Assessment of Dielectric Degradation by Ultrawide-band PD Detection

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ABSTRACT

Partial discharges (PD) and the way they affect insulation quality has for decades been a rewarding subject for many researchers. And still the attention given to this field is considerable, partly because of the quest to predict the residual life of HV components. There are two topics that are of particular interest to the workers in the field of PD. One is the impact of a wide variety of statistical tools on the interpretation of discharge data obtained with standard PD detection apparatus according to IEC270. Pattern recognition techniques applied to phase distributions of PD lead to valuable results and are addressed by other authors in this issue. The other topic is the study of discharge-induced degradation processes by looking into the physics of the discharge process. This can be done by different means but a valuable technique, at least for the laboratory, is the use of ultra-wide band PD detection systems. This paper is a mix of a short review on the progression in the understanding of deterioration by internal PD obtained with such systems and of results recently obtained by the author.

1. INTRODUCTION

IN discussing the progress made in the area of ultra-wide band measurements during the last decade, two developments have to be mentioned that were of major importance. These are the development of extremely fast and affordable digital oscilloscopes and waveform digitizers, and the introduction of high-speed sensitive cameras.

In addition to these more practical events it is important to point out the advances made in the understanding of the physics and chemics of PD aging processes. Therefore a close look will be taken at what has been added to our knowledge and what still has to be discovered. To do justice to the pioneers in the field it must be stated that the roots of many 'discoveries' being made nowadays are the merit of people working on PD many years ago. Most recent progress has been made in linking and interpreting the data obtained with time-resolved or UWB measurements, optical measurements and studies of the chemical degradation processes involved.

Digital oscilloscopes and waveform digitizers sample signals using a fast analog-to-digital converter (ADC). At evenly spaced intervals, the ADC measures the voltage level and stores the digitized value in high-speed dedicated memory. The shorter the intervals, the faster the digitizing rate, and the higher the signal frequency which can be recorded. The more memory, the longer the recording time. The most important advantages of using a digital scope instead of an analog scope are: capture of transient events (PD), pretrigger viewing, accurate measurements at high speed, archiving for later analysis, waveform analysis and complete programmability.

At this moment, a number of 1 GHz bandwidth digital oscilloscopes and waveform digitizers is available on the market. The oscilloscopes to be used for PD measurement necessarily need high sampling rates and deep memories in order to capture the transient discharge in a single shot. Applying Nyquists criterion on the discharge pulses to be measured, sample rates of $\geq$ 2 Gsamples/s are needed in conjunction with an analog bandwidth of at least 1 GHz.

The development of solid state CCD cameras with multiple image intensifiers (amplification $> 10^5$) and high-speed electronic shutters facilitated the recording of the temporal as well as the spatial development of light-emitting events like discharges. For a review of fast optical devices the reader is referred to [79]. By synchronizing camera and oscilloscope the build up and evolution of discharge events can be followed in great detail.

The reader is referred to the literature [16, 27, 38, 47, 55, 73, 96] for an extensive description of UWB and optical measurement setups.

There can be no misunderstanding that the field of deterioration from PD is a multidisciplinary field. From the above it is evident that the field of very high speed instrumentation is of major importance. From the more fundamental point of view, gas discharge physics as well as solid state physics are needed. Once we start off with discharges in an air-filled cavity in a polymer, the amount of discharge byproducts is enormous: chemical expertise cannot be eliminated. And last but not least, PD is a stochastic process and statistics have to be introduced to describe sequences of discharges.

It is not the aim of this paper to cover the entire area of degradation by discharges. The paper concentrates on the knowledge recently gained with ultra-wide band detectors and optical discharge recording systems.

This paper is organized in such a way that in Section 2 the achievements of the last five years are reviewed, with reference to the early workers in the field. Phenomenological data are given that were obtained with UWB and optical studies. A short survey of the chemical degradation is included. In Section 3 the data are discussed and attention is given to the physical mechanisms that play a role in the degradation process. Section 4 summarizes the state of the art and ends with a list of topics that are left for further study. Possible practical implications of the knowledge described in Section 3 are addressed.

2. PHENOMENOLOGY

The discharge reveals itself in a number of ways [52]. It is accompanied by a charge displacement in the cavity that causes current in the leads to the object, radiation emitted by excited particles, ultrasonic sound, heat, from particle impact, and chemical reactions.

Of these five manifestations the first two and the last one will be dealt with in the following sections.

After a short introduction and description of the early years until the 1980's, the state-of-the-art of the phenomenological aspects of internal discharge degradation is listed. The movement of electrons and ions in the cavity and the external measuring circuit determine the pulse shape of the discharge current (Section 2.2). The photons emitted by the discharge make the discharging area visible and facilitate the exact location of the discharge (Section 2.3). The point of impact of the discharge can thus be related to the damage done to the surface of the cavity. Chemical reactions in the gas and at the gas-dielectric interface lead to the creation of degradation products that affect the discharge process (Section 2.4). A distinction is made between three different aging stages: virgin, moderately aged (hours) and severely aged (weeks).

2.1. THE EARLY YEARS

In 1916 Townsend [95] already calculated the development of electron avalanches. Raether [80] was the first to compare calculated (Townsend) breakdowns with electrical and optical measurements in the 50's and early 60's. The relatively large gap distance between electrodes that he used allowed the use of oscilloscopes that are in our eyes extremely slow. We have to wait until 1967 for the first measurements on small cavities in a dielectric when Bailey [1] measured discharges in discshaped cavities with a bandwidth $\sim$ 400 MHz. PD pulses were reported with a rise time of 1 ns, which was the limit of his measuring system. Since the 1980's widespread use of ultra-wide band (UWB) PD detection systems is observed for both laboratory experiments [9, 13, 16, 21, 27, 33, 35, 36, 39, 42, 54-55, 58, 68–74, 96–99] and measurements on HV GIS, cables and generators [11, 12, 16, 19, 24, 83, 88, 102]. What was impossible some 40 years ago due to limitations of the technology is now feasible due to the introduction of affordable high frequency electronic systems with a bandwidth exceeding 1 GHz. The short rise time of these systems have permitted the study of the movement of both electrons and ions in a discharge.

Mason was the first to record the optical appearance of discharges in dielectric bounded cavities [60]. Figure 1(a) shows discharges in a cavity of 5 mm diameter and 0.3 mm depth between a sheet of polyethylene and a photo-sensitive surface. It proved that flat cavities are discharged by a number of discharge events distributed in the cavity. The appearance of the surface discharges that are observed when the discharge channel reaches the other end of the cavity is quite similar to the appearance of the figures found more than two centuries ago by Lichtenberg [57]. Figure 1(b) shows an example of the Lichtenberg figures that appear when PD bridges a dielectric bounded gap [73].

