Corona Propagation and Charge Deposition on a PTFE Surface

N. L. Allen and D. C. Faircloth[1]
Department of Electrical Engineering and Electronics
UMIST, PO Box 88
Manchester M60 1QD, UK

ABSTRACT

A description is given of some properties of the corona discharge when propagating over a cylindrical polytetrafluoroethylene insulator surface placed along the axis of a rod-plane electrode arrangement. A scanning electrostatic probe has been used to measure the density of charge deposited on the surface; it is shown that the total net deposited charge is small compared with the total charge injected into the gap. The velocity of propagation has been measured. Effects of preceding coronas on succeeding ones and the nature of deposited charge after breakdown are described. Discussion is given in terms of electron lifetimes and attachment and photoemission processes.

1 INTRODUCTION

IT is well known that under a given electric stress, the path length required to withstand flashover along an insulator surface is greater than it is in the gas in which it is immersed. The problem is overcome by the use of convoluted surfaces, but information on the pre-breakdown and breakdown processes over the surface itself is sparse. Recent work at UMIST has characterised the behaviour of streamers in the absence of space charge in air when passing over a surface [1,2]. The more practical case of a pre-breakdown corona in air, where development is influenced very significantly by space charge fields set up by the assembly of streamers, is now addressed. The present paper forms the first part of a study of the effects of insulators and their profiles on corona and flashover.

An earlier study [3] has concluded that the attachment of electrons to the surface in the formative avalanches of streamer corona makes important modifications to the growth process and results in a reduction in the total charge generated in the corona. However, measurements of the net charge actually deposited on the surface were not made, so that an assessment of the relative importance of the effects of the charge in encouraging more rapid growth (corresponding to the higher peak currents actually measured) or in distorting the applied field could not be made.

The present work aims to progress a step further by measurement of the deposited charge on a smooth polytetrafluoroethylene (PTFE) surface after the passage of a corona charge over the surface in air. Using a recently developed robotic technique [4,5] a specimen is scanned by an electrostatic probe to yield absolute values, with their distribution, of the net charge density on the surface. The limit of resolution of 1 mm has been shown to be sufficiently small that individual streamers can be distinguished and their charge density and width determined [6]. The measurement technique has been extended by the combination of spatially resolved photomultiplier detection of corona light output, with current and voltage records.

The work has been confined to a short rod-plane geometry, where the corona consists of streamers only with no tendency to leader formation. Comparison has been made throughout with corona in air in the same geometry.

2 EXPERIMENTAL TECHNIQUE

The corona charges were produced in a simple rod-plane electrode gap in which three rod diameters, 6.4 mm, 3.15 mm and 1.06 mm were used. The rods were separated from the plane, of diameter 300 mm, by a vertical gap of 95 mm (6.4 mm rod) or 80 mm (3.15 mm and 1.06 mm rods). Each rod was hemispherically-ended and was placed, in turn, in contact with the surface of a 40 mm diameter, 100 mm long PTFE solid cylinder, machined smooth but with no further mechanical treatment (Figure 1).

A positive impulse voltage rising to peak in about 2 μs and declining to half-value in either 63 μs or 41 μs was produced by a small impulse generator providing peak voltages up to 85 kV. This was applied to the rod elec-

Manuscript received on 12 July 2002, in final form 4 December 2002.
[1]Now with Rutherford Appleton Laboratory, Oxfordshire, UK.

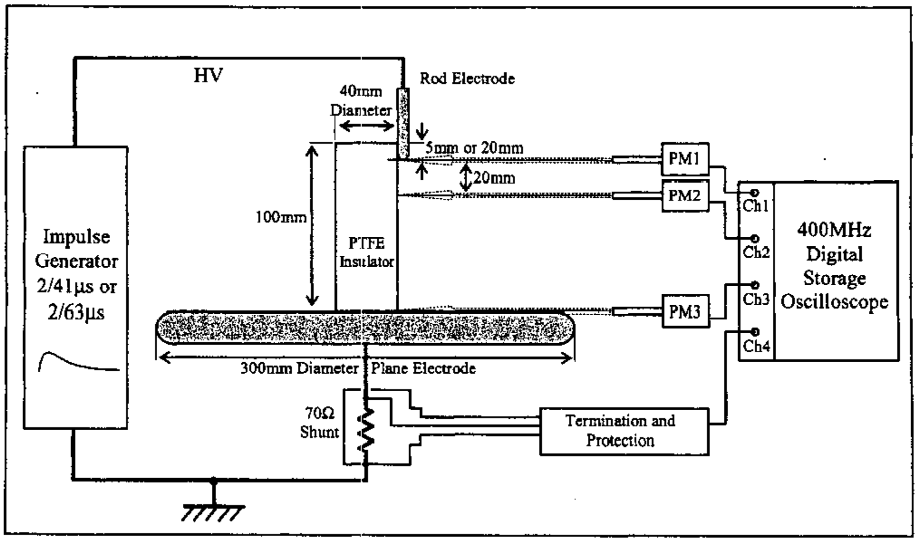


Figure 1. Experimental set-up.

trode. The plane was connected to earth by way of a 70 Ω shunt resistance used for measurement of corona current. Corona development was monitored also by three identical photomultipliers, with vertical fields of view limited by slits to ~3 mm. These were directed respectively to the tip of the rod, to a point 20 mm below the tip and to the

