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Detection and Recording of Partial Discharges below the So-called Inception Voltage

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Abstract: The problem of insulation damage from partial discharges below the so-called inception voltage has not attracted much attention from the insulation community. Indications of possible damage exist from previous research. In the present paper, the possibility of existence of such phenomena is investigated with small air gaps and non-uniform electrode arrangements. It is shown that random discharges below inception voltage exist, which on occasions can be quite numerous. Such discharges are registered and their implications are discussed.

Keywords: Small air gaps, inception voltage, partial discharges, non-uniform electrode arrangement.

1 Introduction

The question regarding insulation damage below inception voltage was already discussed extensively in the scientific literature [1]-[6]. Deterioration of insulating materials below inception voltage was observed in the case of solids [1]-[6], but also in the case of air [7]. In the former papers [1]-[6], it was indicated that the type of by-products appearing at or above inception voltage are qualitatively the same with the by-products below inception. In other words, there is a current below inception which may cause polymer cavity surface chemical changes that are similar to changes that occur when polymer insulation fails under partial discharges at or above inception. The implications of such work are evident, namely, that our understanding of electrical aging is essentially related to the chemistry of solids and, moreover, that chemical changes at or below inception might be used in improving

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the polymer formulation. To validate even more the conclusions of [1]-[6], paper [7] offered experimental data on random discharges that may appear in air gaps, which are larger than the gap in which discharges first appear.

In the present paper, additional evidence is offered with respect to the existence of random discharges below the inception voltage. Three non-uniform electrode arrangements were used for that purpose and the insulating material was air.

2 Experimental Arrangements and Procedure

In this work, a small Greinacher generator was employed [8]. The generator produces invariably 7.5 kV. This is applied to a needle-plane electrode arrangement. The needle has radii of 0.1 mm, 0.3 mm and 0.4 mm. This means that three different electrode arrangements were used. The discharges that take place in the air gap were detected with the aid of a *R*-*C* circuit ($R = 150$ kΩ, $C = 39$ μF). The discharges were observed on the screen of a Tektronix oscilloscope (type 7623 A, bandwidth 20 MHz). There is freedom of movement of the lower plane electrode with respect to the upper needle electrode. The distance between the electrodes is measured with the aid of feeler gauges.

For all three electrode arrangements used, the air discharges first normally at a certain distance (i.e. this is the gap at which the inception voltage is 7.5 kV). In case of normal discharging, the recorded pulses are continuous and on most occasions bridge the gap. Having in mind that the generator gives - by its very construction - a constant voltage of 7.5 kV, it would be interesting to see whether discharge phenomena at air gaps larger - than the one at which discharges first normally occur - can really take place. We believe that, if there are discharges at larger air gaps, this may mean that random events happen below inception.

3 Experimental Results

The needle electrode can be seen in Fig. 11 (expanded view). The maximum electric field developed at the tip of the needle is given by the well known formula of Mason [9]

$$E_{max} = \frac{2sE_{avg}}{r\ln(1+\frac{4s}{r})} \tag{1}$$

where, E_{max} is the field at the needle tip, E_{avg} is the average electric field applied in the gap (= V/s, where V is the applied voltage), s is the electrode gap spacing and r is the radius of the needle tip.

The recording of partial discharges was carried out with a detecting and counting electronic circuit, which incorporated a programmable micro-controller. The latter is programmed in order to register and to add discharge pulses, which are applied at its input, i.e. discharges which occur in the air gap. With the appropriate software the total number of discharges was transferred to the screen of a personal computer. It was experimentally found that the smallest pulse duration, which can be measured, is 12 μs. The control of pulses was performed every 10 μs, consequently, there was sufficient time for the elaboration of each pulse by the micro-controller [10]. In Fig. 2, the whole experimental arrangement is shown. By "electronic circuit" is meant the detecting and counting circuit incorporating a programmable micro-controller which transferred the number of recorded discharges to the personal computer. The resistor of 10 MΩ, appearing in Fig. 2, is connected in series with the high voltage electrode and it has been selected in such a way, so that no damaging discharges may be provoked in the air gap.

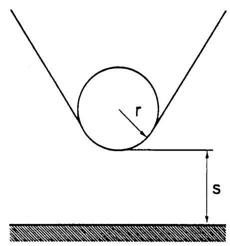

Fig. 1. Expanded view of the needle-plane electrode arrangement.