Concerning chemical degradation in dielectric bounded cavities, Rogers [84, 103] in 1958 probably was the first to observe pits and crystal like structures at the cavity surface using an optical microscope. Starting in the
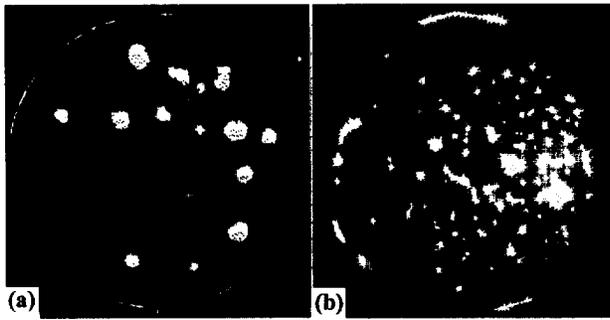
Figure 1.

(a) Discharges in a cavity of 5 mm diameter and 0.3 mm depth between a sheet of polyethylene and a photo sensitive surface [61]. (b) Contact photograph of the surface discharges at the base of the discharge channel (Lichtenberg figures), cavity depth = 1 mm, diameter = 100 mm. The photo was made at the start of the virgin stage [73].

1970's, modern techniques were used to investigate the deterioration by PD of the insulating material. Examples are the use of the scanning electron microscope [34,45, 62] and infrared spectroscopy [64,65]. It was found that, besides a homogeneous erosion of the dielectric, crystals were deposited at the surface and eventually craters appeared. Hiley *et al.* [34] first suggested that discharges would concentrate and cause craters in the direct neighborhood of these crystals.

2.2. PULSE SHAPE OF DISCHARGES

In the literature on UWB measurements of PD, a variety of pulse shapes are mentioned. Of overall importance when comparing the pulse shapes measured by different authors is the way their test circuit influenced their results. Taking this into account there is a large agreement on the different pulse shapes that can be found in dielectric cavities. When discussing the results of PD measurements in dielectric cavities, it is necessary to make a distinction between flat cavities and delaminations on the one hand and spherical or ellipsoid cavities on the other hand.

2.2.1. VIRGIN SAMPLES

If a sample is stressed for the first time, discharge pulses are recorded with a steep front and with a short duration. The amplitude of these pulses can attain high values, with an order of magnitude of $\sim$ 10 mA to $\sim$ 1 A. A typical example of the pulse shape of such a discharge is shown in Figure 2. Concerning the number of discharges, a distinction has to be made between spherical cavities and flat disc-shaped cavities. Spherical cavities are discharged by one single discharge at a time, whereas
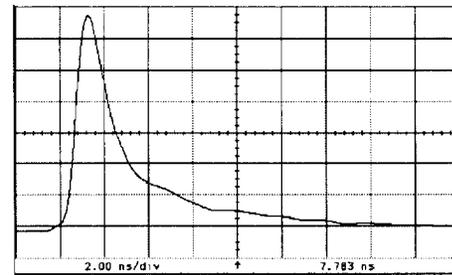

Figure 2.

Fast discharge pulse in a virgin cavity of 0.1 mm depth and 1 mm diameter in polyethylene (streamer like discharge).

flat cavities are discharged by a large number of almost simultaneously occurring discharges [68].

Garcia Colon [27] and Kurrat [55] made PD measurements on spherical cavities in epoxy with a diameter between 0.8 and 2.0 mm. Both found discharges with a front time of < 800 ps, a width of 1 to 2 ns and an amplitude ranging from 60 to 600 mA.

Holbøll [38] recorded discharge pulses in different types of epoxy with spherical cavities with diameters of 1 to 5 mm. He found a fast type with a rise time of < 500 ps, a pulse width of 700 ps and nearly constant pulse height of $\sim$ 5 mA.

The pioneering work of Luczynski [58] at the end of the seventies led to the first characterization of discharge mechanisms in disc-shaped dielectric cavities. He measured 'rapidly developing' PD in virgin samples of polyethylene and polypropylene of 0.6 to 2.0 mm height and a diameter ranging from 5 to 20 mm. The order of magnitude of the discharge pulse amplitude was 10 mA. Both the rise time and the width of the pulses were in the nanosecond range. Luczynski reported that occasionally 'slowly developing discharges' were recorded at the start of a test. These discharges were probably of the type described in the Section on moderately aged samples.

Dejean [16,17] reported the occurrence of discharges with an amplitude of 5 to 20 A in unaged disc-shaped cavities in polyethylene of 19 μm height and 6 mm diameter in the first seconds of voltage application. This is not the measured current but the real current in the cavity, calculated by taking into account the sample geometry. The apparent current would have been of the order of 10 mA. The rise time of the measured pulses, limited by the system bandwidth, was $\sim$ 500 ps.

The author [68,73,74] studied the pulse shape of PD in disc-shaped cavities in polyethylene and other polymers. The height of the cavities was between 30 μm and 3.7 mm and the diameter was between 1 and 10 mm. Typical rise times for the discharges observed in these cavities in the
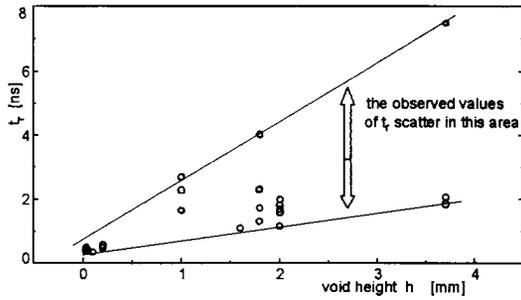
Figure 3.

Discharge pulse rise times of disc shaped cavities in polyethylene with a depth h ranging from 30 μm to 3.7 mm and with a diameter of 1 to 10 mm.
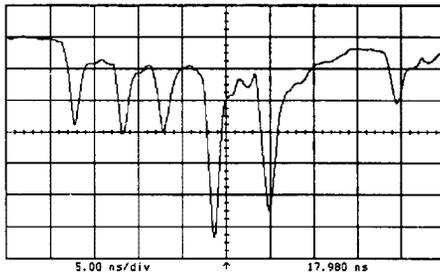

Figure 4.

Superposition of consecutive discharges in a cavity with a large diameter/depth ratio (diameter = 20 mm, depth = 0.1 mm). The first three pulses are single discharges, the fourth and the fifth pulse are the result of superposition of three single discharges.

virgin state are shown in Figure 3. For cavities with a diameter height ratio $\gg$ 1 groups of discharges often were observed with a very short time period between consecutive discharges ($\leqslant$ 1 ns), as can be seen in Figure 4. Often the single discharges can no longer be recognized in the pulse shape of the discharge signal. Figure 5 shows an example of groups of discharges recorded synchronously with an UWB system and an optical system [68]. It is clear that, although a single electrical pulse was detected, several discharges occurred. The fact that flat cavities are discharged by a large number of spatially distributed discharges was already described by Mason in [61]. With the fast detection techniques now available it was shown [68] that these are individual discharges occurring almost simultaneously. The amplitude of individual discharges was observed to have a small scatter, as can be seen in Figure 6. It is evident that with conventional PD detectors the individual discharges cannot be distinguished and superposition of pulses takes place [68].

