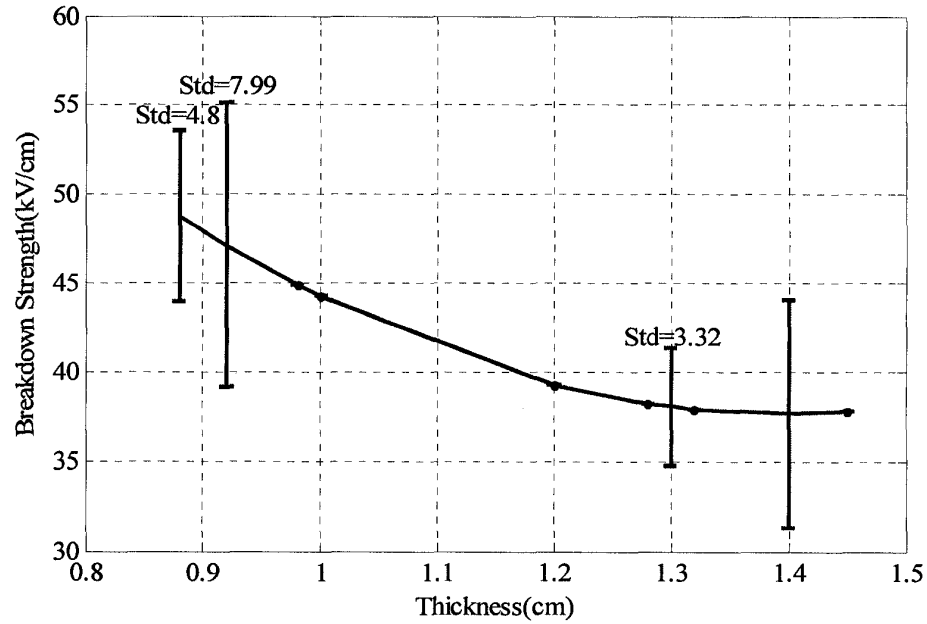


Fig. 31. AC Breakdown Strength versus Thickness of Foam II at 40°C

TABLE 15

AC WITHSTAND TEST RESULTS OF FOAM II AT 60°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.82	29	35.4
0.82	31	37.8
0.85	33	38.8
0.85	38	44.7
0.85	40	47.1
0.95	45	47.4
1.2	38	31.7
1.2	46	38.3
1.25	55	44
1.3	57	43.8
1.3	59	45.4
1.32	44	33.3
1.32	49	37.1
1.35	46	34.1
1.4	64	45.7

Average AC breakdown strength at 60°C is calculated as 40.3 ± 5.4 kV/cm

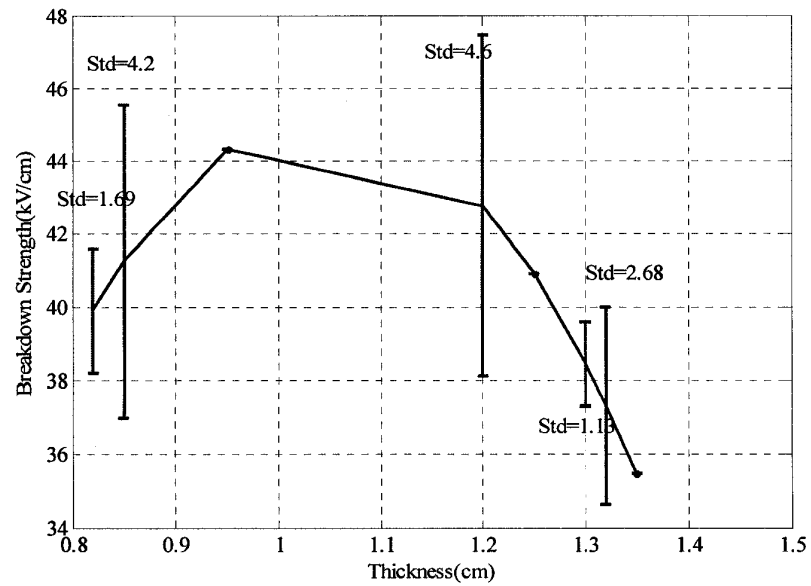


Fig. 32. AC Breakdown Strength versus Thickness of Foam II at 60°C

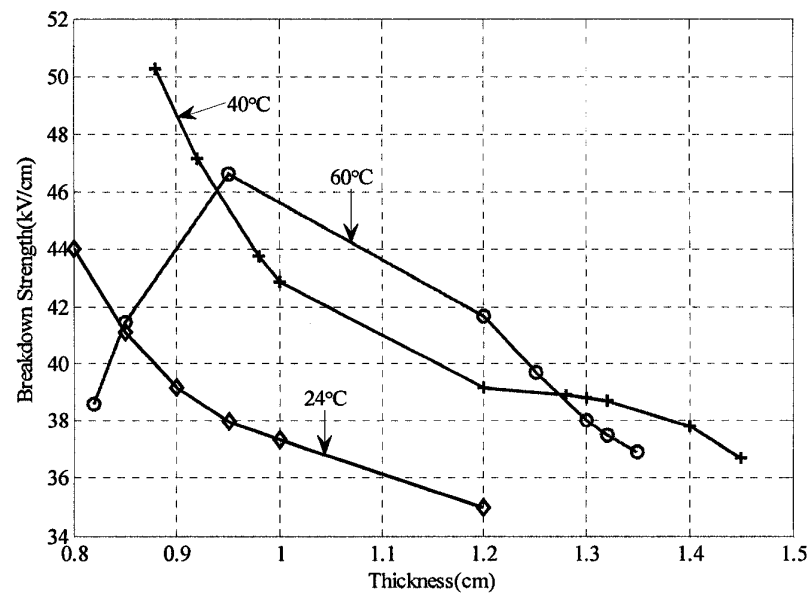


Fig. 33. The comparison of AC Breakdown Strength versus Thickness of Foam II at 24°C, 40°C and 60°C

It is obvious from the above tables that there is not always a linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes within the foam. Results show that the breakdown strength is independent of the temperature given that the strength is lowest for the minimum temperature and highest for the maximum temperature for the thickness range of 0.9 cm and 1.2 cm. The average AC withstand breakdown strength of Foam II under three different temperature level is calculated as 40 ± 7.1 kV/cm.

III. AC VOLTAGE WITHSTAND TEST RESULTS OF FOAM III

A. Tests results under 45%RH and 80%RH

The result of the tests performed with Foam III under 45%RH and 80%RH are illustrated in the following Tables and Figures:

TABLE 16
AC WITHSTAND TEST RESULTS OF FOAM III AT 45%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.68	35	51.5
0.75	38	50.7
0.75	38	50.7
0.8	36	45
0.8	40	50
1.35	49	36.3
1.35	58	43.0
1.35	66	48.9
1.38	64	46.4
1.4	47	33.6
1.4	53	37.9
1.4	58	41.4
1.4	60	42.9
1.42	63	44.4
1.45	60	41.4

Average AC breakdown strength at 45%RH is calculated as 44.3 ± 5.5 kV/cm

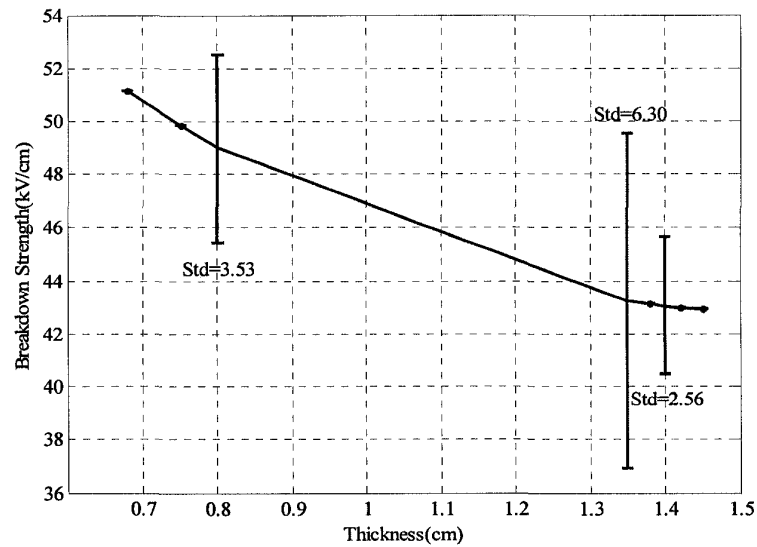


Fig. 34 AC Breakdown Strength versus Thickness of Foam III at 45%RH

TABLE 17

AC WITHSTAND TEST RESULTS OF FOAM III AT 80%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.75	28	37.3
0.75	33	44
0.75	36	48
0.8	34	42.5
0.8	35	43.7
0.8	36	45
1.4	48	34.3
1.5	50	33.3
1.5	52	34.7
1.6	60	37.5
1.6	63	39.4
1.6	63	39.4
1.6	64	40
1.65	66	40
1.65	69	41.8

Average AC breakdown strength at 80%RH is calculated as 40 ± 4.2 kV/cm

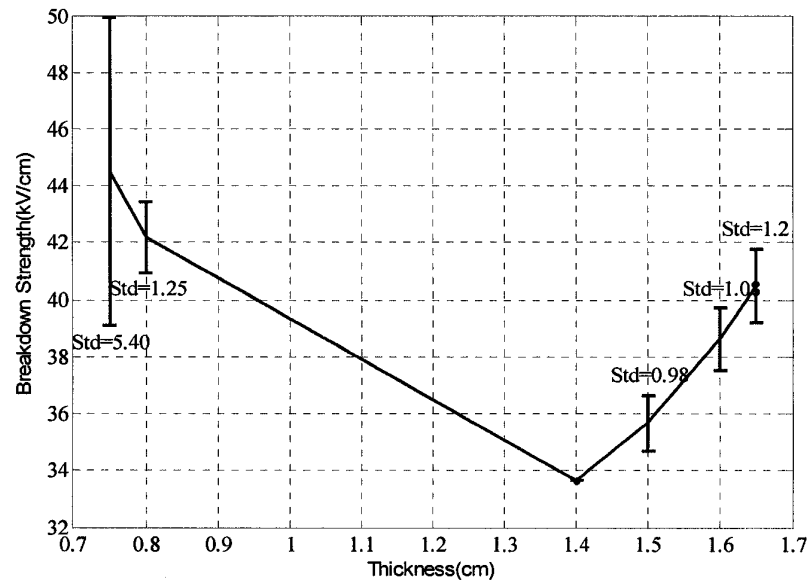


Fig. 35. AC Breakdown Strength versus Thickness of Foam III at 80%RH

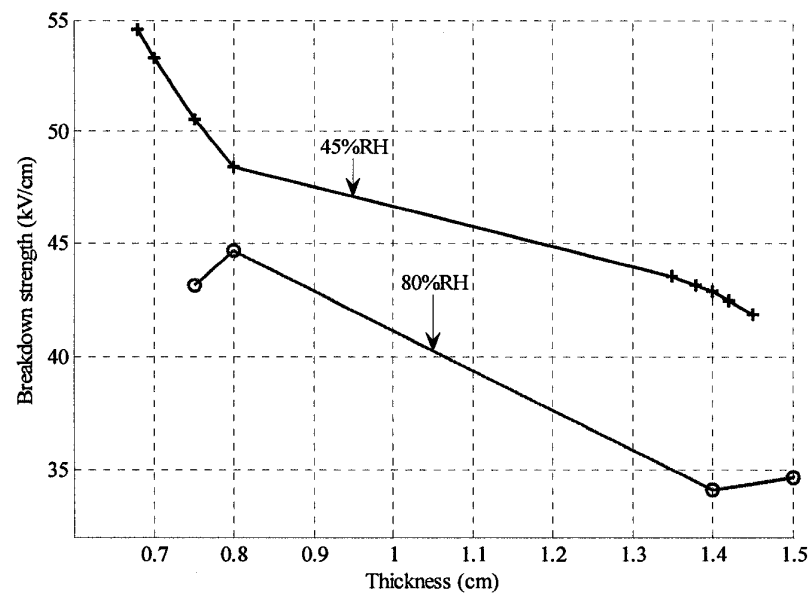


Fig. 36. The comparison of AC Breakdown Strength versus Thickness of Foam III at 45%RH & 80%RH

Fig. 35 and Fig. 36 show that the breakdown strength decreases with increasing humidity in the range of 0.8 cm and 1.4 cm for both cases. The effect of humidity on Foam III is somewhat different than that of Foam I and Foam II as the decrease in humidity results in increase in the strength.

B. Tests results under room temperature (24°C) and 40°C

The result of the tests performed with Foam III under room temperature (24°C) and 60°C are illustrated in the following Tables and Figures:

TABLE 18
AC WITHSTAND TEST RESULTS OF FOAM III AT ROOM TEMPERATURE (24°C)

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.68	35	51.5
0.75	38	50.7
0.75	38	50.7
0.8	36	45
0.8	40	50
1.35	49	36.3
1.35	58	43.0
1.35	66	48.9
1.38	64	46.4
1.4	47	33.6
1.4	53	37.9
1.4	58	41.4
1.4	60	42.9
1.42	63	44.4
1.45	60	41.4

Average AC breakdown strength at 24°C is calculated as 44.3 ± 5.5 kV/cm

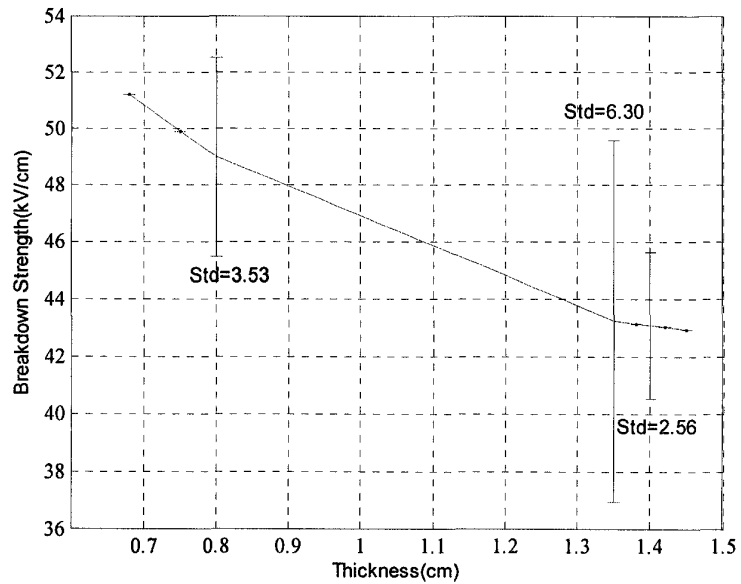


Fig. 37. AC Breakdown Strength versus Thickness of Foam III at 24°C

TABLE 19

AC WITHSTAND TEST RESULTS OF FOAM III AT 40°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.92	47	51.1
0.92	50	54.3
1	48	48
1	48	48
1	53	53
1.01	50	49.5
1.01	52	51.5
1.08	58	53.7
1.45	72	49.7
1.5	80	53.3

Average AC breakdown strength at 40°C is calculated as 51.2 ± 2.3 kV/cm

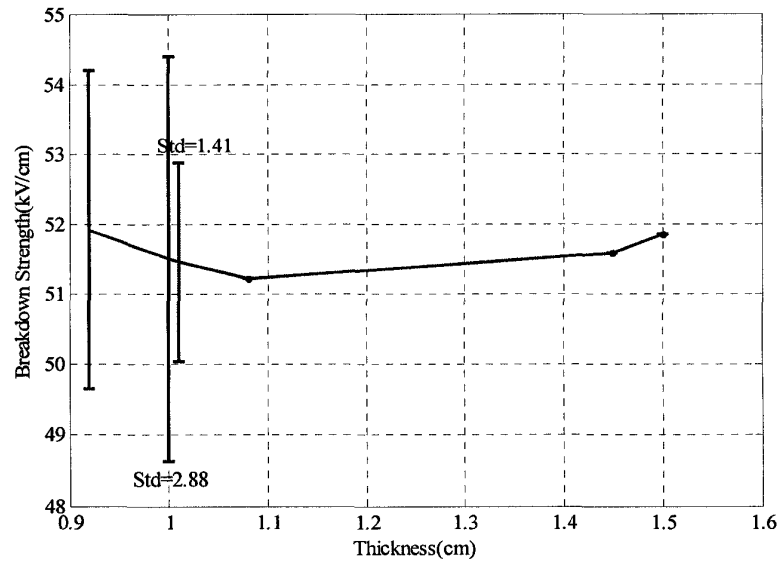


Fig. 38. AC Breakdown Strength versus Thickness of Foam III at 40°C

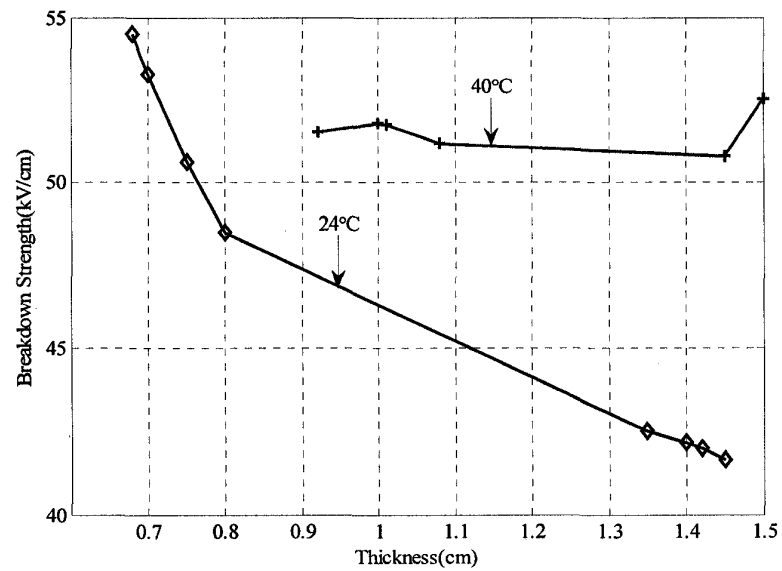


Fig. 39. The comparison of AC Breakdown Strength versus Thickness of Foam III at 24°C & 40°C

It is clear from the above tables that there is a non-linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes within the foam. Results show that the breakdown strength of Foam III is independent of the temperature like Foam I and Foam II because the strength is lowest for the minimum temperature and highest for the maximum temperature for the thickness range of 0.9 cm through 1.5 cm. The average AC breakdown strength of Foam III under three different temperature levels is calculated as 47 ± 5.6 kV/cm.

IV. LIGHTNING IMPULSE TEST RESULTS OF FOAM I

A. Tests results under 36%RH, 45%RH and 80%RH

The result of the tests performed with Foam I under 36%RH, 45%RH and 80%RH are illustrated in the following Tables and Figures:

TABLE 20
LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 36%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.7	139.2	198.9
0.8	143.9	179.9
0.8	156.8	196.0
0.82	163.8	199.8
0.9	175.5	195
1.1	170.8	155.3
1.1	172.0	156.4
1.1	172.0	156.4
1.1	177.8	161.7
1.1	188.4	171.2
1.2	159.1	132.6
1.28	159.1	124.3
1.28	177.8	138.9
1.3	176.7	135.9
1.31	152.1	116.1

Average Lightning Impulse breakdown strength at 36%RH is calculated as 161.2 ± 28.2 kV/cm.

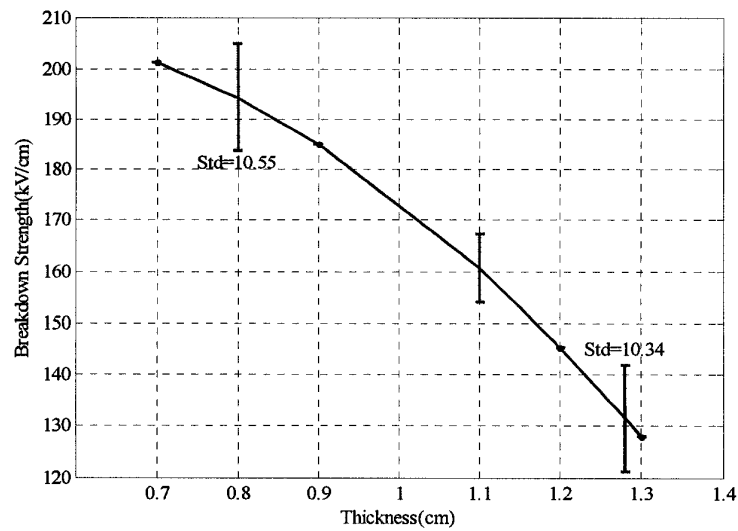


Fig. 40. The Lightning impulse Breakdown Strength versus Thickness of Foam I at
36%RH

TABLE 21

LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 45%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.65	115.8	178.2
0.65	117	180
0.65	119.9	184.5
0.65	140.4	216
1	148.5	148.6
1	153.8	153.9
1.01	138.6	137.3
1.05	150.9	143.7
1.07	155.0	144.9
1.1	170.8	155.3
1.45	157.9	108.9
1.45	157.9	108.9
1.45	160.2	110.5
1.48	176.6	119.4
1.5	189.5	126.4

Average Lightning impulse Breakdown Strength at 45%RH is calculated as

147.7±31.4 kV/cm.

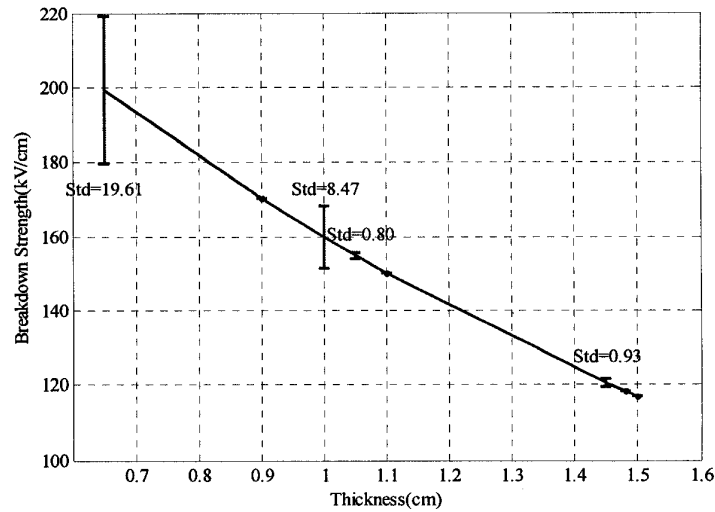


Fig. 41. The Lightning impulse Strength versus Thickness of Foam I at 45%RH

TABLE 22

LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 80%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.6	132.2	220.4
0.6	141.6	236.0
0.6	150.9	251.6
0.65	160.3	246.6
0.65	166.7	256.5
0.7	167.3	239.0
1.1	175.5	159.5
1.1	175.5	159.5
1.2	170	141.4
1.2	177	147.2
1.2	194	161.9
1.2	198.9	165.8
1.22	174.3	142.9
1.28	196.6	153.6
1.3	215.3	165.6
1.4	221.1	158.0

Average Lightning impulse Breakdown Strength at 80%RH is calculated as

187.8 ± 44.2 kV/cm.

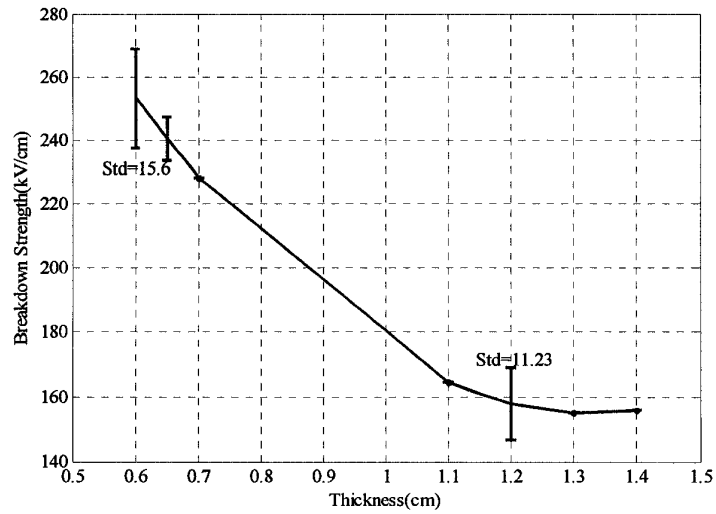


Fig. 42. The Lightning impulse Strength versus Thickness of Foam I at 80%RH

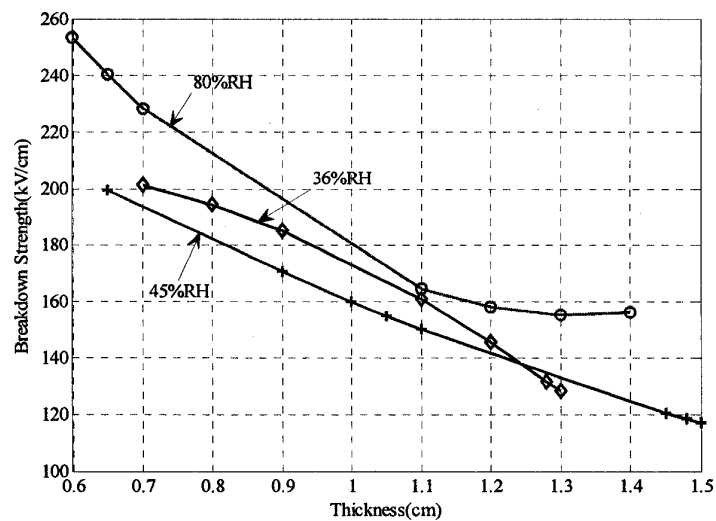


Fig. 43. The comparison of Lightning impulse Strength versus Thickness of Foam I at 36%RH, 45%RH & 80%RH

The above figures and tables indicate that there is not a linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform

distribution of voids of different sizes within the foam. Results show that the breakdown strength is independent of the relative humidity as the strength is lowest for the medium humidity level and highest for the maximum humidity level for the thickness range of 0.7 cm through 1.3 cm. The average Lightning impulse breakdown strength of Foam I is calculated as 166 ± 38.6 kV/cm.