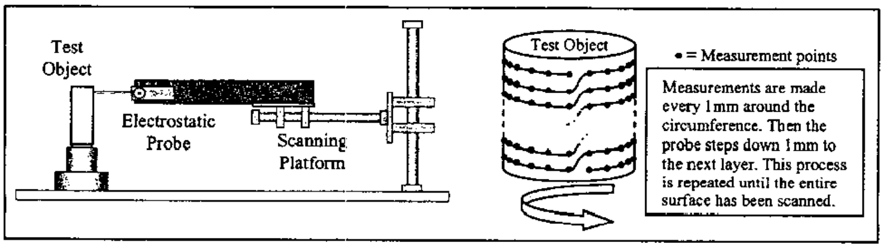
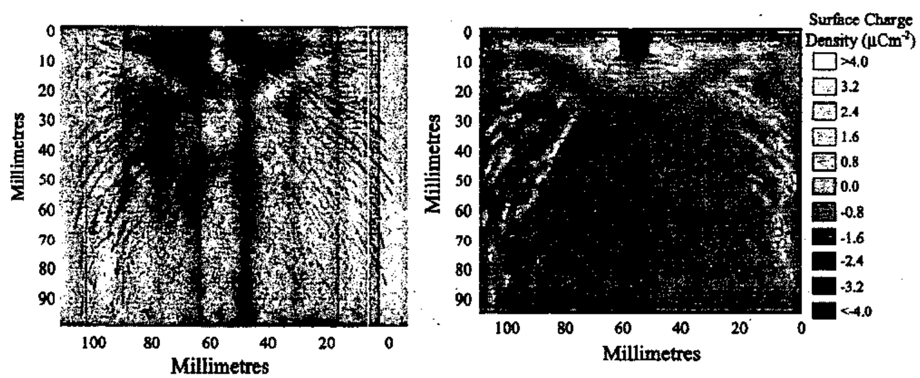


Figure 2. Scanning apparatus described in detail in [5].



(a) Dust Figure *(b) Charge Distribution*

Applied Impulse:	+63.1kVp	Ipeak:	+1.63A
Time of corona:	1.488µs	Injected Q:	+66nC
Instantaneous Voltage:	+41.0kV	Net Surface Charge:	-0.93nC
Initial Velocity:	$16.7\times10^{5}ms^{-1}$	Total Positive:	+1.46nC
Distance Travelled:	100mm	Total Negative:	-2.33nC

Figure 3. An example dust figure and corresponding charge distribution determined by the scanning system.

plane as in Figure 1. Signals from the photomultipliers and from the current measuring shunt were displayed together on a four-channel oscilloscope of bandwidth 400 MHz.

The patterns of charge deposited on the surface were recorded by the scanning technique described elsewhere [5]. For this purpose, the cylinder was carefully removed from the rod-plane system and placed on a rotating platform. The electrostatic probe, of diameter 0.56 mm was brought to a distance 1 mm from the surface and, by means of computer controlled stepper motor drives, scanned horizontally over complete 360° paths as the cylinder was rotated (Figure 2). The probe was reset 1 mm lower after each revolution of the platform until the full length of the cylinder had been traversed. The response was then stored by a personal computer (PC) and displayed, as required; an example is shown in Figure 3.

After scanning, a dust figure was obtained for comparison, by sprinkling photocopy toner powder on to the PTFE and then imaging sections in turn using a standard commercial scanner. A result is shown in Figure 3a, which is of the same specimen as that of Figure 3b, derived from the electrostatic probe. The ends of the streamer trails, with net positive charge $> 4\mu\text{Cm}^{-2}$ are clearly visible and can be seen to correspond closely in both images.

The interaction between corona charges and the PTFE surface could be judged only by a comparison with corona charges in air without the PTFE insulator which thus provided a reference. Therefore, all the experiments with the insulator, reported below, were paralleled by similar tests made in air alone, in which corona current and light output were monitored in the same way.

3 RESULTS

3.1 POSITIVE CORONA CURRENT, CHARGE AND GROWTH CHARACTERISTICS

Corona currents were recorded together with simultaneous photomultiplier observations of the rates of growth of the discharges. Results for all three rods are presented in the following.

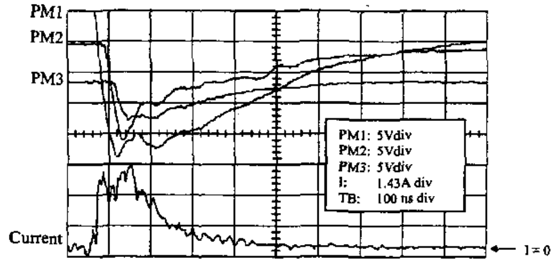


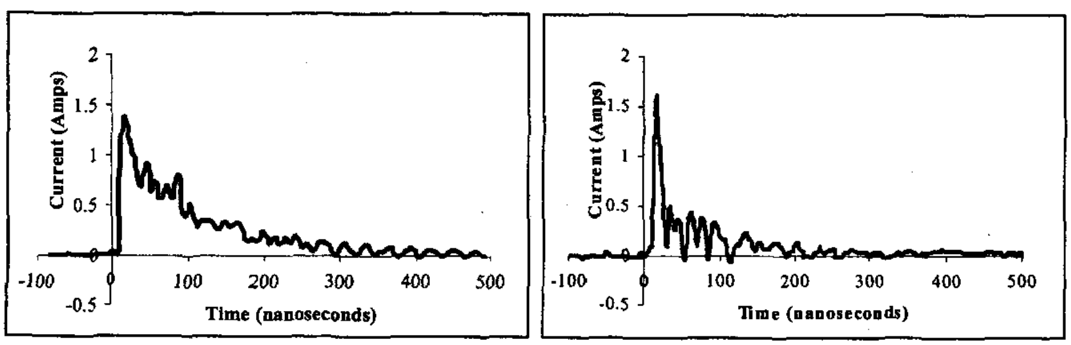
Figure 4. Oscilloscope trace showing the current and photo-multiplier signals for a high current discharge pulse in air.