2.2.2. MODERATELY AGED SAMPLES

After $\sim$ 5 min to $\sim$ 5 h of discharge activity, the shape of the discharge pulses changes. Here again a distinction
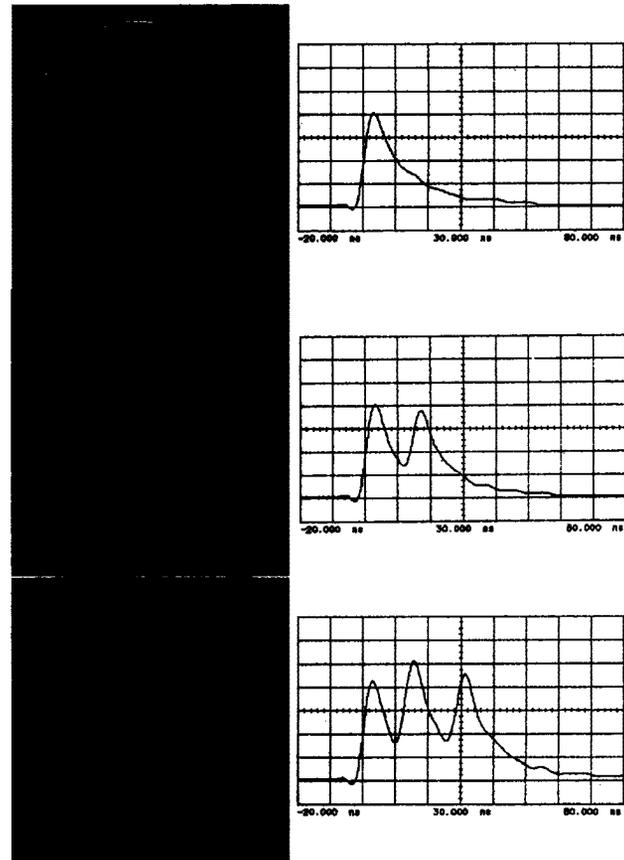

Figure 5.

Synchronously recorded optical and electrical discharge signals of groups of discharges in a disc shaped cavity in polyethylene (diameter = 10 mm, depth = 0.8 mm).
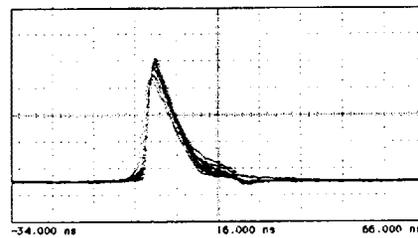

Figure 6.

A succession of discharges in a 1 mm diameter, 1 mm depth cavity in polyethylene. The ten recorded discharges show a remarkable small scatter in amplitude.

must be made between spherical and flat cavities. In flat cavities a significant and reproducible change of the pulse shape is observed [9, 16, 27, 42, 58, 68, 74], whereas in spherical cavities this change is less clear [27, 37, 55].

The rise time and the width of the pulses increase significantly, i.e. to $\sim$ 5 ns, respectively $\sim$ 50 ns. Figures 7 and 8 show typical examples of such discharge pulses. As described in [21, 58, 68] the pulse width in disc-shaped
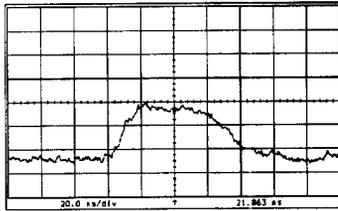
Figure 7.

Slow discharge pulse in a moderately aged cavity
of 0.1 mm depth and 10 mm diameter in polyeth-
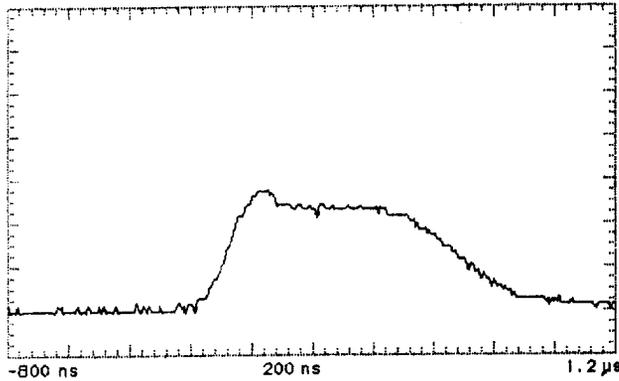ylene (Townsend like discharge).

Figure 8.

Slow discharge pulse in a moderately aged cavity
of 1 mm depth and 10 mm diameter in polyethyl-
ene (Townsend like discharge). The effect of the
depth on the pulse shape and in particular on the
rise time and on the pulse width is clearly visible
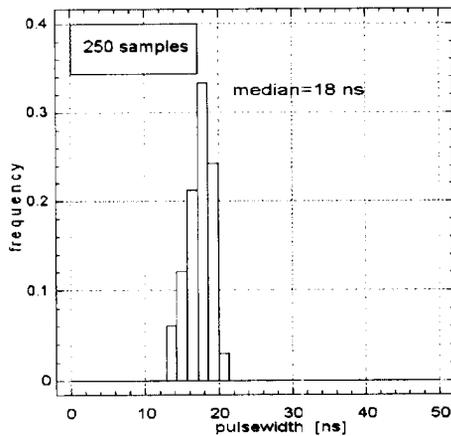if compared with Figure 7.

Figure 9.

Pulse width histogram of slow discharges in a
cylindrical cavity in polyethylene of 50 μm depth
and 10 mm diameter.

cavities is unambiguously determined by the height of
the cavity as can be seen in Figures 9 to 12 where pulse
width histograms are shown for cavities with a height of
50 μm, 0.1, 0.2 and 0.4 mm. The amplitude of these
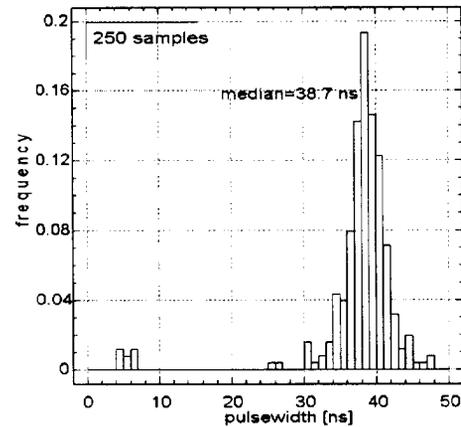pulses ranges from the sensitivity limit of the detection

Figure 10.

Pulse width histogram of slow discharges in a
cylindrical cavity in polyethylene of 0.1 mm
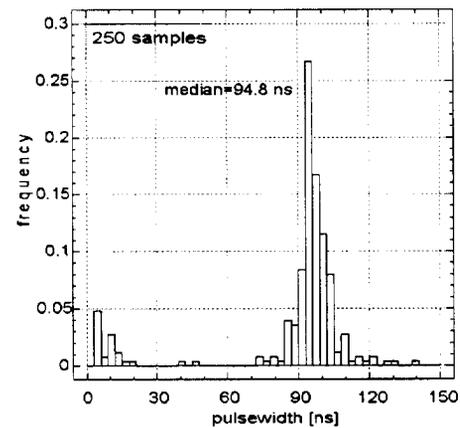depth and 10 mm diameter.

Figure 11.