B. Tests results under room temperature (24°C), 40°C and 60°C.

The result of the tests performed with Foam I under room temperature (24°C), 40°C and 60°C are illustrated in the following Tables and Figures:

TABLE 23
LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 24°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.7	140.5	200.7
0.8	143.9	179.9
0.8	156.8	196.0
0.82	163.8	199.8
0.9	175.5	195
1.1	170.8	155.3
1.1	175.0	159.1
1.1	172.0	156.4
1.1	177.8	161.7
1.1	188.4	171.2
1.2	159.1	132.6
1.28	159.1	124.3
1.28	177.8	138.9
1.3	176.7	135.9
1.31	151.2	115.4

Average Breakdown Strength at 24°C is calculated as 162.1 ± 8.2 kV/cm

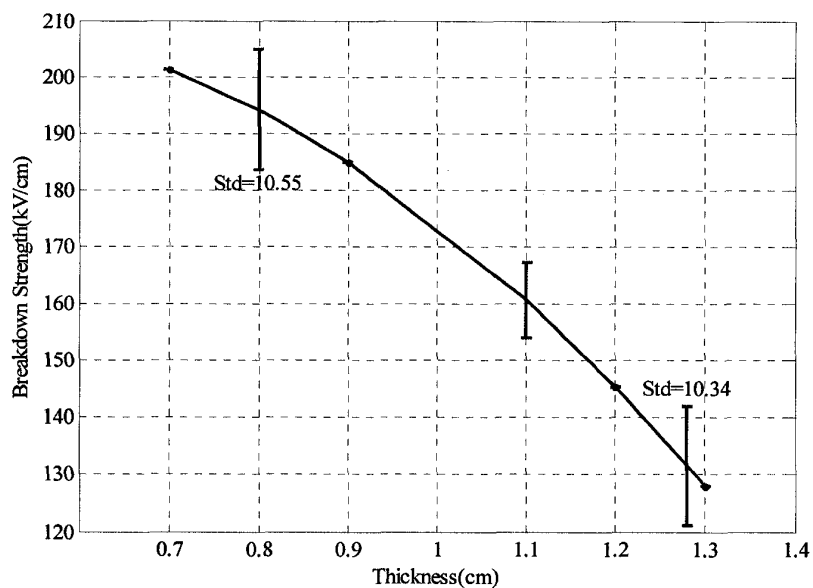


Fig. 44. The Lightning Impulse Breakdown Strength versus Thickness of Foam I at 24°C

TABLE 24

LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 40°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.6	110.0	183.3
0.6	131.0	218.4
0.6	136.9	228.2
0.6	141.0	235.0
0.65	156.8	241.2
1.1	174.3	158.5
1.1	196.6	178.7
1.11	172.0	154.9
1.12	196.6	175.5
1.15	197.7	171.9
1.3	183.7	141.3
1.4	190.7	136.2
1.4	200.1	142.9
1.4	204.8	146.3
1.4	210.6	150.4

Average Lightning impulse breakdown strength at 40°C is calculated as 177.5±36.3 kV/cm.

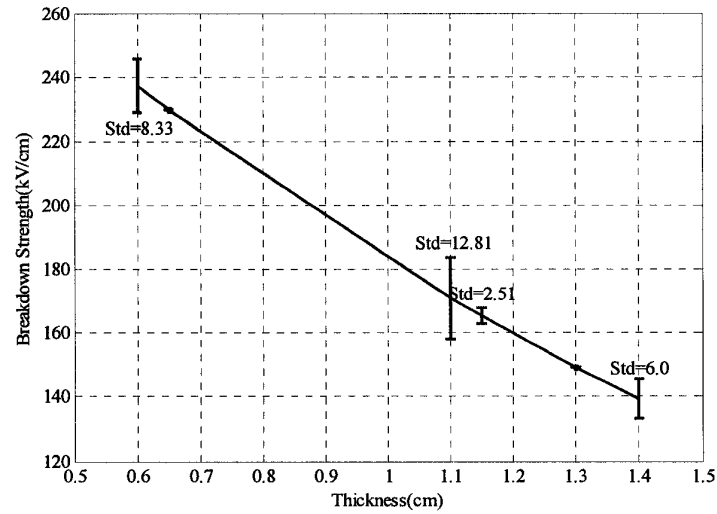


Fig. 45. The Lightning impulse Breakdown Strength versus Thickness of Foam I at 40°C

TABLE 25

LIGHTNING IMPULSE TEST RESULTS OF FOAM I AT 60°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.8	158.0	197.4
0.8	158.0	197.4
0.8	160.3	200.4
0.9	160.3	178.1
0.9	165.0	183.3
1	166.1	166.1
1	172.0	172.0
1.08	172.0	159.3
1.09	154.4	141.7
1.1	172.0	156.4
1.1	174.3	158.5
1.4	176.7	126.2
1.4	182.5	130.4
1.5	172.0	114.7
1.6	183.7	114.8
1.6	186.6	116.6
1.6	204.8	128.0

Average Lightning impulse Breakdown Strength at 60°C is calculated as 155.3 ± 30 kV/cm.

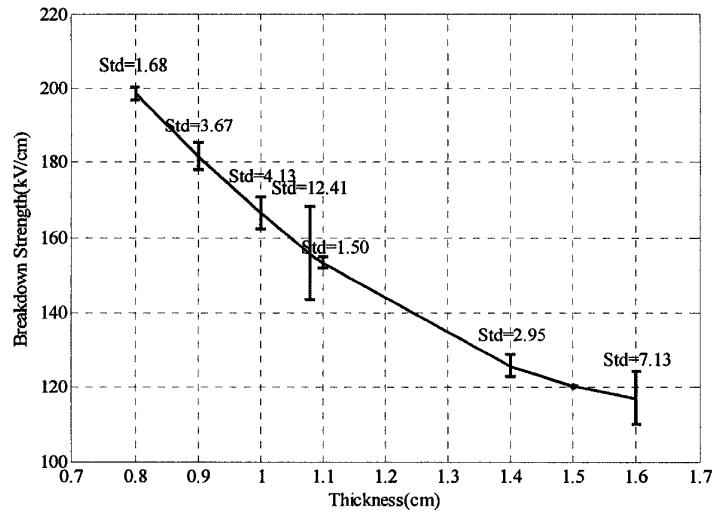


Fig. 46. The Lightning impulse Breakdown Strength versus Thickness of Foam I at 60°C

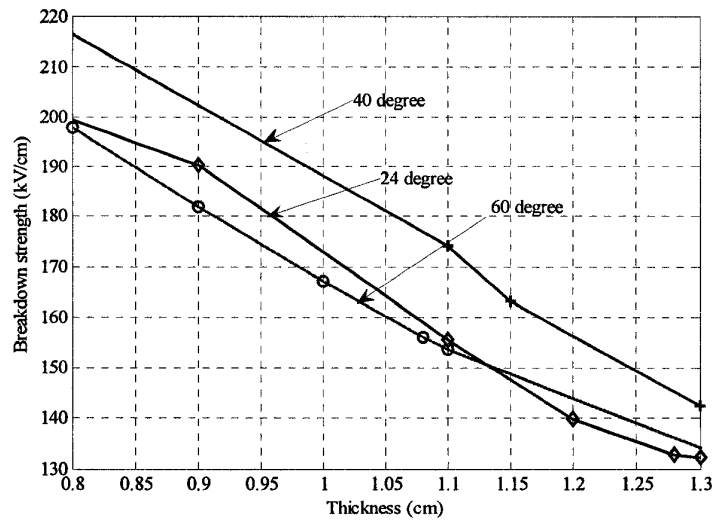


Fig. 47. The comparison of Lightning impulse Breakdown Strength versus Thickness of Foam I at 24°C, 40°C and 60°C

It is evident from the above figures and tables that there is not a constant linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes within the foam. Results show that the breakdown strength is also independent of the temperature as relative humidity given that the strength is highest for the medium temperature and lowest for the maximum temperature for the thickness range of 0.8 cm through 1.3 cm. The lightning impulse breakdown strength of Foam I is calculated as 164.3 ± 32.3 kV/cm.

V. LIGHTNING IMPULSE TEST RESULTS OF FOAM II

A. Tests results under 36%RH, 45%RH and 80%RH

The result of the tests performed with Foam II under 36%RH, 45%RH and 80%RH are illustrated in the following Tables and Figures:

TABLE 26
LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 36%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.9	125.2	139.1
0.9	138.1	153.4
0.9	141.6	157.3
0.98	139.2	142.1
1	149.8	149.8
1.2	141.6	118.0
1.2	142.7	119.0
1.2	150.9	125.8
1.2	156.8	130.7
1.2	170.8	142.4
1.2	172.0	143.3
1.2	187.2	156
1.4	188.4	134.6
1.4	196.6	140.4
1.4	197.7	141.2
1.42	200.1	140.9

Average breakdown strength at 36%RH is calculated as 139.6 ± 11.8 kV/cm.

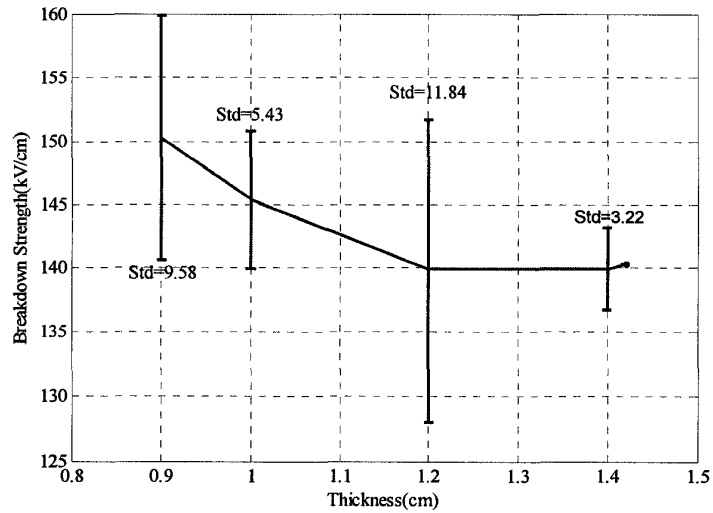


Fig. 48. The Lightning impulse Breakdown Strength versus Thickness of Foam II at 36%RH

TABLE 27

LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 45%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.8	136.3	170.4
0.8	141.0	176.2
0.8	159.1	198.9
0.81	147.4	182.0
0.85	170.2	200.3
0.9	153.9	171.0
1	158.0	158.0
1	162.6	162.6
1	168.5	168.5
1.05	170.8	162.7
1.1	139.2	126.6
1.1	153.3	139.3
1.1	154.4	140.4
1.1	155.0	140.9
1.15	175.5	152.6
1.3	170.8	131.4

1.35	176.7	130.9
1.37	177.8	129.8
1.35	176.7	130.9
1.4	159.1	113.7
1.4	173.2	123.7
1.4	184.9	132.0
1.4	188.4	134.6
1.43	197.7	138.3
1.5	187.2	124.8
1.55	188.4	121.5

Average Lightning impulse Breakdown Strength at 45%RH is calculated as 148.5 ± 24.2 kV/cm.

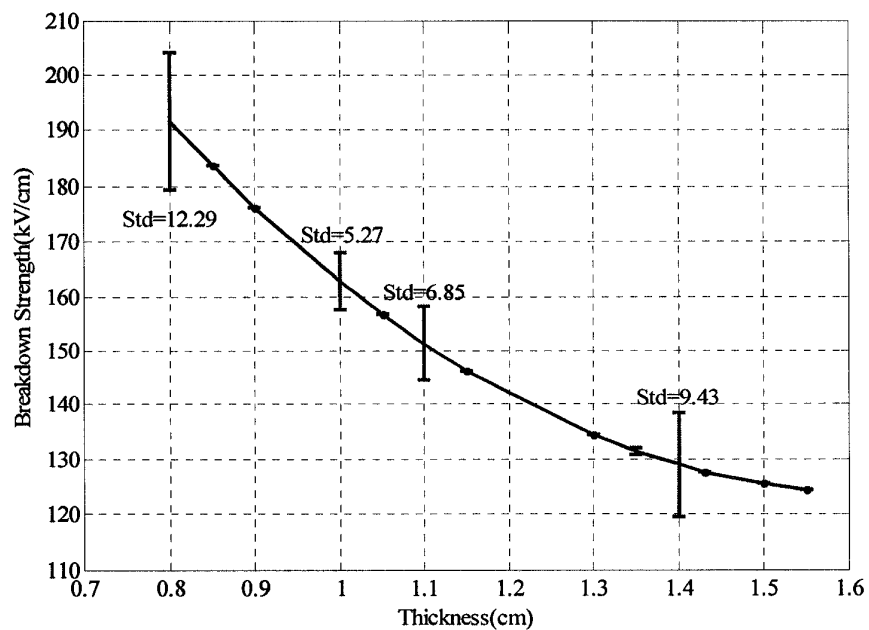


Fig. 49. The Lightning impulse Breakdown Strength versus Thickness of Foam II at 45%RH

TABLE 28
LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 80%RH

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.76	95.4	125.5
0.8	114.1	142.6
0.8	115.2	144.1
0.85	117.0	137.6
0.85	117.6	138.3
0.9	138.1	153.4
1.02	105.3	103.2
1.02	111.2	109.0
1.1	105.3	95.7
1.1	117.0	106.4
1.1	136.9	124.4
1.14	135.1	118.5
1.3	141.6	108.9
1.4	142.2	101.5
1.5	155.6	103.7
1.55	142.7	92.1
1.6	152.1	95.1

Average Lightning impulse strength at 80%RH is calculated as 117.6 ± 19.5 kV/cm.

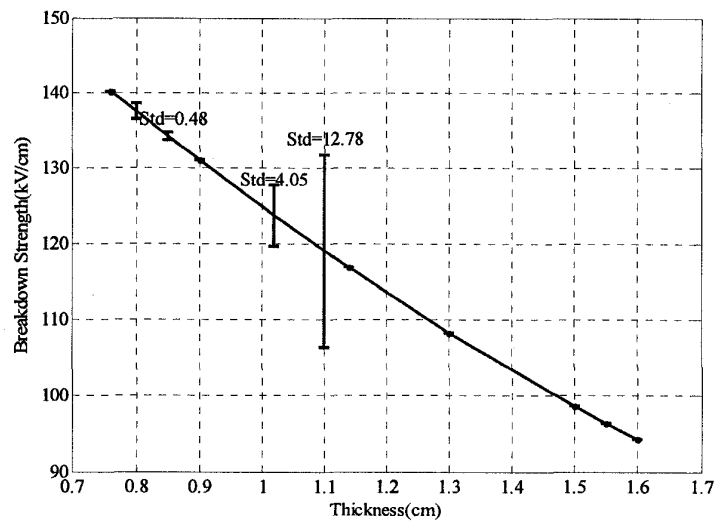


Fig. 50. The Lightning impulse Breakdown Strength versus Thickness of Foam II at
80%RH

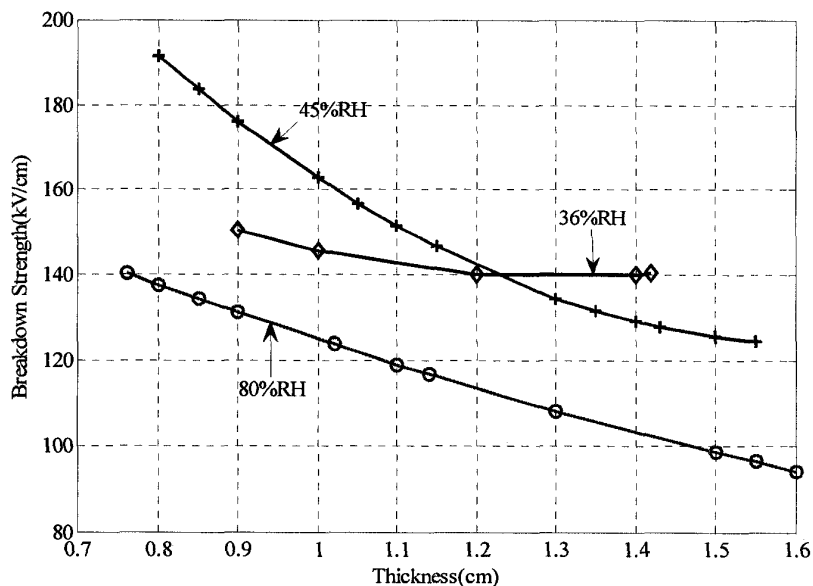


Fig. 51. The comparison of Lightning impulse Breakdown Strength versus Thickness of Foam II at 36%RH, 45%RH and 80%RH

As shown in Fig. 51, breakdown strength of Foam II is independent of humidity level as the strength is highest for the medium humidity level and lowest for the maximum humidity level for the thickness range of 0.9 cm through 1.2 cm, but it is highest for minimum humidity level and lowest for maximum humidity level for the thickness range of 1.2 cm through 1.4 cm. The lightning impulse breakdown strength of Foam II is calculated as 137.2 ± 23.7 kV/cm.

B. Tests results under room temperature (24°C), 40°C and 60°C.

The result of the tests performed with Foam II under room temperature (24°C), 40°C and 60°C are illustrated in the following Tables and Figures:

TABLE 29
LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 24°C

Thickness(cm)	Breakdown voltage(kV)	Breakdown Strength(kV/cm)
0.9	125.2	139.1
0.9	138.1	153.4
0.9	141.6	157.3
0.98	139.2	142.1
1	149.8	149.8
1.2	141.6	118.0
1.2	142.7	119.0
1.2	150.9	125.8
1.2	156.8	130.7
1.2	170.8	142.4
1.2	172.0	143.3
1.2	187.2	156
1.4	188.4	134.6
1.4	196.6	140.4
1.4	197.7	141.2
1.42	200.1	140.9

Average breakdown strength at 24°C is calculated as 139.6 ± 11.8 kV/cm

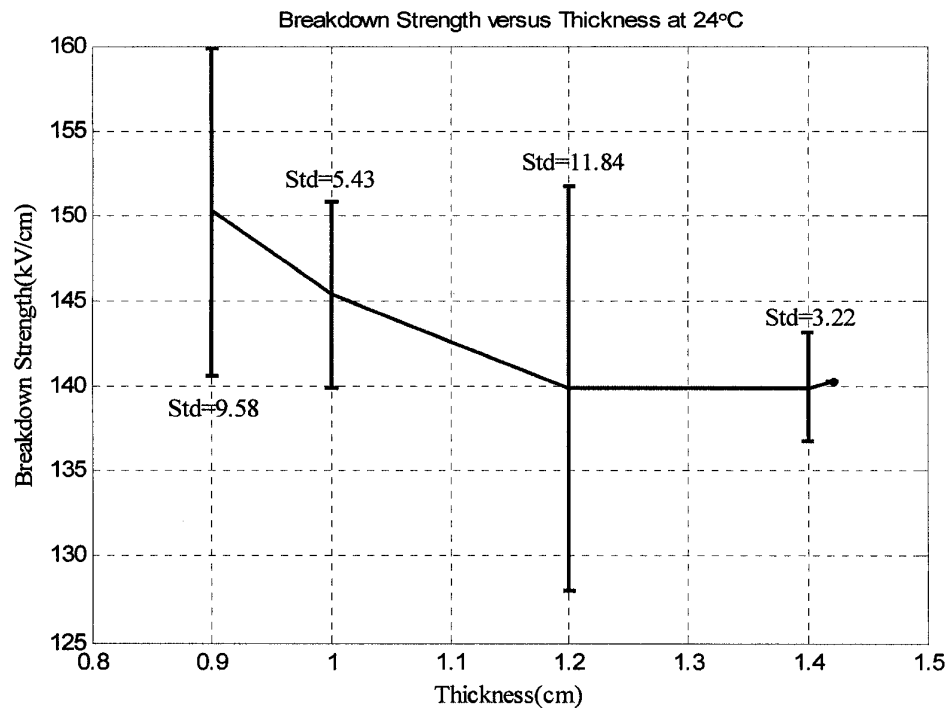


Fig. 52. The Lightning impulse Breakdown Strength versus Thickness of Foam II at 24°C

TABLE 30

LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 40°C

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
0.8	160.3	200.4
0.83	175.5	211.4
0.85	183.7	216.1
0.9	183.7	204.1
0.9	189.5	210.6
1.1	183.7	167.0
1.1	191.9	174.4
1.15	188.4	163.8
1.18	200.1	169.6
1.25	172.0	137.6
1.4	193.1	137.9
1.4	194.2	138.7
1.4	195.4	139.6
1.4	198.9	142.1
1.5	195.4	130.3

Average Lightning impulse Breakdown Strength at 24°C is calculated as
 169.5 ± 31.5 kV/cm

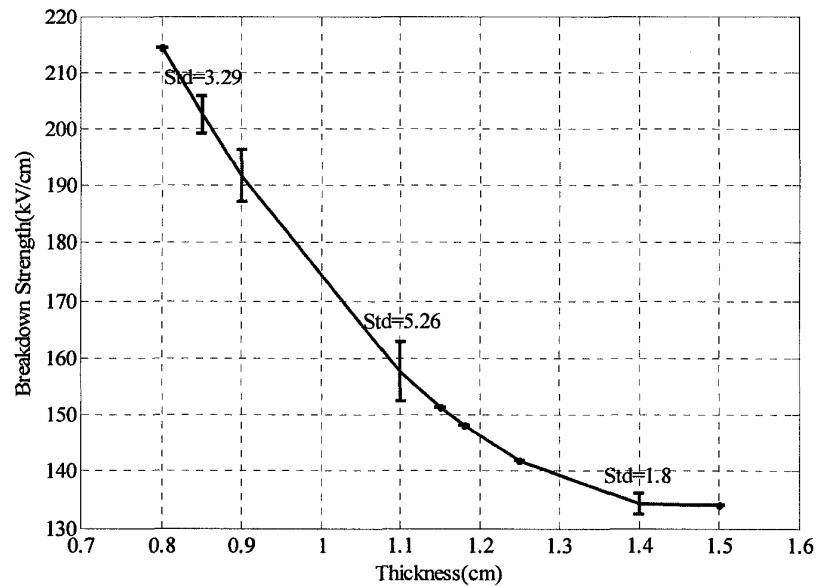


Fig. 53. The Lightning impulse Breakdown Strength versus Thickness of Foam II at 40°C

TABLE 31

LIGHTNING IMPULSE TEST RESULTS OF FOAM II AT 60°C

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
0.8	169.7	212.1
0.9	172.0	191.1
0.9	174.3	193.7
0.95	174.3	183.5
0.98	146.3	149.2
1	175.5	175.5
1	184.9	184.9
1	191.9	191.9
1.2	159.1	132.6
1.3	191.9	147.6
1.4	200.1	142.9
1.4	204.8	146.3
1.5	208.3	138.8

Average Lightning impulse Breakdown Strength at 60°C is calculated as 168.4 ± 26.2 kV/cm.