An example of the oscillograms of current and of light output recorded by the three photomultipliers, is shown in Figure 4 for a corona in air. The differences between the times of appearance of light in the photomultiplier fields of view enabled estimates of streamer propagation velocity to be made.

The corona current pulse shape was changed significantly by the presence of the insulating surface. Figure 5 shows the nature of this change; an increased decay rate in the presence of the PTFE surface is evident. The insulator had smaller effects on the photomultiplier profiles, probably because much of the decay phase was due to afterglow radiation in the surrounding air.

Peak current in air is plotted against instantaneous voltage in Figure 6. For the 6.4 mm rod, currents obtained over a large number of trials appear to separate into two main groups; it is believed that this was due to the existence of two sites for corona initiation.

The initial streamer velocities were measured from the photomultiplier signals received from the rod tip and a point 20 mm. below the tip. When plotted against peak current, Figure 7, a linear relationship was obtained. Finally, the injected charge, plotted against peak current (Figure 8) showed a generally linear relationship though with the largest rod a different slope was obtained; this may be associated with the two groups of current values.



(a) (b)

Figure 5. Corona in air showing current pulse. a, without PTFE insulator; b, near PTFE insulator surface.

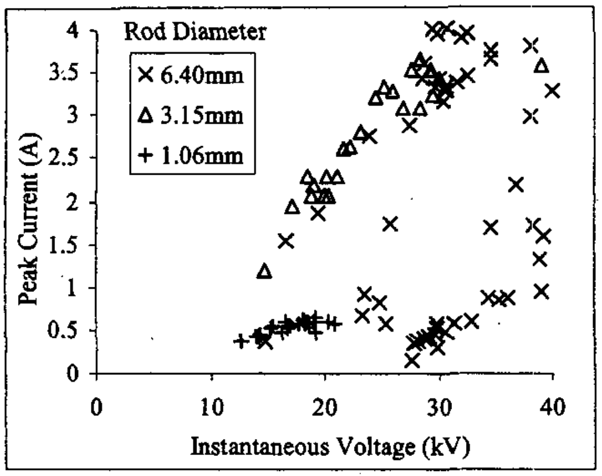


Figure 6. Peak current in air vs instantaneous voltage.

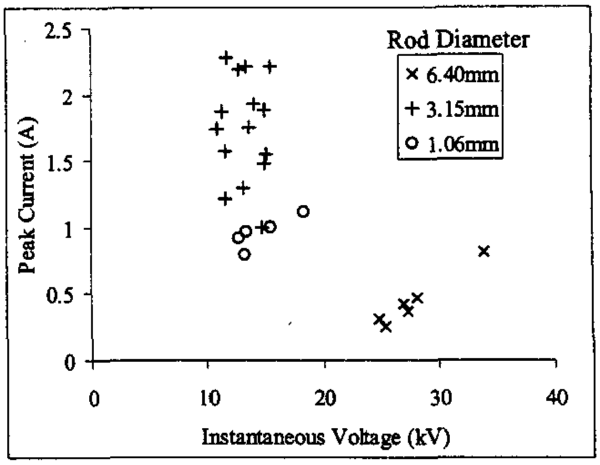


Figure 9. Peak current vs instantaneous voltage (over PTFE surface).

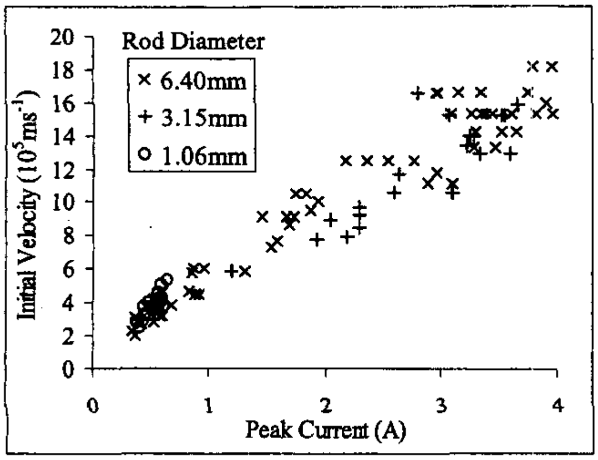


Figure 7. Initial velocity vs peak current in air.

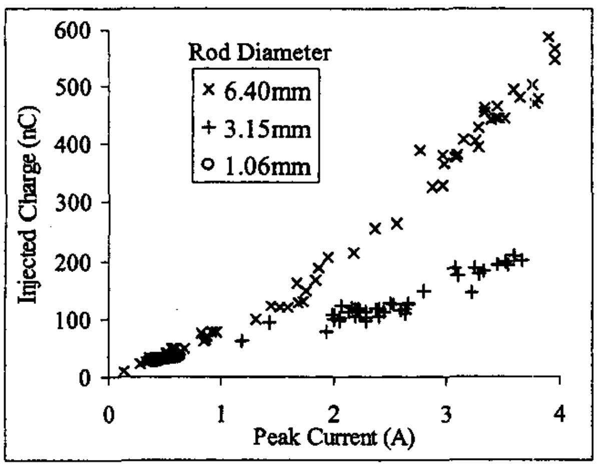


Figure 8. Injected charge vs peak current in air.

These characteristics in air formed an important reference against which surface corona could be compared. Corresponding measurements were made with corona produced at the three rods which were placed in contact with the surface.

Plots of peak current versus instantaneous voltage and of initial velocity versus peak current are shown in Figures 9 and 10, respectively. Scatter was much greater than in the case of air; where earlier initiation occurred, peak currents were also lower. Nevertheless, comparison with those in air shows a tendency for velocities to be slightly higher at a given current. The injected charge is plotted as a function of peak current in Figure 11; this was obtained by integration of the current waveform. Again, the scatter is large, but values are much lower than those in air.