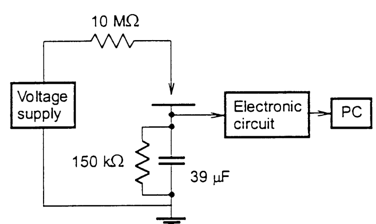

Fig. 2. Exprimental arrangement.

The experimental method was the following: since the output voltage applied to the gap is invariably 7.5 kV, we vary the gap spacing. We define, at first, the gap spacing at which discharges regularly appear on the screen of the oscilloscope - this gap being the gap giving the inception electric field - and then we increase the gap and we observe whether discharges still appear. The method was the same for all three different radii of 0.1 mm, 0.3 mm and 0.4 mm.

Regarding the needle radius of $r = 0.1$ mm, referring to Eq. (1) and by setting $s = 1.40$ mm, the applied voltage V=7.5 kV (and hence E_{avg} = 7.5/1.40=5.35 kV/mm), we have that E_{max} = 16.78 kV/mm. With respect to the needle radius of $r = 0.3$ mm and by setting $s = 1.80$ mm, the applied voltage V = 7.5 kV (hence, E_{avg} = 7.5/1.80 = 4.16 kV/mm), we have that E_{max} = 15.59 kV/mm. Similarly, for the needle radius of $r = 0.4$ mm, by setting $s = 2.10$ mm, we have that E_{max} = 14.85 kV/mm. We remind again that s - in all three cases - is the gap spacing which corresponds to the field at which discharges first regularly appear on the oscilloscope screen, i.e. s is the gap corresponding to the inception field.

Table 1. Results of tests carried out with various gap spacings for a needle of radius of 0.3 mm. Shown also are the time of test as well as the number of recorded discharges.

Gap spacing (mm)	Testing time (min)	Number of discharges	E_{max} (kV/mm)
1.40	10	12470	16.78
1.40	15	18896	16.78
1.40	30	40078	16.78
1.50	60	178	16.42
1.50	60	54	16.42
1.50	60	82	16.42
1.50	90	6	16.42
1.50	90	0	16.42
1.50	120	125	16.42
1.60	60	0	16.10
1.60	120	17	16.10
1.60	240	0	16.10
1.70	120	0	15.80
1.70	240	0	15.80
1.80	120	0	15.53

Tables 1 - 3 below give in detail the experimental results for the three needle radii investigated.

From Tables 1 - 3, it is evident that for all three needle radii investigated, there is a critical electric field which is the inception field (that being 16.78 kV/mm for the needle radius 0.1 mm, 15.59 kV/mm for the needle radius 0.3 mm and 14.85 kV/mm for the needle radius 0.4 mm). We observed that, even below the aforementioned field values, there was discharge activity in the respective gaps. Such experimental data suggest that discharge activity may exist even at lower than the inception field values. This agrees well with previously published data by Bruning et al. [1, 2, 5, 6], who - working with solid dielectrics - indicated that chemical by-products above and below the inception voltage are very similar.

For the recording of discharges and the more thorough study of discharge mechanisms, a Tektronix oscilloscope, type TDS 224 and of bandwidth 100 MHz, was used. This oscilloscope has the possibility of direct connection with a personal computer. The observed pulse waveforms are shown in real time on the screen of the computer with the aid of suitable software (Wavestar). This programme gives the possibility of processing and storing of discharge pulse waveform information. In Figs. 3, 4 and 5 - and with a needle radius of 0.1 mm - pulse waveforms at gaps

Table 2. Results of tests carried out with various gap spacings for a needle of radius of 0.3 mm. Shown also are the time of test as well as the number of recorded discharges.

Gap spacing (mm)	Testing time (min)	Number of discharges	E_{max} (kV/mm)
1.80	5	22299	15.59
1.80	10	33541	15.59
1.80	10	32856	15.59
1.80	30	56235	15.59
1.80	30	17505	15.59
1.90	30	22125	15.29
1.90	30	736	15.29
1.90	30	15326	15.29
2	30	19	15.06
2	30	10	15.06
2	45	7161	15.06
2	45	26765	15.06
2	60	53000	15.06
2	60	1274	15.06
2	120	0	15.06
2	120	0	15.06
2.05	60	12	14.95
2.05	120	231	14.95
2.05	120	105	14.95
2.05	120	0	14.95
2.10	45	0	14.85
2.10	75	0	14.85
2.10	120	4	14.85
2.10	120	0	14.85
2.15	60	0	14.74
2.15	60	0	14.74
2.20	75	0	14.65
2.20	120	0	14.65