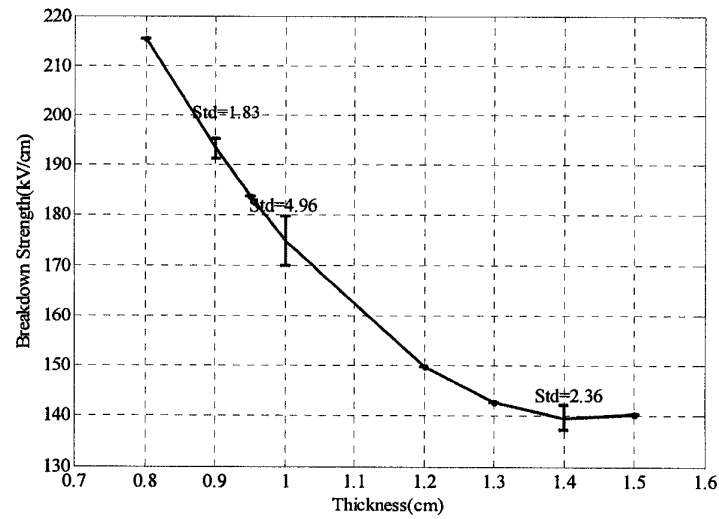


Fig. 54. The Lightning impulse Breakdown Strength versus Thickness of Foam II at 60°C

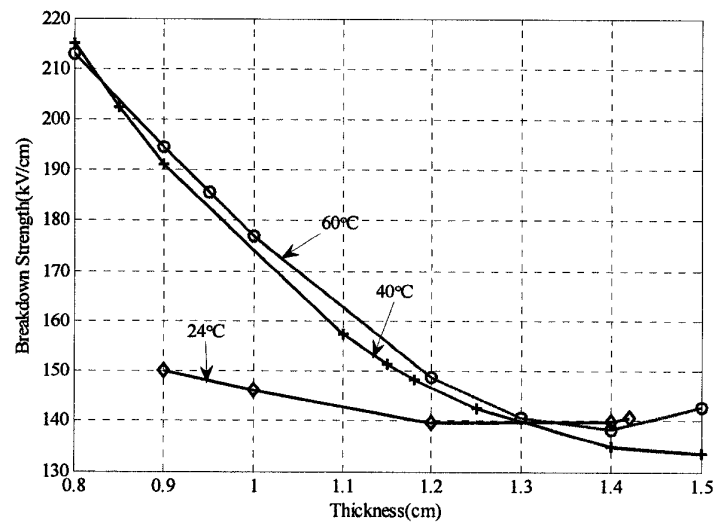


Fig. 55. The comparison of Lightning impulse Breakdown Strength versus Thickness of Foam II at 24 °C, 40°C and 60°C

It is obvious from the above figures and tables that there is nonlinearity between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes inside the foam. Results show that the breakdown strength is independent of temperature as the strength is highest for the medium temperature and lowest for the maximum temperature for the thickness range of 0.9 cm through 1.2 cm, but it is highest for minimum temperature and lowest for temperature level for the thickness range of 1.2 cm through 1.4 cm. The lightning impulse breakdown strength of Foam II is calculated as 158.3 ± 27.7 kV/cm.

VI. LIGHTNING IMPULSE TEST RESULTS OF FOAM III

A. Tests results under 36%RH and 80%RH

The result of the tests performed with Foam III under 36%RH and 80%RH are illustrated in the following Tables and Figures.

TABLE 32
LIGHTNING IMPULSE TEST RESULTS OF FOAM III AT 36%RH

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
0.9	146.3	162.5
1	150.9	150.9
1	165.0	165.0
1.2	165.0	137.5
1.2	174.3	145.3
1.25	194.2	155.4
1.25	204.8	163.8
1.25	204.8	163.8
1.25	204.8	163.8
1.3	209.4	161.1
1.3	210.6	162.0

Average Lightning impulse Breakdown Strength at 36%RH is calculated as
 157.3 ± 9.1 kV/cm

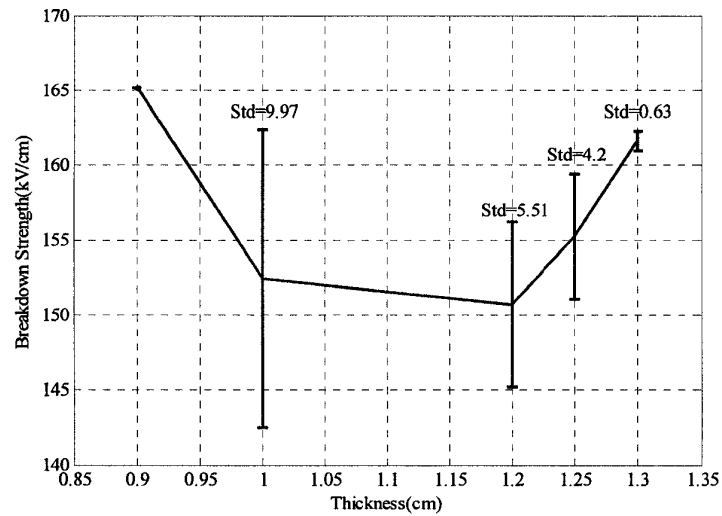


Fig. 56. The Lightning impulse Breakdown Strength versus Thickness of Foam III at
 36%RH

TABLE 33

LIGHTNING IMPULSE TEST RESULTS OF FOAM III AT 80%RH

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
1.2	172.0	143.3
1.2	180.2	150.2
1.2	188.4	157.0
1.2	193.1	160.9
1.25	175.5	140.4
1.25	187.2	149.8
1.4	184.9	132.0
1.4	188.4	134.6
1.5	180.2	120.1
1.53	155.6	101.7
1.55	177.8	114.7
1.55	177.8	114.7
1.58	179.0	113.3
1.6	183.7	114.8

Average Lightning impulse Breakdown Strength at 80%RH is calculated as 131.9 ± 18.8 kV/cm.

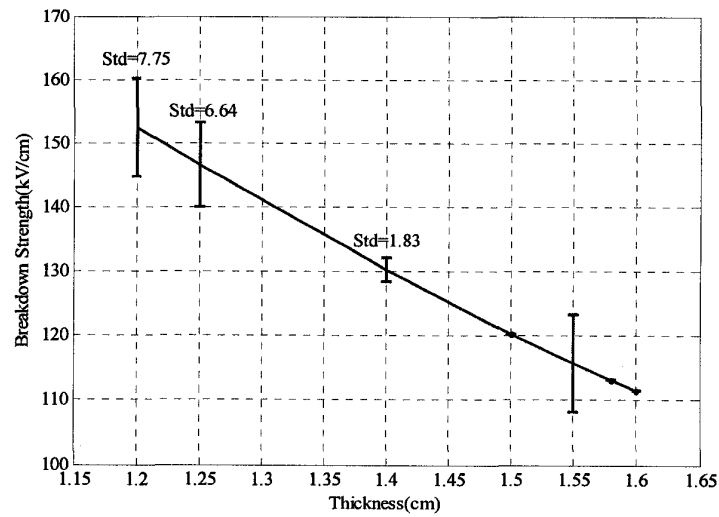


Fig. 57. The comparison of Breakdown Strength versus Thickness of Foam III at 80%RH

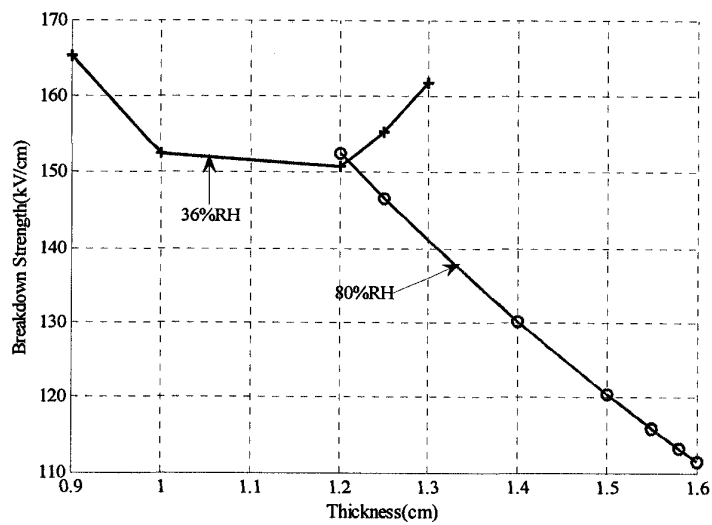


Fig. 58. The Lightning impulse Breakdown Strength versus Thickness of Foam III at 36%RH and 80%RH

Fig. 58 shows that there is not a linear relationship between the thickness of the samples and the breakdown voltage, due to non-uniform distribution of voids of different sizes inside the foam. Lightning impulse breakdown strength is calculated as 157.3 ± 9.1 kV/cm and 131.9 ± 18.8 kV/cm for 36%RH and 80%RH respectively. The strength decreases with increasing humidity level.

B. Tests results under 24°C and 40°C

The result of the tests performed with Foam III under 24°C and 40°C are illustrated in the following Tables and Figures.

TABLE 34
LIGHTNING IMPULSE TEST RESULTS OF FOAM III AT 24°C

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
0.9	146.3	162.5
1	150.9	150.9
1	165.0	165.0
1.2	165.0	137.5
1.2	174.3	145.3
1.25	194.2	155.4
1.25	204.8	163.8
1.25	204.8	163.8
1.25	204.8	163.8
1.3	209.4	161.1
1.3	210.6	162.0

Average Lightning impulse Breakdown Strength at 24°C is calculated as 157.3 ± 9.1 kV/cm.

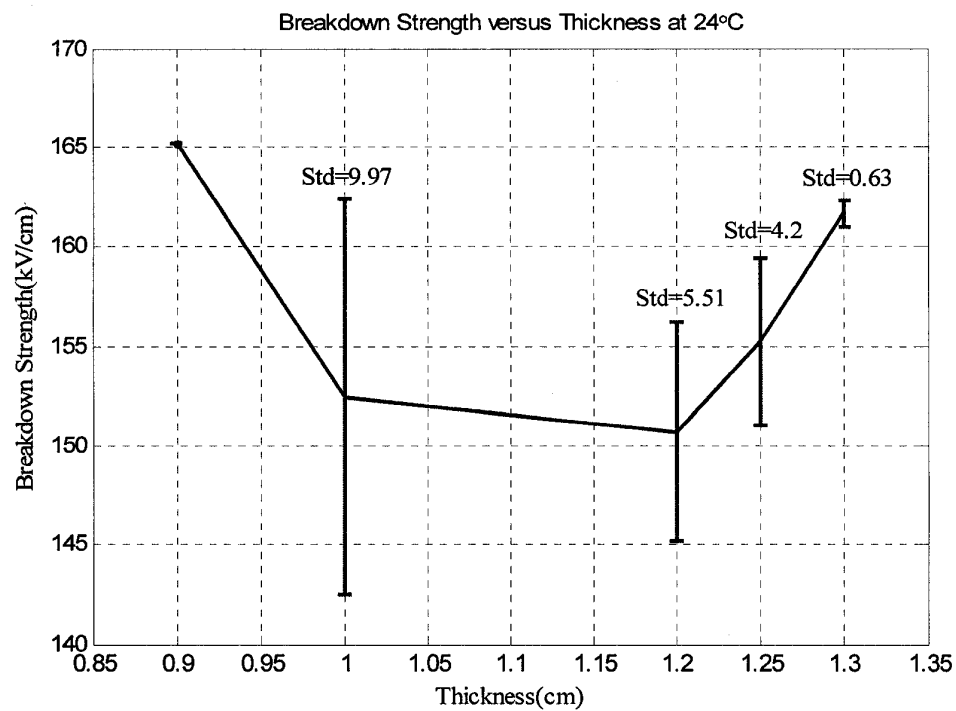


Fig. 59. The Lightning impulse Breakdown Strength versus Thickness of Foam III at
24°C

TABLE 35

LIGHTNING IMPULSE TEST RESULTS OF FOAM III AT 40°C

Thickness(cm)	Breakdown Voltage(kV)	Breakdown Strength(kV/cm)
0.8	165.6	206.9
1	167.3	167.3
1.3	176.7	135.9
1.3	193.1	148.5
1.4	194.2	138.7
1.4	173.7	124.1
1.5	207.7	138.5
1.5	209.4	139.6
1.55	207.7	134.0
1.55	210.6	135.9

Average Lightning impulse Breakdown Strength at 40°C is calculated as 146.9 ± 23.8 kV/cm.

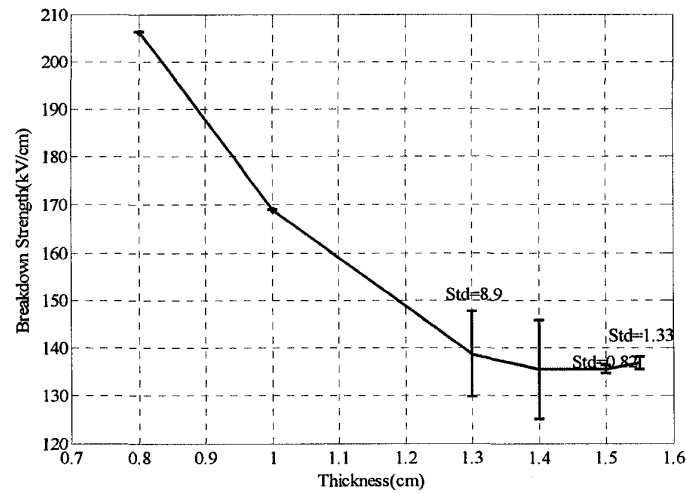


Fig. 60. The Lightning impulse Breakdown Strength versus Thickness of Foam III at 40°C

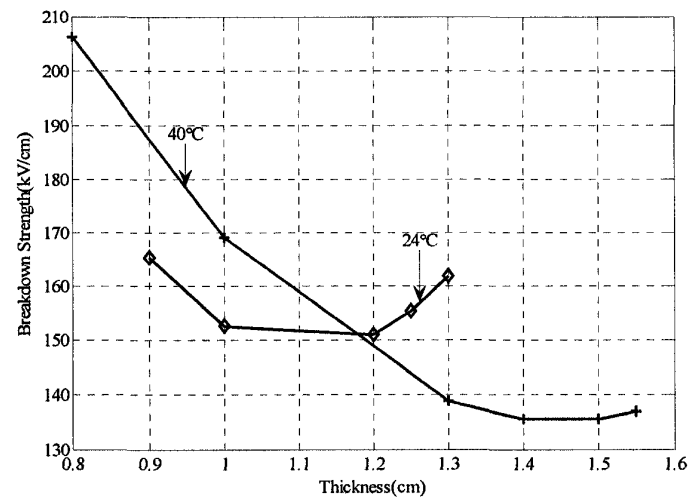


Fig. 61. The comparison of Lightning impulse Breakdown Strength versus Thickness of Foam III at 24°C and 40°C

Fig. 61 shows that the breakdown strength is independent of temperature as the strength is highest for the maximum temperature and lowest for the minimum temperature for the thickness range of 0.9 cm through 1.2 cm, but it is highest for minimum temperature and lowest for temperature level for the thickness range of 1.2 cm through 1.3 cm. The lightning impulse breakdown strength of Foam III is calculated as 154.3 ± 20.3 kV/cm.

VII. STATISTICAL EVALUATION OF THE TEST RESULTS

In general, the breakdown strength of solid insulation materials tends to decrease with increasing temperatures and humidity [32]. But, test results reveal that in some cases the strength decreases, while in other cases it increases. In addition, the standard deviation of the breakdown voltage is substantial. The study of void distribution presented before suggests that the voids have a major effect on the breakdown voltage [31], therefore it is concluded that the effect of humidity and temperature on the breakdown strength of polyurethane foam is small compared to the internal voids produced in variation of the breakdown voltage. Table 36 and Table 37 show the comparison of AC and lightning impulse test results.

TABLE 36
COMPARISON OF AC BREAKDOWN TEST RESULTS.

	AC breakdown strength (kV/cm)					
	Room temperature 24 °C			Room RH 30-36 %		
	36% RH	45% RH	80% RH	24 °C	40 °C	60 °C
Foam 1	36.5±6	53.2±2	55.9±7	37.0±1	54.6±6	44.6±6
Foam 2	39.2±7	45.5±3	35.3±6	39.2±7	40.3±8	40.3±5
Foam 3	NA	44.2±5	40±4.2	44.2±5	51.2±2	NA

TABLE 37
COMPARISON OF LIGHTNING IMPULSE TEST RESULTS

	Lightning impulse strength (kV/cm)					
	36% RH	45% RH	80% RH	24 °C	40 °C	60 °C
Foam 1	161.2±2	147.7±3	187.8±4	162.1±8	177.5±3	155.3±3
Foam 2	139.6±1	148.5±2	117.6±1	141±1	169.5±2	168.4±2
Foam 3	157.3±9	NA	131.9±1	162.3±8	146.9±2	NA

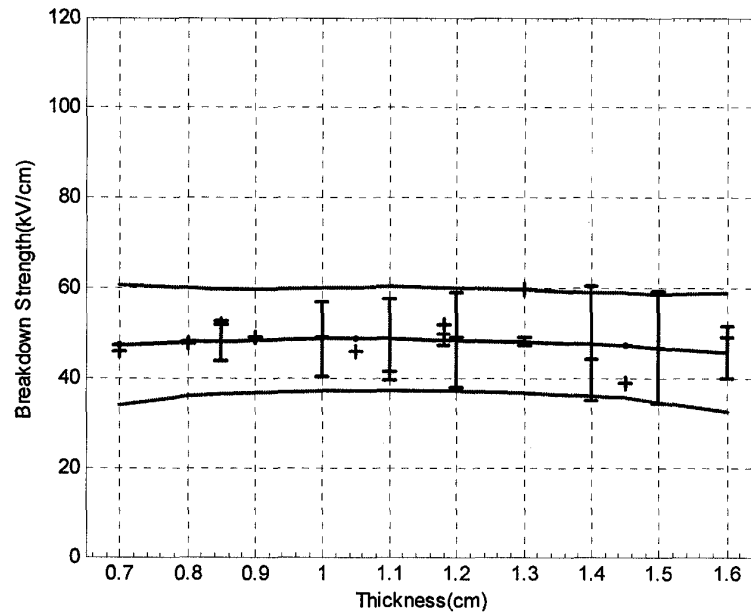


Fig. 62. AC breakdown strength versus thickness of Foam I.

As seen in Fig. 62, the average AC breakdown strength is calculated as 49.7 ± 9.8 kV/cm. The breakdown stress of air insulation, measured with the same arrangement, is 15 kV/cm. Hence, this foam breakdown stress is about 3 times higher than that of air. The Fig. 62 shows that the breakdown strength is practically independent from the thickness of Foam I, which possesses the thickness range of 0.7-1.6 cm.

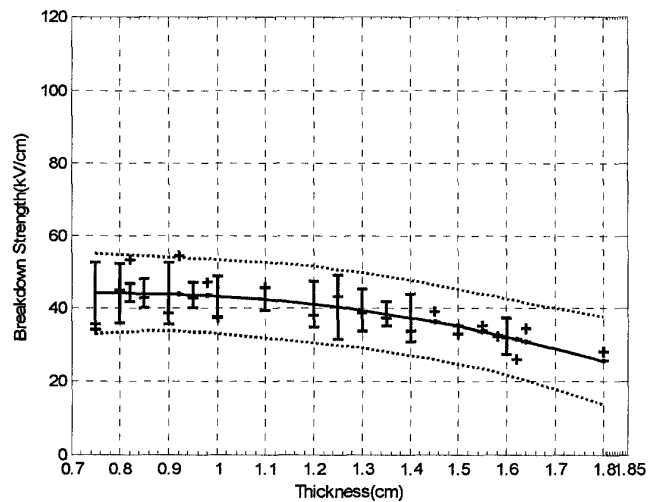


Fig. 63. The ac breakdown strength versus thickness of Foam II..

The breakdown strength decreases due to increasing thickness as shown in

Fig. 63. All data points are within the 95% confidence interval except one. The average ac breakdown strength is calculated as 39 ± 7.0 kV/cm. This foam breakdown stress is about 2.6 times higher than that of air.

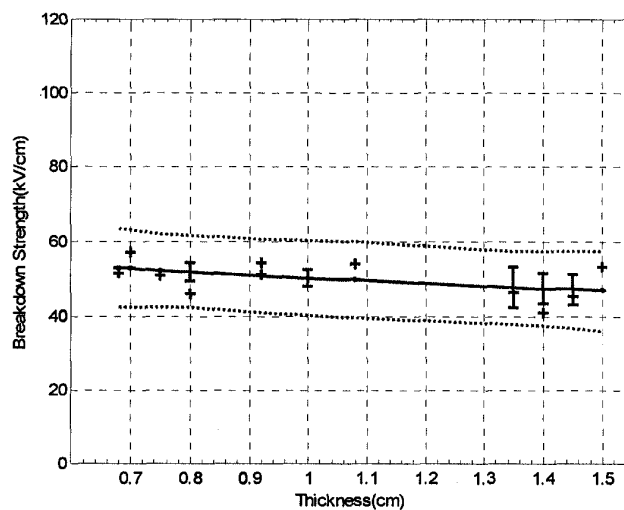


Fig. 64. AC breakdown strength versus thickness of Foam III.

As in Foam II, the breakdown strength of Foam III decreases due to increasing thickness, as seen in Fig. 64. All points are within the 95% confidence interval. The average ac breakdown strength is 44.7 ± 6.3 kV/cm. This foam breakdown stress is about three times higher than that of air. The standard deviation is much less than those found for Foam I and Foam II.

In Fig. 65., the lightning impulse breakdown strength of Foam I decreases rapidly with increasing thickness. All the data points are found to be within 95 % confidence interval.

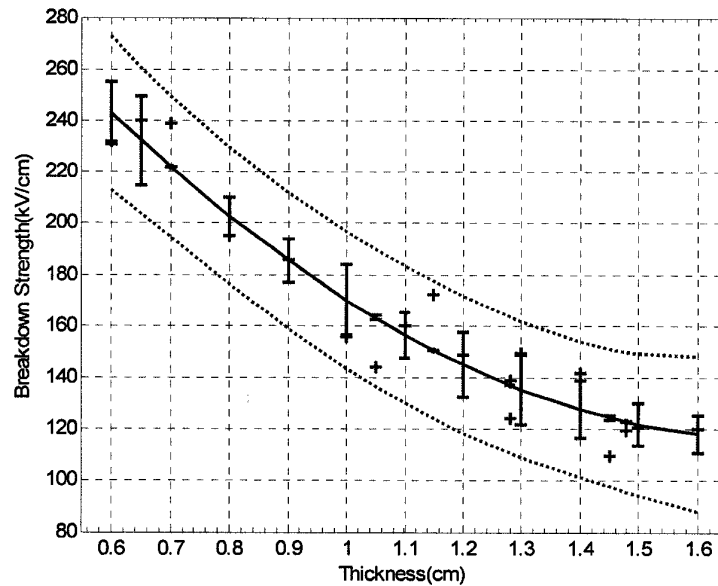


Fig. 65. Lightning impulse breakdown strength versus thickness of Foam I.

There are no outliers. The average lightning impulse breakdown strength is calculated as 166.2 ± 37.3 kV/cm. The breakdown stress of air insulation, measured with the same arrangement, is 55 kV/cm. This foam breakdown stress is about three times higher than that of air.

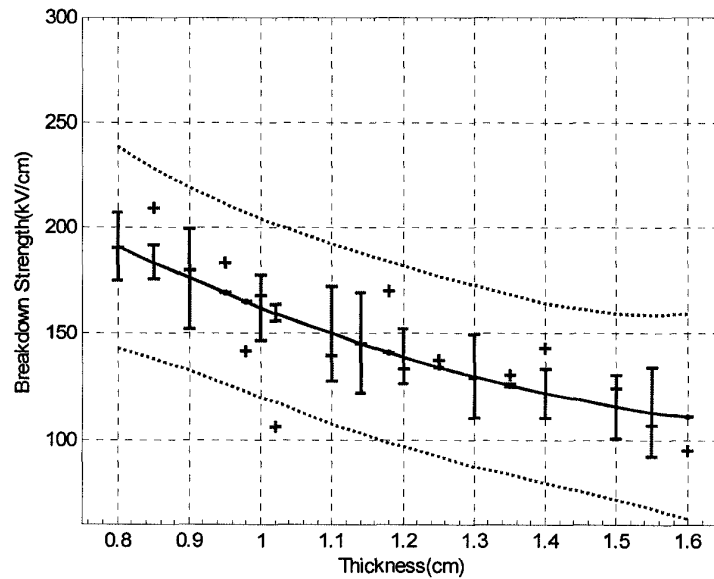


Fig. 66. Lightning impulse breakdown strength versus thickness of Foam II.

Fig. 66. shows that the lightning impulse breakdown strength of Foam 2 decreases with thickness. All data points are within the 95 % confidence interval except for one outlier. The average breakdown strength is 147.9 ± 28.8 kV/cm. This foam breakdown stress is about 2.7 times higher than that of air.