The values reported in the preceding diagrams represent averages over repeated impulses. Charge deposited by one corona may have affected the characteristics of succeeding coronas. The 3.15 mm rod was used in a series of tests at a fixed impulse peak positive voltage, starting with the insulator freshly cleaned with alcohol. A time interval of approximately 10 minutes between each applied impulse was required to scan the insulator for surface

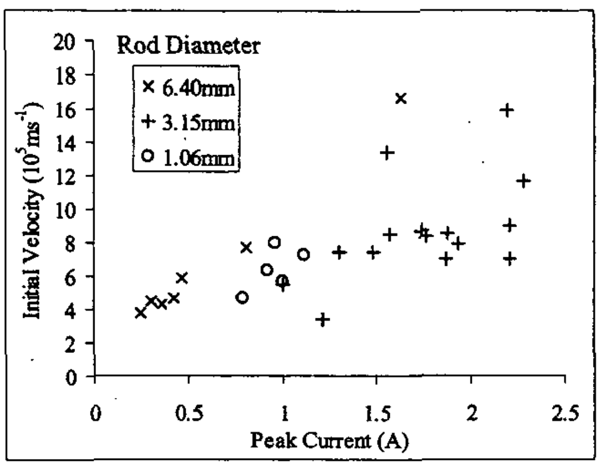


Figure 10. Initial velocity vs peak current (over PTFE surface).

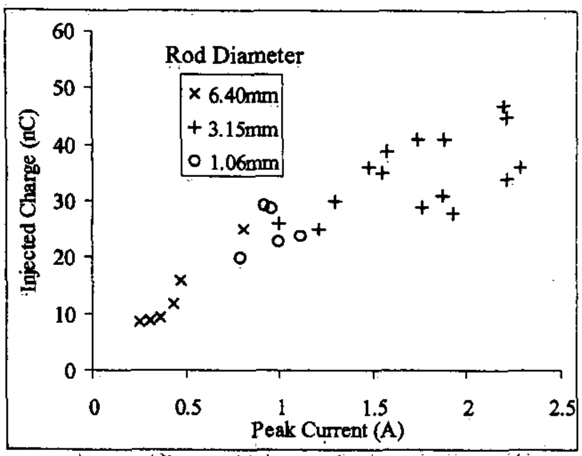


Figure 11. Injected charge vs peak current (over PTFE surface).

charge. Photomultiplier signals obtained with the first three shots are shown in Figure 12 where the light outputs, after the first corona, are seen to be significantly reduced in amplitude.

3.2 SURFACE CHARGE DISTRIBUTION

The scanning technique for measurement of net surface charge density has been described elsewhere [5]. An example scan of a single corona over the PTFE surface is shown in Figure 3b where the 6.4 mm diameter rod was in contact with the insulator. In this figure, the full circumference of the cylindrical specimen is spread out as the width of the two-dimensional diagram. The tip of the rod

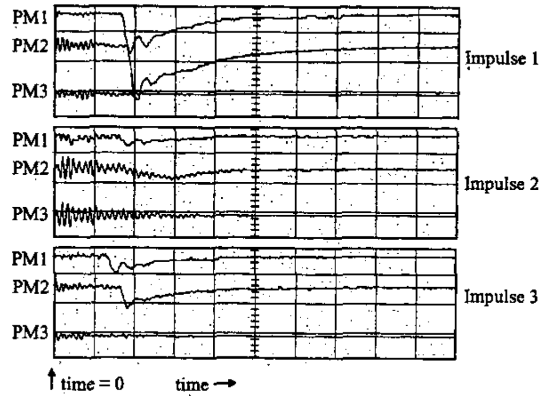


Figure 12. Oscilloscope traces for corona occurring in the first three impulses with the rod in contact with surface; 200ns/div.

was located at the mid-point of the upper horizontal edge. The peak impulse voltage was 63 kV. Streamers reached almost to the plane, which was 95 mm distant from the rod and extended laterally round the cylindrical surface on each side, approaching to within 10 mm of each other at the opposite side. The scan clearly shows regions of net positive charge, from a peak of the order 8 μCm^{-2} at the streamer tips extending backwards along the trails, reducing in net charge density and in width, over a length of about 10 mm. A region of net negative charge was evident around the point of contact with the rod. The total net charge measured over the whole surface was -0.93 nC; the measured negative and positive components were respectively -2.33 nC and $+1.46$ nC. The dust figure of the

Table 1. Data from a series of tests with the 6.40 diameter rod (over PTFE surface)

Instantaneous Voltage (kV)	Peak Current (A)	Initial Velocity (ms^{-1})	Injected Charge (nC)	Net Surface Charge (nC)	Net Positive Surface Charge (nC)	Net Negative Surface Charge (nC)
24.9	0.31	4.6×10^5	8.8	+0.83	1.46	0.63
25.9	0.25	3.9×10^5	8.7	+1.12	1.54	0.42
27.0	0.43	4.8×10^5	11.7	+1.25	1.80	0.55
27.3	0.36	4.4×10^5	9.3	+1.23	1.70	0.47
28.1	0.47	5.9×10^5	16	+1.37	1.64	0.27
34.0	0.81	7.7×10^5	25	+1.2	2.07	0.87
41.0	1.63	16.7×10^5	66	−0.93	1.46	2.33