Pulse width histogram of slow discharges in a
cylindrical cavity in polyethylene of 0.2 mm
depth and 10 mm diameter.

system to ~ 1 mA.

2.2.3. SEVERELY AGED SAMPLES

For severely aged samples two pulse types are reported,
both of them characterized by extremely small amplitude
and a high repetition rate [3, 6, 9, 14, 42–44, 50, 51, 56, 71,
74, 75, 92, 90].

After ~ 10 to ~ 100 h at field strengths of 5 to 20 kV/
mm, the pulse shape in flat cavities changes [71–74]. The
discharge pulses are now characterized by a small ampli-
tude (order of magnitude 10 μA) and a high repetition
rate, up to several discharges per microsecond. The rise
time of these pulses is comparable with the rise time of
the fast discharges detected in a virgin sample. The de-
cay time is considerably longer, typically 10 to 15 ns.
Figure 13 shows a typical example of a series of such
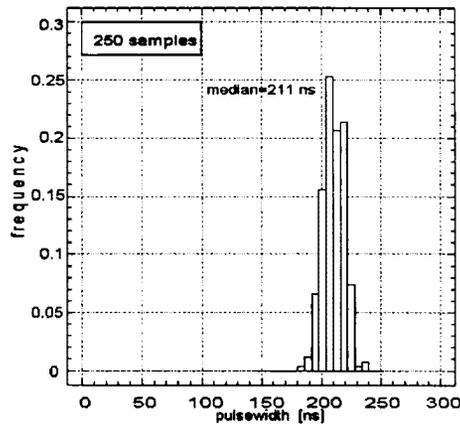discharge pulses.

Figure 12.

Pulse width histogram of slow discharges in a cylindrical cavity in polyethylene of 0.4 mm depth and 10 mm diameter.
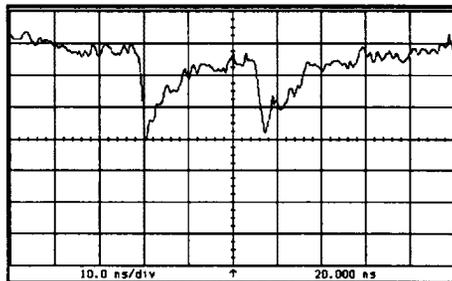

Figure 13.

Typical pulse shape of a series of discharges (pitting discharges) in a severely aged cavity in polyethylene of 5 mm diameter and 0.1 mm depth.

The second discharge type that often has been found (and is referred to as glow, pulseless or swarming pulsive micro discharge) is characterized by long rise times and a high repetition rate [4, 5, 43, 44, 51, 50, 92].

2.3. OPTICAL MEASUREMENTS

To obtain information on the spatial distribution of the discharge in the cavity, additional measurement facilities are necessary. Optical analysis of the light emitted by the discharges enables tracing of the exact location of a discharge and hence the area where deterioration of the dielectric takes place.

In the last three years three PhD theses were published on the simultaneous recording of both electrical and optical signal of discharges in cavities [38, 73, 16]. The authors were able to relate typical optical images to typical pulse shapes as described above.

Holbøll [38] recorded the spatial distribution of discharges in spherical cavities and found two different types of discharges: discharges that produce a light channel through the cavity or on its surface, and more diffuse discharges which covered most of the cavity volume, were
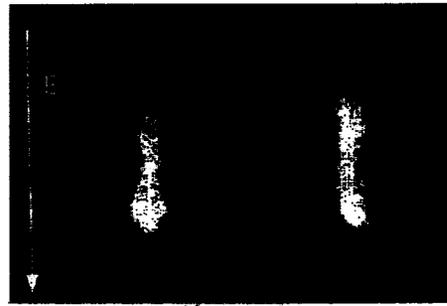

Figure 14.

The spatial development of a fast, filamentary discharge in a spherical cavity in epoxy. The two images show the same discharge as seen from two directions with an angle of 90° in between [38].

Figure 15.

The spatial development of a slow, diffuse discharge in a spherical cavity in epoxy. The two images show the same discharge as seen from two directions with an angle of 90° in between [38].

of considerable less intensity. Figures 14 and 15 show the discharge images that he recorded as seen from two directions with an angle of 90° in between. The difference between the filamentary type and the diffuse type can clearly be seen. The filamentary type was directly related to the fast pulses as described in the section on virgin samples. The diffuse type was always linked to a slower discharge pulse type as described in the section on moderately aged samples.

Morshuis [73] recorded the spatial distribution of discharges in cylindrical cavities and found three types of discharges, related to the three types of discharge pulses described in Section 2.2. In this case the optical observation provided a means to identify single discharges because of their spatial distribution across the surface of the cavity. Figure 16(a) shows the optical images of single discharges for different cavity geometries in the virgin stage. If these discharges are monitored it is observed that there are no preferential ignition sites, i.e. the discharges move across the surface of the cavity. A discharge site is represented by a circular spot of high light intensity, the area of which is approximately equal to the height of the cavity. This confirms the rule of thumb introduced by Mason in [60, 61].
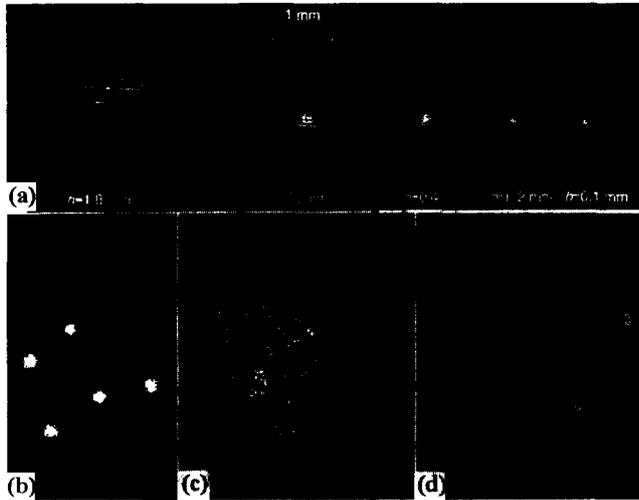
Figure 16.

(a) The spatial development of a single fast, filamentary discharge recorded in disc shaped cavities in polyethylene of different depth. The diameter of the void was 10 mm. Note that the diameter of the discharge is about equal to the depth of the cavity. (b) Optical appearance of a single fast discharge in a disc shaped cavity in polyethylene of 10 mm diameter and 1 mm depth (virgin stage). (c) Optical appearance of a single slow discharge in a disc shaped cavity in polyethylene of 10 mm diameter and 1 mm depth (moderately aged stage). (d) Optical appearance of a a number of pitting discharges in a disc shaped cavity in polyethylene of 10 mm diameter and 1 mm depth (severely aged stage).

In Figures 16(b) to (d) the spatial development of discharges in a disc-shaped cavity in polyethylene of 1 mm depth and 10 mm diameter is shown at different stages of the aging process. In the virgin stage the discharges have the appearance as described above. The appearance of the discharges in the moderately aged stage is of a diffuse nature. A large part of the cavity surface is covered by a single discharge. In the severely aged stage the diffuse discharges have almost disappeared and discharges are seen to ignite at a number of preferential sites.