In Fig. 67, the lightning impulse breakdown strength of Foam III decreases rapidly with increasing thickness. All points are within the 95% confidence interval. The average lightning impulse breakdown strength is calculated as 144.2 ± 20.7 kV/cm. This foam breakdown stress is about 2.6 times higher than that of air. The standard deviation is much less than that of found for Foam I or Foam II, as in the ac test.

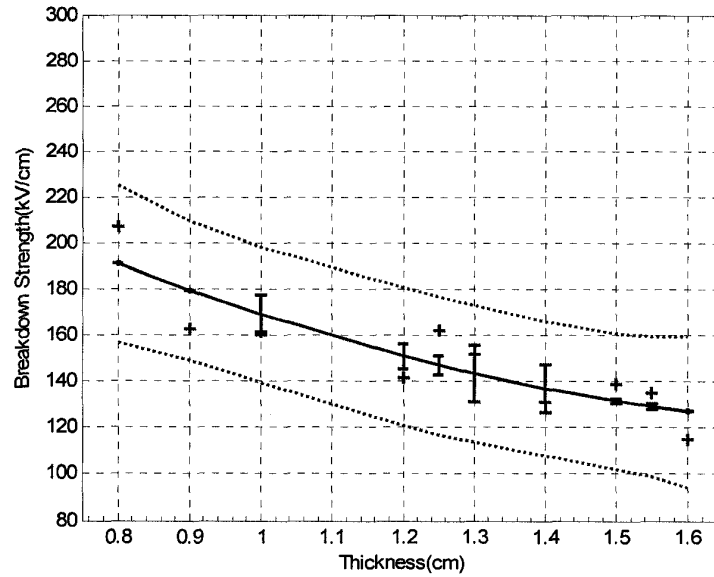


Fig. 67. The lightning impulse breakdown strength versus thickness of Foam III.

VIII. PERFORMANCE ANALYSIS OF FOAM I WITH PAPER TUBES

The insulation of hollow insulation system was modeled by foam filled tubes. Foam I was selected to be used inside the tube. The performance of the foam filled tube was investigated with three tests to determine the quality and limit of the insulation. The AC withstand test for short term, lightning impulse withstand test and partial discharge tests were conducted.

A. AC breakdown test for short term and Partial discharge test

The foam filled tube was energized to various, sequentially increasing, voltage levels, and the partial discharge was measured at each voltage level while voltage was maintained for three minutes. Measurement results are given in Table 38.

TABLE 38
TEST RESULTS FOR AC BREAKDOWN AND PD MEASUREMENTS OF FOAM I

Voltage(kV)	Duration(seconds)	Partial Discharge (pC)
10	180	1.4
20	180	2.1
30	180	1.8
40	180	1.5
50	180	2.5
60	180	2.6 to 5
70	180	5.5 to 6.2
80	180	6.2 to 7.5
90	180	8.2 to 9.7
100	180	19 to 26
110	180	21 to 32
120	180	31 to 65
130	180	55 to 78
140	180	58 to 102

The sample survived up to 140 kV AC rms for over three minutes. This is sufficient AC withstand for a 69kV class device according to IEC and IEEE. The numbers measured for partial discharge also conform to IEC requirements when using this insulator as a 69kV class device.

B. Lightning Impulse Test

AC withstand capability of the foam insulator appeared to be quite good for 69 kV class use, but the Basic Insulation Level (BIL) capability for 69 kV performance has not been established yet.

Lightning impulse tests were conducted under both polarities Therefore; lightning impulse tests were conducted under both polarities to determine BIL capability. Results are given in Table 39 to Table 43.

TABLE 39
TEST RESULTS OF FOAM I AT 150 kV BIL

Positive polarity			
Impulse #	Peak voltage (kV)	WaveForm(μ s/ μ s)	Comment
-	+98	0.96/50	Passed
1	+150	0.92/47	Passed
10	+149		Passed
15	+149	0.934/47	Passed
Negative polarity			
1	-147	0.92/47	passed

TABLE 40
TEST RESULTS OF FOAM I AT 180 kV BIL OF FOAM I

Positive polarity			
Impulse #	Peak voltage (kV)	WaveForm(μ s/ μ s)	Comment
1	+181	0.92/47	Passed
7	+181	0.92/47	Passed
15	+180	0.92/47	Passed
Negative polarity			
1	-182		Passed
4	-178.2	0.89/47	Passed
10	-181	0.93/47	Passed
15	-181	0.89/47	Passed

TABLE 41
TEST RESULTS OF FOAM I AT 250 kV BIL

Positive polarity			
Impulse #	Peak voltage (kV)	WaveForm(μ s/ μ s)	Comment
1	251.7	0.91/48	Passed
5	251	0.90/48	Passed
12	252	0.92/48	Passed
15	252	0.90/48	Passed

TABLE 42
TEST RESULTS OF FOAM I AT 325 kV BIL

Positive polarity			
Impulse #	Peak voltage (kV)	WaveForm(μ s/ μ s)	Comment
1	325	0.91/48	Passed
6	327	0.89/47	Passed
10	326	0.92/47	Passed
15	324	0.89/49	Passed

TABLE 43
TEST RESULTS OF FOAM I AT 350 kV BIL

Positive Polarity			
Impulse #	Peak voltage (kV)	WaveForm(μ s/ μ s)	Comment
2	344	0.88/49	Passed
3	350	0.90/49	Passed
6	348	0.89/49	Passed
12	349	0.90/49	Passed
15	354	0.90/49	Passed
Negative Polarity			
1	-325	0.9/48	Passed
2	-359.7	0.89/1.84	Internal flashover
3	-201.9	0.89/1.56	Internal flashover

Results show that the foam insulation passed all the lightning impulse tests up to 350 kV BIL, but there occurred internal flashover at negative polarity of 350 kV BIL therefore, BIL level does not satisfy the 69 kV class design requirements.

The effect of repeated lightning impulse on the foam filled tube was also investigated. The tube was tested with 600 pulses at 120 kV (positive polarity) with ten second intervals between consecutive pulses. No internal flashover occurred after applying these repeated impulses. After the lightning impulse test, the foam filled tube was opened and polyurethane foam between the two electrodes were cut and investigated with SEM (Scanning Electron Microscopy). It was seen that no discharge path occurred inside the foam. Fig. 68 shows the SEM picture of a portion of the polyurethane foam between the two electrodes.



Fig. 68. SEM picture of the polyurethane foam between the two electrodes

CHAPTER 5

A NOVEL HYPOTHESIS DEVELOPED TO DESCRIBE THE BREAKDOWN MECHANISM OF POLYURETHANE FOAM

In this chapter, first the critical parameters affecting the breakdown strength of polyurethane foam including void size, void distribution, void density, partial discharges, humidity and temperature were studied. The effects of these parameters were discussed and a hypothesis that explains the breakdown mechanism of polyurethane foam was developed and presented. A computer program that shows the breakdown mechanism was developed with COMSOL Multiphysics Program. Simulations were conducted to see the movement of the discharges and to observe the avalanche process. Also, simulation helped to examine the effects of void sizes and the void density on the breakdown voltage. In addition, simulations enabled to verify the experiment results and to demonstrate the proposed hypothesis. Computer program results were discussed and a correlation was made between the experiments and the COMSOL Multiphysics Program.

I. PARAMETERS AFFECTING THE BREAKDOWN STRENGTH

A. Determination of the void distribution

The previous study indicated that the electrical property of the foam depends on the void size and distribution [29]. These properties of the foams were analyzed by preparing ten cross-cut samples from each of the foams (total thirty cross-cuts) and scanning the samples using an Environmental Scanning Electron Microscope (ESEM). A cross-section was taken from each cross-cut (ten cross-sections for each type of foam). Fig. 69, Fig. 70 and Fig. 71 show sample ESEM cross-section images for each type of foam. As seen in these images, voids have circular shapes and there exists solid parts

between the voids. Six diameter measurements in each cross-section were conducted with a ruler. Totally sixty measurements were conducted for each type of foam. Then average diameter size and standard deviation were calculated for each foam type and given in Table 44. Fig. 69, Fig. 70 and Fig. 71 show the measurements of one cross-section.

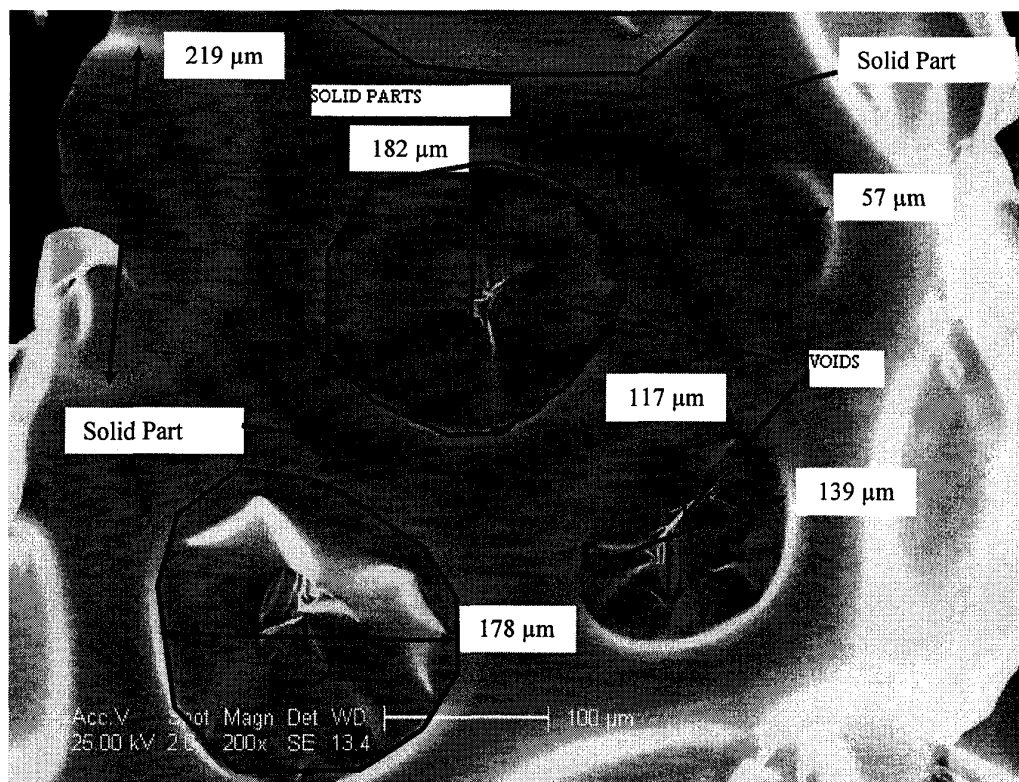


Fig. 69. Void distribution in Foam 1

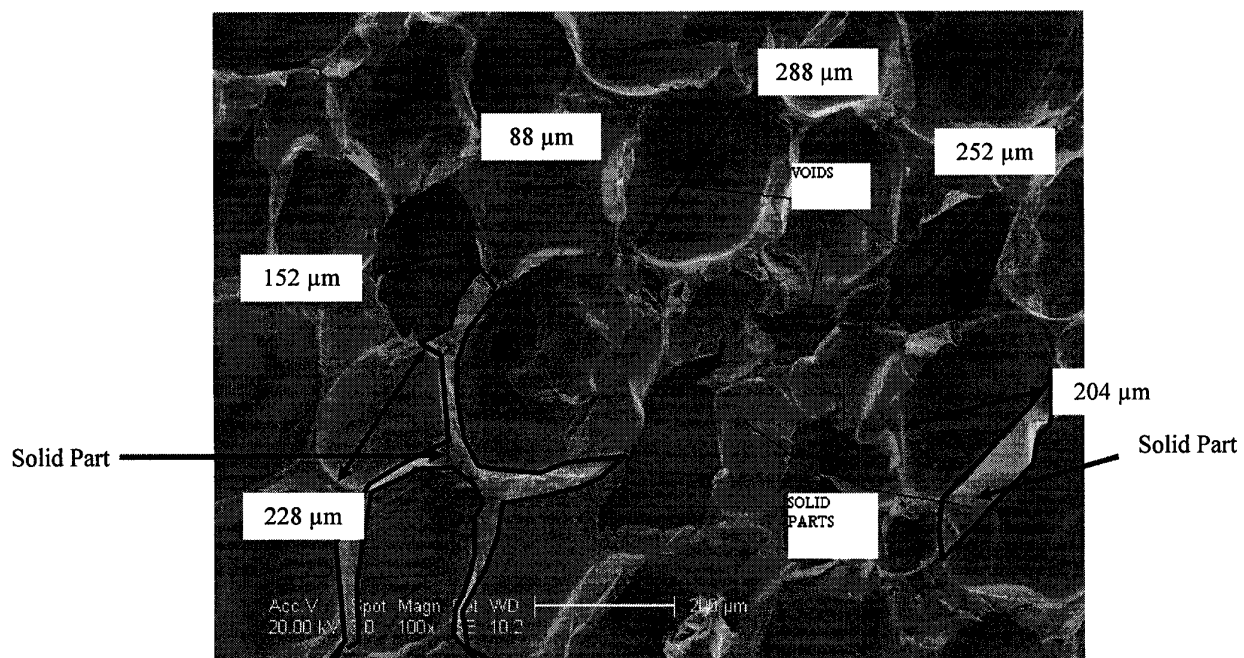


Fig. 70. Void distribution in Foam 2

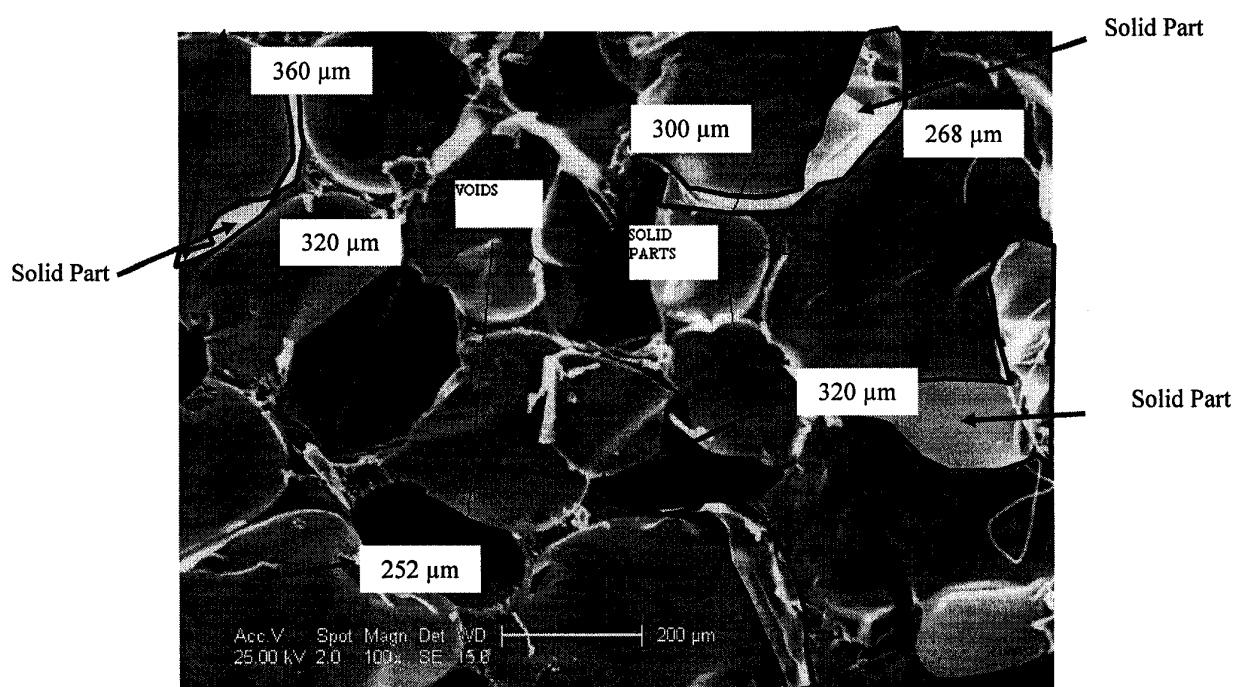


Fig. 71. Void distribution in Foam 3

This ESEM investigation indicates that the size and the distribution of the voids inside the polyurethane foam are not homogeneous [29, 30, and 31]. In order to find the void ratio in a cross-section, area of voids in that cross-section was calculated by using void diameters and divided by area of rectangular cross-section. This procedure was conducted for each cross-section and void ratio was calculated by taking the average.

Density of three types of foam was calculated as the following. Twenty small cubical shaped pieces were cut from each foam type. Then the weight and the volume of each piece were measured and the weight over volume ratio was calculated for each piece, with the average was taken to find the density of each foam. Table 44 reveals the results of ESEM investigation and the foam densities.

TABLE 44
AVERAGE SIZE AND DISTRIBUTION OF VOIDS

Type	Avg. diameter in μm	void ratio (%)	Foam Density gr/cm^3
Foam 1	130 ± 15	50	0.13-0.14
Foam 2	200 ± 8	90	0.10-0.11
Foam 3	210 ± 25	70	0.125-0.13

B. Partial Discharges

Different types of partial discharges are presented in Chapter 3; internal discharges, surface discharges, corona discharges and discharges in electrical trees. Discharges in electrical trees and internal discharges have significance in leading to electrical breakdown of polymeric insulation systems. Localized degradation referred to as electrical treeing due to defects and voids in the insulation occurs at stress enhancements when subjected to high electrical stresses [32]. Fig. 11 shows electrical treeing. After the progression of trees for some time, the stem and the larger branches

grow hollow causing considerable discharges. These discharges are very stable and no detectable discharges are seen for a long time, but when the treeing sets in, discharges become visible and grow rapidly that they may cause breakdown in an extremely short period.

Internal discharges occur in inclusions of low dielectric strength like gas-filled voids. Hence, voids are one of the weakest points in solid insulations. ESEM results show that all three types of polyurethane foams have significant amount of voids. Discharges in voids are expected to form electrical trees, progress in time and finally leads to electrical breakdown of the material. However, that is quite different for polyurethane foam insulation. The effect of discharges on polyurethane foam was studied under AC voltages with 61.0 cm long foam filled tubes which has 20.3 cm diameter. The electrode distance was 15 cm. The discharges were in the range of 2-3 pC under 70 kV constant voltage for a period of 168 hours and the discharges were in the range of 6 pC to 7pC at 90 kV. This indicates that there were almost no discharges at these voltages. The dramatic increase of discharges was only seen immediately before breakdown. Breakdown happens all of a sudden and it was not the result of progress of discharges.

C. Temperature effect

It is believed that temperature does not affect the breakdown stress of gases in the 20°C ~ 100°C range. However, an increase in temperature may decrease the breakdown stress of the solid part of the foam. ESEM investigation revealed that voids composed of gases occupy 50%, 90%, and 70% of Foam 1, Foam 2, and Foam 3, respectively.

Therefore, if discharges that lead to breakdown of the insulation initiates in the voids and the temperature have limited effect on the breakdown stress of gases there, then the temperature effects on the foam breakdown voltage should be very small.

D. Humidity effect

Exposure to high humidity may produce water penetration in the solid insulation. As the amount of water penetration increases, breakdown voltage decreases. Tests were performed and the weight increase due to humidity exposure was measured [29]. It was determined that exposure to 100% RH increases the sample weight by only 0.05% if the sample has skin and 2% if the sample has no skin. These findings verify that humidity must have only a small or negligible effect on the foam breakdown voltage of polyurethane foam insulation.

II. ELECTRICAL BREAKDOWN HYPOTHESIS

The ESEM investigation of polyurethane foam revealed that the foam materials consist of voids surrounded by solid particles. Discharges initially take place in voids because of their lower permittivity with respect to solid parts; consequently the electric field is higher in the voids than in the solid part of the foam [9-12]. As also shown in Table 44, the amount of void is very high in polyurethane foam samples, therefore voids play the most crucial function in the electrical breakdown mechanism.

The investigations also show that the temperature and humidity has insignificant effect on the voids, hence their effects can be neglected in establishing the breakdown mechanism. The partial discharge measurements indicate that partial discharges were low prior to the breakdown during the voltage increase. The dramatic increase of discharges

is only seen immediately before breakdown. AC and lightning impulse breakdown results and ESEM investigations revealed that the foam breakdown stress depends on the void size, void density and void distribution.

In addition, cursory electric field calculations were conducted to see the electric field distribution in voids and solid parts. COMSOL Multiphysics Program was used. The model geometry is 2D. A rectangle was divided into 24 equal parts including three voids and twenty-one solid parts. Relative permittivities were taken as 1 and 5 for voids and solid parts respectively. Boundary conditions are given in Fig. 72. 10 kV was applied and the electric field distribution along the model was calculated and given in Fig. 73.

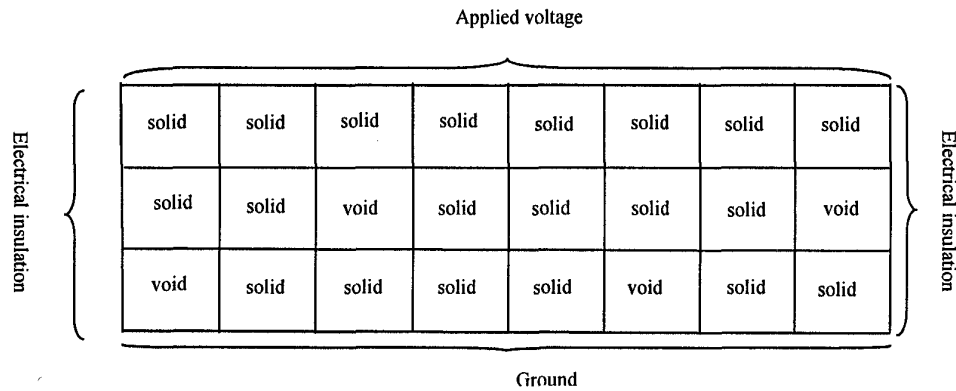


Fig. 72. Boundary conditions

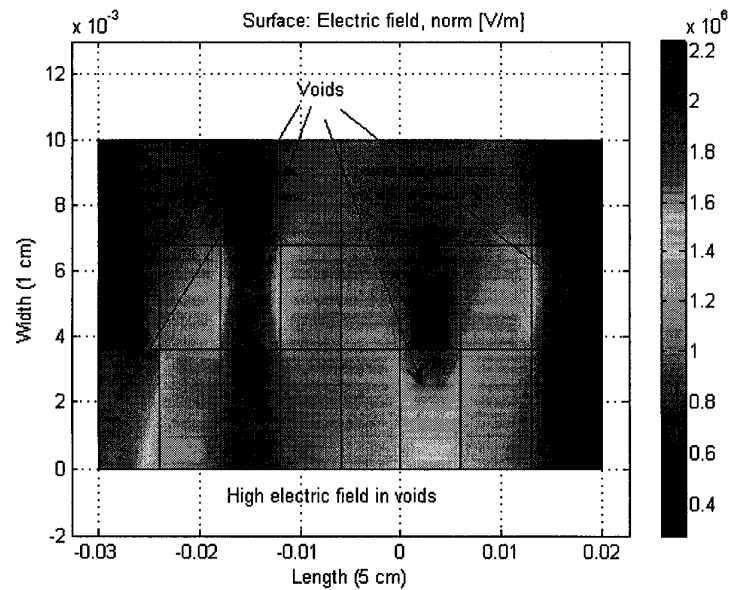


Fig. 73. Electric Field distribution in the sample

In order to see the electric field in voids and solid parts, cross-section plot was obtained between A ($x_0 = -0.03$, $y_0 = 0.0045$) and B ($x_1 = 0.02$, $y_1 = 0.0045$) coordinates.

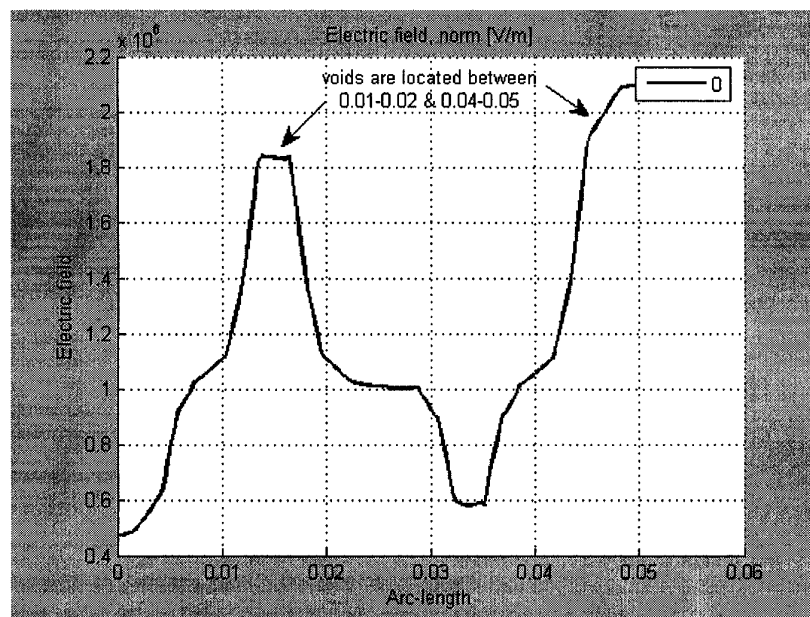


Fig. 74. Electric field distributions along the cross-section

The electric field values are given in Fig. 74. COMSOL codes are given in Appendix A. This clearly shows that the electric field is higher in the voids than in the solid part of the foam.