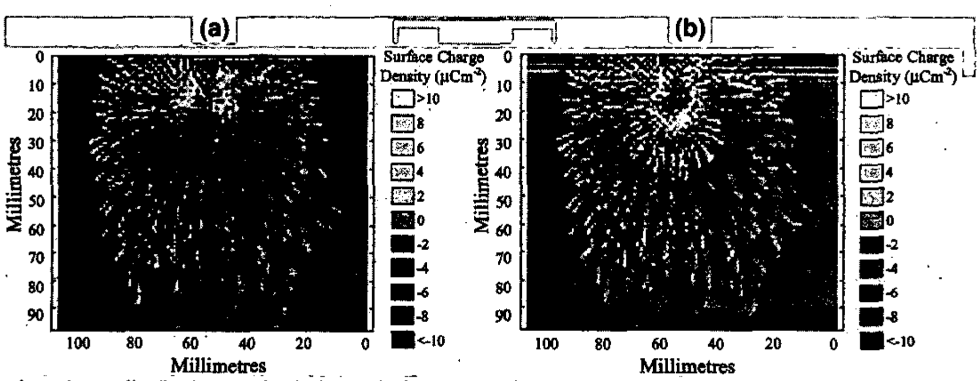


Figure 13. a, Surface charge distribution obtained after a single +45 kVp impulse applied to rod in contact with insulator; b, Surface charge distribution obtained after two +45 kVp impulses applied to rod in contact with insulator.

same event, given for comparison in Figure 3a, shows agreement with the scan, with a region of moderate net negative charge centred about 2 cm from the very dense net negative charge around the point of contact of the rod. The total injected charge was 66 nC. Thus, the net charge detected on the surface was small compared with the injected charge.

Table 1 shows data from a series of tests with the same rod. The current, initial velocity and injected charge (integral of current) are given as a function of the instantaneous voltage. These are compared with the total net charge detected on the surface and with the totals of the net positive and net negative charge components. The net surface charges remain almost unchanged with increasing injected charge and are always small compared with the latter. There was tendency for the negative component to increase at higher instantaneous voltages resulting, in this case, in a negative total net charge at the highest voltage.

With the 3.15 mm rod, a series of up to 20 repeated impulses was applied, after initial cleaning. Scans taken after the first and second shots are shown in Figures 13a and 13b, respectively.

The total accumulated charge on the surface, over the 20 impulses is shown in Figure 14. Accumulation of charge due to the second and subsequent impulses was small. A net positive charge of less than 5 nC remained on the surface after several shots; this may be contrasted with the small net negative charge of −0.93 nC when the 6.4 mm rod was used. The result of Figure 14 may be read in conjunction with that of Figures 12 and 13; the latter shows evidence of a restricted second corona.

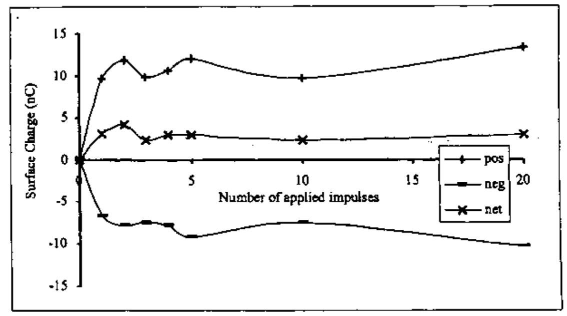


Figure 14. Surface charge after each shot for the rod in contact with the insulator surface.

3.3 FLASHOVER

The 3.15 mm rod was used in a series of experiments at an impulse peak positive voltage of 85 kV, chosen since it was close to the threshold voltage for breakdown of both an 80 mm air gap and of the PTFE cylindrical surface between rod and plane, of the same length.

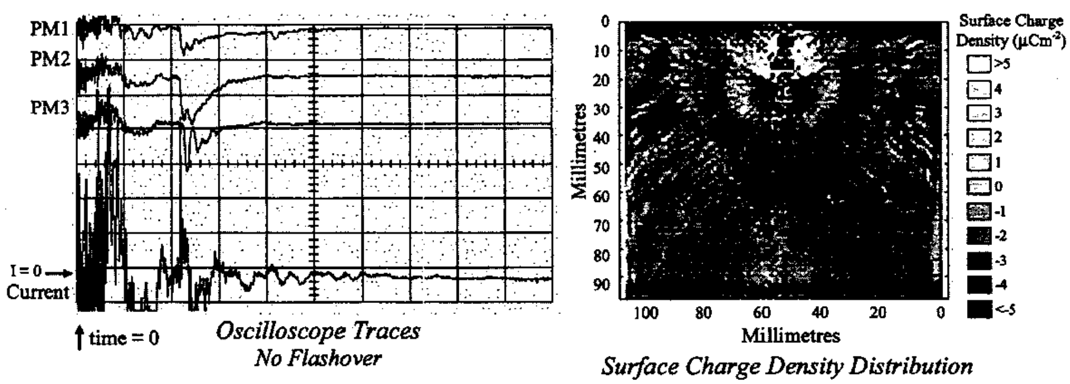


Figure 15. Oscilloscope traces and deposited surface charge for the first +85 kVp impulse.

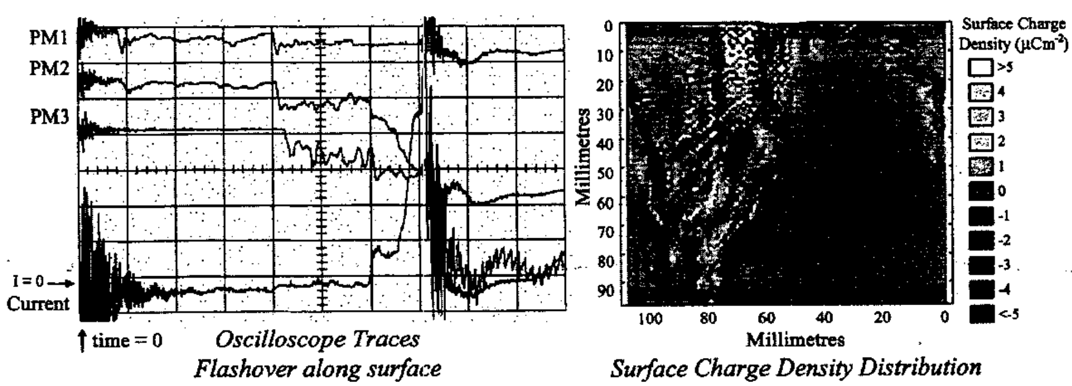


Figure 16. The oscilloscope traces and deposited surface charge for the third +85 kVp impulse.