of 1.40 mm, 1.50 mm and 1. 60 mm are shown respectively. In Figs. 6, 7, 8, 9 and 10 - with a needle radius of 0.3 mm - pulse waveforms at gaps of 1.80 mm, 1.90 mm, 2 mm, 2.05 mm and 2.10 mm are shown respectively. Finally, in Figs. 11, 12, 13 and 14 - with a needle radius of 0.4 mm - discharge pulse waveforms at gaps of 2.10 mm, 2.15 mm, 2.20 mm and 2.30 mm are shown respectively. The aforementioned figures are indicative as to the nature of the recorded waveforms and essential for understanding the variation of different quantities (such as pulse height and pulse duration) with respect to the needle radii used as well as to the gap spacings.

Table 3. Results of tests carried out with various gap spacings for a needle of radius of 0.4 mm. Shown also are the time of test as well as the number of recorded discharges.

Gap spacing (mm)	Testing time (min)	Number of discharges	E_{max} (kV/mm)
2.10	60	21850	14.85
2.10	60	104605	14.85
2.10	60	52304	14.85
2.10	45	36417	14.85
2.10	45	49207	14.85
2.15	60	1875	14.75
2.15	60	5478	14.75
2.15	90	9858	14.75
2.15	90	6254	14.75
2.15	120	1542	14.75
2.20	60	12	14.65
2.20	60	36	14.65
2.20	90	0	14.65
2.20	90	114	14.65
2.20	120	9	14.65
2.20	120	11	14.65
2.20	240	547	14.65
2.20	240	63	14.65
2.30	120	0	14.47
2.30	120	0	14.47
2.30	120	1	14.47
2.30	240	0	14.47
2.40	120	0	14.30

4 Discussion

In a previous publication, experimenting with the arrangement described here, but with only one needle radius (that of 0.3 mm), we indicated that at a gap spacing of 2 mm (a distance distinctly larger than 1.80 mm), the discharge phenomena became intermittent [7]. In the present work, we extended previous work to more needle radii and the conclusions are much the same, namely that, there is a distance between the electrodes beyond which the discharge phenomena become intermittent *but they exist indeed*. The number of discharges decreases as the gap increases and after a certain point they become random. Such randomness was also observed by Bruning and co-workers. In other words, with the applied electrical field going below the so-called inception value, discharges still persist although in a rather random manner. Whether such phenomena are deleterious for the insulation is still

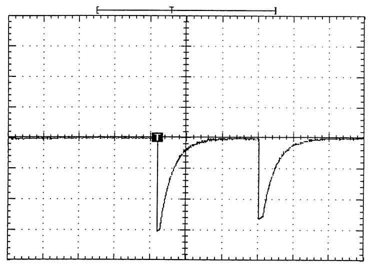

Fig. 3. Discharges recorded in gap 1.40 mm after 18 min (100 V/Div, 250 μs/Div)

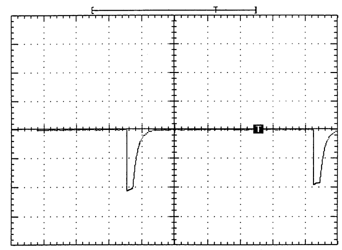

Fig. 4. Discharges recorded in gap 1.50 mm after 35 min (100 V/Div, 100 μs/Div)

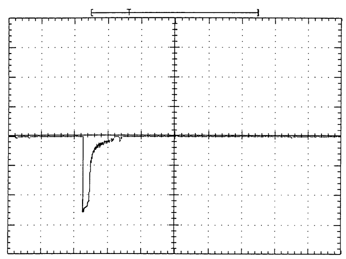

Fig. 5. Discharges recorded in gap 1.60 mm after 83 min (50 V/Div, 250 ms/Div)

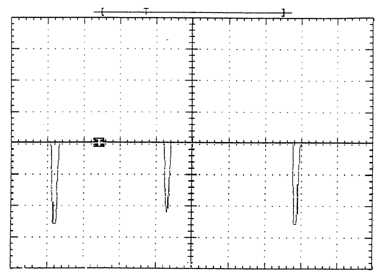

Fig. 6. Discharges recorded in gap 1.80 mm after 6 min (200 V/Div, 500 μs/Div)

a question to deal with, although Bruning and colleagues indicated that chemical by-products at and below inception level are qualitatively the same.