All of these findings lead to the following breakdown hypothesis.

The increase in voltage generates discharges first in the voids. The electric field strength required to initiate these discharges is 30 kV/cm. Therefore, there exists discharges in voids in which the electric field strength is greater than 30 kV/cm. These voids are then filled with conducting ions which increases the conductivity (σ). The increased conductivity (σ) in these voids provides conducting bridge across voids and leads to voltage increase across the solid parts surrounding them. The voltage increase across the solid parts further increases the electric field. Higher electric fields lead to more discharges in other voids and create secondary conducting bridges across them. This further increases the electric field across the other solid particles. The continuation of this process ultimately leads to an electric breakdown of the material. As partial discharge experiments show, discharge values are low before breakdown and tend to increase dramatically immediately before breakdown. This suddenly increases the electric field and produces an avalanche breakdown. The avalanche process ends very fast since it is of the order of nanoseconds. Therefore, if the necessary electric field strength has not been achieved, an avalanche will not occur.

III. SIMULATION OF BREAKDOWN MECHANISM WITH COMSOL PROGRAM

The breakdown mechanism of polyurethane foam is modeled with COMSOL Multiphysics program. COMSOL is software designed to solve complex multiphysics

problems using finite element method techniques. In this study, electromagnetic toolbox of the software is utilized in order to model the breakdown mechanism.

A. Model Geometry and Flow Chart

The model contains a two-dimensional time dependent COMSOL model which is controlled from a MATLAB script. Appendix B includes the MATLAB codes used in the program. In real applications, the electric field distribution should be modeled with 3D, but due to computer memory limitations 2D model geometry is used. Boundary conditions and cell types for the model geometry are given in Fig. 75 and Fig. 76 respectively. Sample has rectangle shape geometry of 1 cm width and 5 cm length. This rectangle shape model is divided into different number of rows and columns to get different sizes of cells. Cells consist of voids and solid parts. The model presented in Fig. 75 and Fig. 76 has 750 cells and includes 25 rows and 30 columns. The void density is 10%.

In order to perform the modeling, certain properties of foam should be determined. The relative permittivity of the solid part of the foam was found via impedance spectroscopy. Ten small cubic samples were cut and squeezed to smaller cubical volumes in order to release the gases inside the voids. Thus the measured permittivity would only be the solid part of the polyurethane foam. Then the permittivity was measured for all samples by the impedance spectroscopy, and an average was found to be 5.5. Voids' relative permittivity is taken as one(1), since they are composed of gases and most gases have relative permittivity of one(1). $E_{\text{threshold}}$ is chosen as 30 kV/cm and

40 kV/cm for voids and solid parts respectively. Flow chart of a model that finds the breakdown voltage is given in Fig. 77.

The program works as follows.

Step 1: Draw the model geometry for the related number of rows and columns, create meshes for the geometry and set the boundary conditions. Then, define parameters of void and solid parts.

Step 2: Define void density of the geometry and generate voids randomly based on the void density.

Step 3: Calculate the electric field distribution on all cells.

Step 4: If the electric field is not greater than any of the cells' threshold electric field, increase the voltage and go back to Step 3.

Step 5: If the electric field is greater than the threshold electric field, increase the conductivity of voids and solid parts to $5.99e^7$.

Step 6: Check the geometry to see if there exists a breakdown path from top electrode to the bottom electrode. If there is a path, stop the program and show the breakdown voltage. If there is no path, go back to Step 3.

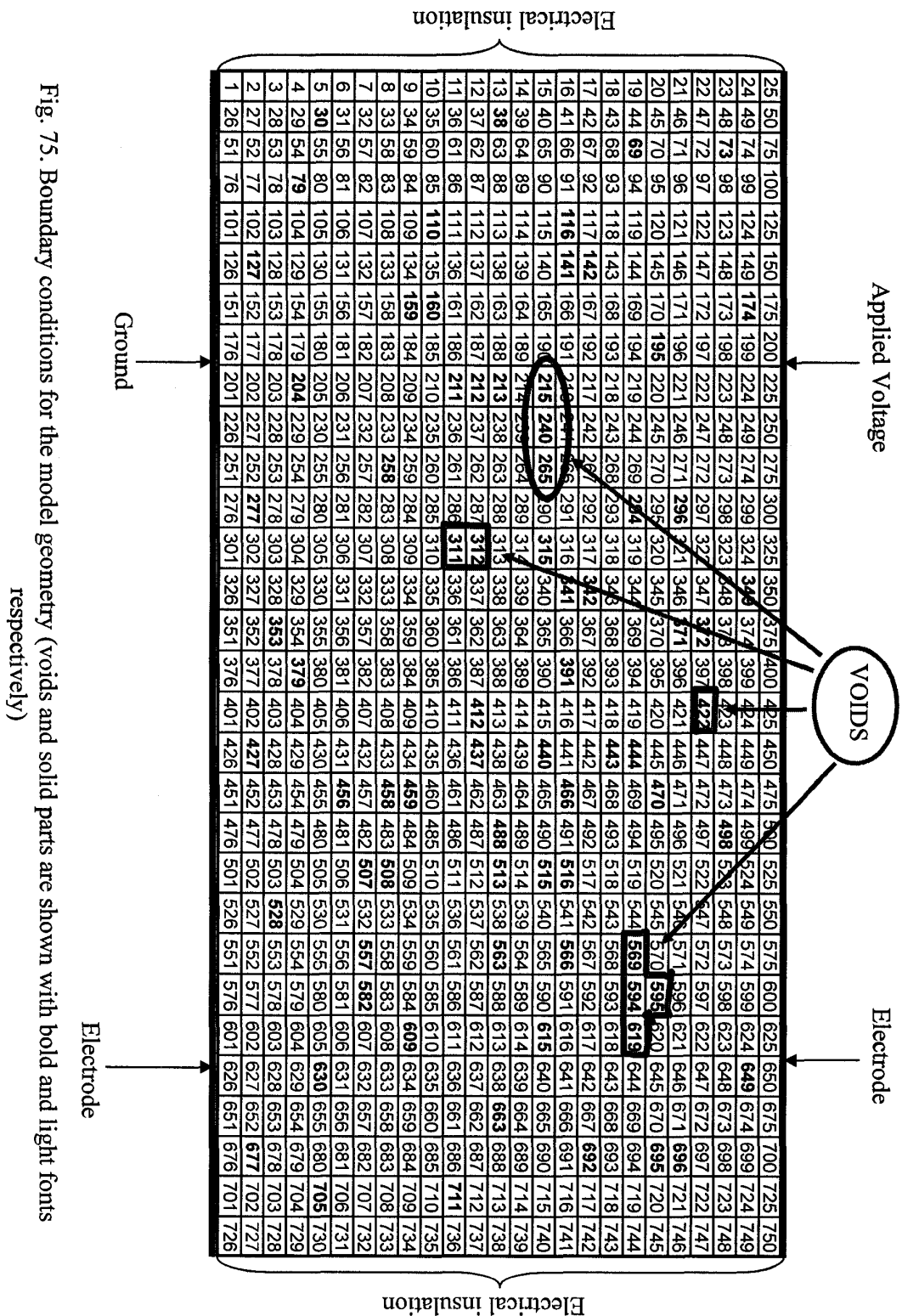


Fig. 75. Boundary conditions for the model geometry (voids and solid parts are shown with bold and light fonts respectively)

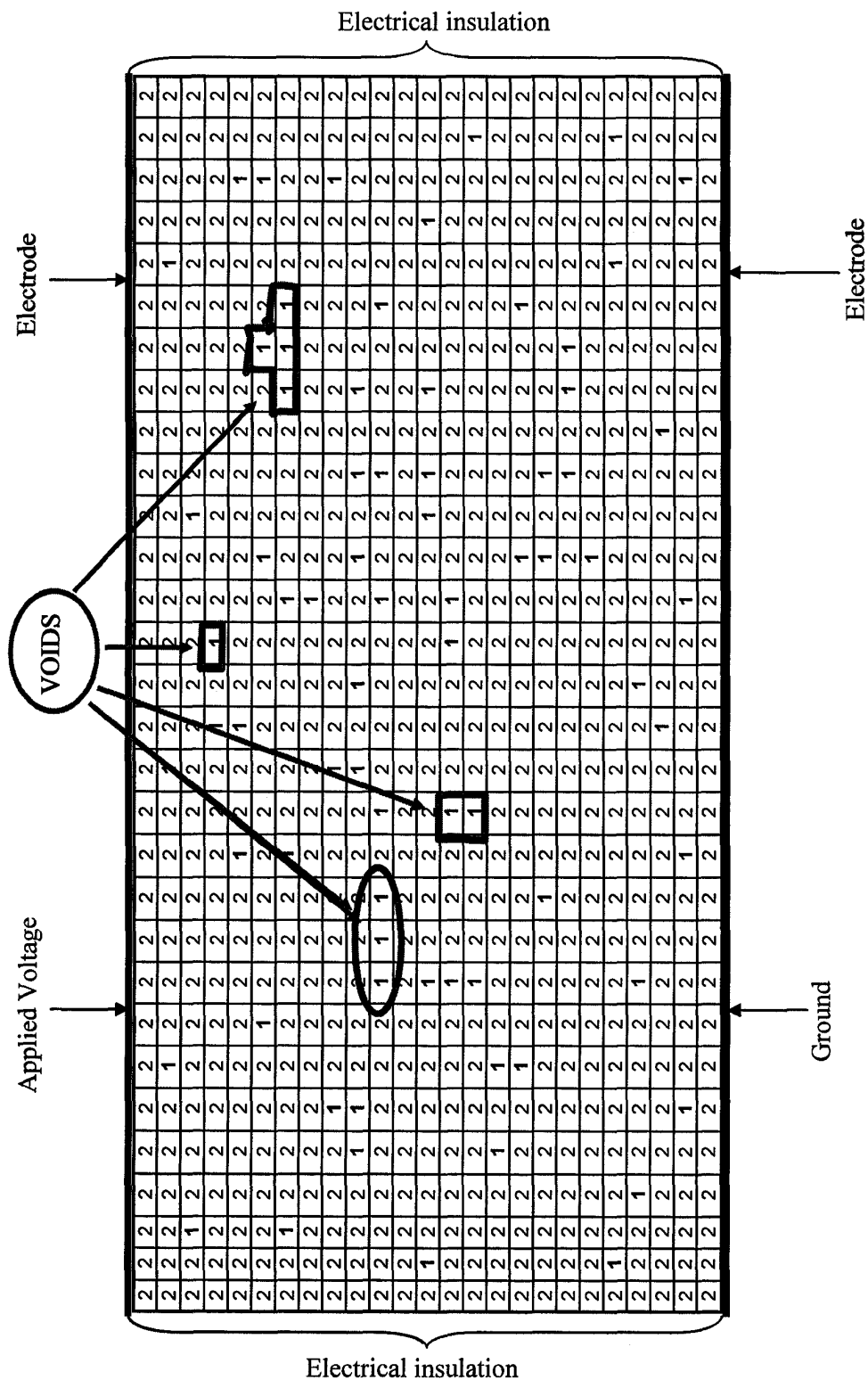


Fig. 76. Type of cells (1 for voids and 2 for solid parts)

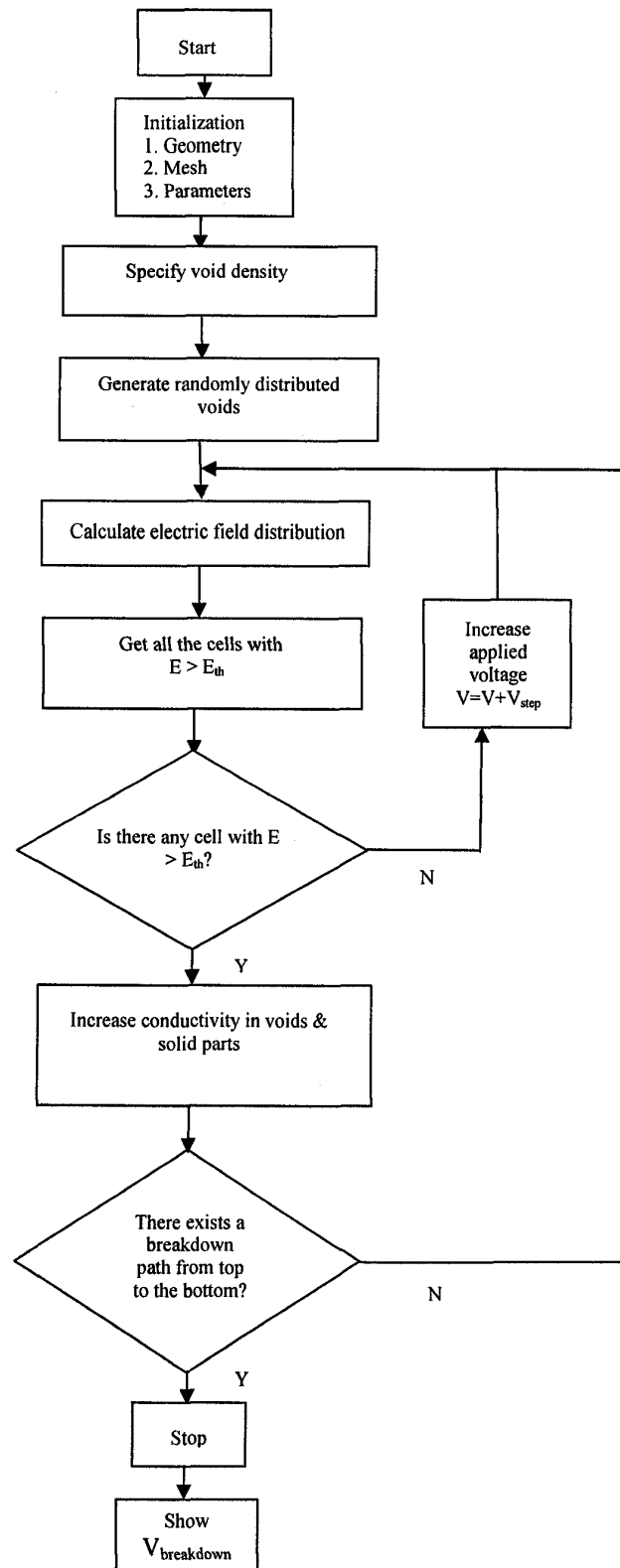


Fig. 77. Flow chart of the model that demonstrates avalanche breakdown mechanism.

IV. SIMULATION RESULTS

Simulations were performed to demonstrate the avalanche breakdown mechanism explained in the hypothesis. In addition, the effect of void density and void sizes were also studied. At last, correlation was made between the experiments and the simulations.

A. Avalanche breakdown mechanism

Geometry model shown in Fig. 75 and Fig. 76 is chosen to demonstrate the avalanche breakdown mechanism in polyurethane foam insulation. 10% void density was considered in simulations. In the first simulation, voltage was gradually increased until breakdown. 17.09 kV was found to be the breakdown voltage of the insulation. Then 17.09 kV was directly applied to see the flashover mechanism in the insulation.

Appendix C gives simulation results that show the cell list broken in each iteration. Fig. 78 through Fig.84 demonstrates the avalanche formation.

In the 1st iteration, the electric field was calculated and the conductivity of the cells having an electric field value of greater than the threshold electric field value was increased to $5.99e^7$ for voids and solid parts and those cells were assumed to be broken. Then, the program recalculated the electric field in each unbroken cell after every iteration and compared with threshold values and increased the conductivities of the broken cells to $5.99e^7$.

In the 1st iteration, total number of 81 cells including all 75 voids and 6 solid parts were broken. Conductivities were increased to set value. Fig. 78 illustrates the avalanche formation in the 1st iteration. Dark cells show broken cells.

In the 2nd iteration, electric field was recalculated and the program checked all cells to see if there were any more breakdowns. As seen in Fig. 79 only four solid parts were broken, therefore their conductivities were increased to $5.99e^7$. Light cells show broken cells in the previous iteration and dark cells show broken cells in this iteration.

Fig. 80 shows the avalanche formation in the 3rd iteration. After recalculating the electric fields, it was seen that as in the 2nd iteration, only four solid parts, cell numbers 348,373,435 and 490, were broken. Conductivities were increased to $5.99e^7$.

In the 4th iteration, five more solid parts were broken and the conductivities were increased to $5.99e^7$. Fig. 81 shows the avalanche formation in this iteration.

More cells tend to breakdown as the iteration number increases. Seven solid parts were broken and the conductivities were increased to $5.99e^7$ in the 5th iteration. Fig. 82 illustrates the avalanche formation in this iteration.

In the 6th iteration, 17 solid parts were broken. As the number of iteration increased and close to breakdown, electric field reached to higher values and more number of solid parts breakdown occurred as given in Appendix C. Fig. 83 illustrates the avalanche formation in this iteration.

Twenty five more solid parts were broken and the entire breakdown accomplished in the 7th iteration. Fig.84 shows the final avalanche formation in the last iteration.

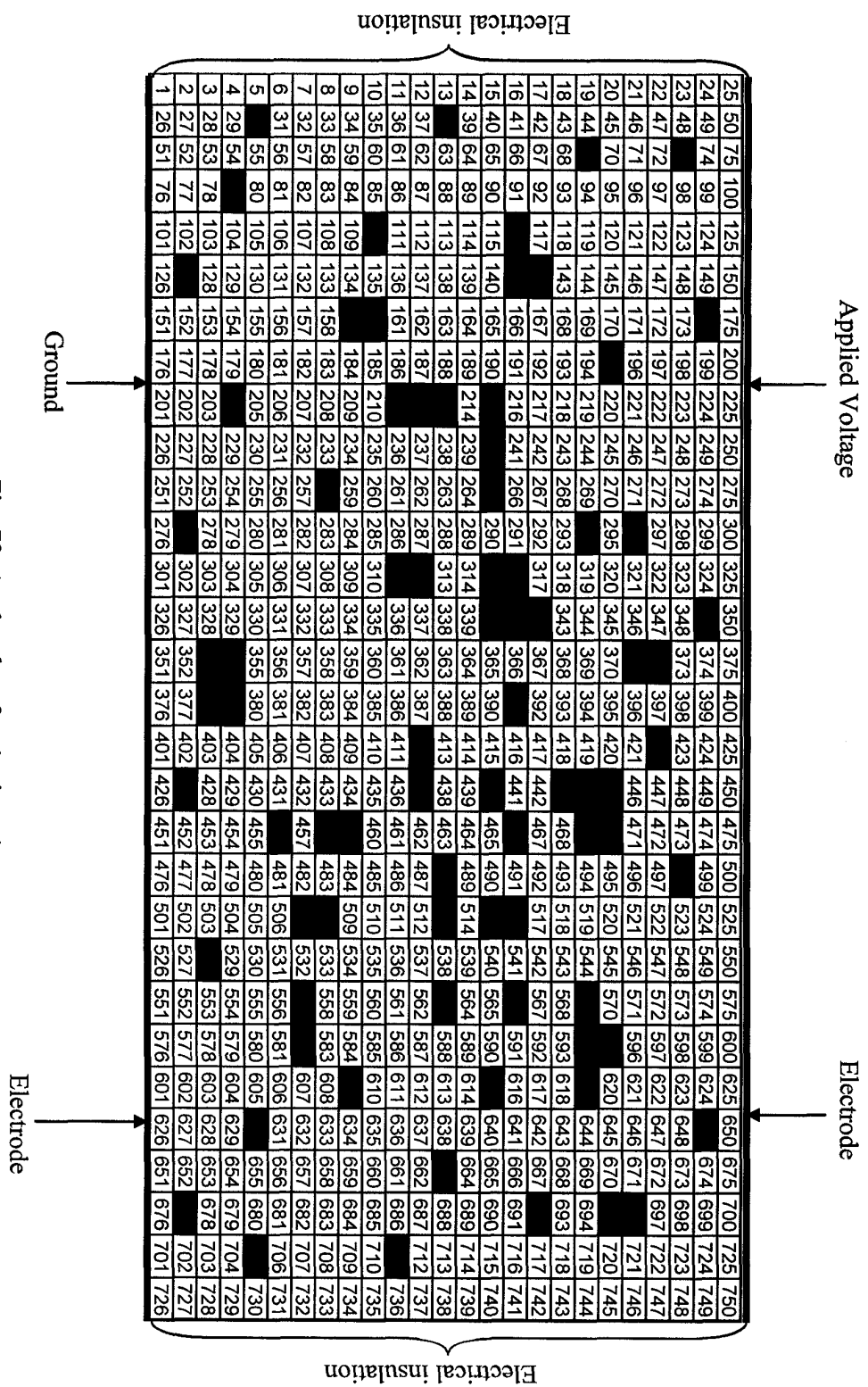
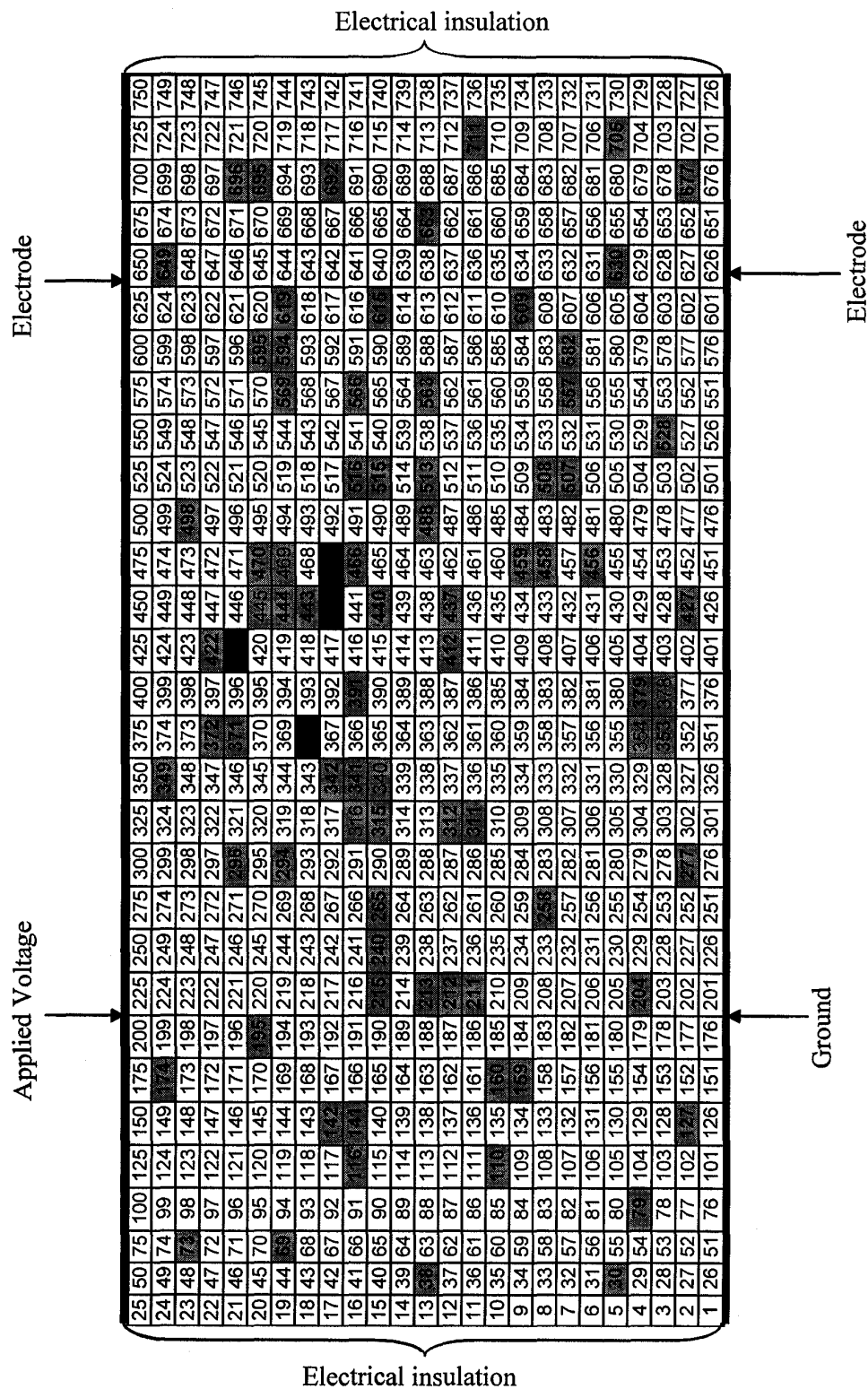
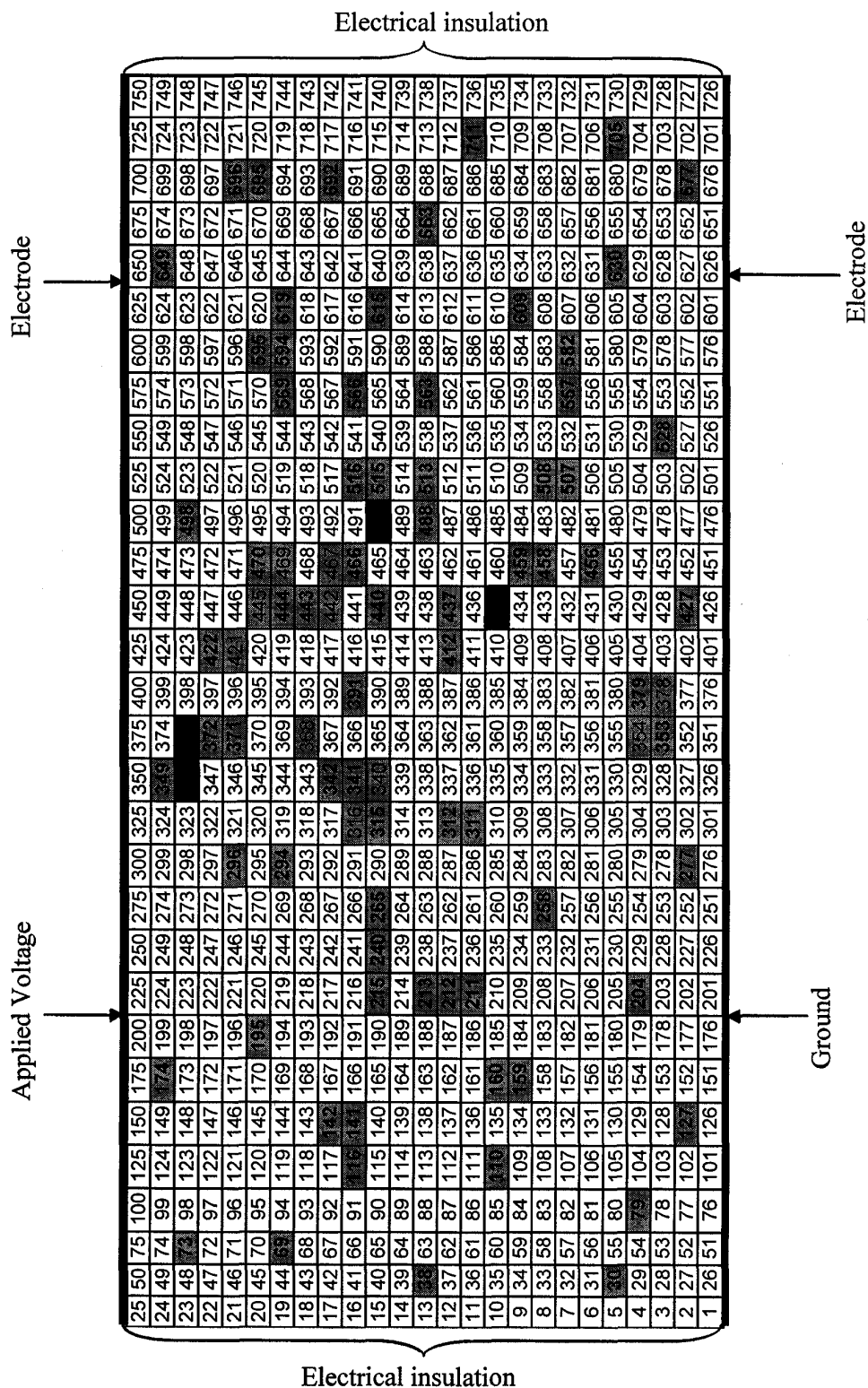