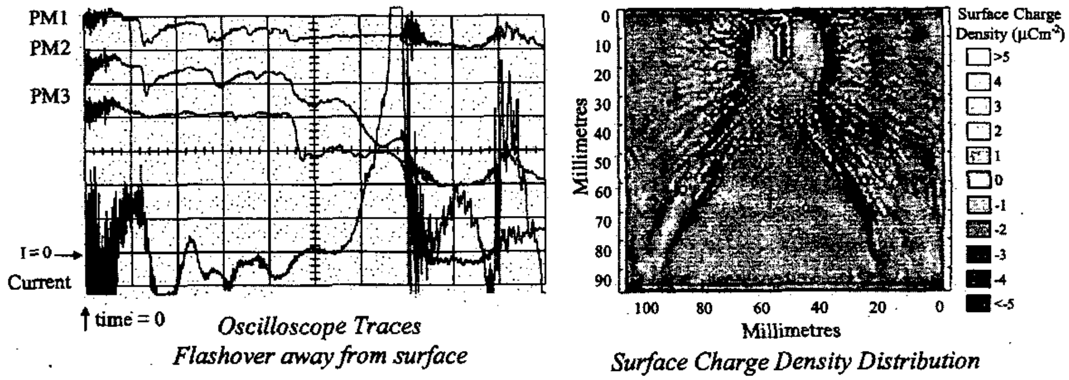


Figure 17. Oscilloscope traces and deposited surface charge for the seventh +85 kVp impulse.

First, 20 impulses were applied to the air gap with a time interval of about 10 minutes between each impulse. No breakdown occurred and the corona data obtained followed similar trends to those discussed in the preceding Sections.

The insulator was cleaned, and any residual charge removed by washing with alcohol and a total of 9 impulses then applied to the rod in succession, a scan being made after each impulse. No breakdown occurred during the first impulse, but all subsequent impulses caused a breakdown, some of which propagated outwards, clear of the surface, while others passed along the surface. The alternative paths appeared to occur at random. Figures 15, 16 and 17 show the photomultiplier signals and the corresponding charge density scans for the first (no breakdown), third (breakdown along surface) and seventh (breakdown away from surface) impulses, respectively. Where breakdown occurred, a very clearly defined region of insignificant charge density was shown, outside which, the ends of streamer trails could be distinguished. A plot of charge density, Figure 18, taken horizontally across the density scan of Figure 17 shows the boundaries of the zero charge density region; narrow regions of net negative charge were deposited there.

It is important to note that in all the examples shown, the streamers reached the plane. The total net charge deposited in the first case (Figure 15) was -4.4 nC. This is consistent with the trends noted earlier, where the total net charge tended to become negative at higher initiating voltages. Where flashover occurred, the total net charge was also negative, but smaller, of the order of a few tenths of nC.

Similar tests were also made with the rod displaced 5 mm horizontally in the air from the surface. Again the first impulse failed to cause a flashover. Subsequent impulses caused flashover with clearly defined boundaries to areas of approximately zero net charge density below the rod. The spark current followed a path away from the surface.

3.4 GEOMETRIC FIELD

The applied, Laplacian field was computed for an example case in which corona was produced at the insulator surface with the 3.15 mm rod, distant 80 mm from the plane. Results are shown in Figure 19, where the per unit applied field distribution is shown; this is superimposed on a scan of the corona charge density. The instantaneous voltage at the rod in this case was 12.7 kV.

Figure 19 shows that streamers propagated towards the plane into a region where the field was $7\times12.7\ \mathrm{kVm^{-1}}$ or

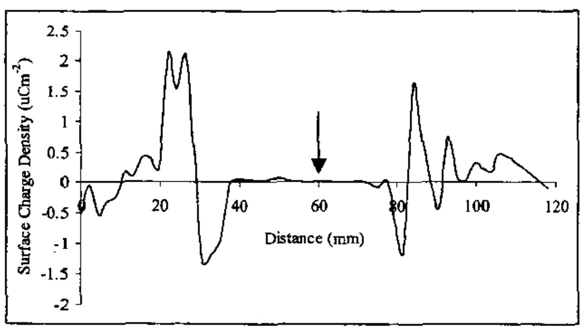


Figure 18. A horizontal plot, taken at 60 mm below the tip of the 3.15 mm rod, showing the charge density distribution for the seventh shot (as shown in Figure 17). The arrow shows the position on the plot which is vertically below the tip of the rod.

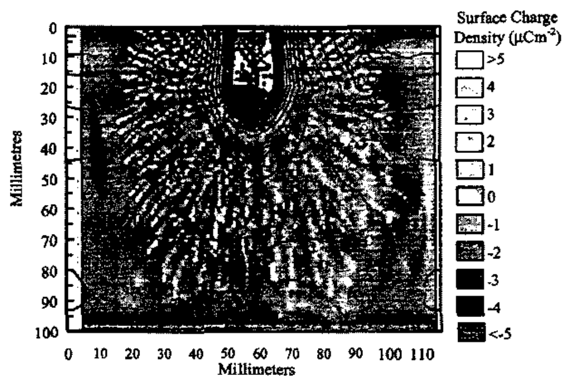


Figure 19. Combined charge density and per unit ambient field map for a discharge at an instantaneous voltage of +12.7kV with the rod in contact with the insulator.