One might object to the term "discharges" below inception. Muhr [11] proposed the term "charging phenomena" instead of "discharges", since according to his opinion, it would be inappropriate to talk about discharges below the inception level. His argument, however, is of a rather philosophical nature. The substance of our claims, however, does not change with either term: the truth is that such phenomena do occur below inception. Evidence offered by the Tektronix type TDS 224 (bandwidth 100 MHz) and the related pulse waveforms supports the claim that we have to deal with discharge events and not just 'charging phenomena'.

The identification of such phenomena below inception is not a trivial matter: observations of the past, namely that partial discharge activity ceases and suddenly a breakdown occurs, may be explained in the light of the present data [12, 13, 14]. Moreover, the line of thought established by Bruning and co-workers did not remain without influence: there is a whole research programme - currently under development - regarding the role of small micro-discharges - even below inception

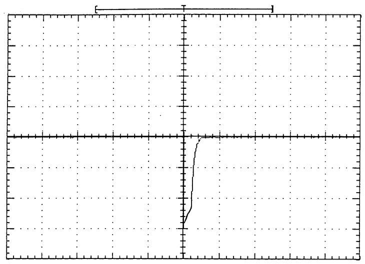

Fig. 7. Discharges recorded in gap 1.90 mm after 18 min (100 V/Div, 500 μs/Div)

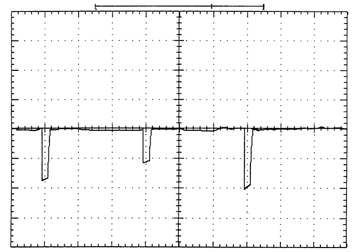

Fig. 8. Discharges recorded in gap 2 mm after 45 min (50 V/Div, 1 ms/Div)

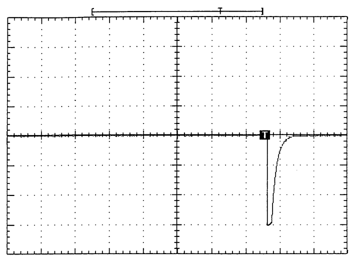

Fig. 9. Discharges recorded in gap 2.05 mm after 58 min (20 V/Div, 500 μs/Div)

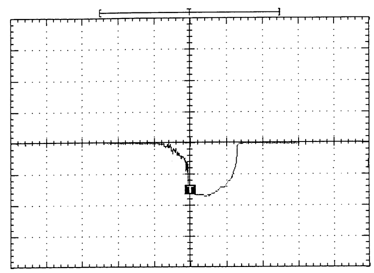

Fig. 10. Discharges recorded in gap 2.10 mm after 124 min (50 V/Div, 5 ms/Div)

- on aircraft interconnect systems sponsored by the Federal Aviation Authority of the USA [20].

An interesting finding of the present work, is that by increasing the gap spacing, the discharge pulse form changes. From the rather sharp form for the smaller gaps, we get a rather flat pulse form as the gap increases. This may suggest a change in discharge mechanism, presumably from a Townsend-type discharge to a discharge of the glow-type. Such pulse form changes have been noted before, albeit with solid dielectrics cite15-[18]. The fact is that such changes are also observed with the present small air gaps. One may argue that the fact that the distance between the electrodes influences the recorded waveform is not only a matter of the physics of the discharge but also on the values of the circuit parameters involved. This is true but the fact remains that a change from a presumably Townsend-type mechanism to a glow-type mechanism may be observed for both gaseous and solid dielectrics.

For needle radius of 0.1 mm, the discharge pulse changed in duration from 150 - 400 s at a gap spacing of 1.40 mm to about 5000 s at a gap of 1.60 mm. Similarly, for the needle radius of 0.3 mm, the discharge pulse changed in duration from 100

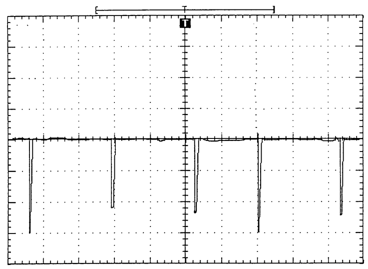

Fig. 11. Discharges recorded in gap 2.10 mm after 18 min (100 V/Div, 500 μs/Div)