Fig. 78. Avalanche after 1st iteration

Fig. 79. Avalanche after 2nd iteration

Fig. 80. Avalanche after 3rd iteration

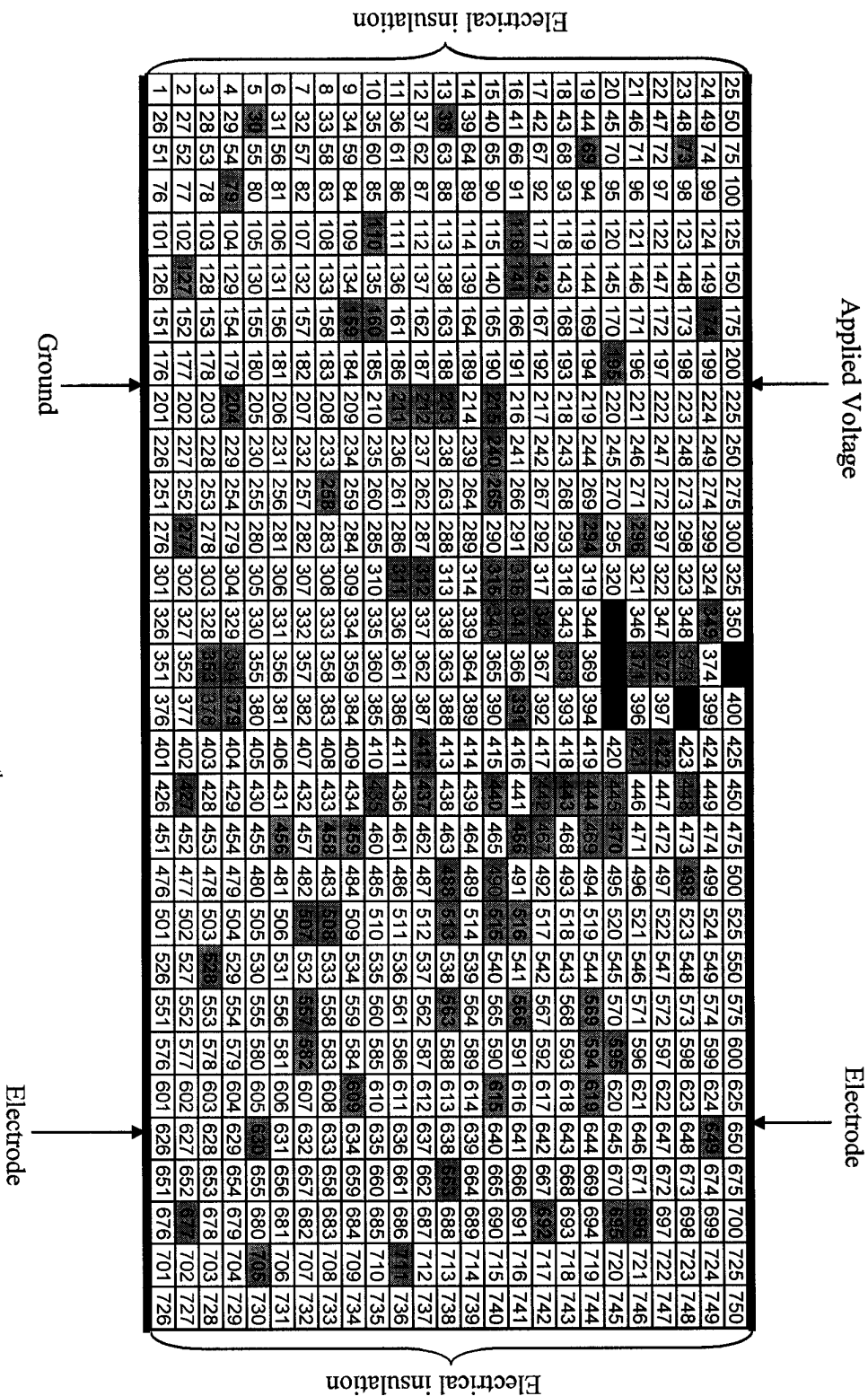
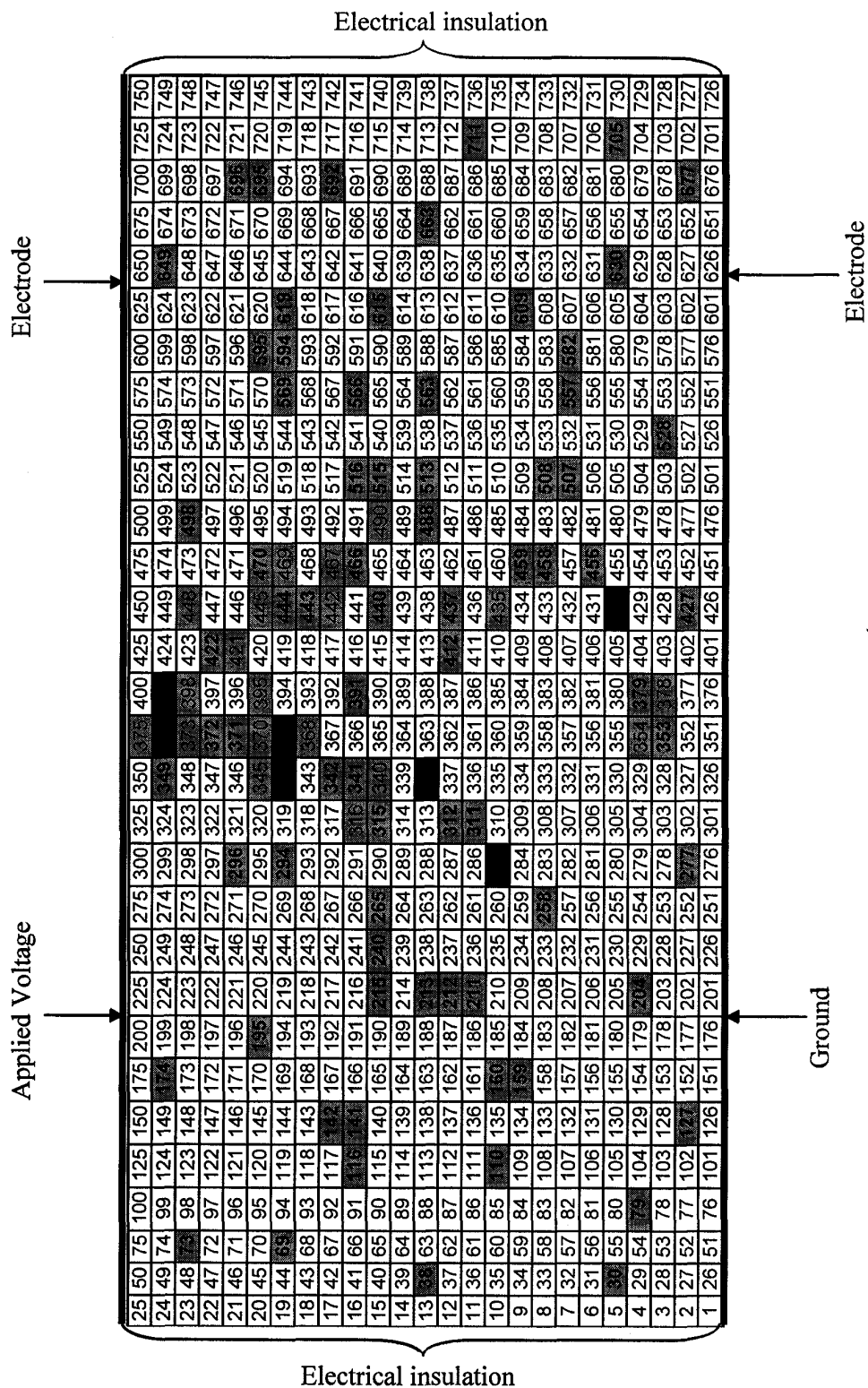


Fig. 81. Avalanche after 4th iteration

Fig. 82. Avalanche after 5th iteration

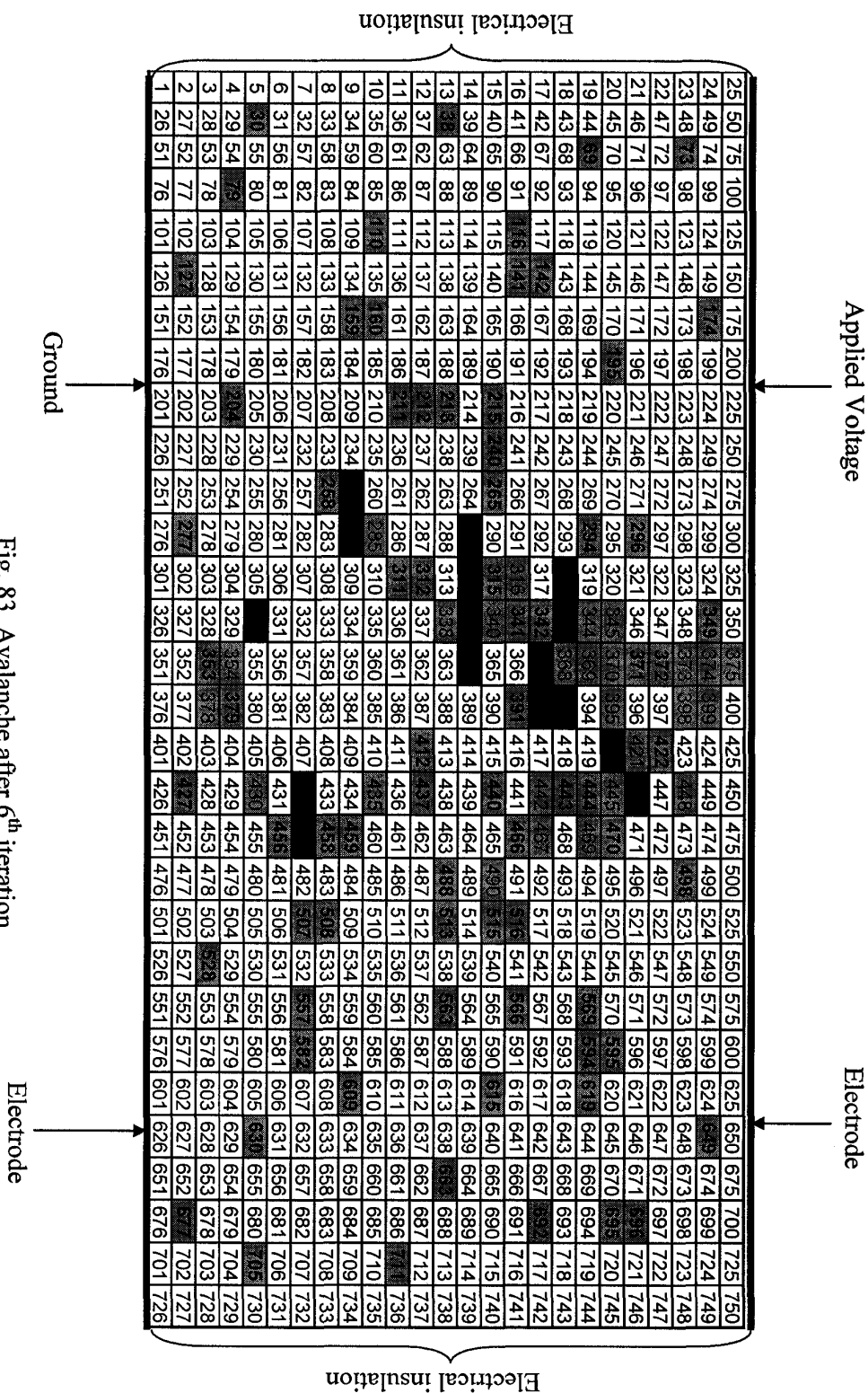


Fig. 83. Avalanche after 6th iteration

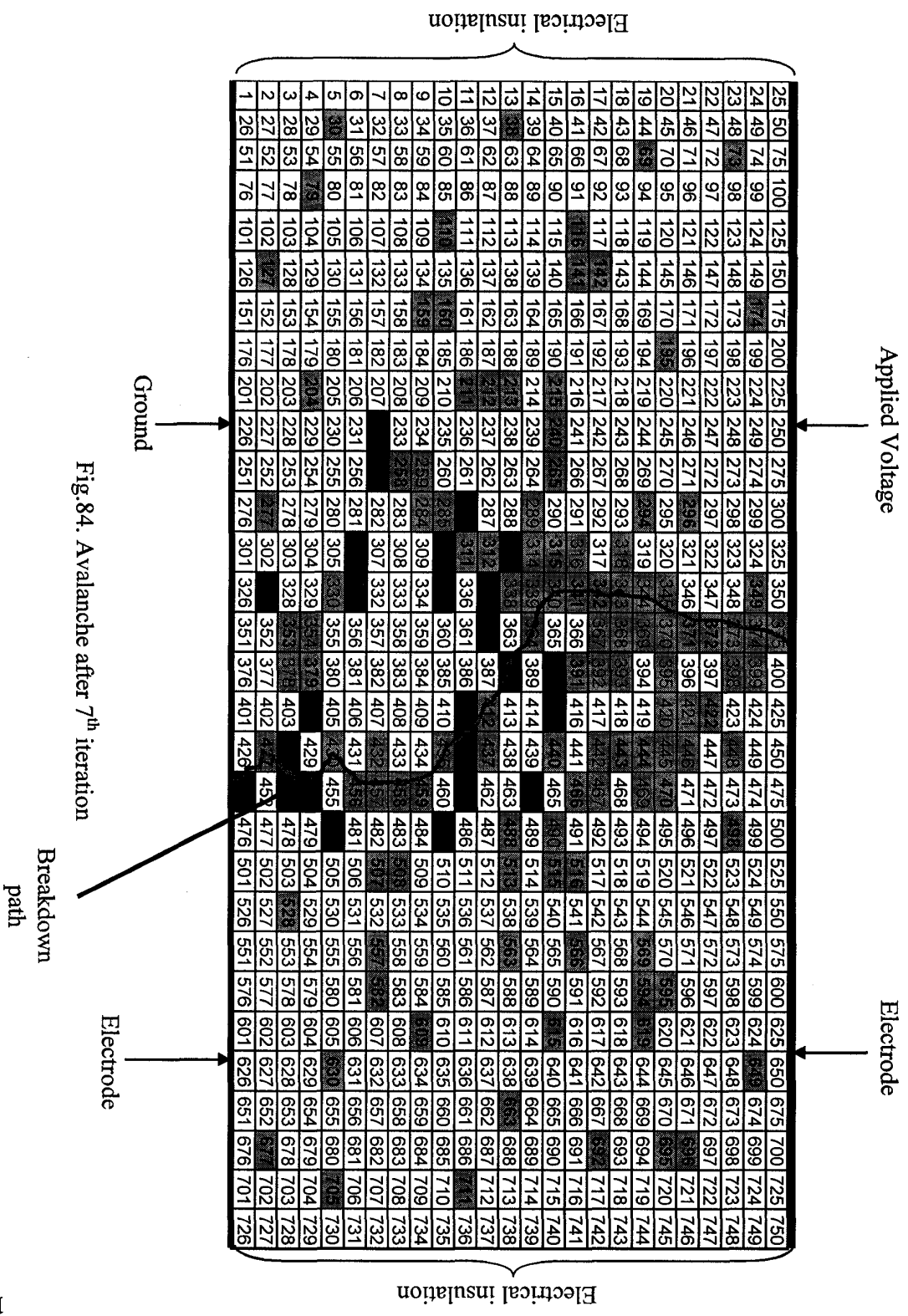


Fig. 84. Avalanche after 7th iteration

B. The effect of void density (10%, 30% and 50%) on the breakdown voltage

ESEM results and AC measurements indicated that the higher the void ratio, lower the breakdown strength of the polyurethane foam. The model (25 rows & 30 columns) was simulated with 10%, 30% and 50% void densities. Sample has rectangle shape geometry of 1 cm width and 5 cm length. The comparison of the simulation is given in Fig. 85.

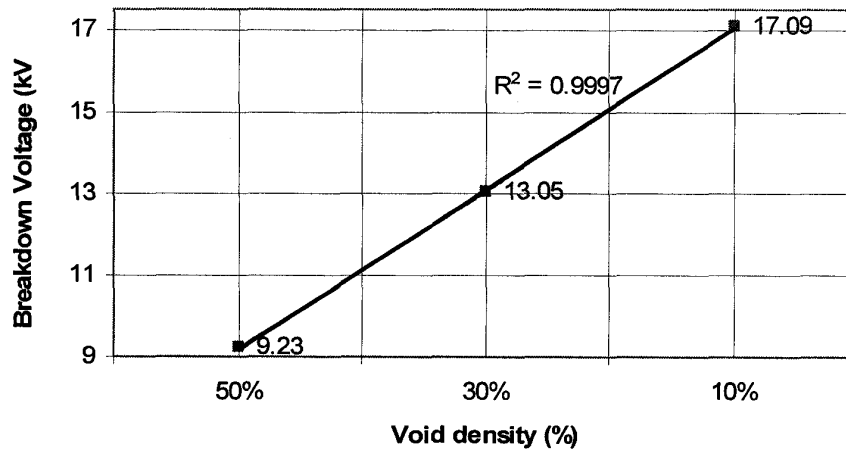


Fig. 85 The comparison of void density versus breakdown voltage

At 50% void density, breakdown voltage was calculated as 9.23 kV. As the void density was increased, breakdown voltage increased and calculated as 13.05 kV and 17.09 kV for 30% and 50% void density respectively. This result clearly indicates that there is an agreement between the simulation results and the test results.

C. Correlation between the experiments and the COMSOL Multiphysics Program.

Correlation was made between experiment results and COMSOL Multiphysics Program. Polyurethane foam with 50% void density and 130 μm average void diameter

was used. Due to computer memory problem, actual area of voids could not be plotted in the model geometry therefore simulations were conducted for larger areas and an extrapolation was done to estimate the breakdown voltage of polyurethane foam.

Simulations were conducted for different areas of voids at %50 void density and model geometries used in simulations has 5 cm length and 1 cm width. The size of model geometries was similar to that of samples used in experiments. As an example, void area calculation of a sample that has 50 rows and 80 columns is explained below.

1cm width is divided into 50 (number of rows) and 5 cm length is divided into 80 (number of columns) equally to find width and length of rectangle shape voids. The multiplication of width and length provided area of a void. Areas of all voids are assumed to be equal to each other since there are slight differences between the areas of voids.

Void areas were calculated by using Equation 2

$$\text{void area} = \pi * r^2 \quad (2)$$

Void area for 130 μm average void diameter was calculated as 0.00132 cm^2 .

MATLAB codes given in Appendix B were used in simulations and breakdown voltages for different sizes of void areas were calculated and given in Table 45.

TABLE 45
BREAKDOWN VOLTAGE VERSUS VOID AREAS

Void area (cm^2)	Breakdown voltage (kV)	# of rows and columns	Void density (%)
0.0012	30	50 by 80	50%
0.0014	26.4	50 by 50	50%
0.0016	26.1	25 by 30	50%
0.002	14	50 by 60	50%
0.0025	15	50 by 40	50%
0.0033	13.3	50 by 70	50%
0.0066	9.23	30 by 50	50%

Fig. 86 shows the linear curve fitting for the values given in Table 45. The breakdown voltage tends to increase with smaller void areas, thus results prove that higher breakdown voltages can be obtained with smaller void sizes. The breakdown voltage of void area (0.00132 cm^2) was extrapolated by using Equation 3 and found to be 33.37 kV.

$$\text{Breakdown voltage} = -3.5575 * (\text{void area}) + 33.377 \quad (3)$$

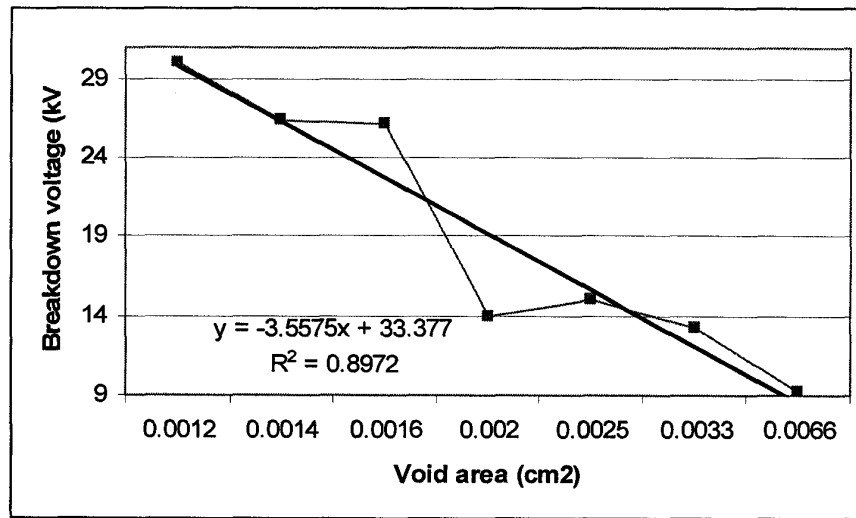


Fig. 86 Breakdown voltage versus void areas

Extrapolation results also show that the simulation result was in the similar magnitude as experiment results.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

I. CONCLUSIONS

Electrical properties of polyurethane foam were studied under different humidity and temperature conditions with three different types of foam. The breakdown mechanism in the voids of polyurethane foam was explained and a hypothesis was developed to describe the mechanism that leads to electrical breakdown of polyurethane foams and simulated with COMSOL Multiphysics program. Conclusions drawn from the study are given below.