The results of Dejean [16] are not entirely consistent with those of Morshuis. He observed discharges concentrated at the periphery of the virgin cavity and a subsequent movement of the discharge activity to the center. Ultimately the discharges were concentrated at a few locations only, which confirms the results of Morshuis. It is not clear whether Dejean makes a distinction between diffuse and filamentary discharges.

2.4. DEGRADATION AND CHEMICAL PROCESSES

The degradation process at the interface between dielectric and gas is accompanied by intricate chemical processes. Many authors have listed all the different gaseous [100,104] and solid byproducts [17,22,25,26,29,41, 48,62–65,82]. One has to distinguish between chemical reactions between the constituents of ambient air, and reactions in which the polymer is involved.

Although the processes are complicated it is now possible to describe the evolution of the chemical byproducts from the start of the aging process to the start of pitting of the dielectric. Roughly there are three stages to be recognized: acidification of the dielectric surface, formation of droplets and crystallization. These stages occur synchronous with the changes observed in the discharge pulse shape and the optical appearance of the discharge (see Sections 2.2 and 2.3).

2.4.1. GASEOUS BYPRODUCTS

The discharge byproducts that have been identified can be divided in three categories: gases, liquids and solids. Wolter et al. [100,104] investigated the gaseous byproducts of low density polyethylene exposed to corona discharges. The main degradation products were found to be hydrogen, carbon monoxide, methane and carbon dioxide. The formation of hydrogen was shown to be a direct result of the interaction between polymer and the radiative energy of the discharges. Oxidation of fragments of polymer chains were believed to lead to the formation of the carbon oxides.
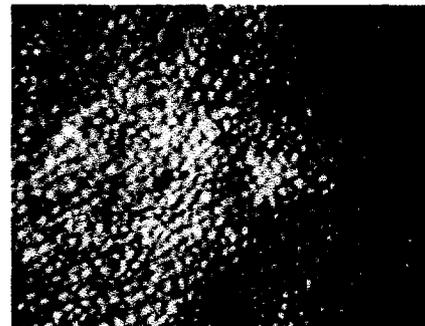

Figure 17.

Droplets covering the surface of a cavity in polyethylene after a short exposure (minutes) to discharges.

2.4.2. ACIDIFICATION, FORMATION OF DROPLETS

Liquid byproducts were found in the form of droplets [18,30,40,48,73] at the insulator surface for a large number of different materials, for instance polyethylene, epoxy and polypropylene, see Figure 17. Gamez-Garcia et al.

[25] showed that the droplets were formed only when an atmosphere containing water and carbon monoxide was present. Morshuis [73] showed that if one of the constituents H, C or O was absent no droplets could be found. The following process is now believed [30, 73] to lead to the formation of the droplets: Scission and oxidation of polymer chains results in the creation of short chain fragments (oligomers). These fragments are dissolved in water and form clusters on the surface of the dielectric. The water originates from the gas atmosphere or from a combustion process taking place on the dielectric surface. Sigmond *et al.* [87] showed that polyethylene and polypropylene surfaces that are subjected to discharges emit significant amounts of water if oxygen is present. Experiments of Morshuis [73] showed that even in an atmosphere of dry air (RH < 5%) droplets were created. The amount of droplets however was smaller and the formation time was longer. This supports the theory that water is formed in the discharge process. Gamez-Garcia *et al.* [25] showed that the introduction of moisture in their test cell led to substantial changes in the types of products. With atmospheres of oxygen and air at 40% RH many droplets were found.
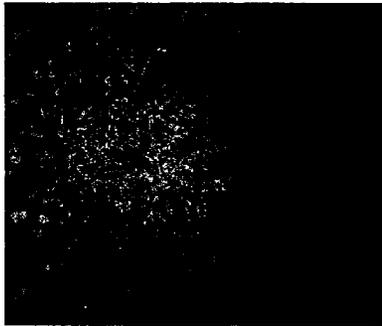

Figure 18.

Crystals covering the surface of a cavity in polyethylene after a long exposure ($\sim$ 100 h) to discharges.

2.4.3. CRYSTALLIZATION

After $\sim$ 100 h of discharge activity, solid byproducts are found in the form of crystals at the insulator surface, for a large number of materials [19, 25, 26, 38, 40, 41, 71-74, 82]. These crystals have been positively identified as hydrated oxalic acid ($C_2H_2O \cdot 2H_2O$) by Hudon *et al.* [41]. As for the droplets mentioned before, these crystals are created only in the presence of H, C and O [25, 73]. Foulon *et al.* [22] have shown that a local crystallization of droplets occurs at the point of impact of the discharges. The same was observed by Morshuis [71-74] and Holbøll [38], see Figure 18.

2.4.4. PITTING

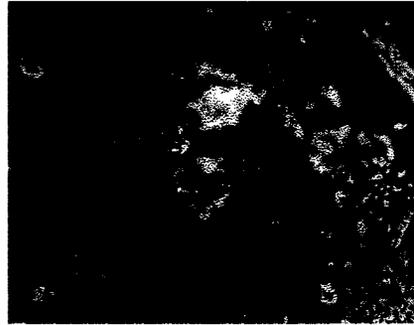After hundreds of hours of discharge activity pits are created by a local attack of the dielectric surface at the

Figure 19.

Crater at the surface of a cavity in polyethylene after $\sim$ 300 h exposure to pitting discharges at the tips of the crystals still visible at the edges of the crater.

locations where clusters of crystals are found [17, 18, 38, 71-74]. Figure 19 shows an example of a crater resulting from the pitting process at such a cluster of crystals. By synchronous electrical and optical recording of the discharge process it was proven by the author that the edges of the crystals are eroded by the discharges and that craters are formed in the dielectric below the crystals [72]. Eventually it was observed that a breakdown of the dielectric occurred starting at such a crater [53].

3. DISCHARGE MECHANISMS

The discharge theory for dielectric bounded cavities has a number of characteristics in common with the theory for electrode bounded gaps. Generally, it is found that discharge ignition voltages are about equal for both situations. Therefore the breakdown values described by Paschen's law are widely used for dielectric cavities, with an error of a few percent only. The most striking difference is obviously the self-limiting effect of the discharge between dielectric planes.

In the small cavities that are considered the effect of both the gas and the dielectric surface have to be considered. The effective ionization coefficient is a property of the gas and is therefore affected by the changing gas chemistry and by a change of pressure in the cavity. It is also strongly related to the overvoltage at which the discharge ignites. Townsend's secondary coefficient γ however is largely affected by the properties of the cathode material. Literature on the value of γ of dielectrics is limited and sometimes contradictory. Morshuis [73] measured the photo-current of different dielectrics by irradiating them with ultraviolet light of 185 and 254 nm. The photocurrent of metals was found to be 2 to 3 orders of magnitude higher than that of dielectrics. Saeki and Gosho [85] made comparative tests on a number of dielectrics as well as on metals to compare the number of photo-electrons liberated by the radiation of an ultraviolet source. The results indicated a significant difference

of two orders of magnitude between insulating materials and metals. Yumoto et al. [101] irradiated different dielectrics with a deuterium lamp emitting a continuous spectrum from 160 nm to the visible light region. It was found that the dielectrics emitted about 500 times less than gold. Tom et al. [94] measured the photo-current of epoxy surfaces. Reference measurements on stainless steel showed a yield only twice that of the epoxy for wave lengths between 160 and 250 nm. Takahashi et al. [89] calculated the value of γ in a setup with two spherical electrodes covered with a dielectric layer. They mentioned values of γ with the same order of magnitude as for metals. The results on the photo-electron emission from dielectric surfaces indicate that the value of γ can not be taken equal to that of metals, as is often done.