88.9 kVm^{-1} and also to a region 40 mm horizontal distance from the rod where the resultant geometric field was less than 4×12.7 kVm^{-1} or <50.8 kVm^{-1}.

4. DISCUSSION

4.1 CORONA CURRENT AND CHARGE

Principal trends in the results, common to the three rod electrodes, of diameter 1.06 mm, 3.15 mm and 6.4 mm are as follows:

1. Corona properties cannot readily be related to the instantaneous voltages owing to shot-to-shot variation in inception times. Nevertheless, a general increase in peak current, at a given voltage, was discernible when the insulator was present.

2. The presence of the insulator surface caused a more rapid decay in the current from the peak for all the rods used, than was the case in air.

3. The injected charge was, with all three rods, reduced for a given peak current, by the presence of the insulator. This occurred in spite of the increase in peak current at a given voltage, and was a consequence of the rapid decay which the insulator induced.

4. The net deposited charge measured over the surface was small compared with the injected corona charge.

5. Peak corona current in air, was registered when the initial velocities, measured over 20 mm from the rod tip by the photomultipliers, showed that streamers had progressed about 6 mm from the tip of the rod (Figure 5a). This distance was generally similar when the insulator was present.

6. The initial velocity of the streamers, showed a linear increase with the peak current both in air and in the presence of the insulator.

In air, the corona current had declined to a small value after about 200 ns while the presence of the insulator reduced this period to the order of 50–100 ns, with a much larger initial drop in the first 50 ns. Since ions would show negligible movement in this time, the registered current must be entirely due to electron movement and to the rate at which critical avalanches, which ensure replication of the streamer heads, develop.

Over a PTFE surface, propagation of streamers can occur only when the electric field exceeds -450 kV/m, where the velocity is of the order 2×10^5 ms^{-1} [1]. Streamers therefore terminate where the total field falls below this value. Figures 3 and 13 show streamers propagating as far as regions where the applied field is ~100 kVm^{-1}. The difference is made up by the space charge field of the streamers themselves, a fact that is known from direct measurements of corona space charge fields [7,8].

Behind the streamer head, the positive ion density, recorded by the scans, is at first little affected by the electrons progressing into the trail, since their velocity is high and their initial rate of attachment is relatively low. After about 1 cm, however, the net density measured falls to a small value, evidently due to trapping of the electrons to form relatively immobile negative ions. The assumed velocity thus indicates an average lifetime of free electrons in the streamer trail of at least 50 ns.

For times of ~20 ns at which peak current occurs, when the streamers have progressed small distances in the very high applied field near the tip of the rod, the trapping, due to attachment either to air molecules or to the surface, is less rapid. Photoemission of electrons from the PTFE occurs [3], shortening avalanches, and leading to high velocities. The free electron lifetime in this region is larger than it is near the ends of the streamer paths. Thus, the recorded current for these short times is due almost entirely to free electrons in avalanches and in the ends of streamer trails. The rapid reduction, after the peak, must therefore be due to attachment of electrons to the PTFE surface, an effect that is absent when the corona is induced in air alone. In the latter case, the free electron lifetime is longer at all stages of corona growth, giving rise to the broader peak and contrast in current oscillograms shown in Figure 5.

The approximately linear dependence of the growth rate of corona with current, Figure 10, can be compared with earlier results showing the velocity of streamers, in the absence of self space charge, which shows a dependence on electric field which is slightly faster than linear [1]. In the present case the linear increase in peak current with the instantaneous voltage at inception, in the case of the largest rod, Figure 9, again suggests a nearly linear dependence upon applied field, with the self space charge field having small effect. With the two smallest rods, the results in Figures 9 and 10 are too erratic to demonstrate a trend.

It is noteworthy that the decay times of the light detected by the photomultipliers were generally similar for both the air and surface coronas. This does not give useful information about the surface processes, as the decaying light signal will be due mainly to the afterglow in the adjacent air.

4.2 SURFACE CHARGE DEPOSITION

The surface corona is characterised by:

1. A very large lateral spread into regions, to the opposite side of the cylindrical specimen, where the surface component of applied electric field is negligible.

2. The approximate neutrality of charge over large areas that have been covered by streamers during development.

3. The small magnitude of the net charge, integrated over the whole insulator surface, compared with the injected charge, obtained by integration of the measured current.

4. The negligible increase in deposited charge on the surface following application of repeated coronas.

5. The existence of small areas of high negative charge density near the rod electrode.

The results 3 and 4 are consistent with deposition of charges by virtue of their thermal energy after streamer formation has occurred. The potential of the net surface charge must, after the first impulse, be equal to the random thermal energy of the positive ions, that is, about 0.034 eV at room temperature. While a form of "dynamic equilibrium" may exist through renewal of charge during a discharge the net charge density deposited could only change as the result of a change in the random energy of ions, which there is no reason to expect. Moreover, the net charge summed over the whole surface decreased, as a proportion of the total injected charge, as the latter increased, again indicating that deposition was determined by ionic thermal energy. Thus, the charge densities measured in this work are likely to be the maxima that can be deposited by corona on an insulator.

The net negative charge region, result 3, detected only in the region near the rod electrode is likely to be caused by "back discharges" between deposited positive charge and the rod, occurring after the impulse voltage has declined. This has been described by Merril and von Hippel [10], by Hussain and Cornick [11] and discussed again recently by Murooka et al. [12].