- The withstand characteristics of polyurethane foam is studied with AC voltages. The average AC breakdown strength for Foam I, Foam II and Foam III are calculated as 49.7 ± 9.8 kV/cm, 39 ± 7.1 kV/cm and 44.73 ± 6.4 kV/cm respectively.
- The withstand characteristics of polyurethane foam is studied with lightning impulse voltages. The average lightning impulse breakdown strength for Foam I, Foam II and Foam III are calculated as 166.2 ± 37.3 kV/cm, 148 ± 28.8 kV/cm and 144.2 ± 20.8 kV/cm respectively.
- The foam breakdown strength is about 2-3 times higher than that of air under similar conditions.
- The significant amount of deviation for breakdown strength is caused by the non-uniform distribution of voids of different sizes inside the foam.
- Four different production techniques are applied in order to minimize the size of voids that exist inside the foam. The sizes of the voids are minimized to a range of 100 μm and 150 μm by applying 125.7-kg/m² of pressure in production.

- Foam I has the highest breakdown strength. It also has the highest density and smallest average void diameter. In addition, voids only occupy 50% of the foam.
- Foam II has the lowest breakdown strength along with the lowest density and a significantly greater average void diameter. In addition, voids occupy 90% of the foam.
- Foam III's breakdown strength is in between that of Foam I and Foam II. Foam III has the second lowest density with voids occupying 70% of the foam.
- These findings show the relationship between the breakdown strength and foam density as well as void size and void distribution. Foam with a higher density, smaller voids, and less void distribution is expected to have larger electric breakdown strength. Therefore, high density foams should be used for electric insulation.
- Water penetration analysis of Foam I was investigated. It is observed that the foam samples with skin do not absorb noticeable amount of water. It is concluded that the skin of Foam I has a significant effect on preventing water entering the foam.
- The insulation of a hollow insulation system was modeled by foam filled tubes. Foam I was used inside the tube. The performance of the foam filled tube has been investigated to determine the quality and limit of the insulation.
- The AC withstand capability of the foam insulation appeared to be quite good for 69 kV class instrument transformer.
- The partial discharge measurements are also found to be within IEC requirements when using this insulator as a 69 kV class device.
- The BIL level does not fulfill the 69 kV class standards.

- Extrapolating from these results, the foam insulation is expected to satisfy all requirements of the IEEE and IEC standards for 69 kV class instrument transformers when the electrode distance is larger than 20 cm (8”).
- It is discovered that electrical breakdown of foam is not the result of progress of discharges in time as in other polymeric materials since the discharge values were in the range of 2-3 pC under 70 kV constant voltage for a period of 168 hours and in the range of 6 pC to 7pC at 90 kV and the dramatic increase of discharges is only seen immediately before breakdown.
- It is found that discharges increase immediately before breakdown, suddenly increases the electric field and produces an avalanche breakdown, therefore it is concluded that the breakdown mechanism within the polyurethane foam is a fast avalanche breakdown.
- The breakdown mechanism within polyurethane foam was explained and a hypothesis was developed to describe the mechanism that leads to electrical breakdown of polyurethane foams
- A computer program is developed with COMSOL controlled by MATLAB script to simulate the avalanche breakdown
- Simulation results indicated that as the void density increases, breakdown voltage decreases.
- There is an agreement between the simulation and experiment results
- Simulation results proved the feasibility of the avalanche progress
- Based on the tests, polyurethane foams show satisfactory electrical properties as a high voltage insulation material.

II. FUTURE WORK

- The electrical property of polyurethane foam was investigated under short term AC and lightning impulse voltages and conclusions were derived based on these studies. The aging tests with AC and lightning impulse voltages can also be conducted and the performance of the polyurethane foam will further be studied under new conditions.
- Hollow insulation systems can be filled with polyurethane foam and AC and lightning impulse voltage tests can be conducted in the field to see the performance of polyurethane foam insulation.
- The COMSOL computer program results can be improved with 3D simulations by using computers that have high memory capacity.
- Results revealed that void size and distribution have major impact on the breakdown strength of polyurethane foam. It is suggested that new foam manufacturing techniques should be developed to control size and distribution of voids in order to increase the dielectric strength of polyurethane foam. These new products will also increase the use of polyurethane foam for high voltage insulation.

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APPENDIX A

COMSOL FIELD PROGRAMMING CODE TO PLOT ELECTRIC FIELD DISTRIBUTION IN 1CM BY 5CM SAMPLE.

```

% COMSOL Multiphysics Model M-file
% Generated by COMSOL 3.2 (COMSOL 3.2.0.222, $Date: 2005/09/01 18:02:30
%)

% This program draws 1 cm by 5 cm model geometry including four voids
%
% and twenty-one solid parts, calculates the electric field in the
%
% geometry and plots the electric field distribution.

flclear fem

% COMSOL version
clear vrsn
vrsn.name = 'COMSOL 3.2';
vrsn.ext = '';
vrsn.major = 0;
vrsn.build = 222;
vrsn.rcs = '$Name: $';
vrsn.date = '$Date: 2005/09/01 18:02:30 $';
fem.version = vrsn;

% Geometry - Draws the model geometry
carr={curve2([-0.03,0.02],[0.0068,0.0068],[1,1])};
g2=geomcoerce('curve',carr);
[g3]=geomcopy({g2});
g3=move(g3,[0,-0.0032]);
carr={curve2([-0.022,-0.022],[0.0096,0],[1,1])};
g4=geomcoerce('curve',carr);
clear g4
carr={curve2([-0.022,-0.022],[0.01,0],[1,1])};
g5=geomcoerce('curve',carr);
[g6]=geomcopy({g5});
g6=move(g6,[0.0080,0]);
[g7]=geomcopy({g6});
g7=move(g7,[0.0080,0]);
[g8]=geomcopy({g7});
g8=move(g8,[0.0080,0]);
[g9]=geomcopy({g8});
g9=move(g9,[0.0080,0]);
[g10,g11]=geomcopy({g5,g9});
g10=move(g10,[-0.0020,0]);
g11=move(g11,[-0.0020,0]);
[g12]=geomcopy({g5});
g12=move(g12,[0.0040,0]);
clear g5
g6=move(g6,[0.0020,0]);
g8=move(g8,[-0.0020,0]);
g11=move(g11,[-0.0020,0]);
g9=move(g9,[0.0020,0]);
g9=move(g9,[0.0010,0]);
clear c s
c.objs={g2,g3,g6,g7,g8,g9,g10,g11,g12};

```

```

c.name={'B1','B2','B4','B5','B6','B7','B8','B9','B10'};
c.tags={'g2','g3','g6','g7','g8','g9','g10','g11','g12'};

s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

fem.draw=struct('c',c,'s',s);
fem.geom=geomcsg(fem);

% Mesh is initialized
fem.mesh=meshinit(fem);

% Application mode 1
clear appl
appl.mode.class = 'ElectrostaticsGeneralized';
appl.module = 'EM';
appl.assignsuffix = '_emqv';
clear bnd
bnd.V0 = {0,0,10000,0}; %Applied voltage is 10000 Volts
bnd.type = {'V0','cont','V','n0'};
%Boundary types are as below
%V0:ground, cont:continuity,V:voltage,n0:electrical insulation
bnd.ind = [4,1,4,2,4,2,3,2,1,2,2,2,2,3,2,1,2,2,2,2,3,2,1,2,2,2,2,3,2,1,
...
2,2,2,2,3,2,1,2,2,2,2,3,2,1,2,2,2,2,3,2,1,2,2,2,2,3,4,4,4];
% shows boundary indices
appl.bnd = bnd;
clear equ
equ.epsilonr = {1,5};
% contains relative permittivities. 1 for voids and 5 for solid parts
equ.ind = [1,2,2,2,2,2,2,1,2,2,2,2,2,2,2,1,2,2,2,2,2,2,1,2];
% shows cell types either void or solid parts.
appl.equ = equ;
fem.appl{1} = appl;
fem.border = 1;
fem.units = 'SI';

% Multiphysics
fem=multiphysics(fem);

% Mesh is extended
fem.xmesh=mesextend(fem);

% Solve problem
fem.sol=femlin(fem, ...
    'solcomp',{'V'}, ...
    'outcomp',{'V'});

% Save current fem structure for restart purposes
fem0=fem;

% Plot solution
postplot(fem, ...

```

```
'tridata',{'normE_emqv','cont','internal'}, ...  
'trimap','jet(1024)', ...  
'title','Surface: Electric field, norm [V/m]', ...  
'refine',5, ...  
'axis',[-0.0325730403447413,0.0225730387056135,-  
0.0118725090662381,0.0218725088427207,0,2033900.5]);
```

APPENDIX B

MATLAB CODES CREATED TO SIMULATE AVALANCHE BREAKDOWN
MECHANISM

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%%                                MAIN PROGRAM
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%-----Parameters Setup-----
---
orig25row30col_setup % model geometry is defined
%-----
---
bUseRandDistSubdomain = 1; % 1-random distribution 0-manual setup
void_density = 0.5;

bBoundaryAlwaysSolid = 1; %1-make boundaries always solids 0-don't
change boundaries

ETh = [3e6 4.0e6 1e12 1e12]; %Electric field thresholds for cells

VApplied_Init =10000; %the initial voltage

%% This program uses variable step for voltage increase.

if length(equ.epsilonr)<3, %if the conductivity is undefined
    equ.epsilonr = {equ.epsilonr{:},'mat1_epsilonr','mat2_epsilonr'};
    equ.sigma = {0,0,'mat1_sigma','mat2_sigma'};

    % Library materials
    clear lib
    lib.mat{1}.name='high_conductivity';% after solids breakdown
    lib.mat{1}.varname='mat1';
    lib.mat{1}.variables.sigma='5.998e7';
    lib.mat{1}.variables.mur='1';
    lib.mat{1}.variables.k='400';
    lib.mat{1}.variables.epsilonr='1';
    lib.mat{1}.variables.rho='8700';
    lib.mat{1}.variables.C='385';
    lib.mat{1}.variables.nu='0.35';
    lib.mat{1}.variables.alpha='17e-6';
    lib.mat{1}.variables.E='110e9';

    lib.mat{2}.name='low_conductivity';% after voids breakdown
    lib.mat{2}.varname='mat2';
    lib.mat{2}.variables.sigma='5.998e7';
    lib.mat{2}.variables.mur='1';
    lib.mat{2}.variables.k='160';
    lib.mat{2}.variables.epsilonr='1';
    lib.mat{2}.variables.rho='2700';
    lib.mat{2}.variables.C='900';
    lib.mat{2}.variables.nu='0.33';
    lib.mat{2}.variables.alpha='23e-6';
    lib.mat{2}.variables.E='70e9';
    fem.lib = lib;
end

```

```

%%% My program starts

%make sure 1->voids and 2->solids
if equ.epsilonr{1} ~= 1
    equ.epsilonr = {equ.epsilonr{[2,1,3:end]}};
    tmp = find(equ.ind == 1)
    tmp1 = find(equ.ind == 2)
    equ.ind(tmp1) = 1;
    equ.ind(tmp) = 2;
end

NSubDom = length(equ.ind);
VappBndInd = strmatch('V',bnd.type,'exact');
NCol = length(find(bnd.ind == VappBndInd));
NRow = NSubDom/NCol;

if bUseRandDistSubdomain,
    %Generate randomly distributed voids
    DomType = 2*ones(1,NSubDom);
    DomType(1:round(void_density*NSubDom)) = 1;
    rand('state',2)%may create other pattern if the number is changed--
--0 is ORIGINAL
    DomType = DomType(randperm(NSubDom));
else
    %% For manually setued subdomain configuration
    DomType = equ.ind;
end

if bBoundaryAlwaysSolid,
    DomType([1:NRow, 1:NRow:NRow*(NCol-1)+1, NRow:NRow:NRow*NCol, ...
            NRow*(NCol-1)+1:NRow*NCol]) = 2;
end

DomTypeInit = DomType;

%-----Network initialization-----
bBreakdownPath = 0;
InitNetwork;
%-----

% Find the boundaries at the top
% TopEdge = find(bnd.ind == strmatch('V',bnd.type,'exact'));

Emax = zeros(1,length(DomType));
VApplied = VApplied_Init; %the initial voltage should be low so that no
cell breaks
Breakdown = 0;
SubDomainsBrokenDown = []; % list of subdomains that have breakdown
BrList = [];

tic

while ~Breakdown,
    bnd.V0 = {0,0,0,0};

```

```

bnd.V0{VappBndInd} = VApplied;
appl.bnd = bnd;

equ.ind = DomType;
appl.equ = equ;
fem.appl{1} = appl;

% Multiphysics
fem=multiphysics(fem);

% Extend mesh
fem.xmesh=meshtend(fem);

% Solve problem
fem.sol=femlin(fem, ...
    'solcomp',{'V'}, ...
    'outcomp',{'V'});

% Get the maximum electric field in each cell and check if the
% cell has broken down
dlBreakdown = []; % list of cells may breakdown in this iteration
for dom = 1:length(DomType),
    % get them maximum electric field in this cell
    Emax(dom)=postmax(fem,'normE_emqv','Dl',dom);
    if Emax(dom)> ETh(DomType(dom)),
        dlBreakdown = [dlBreakdown dom];
    end
end
if isempty(dlBreakdown),
    %increase the voltage so that the next cell breaks
    VApplied = VApplied*min(ETh(DomType)./Emax)+100;
else
    [ignore,sortedind] = sort(Emax(dlBreakdown)-
    ETh(DomType(dlBreakdown)),'descend');
    for i_ind=1:length(sortedind),
        ind = sortedind(i_ind);
        %check if the whole sample has broken down
        %-----Network Analysis-----
        NetworkAnalysis;
        %-----
        if bBreakdownPath,
            break
        end
    end

    if bBreakdownPath,
        dlBreakdown = dlBreakdown(sortedind(1:i_ind));
    end

    %breakdown all the cells that have positive E-ETH difference
    %by changing this cell to high conductivity
    ind = find(DomType(dlBreakdown)==2);
    DomType(dlBreakdown(ind)) = 3; %solids change to 3

```

```

ind = find(DomType(dlBreakdown)==1);
DomType(dlBreakdown(ind)) = 4; %voids changes to 4

if isempty(BrList) || BrList(end).VApplied ~= VApplied,
    tmp.VApplied = VApplied;
    tmp.CellList = {dlBreakdown};
    BrList = [BrList tmp];
else
    BrList(end).CellList = {BrList(end).CellList{:}
dlBreakdown};
end

for ind = 1:length(dlBreakdown),
    if DomTypeInit(dlBreakdown(ind))==1,
        fprintf('Cell #%d\t(void) breaks down at
E=%.2fkV/cm\tVApplied=%.2fkV\n', ...
dlBreakdown(ind), Emax(dlBreakdown(ind))/1e5, VApplied/1000)
    else
        fprintf('Cell #%d\t(solid) breaks down at
E=%.2fkV/cm\tVApplied=%.2fkV\n', ...
dlBreakdown(ind), Emax(dlBreakdown(ind))/1e5, VApplied/1000)
    end
    end
    fprintf('\n')
end

if bBreakdownPath && ~Breakdown,
    Vbreakdown = VApplied;
    Breakdown = 1;
    fprintf('The whole sample will break down\n')
end
end %while ~Breakdown,

toc

%%The following codes are for automatical columns-loading into Excel
f_cell = fopen('cell_list.txt','wt');
f_time = fopen('time_list.txt','wt');
f_vapp = fopen('vapp_list.txt','wt');
time_entry = 1;
cell_ind = 1;
for i = 1:length(BrList),
    fprintf(f_vapp, '%d\t%d\n', cell_ind, round(BrList(i).VApplied));
    for j = 1:length(BrList(i).CellList),
        fprintf(f_time, '%d\t%d\n', cell_ind, time_entry);

        tmp = BrList(i).CellList{j};
        for k = 1:length(tmp)
            fprintf(f_cell, '%d\n', tmp(k));
        end
        cell_ind = cell_ind + length(tmp);
        time_entry = time_entry + 1;
    end
end

```

```

end
time_entry = time_entry + 1; %add extra time delay for new
breakdown voltage
end
fclose(f_cell);
fclose(f_time);
fclose(f_vapp);

f_domtype = fopen('domtype_list.txt','wt');
for i = 1:length(DomTypeInit),
    fprintf(f_domtype,'%d\n',DomTypeInit(i));
end
fclose(f_domtype);
Vbreakdown

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
orig25row30col
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
% COMSOL Multiphysics Model M-file
% Generated by COMSOL 3.2 (COMSOL 3.2.0.222, $Date: 2005/09/01 18:02:30
%)

flclear fem

% COMSOL version
clear vrsn
vrsn.name = 'COMSOL 3.2';
vrsn.ext = '';
vrsn.major = 0;
vrsn.build = 222;
vrsn.rcs = '$Name: $';
vrsn.date = '$Date: 2005/09/01 18:02:30 $';
fem.version = vrsn;

% Geometry
g1=rect2(0.05,0.01,'base','corner','pos',[-0.03,0]);
clear s
s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

fem.draw=struct('s',s);

% Multiphysics
fem=multiphysics(fem);
% COMSOL Multiphysics Model M-file
% Generated by COMSOL 3.2 (COMSOL 3.2.0.222, $Date: 2005/09/01 18:02:30
%)

```

```

% Geometry
carr={curve2([-0.03,0.02],[0.0098,0.0098],[1,1])};
g2=geomcoerce('curve',carr);
[g3]=geomcopy({g2});
g3=move(g3,[0,-1.999999999999999E-4]);
[g4,g5]=geomcopy({g2,g3});
g4=move(g4,[0,-2.000000000000001E-4]);
g5=move(g5,[0,-2.000000000000001E-4]);
[g6,g7]=geomcopy({g4,g5});
g6=move(g6,[0,-2.000000000000001E-4]);
g7=move(g7,[0,-2.000000000000001E-4]);
[g8,g9]=geomcopy({g6,g7});
g8=move(g8,[0,-1.999999999999999E-4]);
g9=move(g9,[0,-1.999999999999999E-4]);
[g10,g11]=geomcopy({g8,g9});
g10=move(g10,[0,-4.000000000000001E-4]);
g11=move(g11,[0,-4.000000000000001E-4]);
[g12,g13,g14,g15]=geomcopy({g8,g9,g10,g11});
g12=move(g12,[0,-8.0E-4]);
g13=move(g13,[0,-8.0E-4]);
g14=move(g14,[0,-8.0E-4]);
g15=move(g15,[0,-8.0E-4]);
[g16,g17,g18,g19]=geomcopy({g12,g13,g14,g15});
g16=move(g16,[0,-8.0E-4]);
g17=move(g17,[0,-8.0E-4]);
g18=move(g18,[0,-8.0E-4]);
g19=move(g19,[0,-8.0E-4]);
[g20,g21,g22,g23]=geomcopy({g16,g17,g18,g19});
g20=move(g20,[0,-8.0E-4]);
g21=move(g21,[0,-8.0E-4]);
g22=move(g22,[0,-8.0E-4]);
g23=move(g23,[0,-8.0E-4]);
[g24,g25,g26,g27]=geomcopy({g20,g21,g22,g23});
g24=move(g24,[0,-8.0E-4]);
g25=move(g25,[0,-8.0E-4]);
g26=move(g26,[0,-8.0E-4]);
g27=move(g27,[0,-8.0E-4]);
[g28,g29,g30,g31]=geomcopy({g24,g25,g26,g27});
g28=move(g28,[0,-8.0E-4]);
g29=move(g29,[0,-8.0E-4]);
g30=move(g30,[0,-8.0E-4]);
g31=move(g31,[0,-8.0E-4]);
[g32,g33,g34,g35]=geomcopy({g28,g29,g30,g31});
g32=move(g32,[0,-8.0E-4]);
g33=move(g33,[0,-8.0E-4]);
g34=move(g34,[0,-8.0E-4]);
g35=move(g35,[0,-8.0E-4]);
[g44,g45,g46,g47,g48,g49]=geomcopy({g30,g31,g32,g33,g34,g35});
g44=move(g44,[0,-0.0012]);
g45=move(g45,[0,-0.0012]);
g46=move(g46,[0,-0.0012]);
g47=move(g47,[0,-0.0012]);
g48=move(g48,[0,-0.0012]);
g49=move(g49,[0,-0.0012]);

```

```

[g50,g51,g52,g53,g54,g55]=geomcopy({g44,g45,g46,g47,g48,g49});
g50=move(g50,[0,-0.0012]);
g51=move(g51,[0,-0.0012]);
g52=move(g52,[0,-0.0012]);
g53=move(g53,[0,-0.0012]);
g54=move(g54,[0,-0.0012]);
g55=move(g55,[0,-0.0012]);
[g56,g57,g58,g59,g60]=geomcopy({g51,g52,g53,g54,g55});
g56=move(g56,[0,-0.0010]);
g57=move(g57,[0,-0.0010]);
g58=move(g58,[0,-0.0010]);
g59=move(g59,[0,-0.0010]);
g60=move(g60,[0,-0.0010]);
[g61]=geomcopy({g60});
g61=move(g61,[0,-2.0E-4]);
carr={curve2([-0.028,-0.028],[0.01,0],[1,1])};
g66=geomcoerce('curve',carr);
[g67]=geomcopy({g66});
g67=move(g67,[0.0020,0]);
[g68]=geomcopy({g67});
g68=move(g68,[0.0020,0]);
[g69]=geomcopy({g68});
g69=move(g69,[0.0020,0]);
[g70]=geomcopy({g69});
g70=move(g70,[0.0020,0]);
[g71]=geomcopy({g70});
g71=move(g71,[0.0020,0]);
[g72]=geomcopy({g71});
g72=move(g72,[0.0020,0]);
[g73]=geomcopy({g72});
g73=move(g73,[0.0020,0]);
[g74]=geomcopy({g73});
g74=move(g74,[0.0020,0]);
[g75]=geomcopy({g74});
g75=move(g75,[0.0020,0]);
[g76]=geomcopy({g75});
g76=move(g76,[0.0020,0]);
[g77]=geomcopy({g76});
g77=move(g77,[0.0020,0]);
[g78]=geomcopy({g77});
g78=move(g78,[0.0020,0]);
[g79]=geomcopy({g78});
g79=move(g79,[0.0020,0]);
[g80]=geomcopy({g79});
g80=move(g80,[0.0020,0]);
[g81]=geomcopy({g80});
g81=move(g81,[0.0020,0]);
[g82]=geomcopy({g81});
g82=move(g82,[0.0020,0]);
[g83,g84]=geomcopy({g81,g82});
g83=move(g83,[0.0040,0]);
g84=move(g84,[0.0040,0]);
[g85,g86]=geomcopy({g83,g84});
g85=move(g85,[0.0040,0]);

```

```

g86=move(g86,[0.0040,0]);
[g87,g88]=geomcopy({g85,g86});
g87=move(g87,[0.0040,0]);
g88=move(g88,[0.0040,0]);
[g89]=geomcopy({g88});
g89=move(g89,[0.0020,0]);
clear c s
c.objs={g2,g3,g4,g5,g6,g7,g8,g9,g10,g11,g12,g13,g14,g15,g16,g17,g18,
...
g19,g20,g21,g22,g23,g24,g25,g26,g27,g28,g29,g30,g31,g32,g33,g34,g35,
...
g44,g45,g46,g47,g48,g49,g50,g51,g52,g53,g54,g55,g56,g57,g58,g59,g60,
...
g61,g66,g67,g68,g69,g70,g71,g72,g73,g74,g75,g76,g77,g78,g79,g80,g81,
...
g82,g83,g84,g85,g86,g87,g88,g89};
c.name={'B1','B2','B3','B4','B5','B6','B7','B8','B9','B10','B11', ...
'B12','B13','B14','B15','B16','B17','B18','B19','B20','B21','B22','B23'
, ...
'B24','B25','B26','B27','B28','B29','B30','B31','B32','B33','B34','B35'
, ...
'B36','B37','B38','B39','B40','B41','B42','B43','B44','B45','B46','B47'
, ...
'B48','B49','B50','B51','B52','B53','B54','B55','B56','B57','B58','B59'
, ...
'B60','B61','B62','B63','B64','B65','B66','B67','B68','B69','B70','B71'
, ...
'B72','B73','B74','B75','B76'};
c.tags={'g2','g3','g4','g5','g6','g7','g8','g9','g10','g11','g12', ...
'g13','g14','g15','g16','g17','g18','g19','g20','g21','g22','g23','g24'
, ...
'g25','g26','g27','g28','g29','g30','g31','g32','g33','g34','g35','g44'
, ...
'g45','g46','g47','g48','g49','g50','g51','g52','g53','g54','g55','g56'
, ...
'g57','g58','g59','g60','g61','g66','g67','g68','g69','g70','g71','g72'
, ...
'g73','g74','g75','g76','g77','g78','g79','g80','g81','g82','g83','g84'
, ...
'g85','g86','g87','g88','g89'};

s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

```

```

fem.draw=struct('c',c,'s',s);

clear c s
c.objs={g86,g28,g71,g57,g13,g22,g69,g44,g19,g6,g88,g74,g30,g66,g9, ...
g25,g84,g52,g32,g8,g76,g17,g51,g83,g72,g70,g10,g21,g80,g50,g67,g61,g56,
...
g81,g58,g14,g12,g2,g87,g59,g48,g15,g3,g49,g27,g16,g5,g20,g35,g79,g33,
...

g47,g77,g60,g55,g23,g73,g7,g11,g54,g31,g4,g75,g53,g18,g34,g46,g68,g29,
...
g45,g78,g89,g82,g24,g85,g26};
c.name={'B73','B27','B58','B48','B12','B21','B56','B35','B18','B5', ...
'B75','B61','B29','B53','B8','B24','B71','B43','B31','B7','B63','B16',
...