In the following the discharge stages described in Section 2 will be discussed with reference to the physical processes in the gas and at the dielectric surface.

3.1. VIRGIN STAGE

Before a discharge ignites, an initiatory electron has to be available at a suitable position in the cavity to start the ionization process. Initiatory electrons are produced by: (1) photo-ionization in the gas or at the surface of the dielectric by natural cosmic and radioactive radiation, and (2) liberation of electrons deposited by earlier discharges and trapped at the surface of the dielectric [73,76]. The very first discharge in a virgin cavity usually has a waiting time for a first electron of the order of minutes or even longer [27]. These electrons are produced by cosmic or radioactive radiation. The succeeding discharges show much shorter time lags, in the order of milliseconds. These electrons are the result of thermal detrapping processes at the dielectric surface [76].

In the early stage of discharge activity the waiting time for a first electron (statistical time lag) is long due to the presence of electronegative oxygen [92] and due to the fact that only few electrons are liberated from the dielectric surface because of the high ionization potential of the unaged material (~ 10 eV for polyethylene). Therefore discharges ignite at overvoltages of up to $\sim 30\%$ resulting in a fast development of the avalanche process.

A significant space charge is build in the cavity due to the slow moving positive ions [21] that were created in a number of generations of avalanches. The resulting space charge field, if large enough, can lead to a breakdown process similar to the cathode directed streamer breakdown: streamer-like discharge [21]. If the overvoltage attains very high values that lead to the well-known number of 10^8 electrons in the first avalanche, an anode directed streamer develops.
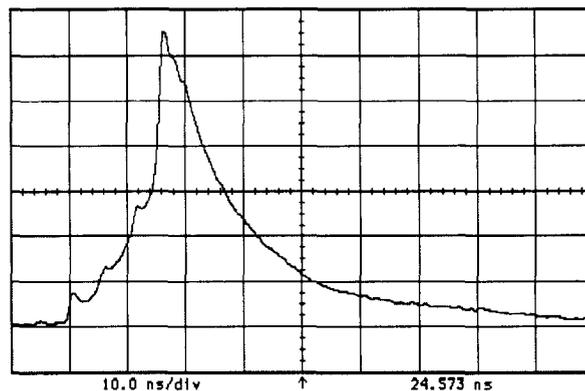

Figure 20.

A number of generations of avalanches leading to a streamer like discharge. The transition is visible after four (visible) avalanches.

In a dielectric bounded cavity there are two competing processes taking place as was described by Devins [21]. The Laplace field in the cavity decreases due to the deposit of charges at the dielectric surface and the space charge field increases due the increasing number of slow moving positive ions in the cavity. If the increase of the space charge field is bigger than the decrease of the Laplace field, a streamer-like discharge takes place. Figure 20 shows an example of such a discharge measured in a 1 mm high, 1 mm diameter cavity, starting with four (visible) generations of avalanches and ending in a streamer-like process.
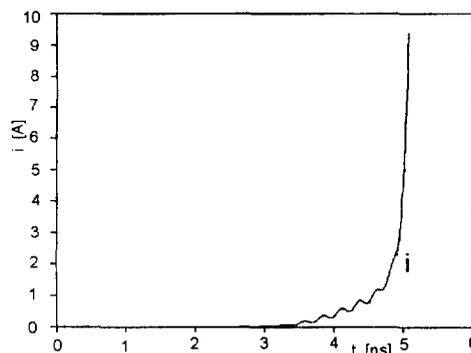
Figure 21.

Calculated discharge signal in a cavity of 0.1 mm depth and 10 mm diameter at an overvoltage of 2.5%. The transition to a streamer like mechanism is visible after some 20 generations of avalanches.

If the development of the discharge is calculated using a quasi two-dimensional model [73], it can be shown that at high overvoltages a transition as shown in Figure 20 will take place. In Figure 21 this transition is calculated for a cavity of 0.1 mm depth and 10 mm diameter at an overvoltage of 2.5%. Kennedy [46,47] calculated the streamer transition in 5 and 10 mm gaps between metal

electrodes using a fully two-dimensional model. He concluded that at overvoltages of ~ 30% an avalanche to streamer transition takes place with photo ionization in the gas playing the dominant role. Moreover, he concluded that at these high overvoltages photoelectron emission at the cathode is of secondary importance.

In virgin cavities of large diameter, groups of discharges often are seen to ignite almost instantaneously, see Figure 5. This is explained by initiation of discharges at other locations, triggered by photons emitted by the first igniting discharge.

3.2. MODERATELY AGED STAGE

The discharges in the early stage of the aging process deposit a layer of degradation products at the surface of the dielectric. The physical properties of the surface are changed by these degradation products. This can be recognized in increased wettability of the surface [16, 30] and in a strong increase of the surface conductivity [40, 58, 68]. The latter is the result of the degradation products that are dissolved in water and form an acid electrolyte surface layer. The water, either produced in the discharge process (see Section 2.4), or present in the ambient air, also promotes the clustering of the acid degradation products [25, 30, 48]. Here we observe the formation of droplets at the surface of the dielectric as described in Section 2.4 and an example of which was shown in Figure 17. Further, the oxidation of the dielectric leads to the creation of large numbers of surface traps. The trapped electrons can contribute to the conduction by hopping processes.

The thus created surface layer acts as a reservoir of electrons from which initiatory electrons can be liberated easily by thermal detrapping [73, 76]. The effect on the statistical time lag is considerable and the overvoltage at which the discharges ignite decreases significantly to ~ 0.5% [73]. The same effect is observed when the cavity is irradiated by strong ultraviolet light or by X-rays [9, 10, 20, 23, 24, 83] when sufficient starting electrons are generated.

Using the same quasi two-dimensional model as above the discharge current was calculated for different (small) overvoltages. Figure 22 shows the effect of the overvoltage on the shape of the discharge pulse. In this case the build up of positive space charge is slow because of the less intense ionization. Before the space charge field attains the high values needed for a transition to a streamer-like process the Laplace field in the cavity drops to very low values so that the resulting field stays below the streamer inception value. The discharge now behaves as a Townsend process, or in other words, as a succession of generations of avalanches all starting by secondary

Figure 22.