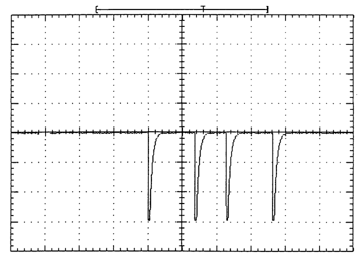

Fig. 12. Discharges recorded in gap 2.15 mm after 25 min (50 V/Div, 500 μs/Div)

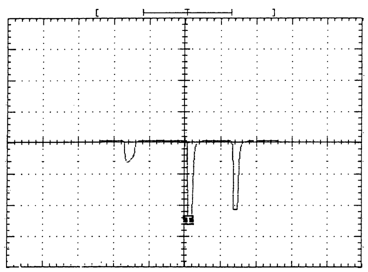

Fig. 13. Discharges recorded in gap 2.20 mm after 39 min (50 V/Div, 500 μs/Div)

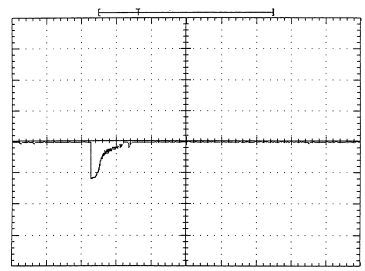

Fig. 14. Discharges recorded in gap 2.20 mm after 39 min (50 V/Div, 5 ms/Div)

- 150 s at a gap of 1.80 mm to about 8000 s at a gap of 2.10 mm. Finally, for the needle radius of 0.4 mm, the discharge pulse changed from 100 - 300 s at a gap of 2.10 mm, to about 5000 s at a gap of 2.30 mm [19]. It seems thus that there is significant change in pulse duration as the gap increases. With increasing of gap spacing, discharge pulses become slower. The change of pulse duration with the needle radius is less clear.

For the needle radius of 0.1 mm, the height of discharge pulse changed from 120 - 600 V at a gap of 1.40 mm to about 130 V at a gap of 1.60 mm. For the needle radius of 0.3 mm, the height of pulse changed from 240 - 520 V at a gap of 1.80 mm to about 90 V at a gap of 2.10 mm. Finally, for the needle radius of 0.4 mm, the pulse height changed from 190 - 340 V at a gap of 2.10 mm to about 60 V at a gap of 2.30 mm. There is a diminution of pulse height as the gap increases. Such findings, with respect to the duration and height of the discharge pulses, can be explained if we bear in mind that the voltage applied is invariably 7.5 kV with increasing gap and also similar work on enclosed cavities in polyethylene [21, 22].

The conclusions of the present work are qualitatively not different from the conclusions offered by Bruning and co-workers, namely that, below inception voltage discharge phenomena are possible indeed. This might have consequences not only in the level of research but also in the industrial field. Phenomena influencing in some way the insulating systems below inception may help us to better understand the mechanism of small current flow at relatively low voltages and may contribute to a better formulation of dielectric materials. Such phenomena manifest themselves as pulses, as was also shown in [23]. Moreover, the way we think about the expected lifetime of insulations may also change since there are indications that no possible voltage lower limit exists below which no damage is expected.

An objection, which might be raised, is that the whole discussion about inception fields or voltages is based on the sensitivity of discharge detectors or the oscilloscopes available. This is correct. This does not refute, however, the basis of our arguments: namely, that discharge phenomena (or events) may occur at very low voltages, that they are of random nature and that their consequences for the lifetime of the insulation may be detrimental. Certainly, the whole question of partial discharges (or charging phenomena) at voltages below inception has to be studied with the aid of very sensitive equipment. One might argue that with very sensitive detecting equipment, if one achieves sensitivities of, say 0.01 pC, any discharges below this level can cause no damage to the insulation. Such view, however, ignores the fact that even very small, minute cavities in a solid insulation can become sources of discharge activity. Whether such activity can cause in the long term appreciable damage is still a subject of discussion and of further research. Another objection to the above might be that in such small air gaps, discharge events at or below inception become blurred [24]. To this, we may argue that the results of the experiments quoted here were reproducible. However, as said already, long time testing and observation of discharge events at inception voltage and below it would give an even clearer idea of the phenomena involved [25].

5 Conclusions

In the present paper it was shown that, even below the so-called inception electrical field, discharge events are possible. Such events manifest themselves as pulses. This conclusion is valid for all three electrode non-uniform electrode arrangements used. The shape of discharge pulses as well as their duration seem to diminish by increasing the gap spacing. The consequences of such discharge phenomena for the industry are discussed.

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