'B42','B70','B59','B57','B9','B20','B67','B41','B54','B52','B47','B68',
...

'B49','B13','B11','B1','B74','B50','B39','B14','B2','B40','B26','B15',
...

'B4','B19','B34','B66','B32','B38','B64','B51','B46','B22','B60','B6',
...

'B10','B45','B30','B3','B62','B44','B17','B33','B37','B55','B28','B36',
...
'B65','B76','B69','B23','B72','B25'};
c.tags={'g86','g28','g71','g57','g13','g22','g69','g44','g19','g6', ...
'g88','g74','g30','g66','g9','g25','g84','g52','g32','g8','g76','g17',
...

'g51','g83','g72','g70','g10','g21','g80','g50','g67','g61','g56','g81'
, ...

'g58','g14','g12','g2','g87','g59','g48','g15','g3','g49','g27','g16',
...

'g5','g20','g35','g79','g33','g47','g77','g60','g55','g23','g73','g7',
...

'g11','g54','g31','g4','g75','g53','g18','g34','g46','g68','g29','g45',
...
'g78','g89','g82','g24','g85','g26'};

s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

fem.draw=struct('c',c,'s',s);

```

```

clear g13 g19 g9 g25 g17 g21 g2 g15 g27 g5 g23 g11
clear g6
clear g33 g31 g29
clear g57 g51 g61 g59 g49 g35 g47 g55 g53 g45
g66=move(g66,[-7.50000000000001E-4,0]);
[g36]=geomcopy({g66});
g36=move(g36,[0.00125,0]);
[g37]=geomcopy({g36});
g37=move(g37,[0.00125,0]);
g67=move(g67,[0.0010,0]);
g68=move(g68,[2.5E-4,0]);
g69=move(g69,[-5.0E-4,0]);
[g38]=geomcopy({g69});
g38=move(g38,[0.00125,0]);
g71=move(g71,[-7.49999999999997E-4,0]);
[g39]=geomcopy({g71});
g39=move(g39,[0.00125,0]);
g72=move(g72,[-2.5E-4,0]);
g73=move(g73,[-0.0010,0]);
[g40]=geomcopy({g73});
g40=move(g40,[0.00125,0]);
[g41]=geomcopy({g40});
g41=move(g41,[0.00125,0]);
g74=move(g74,[7.50000000000001E-4,0]);
g76=move(g76,[-7.50000000000001E-4,0]);
[g62]=geomcopy({g76});
g62=move(g62,[0.00125,0]);
g77=move(g77,[-2.5E-4,0]);
g78=move(g78,[-0.0010,0]);
[g63]=geomcopy({g78});
g63=move(g63,[0.00125,0]);
[g64]=geomcopy({g63});
g64=move(g64,[0.00125,0]);
g79=move(g79,[7.5E-4,0]);
[g65,g90]=geomcopy({g81,g79});
g65=move(g65,[-7.5E-4,0]);
g90=move(g90,[-7.5E-4,0]);
g81=move(g81,[5.0E-4,0]);
clear g90
g82=move(g82,[-2.5E-4,0]);
[g91]=geomcopy({g82});
g91=move(g91,[0.00125,0]);
g83=move(g83,[2.5E-4,0]);
[g92]=geomcopy({g84});
g92=move(g92,[-5.0E-4,0]);
g84=move(g84,[7.50000000000001E-4,0]);
g86=move(g86,[-7.50000000000001E-4,0]);
[g93]=geomcopy({g86});
g93=move(g93,[0.00125,0]);
[g94]=geomcopy({g93});
g94=move(g94,[0.00125,0]);
[g95]=geomcopy({g87});
g95=move(g95,[0.0010,0]);
clear g87

```

```

g88=move(g88,[2.5E-4,0]);
g89=move(g89,[-5.0E-4,0]);
[g96]=geomcopy({g89});
g96=move(g96,[0.00125,0]);
g66=move(g66,[4.10999999999998E-4,0]);
g36=move(g36,[8.27999999999999E-4,0]);
clear g37
g68=move(g68,[4.11999999999999E-4,0]);
g69=move(g69,[8.28999999999996E-4,0]);
clear g38
g71=move(g71,[4.13E-4,0]);
g39=move(g39,[8.30000000000001E-4,0]);
clear g72
g40=move(g40,[4.13999999999999E-4,0]);
g41=move(g41,[8.31E-4,0]);
clear g74
g76=move(g76,[4.15E-4,0]);
g62=move(g62,[8.31999999999999E-4,0]);
clear g77
g63=move(g63,[4.16E-4,0]);
g64=move(g64,[8.33E-4,0]);
clear g79
g65=move(g65,[4.17E-4,0]);
g81=move(g81,[8.34E-4,0]);
clear g82
g83=move(g83,[4.18E-4,0]);
g92=move(g92,[8.35000000000001E-4,0]);
clear g84
g86=move(g86,[4.19000000000001E-4,0]);
g93=move(g93,[8.36E-4,0]);
clear g94
g88=move(g88,[4.2E-4,0]);
g89=move(g89,[8.36999999999998E-4,0]);
clear g96
clear c s
c.objs={g86,g28,g71,g22,g69,g44,g88,g30,g66,g52,g32,g8,g76,g83,g70, ...
    g10,g80,g50,g67,g56,g81,g58,g14,g12,g48,g3,g16,g20,g60,g7,g73,g54,g4,
    ...
    g75,g46,g34,g18,g68,g78,g89,g24,g85,g26,g36,g39,g40,g41,g62,g63,g64,
    ...
    g65,g91,g92,g93,g95};
c.name={'B73','B27','B58','B21','B56','B35','B75','B29','B53','B43',
    ...
    'B31','B7','B63','B70','B57','B9','B67','B41','B54','B47','B68','B49',
    ...
    'B13','B11','B39','B2','B15','B19','B51','B6','B60','B45','B3','B62',
    ...
    'B37','B33','B17','B55','B65','B76','B23','B72','B25','B1','B8','B10',
    ...
    'B12','B14','B16','B18','B20','B22','B24','B26','B30'};
c.tags={'g86','g28','g71','g22','g69','g44','g88','g30','g66','g52',
    ...

```

```

'g32','g8','g76','g83','g70','g10','g80','g50','g67','g56','g81','g58',
...
'g14','g12','g48','g3','g16','g20','g60','g7','g73','g54','g4','g75',
...

'g46','g34','g18','g68','g78','g89','g24','g85','g26','g36','g39','g40'
/ ...
'g41','g62','g63','g64','g65','g91','g92','g93','g95'};

s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

fem.draw=struct('c',c,'s',s);

clear c s
c.objs={g86,g28,g71,g22,g69,g44,g88,g30,g66,g52,g62,g32,g8,g40,g76, ...
g83,g70,g10,g80,g39,g50,g67,g56,g81,g58,g14,g36,g12,g48,g65,g63,g3,g16,
...
g91,g64,g93,g20,g60,g95,g73,g7,g54,g4,g75,g18,g34,g46,g68,g78,g89,g92,
...
g24,g85,g41,g26};
c.name={'B73','B27','B58','B21','B56','B35','B75','B29','B53','B43',
...
'B14','B31','B7','B10','B63','B70','B57','B9','B67','B8','B41','B54',
...
'B47','B68','B49','B13','B1','B11','B39','B20','B16','B2','B15','B22',
...
'B18','B26','B19','B51','B30','B60','B6','B45','B3','B62','B17','B33',
...
'B37','B55','B65','B76','B24','B23','B72','B12','B25'};
c.tags={'g86','g28','g71','g22','g69','g44','g88','g30','g66','g52',
...
'g62','g32','g8','g40','g76','g83','g70','g10','g80','g39','g50','g67',
...
'g56','g81','g58','g14','g36','g12','g48','g65','g63','g3','g16','g91',
...
'g64','g93','g20','g60','g95','g73','g7','g54','g4','g75','g18','g34',
...
'g46','g68','g78','g89','g92','g24','g85','g41','g26'};

s.objs={g1};
s.name={'R1'};
s.tags={'g1'};

fem.draw=struct('c',c,'s',s);

```


2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,
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 ...
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 ...

```

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...
2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,3,4,4,4,4,
...
    4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4];
appl.bnd = bnd;
clear equ
equ.epsilonr = {5.5,1}; % permittivity 5.5 for solid parts
% 1 for voids
equ.ind = [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,
...
1,1,1,1,1,1,1,1,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
...

```



```

%find the largest neighboring network
n_largest = 0;
i_largest = 0;
for i=1:length(nid),
    tmp = length(network_ind{nid(i)});
    if tmp > n_largest,
        n_largest = tmp;
        i_largest = i;
    end
end
nid_largest = nid(i_largest);

%add the new brokendown subdomain to the largest neighboring
network
NetworkID(iRow, iCol) = nid_largest;
network_ind{nid_largest} = [network_ind{nid_largest} dlBrDn];

%add the other neighboring networks to the largest neighboring
network
nid(i_largest)=[];
for i=1:length(nid),
    NetworkID(network_ind{nid(i)}) = nid_largest;
    network_ind{nid_largest} = [network_ind{nid_largest}
network_ind{nid(i)}];
    network_ind{nid(i)} = 0;    %free up the memory of the old
network, but cannot delete the entry.
end

%check for breakdown path
[I,J]=ind2sub([NRow NCol],network_ind{nid_largest});
I=unique(I);
if length(I) == NRow,
    bBreakdownPath = 1;
end
end
end

```

APPENDIX C

THE LIST OF BROKEN CELLS AT 17.09 kV

Cell number		Electric Field Strength	Applied voltage
-------------	--	-------------------------	-----------------

1st iteration

Cell #30	(void)	breaks down at E=51.87kV/cm	VApplied=17.09kV
Cell #38	(void)	breaks down at E=51.27kV/cm	VApplied=17.09kV
Cell #69	(void)	breaks down at E=48.20kV/cm	VApplied=17.09kV
Cell #73	(void)	breaks down at E=44.52kV/cm	VApplied=17.09kV
Cell #79	(void)	breaks down at E=50.58kV/cm	VApplied=17.09kV
Cell #110	(void)	breaks down at E=48.21kV/cm	VApplied=17.09kV
Cell #116	(void)	breaks down at E=67.94kV/cm	VApplied=17.09kV
Cell #127	(void)	breaks down at E=44.43kV/cm	VApplied=17.09kV
Cell #141	(void)	breaks down at E=70.43kV/cm	VApplied=17.09kV
Cell #142	(void)	breaks down at E=49.58kV/cm	VApplied=17.09kV
Cell #159	(void)	breaks down at E=41.36kV/cm	VApplied=17.09kV
Cell #160	(void)	breaks down at E=42.72kV/cm	VApplied=17.09kV
Cell #174	(void)	breaks down at E=42.79kV/cm	VApplied=17.09kV
Cell #195	(void)	breaks down at E=48.89kV/cm	VApplied=17.09kV
Cell #204	(void)	breaks down at E=45.73kV/cm	VApplied=17.09kV
Cell #211	(void)	breaks down at E=38.87kV/cm	VApplied=17.09kV
Cell #212	(void)	breaks down at E=30.46kV/cm	VApplied=17.09kV
Cell #213	(void)	breaks down at E=34.39kV/cm	VApplied=17.09kV
Cell #215	(void)	breaks down at E=62.65kV/cm	VApplied=17.09kV
Cell #240	(void)	breaks down at E=70.42kV/cm	VApplied=17.09kV
Cell #258	(void)	breaks down at E=47.81kV/cm	VApplied=17.09kV
Cell #265	(void)	breaks down at E=68.81kV/cm	VApplied=17.09kV
Cell #277	(void)	breaks down at E=42.46kV/cm	VApplied=17.09kV
Cell #294	(void)	breaks down at E=44.65kV/cm	VApplied=17.09kV
Cell #296	(void)	breaks down at E=42.13kV/cm	VApplied=17.09kV
Cell #311	(void)	breaks down at E=38.27kV/cm	VApplied=17.09kV
Cell #312	(void)	breaks down at E=36.69kV/cm	VApplied=17.09kV
Cell #315	(void)	breaks down at E=63.00kV/cm	VApplied=17.09kV
Cell #316	(solid)	breaks down at E=50.21kV/cm	VApplied=17.09kV
Cell #340	(solid)	breaks down at E=49.72kV/cm	VApplied=17.09kV
Cell #341	(void)	breaks down at E=62.55kV/cm	VApplied=17.09kV
Cell #342	(void)	breaks down at E=41.87kV/cm	VApplied=17.09kV
Cell #349	(void)	breaks down at E=45.04kV/cm	VApplied=17.09kV
Cell #353	(void)	breaks down at E=57.84kV/cm	VApplied=17.09kV
Cell #354	(solid)	breaks down at E=44.11kV/cm	VApplied=17.09kV
Cell #371	(void)	breaks down at E=41.10kV/cm	VApplied=17.09kV
Cell #372	(void)	breaks down at E=40.37kV/cm	VApplied=17.09kV
Cell #378	(solid)	breaks down at E=43.80kV/cm	VApplied=17.09kV
Cell #379	(void)	breaks down at E=58.19kV/cm	VApplied=17.09kV
Cell #391	(void)	breaks down at E=52.52kV/cm	VApplied=17.09kV
Cell #412	(void)	breaks down at E=58.02kV/cm	VApplied=17.09kV
Cell #422	(void)	breaks down at E=49.00kV/cm	VApplied=17.09kV
Cell #427	(void)	breaks down at E=41.69kV/cm	VApplied=17.09kV
Cell #437	(void)	breaks down at E=56.48kV/cm	VApplied=17.09kV
Cell #440	(void)	breaks down at E=49.82kV/cm	VApplied=17.09kV
Cell #443	(void)	breaks down at E=36.20kV/cm	VApplied=17.09kV
Cell #444	(void)	breaks down at E=52.99kV/cm	VApplied=17.09kV
Cell #445	(solid)	breaks down at E=41.85kV/cm	VApplied=17.09kV
Cell #456	(void)	breaks down at E=38.21kV/cm	VApplied=17.09kV
Cell #458	(void)	breaks down at E=32.57kV/cm	VApplied=17.09kV
Cell #459	(void)	breaks down at E=36.47kV/cm	VApplied=17.09kV
Cell #466	(void)	breaks down at E=55.95kV/cm	VApplied=17.09kV
Cell #469	(solid)	breaks down at E=41.76kV/cm	VApplied=17.09kV

Cell number		Electric Field Strength	Applied voltage
Cell #470	(void)	breaks down at E=55.11kV/cm	VApplied=17.09kV
Cell #488	(void)	breaks down at E=60.39kV/cm	VApplied=17.09kV
Cell #498	(void)	breaks down at E=44.20kV/cm	VApplied=17.09kV
Cell #507	(void)	breaks down at E=38.19kV/cm	VApplied=17.09kV
Cell #508	(void)	breaks down at E=37.44kV/cm	VApplied=17.09kV
Cell #513	(void)	breaks down at E=56.40kV/cm	VApplied=17.09kV
Cell #515	(void)	breaks down at E=36.56kV/cm	VApplied=17.09kV
Cell #516	(void)	breaks down at E=40.19kV/cm	VApplied=17.09kV
Cell #528	(void)	breaks down at E=44.06kV/cm	VApplied=17.09kV
Cell #557	(void)	breaks down at E=58.71kV/cm	VApplied=17.09kV
Cell #563	(void)	breaks down at E=43.83kV/cm	VApplied=17.09kV
Cell #566	(void)	breaks down at E=43.00kV/cm	VApplied=17.09kV
Cell #569	(void)	breaks down at E=67.20kV/cm	VApplied=17.09kV
Cell #582	(void)	breaks down at E=58.99kV/cm	VApplied=17.09kV
Cell #594	(void)	breaks down at E=70.21kV/cm	VApplied=17.09kV
Cell #595	(void)	breaks down at E=50.33kV/cm	VApplied=17.09kV
Cell #609	(void)	breaks down at E=51.10kV/cm	VApplied=17.09kV
Cell #615	(void)	breaks down at E=45.07kV/cm	VApplied=17.09kV
Cell #619	(void)	breaks down at E=67.12kV/cm	VApplied=17.09kV
Cell #630	(void)	breaks down at E=49.81kV/cm	VApplied=17.09kV
Cell #649	(void)	breaks down at E=45.28kV/cm	VApplied=17.09kV
Cell #663	(void)	breaks down at E=51.00kV/cm	VApplied=17.09kV
Cell #677	(void)	breaks down at E=46.47kV/cm	VApplied=17.09kV
Cell #692	(void)	breaks down at E=44.07kV/cm	VApplied=17.09kV
Cell #695	(void)	breaks down at E=36.62kV/cm	VApplied=17.09kV
Cell #696	(void)	breaks down at E=38.70kV/cm	VApplied=17.09kV
Cell #705	(void)	breaks down at E=49.69kV/cm	VApplied=17.09kV
Cell #711	(void)	breaks down at E=49.83kV/cm	VApplied=17.09kV

2nd iteration

Cell #368	(solid)	breaks down at E=40.05kV/cm	VApplied=17.09kV
Cell #421	(solid)	breaks down at E=42.16kV/cm	VApplied=17.09kV
Cell #442	(solid)	breaks down at E=40.50kV/cm	VApplied=17.09kV
Cell #467	(solid)	breaks down at E=41.87kV/cm	VApplied=17.09kV

3rd iteration

Cell #348	(solid)	breaks down at E=42.74kV/cm	VApplied=17.09kV
Cell #373	(solid)	breaks down at E=40.27kV/cm	VApplied=17.09kV
Cell #435	(solid)	breaks down at E=40.97kV/cm	VApplied=17.09kV
Cell #490	(solid)	breaks down at E=40.38kV/cm	VApplied=17.09kV

4th iteration

Cell #345	(solid)	breaks down at E=45.12kV/cm	VApplied=17.09kV
Cell #370	(solid)	breaks down at E=41.60kV/cm	VApplied=17.09kV
Cell #375	(solid)	breaks down at E=41.43kV/cm	VApplied=17.09kV
Cell #395	(solid)	breaks down at E=42.31kV/cm	VApplied=17.09kV
Cell #398	(solid)	breaks down at E=40.02kV/cm	VApplied=17.09kV

5th iteration

Cell #285	(solid)	breaks down at E=40.44kV/cm	VApplied=17.09kV
Cell #338	(solid)	breaks down at E=42.77kV/cm	VApplied=17.09kV
Cell #344	(solid)	breaks down at E=42.31kV/cm	VApplied=17.09kV

Cell number	Electric Field Strength	Applied voltage
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Cell #369	(solid) breaks down at E=41.24kV/cm	VApplied=17.09kV
Cell #374	(solid) breaks down at E=44.38kV/cm	VApplied=17.09kV
Cell #399	(solid) breaks down at E=47.48kV/cm	VApplied=17.09kV
Cell #430	(solid) breaks down at E=40.50kV/cm	VApplied=17.09kV

6th iteration

Cell #259	(solid) breaks down at E=46.00kV/cm	VApplied=17.09kV
Cell #284	(solid) breaks down at E=43.98kV/cm	VApplied=17.09kV
Cell #289	(solid) breaks down at E=43.75kV/cm	VApplied=17.09kV
Cell #314	(solid) breaks down at E=46.19kV/cm	VApplied=17.09kV
Cell #318	(solid) breaks down at E=43.60kV/cm	VApplied=17.09kV
Cell #330	(solid) breaks down at E=41.15kV/cm	VApplied=17.09kV
Cell #339	(solid) breaks down at E=44.96kV/cm	VApplied=17.09kV
Cell #343	(solid) breaks down at E=50.17kV/cm	VApplied=17.09kV
Cell #364	(solid) breaks down at E=46.58kV/cm	VApplied=17.09kV
Cell #367	(solid) breaks down at E=49.91kV/cm	VApplied=17.09kV
Cell #392	(solid) breaks down at E=54.26kV/cm	VApplied=17.09kV
Cell #393	(solid) breaks down at E=41.30kV/cm	VApplied=17.09kV
Cell #420	(solid) breaks down at E=41.46kV/cm	VApplied=17.09kV
Cell #432	(solid) breaks down at E=43.84kV/cm	VApplied=17.09kV
Cell #446	(solid) breaks down at E=40.96kV/cm	VApplied=17.09kV
Cell #457	(solid) breaks down at E=40.50kV/cm	VApplied=17.09kV

7th iteration

Cell #415	(solid) breaks down at E=49.09kV/cm	VApplied=17.09kV
Cell #286	(solid) breaks down at E=48.24kV/cm	VApplied=17.09kV
Cell #313	(solid) breaks down at E=48.18kV/cm	VApplied=17.09kV
Cell #310	(solid) breaks down at E=47.73kV/cm	VApplied=17.09kV
Cell #337	(solid) breaks down at E=47.68kV/cm	VApplied=17.09kV
Cell #362	(solid) breaks down at E=47.47kV/cm	VApplied=17.09kV
Cell #232	(solid) breaks down at E=47.41kV/cm	VApplied=17.09kV
Cell #461	(solid) breaks down at E=46.77kV/cm	VApplied=17.09kV
Cell #411	(solid) breaks down at E=46.47kV/cm	VApplied=17.09kV
Cell #335	(solid) breaks down at E=45.33kV/cm	VApplied=17.09kV
Cell #480	(solid) breaks down at E=45.25kV/cm	VApplied=17.09kV
Cell #306	(solid) breaks down at E=44.92kV/cm	VApplied=17.09kV
Cell #453	(solid) breaks down at E=44.68kV/cm	VApplied=17.09kV
Cell #388	(solid) breaks down at E=44.25kV/cm	VApplied=17.09kV
Cell #327	(solid) breaks down at E=44.19kV/cm	VApplied=17.09kV
Cell #404	(solid) breaks down at E=44.07kV/cm	VApplied=17.09kV
Cell #390	(solid) breaks down at E=43.75kV/cm	VApplied=17.09kV
Cell #436	(solid) breaks down at E=43.60kV/cm	VApplied=17.09kV
Cell #485	(solid) breaks down at E=42.87kV/cm	VApplied=17.09kV
Cell #257	(solid) breaks down at E=42.77kV/cm	VApplied=17.09kV
Cell #454	(solid) breaks down at E=42.55kV/cm	VApplied=17.09kV
Cell #428	(solid) breaks down at E=42.47kV/cm	VApplied=17.09kV
Cell #464	(solid) breaks down at E=42.12kV/cm	VApplied=17.09kV
Cell #331	(solid) breaks down at E=41.76kV/cm	VApplied=17.09kV
Cell #451	(solid) breaks down at E=41.40kV/cm	VApplied=17.09kV