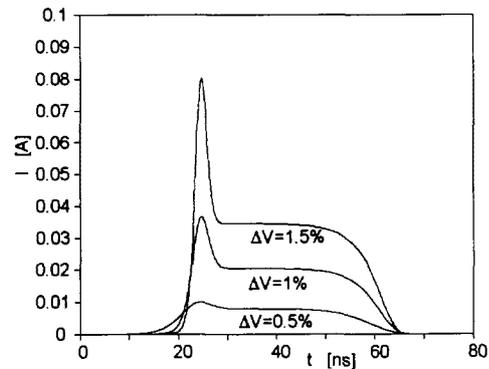The effect of the overvoltage on the shape of the discharge pulse. Calculated discharge signals in a cavity of 0.1 mm depth and 10 mm diameter at different overvoltages. Note that for small overvoltages the amplitude of the discharge pulse can become extremely small.
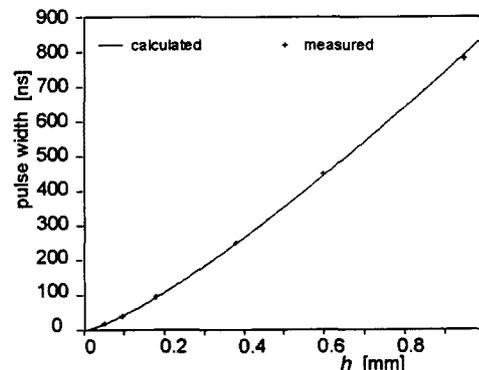

Figure 23.

Relation between the pulse width of a Townsend like discharge and the depth of a cavity (solid line: calculated, crosses: measured).

photo ionization at the cathode. The Townsend-like discharge is by nature a diffuse process, *i.e.* generations of avalanches spread across the surface of the cavity. This can be seen clearly in Figure 16(c) where a large part of the cavity is discharged. Similar results are reported in [9, 38]. In the shape of Townsend-like discharges the contribution of the positive ions to the discharge current can be recognized. The peak at the start of the pulse is due to the electron motion while the plateau behind the peak is due to the motion of the positive ions. Because the majority of the positive ions is created just in front of the anode, the time needed to cross the cavity is approximately equal to the height of the cavity divided by the drift velocity of the positive ions. Therefore the pulse width of Townsend-like discharges is a characteristic feature because it is only dependent on the height of the cavity. Figure 23 shows the pulse width of Townsend-like discharges calculated and measured for a range of cavity heights. The calculated and the measured values
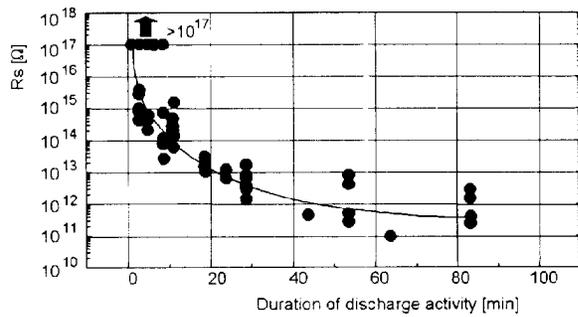
of the pulse width match perfectly.

Figure 24.

Surface resistivity of a cavity in polyethylene as a function of exposure to discharges.
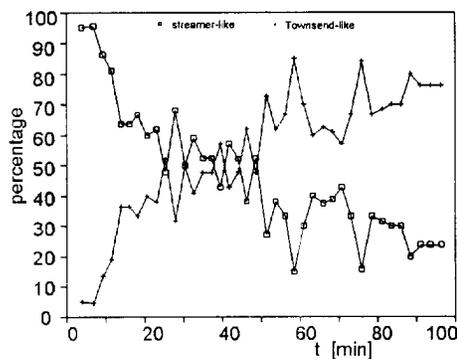

Figure 25.

Percentage of Townsend like and streamer like discharges as a function of discharge exposure of the same cavity as in Figure 24.

To relate the growing layer of degradation products to the change of the discharge mechanism, the following experiment was done [73]. The surface conductivity of a sheet of polyethylene was measured as a function of the time the sheet was subjected to discharges in a cavity. Every five minutes the discharge setup was opened and the conductivity of the sheet was measured. A specially constructed small probe was used with an outer diameter of 20 mm. In this experiment it was found that opening and closing the sample with the cavity several times had no significant effect on the aging process. Figure 24 shows the evolution of the surface conductivity obtained for a polyethylene sheet exposed to discharges for a period of 1 h. It can be seen that the largest increase of the conductivity occurs within the first 10 min of discharge activity. This is in agreement with the fact that for this sheet the first Townsend-like discharges were observed after ~ 10 min. After ~ 1 h, when the conductivity reached a stable value, the large majority of streamer-like discharges was replaced by Townsend-like discharges. This is illustrated in Figure 25 where the percentage of both types of discharges is shown as a function of the time the sheet was exposed to discharges. For the conductivity

of epoxy exposed to discharges a similar behavior was reported [42].

3.3. SEVERELY AGED STAGE

After prolonged discharge activity a crystallization of the droplets is observed and observation of the discharge process with sensitive optical equipment shows that very small discharges of high repetition rate ignite at these crystals. The sharp edges of these crystals act as field emitters and the discharge activity concentrates at these sites only. Avalanches starting at these field concentrations enter a lower field when they move away from the crystals. A process similar to that of corona at a sharp point takes place. This could explain the high repetition rates observed.

The concentrated discharge activity leads to a severe erosion of both the crystals and the dielectric below the crystals. At this moment there is, as far as the author knows, no satisfactory explanation of the process of pitting. It has been observed by the author and by Garcia Colon [28] using micro charge probes that a strong electron injection takes place at these pits. The resulting space charge field in the dielectric could be the initiator of a treeing process.

3.4. DISCHARGE NOMENCLATURE

When it comes to the physics behind the phenomena described above there is some discussion going on. An extensive nomenclature for discharge mechanisms has led to considerable confusion, sometimes leading to misunderstanding [15, 73]. The culmination of the dispute on the discharge mechanisms can be found in the discussion between Novak, Bartnikas and Danikas in [14], where Bartnikas and Novak postulate that all internal discharges are Townsend processes [6]. An overview of the most commonly used discharge nomenclature is given in Table 1, with those names grouped that are indicators of the same discharge mechanism according to the author.

The discharge types in group I are all characterized by their short rise time and short pulse width. Whether these types follow the streamer breakdown mechanism [38, 46, 73] or whether they are examples of Townsend processes [14, 55] at large overvoltages is still a point of discussion. Bartnikas [6] simulated the growth of the discharge current in a cavity of 0.5 mm depth with a 3-dimensional mathematical model and compared the results with measurements on a cavity of the same dimensions. The simulation showed a small but distinguishable ionic current indicating a Townsend process, that could not be observed in the pulses that were measured. Bartnikas stated that, because the amplitude of the ionic current is only a percentage of the electron current, the

Table 1.   Discharge nomenclature.