The creation of surface charge was shown to increase the probability of breakdown (section 3.3). The net charge density over most of the insulator area has been shown to be small, so generating only small field distortions. It is thus difficult to link the higher breakdown probability to space charge fields over the general surface area. Individual densities of positive and negative charges close to the rod are relatively high (Figure 13b) and it is likely therefore that these may be linked to the higher breakdown probabilities by virtue of the local high surface fields and associated supply of initiating ions. The breakdown process must start near the rod, where oscillograms show a period of continuous development of current and light emission for $\sim 1 \mu s$ before breakdown. Further work is needed on the transition to breakdown.

5 CONCLUSION

A study has been made of impulse corona propagation over the surface of a PTFE insulator and the properties characterised. It has been shown that streamers spread widely over an insulator surface, into regions where the applied electric field is very low.

Comparison with air corona shows that the insulating surface causes an increase in peak corona current. This is associated with an increase in the velocity of propagation of streamers due, in turn, to photo-emission of electrons from the PTFE which shortens the formative time of critical avalanches feeding the streamers. Current during corona growth is interpreted entirely in terms of electron movement.

As the result of a higher rate of decay of current after the peak, the total charge injected into the corona decreases, compared with that in air.

Charge scanning measurements show that the total net charge deposited by corona on to the insulating surface is much less than the total charge injected from the rod. It is unlikely to lead to gross field distortion. Significant net positive charge occurs only near the ends of streamer paths and close to the rod after repeated discharges. The latter is likely to have the more significant influence on breakdown.

ACKNOWLEDGMENTS

This work has been partially supported by a Grant from the Engineering and Physical Sciences Research Council.

REFERENCES

[1] N. L. Allen and P. N. Mikropoulos, "Streamer Propagation Along Insulating Surfaces", IEEE Trans. DEI, Vol. 6, pp. 357–362, 1999.

[2] L. S. Pritchard and N. L. Allen, "Streamer Propagation Along Profiled Insulator Surfaces", IEEE Trans. DEI, Vol. 9, pp.371–380, 2001.

[3] I. Gallimberti, G. Marchesi and L. Niemeyer, "Streamer Corona at Insulator Surface", Proc. 5th Int. Symp. on High Voltage Engineering, Dresden, Paper 41.10, 1991.

[4] D. C. Faircloth and N. L. Allen, "A System for Obtaining High Resolution Macroscopic Surface Charge Density Distributions on Contoured Axi-Symmetric Insulator Specimens", Institute of Physics Electrostatics Conference, Cambridge, UK, pp. 451–454, 1999.

[5] D. C. Faircloth and N. L. Allen, "High Resolution Measurements of Surface Charge Densities on Insulator Surfaces", IEEE Trans. DEI, Vol. 10, pp. 285–290, 2002.

[6] D. C. Faircloth and N. L. Allen, "Calculations Based on Measurements of Charge Deposited by a Streamer on a PTFE Surface", Accepted IEEE Trans. DEI, Vol. 10, paper pp. 291–294, 2003.

[7] N. L. Allen and D. Dring, "Effect of Humidity on the Properties of Corona in a Rod Plane Gap under Positive Impulse Voltage", Proc. Roy. Soc. Lond. Vol. A396, pp. 287–295, 1984.

[8] H. J. Geldenhuys, "The Breakdown Voltage of Air in a 50 cm Rod-Plane Gaps over a Practical Range of Air Density and Humidity", Proc. 5th Intern. Symps. HV Engineering, Braunschweig, Paper 14.02, 1987.

[9] S. Badaloni and I. Gallimberti, "Basic Data of Air Discharges", Padova, Univ. of Padova report, Upee 72/05, Chapter III, 1972.

[10] F. H. Merrill and A. Von Hippel, "The Atomphysical Interpretation of Lichtenberg Figures and their Application to the Study of Gas Discharge Phenomena", J. Appl. Phys., Vol. 10, pp. 873–887, 1939.

[11] M. A. Abdul-Hussain and K. J. Cornick, "Charge Storage on Insulator Surfaces in Air under Unidirectional Impulse Conditions", IEE Proc., Vol. 134A, pp. 731–740, 1987.

[12] Y. Murooka, T. Takada and K. Hidaka, "Nanosecond Surface Discharge and Charge Density Evaluation Part 1: Review and Experiments", IEEE Electrical Insulation Magazine, Vol. 17, No. 2, pp. 6–16, 2001.

Daniel C. Faircloth was born in Cambridge, England in 1974 and was educated at UMIST, Manchester where he obtained the BSc., M.Sc. and Ph.D. degrees, in 1995, 1996 and 2000, respectively. He then moved to the National Grid Company's Engineering and Technology Laboratories at Leatherhead to work on condition monitoring systems for transmission equipment. In 2001, he became a Performance Analyst and managed two research projects entitled "Intelligent Data Analysis and Manipulation" and "Risk to Personnel from Explosive Failure of Porcelain Clad Equipment." In May 2002 he moved to the Rutherford Appleton Laboratory, Chilton, Oxfordshire to work as an Ion Source Physicist on ISIS, the world's brightest neutron and muon source. He is currently working on ion source development for the next generation of particle accelerators.

Norman L. Allen was born in Stourbridge, England and obtained his B.Sc. degree in 1948 at Birmingham University and the Ph.D. degree in the plasma physics field in 1951. After an interlude in Canada working on cosmic rays, using balloons at high altitude, he returned to ionised gases by working for three years in the Laboratory for Insulation Research at MIT. He then spent seven years in the fusion programme at the AEI Research Laboratory, Aldermaston, before moving to Leeds University in 1963. Here he spent some years looking at applications of plasma physics techniques to industrial problems before moving into the high voltage field, where he has carried out researches into the physical mechanisms of breakdown of long air gaps and surface flashover of insulators. He has continued this work at UMIST since 1995.