Group	Discharge type
1	spark
	streamer
	fast
2a	pseudo glow
	Townsend
	slow
2b	glow
	pulseless
	swarming micro PD
3	corona
	pitting

ionic current would be invisible in practice. He explains the sharp rise of the discharge pulse at high overvoltages by a strong field at the cathode due to the accumulation of positive space charge in the vicinity of the cathode. This high field would lead to a greatly enhanced photoemission at the cathode, further accelerating the process. The strong radial space charge field result in a constriction of the discharge channel. For a detailed description the reader is referred to [6]. It is not clear whether Bartnikas investigated the effect of secondary ionization in the gas at these high fields.
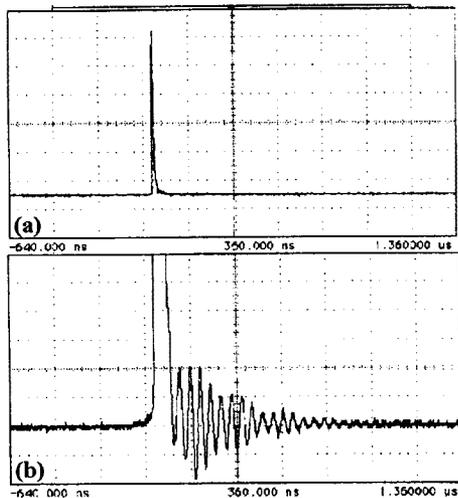

Figure 26.

(a) Discharge pulse optically recognized as a streamer like discharge. Pulse height: 70 mA. Sensitivity: 10 mA/div. (b) Detail of a: no contribution of positive ions to the discharge current can be p observed above 0.02 mA. The oscillations are the result of the inductance of the discharge path. Sensitivity: 100 μA/div.

Morshuis made measurements on a cavity of similar dimensions using a two-channel oscilloscope with two different sensitivity settings, thus being able to record both large and very small signals with a dynamic range of
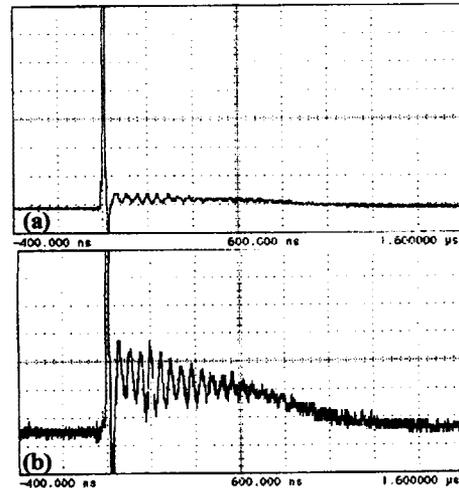

Figure 27.

(a) Discharge pulse optically recognized as a Townsend like discharge. Pulse height: 7 mA. Sensitivity: 400 μA/div. (b) Detail of a: the contribution of the positive ions to the discharge current can clearly be observed. Sensitivity: 80 μA/div.

5000. Figure 26(a) shows a current pulse that was optically recognized as a streamer-like discharge. A detail of this pulse is shown in Figure 26(b). No ionic current is visible, even at this sensitivity. If an ionic current is present it is < 0.02% of the electron current. The oscillations are the result of the unavoidable inductance of the discharge path and are not visible at normal operation of the oscilloscope. The same sample was aged for 30 min until diffuse discharges were recorded optically. In this case an ionic current can be observed, though it is very small, see Figures 27(a) and (b).

The types of group II are all considered to be genuine Townsend mechanisms and consist of several generations of avalanches. Bartnikas' description of pseudo-glow discharges as characterized by minute pulses of long rise time fits in very well. These discharges ignite at very small overvoltages and therefore they develop very slowly, resulting in the long rise times.

Group IIb is a special case because the discharge types very easily escape being detected. It is however the opinion of the author that these types are Townsend discharges ignited at overvoltages that are close to zero. Using a mathematical model of the Townsend process it can be shown easily that the extinction voltage of discharges igniting at very small overvoltages is close to the ignition voltage [73]. Therefore a very high discharge repetition rate is observed of the order of ~ 1 μs [5,92]. Thus the discharge is not pulseless as can be seen very well in [5]. Bartnikas shows an oscilloscope trace with both pseudo-glow and glow discharges, both discernable

as pulses. The author has observed that during the aging process the Townsend-like discharges ignite at ever decreasing overvoltages, resulting in an increasing rise time and a decreasing amplitude.
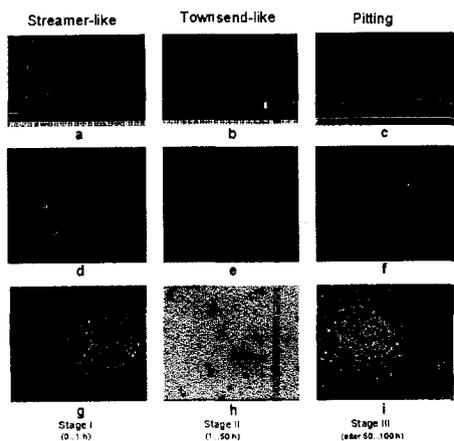

Figure 28.

Three stages of deterioration in a disc-shaped cavity in polyethylene. (a) Pulse shape stage I: streamer-like, (b) optical image of the discharge stage II: Townsend-like, (c) microscopic view with illumination stage III: pitting.

4. CONCLUSIONS

THE large-scale introduction of digitizers and oscilloscopes with bandwidths > 1 GHz on the one hand, and fast and sensitive optical systems on the other hand has led to a better understanding of the aging processes induced by internal discharges in solid dielectrics as polyethylene and epoxy. In the last three years the subject of many a PhD thesis was closely related to discharge aging processes in cavities with a tendency to use extremely fast detection equipment. It shows that despite all the effort that has been put in the understanding of internal discharges and their effect on the insulation, there is still considerable ground to be covered.

It was shown in this paper that UWB measurements and optical recording of the discharge process can fruitfully be used to monitor the discharge aging process and that the onset of severe degradation, ultimately leading to breakdown, can be recognized. It was possible to link the pulse shape and optical appearance of discharges with the chemical degradation processes in the dielectric. Figure 28 [74] shows in condensed form the aging stages that were found for disc-shaped cavities.

The ability to distinguish between different stages of a discharge induced aging process may be used for diagnostic purposes. Especially the detection of the third stage, when the discharge activity is very deleterious, can be of importance. A distinction has to be made between UWB measurements on laboratory samples and measurements

on full-size HV components. In laboratory surroundings the UWB method is now used to test the susceptibility of 'new' insulating materials to discharges.

The applicability of UWB measurements for diagnostics on full-scale HV apparatus has still to be studied extensively. One of the problems that have to be overcome is the distortion of the discharge signal in real components. Several possibilities are suggested to recognize the distorted discharge signal, like the use of neural networks [66] and Fourier analysis [74]. Preliminary results of the author of the use of Fourier analysis of distorted pulses are promising.

The power of the UWB method can be used indirectly as well. In combination with a phase-resolved classical detection system that analyzes the shape of discharge phase distributions a powerful tool is available as was shown in [53]. Combined UWB and phase resolved measurements have shown that the different aging stages have characteristic fingerprints that can be classified by phase resolved discharge analyzers. This might be a promising way to follow because of the large number of classical PD detectors that is used in the world.

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